# Analysing Atmospheric Impacts of Regional Truck Emissions Using an Integrated Modelling Approach

by

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# AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

# ABSTRACT

Transportation technology is providing new ways to mitigate multipollutant emissions co-emitted from on-road sources. Zero-emission vehicles (ZEV) are more common in passenger vehicles and other light-duty vehicles; however, they remain a relatively new technology for most medium-duty and heavy-duty vehicles. As more trucks are adopting zero-emission technology, we need to evaluate whether these mitigation strategies are sufficient in meeting regional reduction goals. Previous studies have evaluated the multipollutant impacts of trucks and other vehicles; however, these methods estimate vehicle activity by empirical data such as surveys, which, unlike process-based models, are not amenable to evaluating significant future technology adoption.

This research presents a new method to quantify the atmospheric impacts and evaluate mitigation strategies of zero-emission technology in trucks at a regional scale using an integrated assessment model (IAM). This model establishes a connection between EMME, a travel demand model, MOVES, a mobile emissions simulator, and EASIUR, a regression model that produces marginal damage estimates. The IAM estimates a baseline and compares the total damages of alternative scenarios, using different ZEV adoption rates applied to trucks. The annual, ground-level emissions were estimated for the following pollutants using the developed IAM: primary $PM_{2.5}$, $NO_X$, $SO_2$, $NH_3$, $CO_2$, $CH_4$, and $N_2O$.

The results from the application of the IAM to the baseline scenario show that the total annual damages resulting from atmospheric emissions from trucks for the Province of Ontario in 2012 is approximately $1.82 Billion (2005 USD). Most of these damages are in Southern Ontario, with Toronto, Peel and York being the top three contributors. Adoption of ZEV decreases these damages linearly. Ontario has an adoption rate goal for ZEV of 5% by 2020. This rate is assumed to hold true for trucks in this transportation network. This goal would yield approximately $89 Million (2005 USD) in benefits annually from trucks alone. This result varies by up to ±25% according to the sensitivity analysis related to the travel and emissions models. Future work should focus on the relationship between emissions to damages, which likely remain the largest source of uncertainty.

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# 1.0 INTRODUCTION

## 1.1. Background

The atmospheric-related impacts of freight transportation remain a policy challenge. At the regional scale (state- or province- wide), the movement of goods is dominated by trucks. Domestic freight movement by trucks in 2016 was approximately 72% by weight in Canada (Transport Canada, 2016), and in 2015 was approximately 60% by weight in the U.S. (USDOT BTS, 2016). Freight presents unique challenges for addressing the atmospheric impacts of this economically vital activity. With passenger vehicles and public transit, many technological advances have been employed to reduce the environmental impacts (e.g., hybrid or electric powertrains). However, trucks currently have limited alternatives and many current trucks still run on diesel fuel, a major source for both greenhouse gases (GHGs) and air pollutants.

GHGs (such as carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$)) are gasses in the atmosphere that have a positive radiative forcing, which means that they contribute to the overall global rise in surface and atmosphere temperatures, and indirectly impacts human health. Air pollutants, such as primary fine particulate matter ($PM_{2.5}$ – particles with a diameter size smaller 2.5μm), nitrogen dioxide ($NO_2$), carbon monoxide (CO), and sulfur dioxide ($SO_2$), have direct impacts to human health. In addition to their direct impacts on human health, nitrogen dioxide ($NO_2$), carbon monoxide (CO), and sulfur dioxide ($SO_2$) are harmful via their contribution to the formation of fine particulate matter in the atmosphere. The World Health Organization (WHO) has estimated 3.7 million deaths globally are attributed to ambient air pollution (primarily due to exposure to $PM_{2.5}$) in 2012 (Smith et al., 2014).

Direct global GHG emissions from transportation have increased by 250% from 2.8 gigatonne (Gt) $CO_2$ equivalent ($CO_2e$) (in 1970) to 7.0 Gt $CO_2e$ (in 2010), and, barring mitigation, could reach 12 Gt $CO_2e$ / yr by 2050 (Sims et al., 2014). As presented in Figure 1, the transportation sector accounts for the largest portion (34%) of anthropogenic GHG emissions in Ontario (Environmental Commissioner of Ontario, 2014). When broken down, on-road freight transportation accounts for 23.5% of transportation-related emissions, or 8% of all anthropogenic GHG emissions in the province.

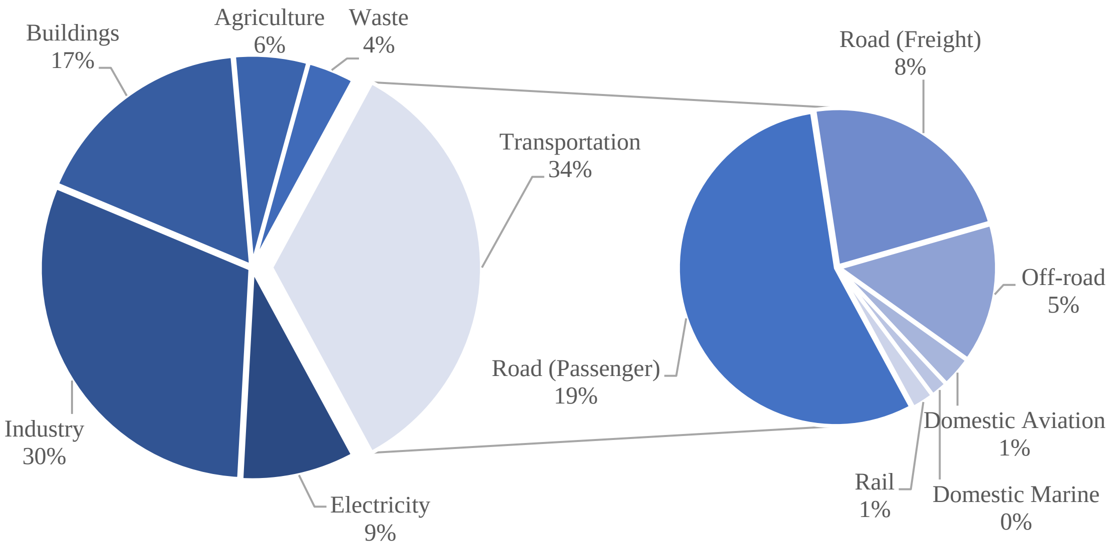

**Figure 1 – Regional GHG emissions from economic sector, Ontario (2012)**

Transportation policies are in place to regulate GHG emissions and air pollutants at various spatial scales (i.e., local, regional, national and global). Though air pollutants are usually regulated separately from GHGs, they are often emitted from the same sources. These compounds are inextricably linked, as the extraction, production, and use of fossil fuels for transportation emits GHGs (such as $CO_2$) and air pollutants (such as $PM_{2.5}$). In addition to being linked through co-emissions, air quality and climate change are linked through atmospheric processes (Fiore et al., 2012; Jacob and Winner, 2009). Simultaneously considering multiple air pollutants and/or GHGs is sometimes termed a ‘multipollutant’ approach.

Policies to reduce GHG emissions can also improve air quality as a “co-benefit”. These co-benefits can be significant (Jack and Kinney, 2010). Nemet et al. (2010) summarized 37 peer-reviewed studies yielding estimates of air quality co-benefits ranging from \$2 to \$147/$tCO_2$ (in 2008\$ USD). Thompson et al. (2014) estimated that the co-benefits can offset 26-1050% of the costs of U.S. climate policy. However, co-benefits studies have not traced the pathway between regional-scale transportation policy (including freight) to multipollutant impacts.

Several studies have estimated the effects of freight transportation or freight policy on emissions of GHGs or air pollutants, but did not assess both, nor estimate their economic impacts. For example, various studies have examined the effects of fuel consumption on GHG emissions (Demir et al., 2011; Patterson et al., 2008), however there is little to no focus on the associated air quality impacts. Other studies have included multipollutant impacts as part of the external costs of freight on a U.S.-scale (Forkenbrock, 2001) or European-scale (Janic, 2007), but these country-scale approaches do not evaluate regional policies.

Integrated Assessment Modelling (IAM) is one approach for estimating multipollutant impacts of on-road freight policy. Numerical IAMs represent more than one discipline and aim to trace the causal pathway from policy to impacts. IAMs can use one of two approaches for estimating the co-benefits of policies: impact models and damage functions. Impact models include a physical representation of atmospheric processes and impacts, and involve a coupling of, for example, emissions models, chemical transport models, and health impact models. They are commonly applied in national policy-making in the U.S. and Canada, but their application is limited by the fact that they are highly resource-intensive from a computational, data, and human resource perspective (Fann et al., 2012).

Another method quantifies the co-benefits of policies using damage estimates. Marginal damages aim to linearize the complex chain of processes from emissions to impacts. The marginal damage of an air pollutant or GHG is the social cost incurred from emitting one additional unit (e.g. $\$/tPM_{2.5}$). Marginal damage estimates provide a resource efficient alternative to a full-scale benefits assessment (Fann et al., 2012). Recent studies account for the marginal damages ($/tonne) of different atmospheric emissions across different spatial and temporal scales as well as impact categories (Fann et al., 2012; Shindell, 2015). They have been applied in benefit analysis of policies in transportation, energy, and climate change by regulators and academics (Greenstone et al., 2013; Anthoff and Tol, 2013; Shindell et al., 2016). Such estimates can be applied to quantify the multipollutant impacts of alternative transportation scenarios.

## 1.2. Problem Statement

The growing focus of the environmental impacts of global climate trends and air quality have led researchers to develop methods to capture these impacts in order to inform mitigation efforts. Transportation is a major contributor for both GHGs and air pollutants in most areas around the world. Within regions, where the main mode of transportation is on-road vehicles, there have been emission mitigation strategies such as electric vehicles being adopted. Previous studies have managed to evaluate transportation policies related to reducing emissions. However, these studies have either estimated emissions for on-road passenger vehicles, or the studies evaluate atmospheric impacts of GHGs and air pollutants separately. Demand for on-road truck travel is significant and projected to increase. There is little research on tracing the pathway between transportation policy to impacts pertaining to the co-emissions of regional freight transportation.

## 1.3. Research Objectives

This research aims to develop an integrated assessment model to evaluate the multipollutant economic impacts from truck movements in Ontario, and to evaluate the benefits of introducing zero-emission trucks.

Transportation policies at the regional scale demand large amounts of data compared to previous country-scale and continent-scale analyses. This IAM links a travel demand model, EMME (Equilibre Multimodal – Multimodal Equilibrium) (Florian et al., 1979), a transportation emissions model, MOVES (MObile Vehicle Emission Simulator) (US EPA, 2016), and marginal damage estimates of air pollutant emissions (from EASIUR – Estimating Social Impact Using Regression model (Heo et al., 2016a) and GHG emissions developed by a suite of IAMs for the US Interagency Working Group on the Social Cost of Carbon. Figure 2 provides a visual representation of the relationship of the IAM components and also indicate that economic damages and/or benefits estimated with this framework can inform policy evaluation and design.

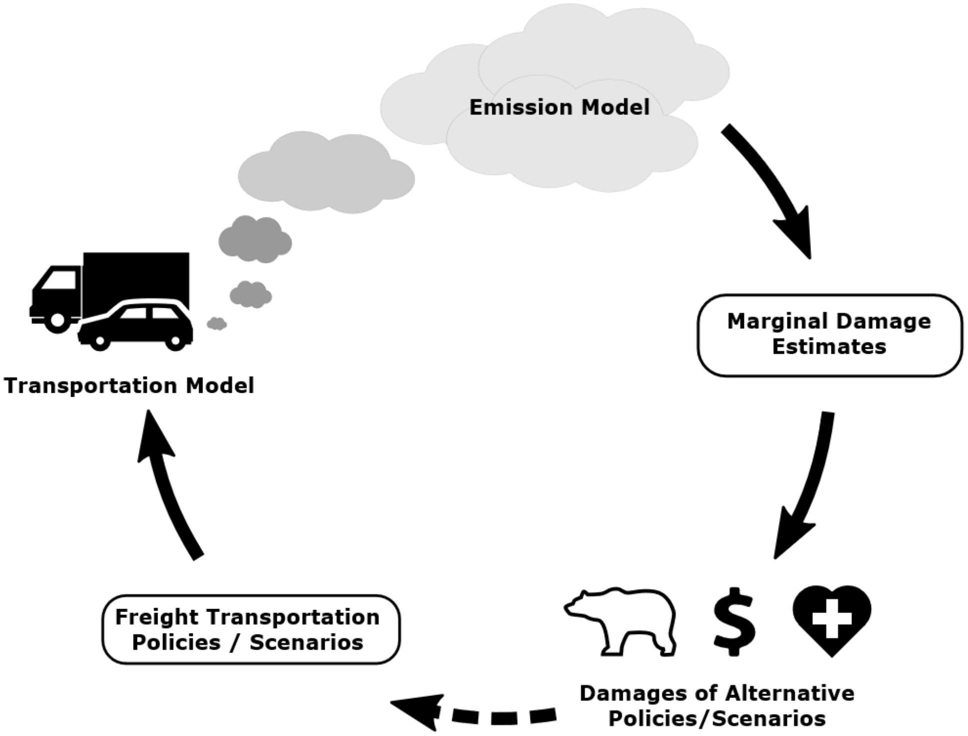

**Figure 2 – Relationship between the Integrated Assessment Model's components and policy-to-impacts pathway**

The developed IAM will be applied to a baseline scenario (which represents the conditions of Ontario, Canada in the year 2012), and alternative scenarios (which represent the potential conditions if transportation policies were implemented affecting the use of zero-emission trucks in the province). The robustness and accuracy of these results will be assessed as best as possible via comparison to other relevant estimates, and parameter sensitivity analysis.

## 1.4. Research Scope

The study domain for this research is the province of Ontario in the year 2012. While travel by passenger vehicles are modelled, they are used only to determine vehicle miles travelled and speed of travel by trucks. Policy scenarios represent a static shock of the transportation network and travel demand in 2012, where the various zero-emission adoption rates are applied to the medium-duty and heavy-duty vehicle population within the network. The baseline scenario represents the province, as it was in 2012. The policy scenarios represent the same province conditions with the exception of adopting a percentage of ZEVs in the vehicle population. This research does not forecast future demands or include any dynamic responses to policy such as rebound or other possible feedbacks. As significant data gathering was required for the travel and emissions modeling, efforts are made to assess the sensitivity of results to uncertainty in these parameters. Since the damages of emissions were drawn from EASIUR, uncertainty in the parameters contained within EASIUR, e.g., its economic valuations, are out of scope and are instead drawn from literature.

## 1.5. Structure of Thesis

The remainder of this thesis is organised into 5 sections.

The next section (Chapter 2) provides a review of the literature related to multipollutant impacts of freight transportation policies and scenarios, marginal damage estimates, freight emission modelling at the regional scale, and green freight technology alternatives.

Chapter 3 presents the methodology and the development of each component of the IAM and how they were linked together. The first subsection describes the transportation model of the IAM, discussing the travel and freight demand modelling in EMME, as well as how data were collected and processed. Chapter 3 also discusses how the transportation model connects with the other model components. The second subsection contains detailed model run specifications used in MOVES to simulate transportation emissions. The section includes the methods used to prepare a custom domain and the associated input tables to obtain results. Additionally, the section describes how MOVES interacts with the other IAM components. The next subsection describes the use of marginal damages from EASIUR and their application to the emission estimates to produce damage estimates. The next subsection describes the baseline and alternative scenarios for which the IAM is applied. The last subsection presents the design of the sensitivity analysis based on the various model parameters being analyzed.

The last two sections present the results (Chapter 4) and the sensitivity analysis (Chapter 5). The results section discusses the implications from applying the IAM to the baseline and alternative scenarios. The sensitivity analysis examines the changes in the baseline scenario's results due to changes in various parameters that are known to affect emission estimates.

# 2.0 LITERATURE REVIEW

The challenges of climate change and health impacts from air pollution at the global scale have spurred research aimed at mitigating these impacts for many sources. In addition to global efforts, regional and local efforts have been made to research, identify and mitigate these impacts. There have been an increasing number of studies with respect to air pollution and GHG emissions in past years, with growing attention to vehicle emissions. Vehicle technology is a rising topic, as advances in technology have made for more cost-efficient strategies for light-duty (passenger) vehicles (e.g., battery electric vehicles). These changes are now being focused towards improving emissions from trucks. However, there is still little research in understanding the multipollutant atmospheric impacts generated from freight trucks at the regional scale. To understand these effects, researchers require models to simulate impacts representative of the real world. This section reviews literature related to developing an integrated assessment model to analyse the multipollutant atmospheric impacts from freight trucks at the regional scale.

## 2.1. Multipollutant Analysis Using Integrated Assessment Modelling

Previous studies have employed integrated modelling approaches to analyze multipollutant impacts, particularly at local, national or global scales. There is a wide variety of integrated modeling methods that capture air quality co-benefits, and they vary in their level of detail in representing various elements of their respective systems (Nemet et al., 2010; Thompson et al., 2014).

Local scale modelling studies of the air quality impacts of transportation often benefit from detailed information about transportation as well as pollutant dispersion, capturing the atmospheric transport of pollution at the expense of detailed atmospheric chemistry or climate feedbacks. Several Canadian examples illustrate this approach. Hatzopoulou et al (2007; 2010) developed an integrated approach linking an activity-based travel model to an emissions model (MOBILE) and a dispersion model (CALMET/CALPUFF) applied to light-duty vehicles in the Greater Toronto Area (GTA). Their activity-based travel demand model provided emissions estimates with high spatial and temporal resolution of certain pollutants (Hatzopoulou and Miller, 2010; Hatzopoulou et al., 2007). Another framework linked a traffic assignment model (VISSUM) and emissions model (MOVES), using emissions as a proxy for exposures in the Montreal area (Sider et al., 2015). Muresan et al. (2016) presented a trajectory-clustering based integrated approach, linking VISSIM to MOVES, to estimate emissions of a transportation network by simulating the individual vehicle's path. However, for these and other local scale analyses, there is limited representation of atmospheric chemistry (which is more important on a regional vs. local scale), there is no link to climate change or the effects of greenhouse gases, and the results include exposures but not impacts (e.g., health outcomes or economic damages).

Conversely, studies at the global or national scales often sacrifice detail in transportation systems, while improving detail in the atmospheric impacts by using chemical transport models or climate-chemistry models. These models capture the effects on pollutant fate and transport from the atmospheric response to policy. For example, Thompson et al. (Thompson et al., 2014) evaluates co-benefits of capping carbon emissions from the transportation sector at the national scale using a chemical transport model and health impacts model. The transportation sector, however, is modeled within a regional computational general equilibrium economic model that does not model vehicle activity within the transportation network, and thus cannot disaggregate damages within a region. Global studies captured climate change and chemistry across a variety of impact categories, but used an accounting (spreadsheet) model to estimate aggregated transportation demands (e.g. Shindell et al. (2012, 2011)), which prevents the types of transport project and policy analysis typically completed with travel demand models at the regional scale (e.g., changes in travel demands, land use changes, changing mode shares, etc.).

## 2.2. Marginal Damages of Transportation Policies

Marginal damage estimates have the benefit of approximating some of the detail of the more powerful atmospheric models used in national or global studies. Recent studies have used various approaches to relate emissions to their associated multipollutant damages (Brown et al., 2017; Holland et al., 2016; Pappin and Hakami, 2013; Shindell et al., 2016). Applications include major reductions from energy or transportation sources (Brown et al., 2017; Shindell et al., 2016), blanket emissions reductions, (Pappin et al., 2016), or global warming goals (Shindell et al., 2016).

