McGill University
Department of Civil Engineering

# Modeling and Evaluation of Quebec's Air Quality due to an Increase in the Electric Vehicle Fleet Combined with Off-Road Emission Reductions

**Master's Research Project**

**G19-06**

By
Jessica Miville

November 2018
Montreal, Quebec

Abstract

*This study examined the impact of electric vehicles (EVs) and electric off-road equipment on air quality in the province of Quebec. All of the modeled scenarios defined in this study demonstrated positive impacts to different extents. The scenario with a reduction of 40% of certain equipment in off-road sector combined with 250,000 electric vehicles showed the largest reductions of 0.36 ppbv (3.6%) for the annual daily maximum $NO_2$ concentrations, 0.30 ppbv (0.75%) for the maximum daily 8-hour average $O_3$ concentrations, and 0.07 µg/m$^3$ (0.7%) for the annual daily average $PM_{2.5}$ concentrations. The scenario with the smallest benefit was the scenario with the replacement of 187,500 electric vehicles with maximum reductions of 0.030 ppbv (0.3%) for the annual daily maximum $NO_2$ concentrations, 0.022 ppbv (<0.01%) for the maximum daily 8-hour average $O_3$ concentrations, and 0.005 µg/m$^3$ (0.05%) for the annual daily average $PM_{2.5}$ concentrations. For all scenarios, the majority of the benefits were seen near Quebec's large urban areas, with little to no benefits seen in the northern parts of Quebec. In some scenarios, small reduction values could be seen in the eastern United States and Maritime Provinces. A reduction of 10% in the off-road sector showed nearly the double of concentration reductions than the substitution of 312,500 (6%) EVs, demonstrating that electrifying off-road equipment generates more benefits than the electrification of on-road vehicles.*

Cette étude a examiné l'impact des véhicules électriques et de l'équipement électrique hors route sur la qualité de l'air dans la province de Québec. Tous les scénarios modélisés définis dans cette étude ont démontré divers degrés d'impact positif. Le scénario combinant une réduction de 40% de certains équipements dans le secteur non routier et l'ajout de 250 000 véhicules électriques a engendré les réductions les plus importantes: 0.36 ppbv (3.6%) pour les concentrations maximales annuelles de $NO_2$, 0.30 ppbv (0.75%) pour les concentrations moyennes de l'$O_3$ sur 8 heures et 0.07 µg/m3 (0.7%) pour les concentrations moyennes journalières de $PM_{2.5}$. Le scénario dans lequel 187 500 véhicules électriques sont remplacés résulte en la plus faible amélioration de la qualité de l'air, avec des réductions maximales de seulement 0.030 ppbv (0.3%) pour les concentrations maximales annuelles quotidiennes de $NO_2$, 0.022 ppbv (<0.01%) pour la moyenne journalière maximale sur 8 heures et 0.005 µg/m$^3$ (0.05%) pour les concentrations moyennes annuelles moyennes de $PM_{2.5}$. Les bénéfices sur la qualité de l'air ont été observés à proximité des grandes régions urbaines du Québec avec des réductions mineures notées dans le nord du Québec. Dans certains scénarios, de faibles réductions pouvaient aussi être observées dans l'est des États-Unis et dans les provinces maritimes. Le retrait de 10% des émissions du secteur hors route a provoqué une réduction de concentration de polluants correspondant au double de la réduction obtenue en remplaçant 312 500 (6%) des véhicules à carburant par des véhicules électriques, ce qui démontre que l'électrification d'équipement hors route génère plus de bénéfices que l'électrification de véhicules routiers.

Dedication

*This report is dedicated to the loving memory of my father who encouraged me to study engineering and to pursue this master's degree.*

*Je t'aime.*

Acknowledgements

I would like to thank the Air Quality Policy-Issue Response Section (REQA), notably: Rabab Mashayekhi, Jacinthe Racine, Patrick M. Manseau, Annie Duhamel, Mourad Sassi, Calin Zaganescu, Sophie Cousineau, and Radenko Pavlovic as well as Brett Taylor from Pollutant Inventories and Reporting Division (PIRD) at Environment and Climate Change Canada for their support and supervision over the course of this project.

I would also like to thank Professor Subhasis Ghoshal, eng. for his supervision of this project.

Finally, I would like to thank Françoys-Xavier Stephenson for his continuous love and support.

Table of Contents

List of Figures

List of Tables

List of Symbols and Abbreviations

- **μg/m³:** microgram per meter cubed
- **APEI:** Air Pollutant Emission Inventory
- **AQMS:** Air Quality Management System
- **AURAMS:** A Unified Regional Air-quality Modelling System
- **BAU:** Business As Usual
- **BEV:** Battery Electric Vehicle
- **CAAQS:** Canadian Ambient Air Quality Standards
- **CTM:** Chemical Transport Model
- **CV:** Conventional Vehicle
- **E3MC:** Energy, Emissions, and Economy Model for Canada
- **ECCC:** Environment and Climate Change Canada
- **EPA:** Environmental Protection Agency
- **EV:** Electric Vehicle
- **FCHEV:** Fuel Cell Hybrid Electric Vehicle
- **FCV:** Fuel Cell Vehicle
- **GEM:** Global Environmental Multiscale
- **GHG:** GreenHouse Gas
- **HDDV:** Heavy Duty Diesel Vehicle
- **HDGV:** Heavy Duty Gasoline Vehicle
- **LDDT:** Light Duty Diesel Truck
- **LDDV:** Light Duty Diesel Vehicle
- **LDGT:** Light Duty Gasoline Truck
- **LDGV:** Light Duty Gasoline Vehicle
- **LDT:** Light Duty Truck
- **LDV:** Light Duty Vehicle
- **LEV:** Low-Emission Vehicle
- **LPG:** Liquefied Petroleum gas
- **MC:** MotorCycle
- **MDA8:** Maximum Daily 8-hour Average
- **MDDELCC:** *Ministère du Développement Durable et la Lutte contre les Changements Climatiques*
- **MOVES:** Motor Vehicle Emission Simulator
- **NEI:** National Emission Inventory
- **PHEV:** Plug-in Hybrid Electric Vehicle
- **PIRD:** Pollutant Inventories and Reporting Division
- **PM:** Particulate Matter
- **ppbv:** Parts per billion volume

- **REQA:** Air Quality Policy-Issue Response Section
- **SAAQ:** *Société de l'Assurance Automobile du Québec*
- **SMOKE:** Sparse Matrix Operator Kernel Emissions
- **VOC:** Volatile Organic Compounds
- **ZEV:** Zero-Emission Vehicles

# 1 - Introduction

The province of Quebec is known for its generation capacity and use of renewable energy. In 2016, 99.8% of the province's energy was generated using renewable sources, with hydroelectricity accounting for 95.2% of the electricity production, followed by wind and biomass National (National Energy Board, 2017). In 2017, Hydro-Quebec exported 34.4 TWh (Hydro-Québec, 2018a), displaying an abundance of renewable energy that could be used to power Electric Vehicles (EVs) in Quebec. This makes the province an ideal candidate to implement a fleet of electric vehicles in order to reduce air pollution. The government of Quebec has plans to increase the number of electric vehicles, with the goal of registering 100,000 EVs by 2020, and at least 300,000 EVs by 2026 (Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques (MDDELCC, 2017)). The government of Quebec is providing economic and social incentives, by awarding (EV) owners a rebate of up to $8,000 upon purchase of a new EV, access to certain reserved bus and taxi lanes, free access to certain toll bridges, and free parking in certain municipalities (AVEQ, 2017). EV owners will also obtain several other rebates over the lifetime of their vehicle as compared to a Conventional Vehicle (CV): electricity costs less than conventional fuel, less vehicle maintenance is required, and insurance costs up to 20% less (Hydro-Québec, 2018b). An EV typically costs more upon purchase, however savings of up to $6,400 can be found after driving 100,000 km (Branchez-Vous, 2018). With these benefits, it is hoped that there will be a large increase in EVs sales in order to reach the objectives. Many off-road equipment also have electric equivalents, such as electric lawn mowers, and recreational vehicles. With the cost of fuel being higher than the cost of electricity (Gouvernement du Québec, 2018), it is logical to believe that consumers will opt for electric alternatives, as long as the price of the equipment is comparable. As such, this study's objective is to cover a quantitative analysis regarding the impact of electric vehicles and electric off-road equipment on the air quality in the province of Quebec for the year 2025, by running several scenarios through an air quality model.

Several studies have been conducted to determine the impact EVs will have on GreenHouse Gas (GHG) reductions in the form of $CO_2$ or $CO_2$-equivalent emission reductions (Calnan, Deane, & Ó Gallachóir, 2013; Camus & Farias, 2012; Göransson, Karlsson, & Johnsson, 2010; Hedegaard, Ravn, Juul, & Meibom, 2012; Hu, Zou, & Yang, 2016; Kantor, Fowler, Hajimiragha,

& Elkamel, 2010; Nichols, Kockelman, & Reiter, 2015; Oshiro & Masui, 2015; Smith, 2010; Varga, 2013). Studies showed that $CO_2$ emission reductions are expected when the EVs are powered through renewable or nuclear energy sources (Calnan et al., 2013; Camus & Farias, 2012; Göransson et al., 2010; Hedegaard et al., 2012; Hu et al., 2016; Oshiro & Masui, 2015; Smith, 2010). However, regions that rely on fossil fuels for their energy did not experience $CO_2$ emissions reduction (Kantor et al., 2010; Nichols et al., 2015; Varga, 2013). Fewer studies considered the impact of EVs on air quality. Of these studies, most only considered the impact of fuel exhaust emissions versus the emissions due to the increased electricity production needed to power the EVs.

Kantor et al. (2010) focused on the mobile emissions in Toronto regarding the impact of alternative fuel vehicles, notably Plug-in Hybrid Electric Vehicles (PHEVs), fuel cell vehicles (FCV), and fuel cell plug-in hybrid electric vehicles (FCPHEVs), on air quality. The study simulated the market penetration of these vehicles from the year 2008 to the year 2025 and deduced the emission impact. The year 2025 had the largest market penetration for all vehicles, which also showed the largest reductions in $CO_2$, $NO_X$, and VOC. The FCV also showed $PM_{2.5}$, $PM_{10}$, and $SO_X$ emission reductions, which was not always the case for FCPHEVs and PHEVs. Analyses for these latter vehicles showed both emission reductions and increases, depending on whether additional coal electricity production was needed to power the vehicles (Kantor et al, 2010). It should be noted that no Chemical Transport Model (CTM) was used in that study, and therefore, the formation of $O_3$, and secondary PM, as well as pollutant transport was not studied, which could potentially influence the results (Kantor et al., 2010).

A study performed by Nichols et al. (2015) focused on the state of Texas, where they depend predominantly on coal energy. Several scenarios were conducted to see the impact of electric vehicles on air quality with different energy mixes (coal, natural gas, biomass, nuclear, etc.). It was found that EVs powered by electricity produced by coal or by the typical energy mix, showed 289 and 93 times more $SO_2$ emissions, respectively, compared to a gasoline-powered passenger car. Natural gas, on the other hand does not release $SO_2$. The implementation of a Plug-in Electric Vehicles (PEV) fleet caused a penalty of increased $CH_4$ emissions (up to 2,000 times more), and increased $N_2O$ emissions (up to 5,000 times more) than CVs, depending on the source of electricity used to power the vehicles. $NO_X$, $CO_{2eq}$, and $PM_{10}$ emissions were lower for all sources of electricity as compared to conventional vehicles, except for coal. The increase in VOC and CO emissions due to an increased electricity demand needed to power the PEV were lower for all energy mixes compared to conventional vehicles (Nichols et al., 2015). It should be noted that similar to the study performed by Kantor et al. (2010), no CTM was used in this study, thus the transportation of pollutants downwind of power plants and the formation of PM and $O_3$ remains to be explored.

A study conducted by Duvall et al. (2007) found similar results to Nichols et al. (2015). Their study focused on the year 2050, examining the impact of plug-in hybrid electric vehicles (PHEVs) on air quality over the United States. Their analyses concluded that there would be an increase in coal power generation needed to provide sufficient electricity to power the PHEVs. Despite this, all of their scenarios showed a large $CO_2$ reduction, with the largest reduction shown with a high PHEV fleet penetration (Duvall, Knipping, Alexander, Tonachel, & Clark, 2007b). However, there was an increase of 10% in primary PM emissions due to an increase in coal-powered electricity. Although, most regions experienced a decrease in PM concentrations as there was a decrease in VOC, $NO_X$, and $SO_2$ concentration, which lead to a decrease in secondary PM formation. Overall, most regions showed a small but significant improvement in air quality (Duvall, Knipping, Alexander, Tonachel, & Clark, 2007a; Duvall et al., 2007b).

A study performed by Li et al. (2016), looked at replacing 100% of conventional light-duty vehicles fleet (20.6 million vehicles) in Taiwan with electric vehicles. They examined two energy sources to power the fleet: coal-fired power plants and renewable energy sources. They found emission reductions in the transportation sector of 1500 Gg $yr^{-1}$ (85%) for CO, 165 Gg $yr^{-1}$ (79%) for VOCs, 33.9 Gg $yr^{-1}$ (27%) for $NO_X$, and 7.2 Gg $yr^{-1}$ (27%) for $PM_{2.5}$ for both energy sources. However, an increase of 29% of emissions was seen for all pollutants ($SO_2$, $NO_X$, VOC, CO, $NH_3$, and $PM_{2.5}$) for coal power generation. Annual mean surface concentrations were similar for both the coal and the renewable energy scenarios. For the coal power generation scenario, there were increases of 2-5% in $SO_2$ concentrations, a reduction of 7-18% in $NO_X$ concentrations, a decrease of 45-65% in CO concentrations, a decrease of 20-21% in VOC concentrations, a decrease of 4-6% in $PM_{2.5}$ concentrations, and a 1% decrease in 24-h average $O_3$ in rural areas and a 3% increase in 24-h average $O_3$ concentrations in urban areas. Similar reductions and increases were seen for the clean power scenario for CO, VOC, $PM_{2.5}$, and 24-h $O_3$ concentrations. However, there were larger $NO_X$ concentration reductions were larger for the clean power scenario, ranging between 13-21%, and there was a less than 1% increase in $SO_2$ concentrations in both urban and rural regions. The regional mean pollution episode days would also decrease by up to seven for the coal power generation scenario and up to nine days for the clean power scenario per year with the addition of EV (Li et al., 2016).

A study carried out by Soret et al. (2014) examined the implementation of an electric fleet in Barcelona and Madrid, for a high implementation rate of 40% in both cities. A natural gas combined-cycle power plant, just outside of Barcelona, sources the electricity for these two cities. An emission inventory during an air pollution episode that occurred in 2011 was used as a worst-case scenario. The addition of EV showed reductions of 11% and 17% for $NO_X$, 5% and 3% for $PM_{10}$, and 41% and 38% for CO in Barcelona and Madrid, respectively. However, exceedances in the $NO_2$ hourly limit of 200 $\mu g/m^3$ and the maximum 24-h level of $NO_2$ value of 40 $\mu g/m^3$ were seen in both Madrid and Barcelona. $PM_{2.5}$ emissions were also elevated, reaching 40 $\mu g/m^3$ in both cities, surpassing the threshold value of 25 $\mu g/m^3$. $O_3$, $SO_2$, and CO concentrations were far lower than their maximum target levels, though it can be seen that maximum hourly $O_3$ concentrations increased by 4% with fleet electrification. This was because modifications to the VOC to $NO_X$ ratio, which increased the formation of $O_3$. $SO_2$ reductions due to vehicle electrification were not significant (under 2 $\mu g/m^3$). Overall, it was concluded that fleet electrification would improve urban air quality, even while using electricity produced by a natural gas combined-cycle plant. Although, the authors mentioned that the results would differ if coal were used as a source of electricity (Soret, Guevara, & Baldasano, 2014).

Brady and O'Mahony (2011) modeled a high (30%), medium (15%), and low (10%) electric vehicle fleet penetration of Battery Electric Vehicles (BEVs) and PHEVs for the year 2020. Significant reductions were found for CO, VOC, PM, $NO_2$, and $NO_X$ emissions while running the emission model COPERT 4, which is similar to the EPA MOVES 2014a model. The greatest reductions observed for the high adoption scenario with following pollutants having the largest reductions: $PM_{10}$ (27%), $NO_X$ (26%), and VOC (17%). However, the authors expect that the low adoption scenario is the most realistic scenario, which demonstrated an 8% reduction in $PM_{10}$ and $PM_{2.5}$, as well as a reduction of 9% for $NO_X$. The lowest reductions for the low adoption scenario are CO and $NO_2$ with 4% and <1%, respectively (Brady & O'Mahony, 2011).

Yu and Stuart (2017) studied the impact of compact growth, electric vehicles and urban sprawl growth for the region of Tampa Bay. They studied what the impacts on air quality would be and whether it would be beneficial to adopt one of the mentioned constructs for the year 2050. All future scenarios showed reductions in butadiene and benzene concentrations compared to the 2002 base case. Although, all showed increased $NO_X$ concentrations using the population weighted exposure concentration metric. The EVs scenario displayed the highest $NO_X$ concentrations due to increased coal power plant emissions from an increased electricity demand, whereas the compact growth scenario showed the lowest $NO_X$ concentrations. The authors mentioned that clean energy initiatives might reduce $NO_X$ emissions due to the increased electricity demand required to power EVs (Yu & Stuart, 2017).

One study looked at the air quality impact of replacing the diesel buses in London by alternatively fueled buses using the emissions inventory from 2010. The highest contending scenarios were the hybrid buses and the natural gas fueled buses. The hybrid bus scenario showed the lowest emission reduction compared to the base case with reductions of 68, 77, 51, and 42% for non-methane hydrocarbons (NMHC), CO, $NO_X$, and PM pollutants, respectively. Although, regarding $O_3$, the hybrid bus scenario resulted in 50% more $O_3$ concentration than the base case. The natural gas scenario however showed a decrease in population-weighted $O_3$ exposure by 39%. However, the hybrid scenario resulted in a decrease of $1.20 \times 10^8$ kg/year of equivalent $CO_2$, whereas the natural gas scenario resulted in an increase of $4.46 \times 10^8$ kg/year. This included an estimate of the energy required to produce the hybrid bus batteries. A cost-benefit analysis was then performed, which included the number of premature mortalities for the different scenarios. The base case scenario reported five premature deaths per year in Greater London, while the hybrid scenario would cause four deaths and the natural gas scenario would cause one death. By their cost-benefit calculations, the hybrid buses were less expensive than the natural gas ones, which had a low engine efficiency and high $CH_4$ emissions (Chong, Yim, Barrett, & Boies, 2014).

Razeghi et al. studied the impact of the implementation of an electric fleet in the South Coast Air Basin (SoCAB) of Califonia. This area was chosen as it has exceeded the 24-h $PM_{2.5}$ standard over 15 to 30 days in the past despite a relatively clean electric grid mix. A BEV with a 160 km range and a PHEV with a 64 km all-electric range were considered. A base case and several scenarios were studied with several combinations involving either 40% electric fleet of BEVs or

PHEVs, a Business As Usual (BAU) or off-peak electric vehicle charging (charging early in the morning or late at night), and a wind energy penetration of 7%, 33%, and 50%. All scenarios results in a reduction of 8-h average ozone and 24-h average of $PM_{2.5}$ concentrations compared to the BAU. Despite the higher electricity demand, the BEV scenarios showed overall greater $O_3$ and $PM_{2.5}$ concentration reductions compared to the PHEV. However, there were localized $O_3$ increases near the power plants for the low wind energy penetration scenarios. The off-peak charging scenarios resulted in small reductions to $O_3$ and $PM_{2.5}$ average concentrations compared to the BAU charging scenarios, though the reductions were greater with increasing wind energy. The impact of increased wind energy penetration did not have as significant impact as expected by the authors. A small increase in 8-h average $O_3$ was observed, which is due to the decrease in $NO_X$, which in turn altered the VOC to $NO_X$ ratio, resulting in increased $O_3$ formation. As such, the authors caution that careful planning in the transportation and power generation sectors are required in order to increase air quality benefits and mitigate negative impacts (Razeghi et al., 2016).

Little information has been found regarding the electrification of off-road equipment and vehicles. To the best of my knowledge, only one study has been performed regarding the subject pertaining to air quality. Nopmongcol et al. (2017) conducted this study, examining electrification of vehicles and off-road equipment. It was concluded that electrification resulted in modest air quality benefits. There were larger $O_3$ and PM reductions in urban areas due to lower mobile emissions, leading to reduced human exposure to these pollutants. Off-road equipment electrification was found to be more beneficial than on-road fleet electrification, on the continental United States (Nopmongcol et al., 2017). The electrification of lawn and garden equipment accounted for 48% of total VOC and 12% of total $NO_X$ emission reductions. The authors believe that the off-road equipment has a good electrification potential as they have little energy requirements and could yield the users long-term operation and maintenance savings. They also believe that financial incentives could promote the use of electric off-road equipment, which would further enhance air quality benefits. The benefits of electric on-road vehicles are thought to be constrained due to market penetration, and on-road vehicle emissions are regulated by the "Tier 3" standards. A reduction of marine vessel emissions is also possible if there is a decrease in crude oil import demands, allowing for increased air quality benefits in port cities (Nopmongcol et al., 2017).

This literature review confirms that there has yet to be a study evaluating the impact of electric vehicles in a region where the electricity is mainly from nearly 100% renewable sources, such as the province of Quebec. As well, there has only been one study to date that has investigated the impact of electric off-road on air quality in a region, which does not primarily rely on renewable energy. Therefore, this current study focusing on the impact electric vehicles and off-road equipment on air quality in the province of Quebec constitutes as a source of original knowledge.

## 2 - Air Quality Modeling Platform

### 2.1 Air Quality

Several meteorological conditions, such as wind speed, temperature, humidity, atmospheric pressure and solar radiation can influence the concentration of pollutants in the atmosphere. Wind can propel clean air from the ocean or a forest towards a city or likewise, it can transport polluted air over long distances. A strong wind can increase pollutant dispersion, and it can even sweep up pollutants on the ground into the air. A rise in temperature favors chemical reactions and volatilization of gases. A temperature increase can also promote the creation of tropospheric ozone, whereas a large drop in temperature can trap pollutants near the surface. Likewise, higher atmospheric pressure can lead to stagnant air, limiting pollutant dispersion, whereas low pressure increases ventilation, resulting in better air quality (Grundstrom et al., 2015). As well, humidity and precipitation can dissolve some pollutants, leading to the formation of acid rain or entrapping pollutants in the soil. In addition, solar radiation favors photochemical reactions, especially the creation of ozone. Time and location also play in the role to one's exposure to air contaminants. The closer one is to an emitter, the more one will be affected by a higher concentration of pollutants. Additionally, anthropogenic sources can peak at various moments throughout the day (e.g. traffic in the morning and evening) or year (e.g. residential wood combustion during the winter) (Laumbach, Meng, & Kipen, 2015).

The contaminants that are of greatest concern are $SO_X$, $NO_X$, VOC, $NH_3$, CO, PM, and $O_3$. These air pollutants can come from various sources such as industrial activity ($PM_{2.5}$, $SO_X$, VOC), agriculture ($NH_3$), wood combustion ($PM_{2.5}$), fossil fuels ($PM_{2.5}$, CO, $SO_X$, $NO_X$, VOC), road dust ($PM_{10}$, $PM_{2.5}$), solvents (VOC), biogenic emissions (VOC), forest fires ($PM_{10}$, $PM_{2.5}$) (EPA, 2018). These criteria air contaminants are continuously studied due to their impact on human health, the environment, and the economy. They can cause numerous health issues, such as nose and throat irritation ($PM_{10}$, $O_3$, and $NO_X$), eye irritation ($O_3$); aggravate respiratory diseases ($O_3$, $NO_X$); lung irritation ($PM_{2.5}$, $O_3$); and cardiac issues ($PM_{2.5}$, CO). Environmental issues can also arise from exposure to pollutants, such as reduced visibility ($PM_{10}$, $PM_{2.5}$, $SO_X$, and $NO_X$); smog ($PM_{2.5}$, $O_3$); decreased plant growth rate ($O_3$), acid rain ($SO_X$, $NO_X$), algal growth due to increased nutrition ($NO_X$, $NH_3$) (EPA, 2018). As such, it is important to limit environmental and human exposure to these critical air contaminants.

All the criteria air pollutants save $O_3$ can be directly emitted and are considered primary pollutants. Ozone is a secondary pollutant, created due to photochemical reactions between $NO_x$ and VOC. Particulate matter can also be created by other pollutant interactions, and as such can be considered a secondary pollutant as well as a primary pollutant. Particulate matter is typically categorized by size, namely under 10 micrometers ($PM_{10}$) or under 2.5 micrometers in diameter ($PM_{2.5}$) (Moran, Dastoor, & Morneau, 2014). These pollutants do not have a long atmospheric lifetime. $NO_2$ spends about two days near the Earth's surface or two weeks between the planetary boundary layer and the stratosphere. $SO_2$ has a lifespan of two days, PM around a week, $O_3$ around a month, and CO has a lifetime of about one to three months (Seinfeld & Pandis, 2016; Summers & Fricke, 1989).

## 2.2 REQA's 2006 Modeling Platform

### 2.2.1 2006 Modeling Platform Overview

Several programs and models were used to obtain the results of this project. The overall ensemble is known as the 2006 platform, which is used by the air quality modeling team Air Quality Policy-Issue Response Section (REQA) at Environment and Climate Change Canada (ECCC) at the Canadian Meteorological Centre (CMC). The year 2006 represents the meteorological reference year, which is used to run the A Unified Regional Air-quality Modeling System (AURAMS) CTM as an offline air quality model. The platform includes different processes that are run before and after AURAMS. The three main components of the 2006 platform are: the meteorological data from the Global Environmental Multiscale Model (GEM), the emission data processing system Sparse Matrix Operator Kernel Emissions (SMOKE), and the CTM AURAMS (Chen et al., 2010). Figure 1 shows how the main components of the 2006 platform interact with one another.

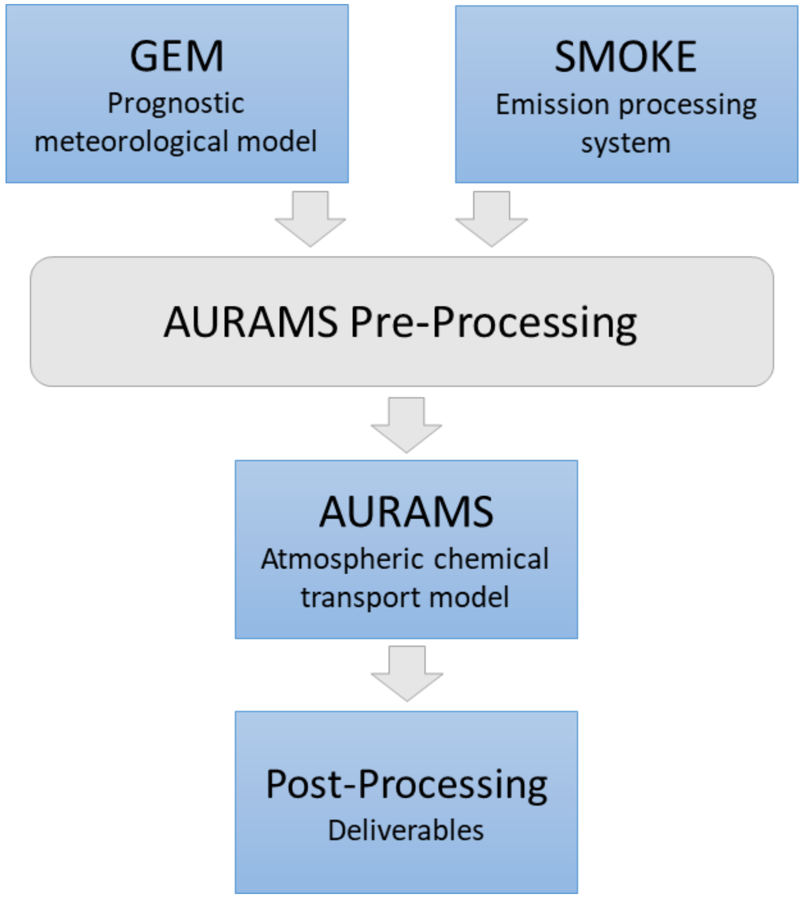



*Figure 1 Schematic of the 2006 air quality modelling platform. Based on Chen et al. 2010*

The process begins with an anthropogenic pollutant emission inventory composed of several sectors, namely: industrial sector, agriculture, on-road, off-road, etc. from Canada, the United States, and Mexico. The inventories vary by country, as each country follows their own method to record emissions. The Canadian inventory used in this study was obtained from the REQA section at ECCC. The Canadian inventory is derived from the 2025 BAU inventory, which was projected from the 2014 Air Pollutant Emission Inventory (APEI) to the year 2025 using ECCC's Energy, Emissions, and Economy Model for Canada (E3MC) along with economic and energy projections as inputs (Sassi, 2018). This was done for all the Canadian sectors except for the transport sector (off-road, on-road, marine, locomotive, and aircraft), which was derived using the 2013 inventory projected to the year 2025 (Brett Taylor, personal communication, June 8th, 2018). The on-road inventory was obtained from PIRD. They modeled the on-road emissions using the Motor Vehicle Emission Simulator (MOVES) version 2014a which was developed by the

United States Environmental Protection Agency (EPA) (Sassi, 2018). This model uses inputs such as vehicle types, vehicle year, meteorological data, vehicle operating characteristics, and road types to produce emission factors or emission inventories (EPA, 2016). In this case, an emission inventory for the year 2013 was produced and the outputs from the model were re-normalized based on the quantity of fuel sold in each province in that year, and then projected to the year 2025 (Brett Taylor, personal communication, June 8$^{th}$, 2018). The United States emissions are from the 2016 United States projected National Emission Inventory (NEI), which were projected from the 2005 NEI. The on-road and off-road inventory data were both generated using MOVES. The Mexican emissions correspond to the 1999 Mexico NEI (EPA, 2017).

### 2.2.2 Pollutant Emission Inventory and SMOKE

Inventories come in different formats, both spatial and temporal. Certain inventory sectors represent an annual total, whereas others are composed of average month or day emission data. As well, certain sources are listed as precise location (by coordinates), and others by regional total. The inventories are processed by SMOKE in order to obtain AURAMS-ready emissions (Racine, 2018). It is important to note that SMOKE is not a model but a processing system that disaggregates emissions temporally and spatially and creates gridded, chemically speciated, hourly emissions that can then be used as inputs for the AURAMS model. SMOKE was developed in the United States in the early 2000s with financing from the United States Environmental Protection Agency (EPA) and supported by the Community Modeling and Analysis System (CMAS). SMOKE is an ensemble of multiple C Shell scripts and FORTRAN 90 programs. The system uses spatial surrogates and temporal allocation codes (hourly, weekly, and monthly) which correspond to when and where an emission is distributed on the grid. For example, on-road vehicle emissions would be allocated to the road network, with peak emissions during the morning and evening traffic rush, while residential wood combustion emissions would be allocated over residential areas during the winter months. Sources that have coordinates (point sources) do not use surrogates as their coordinates already spatially allocate them; however, the emissions are distributed temporally. SMOKE is also able to vertically distribute emissions knowing the stack height of point sources (CMAS, 2018). Additionally, SMOKE transforms typical pollutants into chemical species accepted by the Atmospheric Deposition Oxidant Model (ADOM-II) chemical mechanism in AURAMS. For example, VOC emissions are separated into paraffin, olefin, xylene, toluene, isoprene, etc. Statistics Canada provided Canadian spatial surrogates, whereas the American and Northern Mexican surrogates were derived from the EPA website (Sassi, 2018). Temporal surrogates for Canada, US, and Northern Mexico follow the default SMOKE profiles. Some adjustments were made to the Canadian temporal surrogates, such as for residential wood combustion and road dusts, and in the case of this project, to the off-road sector (Racine, 2018).

SMOKE outputs are hourly and spatially allocated model-ready emissions for the anthropogenic sources, which are grouped into four main categories: mobile, non-mobile, major points, and minor points for AURAMS. The mobile category is composed of on-road and off-road vehicles, ships, locomotives, planes, including brake lining and tire wear emissions. The non-mobile category comprises of dust emissions from construction, agriculture, mining, fugitive dust, etc. as well as ammonia emissions from the agricultural sector. Major points refer to facilities with a chimney stack height greater than 30 meters for Canadian sources and greater than 35 meters for American sources. These facilities include power plants, refineries, smelters, etc. These sources contain precise location information given by their latitude and longitude, stack height and diameter, ejection velocity, and ejection temperature, which will allow AURAMS to calculate the plume rise, as well as the extent of the plume. The minor point sources have a stack less than 30 meters. The mobile and non-mobile emissions are gridded using the United States EPA surrogate tool, which spatially allocates the emissions. A set of four emission categories is produced for each simulation. The data is then further processed by KornShell (ksh) and Tool Command Language (Tcl) scripts to adhere to the file format supported by AURAMS (Racine, 2018).

Biogenic emissions are processed with the US EPA's Biogenic Emission Inventory System (BEIS) model v3.09 using land us maps from Canadian forest surveys instead of the default Biogenic Emissions Land use Database (BELD3) data. The biogenic emissions are processed separately from the anthropogenic sources as the data is rarely modified (Racine, 2018).

### 2.2.3 Meteorology data and GEM

The GEM model v.3.3.2 predicts short-term and medium-term weather data. It is used to generate meteorological files containing all the necessary variables to run a simulation on

AURAMS, such as wind velocity, humidity, temperature, solar radiation, precipitation, etc. The horizontal GEM domain covers all of North America and is composed of 575x641 variable points, with a fixed core composed of 432x565 points with a 15 km resolution (see Figure 2). The vertical domain is composed of 58 hybrid levels that linearly augment from the surface to a pressure level of 10 hPa. For the 2006 platform, the model is run for the year 2006 in 30 hour segments, with the first 6 hours being spin-up, which allow for the model to reach an equilibrium state. The results are then interpolated to satisfy the AURAMS grid and other requirements (Chen et al., 2010).

### 2.2.4 AURAMS

The model inputs for AURAMS v.1.5.4 include the emissions processed by SMOKE, as well as already processed natural emissions. The natural sources include biogenic emissions (vegetation VOC emissions and NO soil emissions), wildfire emissions, lightning emissions, sea-salt emissions, etc. The modeling of pollutant transport and chemistry processes is a crucial step in the production of scenarios. These processes are non-linear and difficult to predict. Pollutants can travel long distances during which they can settle to the ground or react with other pollutants to create new species. The model mimics the three primary removal processes: chemical reactions, dry deposition, and wet deposition (Moran et al., 2014). As these pollutants can be transported over several hours, even days, over hundreds of kilometers, one must also consider the changing meteorological conditions.

The AURAMS CTM model is a Eulerian, regional and offline (independent of GEM) model that requires inputs from GEM and SMOKE. The model can predict PM and $O_3$ concentrations, acid depositions and other pollutants. Additionally, gaseous chemistry is modeled using the Acid Deposition and Oxidation Model (ADOM-II), which handles 49 gas species, 9 particulate species, and 117 chemical reactions. In AURAMS, particulate matter is separated into 12 size categories, ranging from 0.01 to 41 micrometers in diameter and nine different chemical compositions: $SO_4$, $NO_3^-$, $NH_4^+$, black carbon, primary organic carbon, secondary organic carbon, crustal matter, sea salt, and $H_2O$. Many aerosol and phase liquid processes are implemented in the model: nucleation, condensation, coagulation, activation, sedimentation, etc. (Chen et al., 2010). For this project, AURAMS was run using a 143x107 point grid, which covers nearly all of North America and gives a resolution of 45 km, true at 60°N. There are 28 vertical levels that follow terrain topography, ranging from the surface to 29 km in altitude (Chen et al., 2010). The following image (Figure 2) illustrates the GEM grid in grey, and the AURAMS CTM 45 km grid in blue.

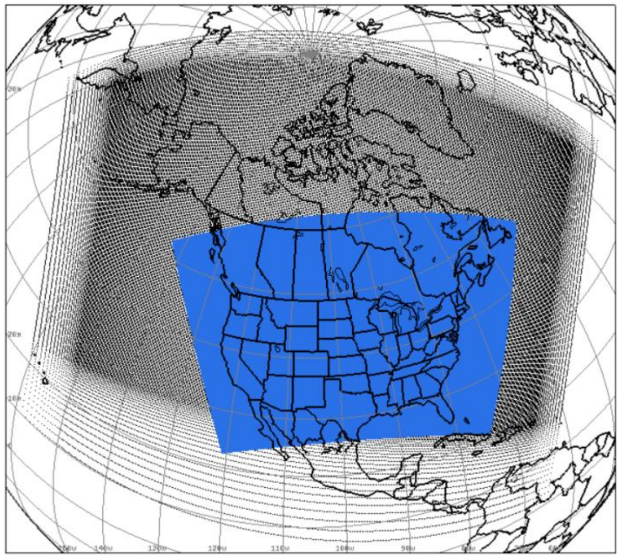


*Figure 2 The different grids of the 2006 platform: the GEM grid (grey), the 45 km AURAMS grid (blue) (Chen et al. 2010)*

### 2.2.5 Post-Processing

AURAMS' post-processing suite is composed of ksh and tcl scripts programmed by REQA at ECCC. It calculates finer end-products from AURAMS' outputs. These products are typically composed of a single pollutant (e.g. ozone) and one metric, such as: daily maximum calculated from running mean (8h or 24h), running maximum (8h or 24h), running mean (8h or 24h), daily maximum, daily average, etc. (Racine, 2018). For this project, only the pollutants and metrics that follow the Canadian Ambient Air Quality Standards (CAAQS) ($NO_2$ annual daily maximum concentrations in ppbv, Maximum Daily 8-hour Average (MDA8) summer $O_3$ concentrations in ppbv, and annual daily average of $PM_{2.5}$ concentrations in $\mu g/m^3$) are considered. The CAAQS metrics were chosen for this study as they are an element of the Air Quality Management System (AQMS) that were established through a consensus-based process which included representatives from Health Canada, ECCC, provinces and territories, Indigenous peoples, as well as stakeholders from industry, health, and environmental organizations (CCME, 2017). These metrics allow for the verification of results in the air quality field. AURAMS' post-processing scripts can also produce differences between the BAU and the reduction scenarios, which allow us to see the impact of the reduction scenarios versus the BAU (Racine, 2018).

# 3 - Methodology

## 3.1 Modeling Scenario Selection

Table 1 lists all the scenarios that were used for modelling. The BAU value of 250,000 electric vehicles was selected based on the government's intention of reaching 100,000 electric vehicles by 2020 and 300,000 by 2026 (MDDELCC, 2017). The values for the other electric vehicle scenarios were based on the BAU, by trying to maintain realistic scenarios that are close to the targets that the government of Quebec has set by varying the number of electric vehicles by +/- 10% and +/-25%. All electric vehicles are assumed to be battery electric vehicles in the modelling of light duty vehicles and light duty trucks. PHEVs were not included as the driver profile is inconsistent. A study performed by Nicholas and Turrentine (2017) claim that as high as 30% of PHEV users do not charge their vehicle and that others plugging in less when the price of fuel was around 20% lower than usual. As well, it was shown that drivers with a lower electric range plugged in their vehicle less frequently than those with a larger electric range (Nicholas & Turrentine, 2017). Motorcycles do exist in an electric version but were not considered in this study, as they are not included in the 300,000 electric vehicle objective set by the Government of Quebec (MDDELCC, 2017).

*Table 1 List of scenarios modeled*

| Scenario | Number of electric vehicles | Percentage of electric off-road (%) |
|---|---|---|
| **BAU** | 0 | 0 |
| **1** | 0 | 10 |
| **2** | 0 | 25 |
| **3** | 0 | 40 |
| **4** | 250,000 | 0 |
| **5** | 250,000 | 10 |
| **6** | 250,000 | 25 |
| **7** | 250,000 | 40 |
| **8** | 275,000 (+10%) | 0 |

| | | |
|---|---|---|
| **9** | 225,000 (-10%) | 0 |
| **10** | 312,500 (+25%) | 0 |
| **11** | 187,500 (-25%) | 0 |

## 3.2 On-road Calculations

The preferred method for revising the emissions to account for the electric vehicles would have been to use the EPA model MOVES that is designed to perform series of calculations based on user specified vehicle type and operating characteristics to provide an estimate of bulk emission or emission rates. However, the use of MOVES for emission processing requires multiple national or regional scale input data retrieved from many different sources. The access to the full list of input data of MOVES for Canada was very limited at the time of this project; specifically, the post-processing data that is required to re-normalize MOVES data with the quantity of projected fuel sales for the year 2025 was unavailable. This re-normalization process must be conducted, according to the UN-FCC and the IPCC, in order to account for the amount of fuel used as part of an energy balance initiative (Brett Taylor, personal communication, June 8th, 2018). Therefore, considering the limitation of required data and the time constraint of this project, the MOVES approach was not used for emissions calculations. However, the internal tables and profiles provided by MOVES were used to develop a methodology to estimate emissions for each scenario.

As the on-road inventory was already projected to the year 2025, it was decided that the emissions would be divided by the number of vehicles expected for the year 2025. The number of vehicles forecasted for the year 2025 was calculated using the MOVES tables to account for vehicle type (car or truck) and, type of fuel (gasoline or diesel). As such, the number of vehicles per vehicle type per fuel type was determined. As the inventory is further subdivided by road type, a method to allocate the vehicles properly per road type was developed. In the on-road inventory, there are five road type categories: off-network, rural restricted access, rural unrestricted access, urban restricted access, and urban unrestricted access. The off-network road type includes parking lots, driveways, and gas stations; the rural restricted access road type denotes rural highways; rural unrestricted access represents rural non-highway roads such as: collectors, ramps, and local roads; urban restricted access denotes urban highways; and urban unrestricted, which has the definition as rural unrestricted but for urban regions (Laurita, 2012). Since the off-network includes parking lots and refueling areas, it was determined that all vehicles must at one point be stationary and parked, which accounts for a larger portion of emissions than other road types. Hence, all vehicles were allocated to the off-network road type, and the emissions were divided by the total number of vehicles per vehicle type per fuel type. The same could not be said for urban and rural roads.