Methods to estimate marginal damages have employed a variety of techniques, from source-receptor matrices, to surface response methods, integrated assessment modeling, and global climate and chemistry modeling (Anthoff and Tol, 2013; Fann et al., 2012, 2009; Greenstone et al., 2013; Levy et al., 2009; Muller et al., 2011; Muller and Mendelsohn, 2009; Shindell, 2015). A comparison of approaches reveals differences in their sophistication, magnitude, and applicability to various problems (Heo et al., 2016a).

Some studies have included estimates of marginal damages from on-road transportation that could be applied in the integrated modeling framework developed in this research. A study by Fann et al. (2012) provides marginal damages for 17 sectors in the U.S. for NOx, $SO_2$, and $PM_{2.5}$, including all on-road mobile sources in one category. The study compares benefits estimates between 2005 and 2016, and results show a 34% increase in benefits per ton of direct $PM_{2.5}$ emissions avoided from on-road mobile sources ($240,000 and $370,000/ton $PM_{2.5}$ for 2005 and 2016 respectively). However, this approach only yields marginal damage estimates in the U.S. Shindell (2015) presents the Social Cost of Atmospheric Release (SCAR), which is applied to evaluate the damages from major air pollutants and GHGs from fuel consumption by passenger vehicles. While comprehensive in the emissions and impacts it considers, it presents results only at the global scale, and is thus ill-suited for regional analysis. Finally, EASIUR provides marginal damage estimates based on the economic valuation of increased mortality risk due to emissions of fine particulate matter and its precursors (NOx, $SO_2$, and ammonia). EASIUR uses the same state-of-the-art underlying atmospheric models as these other studies by Fann et al. (2012) and Shindell (2015), while also providing results for Ontario on a 36-km grid, making them suitable to this study (Heo et al., 2016b).

### 2.3. Freight Emissions Modelling

Recent literature, including a review of nearly 60 papers, on the atmospheric impacts of green on-road freight transportation, focuses on GHGs rather than air pollutants (Demir et al., 2014). Similar work compares freight emissions models (Demir et al., 2011). Wygonik and Goodchild (2011) developed a model of emissions, cost, and service quality to evaluate an urban delivery system that includes trucks, and derived a marginal cost of $3.50/kg$CO_2$ (USD) (Wygonik and Goodchild, 2011).

As opposed to GHGs, fewer studies analyze the impacts of multiple air pollutants from on-road freight transportation. Janic (2007) includes air pollution along with congestion, noise pollution, and traffic accidents to estimate the full costs of a simplified trans-European intermodal and road freight transportation network. Forkenbrock (2001) applies marginal damage estimates of multiple air pollutants and $CO_2$ to compare the external costs of freight and rail on a per-ton-mile basis across the U.S. Various measurement studies have estimated emissions of pollutants from trucks (Dallmann et al., 2012). However, these studies do not appear to have estimated the multipollutant impacts of freight scenarios on a regional scale.

### 2.4. Green Freight Alternatives

The adoption of electric vehicles (EV) has been the focus of many countries recently, in response to air pollution and greenhouse abatement goals. In 2012, the global sales for EV passenger cars were over 180,000, however this was small (0.02%), compared to the total global passenger car fleet (International Energy Agency, 2013). The trend in EV adoption rose, and in 2017, it was reported that approximately 3.1 million EV passenger cars were available globally (International Energy Agency, 2018). These electrification trends are seen to be slower for freight transport, especially heavy-duty long-haul trucks. Current use of EV trucks have been more commonly used in urban municipal services such as package/postal deliveries like Canada Post (Robinson, 2011), refuse trucks (Motiv Power Systems, 2017), or commercial delivery fleets (Pepsico, 2013). However, with the release of the Tesla Semi, which is a heavy-duty zero-emission freight truck (Tesla, 2018) and other future heavy-duty EV trucks, there will be a need to assess the associated impacts from the change in vehicle fleet composition.

## 2.5. Summary

The negative trends of atmospheric impacts on the environment have spurred research to mitigate these effects from various sources. One mitigation approach is the development of green vehicle technology. Recently the focus of green vehicle technology has expanded to include freight vehicles, namely heavy-duty long-haul trucks. Evaluating vehicle emissions has previously been focused on passenger vehicles and at smaller, more local scales. This work is novel in the methods and analysis it develops to capture the damages of multi-pollutant impacts on a regional scale, while still providing the flexibility to analyze alternative transportation projects and policies.

# 3.0 METHODOLOGY

## 3.1. Integrated Modelling

Figure 3 shows the framework for the integrated assessment model. The application of the integrated modelling approach illustrates the pathway from transportation policies to the multipollutant impacts of transportation policies/scenarios. Given a transportation policy, a travel demand model is developed using various network and transportation data to represent a scenario pertaining to that policy. The transportation model is then linked to a transportation emissions model with vehicle activity outputs and supported with additional exogenous data. The transportation emissions model produces total emissions (in tonnes) that are then combined with marginal damages in $/tonne/year to estimate the relative damages from that scenario. Data collection and manipulation are considerable underlying parts to the development of the IAM. Data used in the application of this modelling framework came from readily available (open) sources. Many data sources were not consistent with each other, so great efforts were required to manipulate the data into acceptable formats, and provide appropriate spatial, temporal, and categorical correspondence across the three models.

### *3.1.1. Transportation Model*

Policy can influence the transportation system with management strategies designed to, for example, reduce congestion, reduce air pollution, improve regional mobility, etc. (Meyer, 1999). The effects of policies on a transportation system are reflected in the transportation network through implementing various changes to the network attributes. The key characteristic of a transportation model for emissions purposes is to develop vehicle activity information such as speeds, drive cycles, travel times, etc. Vehicle activity can be developed from empirical methods using historical data and trends or field studies/surveys. This however, can be resource intensive, economically and temporally. An alternative method is to simulate the transportation network with a computerized software. In this research, a policy scenario that looks at reducing vehicle emissions at a regional scale was simulated with a transportation model. There are several methodological approaches and corresponding software programs to use; however selecting one is based on a few considerations such as the scale of the network, the capabilities of the software program, the readily available data, etc.

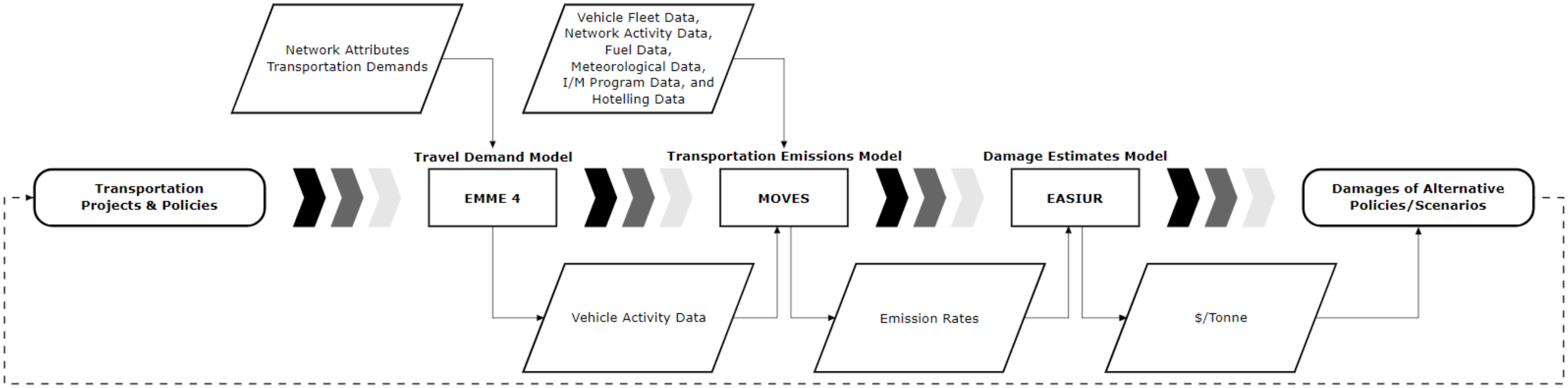

**Figure 3 – Integrated assessment modelling framework**

Traffic modelling can be macroscopic, microscopic, or a hybrid of the two known as mesoscopic (Sider et al., 2014). Macroscopic models typically simulate a large network using aggregated road characteristics such as average speed, density and flow. Similarly, traffic assignment models use macroscopic link-performance (or volume-delay) functions relating flow and travel time (Sheffi, 1985). Microscopic models simulate the individual driving behavior of every vehicle, generating instantaneous driving cycles. The appropriate model for a given policy application would depend on considerations including data availability, traffic and population density within the region, geographic extent of the region, and the study scope and objectives. There are scenarios where local data are not available, so data from other regions with similar local conditions are used. Presented in a study by Huo et al. (2011) in Chinese cities, they estimated vehicle activity data such as VKT for cities that did not have locally collected data. They mentioned it was difficult to provide accurate estimates, and that to estimate a national inventory using a set of cities with readily available data was not a proper estimation of the national emission average.

Given the size of the Ontario road network (approximately 35,000 links and 14,500 nodes), a traffic assignment model was selected. The network is presented as Figure 4 in section 3.1.3. The travel demand modelling software, EMME (Equilibre Multimodal – Multimodal Equilibrium) (Florian et al., 1979), was selected to analyse a regional-scale transportation system since it was readily available to use for this research. Furthermore, an existing road network of Ontario in EMME with developed transportation demands for freight movement and background auto demands were developed previously (Ashrafi et al., 2016).

#### 3.1.1.1. EMME model properties

Traditionally, travel demand modelling includes a ‘four-step process’: trip generation (total number of trips produced and attracted by zone), trip distribution (linking trip productions and attractions), mode split (determining the mode of travel for a given trip) and trip assignment (the routes taken from origins to destinations). For this IAM, the transportation model follows the four-step process. In a previous study, the existing road network, trip generation, trip distribution and mode split were already completed (Ashrafi et al., 2016). It is assumed that introduction of new policies to the transportation model will not change the behaviour of the model (i.e. will not affect the behaviour of drivers, route choice, mode choice, etc.). In the network, only two mode types were used, (passenger) autos and trucks. The auto demands were developed from the Transportation Tomorrow Survey (TTS), and the truck demands were developed from the Ontario Ministry of Transportation (MTO) Commercial Vehicle Survey (CVS) (Ashrafi, 2017). EMME’s Second Order Linear Approximation (SOLA) user equilibrium (UE) traffic assignment (TA) was used as the tool to model each trip’s route choice. The traffic assignment followed the principle of network user equilibrium

– a network is said to be in equilibrium when no single trip maker can improve their travel time by changing their route.

The results from the traffic assignment were stored in two built-in tables within EMME and exported for each hour. Link-level assignment results including travel time, volume, average speed, and mode specific vehicle hours travelled (VHT) were stored in the first table. The second table contained aggregated link-level results for the 49 zones, including vehicle kilometers travelled (VKT), but not average speed. Aggregation of the VHT and VKT into zones required a pre-processing step in EMME, since there were links that intersect multiple zone boundaries. Three assumptions were made to assign VHT and VKT to associated zones: 1) If one of the nodes of a link is an external node, then all allocation belongs to the internal zone; 2) If both nodes of a link exists in two separate zones, then 50% will be allocated to each zone; 3) If both nodes of a link exists in a single (internal) zone, then all will be allocated to that zone. MOVES requires input in miles, so an extra post-processing unit conversion was applied to the resulting VKT from EMME.

Intrazonal demands are not assigned in network models, so a post-processing step was used to include the intrazonal VKT. Intrazonal trip lengths were developed separately between auto and truck modes. A TTS data query was exported from an online database (run by the Data Management Group, DMG, at the University of Toronto Transportation Research Institute (Briggs, n.d.)). This consisted of multiple destination tables that contained a list of origins and associated trip lengths and number of trips for auto-passenger mode. From this data, average intrazonal trip lengths were calculated for each zone and then applied to the hourly intrazonal trips to get intrazonal VKT. Average intrazonal trip lengths for trucks were extracted from the MTO CVS based on the average distance of recorded intrazonal trips and applied to the hourly truck intrazonal trips. Comparatively, another method was developed to estimate the intrazonal trip lengths for both autos and trucks. This method took the area of each zone, set the area equivalent to the area equation of a circle, and calculated the radius of that circle. Evidently, this method was found to be less representative than using the MTO CVS estimates by approximately 10-20%.

### *3.1.2. Transportation Emission Model*

MOVES is a widely used transportation emissions model in North America, developed by the U.S. Environmental Protection Agency (U.S. EPA). MOVES is the current emission modelling system developed by the U.S. EPA, which superseded the MOBILE model series. The version of MOVES used in this research is MOVES2014a (US EPA, 2016). It is an emission modelling tool that can estimate transportation emissions at various scales: national, county, and project. MOVES functions by simulating user-specific “runs” of scenarios (controlled by a so-called “runspec” file), which follows a general formula:

$$Vehicle\ Emissions = Emission\ Factor\ \times\ Vehicle\ Activity^{*}$$

[*] Depending on the emission model, vehicle activity may be replaced with vehicle operation attributes (e.g. the Comprehensive Modal Emission Model, CMEM)

Integrating a transportation model with MOVES requires post-processing the vehicle activity data appropriately to the templates generated by the CDM. Vehicle activity data from EMME was output for two vehicle source types: auto and trucks. MOVES contains 13 vehicle source type classifications and 5 Highway Performance Monitoring System (HPMS) source type classifications. Of the 13 types of vehicles, only those that are considered to be "autos" or "trucks" were selected for modelling (i.e. busses were not modelled). Fuel, meteorological, inspection and maintenance (I/M) program and vehicle fleet data were developed from online open sources from the Canadian and/or Ontario Governments. Table 1 provides a summary of the data requirements that are used in linking the transportation model with the emission model. The input data tables are presented in Appendix A.

#### 3.1.2.1. Model Run Specification Setup

Prior to running a simulation in MOVES, a runspec was created with all the parameters associated with the baseline scenario. Setting up the runspec allows MOVES to prepare the proper input tables and calculations for use in the simulation. For the baseline scenario, the runspec was setup to perform a county-scale emission inventory calculation. The county domain was selected to be a custom domain since all of the inputs were local (and Canadian). The temporal setup was selected for an hour of a weekday in April in 2012. This means that MOVES only required data for only the specified hour, month and year. If any other data was imported, it was not used. To match the transportation network, only diesel and gasoline vehicles were selected, excluding busses. All road types were selected. Most of the emissions estimated from MOVES were from running and start exhaust, however, all of the emission processes (other than evaporative fuel venting) was selected for some pollutants and energy consumption shown in Appendix B as Figure B.1. Although some of these pollutants are not analysed, MOVES required them as internal calculations that are related to the pollutants being analysed.

Desired outputs and units were specified. The output units for the mass, energy consumption and distance travelled were in grams, joules and kilometers respectively. As a validation to see if the input was properly completed, the distance travelled as an output was included. The internal calculations of MOVES can be outputted at different levels of detail such as by temporal aggregation and scale. The output was set to show hourly results, and have the capability to organize it by zone. Additionally, other properties such as the fuel type, road type and source use type were added so the output could be organised by those categories if needed.

**Table 1 – Data inputs for MOVES simulation run**

| | Data Type | Attributes | Definitions |
|---|---|---|---|
| **EMME** | Network Attributes | Network nodes and link positions | Network components that represent the intersections and roads |
| | | Link speeds | Average speeds vehicles are travelling on each link |
| | | Link lengths | Distance of the link, between two nodes |
| | | Link volume delay functions (VDF) | A modified Bureau of Public Roads (BPR) function representing the relationship between the volume and speeds on each link type |
| | Transportation Demands | O-D matrix (by mode) | Matrix containing travel demands between each O-D pair for each mode defined in the network |
| **MOVES** | Vehicle Activity Data* | Vehicle distance travelled (VDT – km or mi) | Total distance a vehicle mode travelled within the network (in kilometers or miles) |
| | | Temporal adjustments | Adjustment factors applied to VDT. Total VDT is specified by month, day and hour |
| | | Vehicle hours travelled (VHT) | Total hours travelled by vehicle mode |
| | | Average speed distribution | Fraction of VDT by average speed bins, for vehicle, road, and day types |
| | Vehicle Fleet Data | Vehicle age distribution | Fraction of vehicle ages between 0-30 years old for each vehicle type of a given year |
| | | Vehicle types | Vehicle types according to Highway Performance Monitoring System (HPMS) or MOVES |
| | Network Activity Data* | Road type distribution | Fraction of VDT on each road type by a vehicle type |
| | | Ramp fraction | Fraction of road types that are ramps, distributed by the fraction of VHT on each ramp |
| | Fuel Data | Fuel supply | Local fuel supply data |
| | | Fuel formulation | |
| | Meteorological Data | Temperature | Local temperature data |
| | | Relative humidity | Local relative humidity data |
| | Inspection/Maintenance Programs | I/M coverage | Local data describing inspection and maintenance programs |
| | Hotelling | Hotelling activity distribution | Fraction of time spent while "resting" (idle or engine off) |
| | | Hotelling hours | |

#### 3.1.2.2. Vehicle fleet

The characteristics of the vehicle fleet such as source type population and source type by age are required to model the emissions released from different sources. Vehicle fleet data for Ontario were not completely available, so Canadian fleet characteristics were used and distributions were produced. These were then applied to available Ontario data for use in the baseline scenario. A vehicle registration data table from the Canadian Vehicle Survey (CanVS) (Government of Canada, 2017a) contained total vehicle populations for Ontario in 2012. However, the source types did not match perfectly with the MOVES source types, so an intermediate step mapping the source types to the MOVES ones was completed. The HPMS source types were used to map the Canadian vehicle registrations to MOVES since the HPMS source types were representative of the registration data. Table 2 presents the relationship of the vehicle source types from the Canadian registration source types (i.e. HPMS) to the MOVES source types.

**Table 2 – MOVES source types and the equivalent HPMS source types**

| sourceTypeID | Source type name | HPMSVtypeID | HPMS source type name |
|---|---|---|---|
| 11 | Motorcycles | 10 | Motorcycles |
| 21 | Passenger Cars | 25 | Light-Duty Vehicles |
| 31 | Passenger Trucks (primarily personal use) | | |
| 32 | Light Commercial Trucks (primarily non-personal use) | | |
| 41 | Intercity Buses (non-school non-transit) | 40 | Buses |
| 42 | Transit Buses | | |
| 43 | School Buses | | |
| 51 | Refuse Trucks | 50 | Single Unit Trucks |
| 52 | Single Unit Short-Haul Trucks | | |
| 53 | Single Unit Long-Haul Trucks | | |
| 54 | Motor Homes | | |
| 61 | Combination Short-Haul Trucks | 60 | Combination Trucks |
| 62 | Combination Long-Haul Trucks | | |

*Note ‘short-haul’ and ‘long-haul’ refer to the distance the trucks drive. Short – less than 200 miles.

Source types: 21, 31 and 32 were considered light-duty vehicles (LDV); single unit truck source types: 51, 52, 53, and 54 were considered medium-duty vehicles (MDV); combination truck source types: 61 and 62 were considered heavy-duty vehicles (HDV); and source type 11 are motorcycles. Busses were not modelled in this scenario, however, MOVES is capable of modelling transit vehicles. A second data table (Government of Canada, 2018a) from the CanVS contained the number of vehicles by vehicle type and type of body in 2009, which was used to distribute the total (LDV) vehicle class population to their respective vehicle source types. Table 3 shows the fractions that were created among each vehicle classes based on the total population for that source type (e.g., passenger cars, which is the sum of 'car' and 'station wagon' made up 59% of the vehicle population for LDVs. For MDVs and HDVs, the distribution of the class population to the source type populations was developed from the MTO CVS and the EMME network. From the MTO CVS, the observed vehicle configuration and body type information was used to tally the number of vehicles in each of the MDV and HDV class' source types. Furthermore, the EMME network was used to count the number of short- and long-haul vehicles, which was then applied to the single-unit and combination trucks.

**Table 3 – Population distribution among MOVES source types**

| Vehicle Group | Source Type ID | Source Type Name | Fractions |
|---|---|---|---|
| Motorcycle | 11 | Motorcycles | 1 |
| | | | |
| LDV | 21 | Passenger Cars | 0.590 |
| | 31 | Passenger Trucks | 0.408 |
| | 32 | Light Commercial Trucks | 0.002 |
| | | | |
| MDV | 51 | Refuse Trucks | 0.040 |
| | 52 | Single Unit Short-Haul Trucks | 0.828 |
| | 53 | Single Unit Long-Haul Trucks | 0.132 |
| | 54 | Motor Homes | 0.000 |
| | | | |
| HDV | 61 | Combination Short-Haul Trucks | 0.862 |
| | 62 | Combination Long-Haul Trucks | 0.138 |

Another vehicle fleet characteristic required for MOVES is the vehicle age distribution (the distribution of vehicle ages from the simulation model year (i.e. for the year 2012, vehicle ages are 0 to 30 years old). Vehicle ages were retrieved from CanVS for LDV (Government of Canada, 2017b), MDV (Government of Canada, 2018b), and HDV (Government of Canada, 2017c) for Ontario between 2000-2009. Each of those years contained vehicle age data going back 18 years. Since this was the best representative data for the baseline scenario, 2009 was set as the scenario model year and the associated data were used (available up to 1991). A backwards trend was extrapolated to estimate the other 12 years for each of the three vehicle classes. The best fitting trend was a negative exponential with a correlation coefficient of 0.9886 0.9513, and 0.8913 for LDV, MDV and HDV respectively. A plot of these trendlines are presented in Appendix C. The trendlines were developed using a subset of the data (1991-1995) to provide a better correlation of the extrapolated values, without capturing the uncertain up and down trends seen in the plots. Additionally, an exponential trendline was fitted, because it was assumed that the number of vehicles would never reach zero, and never be negative. Since these extrapolated years comprised less than about 5% of the total vehicle population, the effect of this approximation is expected to be relatively minor; nonetheless, the effect of adjusting this distribution was explored in sensitivity analysis described later in this thesis. Within each vehicle class, the source types have the same age distribution. Motorcycles were assigned the same age distribution as LDVs, since data specific to this source type was unavailable.

#### 3.1.2.3. VMT

Vehicle miles travelled (VMT), which are required by MOVES in imperial units were used as a basis for multiple required inputs. VMT can be provided by source types based on the MOVES types or the HPMS types. The VMT is necessary for the calculation of emissions from vehicle activity such as the distance travelled. Daily VMT data can be entered using two tables, one that requires the total daily VMT by source type and day type, and the other table that distributes the daily VMT by each hour. Supplying annual VMT data requires additional tables to distribute the data by months, days and hours. For the baseline scenario used in this research, daily VMT was supplied from the results of the EMME TA. The two sources types from EMME were simpler to map to the HPMS types, so the VMT was distributed among the 5 HPMS source types. Mapping the EMME source types to HPMS was done by using the distribution of vehicle populations from Statistics Canada. As such, the total daily auto VMT was split among the motorcycles and LDV, while the daily truck VMT was split among the MDV and HDV.

Hourly VMT distributions were developed by calculating the hourly fraction of VMT by source type from the EMME TA results. The EMME model does not have distinct road types, so within each source type and day type combination, the same hourly VMT distributions were assigned for each road type.

#### 3.1.2.4. Zone

Vehicle demands (O-D matrices) were used to estimate and vary the distribution of off-road activity such as starts. Emissions depend on the zonal distribution for off-road (vehicle starts, hotelling, and parking) and on-road (source hours operating, SHO) emission processes. Off-road activity data was unavailable, so the zonal distribution of vehicle starts were estimated from the Ontario O-D matrices, with the assumption that one trip prompted one start. The 24, 1-hour O-D matrices for both autos and trucks were added together for each zone and then divided by the total sum of starts for the whole network to create the daily start distributions. This was used to vary the starts between zones. Hotelling and parking distributions were both estimated from vehicle population totals from EMME. To get the SHO, the daily VMT from EMME for both source types were added together and divided by the total VMT in the network. This was then distributed to the zones and applied to all road types (i.e. for each road type, the 49 zonal VMT values have the same distribution, and sum to 1).

#### 3.1.2.5. Starts

Vehicle starts information is required, not only zonally, but at the time scale of interest. There are four required MOVES input tables that were used to represent the vehicle start activity within the network. The combination of tables was used in conjunction with each other (or individually) to provide start activity information on the network. The total number of starts per day was calculated from the O-D matrices, the daily sum of all vehicle starts for each zone. The other three tables distributed hourly starts within a zone, distributed the number of starts by the vehicle source type for the whole network, and applied a monthly adjustment factor to account for the seasonal activity levels (e.g. there is typically more vehicle activity in the summer months than the winter months). Hourly starts distributions were calculated from the O-D matrices, taking the fraction of each hour's total starts in a zone, divided by the total daily starts in that zone. The distribution of starts by source type was for the whole network, taking the number of starts for autos and trucks, multiplying it by their respective source type population distributions, then dividing by the total starts in the network. The monthly adjustment factor was set to 1 as a default since the VMT from the transportation model is for a typical day in the year.

#### 3.1.2.6. Average Speed

Subsequent to the EMME traffic assignment, the average vehicle speeds were stored on each link (i.e., every vehicle had the same average travel time within any given link). The distribution of average vehicle speeds was post-processed from the traffic assignment, composed of the fraction of VHT in one of the 16 defined speed bins in MOVES. The distribution is stored separately by source type and varies by hour. Given the two modes used in EMME, each of the truck source types would have the same average speed distribution within the same hour (e.g. single unit trucks have the same average speed distribution as combination trucks for the same hour and for all road types). This is the same with auto source types. From the EMME traffic assignment, the average speed (in units of mph) of the link was categorized into one of the 16 speed bins defined in MOVES, and the associated truck and auto VHTs were stored in those bins. Fractions for each bin were calculated by taking the sum of each bin over the total sum of all bins.

#### 3.1.2.7. Road Types and Ramps

MOVES uses the road type distribution table to vary the drive cycles on the different types of roadways (e.g. on freeways, it is assumed that there are less stop-and-go movements, less acceleration and deceleration periods (US EPA, 2015)). The distribution of road types and ramps were developed by applying a fraction of urban and rural populations for each of the 49 zones in Ontario to the road types used in the EMME network. EMME did not specify road types beyond identifying freeways. Effectively there are 5 road types used in MOVES, based on the level of restriction and urban character. For consistency with MOVES, any freeway in the Ontario network is considered restricted access (i.e. a road with a ramp access), and non-freeway links are considered unrestricted. Census division (CD) population data contained rural population totals for 2011 by each CD in addition to total population by CD. Rural fractions were calculated for each zone, and the urban fractions were calculated as the complement of the rural fractions. Applying these fractions to the fraction of restricted and unrestricted roads produced a distribution of restricted and unrestricted, urban and rural roads.

The ramp fractions table is an optional table, which can have a default of 8% of VHT. However, for this research, calculated ramp fractions were used and developed the same way as the road distribution fractions. The EMME network contained a total number of links that had ramps, so the urban and rural fractions were applied to it.

#### 3.1.2.8. Fuel

Fuel characteristics and vehicle fuel usage information was organised into four input tables: AVFT, fuel supply, fuel formulation, and fuel usage fraction tables. The AVFT table was used to represent the distribution of vehicle fuel type technologies. The table showed the fraction of vehicles using a fuel type for each of the source type, model year and engine type combinations. It was assumed that all vehicles in the model were using internal combustion engines (ICEs). Data for this table was retrieved from the 2009 Canadian Vehicle Survey (Government of Canada, 2018c) for Canada and applied to baseline scenario model year. From this table, the number of diesel and gasoline vehicles were extracted for LDV, MDV and HDV for the years 2000-2009. Similar to the vehicle fleet data, a trendline backwards was developed to extrapolate the missing years for both fuel types and vehicle source types. This provided a fraction of engine fuel usage for each year and each source type, which is presented in the figures located in Appendix C.

Chemical formulations were supplied for the fuels being used in the region. The fuel formulation input table had many fuel characteristics that required region specific customization such as Reid vapour pressure (RVP), sulfur level, distillation temperatures, etc. These fuel characteristics change based on the month, so 12 fuel formulations were created for gasoline and diesel to represent a new fuel formulation for a specific month. Fuel formulation data were retrieved from the National Standards of Canada for automotive gasoline (Canadian General Standards Board, 2016) and diesel (Canadian General Standards Board, 2017), which was applied to Ontario.

The fuel supply table was used to associate the fuel formulations to a region, and the market share of the fuel formulations with a fuel type (i.e. if there are two different fuel formulations being used for gasoline, the market share determines the fractions of fuel formulation 1 and 2 in use). The sum of the market shares for each fuel type should be 1.

The fuel usage fraction table was used to describe the fraction of vehicles that are using gasoline or E-85 given that the vehicle is capable of using E-85. The baseline scenario does not include any vehicles that use E-85 fuels, so the fraction given to gasoline is 1. Since the baseline scenario does not include E-85 fuels, this table was left as the default values that MOVES supplies.

#### 3.1.2.9. I/M Program

An optional table that can be used in MOVES is for describing any inspection and maintenance (I/M) programs being used in a particular region. Table 4 summarizes the Drive Clean Program details used in the baseline scenario. The Drive Clean Program has different properties depending on the vehicle type and fuel usage. In MOVES the only corresponding I/M tests available are for gasoline vehicles. Light-duty gasoline vehicles (LDGV) were tested using a dynamometer under 25% load and a steady state driving cycle at 25mph at final cutpoints (ASM 2525 Final Cutpoints) (US EPA, 2015b). Heavy-duty gasoline vehicles (HDGV) were tested with the two-mode idle test, while the vehicle is idle and at 2500 rpm (US EPA, 2015b).

**Table 4 – Summary of Ontario Drive Clean Program**

| Program Details | Light Duty Vehicles | Heavy Duty Vehicles |
|---|---|---|
| Coverage | Southern Ontario (Windsor – Ottawa) | Diesel: All of Ontario<br>Gasoline: Southern Ontario |
| Vehicle Classification | Vehicle Weight: ≤ 4.5 tonnes<br>Model Year: ≥ 1988<br>Exempt: “Historic” vehicles and motorcycles | Vehicle Weight: ≥ 4.5 tonnes<br>Model Year: ≥ 1982<br>Exempt: “Historic” vehicles |
| Testing Frequency | Biennial | Annual |
| Testing Method(s) | ASM 2525 Final Cutpoints | Two-mode, 2500 RPM/Idle Test |

*Adapted from: (Eastern Research Group, Inc., 2005; Office of the Auditor General of Ontario, 2012)

The I/M Program input table provided details about the I/M program and also provided the percentage of the total vehicle population that receive the benefits of the program – the compliance factor (US EPA, 2015b). The compliance factor for a program was determined by the fraction of vehicles subject to the program (compliance rate – CR), the fraction of vehicles that failed an initial test and a retest, but still received a certificate of compliance (waiver rate – WR), and the regulatory class coverage adjustment (RCC). The RCC adjustment factor was defined in MOVES, which classified the 13 vehicle source types by their gross vehicle weight rating (GVWR), having associated emission rates by grouping similar vehicles by their vehicle activity and their weight. The CR and WR for both LDV and HDV was 98.7% and 1.6% respectively (Eastern Research Group, Inc., 2005). The RCC adjustment factor used was 100% for all vehicles except for passenger trucks (98%) and light commercial trucks (92%). The compliance rate was assumed to be the same for trucks that were not registered in Ontario, but passing through (external to external nodes).

#### 3.1.2.10. Meteorological Inputs

Meteorological properties (temperature and relative humidity) influence vehicle emissions directly and indirectly (Choi et al., 2010). These meteorological conditions were varied by month, by hour and by zone. Historical 2012 meteorological data were retrieved from Environment Canada (2011) as a weather station inventory list. From this list, data for all weather stations that contained 2012-year and contained both temperature and relative humidity data were extracted from the Environment Canada website by organising the stations by zone. Since there were multiple weather stations for each of the CD zones, meteorological data were averaged by zone for each hour. For certain zones, if the data was incomplete or missing, the data from neighbouring weather stations were used, selected by proximity.

#### 3.1.2.11. Hotelling Activity

Hotelling refers to the time spent by truck drivers on a mandatory rest period during their long-haul trips. Therefore, hotelling activity only applies to source type 62 – long-haul combination trucks. There are two optional tables used to distribute the hotelling activity among operating modes, and to distribute the hotelling hours. However, lack of Ontario-specific data led to using the default values, calculated in MOVES based off the VMT and VHT provided from the other input tables.

### *3.1.3. Marginal Damages Estimates*

Marginal costs developed from the EASIUR model were applied to the emission results from MOVES. EASIUR presented marginal social costs of primary $PM_{2.5}$ and three precursors ($SO_2$, $NO_X$, $NH_3$) to the formation of secondary $PM_{2.5}$ due to atmospheric processes (Heo et al., 2016b). The spatial domain covers a 36km x 36km grid across America, as well as portions of Canada (including Ontario). The marginal costs from EASIUR were selected because it was the most applicable to the region of Ontario, and since it also included $PM_{2.5}$ mortality in its damage cost estimates, which is known to be the most significant source of damages from atmospheric emissions. Developing the marginal damages per CD and total damages for all of Ontario required a pre-processing step to relate the emission sources to the associated costs. Figure 4 shows the application of the EASIUR grid to Ontario. Each grid cell contains the annual and seasonal marginal costs of $PM_{2.5}$ at three elevations. The annual ground-level costs were used for all four species.

Since the IAM was estimating the damages from on-road freight vehicles, only the EASIUR grids that contained any of the Ontario roads were considered. Using a geographic information system (GIS) application, QGIS (QGIS, n.d.), two spatial joins were created: the Ontario road network to the 49 CDs; which was then joined with the marginal damages grid. Once each road link in the network had an associated CD and marginal costs, a weighted average based on the link length within a zone was produced for each of the CDs for the annual ground-level costs of each species. These marginal costs were then applied to the emission outputs from MOVES at a zonal scale to estimate the total zonal impact. To include the impacts due to $CO_2$, the marginal damages of which are considered to be relatively consistent across sources and locations, were obtained from the U.S. interagency working group exercise to estimate the Social Cost of Carbon (the application of which to Canada was previously endorsed by Environment and Climate Change Canada) (2016).

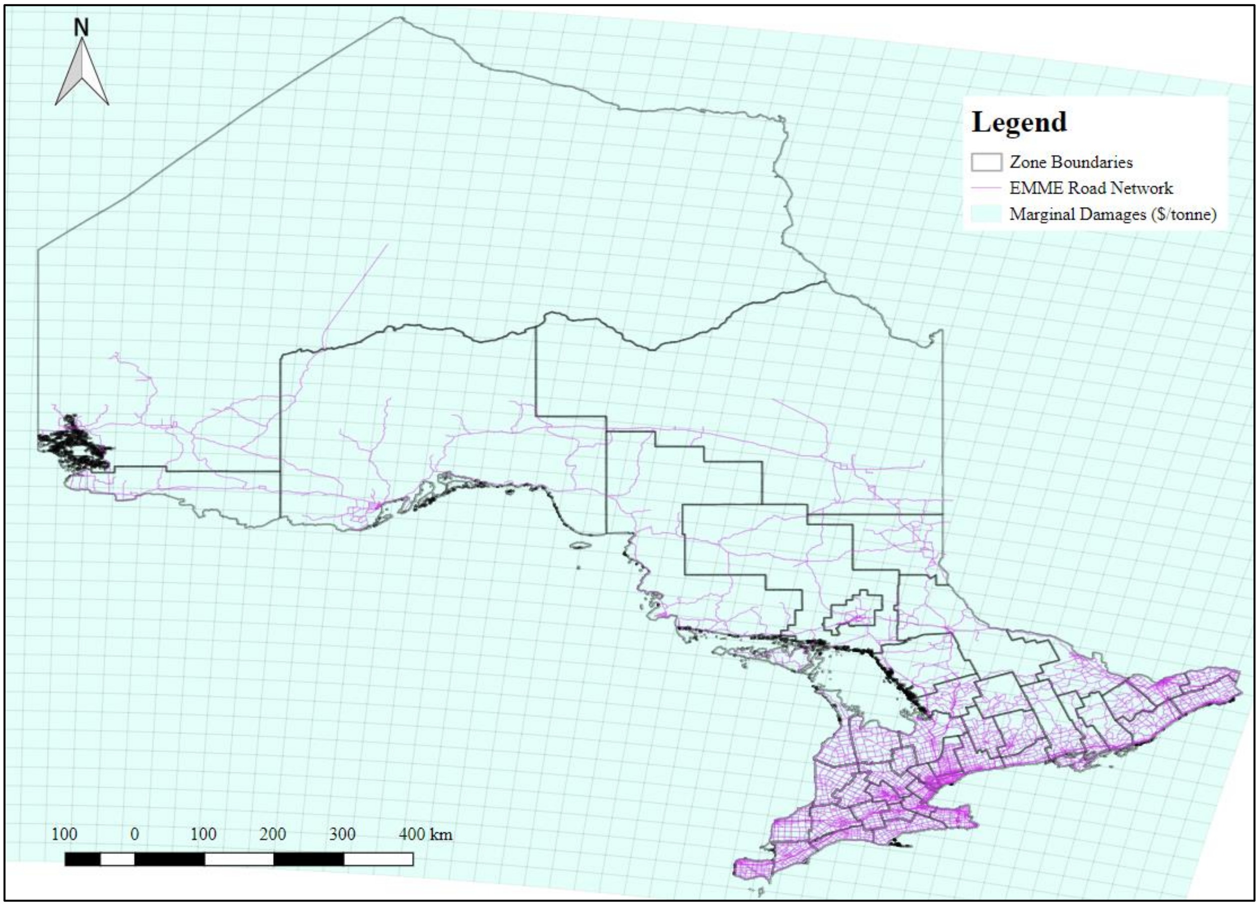

**Figure 4 – Overview of EASIUR grid overlaid on Ontario road network**

### *3.1.4. Ontario Case Studies*

#### 3.1.4.1. Baseline Scenario

The IAM framework is used here to evaluate five policy scenarios relative to a baseline. The baseline scenario represents the emissions and multipollutant impacts of on-road freight movement for Ontario in the year 2012. The vehicles of interest modelled in MOVES include all available diesel and gasoline vehicles except busses.

As a result of the available data, the baseline scenario was set so that the runspec simulates a 1-hour run, which was scaled up to represent a yearly total. In order to reduce the computational burden of simulating 24 hours of every month in a year, an hour and month were selected. 8am-9am was selected for simulation hour and April as the month. This hour and month represent a time period that is not extreme in terms of weather. It should be noted that this hour is not typical for travel or for freight demands, however this represents the busiest hour of the day, with the most congestion, and lowest average speeds. Having the time period with the busiest hour produces the greatest emissions due to vehicle activity (all else being equal). The effect of this selection is later tested in sensitivity analysis by choosing different hours and months.