The vehicle population circulating on urban roads and rural roads was determined by examining municipality population data across Quebec, using vehicle populating data from the *Société de l'Assurance Automobile du Québec* (SAAQ) (SAAQ, 2018) and using population census data (Statistics Canada, 2018). A municipality was considered urban if it had the population requirements per the Statistics Canada standards: a population of at least 1,000 and a population density of at least 400 people per square kilometer (Statistics Canada, 2017). Additionally, municipalities that did not have the Statistics Canada qualifications to be considered urban but bordered large urban areas (Montreal and Quebec), were also considered urban. The complete list of municipalities and how they were classified in this study can be found in Appendix B. Vehicles not assigned to a municipality in the SAAQ database were assumed to be urban. A ratio between the vehicle population in rural and urban municipalities was calculated to be 1.343:1, which was used as the ratio between the number of vehicles that circulate on urban and rural roads. It was then determined that vehicles typically circulate on both unrestricted and restricted roads, and therefore the vehicle population for rural un-restricted and rural unrestricted, as well as urban restricted and urban unrestricted had the same vehicle population. With the vehicle populations now calculated for each vehicle, fuel, and road type, calculations were performed to calculate the emissions emitted per vehicle. The number of vehicles per vehicle type per fuel type that were replaced by EVs was determined using ratios based off the current vehicle population. For example, there is a larger Light Duty Gasoline Vehicle (LDGV) fleet than in the Light Duty Diesel Vehicle (LDDV), and as such, there was a larger number of EVs replacing vehicles in the LDGV category than the LDDV category.

The emission factors per vehicle varied depending on the pollutant, vehicle type, fuel type, and road type, which was to be expected. Given that electric vehicles do not emit any exhaust emissions, the inventory was modified to remove emissions equivalent to the number of vehicles present in the scenario (e.g. 250,000 electric vehicles). Non-exhaust emissions in the form of tire wear emissions remained in the inventory. Brake wear emissions of electric vehicles the value was assumed to be zero such as in the study by Timmers and Achten (2016), however the brake wear emission values remained unchanged to compensate for the additional tire wear electric vehicles experience due to an increase in weight of 24% compared to a conventional vehicle. It was determined that because of this extra weight, electric vehicles emit 18.7% more $PM_{10}$ emissions and 22.5% more $PM_{2.5}$ emissions than conventional vehicles (Timmers & Achten, 2016). The additional brake emissions to compensate for the lack tire emissions from the electric vehicles and were calculated to add 18% to the $PM_{10}$ and 20% to the $PM_{2.5}$ emissions, which is similar to the values found by Timmers and Achten (2016). They also stated that electric vehicles cause 19% more $PM_{10}$ and 23% more $PM_{2.5}$ road surface wear as well as 24% more $PM_{10}$ and $PM_{2.5}$ resuspension of road dust. As found in several studies (EPA, 2006; Gillies, Etyemezian, Kuhns, Nikolic, & Gillette, 2005; Timmers & Achten, 2016), the resuspension of dust follows a linear relationship with the weight of a vehicle. However, a study by Hooftman et al. (2016) declared that resuspension would be too difficult to quantify due to its dependence on season, precipitation and road moisture content (Hooftman, Oliveira, Messagie, Coosemans, & Van Mierlo, 2016). The province of Quebec is known for its long winters, during which snow is usually covering the ground, and where most of the province usually receives around 1,000 mm of precipitation a year (ECCC, 2018). The addition of electric vehicles would therefore lead to a perhaps minute increase in road dust resuspension values and was hence excluded.

Overall, five on-road scenario inventories were created, along with a BAU. The scenario with 187,500 EV replaced 3.60% of the Light Duty Vehicle (LDV) and LDT fleet with electric vehicles, with the other scenarios with similar replacement values: the 225,000 EV scenario replaced 4.32%; the 250,000 EV scenario replaced 4.80%; the 275,000 EV scenario replaced 5.28%; and the 312,500 EV scenario replaced 6.00%.

### 3.3 Off-road Calculations

The off-road equipment selected for electrification was based on the study by Nopmongcol et al. (2017) and can be sorted into the following categories: lawn and garden equipment, recreational equipment, and industrial/commercial equipment. The lawn and garden equipment category consist of chain saws, chippers/shredders, commercial turf equipment, leaf blowers, push lawn mowers, riding lawn mowers, trimmers/edgers, snow blowers, and specialty vehicle carts, etc. The recreational equipment category is composed of golf carts, all-terrain vehicles (ATVs), motorcycles, snowmobiles, etc. Industrial/commercial equipment includes refrigeration, light commercial pumps and air compressors, forklifts, sweepers/scrubbers, etc. (Nopmongcol et al., 2017). The full list can be seen in Table A1 in Appendix A. It should be noted that most of the equipment listed only operate during a certain part of the year. SMOKE accounts for this by allocating them temporally so that the emissions follow the proper seasonal trend.

The off-road scenario reduction values were chosen as part of a sensibility study, to study the impact of electric off-road replacements at varying proportions. The reduction values were also chosen to try and maintain realistic scenarios considering the lack of a market penetration study. It was thought to be unlikely that the electric off-road equipment selected for the study would reach market penetration as high as 50%; therefore, the percentage emission reduction values of 10%, 25%, and 40% of the selected fuel-based equipment were chosen. Henceforth, the reduction scenarios will be known as percent reductions to the off-road sector, though it is only a select few off-road equipment that were chosen for this study.

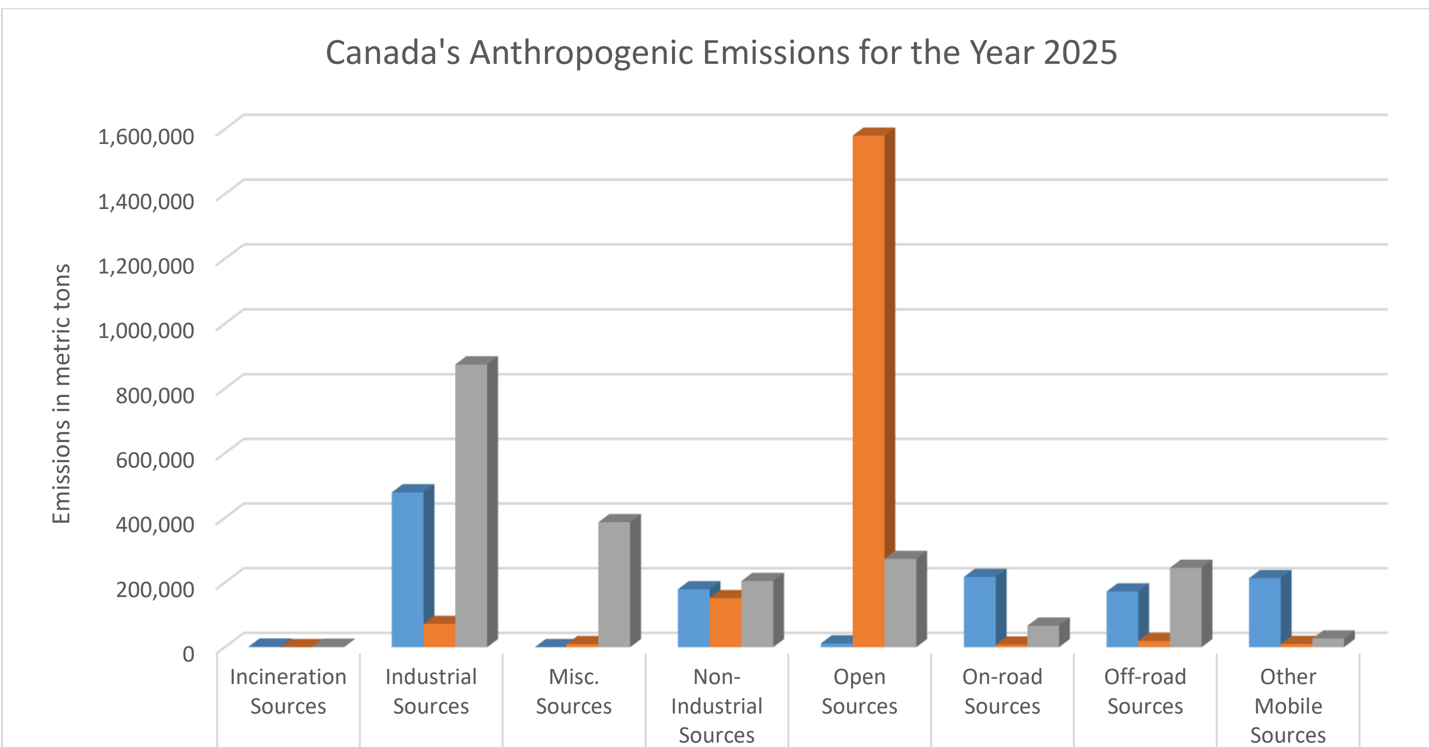
### 3.4 SMOKE, AURAMS, and Post-Processing

The above calculations to both the on-road and off-road sectors were applied to the 2025 emission inventory, which created. After which, SMOKE, AURAMS, and the post-processing were run for the BAU and the eleven scenarios. The SMOKE runs were verified and the emission images can be found in the Results and Discussion section under subsection 4.2 SMOKE Emission Results. The AURAMS modeled results can be found under the subsection 4.3 Model Results.

## 4 - Results and Discussion

### 4.1 Emission Calculation Results

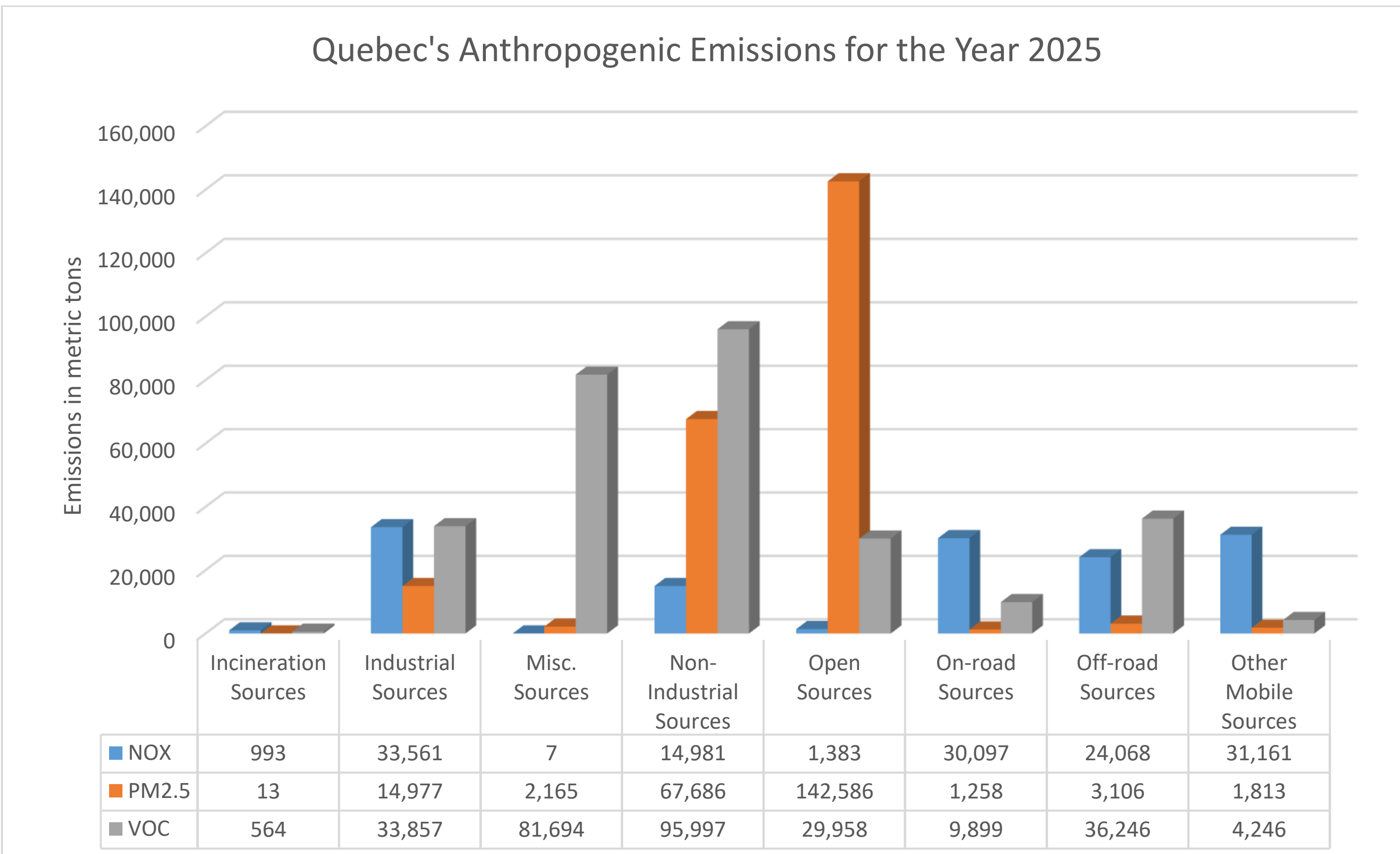
Figure 3 illustrates the total annual emission amount for $NO_X$, $PM_{2.5}$, and VOC emissions across all sectors present in the emission inventory for BAU case. The large emission values for the industrial sources were expected, especially since it includes the emissions due to petroleum industries. The open source $PM_{2.5}$ emissions are mostly due to the amount of dust from construction projects, agriculture, as well as dust from paved and unpaved roads (see Figure C1 in Appendix C for additional details regarding $PM_{2.5}$ emissions open source sector). VOC emissions in the miscellaneous sources sector are high due to general solvent use, the refining of retail petroleum products, and surface coatings. In comparison, the on-road and off-road emissions seem almost inconsequential. However, there are still around 200,000 $NO_X$ emissions in metric tons predicted to be emitted in both sectors and nearly 250,000 metric ton VOC emissions in the off-road sector in 2025.




| | Incineration Sources | Industrial Sources | Misc. Sources | Non-Industrial Sources | Open Sources | On-road Sources | Off-road Sources | Other Mobile Sources |
|---|---|---|---|---|---|---|---|---|
| NOX | 1,712 | 478,906 | 31 | 179,074 | 11,531 | 217,311 | 172,211 | 213,461 |
| PM2.5 | 35 | 71,729 | 9,410 | 151,665 | 1,579,737 | 7,786 | 19,041 | 9,748 |
| VOC | 1,067 | 874,419 | 386,660 | 204,653 | 273,142 | 66,398 | 245,358 | 26,845 |

*Figure 3 Canada's anthropogenic emissions for the year 2025 BAU*

Quebec does not follow the same sector emission distribution as Canada for the $NO_x$, $PM_{2.5}$, and VOC emissions, as can be seen in Figure 4. Open sources $PM_{2.5}$ emissions are still high, again due to dust from construction, agriculture, and paved and unpaved roads. The non-industrial sector has higher emissions compared to Canada, which is due to the amount of residential wood combustion, as seen in the emissions inventory. Industrial source emissions are much lower, most likely due to the lack of petroleum industries in the province. In comparison, on-road and off-road sources appear consequentially larger.

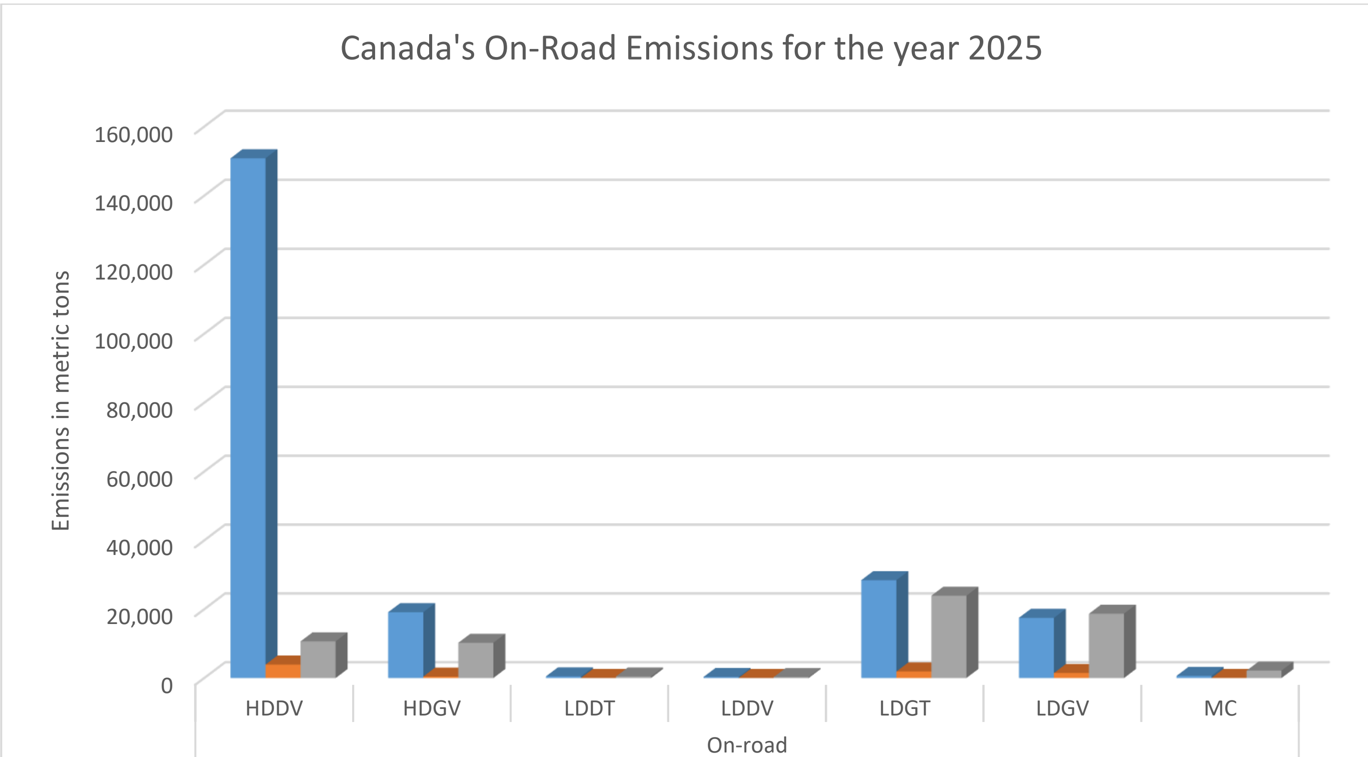



| | Incineration Sources | Industrial Sources | Misc. Sources | Non-Industrial Sources | Open Sources | On-road Sources | Off-road Sources | Other Mobile Sources |
|---|---|---|---|---|---|---|---|---|
| NOX | 993 | 33,561 | 7 | 14,981 | 1,383 | 30,097 | 24,068 | 31,161 |
| PM2.5 | 13 | 14,977 | 2,165 | 67,686 | 142,586 | 1,258 | 3,106 | 1,813 |
| VOC | 564 | 33,857 | 81,694 | 95,997 | 29,958 | 9,899 | 36,246 | 4,246 |

*Figure 4 Quebec's anthropogenic emissions for the year 2025 BAU*

Figure 5 illustrates the total Canadian on-road emissions break down into different vehicle categories. The bulk of Canada's on-road emissions are from Heavy Duty Diesel Vehicles (HDDV) $NO_X$ emissions, followed by the $NO_X$ and VOC emissions from the Light Duty Gasoline

Trucks (LDGT). Light Duty Gasoline Vehicles (LDGV) and Heavy Duty Gasoline Vehicles (HDGV), same similar $NO_X$ emissions but LDGVs have higher VOC emissions. Light Duty Diesel Trucks (LDDT) and Light Duty Diesel Vehicles (LDDV) have the lowest emissions, even lower than motorcycles (MC). A fuel preference is therefore shown for the LDV and LDT, where gasoline fuels the vast majority of these vehicles. In the case of the HDV, diesel seems to fuel the majority of the vehicles.




| | HDDV | HDGV | LDDT | LDDV | LDGT | LDGV | MC |
|---|---|---|---|---|---|---|---|
| NOX | 150,827 | 19,134 | 483 | 317 | 28,435 | 17,490 | 625 |
| PM2.5 | 3,909 | 421 | 17 | 20 | 1,908 | 1,469 | 42 |
| VOC | 10,661 | 10,237 | 448 | 283 | 23,921 | 18,696 | 2,151 |

*Figure 5 Canada's on-road emissions for the year 2025 BAU*

Quebec's emission ratio for the on-road sector is very similar to that of Canada's, as seen in Figure 6. HDDV $NO_X$ emissions dominate, followed by LDGT and LDGV $NO_X$ and VOC emissions, respectively. MC emissions are still higher in Quebec than those of LDDT and LDDV. The same fuel preferences seen for Canada also apply to Quebec, with LDV vehicles being predominantly fueled by gasoline and HDV vehicles by diesel.