#### 3.1.4.2. Alternative Scenarios

The IAM framework was applied to assess the multipollutant benefits of green truck technology. Alternative scenarios were developed to compare the effects of changing the vehicle fleet composition to include zero-emission (or really low emission) trucks (mainly medium-duty and heavy-duty). This represents a transportation policy scenario of adopting new green technology into regional vehicle fleets.

Alternative scenarios applied various adoption rates to the medium-duty and heavy-duty source types (51-54, 61, and 62), as shown in Table 5.

**Table 5 – Alternative scenarios' adoption rates**

| Alternative Scenario | Adoption Rate |
|---|---|
| 1 | 5% |
| 2 | 25% |
| 3 | 50% |
| 4 | 75% |
| 5 | 95% |

Alternative 1 represents Ontario’s goal of achieving 1 of 20 vehicles on the roads to be electric (Ontario Ministry of Transportation, 2009). Additional scenarios contain adoption rates to show the different levels of impacts from changing the fleet composition. To model the effects of changing a percentage of the MDV and HDV fleet to ZEV, the vehicle fleet emissions in these alternative scenarios were reduced by the adoption rates (i.e. for alternative scenario 4 – 75% adoption rate, the emissions from that number of MDVs and HDVs were reduced by 75%, thus only 25% of the baseline fleet emissions remained). These reductions are applied as a static shift, as a dynamic shift is beyond the scope of this research, and introduces more uncertainty.

## 4.0 RESULTS AND DISCUSSION

The integrated assessment model described in the previous sections was applied to a baseline scenario and five other alternative scenarios to estimate regional emissions. The baseline represents the emissions produced from vehicles from the region in the year 2012. These emission estimates from air pollution (CO, $NO_X$, $NH_3$, $SO_2$, total primary $PM_{2.5}$, and VOCs) were compared to the Canadian Air Pollution Emission Inventory (APEI), while the GHGs in $CO_2$ equivalent emissions were compared to the Canadian National Inventory Report (NIR) for Ontario.

### 4.1. Baseline Scenario

Table 6 is a summary of the estimated emissions of MDVs and HDVs for the baseline scenario. The model estimates numerous greenhouse gasses and air pollutants; however, the subset of pollutants presented in this table are shown because they were used to compare across scenarios and with the APEI and NIR values. These results represent the total emissions for both gasoline and diesel fuel type combinations of MDV and HDV in the model. GHG emissions can be combined based on the global warming potential of each gas with respect to $CO_2$. This value, presented as $CO_2$ equivalent ($CO_2e$) is measured in megatonnes (Mt). The air pollutants are measured in tonnes. The low $SO_2$ estimate can be attributed to the low sulphur content in automotive fuels in Canada, which have been decreasing over several years (Government of Canada, n.d.). $SO_2$ is released into the air from burning fossil fuels that contain sulphur. $NH_3$ is largely emitted from the agriculture sector; however, it is still emitted from the internal reactions from three-way catalyst engines (Durbin et al., 2001).

**Table 6 – Summary of model emissions (Baseline Scenario)**

| | GHG | Air Pollutants | | | | | |
|---|---|---|---|---|---|---|---|
| | $CO_2e$ [Mt] | $NO_X$ [Tonnes] | $NH_3$ [Tonnes] | CO [Tonnes] | $SO_2$ [Tonnes] | $PM_{2.5}$ [Tonnes] | VOC [Tonnes] |
| Emissions | 16 | 71,925 | 361 | 72,505 | 160 | 3,121 | 9,757 |

Figure 5 disaggregates the baseline scenario results by the MOVES source types. From this figure, it can be seen that the largest contributions of emissions are from source type 52 (single unit short-haul) and source type 61 (combination short-haul). This can be attributed to these source types having a larger fraction of starts (16.2% and 69.3% respectively, of all MDV and HDV starts). Additionally, of all the MDV and HDV source types, the two short-haul trucks make up of about 84% of the vehicle population in the model.

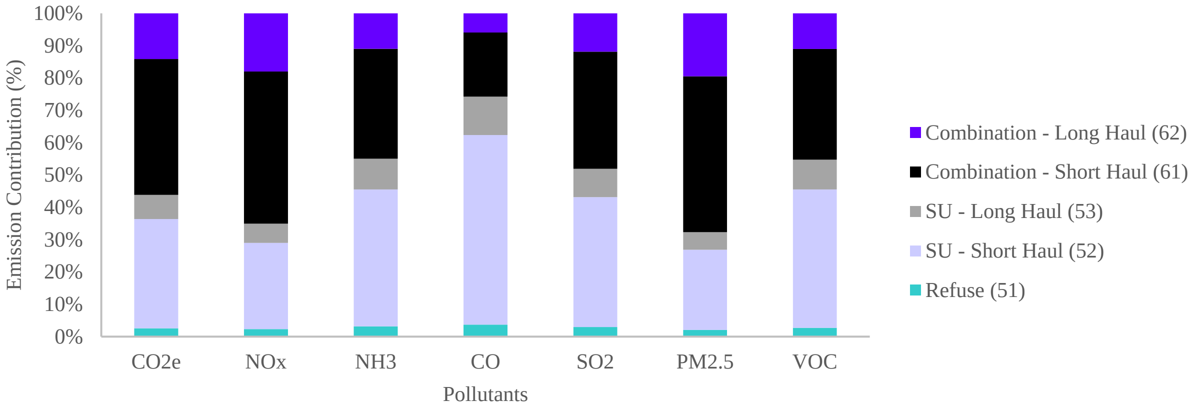

**Figure 5 – Baseline scenario results by MOVES source type**

Figure 6 shows the damages by zone, produced from the baseline estimates. The total damages in the region due to MDV and HDV sources is $1.82 Billion (2005 USD). The damage occurs largely in the southern part of Ontario, since there is a higher population and more vehicle activity. In particular, the census divisions of Toronto, York and Peel create the highest damages due to emissions from trucks. This is due to the large urban populations, high vehicle activity, and large freight hubs located in these zones.

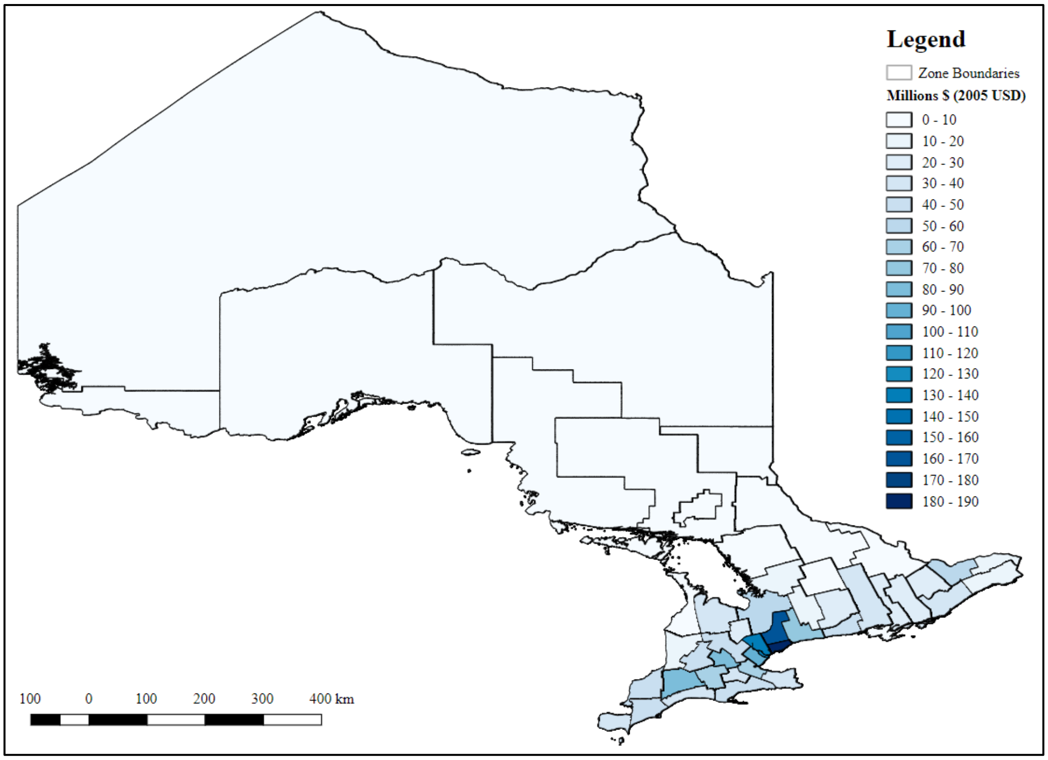

**Figure 6 – Ontario provincial damages in millions $ (2005 USD) in 2012 (Baseline Scenario)**

Figure 7a) and b) show the annual damages generated per capita per zone from the baseline scenario. Unlike the results presented in Figure 6, the 3 highest zones with regards to the damages per capita are the census divisions: Lennox and Addington, Oxford, and Perth. This may be attributed to the higher urban population and vehicle activity and a below average total population (Oxford); having one of the lowest total populations compared to the vehicle activity (Lennox and Addington); or above average emission output compared to a below average total populations (Perth). Though it may not be reflected in the per capita values, the census divisions that contain a high percentage of urban population had an associated total marginal damage estimate in the top 25th percentile. Compared to Figure 6, Figure 7 shows that, while the GTA produces the most damages, it produces relatively few damages per capita compared to other regions where truck activity is relatively high, or with conditions especially amenable to particulate matter pollutant formation.

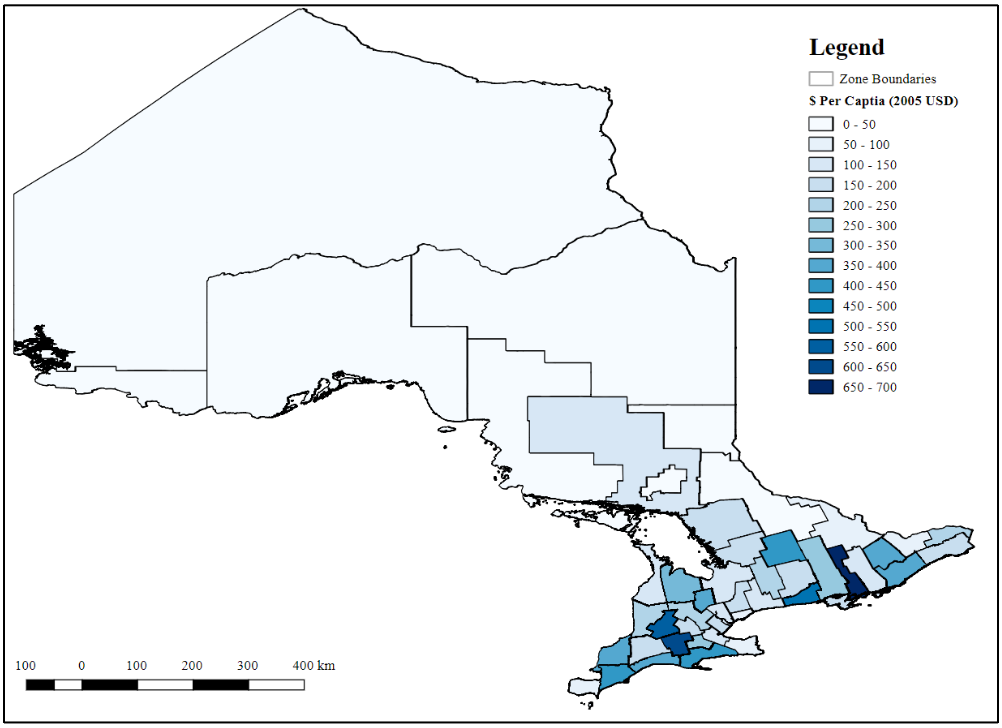

**Figure 7a) – Ontario zonal annual damages per capita in 2012**

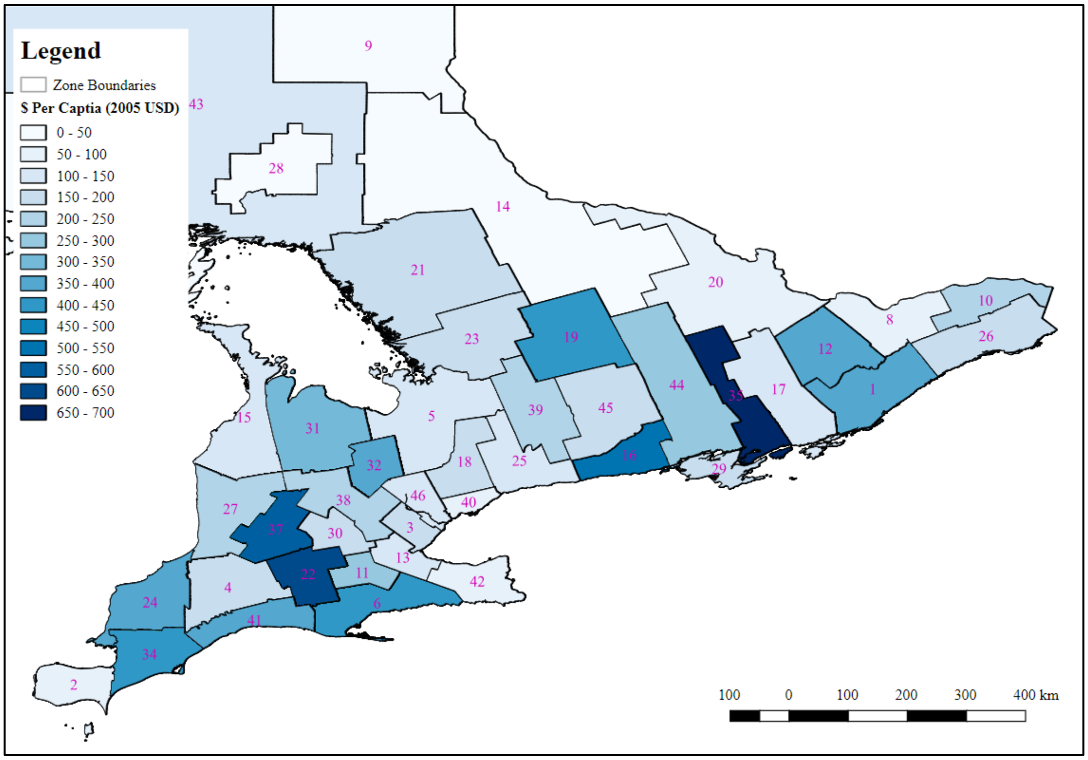

**Figure 7b) – Southern Ontario zonal annual damages per capita in 2012**

### *4.1.1. Baseline Validation*

Capturing the complex policy-impact pathway requires multiple integrated modelling components, each of which influences the model results. Therefore, the accuracy of the resulting impacts and the usefulness of the resulting insights will depend in part on overcoming challenges for each component. There is a trade-off between complex models and data availability. Complex models require more input parameters, which may not be readily available. However, these models have the ability to provide a better insight in their results (Smit et al., 2010). Ideally, data sources should be consistent; however, to avoid strenuous data collection, model parameters were developed from available sources, and were applied to the network.

Validation of the model outputs tests the accuracy of the representation to the real world. Real-world measurements related to freight emissions at the regional scale is severely limited. At the national level, Canada has the APEI and the NIR to report annual air pollution emissions and GHG emissions. These sources are not based on measured emissions, either, but on calculations and models (including MOVES). Comparison to these sources is imperfect and limited by important methodological differences, but serve at least as a comparison to Ontario-specific emission estimates. The Ontario-specific estimates are extracted from those national inventories. Figure 8 presents the comparison between the emission estimates from this research to the emission estimates produced from the national inventory.

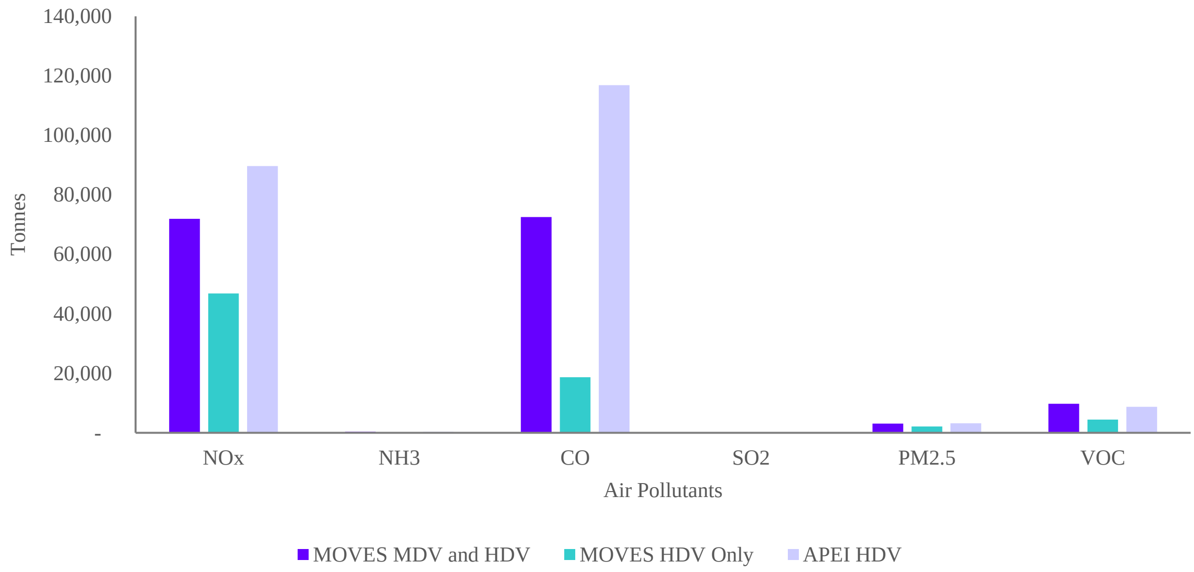

**Figure 8 – Comparison of emission estimates between Canadian APEI and MOVES**

Data availability and model-specific parameters dictate the format of the results. As presented in Figure 8, there are two emission estimates from the MOVES model for the air pollutant species. The results are presented this way because the estimates by source types are not equivalent between MOVES and the Canadian APEI. As labeled, the APEI emission estimates presented are of heavy-duty gasoline and diesel vehicles, however, their definition of "heavy-duty" also contains some MDV. These results are similar to the MOVES estimates when the total MDV and HDV (gasoline and diesel) source types are added together (3%-41% difference). When compared to the MOVES estimates of only heavy-duty (gasoline and diesel) vehicles, all the results are approximately 32%-85% lower than the APEI results.

Figure 9 compares the MOVES estimates to the Canadian NIR estimate for GHGs in Mt $CO_2$ equivalents. The MOVES estimates include both short-haul and long-haul, single-unit and combination trucks, as an equivalent to the NIR's vehicle type for on-road freight vehicles. Additionally, MOVES estimates $CO_2$, $CH_4$, and $N_2O$, whereas the NIR estimates $CO_2$, $CH_4$, $N_2O$, hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulfur hexafluoride ($SF_6$) and nitrogen trifluoride ($NF_3$). The GHG emissions estimated by MOVES across these sources is approximately 20% higher than that of the NIR for Ontario in 2012. The differences in the estimates can be attributable to the different definitions of vehicle source type.

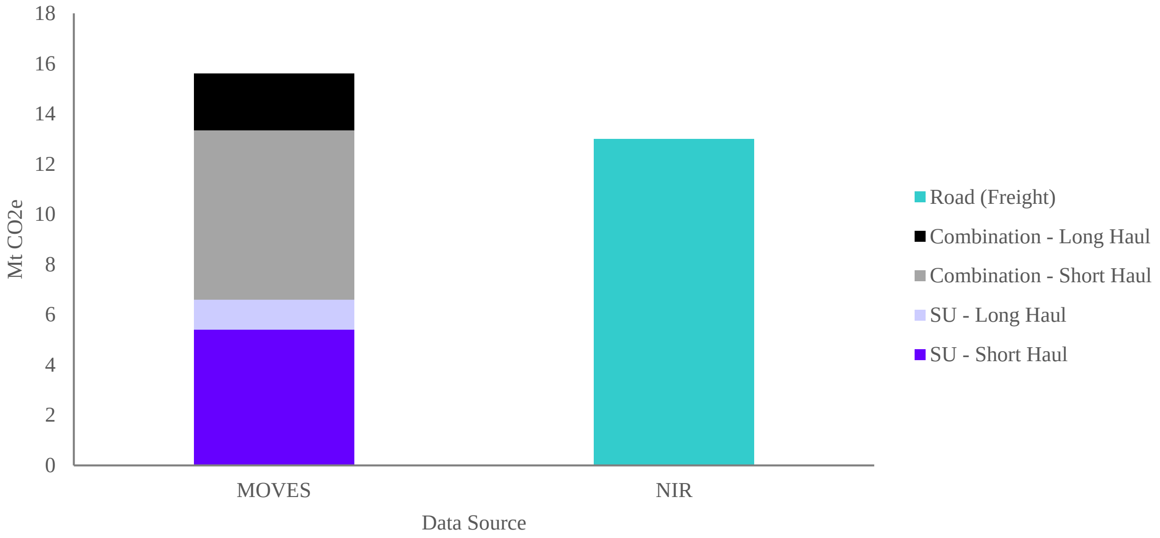

**Figure 9 – Comparison of $CO_2e$ emission estimates between NIR and MOVES**

Given the issues with mapping source types, and methodological differences, the comparison between this framework and these national inventories is understandable. Validation challenges are limited by the accuracy of the estimates used for comparison or any gaps in the collected data where it was not captured properly (Smit et al., 2010). This can be seen in the difference of how the vehicle types are mapped out between the data sets. The APEI classifies vehicles by their gross weight and fuel type (Environment and Climate Change Canada, 2017), however, these classifications are broad, as such, heavy-duty vehicles include MDVs as well. In addition to the misclassification of source types between models, the APEI also estimates its vehicle activity by multiplying the vehicle counts to the mileage accumulation rates (Environment and Climate Change Canada, 2017). The effect of this approach is to assign kilometers travelled, and thus, emissions, based on vehicle registration data. Conversely, the approach presented in this study tracks travel through and within the province. This creates a significant difference that may explain in particular why the pollutant emissions estimated by this framework are lower than that of the APEI. Namely, this framework only includes emissions from kilometers that were travelled within the province, excluding those due to out of province travel. Conversely, the APEI would assign all emissions to Ontario for any vehicle registered to this province. While this is a reasonable approach, especially for a national inventory perspective, it is preferred to track actual emissions based on travel when attempting to assign spatial damages, as in this study. From the collected travel demands, 78% of trucks travelled internally within the province, 20% had an origin or destination out-of-province, and 2% were travelling through the province. This approach captures the kilometers travelled on roads within the province, which includes the parts of the trips on roads even if the trip may have an external node (origin or destination out of the province. Given these considerations, the level of agreement within 50% or better that we generally see is encouraging. The agreement for greenhouse gases is even better, within 20% of the NIR, though methodological differences remain, and the data also are not directly comparable as reported; for example, it is possible that this study's results overestimate the NIR because it assigns all emissions from short-haul and long-haul, single-unit and combination trucks to compare with a single data point "on-road freight" from the NIR. Barring more robust and suitable validation data, a sensitivity analysis is performed (presented later) to assess uncertainty in the baseline emissions.

## 4.2. Alternative Scenarios

Table 7 summarizes the results from 6 scenario simulation runs performed in MOVES for MDV and HDV: Baseline, Alternative 1 (5% ZEV), Alternative 2 (25% ZEV), Alternative 3 (50% ZEV), Alternative 4 (75% ZEV) and Alternative 5 (95% ZEV). The table shows the four air pollutants, measured in tonnes/yr, and the total $CO_2$ equivalents, measured in megatonnes/yr. The alternative scenarios differ by a comparative static change in the level of adoption of ZEVs. This represents potential levels of change in ZEV adoption due to a transportation policy, which could have an impact on the levels of vehicle emissions produced.

**Table 7 – Summary of emission estimates for MDV and HDV for the alternative scenarios.**

| **Scenarios** | **Source Type Categories** | **Pollutants** | | | | |
|---|---|---|---|---|---|---|
| | | **$PM_{2.5}$ (tonnes/yr)** | **$NO_X$ (tonnes/yr)** | **$SO_2$ (tonnes/yr)** | **$NH_3$ (tonnes/yr)** | **$CO_2e$ (Mt/yr)** |
| Baseline | MDV | 1,009 | 25,113 | 83 | 199 | 7 |
| | HDV | 2,112 | 46,812 | 77 | 162 | 9 |
| | | | | | | |
| Alternative 1 (5% ZEV) | MDV | 959 | 23,857 | 79 | 189 | 7 |
| | HDV | 2,007 | 44,598 | 73 | 155 | 9 |
| | | | | | | |
| Alternative 2 (25% ZEV) | MDV | 757 | 18,835 | 62 | 149 | 5 |
| | HDV | 1,585 | 35,209 | 58 | 122 | 7 |
| | | | | | | |
| Alternative 3 (50% ZEV) | MDV | 504 | 12,556 | 41 | 99 | 4 |
| | HDV | 1,056 | 23,473 | 38 | 81 | 4 |
| | | | | | | |
| Alternative 4 (75% ZEV) | MDV | 252 | 6,278 | 20 | 49 | 2 |
| | HDV | 528 | 11,736 | 19 | 41 | 2 |
| | | | | | | |
| Alternative 5 (95% ZEV) | MDV | 50 | 1,256 | 4 | 9 | 0 |
| | HDV | 105 | 2,347 | 4 | 8 | 0 |

Each emission estimate sums the total emissions for each of the source type groups (MDV and HDV) across both gasoline and diesel fuel types and across all zones. While maintaining the distributions and fractions developed for the baseline scenario, for each alternative scenario, truck population and the number of starts per day were decreased by a ZEV adoption rate, effectively transferring a portion of the fleet from emitting to non-emitting. This static change is reflected in the results from the alternative scenarios. The baseline scenario produced the greatest vehicle emissions and, as expected, the emission levels decrease as more ZEV replace gasoline and diesel trucks in the fleet composition.

Figure 10 presents the benefits of adopting ZEV in the MDV and HDV fleet (determined as the reduction in damages compared to the baseline). Two lines are shown to represent the trend of benefits: the benefits received from air pollutant reduction only, and the benefits received from both air pollutant and GHG reductions. The figure suggests that as the adoption rate increases, the benefits follow a positive linear trend. At 95% ZEV adoption rate, annual benefits in 2012 received solely from the effects of reducing air pollution is nearly $1.3 billion (2005 USD), and the benefit received from reducing both GHGs and air pollution is about $1.7 billion (2005 USD).

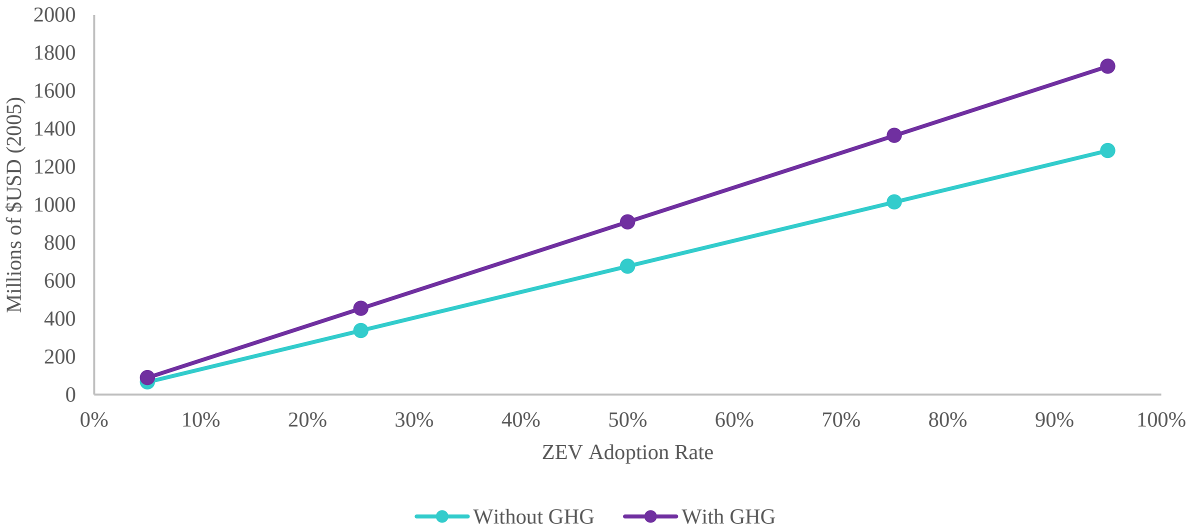

**Figure 10 – Annual benefits by ZEV adoption**

The 95% ZEV adoption rate scenario is not a realistic adoption rate in the near future. Evaluating the IAM for a more applicable and realistic scenario to Ontario in the near future can provide more valuable insight for shaping a potential policy of this nature. Looking at the 5% ZEV adoption rate, which represents Ontario's adoption rate goals for 2020, the marginal benefits received is greatly lower than that of the 95%

adoption rate scenario. The regional annual benefits received from air pollution-only impacts and multipollutant impacts at the 5% adoption rate is \$64.7 million (2005 USD) and \$89 million (2005 USD) respectively. Given the total benefits under the 5% adoption rate, it may be possible to incentivize a shipper to adopt a ZEV by subsidizing \$7,645 (2005 USD) per vehicle adopted. Figure 11a) present the zonal benefits received at the 5% adoption rate and Figure 11b) presents the same benefits, but a closer look at Southern Ontario. Similar to the baseline marginal damage map shown in the previous section, the top three census divisions that have the greatest benefits are Toronto, York and Peel. The zonal benefits at the other adoption rates are presented in figures located in Appendix D.

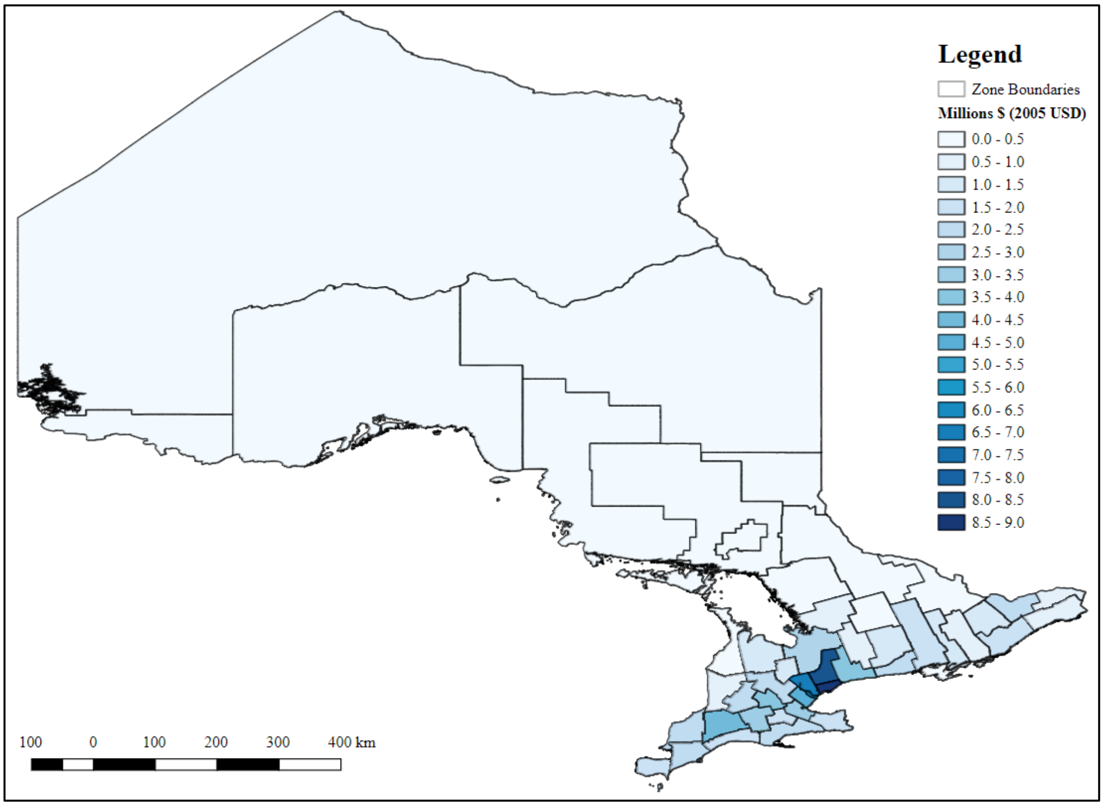

**Figure 11a) – Ontario provincial annual marginal benefits under 5% ZEV adoption in 2012**

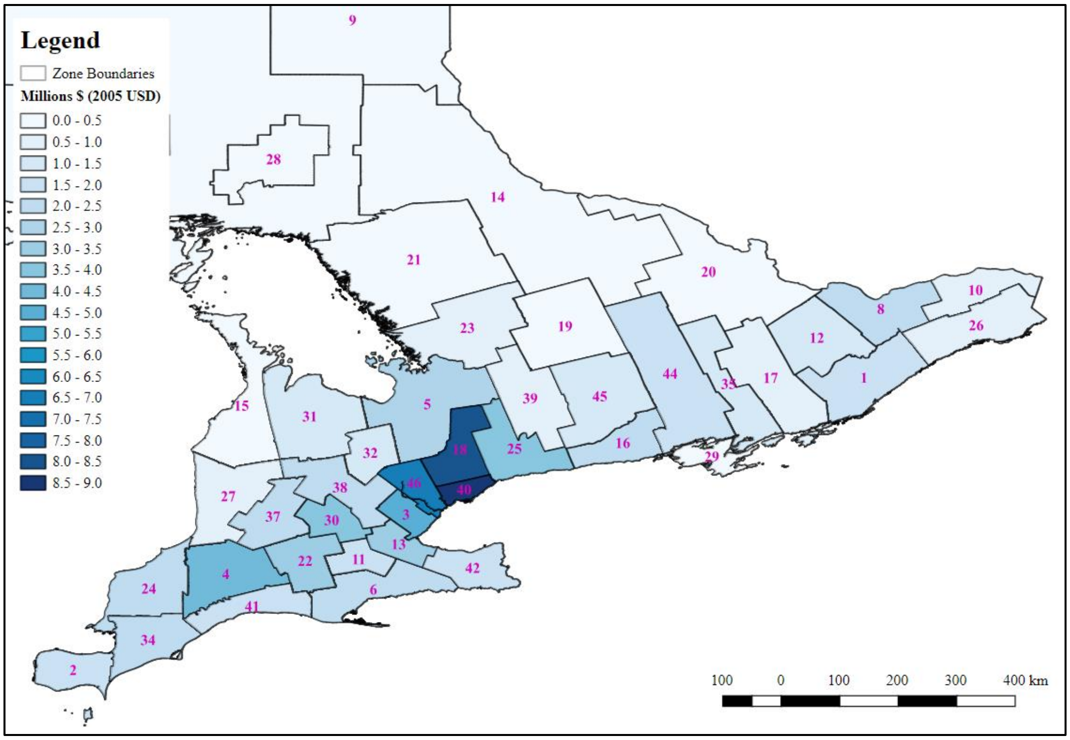

Figure 11b) – Annual marginal benefits of Southern Ontario zones under 5% ZEV adoption in 2012

# 5.0 SENSITIVITY ANALYSIS

## 5.1. Sensitivity Analysis Scenarios Development

The uniqueness of the integrated assessment model presented in this research relied on developing regional inputs from various data sources and connecting these three models. This resulted in taking readily available data and applying it to the specific baseline scenario. Individual model components have been previously evaluated, including the Ontario travel demand model (Ashrafi et al., 2016), and the marginal damages model (Heo et al., 2016b). The results of the integrated assessment model cannot be directly validated, as it is not possible to observe the economic damages of emissions directly, in part due to the complex chain of events between travel and damages. Thus, the robustness of results is tested using sensitivity analyses on multiple parameters individually. This subsection provides the methods used in developing the sensitivity analysis scenarios.

### *5.1.1. Meteorological Bounds*

Two scenarios were developed to create bounds for the model sensitivity to meteorological changes by identifying maximum and minimum temperatures in the meteorological record. The meteorological table that was produced for the baseline scenario was used to determine the upper and lower bounds of temperature. For each month, the highest and lowest temperature was recorded, and whichever month corresponded to the lowest and highest temperature, was selected as the month to be used in the sensitivity analysis. Additionally, the associated hour containing the hottest and coldest temperature was used as the hour of simulation. Functionally, in MOVES, this step meant copying the minimum/maximum temperature and relative humidity data over into the appropriate month file, and moving the VKT being studied into the appropriate hour of the day.

### *5.1.2. Average Speeds*

The change in average speeds produced four scenarios from 50% reduction in the average speeds, to 50% increased average speeds. These were scalar changes to the traffic assignment results for each hour. Looking at the validation plots for travel time from the demand model, the correlation coefficients suggest a 20-30% error (Ashrafi, 2017). When calculating the mean absolute error, the travel times MAE range from 27-35%. Thus, analysing a 50% change in average speeds is a higher bound that considers the potential errors in the vehicle speeds in the network. These results were then organized into the average speed bins, as was done to the baseline scenario.

### *5.1.3. VKT*

On its own, the change in the zero-emission vehicle adoption rates defined its sensitivity to changes in VKT, since the reduction in emissions was modelled by reducing VKT.

### *5.1.4. Mean Vehicle Age*

The mean vehicle age of the baseline was calculated by a weighted sum given by the following equation, which was applied to the dataset used for the baseline scenario:

$$\bar{x} = \frac{\sum_{i=0}^{30}(N_i \times (Y - i))}{\sum_{i=0}^{30} N_i}$$

Where: $\bar{x}$ is the mean age (years),

$i$ is the age relative to the model year (years),

$N$ is the number of vehicles that are of age $i$, and

$Y$ is the model year (2009, which is based off the dataset).

This weighted mean vehicle age was calculated separately among LDV, MDV and HDVs, however, the mean ages were all about 7 years. The sensitivity analysis for two scenarios were produced for shifting the mean age 1 year older and 1 year younger. This was done by partitioning the vehicle years into two groups by the cumulative percentage of vehicles. For each scenario, the oldest or youngest group of ages contained roughly a third of the number of vehicles respectively. To make the mean age older (i.e. moving it such that the mean age is 1 year older, from 7 years to 8 years old), younger vehicles were removed from the younger group and distributed to the second group. The same method was applied to shifting the mean age younger. The following two equations in association with the equation presented above, represent the change in mean ages:

$$R_x = \sum_i N_i \times f \qquad \forall i; i \in x$$

$$x_i = N_i + \left(\frac{N_i}{\sum_i N_i} \times R_x\right) \qquad \forall i; i \in y$$

Where: $R_x$ is the total number of vehicles removed from group 1 to be distributed to group 2.

$N$ is the number of vehicles of age $i$,

$i$ is the age,

$x$ contains all the ages in group 1,

$y$ contains all the ages in group 2, and

$f$ is the fraction such that the mean age.