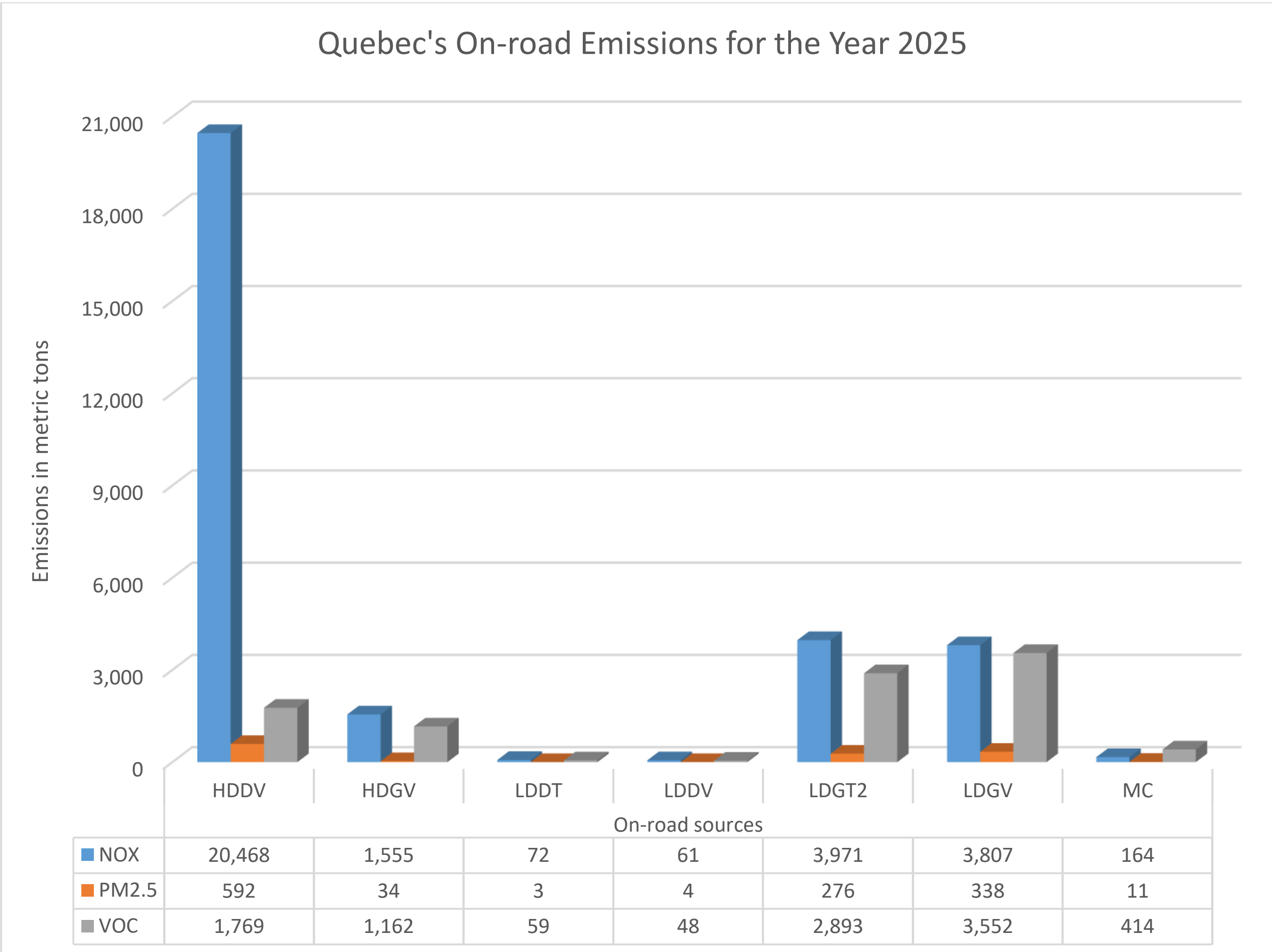



*Figure 6 Quebec's on-road emissions for the year 2025*

Canada's off-road emissions seen in Figure 7 have high off-road gasoline VOC emissions, and high $NO_X$ off-road diesel emissions. This demonstrates how different fuels have different pollutant emission ratios. Other fuels such as Liquefied Petroleum Gas (LPG), multi-fuel (which typically burns coal, wood pellets, etc.), and natural gas emissions are also present but in much smaller quantities.

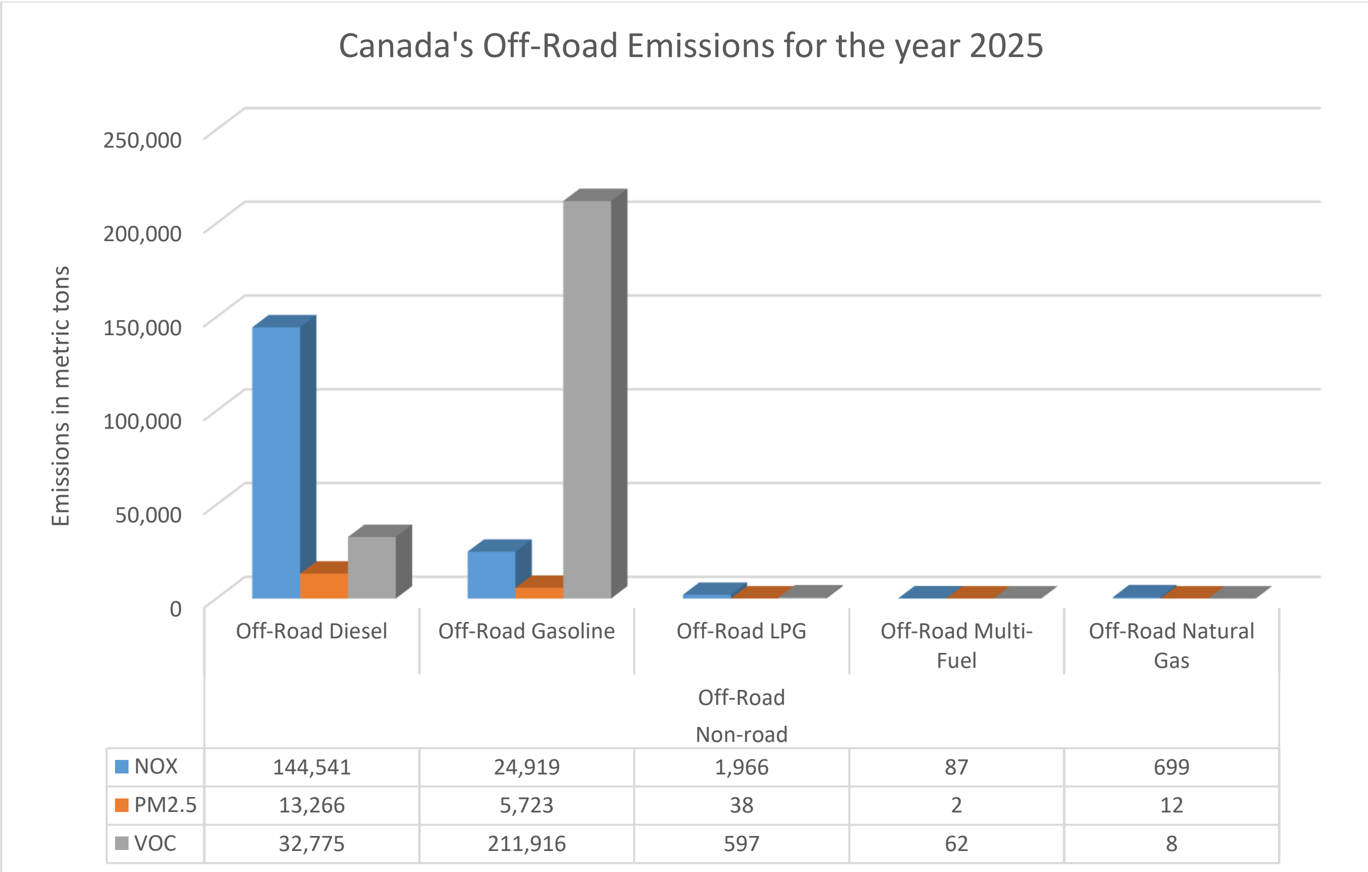
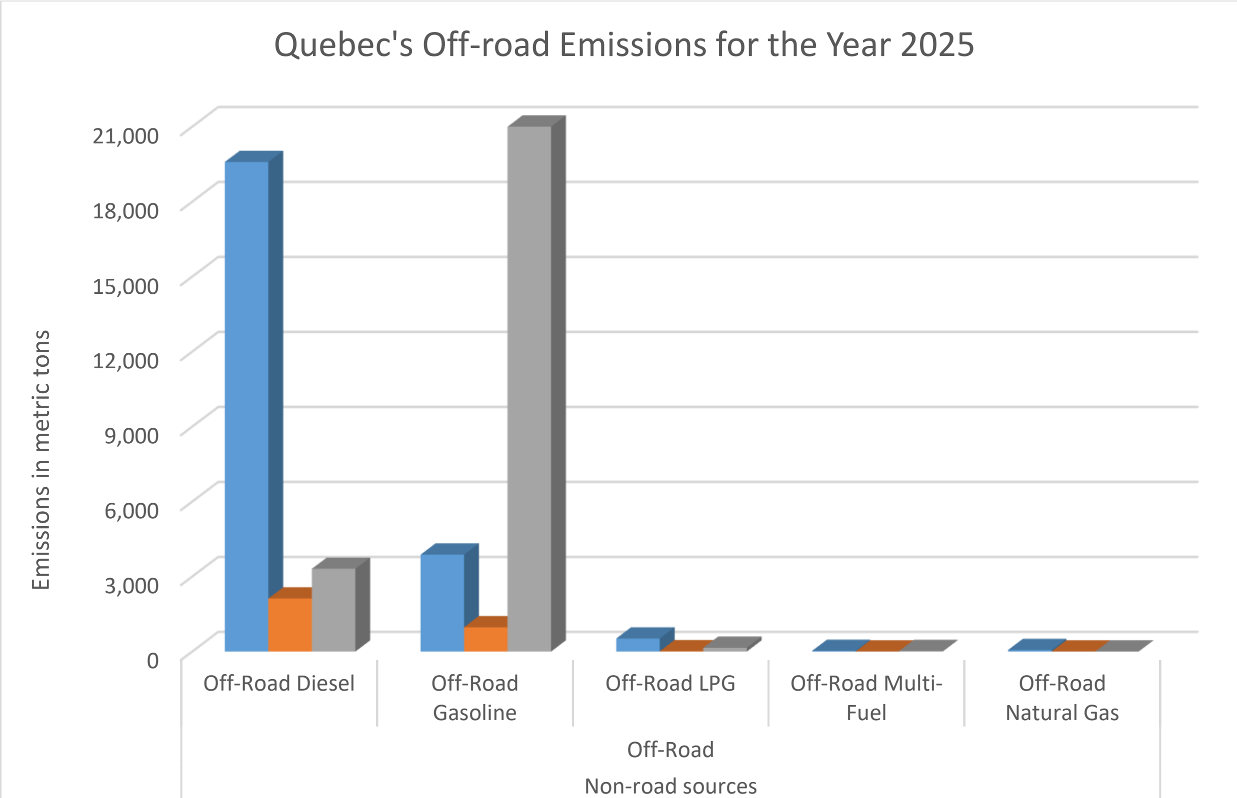



*Figure 7 Canada's off-road emissions for the year 2025*

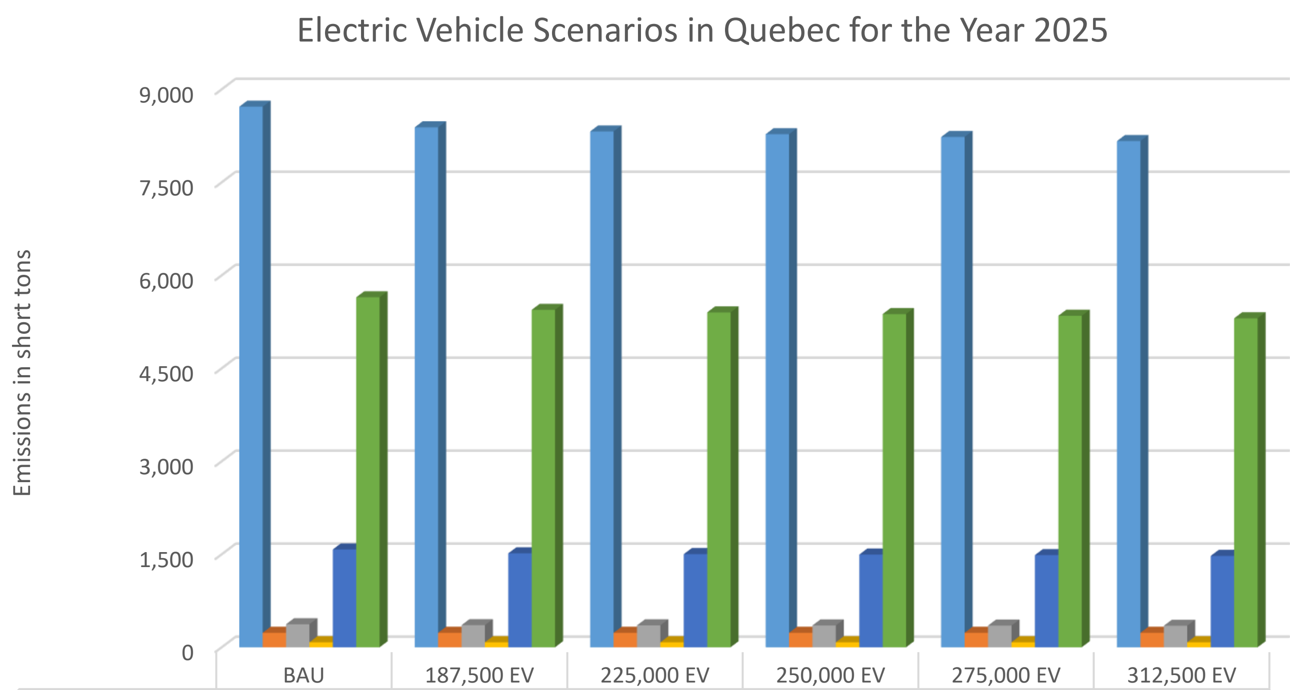
Nearly the same fuel ratios seen for all of Canada are present in Quebec as can be seen in Figure 8. Although, the off-road diesel emissions have a higher ratio, meaning that off-road diesel equipment is more popular in Quebec than in Canada in general. Off-road gasoline still has the highest proportion of VOC and $NO_X$ emissions in Quebec overall.




| | Off-Road Diesel | Off-Road Gasoline | Off-Road LPG | Off-Road Multi-Fuel | Off-Road Natural Gas |
|---|---|---|---|---|---|
| NOX | 19,586 | 3,877 | 521 | 25 | 59 |
| PM2.5 | 2,121 | 972 | 11 | 1 | 1 |
| VOC | 3,310 | 32,767 | 149 | 20 | 1 |

*Figure 8 Quebec's off-road emissions for the year 2025 BAU*

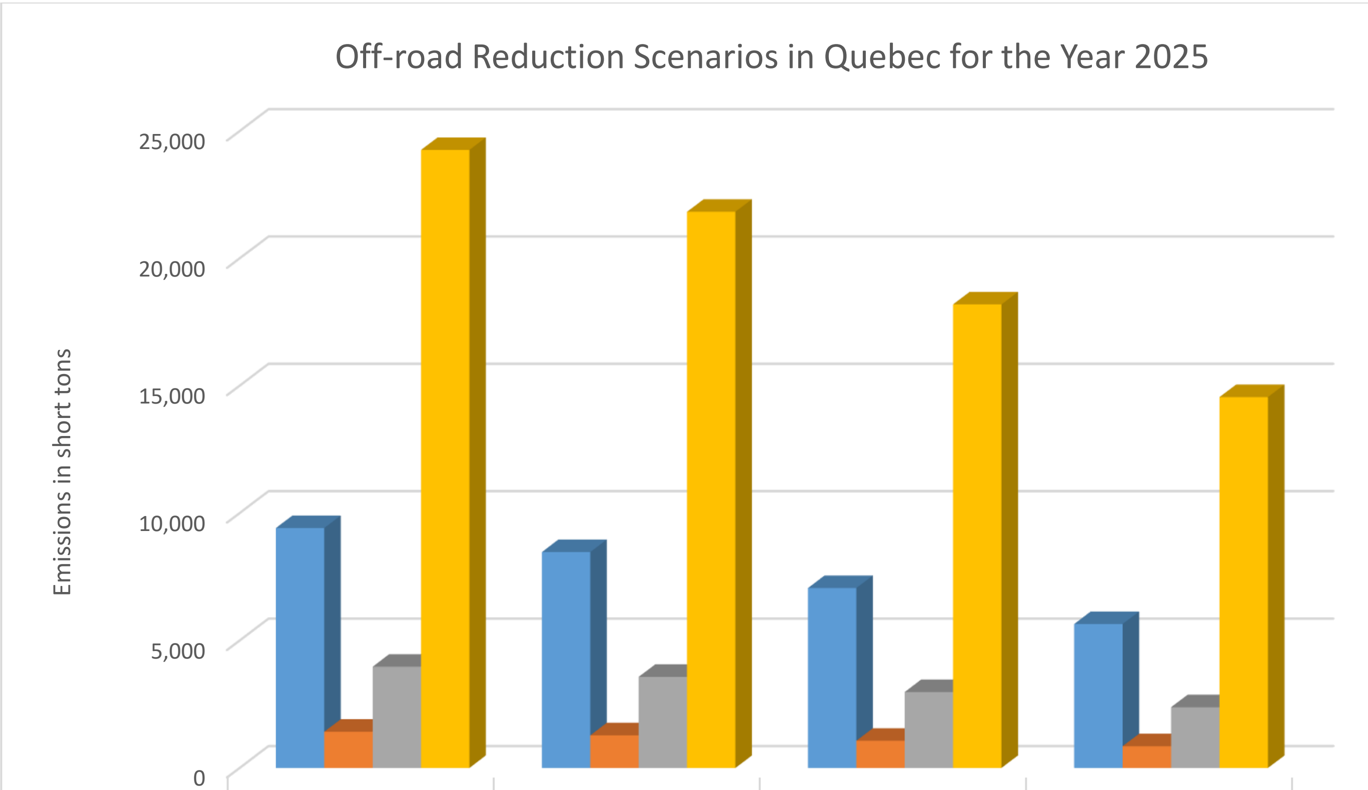
Figure 9 illustrates the emissions for the LDDT, LDGT, LDDV, and LDGV that are affected by the substitution of conventional vehicles for their electric equivalent. The largest decrease in emissions can be seen between the BAU and the addition of 187,500 electric vehicles. Otherwise, no noticeable decreases can be seen from the graph in terms of emission reductions due to the addition of extra electric vehicles. This is due to the small percentage difference between the scenarios. The scenario with 187,500 EVs replaced 3.60% of the LDVs and LDTs fleet with electric vehicles, with the other scenarios with similar replacement values: the 225,000 EVs scenario replaced 4.32%; the 250,000 EVs scenario replaced 4.80%; the 275,000 EVs scenario replaced 5.28%; and the 312,500 EVs scenario replaced 6.00%. As previously mentioned, the values for brake and tire emissions remained unchanged, as electric vehicles still emit these non-exhaust emissions.




| | BAU | 187,500 EV | 225,000 EV | 250,000 EV | 275,000 EV | 312,500 EV |
|---|---|---|---|---|---|---|
| NOX | 8,720 | 8,387 | 8,321 | 8,276 | 8,232 | 8,165 |
| Brakes PM2.5 | 233 | 233 | 233 | 233 | 233 | 233 |
| Exhaust PM2.5 | 371 | 357 | 354 | 352 | 350 | 347 |
| Tires PM2.5 | 80 | 80 | 80 | 80 | 80 | 80 |
| Evaporative VOC | 1,577 | 1,515 | 1,503 | 1,495 | 1,487 | 1,474 |
| Exhaust VOC | 5,646 | 5,442 | 5,402 | 5,374 | 5,347 | 5,307 |

*Figure 9 Electric vehicle scenarios in Quebec for the year 2025*

As can be seen from Figure 10 below, the emission reductions are much more obvious for the off-road scenarios between BAU and the scenarios, and among the scenarios themselves, compared to the on-road scenarios. All off-road scenario emissions show a noticeable decrease, which was not seen with the on-road scenarios.




| | BAU | 10% reduction | 25% reduction | 40% reduction |
|---|---|---|---|---|
| NOX | 9,412 | 8,471 | 7,059 | 5,647 |
| EXH__PM2_5 | 1,422 | 1,280 | 1,067 | 853 |
| EVP__VOC | 3,971 | 3,574 | 2,979 | 2,383 |
| EXH__VOC | 24,256 | 21,831 | 18,192 | 14,554 |

*Figure 10 Off-road reduction scenarios in Quebec for the year 2025*

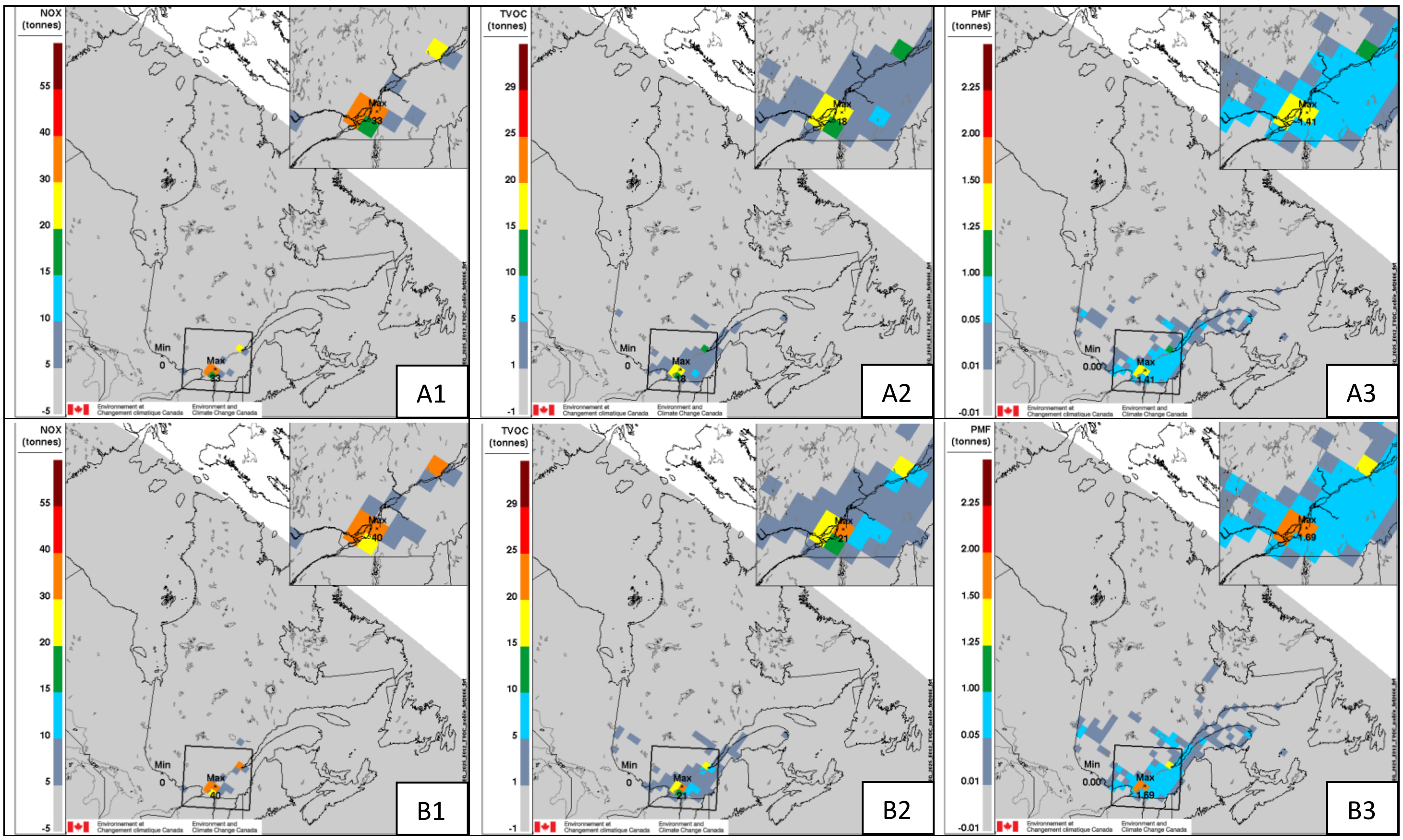
## 4.2 SMOKE Emission Results

### 4.2.1 On-road Scenarios

Of the modeled scenarios, only scenarios 4, 8, 9, 10, and 11 have reductions exclusively in the on-road sector. Each scenario was modeled with a different number of electric vehicles, as seen in Table 1. Results for the emission differences between the BAU and the scenarios (BAU-SCENARIO) before the AURAMS model processed them can be seen below in Figures 11, 12, & 13. These results display the annual sum of how the emissions were spatially allocated by SMOKE.

As can be seen in Figure 11, the differences between the BAU and the on-road scenarios are mostly concentrated in the Montreal and Quebec City regions. The figures illustrating the $NO_X$

emissions demonstrate that there are few points, however in the regions where there are differences; there are large differences as compared to the BAU. The figures depicting the differences in the VOC emissions are slightly more spread out, with a cloud of small emission differences surrounding the large metropolitan regions. The cloud of differences is even larger in the images displaying the differences between the BAU and the scenarios for the $PM_{2.5}$ emissions. In all cases, the maximum difference value can be seen in the eastern part of Montreal.



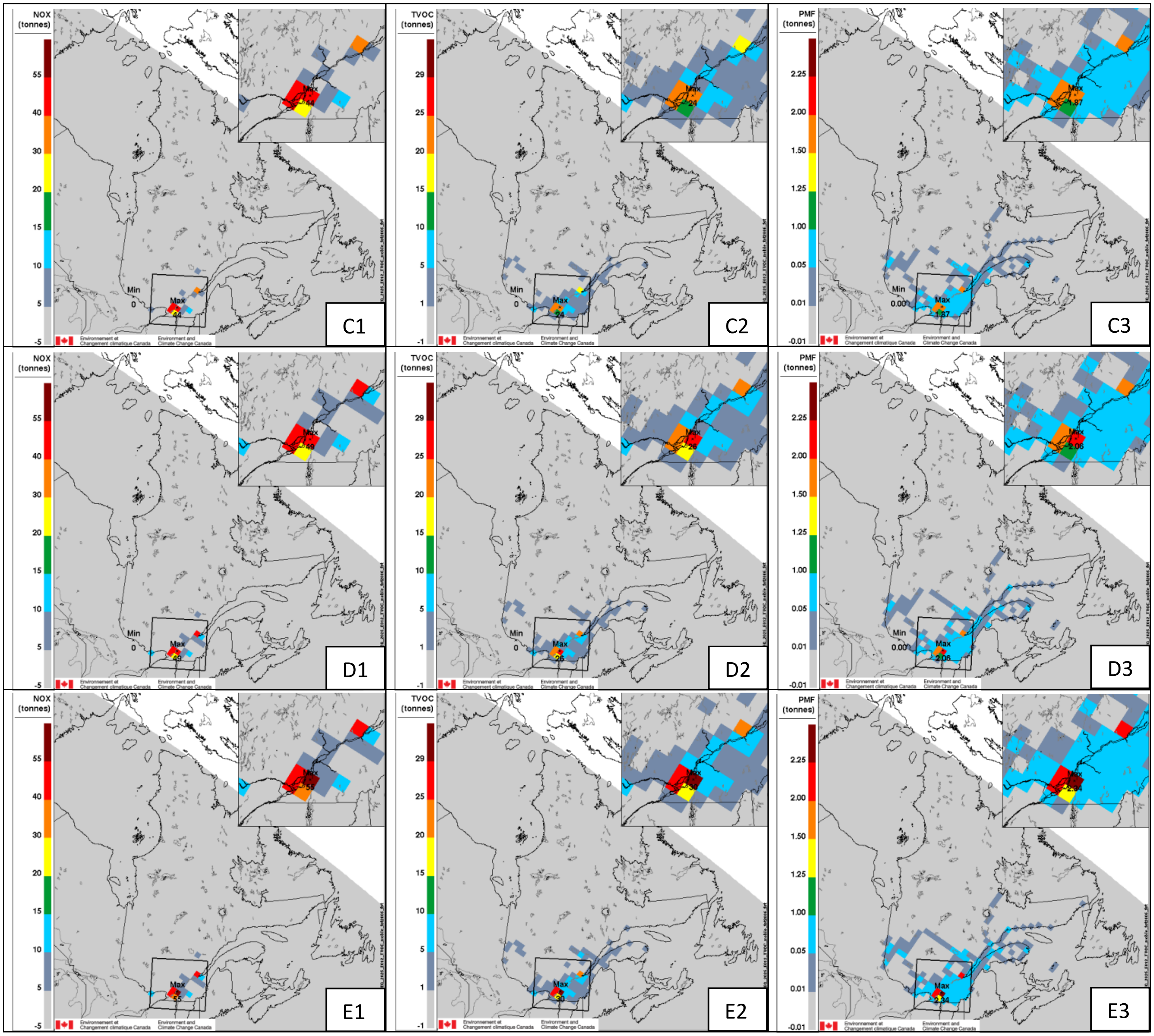



*Figure 11 Difference between the BAU and scenarios (A) 187,500 electric vehicles (B) 225,000 electric vehicles (C) 250,000 electric vehicles (D) 275,000 electric vehicles (E) 312,500 electric vehicles for (1) $NO_X$ emissions (tonnes) (2) VOC emissions (tonnes) (3) $PM_{2.5}$ emissions (tonnes)*

### 4.2.2 Off-road Scenarios

Compared to the on-road emission images in Figure 11, there is a larger cloud of emissions for the images illustrating the differences between the BAU and the scenarios for $NO_X$ emissions for the off-road scenarios, as seen in Figure 12. A similar cloud of emissions is seen in the VOC images, though with overall much larger difference values. The same is seen for $PM_{2.5}$ emissions, where the cloud's values remain similar to that of the on-road scenarios, though there are some regions where the values are much larger. An increase in emission reduction also increased the size of the cloud, which is more noticeable for the VOC emissions. As seen with the on-road scenarios, the maximum difference value can be found in the eastern Montreal region.

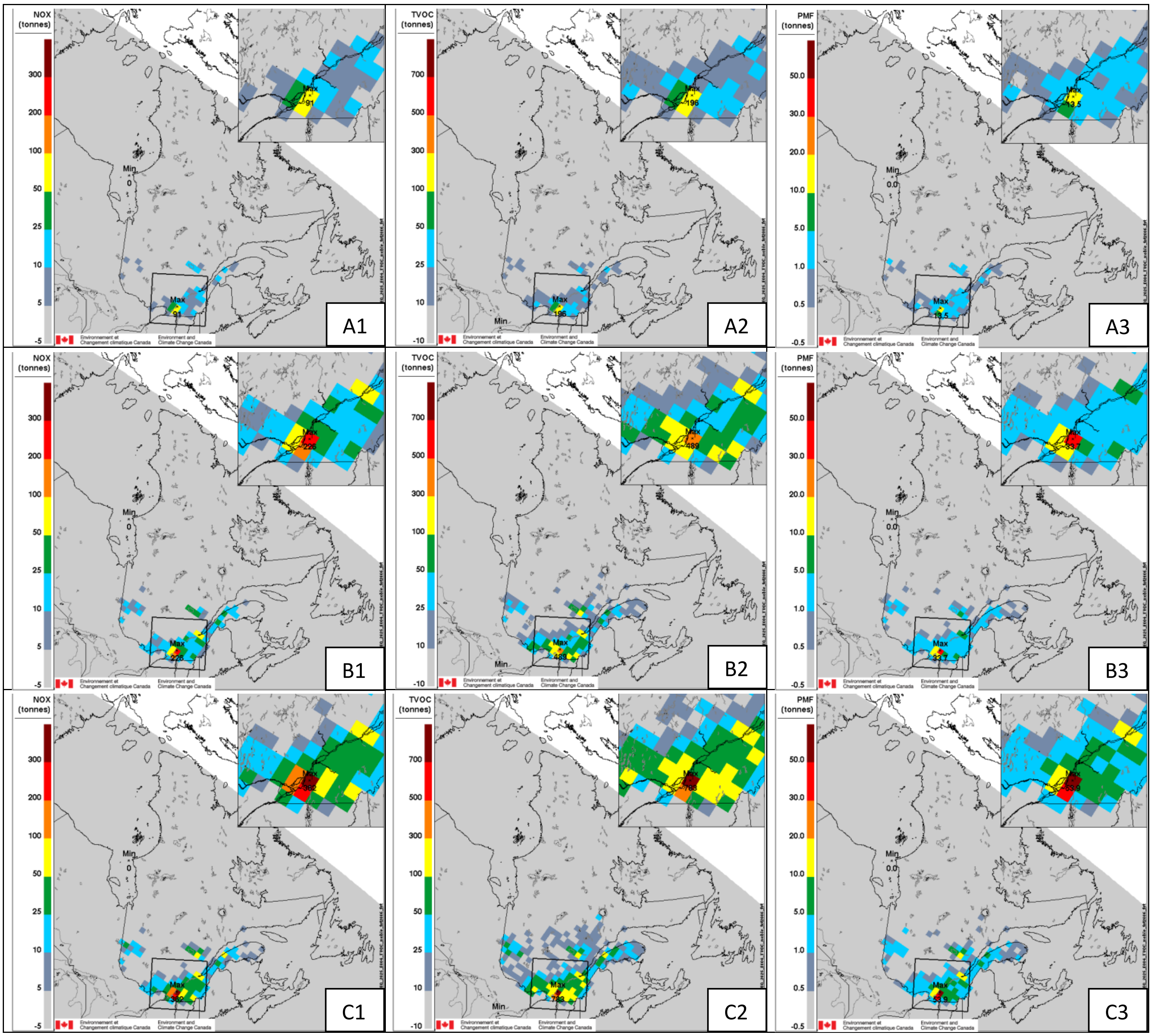
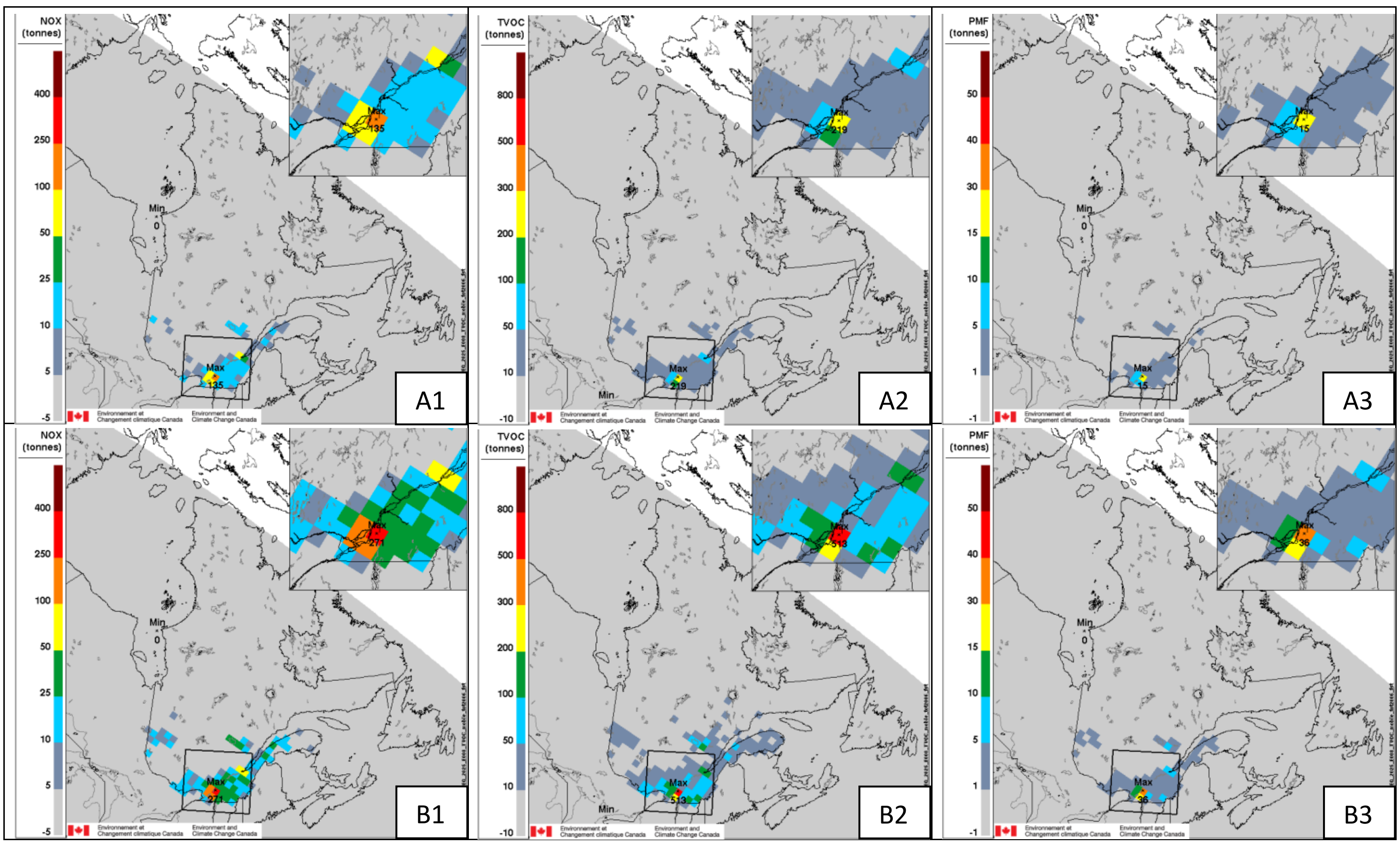



*Figure 12 Difference between the BAU and scenarios (A) 10% off-road reduction (B) 25% off-road reduction (C) 40% off-road reduction for (1) $NO_X$ concentrations (tonnes) (2) VOC concentrations (tonnes) (3) $PM_{2.5}$ concentrations (tonnes)*

### 4.2.3 <u>On-road and Off-road Combined Scenarios</u>

The scenarios with the combination of on-road and off-road reductions show the same pattern as the scenarios with uniquely off-road reductions. It is logical that the combination scenarios follow the same pattern as the off-road scenarios as there are more reductions in the off-road sector than in the on-road sector. The clouds of emission differences are present across all scenarios and pollutants but are most evident for the VOC emissions. As with all of the other scenarios, the maximum difference value can be seen in the eastern region of Montreal.



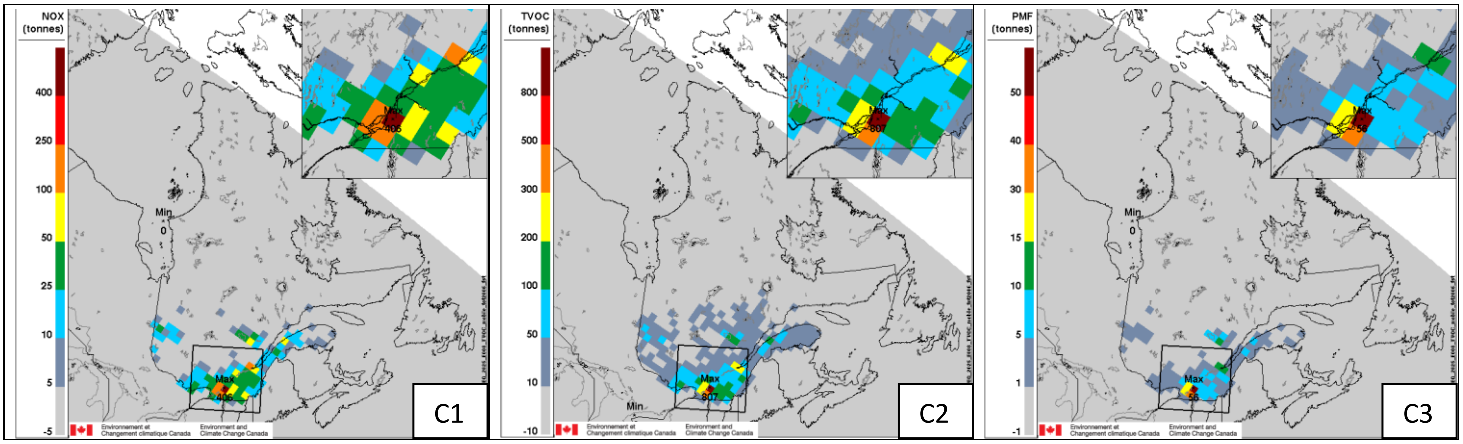



*Figure 13 Difference between the BAU and scenarios (A) 10% off-road reduction + 250,000 electric vehicles (B) 25% off-road reduction + 250,000 electric vehicles (C) 40% off-road reduction + 250,000 electric vehicles for (1) $NO_X$ concentrations (tonnes) (2) VOC concentrations (tonnes) (3) $PM_{2.5}$ concentrations (tonnes)*

## 4.3 **Model Results**

As seen in the concentration results section, the modeled scenarios, scenarios 4, 8, 9, 10, 11 have reductions only in the on-road sector. Each scenario was modeled with a different number of electric vehicles, as seen in table 1. Results for the differences between the BAU and the scenarios (BAU-SCENARIO) after the AURAMS model has processed them are below in Figures 15, 16 & 17. These results show the annual sum of how the concentrations were spatially allocated by SMOKE and how they were further affected by chemistry and meteorology processes that are active in AURAMS. Figures that follow the CAAQS air quality management levels and guidelines were selected. This includes the MDA8 summer $O_3$ concentrations, the annual daily maximum concentrations of $NO_2$, and the annual daily average concentrations of $PM_{2.5}$.

The BAU case images in Figure 14 display the concentrations in Canada and the United States with a focus on the province of Québec and its surroundings. High concentrations values were observed in the region of Montreal for $PM_{2.5}$ and $NO_2$, with relatively high values observed for $O_3$. It is important to keep in mind when viewing the images with the differences between the BAU and the scenarios that they resemble the images seen above, with slight differences that are not observable at that scale.

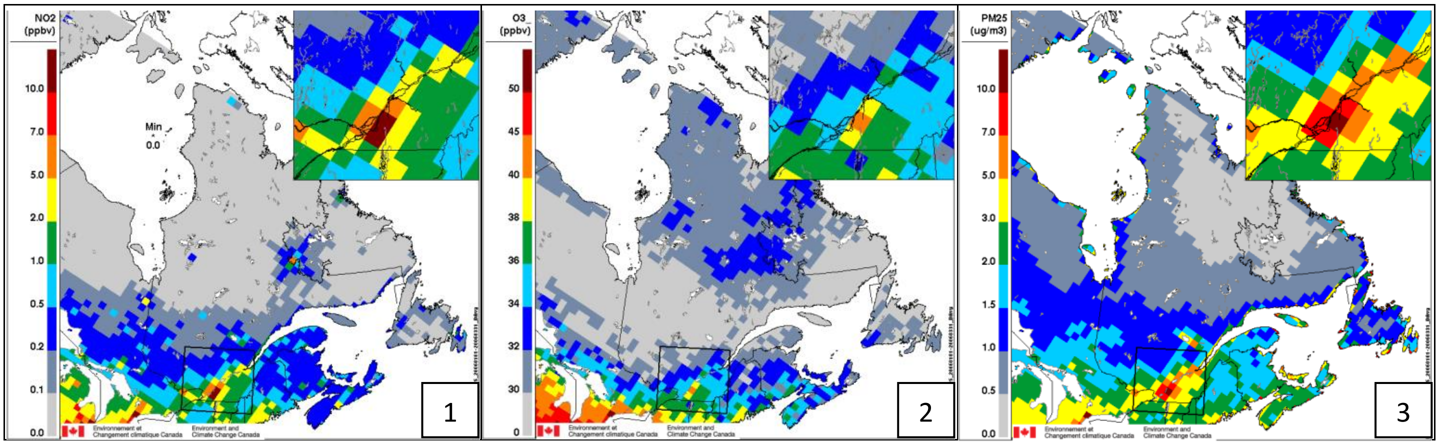



*Figure 14 Results for the BAU for (1) $NO_2$ annual daily maximum concentrations (ppbv) (2) summer $O_3$ MDA8 concentrations (ppbv) (3) annual daily average of $PM_{2.5}$ concentrations (µg/m3)*

The images depicting the differences between the BAU and the scenarios for the difference in annual daily maximum concentrations of $NO_2$ for the scenarios involving the fleet of electric vehicles (Figure 15-1) are quite similar. The maximum ranges between 0.030 and 0.050 ppbv, depending on the scenario. In comparison, the BAU concentration value for the Montreal region where the maximum value is located is about 10.0 ppbv (Figure 14-1). These differences between the BAU and the scenarios are therefore not large, with a relative difference of 0.3 % to 0.5 %.