### *5.1.5. Sensitivity Analysis Results*

As discussed, appropriate validation data are lacking. While the comparison performed with the national inventories is reasonable considering the methodological differences, it does not serve to quantify the uncertainty in the baseline or assess its underlying sources. For this, a sensitivity analysis is performed. The IAM developed in this research used data, which were configured to support the required input tables for proper estimation. However, this leads to some uncertainties with various parameters. An input guideline by Porter et. al (2014) included sensitivity analysis on various input parameters such as vehicle age, average speeds, temperature, VMT, etc. Using the parameters that were considered to have an impact on emissions that was “substantial” to “very substantial” in the guideline, a sensitivity analysis was performed on the input parameters of the IAM for the baseline scenario to assess the effect of parameter uncertainty on the estimated emissions.

Four input parameters were analysed, which are presented in Figure 12: mean age of vehicle population used, average speed of vehicles, extreme temperature effects, and VMT changes. In itself, the VMT changes were presented in the previous section, describing the changes in the benefits (damages saved) based on the changes in the VMT and number of starts. Other VMT sensitivity analysis can be found in the input guideline (Porter et al., 2014). Each sensitivity analysis scenario kept every other input parameter the same as in the baseline scenario, i.e., a one-at-a-time sensitivity analysis was performed for the key parameters. The baseline damages were calculated and summed for $NO_X$, $NH_3$, $SO_2$, $PM_{2.5}$, and $CO_2$e. Figure 12 shows the damages, relative to the baseline scenario, which is set at 0. Negative values are benefits (damages saved), while positive values are damages.

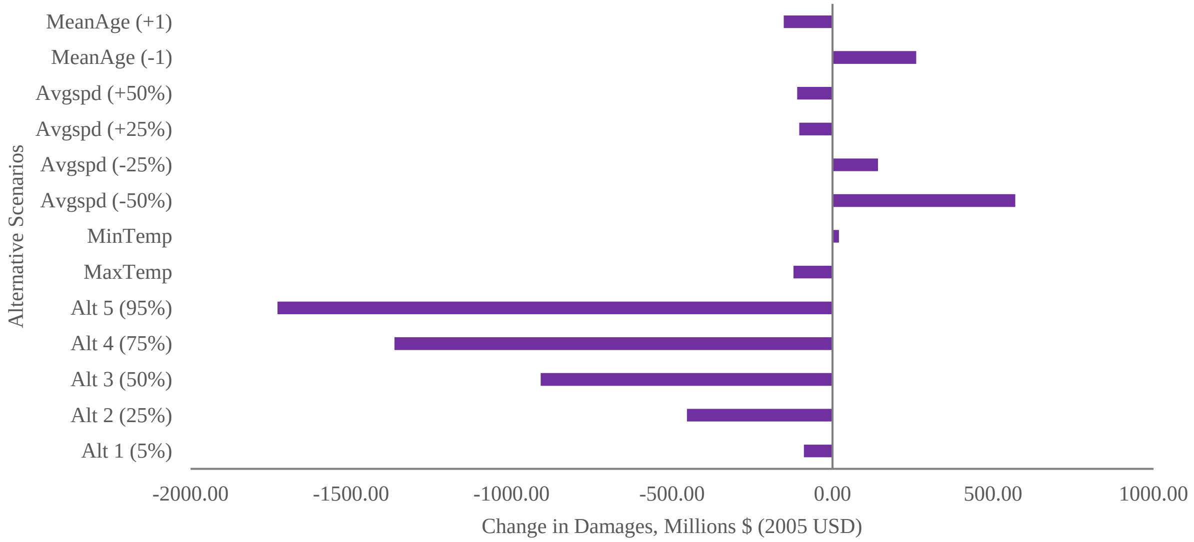

**Figure 12 – Sensitivity analysis results (damages relative to baseline scenario = 0)**

#### 5.1.5.1. Mean Vehicle Age

Vehicle age was retrieved for the year 2009 and for Canada. The uncertainty with the unavailable data in addition to the application of this data set to the model in this research required an analysis to determine whether better data would be needed. Two scenarios were created: increasing and decreasing the mean vehicle population age by 1 year. The mean age for the baseline data set was 7 years old. 12 years of the data set was missing, so a backwards extrapolation was used to estimate the vehicle population for those age categories. Changing the mean age represents scenarios where some of the new vehicles were actually older, or older vehicles were actually newer. From Figure 12, redistributing 40% of newer vehicles to older age categories increased the damages by 14% ($260 million); and redistributing 35% of older vehicles to newer age categories decreased damages by 8% ($152 million). The different redistribution percentages were due to the population distribution of the age categories. Additionally, a shift of 2 years up or down would result in moving more than 90% of the old age categories to new or new age categories to old. This was not calculated as this level of misclassification in the age data was deemed unlikely.

#### 5.1.5.2. Average Speed

The baseline vehicle average speed distributions were statically adjusted by increasing or decreasing them by a factor of 25% or 50%. A decrease in the average speed distributions by 25% and 50% resulted in an increase in the marginal damages by 8% ($141 million) and 31% ($569 million) respectively. Decreasing the speeds represent an increase in slower moving traffic and congestion in the network. An increase in the average speed distributions by the same 25% and 50% resulted in a decrease of marginal damages by 6%

($103 million) and 6% ($110 million) respectively. From Figure 12, the change in speeds are not symmetric between increasing and decreasing the distributions. Figure 13 presents the two increased average speed scenarios and the baseline scenario. The average speed distribution of the baseline scenario is mostly in the upper half of the speed bins, since the model is estimating transportation movement at a regional scale on the roadways, which are mostly freeways.

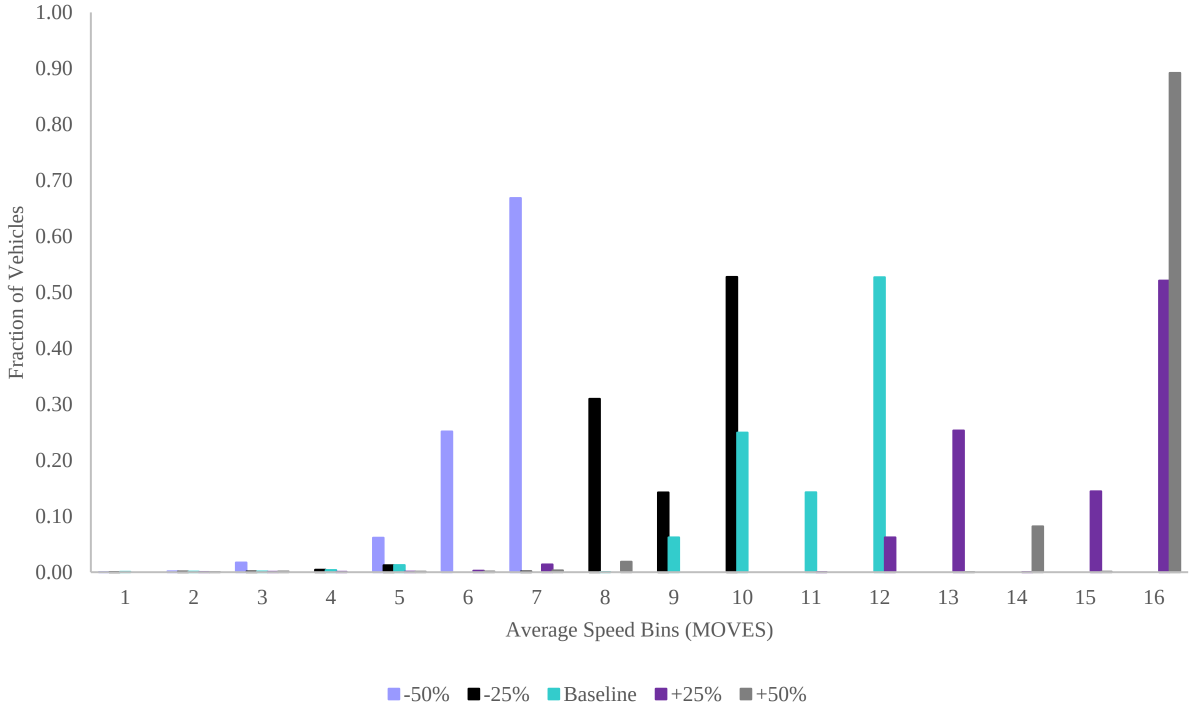

**Figure 13 – Average speed distribution profiles for Baseline and alternative Scenarios**

From this figure, it should be noted that increasing the average speeds by 25% already largely adds many vehicles into the 16th speed bin. This jump is even higher when increasing the average speeds by 50%. This shows that the vehicles are already travelling at the max speeds categorized by MOVES, and suggests that any increase in speeds greater than 25% will not provide a true test of average speed increase due to modeling limitations. Additional distribution profile plots are presented for the other parameters in Appendix E.

#### 5.1.5.3. Meteorological Extremes

Emissions are very sensitive to the ambient air temperatures, as well as the emission processes. The temperature profile selected for the baseline scenario did not reflect any extreme temperatures (i.e. winter or summer). The scenarios performed on the extreme temperature profiles reflected a cold winter month and a hot summer month. These scenarios were created to bound the problem and determine whether the emission estimates would be greatly influenced in temperature changes alone. For the high extreme, the average temperature of the region during the hour of simulation was increase by nearly 100%. This provided a benefit of 7% ($121 million). On the other spectrum, the average temperature of the region during the hour of simulation was decreased by approximately 50%. This increased the damages by 1% ($20 million). Since the baseline scenario is bounded by these two scenarios, it seems like temperature, by itself, does not have a major impact on the emission estimates.

Emissions are affected by temperature directly, and indirectly. This sensitivity analysis only looks at the direct effects of temperature. However, more work can be done to adjust vehicle activity, and the fuel tables which are affected by changes in temperature (i.e. more vehicle activity in the hotter months; heating in the winter, etc).

#### 5.1.5.4. Marginal Damages

Estimates of the marginal damages of pollutant emissions is a recent and growing field. It remains uncertain, largely due to epistemic uncertainty in estimates of the relationships between pollution exposures and health risks, and the relationship between health risks and economic damages. While this study did not seek to alter or improve these relationships, they could be the largest source of uncertainty in the results. The creators of the EASIUR model have explored the effect on marginal damages of parameter uncertainty in health responses (-33% to +270%) and economic valuation (-90% to +160%) (Heo et al., 2016a). This type of epistemic uncertainty is different than uncertainty in input parameters that were explored in the sensitivity analysis presented here. They are thus not comparable. Nonetheless, this source of uncertainty is significant and thus worth mentioning to provide context for interpreting these results.

## 6.0 CONCLUSION

Evaluating the multipollutant impacts of transportation policies require methods to trace the pathway from policy to impacts. Prior studies have estimated the co-benefits of the transportation sector at various scales, by estimating vehicle activity through empirical methods. In this research, an integrated assessment model (IAM) was developed to capture the multipollutant impacts of freight transportation at a regional scale. The IAM connects three components: a transportation model, a transportation emissions model, and marginal damage estimates. This linkage provides a method to evaluate a transportation policy such as zero-emission vehicle adoption.

Multiple data sources were used to develop region-specific input tables for the transportation emission model. This process included adapting Canadian values to the province of Ontario, estimating missing values such as vehicle age, or weather stations with incomplete data. Vehicle activity data were generated through travel demand modelling, using the four-step modelling technique. Since there were only two modes of transportation (autos and trucks) in the travel demand model, all light-duty vehicles (LDV) were assumed to have the same auto activity data and all medium-duty (MDV) and heavy-duty vehicles (HDV) were assumed to have the same truck activity data.

Vehicle emissions were estimated through a vehicle emission simulator (MOVES) for MDVs and HDVs for a baseline scenario of the Province of Ontario in 2012. MOVES simulated vehicle emissions for 1 day, and the results were statically scaled up to a yearly total. The air pollutants estimated were for primary $PM_{2.5}$, $NO_X$, $SO_2$, and $NH_3$. The GHGs ($CO_2$, $CH_4$, and $N_2O$) were estimated as a total value, measured in $CO_2$ equivalent. The result of the first two components of the IAM was compared to the national Air Pollutant Emission Inventory (APEI) and the National Inventory Report (NIR). The challenge in comparing the results from the baseline scenario is that the vehicle types were not exactly the same, and that the underlying methods calculating the national results were different with the methods presented in this research. Vehicle type classifications between sources (APEI, NIR, MOVES, HPMS and CanVS) prove to be a challenge when validating the model with real-world results. The classifications from the government sources were more general, so vehicles from MOVES or HPMS might be split (i.e. some light-duty commercial trucks may be counted as MDVs; some MDVs might be classified as HDVs, etc.). Marginal social costs, developed from EASIUR were applied to the emission estimates to present the regional damages.

Adopting ZEVs will provide a marginal benefit of approximately $1.7 billion (2005 USD) at 95% adoption. However, this is not a realistic scenario in the near future. Evaluating the policy scenario of 5% ZEV adoption, the marginal benefits received is approximately $89 million (2005 USD). This benefit represents the static comparison of a policy scenario (i.e., if 5% of MDV and HDVs were actually zero-emission vehicles in Ontario in 2012, then the multipollutant impacts from freight emissions would be about $89 million (2005 USD) less). The majority of benefits accrue to Ontario's population centre in the Greater Toronto Area.

This study presents the first estimates of the multipollutant benefits of adopting zero-emission trucks in Ontario. Its findings are generally in line with national emissions inventories. This study agrees with prior work that multipollutant benefits of clean transportation are significant (Forkenbrock, 2001; Janic, 2007; Thompson et al., 2014). It combined state-of-the art techniques in modeling regional truck travel, emissions, and damages. A significant effort was involved in identifying, processing, and adapting data and coordinating input and output across models. With the introduction of long-haul heavy-duty electric trucks, more relevant data can be collected to produce more reliable estimates. Data collection is still resource extensive; however, updating the travel demand model to reflect more recent years may provide a better estimate on how close Ontario is to meeting its reduction goals.

## 6.1. Limitations and Future Work

Proper data collection is integral to the functionality of the model and meaningfulness of the results. Three model components were developed in the IAM, each with its own set of data inputs. The model parameters were constrained by the availability of data, and as such, some assumptions were made in developing these model parameters to develop a consistent database for the province. The data collected for the input tables in the emission model could be improved, such as by having a complete set of vehicle age distributions for the model year to 30 years old. Other input parameters such as the fuel-related tables were generated and pieced together based off various available data for Canada. This data was applied to the region of Ontario, but a more thorough survey may produce more accurate fuel data for the region. Most of these input parameters were retrieved through open source data provided by the government.

Currently in the travel demand model there are two modes of travel: auto (passenger) and trucks. Further development in the travel demand model is needed to better validate the light-duty estimates and to provide more modes in the network. The correlation coefficients of the predicted to observed auto demands were lower than that of the truck demands, which imposes more uncertainties. Improvement of those auto demand estimates may lead to a more accurate estimate of truck emissions (since the change in auto demand will affect the travel times on the links). Development of the travel demand model to include more modes that are similar to the MOVES source types would provide better accuracy in the results.

The model developed in this research can be adapted to other transportation projects or policy scenarios. A potential adaptation to the current scenario could be to spatially and temporally change the model parameters. Further work can be done to model the current scenario at various months, thus changing the associated fuel profiles, vehicle activities and meteorological inputs. The results were modelled from an hour, which was scaled up to 24 hours; however, the time of day also has an impact on the changes in some input parameters such as meteorology, and vehicle activity.

The versatility of this model can be used in potential scenarios to estimate the impacts of routing choices. The potential application of a route choice model is possible with this IAM. The scenario can evaluate the economic impact of selecting a different route, incorporating the economic and environmental impacts associated with those routes. In addition to route choice modelling, there is a possibility to adapt this model to evaluating the atmospheric impacts at border crossings for on-road freight vehicles. Typically, travel demand models include border crossings as entrance and exit nodes into the network, but realistically, the delay and congestion at those nodes have an impact that are not being accounted for.

The scenario presented in this research models the Province of Ontario in the year 2012. Given that new technology is changing the vehicle fleet composition, vehicle activity, and fuel characteristics, further work can be done to apply this research to future years.

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# 8.0 APPENDICIES

## Appendix A – MOVES Input tables (Baseline Scenario)

Some of the tables have been shortened to highlight the key parameters in relation to the baseline scenario.

**Table A.1 – Zonal vehicle activity distribution table**

| zoneID | countyID | startAllocFactor | idleAllocFactor | SHPAllocFactor |
|---|---|---|---|---|
| 1 | 99001 | 0.008338 | 0.009871 | 0.009871 |
| 2 | 99001 | 0.034826 | 0.006713 | 0.006713 |
| 3 | 99001 | 0.043013 | 0.045575 | 0.045575 |
| 4 | 99001 | 0.036892 | 0.039537 | 0.039537 |
| 5 | 99001 | 0.038788 | 0.023265 | 0.023265 |
| 6 | 99001 | 0.009487 | 0.013551 | 0.013551 |
| 7 | 99001 | 0.001701 | 1.05E-05 | 1.05E-05 |
| 8 | 99001 | 0.059511 | 0.04627 | 0.04627 |
| 9 | 99001 | 0.002712 | 4.36E-05 | 4.36E-05 |
| 10 | 99001 | 0.007069 | 0.004767 | 0.004767 |
| 11 | 99001 | 0.014255 | 0.016112 | 0.016112 |
| 12 | 99001 | 0.005228 | 0.006935 | 0.006935 |
| 13 | 99001 | 0.043887 | 0.049639 | 0.049639 |
| 14 | 99001 | 0.007089 | 0.000755 | 0.000755 |
| 15 | 99001 | 0.00573 | 0.001818 | 0.001818 |
| 16 | 99001 | 0.007101 | 0.00962 | 0.00962 |
| 17 | 99001 | 0.012258 | 0.011685 | 0.011685 |
| 18 | 99001 | 0.077256 | 0.115611 | 0.115611 |
| 19 | 99001 | 0.00151 | 0.001165 | 0.001165 |
| 20 | 99001 | 0.00886 | 0.001616 | 0.001616 |
| 21 | 99001 | 0.003708 | 0.001598 | 0.001598 |
| 22 | 99001 | 0.009211 | 0.027365 | 0.027365 |
| 23 | 99001 | 0.005085 | 0.005755 | 0.005755 |
| 24 | 99001 | 0.011136 | 0.011086 | 0.011086 |
| 25 | 99001 | 0.046954 | 0.044621 | 0.044621 |
| 26 | 99001 | 0.009308 | 0.004665 | 0.004665 |
| 27 | 99001 | 0.005088 | 0.002035 | 0.002035 |
| 28 | 99001 | 0.013684 | 0.000581 | 0.000581 |
| 29 | 99001 | 0.002219 | 0.001257 | 0.001257 |
| 30 | 99001 | 0.052036 | 0.053968 | 0.053968 |
| 31 | 99001 | 0.007958 | 0.00493 | 0.00493 |
| 32 | 99001 | 0.005 | 0.006044 | 0.006044 |
| 33 | 99001 | 0.009865 | 8.76E-05 | 8.76E-05 |
| 34 | 99001 | 0.0093 | 0.0097 | 0.0097 |

| zoneID | countyID | startAllocFactor | idleAllocFactor | SHPAllocFactor |
|---|---|---|---|---|
| 35 | 99001 | 0.003608 | 0.005166 | 0.005166 |
| 36 | 99001 | 0.001089 | 3.53E-05 | 3.53E-05 |
| 37 | 99001 | 0.006393 | 0.006559 | 0.006559 |
| 38 | 99001 | 0.017793 | 0.019458 | 0.019458 |
| 39 | 99001 | 0.006187 | 0.00626 | 0.00626 |
| 40 | 99001 | 0.15185 | 0.222083 | 0.222083 |
| 41 | 99001 | 0.007648 | 0.009848 | 0.009848 |
| 42 | 99001 | 0.039711 | 0.017569 | 0.017569 |
| 43 | 99001 | 0.001756 | 0.000104 | 0.000104 |
| 44 | 99001 | 0.011761 | 0.013118 | 0.013118 |
| 45 | 99001 | 0.014384 | 0.009444 | 0.009444 |
| 46 | 99001 | 0.098011 | 0.111856 | 0.111856 |
| 47 | 99001 | 0.006638 | 3.25E-05 | 3.25E-05 |
| 48 | 99001 | 0.00462 | 0.000121 | 0.000121 |
| 49 | 99001 | 0.01249 | 9.47E-05 | 9.47E-05 |