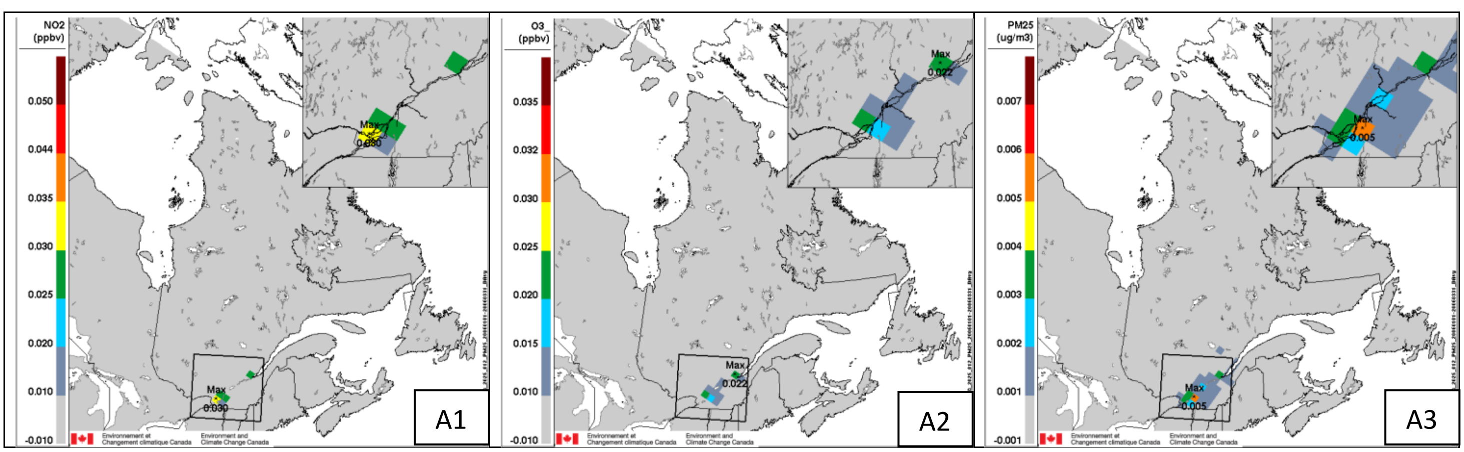
The images in Figure 15-2 illustrating the summer $O_3$ MDA8 concentrations differences between the BAU and the scenarios demonstrate that all scenarios are quite similar across all pollutants and that the number of vehicles ranging from 187,500 – 312,500 has had little effect on the maximum concentrations. The maxima ranged between 0.0022 and 0.0037 ppbv. The largest concentration reductions were seen in urban areas, such as the region of Montreal and that of Quebec. The largest reductions in concentrations were seen in Quebec City region, with a BAU concentration value of approximately 34 pbbv (Figure 14-2). The differences between the BAU and the scenarios are quite small, at a percent reduction of less than 0.01%, which is a hardly noticeable difference.

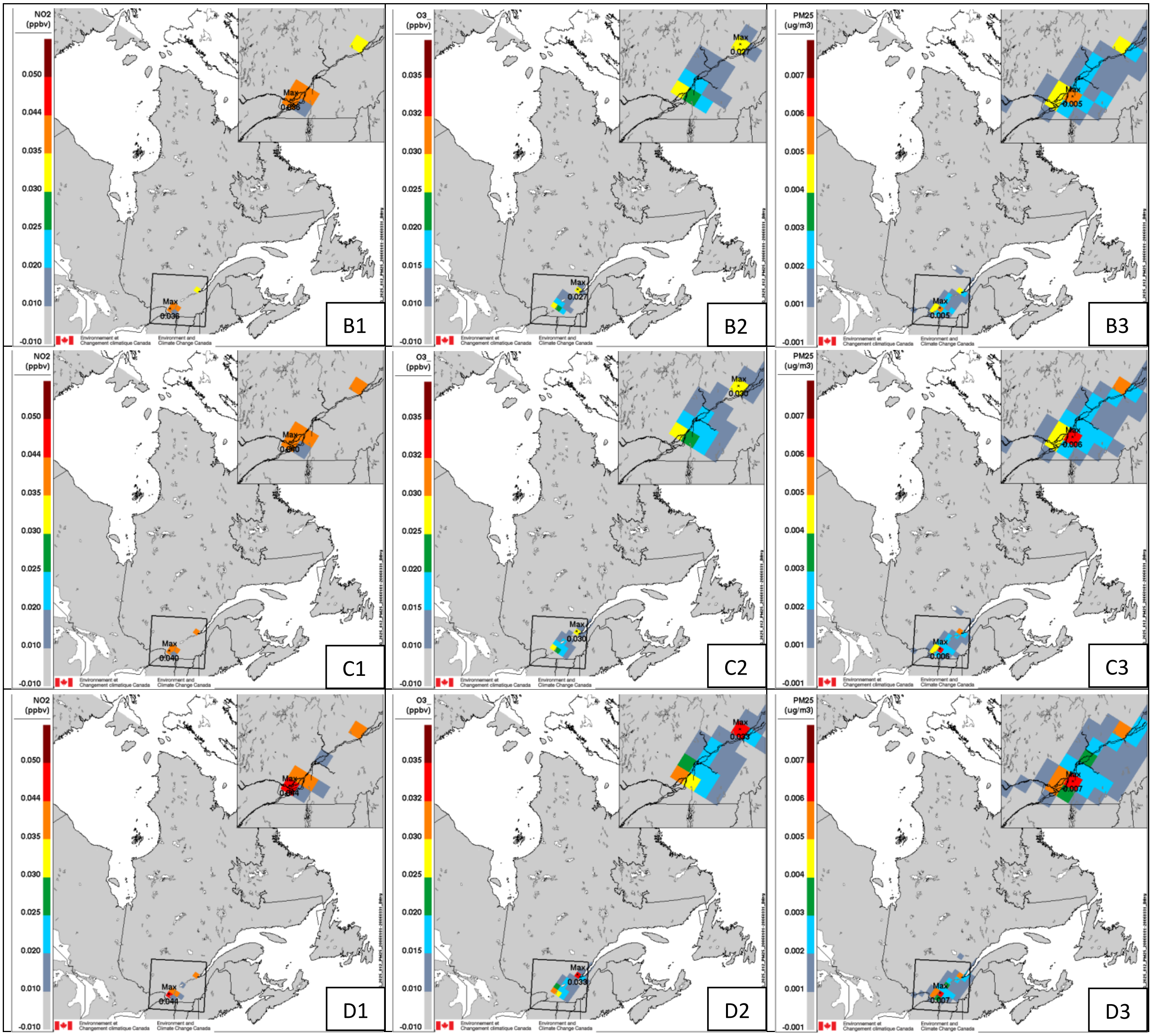
The maximum values depicted in the images displaying the different in annual daily average concentrations of $PM_{2.5}$ (Figure 15-3) range between 0.005 and 0.008 µg/m$^3$. The $PM_{2.5}$

concentrations in the BAU for Montreal are around 10 µg/m$^3$ (Figure 14-3), allowing for a maximum percentage difference of 0.05% to 0.08%, which is rather quite small.

It should also be noted that while the maximum difference value for $NO_X$ and $O_3$ is still in Montreal, it is no longer in the eastern Montreal region as seen in Figure 11 which depicts the pollutant spatial allocation before the data was fed to AURAMS. The maximum concentration value difference for both $NO_X$ and $O_3$ is shown in the western Montreal region. This is most likely due to a change in the VOC to $NO_X$ ratio, which could have occurred due to a change in the number of diesel and/or gasoline vehicles. As previously mentioned when examining Figure 8, gasoline fuel emits more VOC whereas diesel fuel emits more $NO_X$ (Cai, Burnham, & Wang, 2013). Since both diesel and gasoline vehicles and trucks were replaced with electric vehicles, the VOC to $NO_X$ ratio was modified. The meteorology could also have impacted the location of the maximum difference value, with the wind, humidity, and temperature being the main factors.

All the images presented for the various metrics regarding $NO_2$, $O_3$, and $PM_{2.5}$, have shown a small percentage differences between the BAU and the scenarios. It is therefore apparent that a fleet of up to 312,500 electric vehicles has a slight effect on air quality in the province of Quebec. Nevertheless, as concentration reductions are still present, however small, it is thought that a much larger fleet of electric vehicles will have an even greater reduction in pollutant concentrations.




NO2 (ppbv)
0.050
0.044
0.035
0.030
0.025
0.020
0.010
-0.010
O3 (ppbv)
0.035
0.032
0.030
0.025
0.020
0.015
0.010
-0.010
PM25 (ug/m3)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
-0.001
Max 0.036
B1
Max 0.027
B2
Max 0.005
B3
Max 0.040
C1
Max 0.030
C2
Max 0.006
C3
Max 0.044
D1
Max 0.033
D2
Max 0.007
D3
Environnement et Changement climatique Canada
Environment and Climate Change Canada

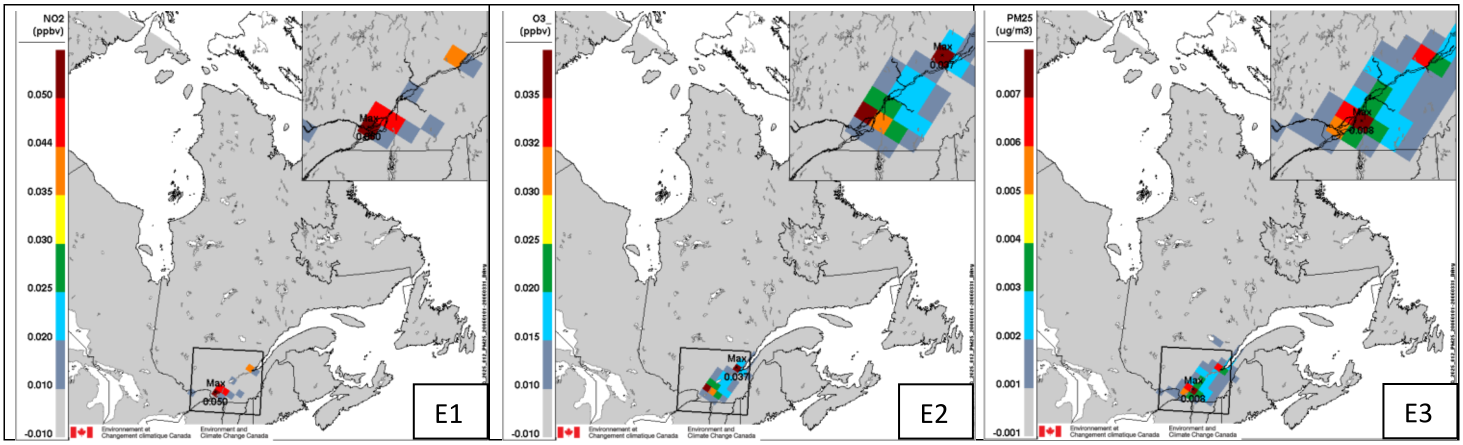



*Figure 15 Difference between the BAU and scenarios for (A) 187,500 electric vehicles (B) 225,000 electric vehicles (C) 250,000 electric vehicles (D) 275,000 electric vehicles (E) 312,500 electric vehicles (1) $NO_2$ annual daily maximum concentrations (ppbv) (2) summer $O_3$ MDA8 concentrations (ppbv) (3) annual daily average of $PM_{2.5}$ concentrations ($\mu g/m^3$)*

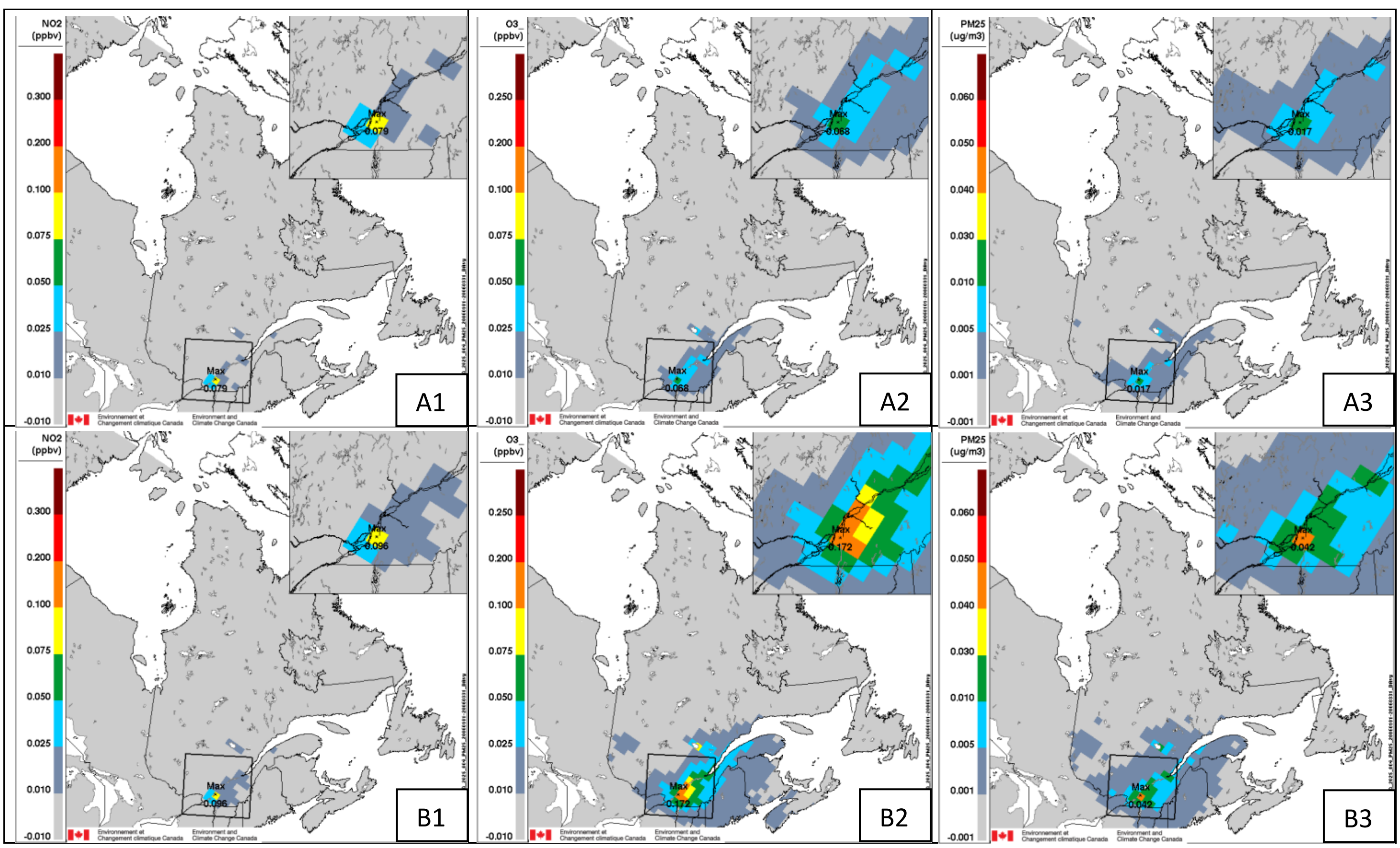
Unlike with the on-road scenarios, the off-road scenarios have more noticeable differences in terms of results overall. As mentioned with the on-road scenarios, the maximum value across all scenarios and pollutants is seen in the Montreal area, with large concentration values extending from the Montreal region to the Quebec City region.

As the off-road scenarios have reductions of 10, 25, 40% in the off-road sector, the results were expected to be more distinct compared to the on-road scenarios. In the case of the $NO_2$, the images illustrating the differences between the BAU and the scenario for the annual daily maximum concentrations, the maximum values seen are between 0.079 and 0.318 ppbv, as seen in Figure 16-1. Comparing the BAU value in the Montreal area of 10 ppbv (Figure 14-1) to those of the scenarios yields maximum relative differences of 0.79% to 3.18%.

Regarding the differences between the BAU and scenarios seen in the average annual daily maxima concentrations of $O_3$ (Figure 16-2), the maximum values range between 0.068 to 0.276 ppbv. The BAU value in the Montreal region is around 40 ppbv (Figure 14-2), and therefore the maximum relative differences range from 0.17% to 0.69%, which are much lower than the relative differences seen for $NO_2$. However, the spread of differences in concentrations is much larger than that of $NO_2$, with reductions observed in New Brunswick, Nova Scotia, Newfoundland, and a few states in the United States, for the scenario with a 40% reduction in the off-road sector. The scenario with a 25% reduction has a lower scope, and the 10% reduction scenario only displays differences in the province of Quebec.

The images showing the differences between the BAU and the scenarios for the annual daily average concentrations of $PM_{2.5}$ (Figure 16-3) shows maximum values depicted at 0.017 to 0.067 $\mu g/m^3$ seen across the scenarios with the largest value seen in the scenario with 40% reduction (Figure 16.C3). The BAU (Figure 14-3) depicted a value of 10 $\mu g/m^3$ in the Montreal region, which yields maximum relative differences of 0.17% to 0.67%. As with the $O_3$ concentration values seen above, the $PM_{2.5}$ values also spread across a few states and the province of New Brunswick for the 40% off-road reduction scenario, with a small spread for the 25% reduction scenario, and a nearly non-existent spread for the 10% reduction scenario.

Overall, it can be seen that there are positive reductions to the $NO_2$, $O_3$, and $PM_{2.5}$ pollutants, with percentage reductions as high as 3.18% as was seen for $NO_2$ for the 40% off-road reduction scenario. As such, there are noticeable reductions, which in turn could potentially provide health benefits to those who inhabit the region.



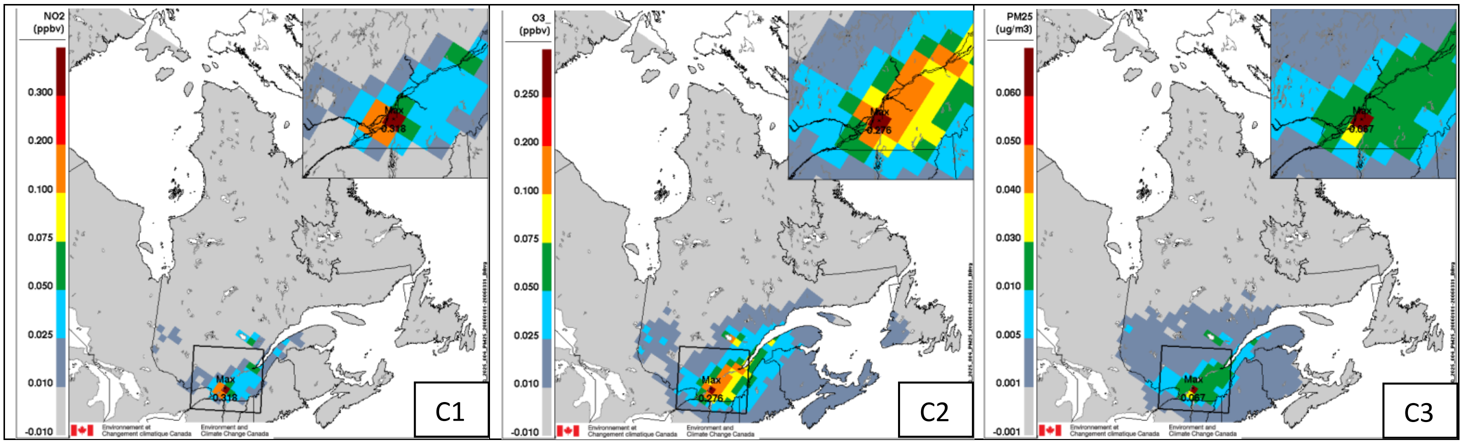



*Figure 16 Difference between the BAU and scenarios for (A) 10% off-road reduction (B) 25% off-road reduction (C) 40% off-road reduction (1) $NO_2$ annual daily maximum concentrations (ppbv) (2) summer $O_3$ MDA8 concentrations (ppbv) (3) annual daily average of $PM_{2.5}$ concentrations (µg/$m^3$)*

The following results are the combination of the three off-road scenarios (10%, 25%, 40% reductions in the off-road sector) with the addition of 250,000 electric vehicles. As previously mentioned, the maximum value in the case of all scenarios and pollutants can be found in the Montreal region.

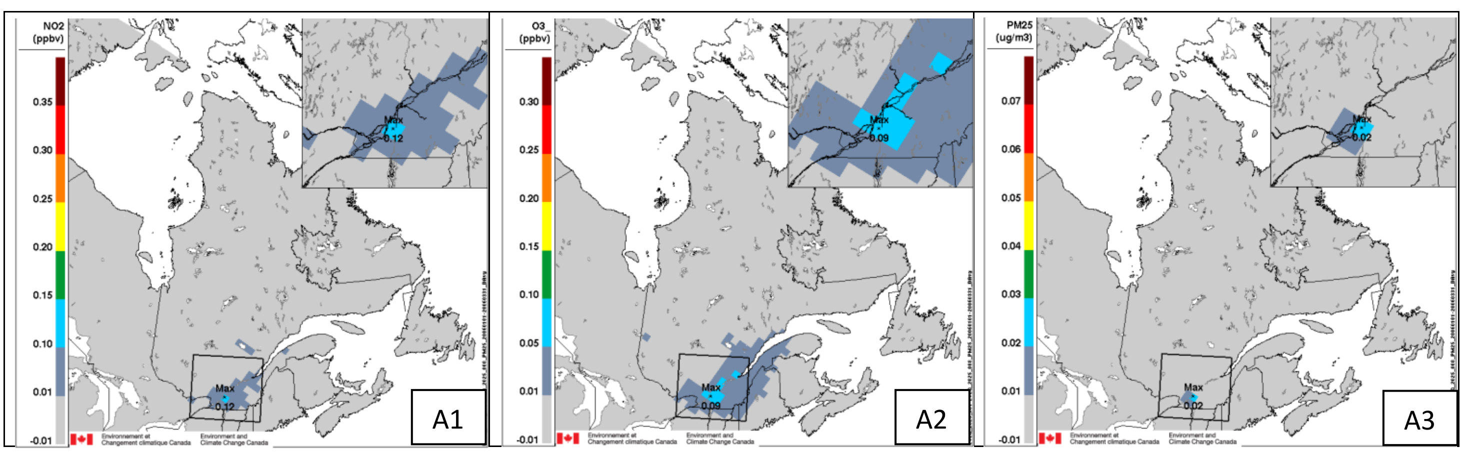
The maximum values for the $NO_2$ annual daily maximum concentrations range between 0.12 and 0.36 ppbv as seen in Figure 17-1, with the BAU value for the value where the maximum difference values reside (Montreal) is 10 ppbv (Figure 14-1). This yields a percentage difference of 1.2% to 3.6%, which is a noticeable decrease in $NO_2$ concentrations.

The images displaying the differences between the BAU and the scenarios for the summer $O_3$ MDA8 concentrations (Figure 17-2) illustrate an increasing spread of differences with an increasing percentage of reductions in the off-road sector. The 10% reduction in the off-road sector combined with 250,000 electric vehicles shows little spread compared to the scenarios with 25% or 40% reduction in the off-road sector with the same number of electric vehicles. The 40% reduction in the off-road sector along with the 250,000 electric vehicles shows a decrease in concentration covering New Brunswick, Nova Scotia, Newfoundland and some U.S. states. The maximum difference values range from 0.09 to 0.3 ppbv, compared to the BAU of 40 ppbv in Montreal (Figure 14-2). This gives rise to a percentage difference of 0.23% to 0.75%, which is far less than the percentage reductions for $NO_2$.

The $PM_{2.5}$ values for the annual daily average concentrations for the BAU (Figure 17-3) in the Montreal area is approximately 10.0 µg/m$^3$, whereas the maximum differences between the BAU and the scenarios are between 0.02 to 0.07 µg/m$^3$ (Figure 17-3). This leads to a percentage difference of 0.2% to 0.7%, which is similar to the percent reduction value of $O_3$, which is far smaller than the percentage reduction for $NO_2$.

The maximum difference value between the BAU and the off-road scenarios did not shift grid cells, unlike the on-road scenarios. This suggests that the VOC to $NO_X$ ratio remains unchanged. This is reasonable, as the emission reductions for the off-road sector were percentage-based reductions, which affected all pollutants equally. Of course, there were reductions to the on-road sector with the addition of 250,000 electric vehicles although the reductions to the off-road sector were much larger than those of the on-road sector, which could have dominated the trend of the air pollution concentrations.

Ultimately, a noticeable $NO_2$ reduction of 3.6% was observed, with modest reductions of up to 0.75% for $O_3$ and up to 0.7% for $PM_{2.5}$. These concentration reductions could possibly produce health benefits to those who inhabit the area.



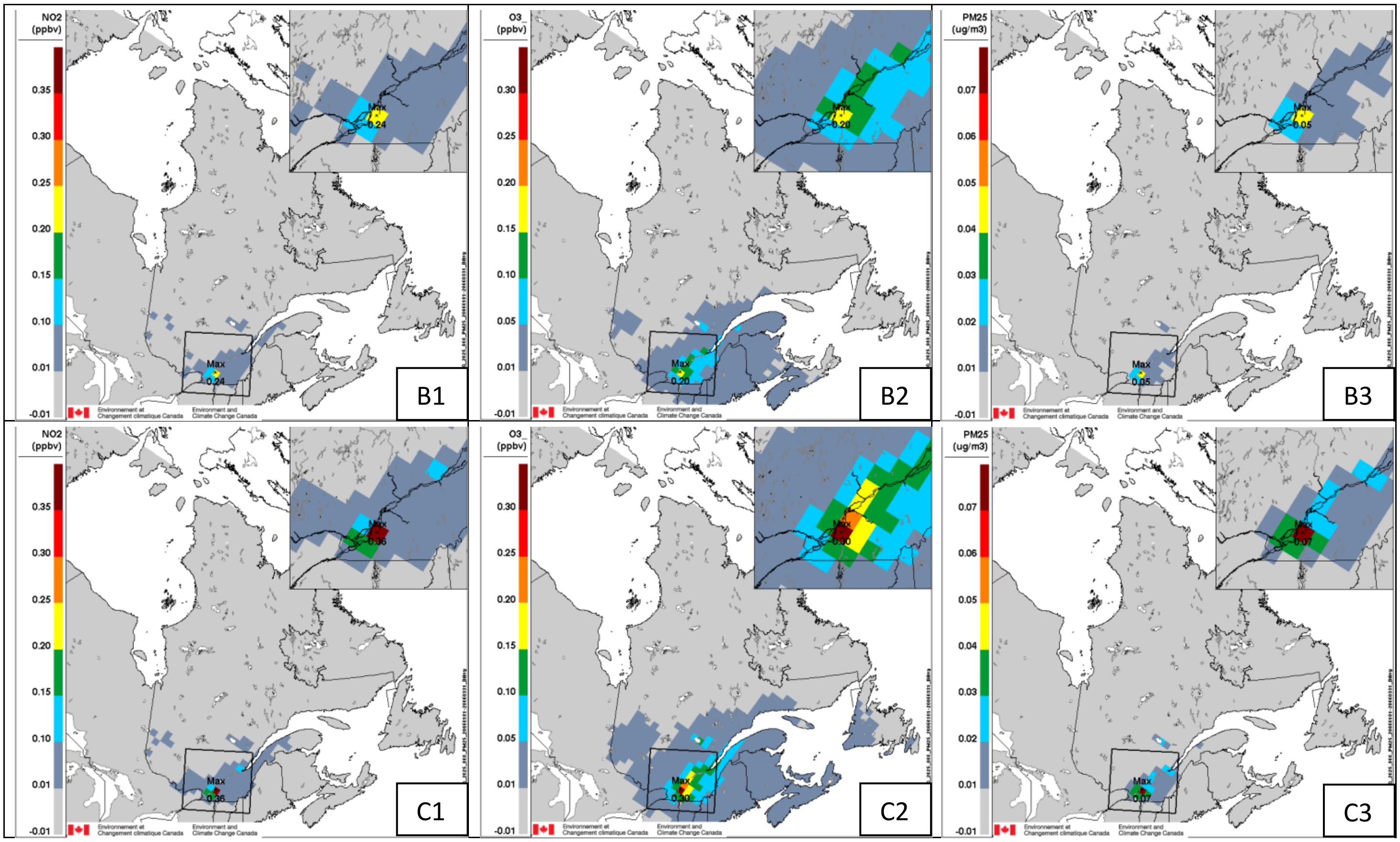


*Figure 17 Difference between the BAU and scenarios for (A) 10% off-road reduction + 250,000 electric vehicles (B) 25% off-road reduction + 250,000 electric vehicles (C) 40% off-road reduction + 250,000 electric vehicles (1) $NO_2$ annual daily maximum concentrations (ppbv) (2) summer $O_3$ MDA8 concentrations (ppbv) (3) annual daily average of $PM_{2.5}$ concentrations (μg/m$^3$)*

The modelling of all electrification cases resulted in net decreases for all scenarios, for all pollutants ($NO_2$, $O_3$, and $PM_{2.5}$) examined. This means that $O_3$ concentrations that are dependent on the ratio of $NO_2$ and VOC concentrations (Sillman, 1999) remain relatively constant in the area considered. All scenarios and pollutants showed a maximum concentration value in the Montreal region, except for $O_3$ values seen in the scenarios regarding the electric vehicles (Figure 15), where the maximum concentration is seen in the Quebec City area, with similar values seen in the Montreal region. This could be due to varying $NO_2$ and VOC ratio levels, which resulted in an overall lower $O_3$ concentration in Quebec City than in Montreal. As the majority of Quebec's population live along the stretch of the Saint Lawrence River, especially the greater Montreal area (Statistics Canada, 2018), it was expected to have the bulk of the reductions in that region. This increase in reductions in the urban areas translates to a decrease in exposure to pollutants where a large extent of the population resides.

Of all of the scenarios, the one with the largest concentration reduction is the one with a 40% reduction in the off-road sector + 250,000 electric vehicles (Figure 17-C), followed by the scenario with a 40% reduction in the off-road sector (Figure 16-C) and the scenario with a 25% reduction in the off-road sector + 250,000 electric vehicles (Figure 17-B). This indicates that the electrification of an additional 15% of certain off-road equipment exhibits better air contaminant reductions than the equivalent of 250,000 electric vehicles. Even a reduction of 10% in the off-road sector (Figure 17-A) showed nearly the double of pollutant concentration reductions with respect to $NO_2$, $O_3$, and $PM_{2.5}$ than 312,500 electric vehicles (Figure 15-E), where 312,500 EVs is equivalent to 6% of the total fleet of LDV and LDT. These results correspond to a study performed by Nopmongcol et al. (2017), where their results showed that the electrification of up to 80% of certain off-road equipment offered more benefits than the electrification of 17% of the light-duty and 8% of the heavy-duty fleet of vehicles in all of the United States for the year 2030. Of course, their study also accounted for the pollution that would be created due to a 5% increased electrical demand, which they supposed would be met with natural gas, wind, solar, and nuclear energy (Nopmongcol et al., 2017). As previously mentioned, this study did not consider the additional pollution from the generation of electricity due to the abundance of hydroelectricity produced in Quebec, which Hydro-Québec has stated that the current electric distribution network can handle up to one million electric vehicles, regardless of the season and time of day (Gouvernement du Québec, 2017).

As the air pollutant reductions are considerably small, there should be little to no effect on the CAAQS metrics. However, additional health benefits are still possible from these pollutant reductions and additional health studies should be conducted to properly assess the impact of electric vehicles and equipment on human and environmental health.

It should be noted that as of June 2018, there are 30,213 electric vehicles registered in Quebec, of which 45% of these are entirely electric vehicles, and 55% being PHEVs (AVEQ, 2018). As this study considered all vehicles entirely electric, the reductions shown above for all scenarios would not be entirely accurate due to the fuel emissions that would have to be accounted for the PHEVs, should the above ratio remain constant for the year 2025. Due to this, the off-road scenarios present additional reductions compared to the on-road scenarios. Furthermore, turning to electric vehicles and off-road equipment will allow Quebec to reduce its dependence on imported oil and further contribute to Quebec's economy (Gouvernement du Québec, 2017).

The government of Quebec currently subsidizes electric vehicles in order to entice citizens into purchasing electric vehicles. The subsidies range between $3,000 to $8,000 for entire electric vehicles, and $500 to $8,000 for PHEVs, with the rebate corresponding to the electric battery capacity of the vehicle (Gouvernement du Québec, 2018). This subsidy, which is largely funded by the carbon market revenues, has been the subject of much criticism, as some believe that it is not worth the cost. A study performed by Canada's Ecofiscal Commission demonstrated that in order for the program to be economically rational and cost effective, the price equivalent of a tonne of carbon would have to be as high as $395 for the year 2030 as a result of the subsidy. This high carbon cost considered the additional cost of the electric vehicle by the consumer, the cost of the subsidy, the operating costs of the electric vehicle over its lifetime, cost of market barriers (customer lack of awareness regarding the electric vehicle technology), and the benefit of addressing market failures (how consumers perceive the cost of electric vehicles). The cost-benefits associated with a reduction in air pollution and their accompanying health impacts were not included in the study, though the authors wrote that a wide deployment of electric vehicles would increase the benefits to the subsidy policy due to the reduced air pollution (Canada's Ecofiscal Commission, 2017). This present study demonstrates that there are noticeable air pollutant reductions due to the adoption of electric vehicles (Figure 15), which can translate into health benefits, and therefore, increase the benefits to the subsidy policy. Some municipalities (Saint-Laurent, Lorraine, Granby, and Joliette) have offered subsidies to electric or manual lawn mowers ranging from $50 to $150 (Ville de Granby, 2014; Ville de Joliette, 2018; Ville de Lorraine, 2018; Ville de Montréal, 2018). These subsidies were instated with the aim of reducing GHGs (Ville de Joliette, 2018; Ville de Montréal, 2018) however, there is of course the added benefit of the reduction of air contaminants, as seen by the above results of this present study (Figure 16).

The Quebec government has recently implemented the ZEV (Zero-Emission Vehicle) standard as of January $11^{th}$, 2018 stating that automakers must now gain credits by selling ZEVs or LEVs (Low-Emission Vehicle) in Quebec. The number of credits gained varies, depending on the autonomy in electric mode of the vehicle: the greater the electric range of the vehicle, the greater the number of credits earned, thus requiring less credits for the automaker to reach its goal. As the automakers have a credit goal they must reach, it should incentivize them to develop and sell more low- and zero-emission vehicles (MDDELCC, 2018). This law was established in part due to mitigate the complaints from Quebec customers stating that there was a limited choice of electric vehicles compared to American states, the lack of electric vehicles available for a road test, and the long delivery wait time once an electric vehicle was ordered (MDDELCC, 2017). Therefore, due to the implementation of the electric vehicle subsidy and the ZEV standard, the government of Quebec anticipates an increase of electric vehicles on the roads, hoping to reach its goal of 100,000 electric vehicles registered in Quebec by 2020 and 300,000 by 2026 (MDDELCC, 2017, 2018). Of course, public perception of electric vehicles will have to improve. Many do not believe that electric vehicles are viable due to their low autonomy, that they cannot be plugged into normal wall sockets, that there are few places to charge electric vehicles and that they are not practical for the average driver due to the amount of time they take to charge (WWF, 2014). However, the number of electric vehicles in Quebec is growing exponentially (AVEQ, 2018), meaning that public perception is improving and that the government of Quebec has a better chance of reaching its goal.

# 5 - Conclusion

In summary, the impact of electric vehicles on air quality is positive, however slight. It appears that an increase in electric vehicles can only improve air quality, though further air quality modeling studies should be performed to ensure that that is the case. The electric off-road scenarios showed a larger positive impact than all of the on-road electric vehicles scenarios. A reduction of 10% in the off-road sector, which showed maximum annual concentration reductions of 0.079 ppbv for $NO_2$, 0.068 ppbv for $O_3$, and 0.017 µg/m$^3$ for $PM_{2.5}$, showed nearly double the concentration reductions compared to the scenario with 312,500 EV, which showed reductions of 0.050 ppbv for $NO_2$, 0.037 ppbv for $O_3$, and 0.008 µg/m$^3$ for $PM_{2.5}$. The results from the off-road combined with 250,000 EV scenarios were similar to those of the off-road scenarios, with added concentration reductions from the on-road sector. As such, the scenario with the largest air quality benefit was the scenario with 40% reductions in the off-road sector + 250,000 electric vehicles, which showed maximum reductions of 0.36 ppbv (3.6%) for the annual daily maximum $NO_2$ concentrations, 0.30 ppbv (0.75%) for the maximum daily 8-hour average $O_3$ concentrations, and 0.07 µg/m$^3$ (0.70%) for the annual daily average $PM_{2.5}$ concentrations, which are relatively small reduction values however a health study would have to be done to see whether these reductions do in fact have an impact on human and environmental health.. The scenario with the smallest benefit was the scenario with the replacement of 187,500 electric vehicles with maximum reductions of 0.030 ppbv (0.3%) for the annual daily maximum $NO_2$ concentrations, 0.022 ppbv (<0.010%) for the maximum daily 8-hour average $O_3$ concentrations, and 0.005 µg/m$^3$ (0.050%) for the annual daily average $PM_{2.5}$ concentrations, which appear to be insignificant reductions, though again, a health study might show that these reductions might improve human and environmental health.

Several improvements could have been made to this study. MOVES could have been run to produce a more accurate on-road inventory, as many calculations and assumptions have been made throughout the course of the project to obtain emission inventories with the addition of EVs. A 10 km or 15 km grid would have a higher resolution and would therefore display additional emission and concentration details. Unfortunately, even if such a grid were available for this project, it would have also drastically increased the model run time. However, even without those above mentioned potential improvements, this project provides a good overview of what benefits electrification of vehicles and off-road equipment can provide. Additionally, as previously mentioned, future health studies can be conducted to determine the extent of the impact of electric vehicles and off-road equipment can have on humans and the environment.

References

AVEQ. (2017). Avantages Plaque Verte. Retrieved from http://www.aveq.ca/avantages-plaque-verte.html

AVEQ. (2018). Statistiques SAAQ-AVÉQ sur l'électromobilité au Québec en date du 30 juin 2018 [Infographie] Retrieved from http://www.aveq.ca/actualiteacutes/statistiques-saaq-aveq-sur-lelectromobilite-au-quebec-en-date-du-30-juin-2018-infographie

Brady, J., & O'Mahony, M. (2011). Travel to work in Dublin. The potential impacts of electric vehicles on climate change and urban air quality. *Transportation Research Part D: Transport and Environment, 16*(2), 188-193. doi:https://doi.org/10.1016/j.trd.2010.09.006

Branchez-Vous. (2018). Évaluer vos besoins. Retrieved from https://branchezvous.org/evaluer-vos-besoins/

Cai, H., Burnham, A., & Wang, M. (2013). Updated emission factors of air pollutants from vehicle operations in GREETTM using MOVES. *Systems Assessment Section, Energy Systems Division, Argonne National Laboratory*.

Calnan, P., Deane, J. P., & Ó Gallachóir, B. P. (2013). Modelling the impact of EVs on electricity generation, costs and CO2 emissions: Assessing the impact of different charging regimes and future generation profiles for Ireland in 2025. *Energy Policy, 61*, 230-237. doi:https://doi.org/10.1016/j.enpol.2013.05.065

Camus, C., & Farias, T. (2012). The electric vehicles as a mean to reduce CO2 emissions and energy costs in isolated regions. The São Miguel (Azores) case study. *Energy Policy, 43*, 153-165. doi:https://doi.org/10.1016/j.enpol.2011.12.046

Canada's Ecofiscal Commission. (2017). *Supporting Carbon Pricing: How to identify policies that genuinely complement an economy-wide carbon price*. Retrieved from

CCME. (2017). CAAQS. Retrieved from http://airquality-qualitedelair.ccme.ca/en/

Chen, J., Boucher, L., Cousineau, S., Davignon, D., Duhamel, A., Gilbert, S., . . . Sassi, M. (2010). *2006 Annual Operational Evaluation of the Environment Canada Air Quality Modelling System*. Paper presented at the 9th Annual CMAS Conference, Chapel Hill, NC.

Chong, U., Yim, S. H., Barrett, S. R., & Boies, A. M. (2014). Air quality and climate impacts of alternative bus technologies in Greater London. *Environ Sci Technol, 48*(8), 4613-4622. doi:10.1021/es4055274

CMAS. (2018). SMOKE. Retrieved from https://www.cmascenter.org/smoke/

Duvall, M., Knipping, E., Alexander, M., Tonachel, L., & Clark, C. (2007a). Environmental assessment of plug-in hybrid electric vehicles. *EPRI, July, 2*.

Duvall, M., Knipping, E., Alexander, M., Tonachel, L., & Clark, C. (2007b). Environmental assessment of plug-in hybrid electric vehicles. *EPRI, July, 1*.