**Table A.2 – Zonal road type distribution table**

| zoneID | roadTypeID | SHOAllocFactor |
|---|---|---|
| 1 | All | 0.025383 |
| 2 | All | 0.011829 |
| 3 | All | 0.048346 |
| 4 | All | 0.043155 |
| 5 | All | 0.035377 |
| 6 | All | 0.023257 |
| 7 | All | 0.000105 |
| 8 | All | 0.030702 |
| 9 | All | 0.000546 |
| 10 | All | 0.011251 |
| 11 | All | 0.020251 |
| 12 | All | 0.015504 |
| 13 | All | 0.032501 |
| 14 | All | 0.001421 |
| 15 | All | 0.005422 |
| 16 | All | 0.025017 |
| 17 | All | 0.012859 |
| 18 | All | 0.092452 |
| 19 | All | 0.005279 |
| 20 | All | 0.007339 |
| 21 | All | 0.006764 |
| 22 | All | 0.035312 |

| zoneID | roadTypeID | SHOAllocFactor |
|---|---|---|
| 23 | All | 0.009084 |
| 24 | All | 0.020452 |
| 25 | All | 0.042371 |
| 26 | All | 0.012368 |
| 27 | All | 0.008055 |
| 28 | All | 0.001421 |
| 29 | All | 0.002713 |
| 30 | All | 0.042626 |
| 31 | All | 0.020195 |
| 32 | All | 0.013833 |
| 33 | All | 0.000988 |
| 34 | All | 0.018507 |
| 35 | All | 0.018837 |
| 36 | All | 0.000328 |
| 37 | All | 0.023351 |
| 38 | All | 0.024825 |
| 39 | All | 0.011401 |
| 40 | All | 0.091757 |
| 41 | All | 0.01708 |
| 42 | All | 0.015569 |
| 43 | All | 0.002297 |
| 44 | All | 0.022927 |
| 45 | All | 0.014359 |
| 46 | All | 0.071701 |
| 47 | All | 0.000464 |
| 48 | All | 0.001153 |
| 49 | All | 0.001264 |

**Table A.3 – Meteorological input table**

| Month ID | Zone ID | Hour ID | Temperature (°F) | Relative Humidity (%) |
|---|---|---|---|---|
| 4 | 1 | 9 | 40.837 | 68.03333 |
| 4 | 2 | 9 | 46.254 | 68.23333 |
| 4 | 3 | 9 | 43.334 | 60.06667 |
| 4 | 4 | 9 | 42.365 | 67.48333 |
| 4 | 5 | 9 | 40.08967 | 72.63333 |
| 4 | 6 | 9 | 42.968 | 63.46667 |
| 4 | 7 | 9 | 38.333 | 70.31667 |
| 4 | 8 | 9 | 40.346 | 64.2 |
| 4 | 9 | 9 | 32.596 | 74.26667 |

| Month ID | Zone ID | Hour ID | Temperature (°F) | Relative Humidity (%) |
|---|---|---|---|---|
| 4 | 10 | 9 | 42.344 | 66.23333 |
| 4 | 11 | 9 | 44.546 | 64.3 |
| 4 | 12 | 9 | 39.69767 | 66.33333 |
| 4 | 13 | 9 | 36.248 | 69.56667 |
| 4 | 14 | 9 | 35.096 | 66.13333 |
| 4 | 15 | 9 | 38.036 | 73.06667 |
| 4 | 16 | 9 | 41.006 | 67.8 |
| 4 | 17 | 9 | 41.036 | 66.2 |
| 4 | 18 | 9 | 42.368 | 63.46667 |
| 4 | 19 | 9 | 38.192 | 66.66667 |
| 4 | 20 | 9 | 37.91 | 66.76667 |
| 4 | 21 | 9 | 38.006 | 73.73333 |
| 4 | 22 | 9 | 37.838 | 71.4 |
| 4 | 23 | 9 | 38.15 | 74.06667 |
| 4 | 24 | 9 | 44.387 | 70.16667 |
| 4 | 25 | 9 | 42.548 | 62.96667 |
| 4 | 26 | 9 | 41.17567 | 66.15556 |
| 4 | 27 | 9 | 42.512 | 68.13793 |
| 4 | 28 | 9 | 34.706 | 70.66667 |
| 4 | 29 | 9 | 40.808 | 68.16667 |
| 4 | 30 | 9 | 40.112 | 73.76667 |
| 4 | 31 | 9 | 32 | 63 |
| 4 | 32 | 9 | 38.084 | 76.33333 |
| 4 | 33 | 9 | 33.524 | 71.06667 |
| 4 | 34 | 9 | 44.468 | 69.9 |
| 4 | 35 | 9 | 38.714 | 71.3 |
| 4 | 36 | 9 | 38.642 | 71.06667 |
| 4 | 37 | 9 | 39.716 | 70.93333 |
| 4 | 38 | 9 | 39.503 | 70.25 |
| 4 | 39 | 9 | 45.026 | 62.53333 |
| 4 | 40 | 9 | 43.982 | 61.36667 |
| 4 | 41 | 9 | 42.4052 | 68.48333 |
| 4 | 42 | 9 | 44.012 | 66.58889 |
| 4 | 43 | 9 | 32.582 | 67.23333 |
| 4 | 44 | 9 | 39.569 | 66.76667 |
| 4 | 45 | 9 | 40.853 | 66.31667 |
| 4 | 46 | 9 | 43.184 | 61.26667 |
| 4 | 47 | 9 | 29.26933 | 73.42381 |
| 4 | 48 | 9 | 31.35067 | 70.14264 |

| Month ID | Zone ID | Hour ID | Temperature (°F) | Relative Humidity (%) |
|---|---|---|---|---|
| 4 | 49 | 9 | 32.96867 | 77.16491 |

### Table A.4 – Total VMT by HPMS vehicle type

| HPMSVtypeID | yearID | monthID | dayID | VMT |
|---|---|---|---|---|
| 10 | 2012 | 4 | 5 | 8546889 |
| 25 | 2012 | 4 | 5 | 3.07E+08 |
| 50 | 2012 | 4 | 5 | 5156020 |
| 60 | 2012 | 4 | 5 | 5130703 |

### Table A.5 – Hourly VMT distribution by vehicle type and road type

| SourceTypeID | roadTypeID | dayID | hourID | hourVMTFraction |
|---|---|---|---|---|
| 11 | 1 | 5 | 9 | 0 |
| 11 | 2 | 5 | 9 | 0.083338 |
| 11 | 3 | 5 | 9 | 0.083338 |
| 11 | 4 | 5 | 9 | 0.083338 |
| 11 | 5 | 5 | 9 | 0.083338 |
| 21 | 1 | 5 | 9 | 0 |
| 21 | 2 | 5 | 9 | 0.083338 |
| 21 | 3 | 5 | 9 | 0.083338 |
| 21 | 4 | 5 | 9 | 0.083338 |
| 21 | 5 | 5 | 9 | 0.083338 |
| 31 | 1 | 5 | 9 | 0 |
| 31 | 2 | 5 | 9 | 0.083338 |
| 31 | 3 | 5 | 9 | 0.083338 |
| 31 | 4 | 5 | 9 | 0.083338 |
| 31 | 5 | 5 | 9 | 0.083338 |
| 32 | 1 | 5 | 9 | 0 |
| 32 | 2 | 5 | 9 | 0.083338 |
| 32 | 3 | 5 | 9 | 0.083338 |
| 32 | 4 | 5 | 9 | 0.083338 |
| 32 | 5 | 5 | 9 | 0.083338 |
| 51 | 1 | 5 | 9 | 0 |
| 51 | 2 | 5 | 9 | 0.055629 |
| 51 | 3 | 5 | 9 | 0.055629 |
| 51 | 4 | 5 | 9 | 0.055629 |
| 51 | 5 | 5 | 9 | 0.055629 |
| 52 | 1 | 5 | 9 | 0 |
| 52 | 2 | 5 | 9 | 0.055629 |
| 52 | 3 | 5 | 9 | 0.055629 |

| SourceTypeID | roadTypeID | dayID | hourID | hourVMTFraction |
|---|---|---|---|---|
| 52 | 4 | 5 | 9 | 0.055629 |
| 52 | 5 | 5 | 9 | 0.055629 |
| 53 | 1 | 5 | 9 | 0 |
| 53 | 2 | 5 | 9 | 0.055629 |
| 53 | 3 | 5 | 9 | 0.055629 |
| 53 | 4 | 5 | 9 | 0.055629 |
| 53 | 5 | 5 | 9 | 0.055629 |
| 54 | 1 | 5 | 9 | 0 |
| 54 | 2 | 5 | 9 | 0 |
| 54 | 3 | 5 | 9 | 0 |
| 54 | 4 | 5 | 9 | 0 |
| 54 | 5 | 5 | 9 | 0 |
| 61 | 1 | 5 | 9 | 0 |
| 61 | 2 | 5 | 9 | 0.055629 |
| 61 | 3 | 5 | 9 | 0.055629 |
| 61 | 4 | 5 | 9 | 0.055629 |
| 61 | 5 | 5 | 9 | 0.055629 |
| 62 | 1 | 5 | 9 | 0 |
| 62 | 2 | 5 | 9 | 0.055629 |
| 62 | 3 | 5 | 9 | 0.055629 |
| 62 | 4 | 5 | 9 | 0.055629 |
| 62 | 5 | 5 | 9 | 0.055629 |

**Table A.6 – Road type distribution table**

| sourceTypeID | roadTypeID | roadTypeVMTFraction |
|---|---|---|
| All | 1 | 0 |
| All | 2 | 0.040328 |
| All | 3 | 0.1002 |
| All | 4 | 0.246646 |
| All | 5 | 0.612826 |

**Table A.7 – Ramp fractions by road type**

| roadTypeID | rampFraction |
|---|---|
| 2 | 0.027719 |
| 4 | 0.169533 |

**Table A.8 – Total number of vehicles by source type**

| yearID | sourceTypeID | sourceTypePopulation |
|---|---|---|
| 2012 | 11 | 209412 |

| yearID | sourceTypeID | sourceTypePopulation |
|---|---|---|
| 2012 | 21 | 4429788 |
| 2012 | 31 | 3068203 |
| 2012 | 32 | 16145.93 |
| 2012 | 51 | 6057.338 |
| 2012 | 52 | 125265.3 |
| 2012 | 53 | 20012.31 |
| 2012 | 54 | 0 |
| 2012 | 61 | 70262.9 |
| 2012 | 62 | 11225.15 |

**Table A.9 – Vehicle age distribution table (LDV)**

| yearID | ageID | ageFraction |
|---|---|---|
| 2012 | 0 | 0.047546 |
| 2012 | 1 | 0.077771 |
| 2012 | 2 | 0.081366 |
| 2012 | 3 | 0.074863 |
| 2012 | 4 | 0.075399 |
| 2012 | 5 | 0.067999 |
| 2012 | 6 | 0.080571 |
| 2012 | 7 | 0.075576 |
| 2012 | 8 | 0.064616 |
| 2012 | 9 | 0.068988 |
| 2012 | 10 | 0.053417 |
| 2012 | 11 | 0.050622 |
| 2012 | 12 | 0.04197 |
| 2012 | 13 | 0.027122 |
| 2012 | 14 | 0.02612 |
| 2012 | 15 | 0.019726 |
| 2012 | 16 | 0.014941 |
| 2012 | 17 | 0.012805 |
| 2012 | 18 | 0.008879 |
| 2012 | 19 | 0.007095 |
| 2012 | 20 | 0.005476 |
| 2012 | 21 | 0.004226 |
| 2012 | 22 | 0.003262 |
| 2012 | 23 | 0.002518 |
| 2012 | 24 | 0.001943 |
| 2012 | 25 | 0.0015 |
| 2012 | 26 | 0.001157 |
| 2012 | 27 | 0.000893 |

| yearID | ageID | ageFraction |
|---|---|---|
| 2012 | 28 | 0.000689 |
| 2012 | 29 | 0.000532 |
| 2012 | 30 | 0.000411 |

**Table A.10 – Vehicle age distribution table (MDV & HDV)**

| yearID | ageID | ageFraction |
|---|---|---|
| 2012 | 0 | 0.036992 |
| 2012 | 1 | 0.10004 |
| 2012 | 2 | 0.088994 |
| 2012 | 3 | 0.094102 |
| 2012 | 4 | 0.08428 |
| 2012 | 5 | 0.07284 |
| 2012 | 6 | 0.07372 |
| 2012 | 7 | 0.059275 |
| 2012 | 8 | 0.058962 |
| 2012 | 9 | 0.056999 |
| 2012 | 10 | 0.061784 |
| 2012 | 11 | 0.03687 |
| 2012 | 12 | 0.033866 |
| 2012 | 13 | 0.023144 |
| 2012 | 14 | 0.027756 |
| 2012 | 15 | 0.01929 |
| 2012 | 16 | 0.015669 |
| 2012 | 17 | 0.011966 |
| 2012 | 18 | 0.011349 |
| 2012 | 19 | 0.006968 |
| 2012 | 20 | 0.005555 |
| 2012 | 21 | 0.004429 |
| 2012 | 22 | 0.003531 |
| 2012 | 23 | 0.002815 |
| 2012 | 24 | 0.002244 |
| 2012 | 25 | 0.001789 |
| 2012 | 26 | 0.001426 |
| 2012 | 27 | 0.001137 |
| 2012 | 28 | 0.000907 |
| 2012 | 29 | 0.000723 |
| 2012 | 30 | 0.000576 |

### Table A.11 – Hourly average speed distribution table (LDV)

| hourDayID | avgSpeedBinID | avgSpeedFraction |
|---|---|---|
| 95 | 1 | 0.973298 |
| 95 | 2 | 0.001168 |
| 95 | 3 | 0.000626 |
| 95 | 4 | 0.000389 |
| 95 | 5 | 0.000479 |
| 95 | 6 | 0.000468 |
| 95 | 7 | 0.000448 |
| 95 | 8 | 0.001321 |
| 95 | 9 | 0.002993 |
| 95 | 10 | 0.004694 |
| 95 | 11 | 0.009147 |
| 95 | 12 | 0.001571 |
| 95 | 13 | 0.003398 |
| 95 | 14 | 0 |
| 95 | 15 | 0 |
| 95 | 16 | 0 |

### Table A.12 - Hourly average speed distribution table (MDV & HDV)

| hourDayID | avgSpeedBinID | avgSpeedFraction |
|---|---|---|
| 95 | 1 | 0.90063 |
| 95 | 2 | 0.001382 |
| 95 | 3 | 0.00087 |
| 95 | 4 | 0.000719 |
| 95 | 5 | 0.000905 |
| 95 | 6 | 0.000946 |
| 95 | 7 | 0.000475 |
| 95 | 8 | 0.001322 |
| 95 | 9 | 0.004075 |
| 95 | 10 | 0.008888 |
| 95 | 11 | 0.028788 |
| 95 | 12 | 0.013019 |
| 95 | 13 | 0.037982 |
| 95 | 14 | 0 |
| 95 | 15 | 0 |
| 95 | 16 | 0 |

**Table A.13 – Total number of starts per day by zone**

| zoneID | dayID | yearID | startsperday |
|---|---|---|---|
| 1 | 5 | 2012 | 183309.2 |
| 2 | 5 | 2012 | 765601.6 |
| 3 | 5 | 2012 | 945581.4 |
| 4 | 5 | 2012 | 811018.8 |
| 5 | 5 | 2012 | 852703.2 |
| 6 | 5 | 2012 | 208569.4 |
| 7 | 5 | 2012 | 37384.78 |
| 8 | 5 | 2012 | 1308287 |
| 9 | 5 | 2012 | 59622.8 |
| 10 | 5 | 2012 | 155409.4 |
| 11 | 5 | 2012 | 313376.1 |
| 12 | 5 | 2012 | 114924.9 |
| 13 | 5 | 2012 | 964809.6 |
| 14 | 5 | 2012 | 155842 |
| 15 | 5 | 2012 | 125969.3 |
| 16 | 5 | 2012 | 156097.4 |
| 17 | 5 | 2012 | 269472 |
| 18 | 5 | 2012 | 1698380 |
| 19 | 5 | 2012 | 33193.72 |
| 20 | 5 | 2012 | 194775.9 |
| 21 | 5 | 2012 | 81522.76 |
| 22 | 5 | 2012 | 202490 |
| 23 | 5 | 2012 | 111782.3 |
| 24 | 5 | 2012 | 244817.6 |
| 25 | 5 | 2012 | 1032220 |
| 26 | 5 | 2012 | 204622.2 |
| 27 | 5 | 2012 | 111845.6 |
| 28 | 5 | 2012 | 300828 |
| 29 | 5 | 2012 | 48787.13 |
| 30 | 5 | 2012 | 1143963 |
| 31 | 5 | 2012 | 174938.9 |
| 32 | 5 | 2012 | 109920.8 |
| 33 | 5 | 2012 | 216881.2 |
| 34 | 5 | 2012 | 204455.4 |
| 35 | 5 | 2012 | 79316.76 |
| 36 | 5 | 2012 | 23936.09 |
| 37 | 5 | 2012 | 140537 |
| 38 | 5 | 2012 | 391169.9 |
| 39 | 5 | 2012 | 136021.3 |

| zoneID | dayID | yearID | startsperday |
|---|---|---|---|
| 40 | 5 | 2012 | 3338249 |
| 41 | 5 | 2012 | 168124 |
| 42 | 5 | 2012 | 873004.1 |
| 43 | 5 | 2012 | 38614.41 |
| 44 | 5 | 2012 | 258545.6 |
| 45 | 5 | 2012 | 316215.2 |
| 46 | 5 | 2012 | 2154669 |
| 47 | 5 | 2012 | 145934.8 |
| 48 | 5 | 2012 | 101555.9 |
| 49 | 5 | 2012 | 274570.1 |