ECCC. (2018). Station Results - 1981-2010 Climate Normals and Averages. Retrieved from http://climate.weather.gc.ca/climate_normals/station_select_1981_2010_e.html?searchType=stnProv&lstProvince=QC

EPA. (2006). *AP42 Section 13.2.1 Paved Roads*. Retrieved from Washington, DC: http://www3.epa.gov/ttnchie1/ap42/ch13/final/c13s0201.pdf

EPA. (2016). *Air Toxic Emissions from On-road Vehicles in MOVES2014*. Retrieved from

EPA. (2017). National Emissions Inventory. Retrieved from https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei

EPA. (2018). Criteria Air Pollutants. Retrieved from https://www.epa.gov/criteria-air-pollutants
Gillies, J. A., Etyemezian, V., Kuhns, H., Nikolic, D., & Gillette, D. A. (2005). Effect of vehicle characteristics on unpaved road dust emissions. *Atmospheric Environment, 39*(13), 2341-2347. doi:https://doi.org/10.1016/j.atmosenv.2004.05.064
Göransson, L., Karlsson, S., & Johnsson, F. (2010). Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system. *Energy Policy, 38*(10), 5482-5492. doi:https://doi.org/10.1016/j.enpol.2010.04.001
Gouvernement du Québec. (2017). Mythes et réalités. Retrieved from https://transportselectriques.gouv.qc.ca/mythes-et-realites/
Gouvernement du Québec. (2018). Coûts et Utilisation. Retrieved from http://vehiculeselectriques.gouv.qc.ca/particuliers/vehicules-electriques-cout-utilisation.asp
Grundstrom, M., Tang, L., Hallquist, M., Nguyen, H., Chen, D., & Pleijel, H. (2015). Influence of atmospheric circulation patterns on urban air quality during the winter. *Atmospheric Pollution Research, 6*(2), 278-285. doi:https://doi.org/10.5094/APR.2015.032
Hedegaard, K., Ravn, H., Juul, N., & Meibom, P. (2012). Effects of electric vehicles on power systems in Northern Europe. *Energy, 48*(1), 356-368. doi:https://doi.org/10.1016/j.energy.2012.06.012
Hooftman, N., Oliveira, L., Messagie, M., Coosemans, T., & Van Mierlo, J. (2016). Environmental Analysis of Petrol, Diesel and Electric Passenger Cars in a Belgian Urban Setting. *Energies, 9*(2), 84.
Hu, X., Zou, Y., & Yang, Y. (2016). Greener plug-in hybrid electric vehicles incorporating renewable energy and rapid system optimization. *Energy, 111*, 971-980. doi:https://doi.org/10.1016/j.energy.2016.06.037
Hydro-Québec. (2018a). Hydro-Québec: North America's Leading Provide of Clean Energy. Retrieved from http://www.hydroquebec.com/international/en/exports/
Hydro-Québec. (2018b). Les nombreux avantages des voitures tout électriques ou hybrides rechargeables. Retrieved from http://www.hydroquebec.com/electrification-transport/voitures-electriques/
Kantor, I., Fowler, M. W., Hajimiragha, A., & Elkamel, A. (2010). Air quality and environmental impacts of alternative vehicle technologies in Ontario, Canada. *International Journal of Hydrogen Energy, 35*(10), 5145-5153. doi:https://doi.org/10.1016/j.ijhydene.2009.08.071
Laumbach, R., Meng, Q., & Kipen, H. (2015). What can individuals do to reduce personal health risks from air pollution? *Journal of thoracic disease, 7*(1), 96-107. doi:10.3978/j.issn.2072-1439.2014.12.21
Li, N., Chen, J.-P., Tsai, I. C., He, Q., Chi, S.-Y., Lin, Y.-C., & Fu, T.-M. (2016). Potential impacts of electric vehicles on air quality in Taiwan. *Science of The Total Environment, 566-567*, 919-928. doi:https://doi.org/10.1016/j.scitotenv.2016.05.105
MDDELCC. (2017). *Analyse d'impact réglementatire du règlement d'application de la Loi visant l'augmentation du nombre de véhicules automobiles zéro émission au Québec agin de réduire les émissions de gaz à effet de serre et autres polluants* (978-2-550-80251-8). Retrieved from Québec: http://www.mddelcc.gouv.qc.ca/changementsclimatiques/vze/AIR-reglement201712.pdf
MDDELCC. (2018). The zero-emission vehicle (ZEV) standard Retrieved from http://www.environnement.gouv.qc.ca/changementsclimatiques/vze/index-en.htm

Moran, M. D., Dastoor, A., & Morneau, G. (2014). Long-Range Transport of Air Pollutants and Regional and Global Air Quality Modelling. In E. Taylor & A. McMillan (Eds.), *Air Quality Management: Canadian Perspectives on a Global Issue* (pp. 69-98). Dordrecht: Springer Netherlands.

National Energy Board. (2017). Canada's Renwable Power Landscape 2017 – Energy Market Analysis. Retrieved from https://www.neb-one.gc.ca/nrg/sttstc/lctrct/rprt/2017cndrnwblpwr/prvnc/qc-eng.html

Nicholas, M. A., & Turrentine, T. S. (2017). *Advanced Plug-in Electric Vehicle Travel and Charging Behavior*. Retrieved from

Nichols, B. G., Kockelman, K. M., & Reiter, M. (2015). Air quality impacts of electric vehicle adoption in Texas. *Transportation Research Part D: Transport and Environment, 34*, 208-218. doi:https://doi.org/10.1016/j.trd.2014.10.016

Nopmongcol, U., Grant, J., Knipping, E., Alexander, M., Schurhoff, R., Young, D., . . . Yarwood, G. (2017). Air Quality Impacts of Electrifying Vehicles and Equipment Across the United States. *Environ Sci Technol, 51*(5), 2830-2837. doi:10.1021/acs.est.6b04868

Oshiro, K., & Masui, T. (2015). Diffusion of low emission vehicles and their impact on CO2 emission reduction in Japan. *Energy Policy, 81*, 215-225. doi:https://doi.org/10.1016/j.enpol.2014.09.010

Racine, J. (2018). *Description of AURAMS model for the Ozone science assessment* (AQSC-18-004). Retrieved from

Razeghi, G., Carreras-Sospedra, M., Brown, T., Brouwer, J., Dabdub, D., & Samuelsen, S. (2016). Episodic air quality impacts of plug-in electric vehicles. *Atmospheric Environment, 137*, 90-100. doi:https://doi.org/10.1016/j.atmosenv.2016.04.031

SAAQ. (2018). Nombre de véhicules en circulation selon le type d'utilisation, le type de véhicule et l'âge du véhicule, Québec et régions administratives. Retrieved from http://www.bdso.gouv.qc.ca/pls/ken/ken213_afich_tabl.page_tabl?p_iden_tran=REPER7EWI5822-1186897029100Mf1&p_lang=1&p_m_o=SAAQ&p_id_ss_domn=718&p_id_raprt=3372

Sassi, M. (2018). *Documentation for SMOKE-Ready 2014 Air Pollutant Emission Inventory (APEI) Package version 1*. Retrieved from Dorval, Quebec:

Seinfeld, J. H., & Pandis, S. N. (2016). *Atmospheric chemistry and physics: from air pollution to climate change*: John Wiley & Sons.

Sillman, S. (1999). The relation between ozone, NOx and hydrocarbons in urban and polluted rural environments. *Atmospheric Environment, 33*(12), 1821-1845. doi:https://doi.org/10.1016/S1352-2310(98)00345-8

Smith, W. J. (2010). Can EV (electric vehicles) address Ireland's CO2 emissions from transport? *Energy, 35*(12), 4514-4521. doi:https://doi.org/10.1016/j.energy.2010.07.029

Soret, A., Guevara, M., & Baldasano, J. M. (2014). The potential impacts of electric vehicles on air quality in the urban areas of Barcelona and Madrid (Spain). *Atmospheric Environment, 99*, 51-63. doi:https://doi.org/10.1016/j.atmosenv.2014.09.048

Statistics Canada. (2017). Population Centre and Rural Area Classification 2016. Retrieved from https://www.statcan.gc.ca/eng/subjects/standard/pcrac/2016/introduction

Statistics Canada. (2018). Population and Dwelling Count Highlight Tables, 2016 Census. Retrieved from https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/hlt-fst/pd-pl/Table.cfm?Lang=Eng&T=302&PR=24&S=86&O=A&RPP=25

Summers, P. W., & Fricke, W. (1989). Atmospheric decay distances and times for sulphur and nitrogen oxides estimated from air and precipitation monitoring in eastern Canada. *Tellus B, 41B*(3), 286-295. doi:doi:10.1111/j.1600-0889.1989.tb00307.x

Timmers, V. R. J. H., & Achten, P. A. J. (2016). Non-exhaust PM emissions from electric vehicles. *Atmospheric Environment, 134*, 10-17. doi:https://doi.org/10.1016/j.atmosenv.2016.03.017

Varga, B. O. (2013). Electric vehicles, primary energy sources and CO2 emissions: Romanian case study. *Energy, 49*, 61-70. doi:https://doi.org/10.1016/j.energy.2012.10.036

Ville de Granby. (2014). Programmes de subvention. Retrieved from http://www.ville.granby.qc.ca/fr/ville/nav/7C18/programmes.html

Ville de Joliette. (2018). Équipements écologiques d'entretien des pelouses.

Ville de Lorraine. (2018). Équipement écologique d'entretien des pelouses. Retrieved from http://www.ville.lorraine.qc.ca/developpement-durable/subventions/equipement-ecologique-entretien-pelouses

Ville de Montréal. (2018). Tondeuse écologique. Retrieved from http://ville.montreal.qc.ca/portal/page?_pageid=7937,143028928&_dad=portal&_schema=PORTAL

WWF. (2014). *Transportation rEVolution: Electric Vehicle Status Update 2014*. Retrieved from Canada: http://awsassets.wwf.ca/downloads/wwf_ev_progress_update_report_2014_2.pdf

Yu, H., & Stuart, A. L. (2017). Impacts of compact growth and electric vehicles on future air quality and urban exposures may be mixed. *Science of The Total Environment, 576*, 148-158. doi:https://doi.org/10.1016/j.scitotenv.2016.10.079

# Appendix

## Appendix A: List of Electric Off-road Equipment

*Table A1 Non-road Equipment Electrification*

| Equipment | Equipment category |
|---|---|
| 2-Wheel Tractors | Lawn & Garden |
| Chain Saws < 6 HP | Lawn & Garden |
| Chippers/Stump Grinders | Lawn & Garden |
| Commercial Turf Equipment | Lawn & Garden |
| Lawn & Garden Equipment | Lawn & Garden |
| Lawn & Garden Tractors | Lawn & Garden |
| Lawn mowers | Lawn & Garden |
| Leaf blowers/Vacuums | Lawn & Garden |
| Rear Engine Riding Mowers | Lawn & Garden |
| Rotary Tillers < 6 HP | Lawn & Garden |
| Shredders < 6 HP | Lawn & Garden |
| Trimmers/Edgers/Brush Cutters | Lawn & Garden |
| All-Terrain Vehicles | Recreational |
| Golf Carts | Recreational |
| Inboards | Recreational |
| Motorcycles: Off-Road | Recreational |
| Outboards | Recreational |
| Personal Watercraft | Recreational |
| Sailboat Auxiliary Engines | Recreational |
| Snowmobiles | Recreational |
| Specialty Vehicle Carts (Racing Karts) | Recreational |
| AC\Refrigeration | Industrial/Commercial |
| Airport Support Equipment | Industrial/Commercial |
| Cranes | Industrial/Commercial |
| Forklifts | Industrial/Commercial |
| Front Mowers | Industrial/Commercial |
| Hydro Power Units | Industrial/Commercial |
| Irrigation Sets | Industrial/Commercial |
| Light Commercial Air Compressors | Industrial/Commercial |
| Light Commercial Pumps | Industrial/Commercial |
| Material Handling Equipment | Industrial/Commercial |
| Paving Equipment (Slip Form Pavers) | Industrial/Commercial |
| Rough Terrain Forklifts | Industrial/Commercial |
| Signal Boards | Industrial/Commercial |
| Specialty Vehicle Carts (Ice Maintenance) | Industrial/Commercial |
| Specialty Vehicle Carts (Other) | Industrial/Commercial |
| Specialty Vehicle Carts (Tracked Transporters/Ice Maintenance) | Industrial/Commercial |
| Specialty Vehicle Carts (Transporters/Snow Groomers) | Industrial/Commercial |
| Specialty Vehicle Carts (Turf Maintenance/Personnel Carriers) | Industrial/Commercial |
| Specialty Vehicle Carts (Turf/Utility Vehicles) | Industrial/Commercial |
| Specialty Vehicle Carts (Wheeled/Tracked Military Vehicles) | Industrial/Commercial |
| Sweepers/Scrubbers | Industrial/Commercial |
| Terminal Tractors | Industrial/Commercial |

## Appendix B: List of Municipalities and their Urban or Rural Status

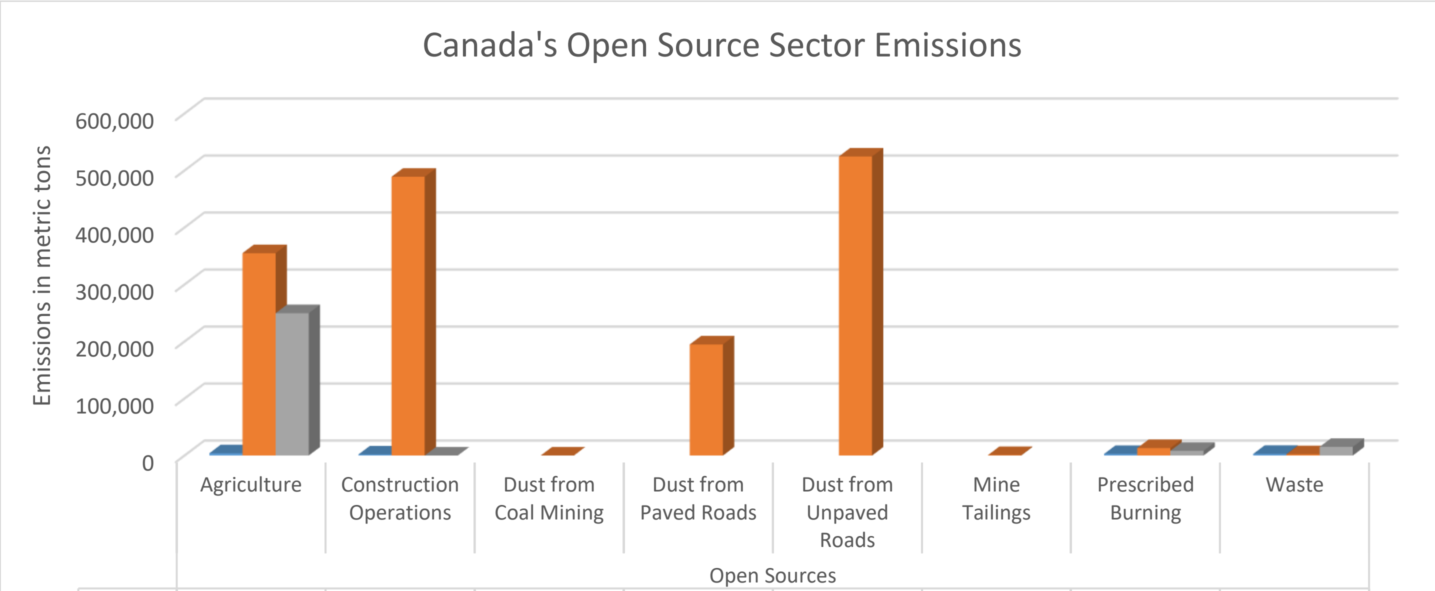
*Table B1 List of Municipalities in Quebec, as well as their vehicle population and their population centre category for this project*

| Municipality | Vehicle population | Population centre category |
|---|---|---|
| Abitibi | 19,247 | Rural |
| Abitibi-Ouest | 15,842 | Rural |
| La Vallée-de-l'Or | 31,258 | Rural |
| Rouyn-Noranda | 30,467 | Rural |
| Témiscamingue | 12,353 | Rural |
| Kamouraska | 15,189 | Rural |
| La Matanie | 15,767 | Rural |
| La Matapédia | 13,599 | Rural |
| La Mitis | 13,228 | Rural |
| Les Basques | 6,766 | Rural |
| Rimouski-Neigette | 39,236 | Rural |
| Rivière-du-Loup | 24,538 | Rural |
| Témiscouata | 14,770 | Rural |
| Charlevoix | 9,303 | Rural |
| Charlevoix-Est | 11,031 | Rural |
| La Côte-de-Beaupré | 20,371 | Rural |
| La Jacques-Cartier | 30,329 | Rural |
| L'Île-d'Orléans | 5,183 | Rural |
| Portneuf | 40,648 | Rural |
| Arthabaska | 52,379 | Rural |
| Bécancour | 15,552 | Rural |
| Drummond | 73,224 | Rural |
| L'Érable | 17,093 | Rural |
| Nicolet-Yamaska | 17,871 | Rural |
| Beauce-Sartigan | 38,703 | Rural |
| Bellechasse | 28,191 | Rural |
| La Nouvelle-Beauce | 27,711 | Rural |
| Les Appalaches | 30,695 | Rural |
| Les Etchemins | 12,361 | Rural |
| L'Islet | 13,327 | Rural |
| Lotbinière | 24,635 | Rural |
| Montmagny | 16,792 | Rural |
| Robert-Cliche | 14,166 | Rural |
| Caniapiscau | 2,200 | Rural |
| La Haute-Côte-Nord | 8,365 | Rural |
| Le Golfe-du-Saint-Laurent | 2,465 | Rural |
| Manicouagan | 21,419 | Rural |
| Minganie | 4,321 | Rural |
| Sept-Rivières | 23,505 | Rural |
| Coaticook | 13,364 | Rural |
| Le Granit | 15,631 | Rural |
| Le Haut-Saint-François | 16,333 | Rural |

| | | |
|---|---|---|
| Le Val-Saint-François | 22,586 | Rural |
| Les Sources | 9,951 | Rural |
| Memphrémagog | 37,883 | Rural |
| Avignon | 11,329 | Rural |
| Bonaventure | 14,538 | Rural |
| ÎlesDeLaMadeleine | 9,791 | Rural |
| La Côte-de-Gaspé | 12,896 | Rural |
| La Haute-Gaspésie | 8,084 | Rural |
| Le Rocher-Percé | 13,592 | Rural |
| D'Autray | 31,147 | Rural |
| Joliette | 45,467 | Rural |
| Matawinie | 37,764 | Rural |
| Montcalm | 39,252 | Rural |
| Antoine-Labelle | 25,832 | Rural |
| Argenteuil | 22,617 | Rural |
| La Rivière-du-Nord | 89,923 | Rural |
| Les Laurentides | 34,411 | Rural |
| Les Pays-d'en-Haut | 32,041 | Rural |
| Mirabel | 37,145 | Rural |
| Les Chenaux | 15,270 | Rural |
| Mékinac | 9,709 | Rural |
| Acton | 11,755 | Rural |
| Brome-Missisquoi | 43,336 | Rural |
| La Haute-Yamaska | 61,339 | Rural |
| La Vallée-du-Richelieu | 85,790 | Rural |
| Le Haut-Richelieu | 83,770 | Rural |
| Le Haut-Saint-Laurent | 17,155 | Rural |
| Les Jardins-de-Napierville | 22,420 | Rural |
| Les Maskoutains | 65,301 | Rural |
| Marguerite-D'Youville | 55,066 | Rural |
| Pierre-De Saurel | 36,794 | Rural |
| Rouville | 27,490 | Rural |
| Admin. régionale Kativik | 704 | Rural |
| Eeyou Istchee | 5,453 | Rural |
| Jamésie | 10,405 | Rural |
| La Vallée-de-la-Gatineau | 16,098 | Rural |
| Les Collines-de-l'Outaouais | 38,494 | Rural |
| Papineau | 16,887 | Rural |
| Pontiac | 11,081 | Rural |
| Lac-Saint-Jean-Est | 37,754 | Rural |
| Le Domaine-du-Roy | 23,500 | Rural |
| Le Fjord-du-Saguenay | 16,597 | Rural |
| Maria-Chapdelaine | 19,274 | Rural |
| Saguenay | 98,488 | Rural |
| Québec | 356,956 | Urban |
| Sherbrooke | 99,343 | Urban |

| | | |
|---|---|---|
| L'Assomption | 85,761 | Urban |
| Les Moulins | 109,340 | Urban |
| Deux-Montagnes | 67,751 | Urban |
| Thérèse-De Blainville | 106,599 | Urban |
| Laval | 261,315 | Urban |
| Trois-Rivières | 88,747 | Urban |
| Longueuil | 248,974 | Urban |
| Roussillon | 120,144 | Urban |
| Montréal | 870,164 | Urban |
| Gatineau | 164,629 | Urban |
| (blank) | 19,198 | Urban |
| Lévis | 98,358 | Urban |
| La Tuque | 9,349 | Urban |
| Maskinongé | 27,375 | Urban |
| Shawinigan | 33,635 | Urban |
| Vaudreuil-Soulanges | 106,347 | Urban |
| Beauharnois-Salaberry | 45,456 | Urban |

## Appendix C: Canada’s Open Source Sector Emissions




| | Agriculture | Construction Operations | Dust from Coal Mining | Dust from Paved Roads | Dust from Unpaved Roads | Mine Tailings | Prescribed Burning | Waste |
|---|---|---|---|---|---|---|---|---|
| NOX | 3,914 | 1,954 | | | | | 2,755 | 2,908 |
| PM2_5 | 354,962 | 489,014 | 39 | 194,925 | 524,579 | 864 | 13,119 | 2,235 |
| VOC | 249,667 | 74 | | | | | 8,264 | 15,137 |

*Figure C18 Canada's Open Source Sector Emissions: Breakdown of the largest sources of $PM_{2.5}$*