**Table A.14 – Hourly distribution of starts by zone**

| zoneID | dayID | hourID | allocationFraction |
|---|---|---|---|
| 1 | 5 | 9 | 0.06776 |
| 2 | 5 | 9 | 0.067759 |
| 3 | 5 | 9 | 0.071887 |
| 4 | 5 | 9 | 0.067799 |
| 5 | 5 | 9 | 0.066767 |
| 6 | 5 | 9 | 0.067788 |
| 7 | 5 | 9 | 0.067755 |
| 8 | 5 | 9 | 0.067837 |
| 9 | 5 | 9 | 0.067815 |
| 10 | 5 | 9 | 0.067819 |
| 11 | 5 | 9 | 0.068498 |
| 12 | 5 | 9 | 0.067821 |
| 13 | 5 | 9 | 0.070507 |
| 14 | 5 | 9 | 0.067787 |
| 15 | 5 | 9 | 0.06783 |
| 16 | 5 | 9 | 0.067819 |
| 17 | 5 | 9 | 0.067799 |
| 18 | 5 | 9 | 0.079523 |
| 19 | 5 | 9 | 0.067833 |
| 20 | 5 | 9 | 0.067834 |
| 21 | 5 | 9 | 0.067782 |
| 22 | 5 | 9 | 0.067708 |
| 23 | 5 | 9 | 0.067778 |
| 24 | 5 | 9 | 0.067784 |
| 25 | 5 | 9 | 0.068839 |
| 26 | 5 | 9 | 0.067707 |
| 27 | 5 | 9 | 0.067831 |

| zoneID | dayID | hourID | allocationFraction |
|---|---|---|---|
| 28 | 5 | 9 | 0.067819 |
| 29 | 5 | 9 | 0.067811 |
| 30 | 5 | 9 | 0.073998 |
| 31 | 5 | 9 | 0.067827 |
| 32 | 5 | 9 | 0.059426 |
| 33 | 5 | 9 | 0.067795 |
| 34 | 5 | 9 | 0.067767 |
| 35 | 5 | 9 | 0.067827 |
| 36 | 5 | 9 | 0.067832 |
| 37 | 5 | 9 | 0.067794 |
| 38 | 5 | 9 | 0.07401 |
| 39 | 5 | 9 | 0.063239 |
| 40 | 5 | 9 | 0.094354 |
| 41 | 5 | 9 | 0.06779 |
| 42 | 5 | 9 | 0.065738 |
| 43 | 5 | 9 | 0.067795 |
| 44 | 5 | 9 | 0.067798 |
| 45 | 5 | 9 | 0.068265 |
| 46 | 5 | 9 | 0.086353 |
| 47 | 5 | 9 | 0.067684 |
| 48 | 5 | 9 | 0.067742 |
| 49 | 5 | 9 | 0.06775 |

**Table A.15 – Distribution of starts per day by source type**

| sourceTypeID | allocationFraction |
|---|---|
| 11 | 0.026975 |
| 21 | 0.570609 |
| 31 | 0.395221 |
| 32 | 0.00208 |
| 51 | 4.01E-05 |
| 52 | 0.000829 |
| 53 | 0.000132 |
| 54 | 0 |
| 61 | 0.003547 |
| 62 | 0.000567 |

**Table A.16 – Monthly adjustment of starts**

| monthID | monthAdjustment |
|---|---|
| All | 1 |

**Table A.17 – Inspection and maintenance coverage table**

| polProcessID | stateID | countyID | yearID | sourcetypeID | fuelTypeID | IMProgramID | inspectFreq | testStandardsID | begModelYearID | endModelYearID | useIMyn | complianceFactor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 101 | 99 | 99001 | 2012 | 51 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 102 | 99 | 99001 | 2012 | 51 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 201 | 99 | 99001 | 2012 | 51 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 202 | 99 | 99001 | 2012 | 51 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 301 | 99 | 99001 | 2012 | 51 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 302 | 99 | 99001 | 2012 | 51 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 101 | 99 | 99001 | 2012 | 52 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 102 | 99 | 99001 | 2012 | 52 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 201 | 99 | 99001 | 2012 | 52 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 202 | 99 | 99001 | 2012 | 52 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 301 | 99 | 99001 | 2012 | 52 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 302 | 99 | 99001 | 2012 | 52 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 101 | 99 | 99001 | 2012 | 53 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 102 | 99 | 99001 | 2012 | 53 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 201 | 99 | 99001 | 2012 | 53 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 202 | 99 | 99001 | 2012 | 53 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 301 | 99 | 99001 | 2012 | 53 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 302 | 99 | 99001 | 2012 | 53 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 101 | 99 | 99001 | 2012 | 54 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 102 | 99 | 99001 | 2012 | 54 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 201 | 99 | 99001 | 2012 | 54 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 202 | 99 | 99001 | 2012 | 54 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 301 | 99 | 99001 | 2012 | 54 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 302 | 99 | 99001 | 2012 | 54 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 101 | 99 | 99001 | 2012 | 61 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 102 | 99 | 99001 | 2012 | 61 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 201 | 99 | 99001 | 2012 | 61 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 202 | 99 | 99001 | 2012 | 61 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 301 | 99 | 99001 | 2012 | 61 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |
| 302 | 99 | 99001 | 2012 | 61 | 1 | 2112 | 1 | 12 | 1982 | 2012 | 'y' | 97.1208 |

**Table A.18 – Sample AVFT table for source type 52 – Single Unit Short-Haul**

| sourceTypeID | modelYearID | fuelTypeID | engTechID | fuelEngFraction |
|---|---|---|---|---|
| 52 | 1960 | 1 | 1 | 0.99 |
| 52 | 1960 | 2 | 1 | 0.01 |
| 52 | 1961 | 1 | 1 | 0.99 |
| 52 | 1961 | 2 | 1 | 0.01 |
| 52 | 1962 | 1 | 1 | 0.99 |
| 52 | 1962 | 2 | 1 | 0.01 |
| 52 | 1963 | 1 | 1 | 0.99 |
| 52 | 1963 | 2 | 1 | 0.01 |
| 52 | 1964 | 1 | 1 | 0.99 |
| 52 | 1964 | 2 | 1 | 0.01 |
| 52 | 1965 | 1 | 1 | 0.99 |
| 52 | 1965 | 2 | 1 | 0.01 |
| 52 | 1966 | 1 | 1 | 0.99 |
| 52 | 1966 | 2 | 1 | 0.01 |
| 52 | 1967 | 1 | 1 | 0.99 |
| 52 | 1967 | 2 | 1 | 0.01 |
| 52 | 1968 | 1 | 1 | 0.99 |
| 52 | 1968 | 2 | 1 | 0.01 |
| 52 | 1969 | 1 | 1 | 0.99 |
| 52 | 1969 | 2 | 1 | 0.01 |
| 52 | 1970 | 1 | 1 | 0.99 |
| 52 | 1970 | 2 | 1 | 0.01 |
| 52 | 1971 | 1 | 1 | 0.9705 |
| 52 | 1971 | 2 | 1 | 0.0295 |
| 52 | 1972 | 1 | 1 | 0.941 |
| 52 | 1972 | 2 | 1 | 0.059 |
| 52 | 1973 | 1 | 1 | 0.9115 |
| 52 | 1973 | 2 | 1 | 0.0885 |
| 52 | 1974 | 1 | 1 | 0.882 |
| 52 | 1974 | 2 | 1 | 0.118 |
| 52 | 1975 | 1 | 1 | 0.8525 |
| 52 | 1975 | 2 | 1 | 0.1475 |
| 52 | 1976 | 1 | 1 | 0.823 |
| 52 | 1976 | 2 | 1 | 0.177 |
| 52 | 1977 | 1 | 1 | 0.7935 |
| 52 | 1977 | 2 | 1 | 0.2065 |
| 52 | 1978 | 1 | 1 | 0.764 |
| 52 | 1978 | 2 | 1 | 0.236 |
| 52 | 1979 | 1 | 1 | 0.7345 |

| sourceTypeID | modelYearID | fuelTypeID | engTechID | fuelEngFraction |
|---|---|---|---|---|
| 52 | 1979 | 2 | 1 | 0.2655 |
| 52 | 1980 | 1 | 1 | 0.705 |
| 52 | 1980 | 2 | 1 | 0.295 |
| 52 | 1981 | 1 | 1 | 0.6755 |
| 52 | 1981 | 2 | 1 | 0.3245 |
| 52 | 1982 | 1 | 1 | 0.776959 |
| 52 | 1982 | 2 | 1 | 0.223041 |
| 52 | 1983 | 1 | 1 | 0.76991 |
| 52 | 1983 | 2 | 1 | 0.23009 |
| 52 | 1984 | 1 | 1 | 0.762707 |
| 52 | 1984 | 2 | 1 | 0.237293 |
| 52 | 1985 | 1 | 1 | 0.75535 |
| 52 | 1985 | 2 | 1 | 0.24465 |
| 52 | 1986 | 1 | 1 | 0.747841 |
| 52 | 1986 | 2 | 1 | 0.252159 |
| 52 | 1987 | 1 | 1 | 0.74018 |
| 52 | 1987 | 2 | 1 | 0.25982 |
| 52 | 1988 | 1 | 1 | 0.73237 |
| 52 | 1988 | 2 | 1 | 0.26763 |
| 52 | 1989 | 1 | 1 | 0.724412 |
| 52 | 1989 | 2 | 1 | 0.275588 |
| 52 | 1990 | 1 | 1 | 0.71631 |
| 52 | 1990 | 2 | 1 | 0.28369 |
| 52 | 1991 | 1 | 1 | 0.708065 |
| 52 | 1991 | 2 | 1 | 0.291935 |
| 52 | 1992 | 1 | 1 | 0.699681 |
| 52 | 1992 | 2 | 1 | 0.300319 |
| 52 | 1993 | 1 | 1 | 0.691161 |
| 52 | 1993 | 2 | 1 | 0.308839 |
| 52 | 1994 | 1 | 1 | 0.68251 |
| 52 | 1994 | 2 | 1 | 0.31749 |
| 52 | 1995 | 1 | 1 | 0.67373 |
| 52 | 1995 | 2 | 1 | 0.32627 |
| 52 | 1996 | 1 | 1 | 0.664827 |
| 52 | 1996 | 2 | 1 | 0.335173 |
| 52 | 1997 | 1 | 1 | 0.655805 |
| 52 | 1997 | 2 | 1 | 0.344195 |
| 52 | 1998 | 1 | 1 | 0.646669 |
| 52 | 1998 | 2 | 1 | 0.353331 |
| 52 | 1999 | 1 | 1 | 0.637425 |

| sourceTypeID | modelYearID | fuelTypeID | engTechID | fuelEngFraction |
|---|---|---|---|---|
| 52 | 1999 | 2 | 1 | 0.362575 |
| 52 | 2000 | 1 | 1 | 0.628078 |
| 52 | 2000 | 2 | 1 | 0.371922 |
| 52 | 2001 | 1 | 1 | 0.618634 |
| 52 | 2001 | 2 | 1 | 0.381366 |
| 52 | 2002 | 1 | 1 | 0.6091 |
| 52 | 2002 | 2 | 1 | 0.3909 |
| 52 | 2003 | 1 | 1 | 0.557799 |
| 52 | 2003 | 2 | 1 | 0.442201 |
| 52 | 2004 | 1 | 1 | 0.463084 |
| 52 | 2004 | 2 | 1 | 0.536916 |
| 52 | 2005 | 1 | 1 | 0.44278 |
| 52 | 2005 | 2 | 1 | 0.55722 |
| 52 | 2006 | 1 | 1 | 0.402845 |
| 52 | 2006 | 2 | 1 | 0.597155 |
| 52 | 2007 | 1 | 1 | 0.298865 |
| 52 | 2007 | 2 | 1 | 0.701135 |
| 52 | 2008 | 1 | 1 | 0.3001 |
| 52 | 2008 | 2 | 1 | 0.6999 |
| 52 | 2009 | 1 | 1 | 0.273094 |
| 52 | 2009 | 2 | 1 | 0.726906 |
| 52 | 2010 | 1 | 1 | 0.268685 |
| 52 | 2010 | 2 | 1 | 0.731315 |
| 52 | 2011 | 1 | 1 | 0.263415 |
| 52 | 2011 | 2 | 1 | 0.736585 |
| 52 | 2012 | 1 | 1 | 0.267558 |
| 52 | 2012 | 2 | 1 | 0.732442 |
| 52 | 2013 | 1 | 1 | 0 |
| 52 | 2013 | 2 | 1 | 1 |
| 52 | 2014 | 1 | 1 | 0 |
| 52 | 2014 | 2 | 1 | 1 |
| 52 | 2015 | 1 | 1 | 0 |
| 52 | 2015 | 2 | 1 | 1 |
| 52 | 2016 | 1 | 1 | 0 |
| 52 | 2016 | 2 | 1 | 1 |
| 52 | 2017 | 1 | 1 | 0 |
| 52 | 2017 | 2 | 1 | 1 |
| 52 | 2018 | 1 | 1 | 0 |
| 52 | 2018 | 2 | 1 | 1 |
| 52 | 2019 | 1 | 1 | 0 |

| sourceTypeID | modelYearID | fuelTypeID | engTechID | fuelEngFraction |
|---|---|---|---|---|
| 52 | 2019 | 2 | 1 | 1 |
| 52 | 2020 | 1 | 1 | 0 |
| 52 | 2020 | 2 | 1 | 1 |
| 52 | 2021 | 1 | 1 | 0 |
| 52 | 2021 | 2 | 1 | 1 |
| 52 | 2022 | 1 | 1 | 0 |
| 52 | 2022 | 2 | 1 | 1 |
| 52 | 2023 | 1 | 1 | 0 |
| 52 | 2023 | 2 | 1 | 1 |
| 52 | 2024 | 1 | 1 | 0 |
| 52 | 2024 | 2 | 1 | 1 |
| 52 | 2025 | 1 | 1 | 0 |
| 52 | 2025 | 2 | 1 | 1 |
| 52 | 2026 | 1 | 1 | 0 |
| 52 | 2026 | 2 | 1 | 1 |
| 52 | 2027 | 1 | 1 | 0 |
| 52 | 2027 | 2 | 1 | 1 |
| 52 | 2028 | 1 | 1 | 0 |
| 52 | 2028 | 2 | 1 | 1 |
| 52 | 2029 | 1 | 1 | 0 |
| 52 | 2029 | 2 | 1 | 1 |
| 52 | 2030 | 1 | 1 | 0 |
| 52 | 2030 | 2 | 1 | 1 |
| 52 | 2031 | 1 | 1 | 0 |
| 52 | 2031 | 2 | 1 | 1 |
| 52 | 2032 | 1 | 1 | 0 |
| 52 | 2032 | 2 | 1 | 1 |
| 52 | 2033 | 1 | 1 | 0 |
| 52 | 2033 | 2 | 1 | 1 |
| 52 | 2034 | 1 | 1 | 0 |
| 52 | 2034 | 2 | 1 | 1 |
| 52 | 2035 | 1 | 1 | 0 |
| 52 | 2035 | 2 | 1 | 1 |
| 52 | 2036 | 1 | 1 | 0 |
| 52 | 2036 | 2 | 1 | 1 |
| 52 | 2037 | 1 | 1 | 0 |
| 52 | 2037 | 2 | 1 | 1 |
| 52 | 2038 | 1 | 1 | 0 |
| 52 | 2038 | 2 | 1 | 1 |
| 52 | 2039 | 1 | 1 | 0 |

| sourceTypeID | modelYearID | fuelTypeID | engTechID | fuelEngFraction |
|---|---|---|---|---|
| 52 | 2039 | 2 | 1 | 1 |
| 52 | 2040 | 1 | 1 | 0 |
| 52 | 2040 | 2 | 1 | 1 |
| 52 | 2041 | 1 | 1 | 0 |
| 52 | 2041 | 2 | 1 | 1 |
| 52 | 2042 | 1 | 1 | 0 |
| 52 | 2042 | 2 | 1 | 1 |
| 52 | 2043 | 1 | 1 | 0 |
| 52 | 2043 | 2 | 1 | 1 |
| 52 | 2044 | 1 | 1 | 0 |
| 52 | 2044 | 2 | 1 | 1 |
| 52 | 2045 | 1 | 1 | 0 |
| 52 | 2045 | 2 | 1 | 1 |
| 52 | 2046 | 1 | 1 | 0 |
| 52 | 2046 | 2 | 1 | 1 |
| 52 | 2047 | 1 | 1 | 0 |
| 52 | 2047 | 2 | 1 | 1 |
| 52 | 2048 | 1 | 1 | 0 |
| 52 | 2048 | 2 | 1 | 1 |
| 52 | 2049 | 1 | 1 | 0 |
| 52 | 2049 | 2 | 1 | 1 |
| 52 | 2050 | 1 | 1 | 0 |
| 52 | 2050 | 2 | 1 | 1 |

## Table A.19 – Fuel formulations for gasoline and diesel fuels by month

| fuelFormulationID | fuelSubtypeID | RVP | sulfurLevel | ETOHVolume | MTBEVolume | ETBEVolume | TAMEVolume | aromaticContent | olefinContent | benzeneContent | e200 | e300 | BioDieselEsterVolume | CetaneIndex | PAHContent | T50 | T90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1001 | 10 | 14.14121 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 185 | 365 |
| 1002 | 10 | 11.60304 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 185 | 365 |
| 1003 | 10 | 11.24045 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 185 | 365 |
| 1004 | 10 | 10.2977 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 194 | 365 |
| 1005 | 10 | 8.774799 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 195.8 | 374 |
| 1006 | 10 | 7.759533 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 199.4 | 374 |
| 1007 | 10 | 7.759533 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 199.4 | 374 |
| 1008 | 10 | 7.759533 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 199.4 | 374 |
| 1009 | 10 | 8.774799 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 195.8 | 374 |
| 1010 | 10 | 11.24045 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 194 | 374 |
| 1011 | 10 | 11.24045 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 185 | 365 |
| 1012 | 10 | 11.60304 | 30 | 0 | 0 | 0 | 0 | 27.5 | 5.6 | 1 | 50 | 85 | 0 | 0 | 0 | 185 | 365 |
| 25001 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 32.6 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25002 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 32.6 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25003 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 32.6 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25004 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 36.9 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25005 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 36.9 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25006 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 36.9 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25007 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 35 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25008 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 35 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25009 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 35 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25010 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 20.3 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25011 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 20.3 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |
| 25012 | 20 | 0.290075 | 15 | 0 | 0 | 0 | 0 | 20.3 | 0 | 0 | 1 | 1.889 | 0 | 0 | 0 | 0 | 680 |

### Table A.20 – Fuel supply table for April

| fuelRegionID | fuelYearID | monthGroupID | fuelFormulationID | marketShare | marketShareCV |
|---|---|---|---|---|---|
| 100000000 | 2012 | 4 | 1004 | 1 | 0.5 |
| 100000000 | 2012 | 4 | 25004 | 1 | 0.5 |

### Table A.21 – Fuel formulations table

| countyID | fuelYearID | modelYearGroupID | sourceBinFuelTypeID | fuelSupplyFuelTypeID | usageFraction |
|---|---|---|---|---|---|
| 99001 | 2012 | 0 | 1 | 1 | 1 |
| 99001 | 2012 | 0 | 2 | 2 | 1 |
| 99001 | 2012 | 0 | 3 | 3 | 1 |
| 99001 | 2012 | 0 | 5 | 1 | 0.986574 |
| 99001 | 2012 | 0 | 5 | 5 | 0.013426 |
| 99001 | 2012 | 0 | 9 | 9 | 1 |

## Appendix B – MOVES baseline RunSpec

```
<runspec version="MOVES2014a-20151201">
        <description><![CDATA[Ontario

BASECASE

1 hour (8am-9am)
April

Pollutants:     CO2
        CH4
        N2O

        CO
        NO2
        PM2.5
        SO2
        VOC
        NH3
        NOx]]></description>
        <models>
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        </models>
        <modelscale value="Inv"/>
        <modeldomain value="SINGLE"/>
        <genericcounty>
                <shortid value="1"/>
                <stateid value="99"/>
                <description value=""/>
                <gpafraction value="0.0"/>
                <barometricpressure value="28.9"/>
                <refuelvaporadjust value="0.0"/>
                <refuelspilladjust value="0.0"/>
        </genericcounty>
        <geographicselections>
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        </geographicselections>
        <timespan>
                <year key="2012"/>
                <month id="4"/>
                <day id="5"/>
```

```
                        <beginhour id="9"/>
                        <endhour id="9"/>
                        <aggregateBy key="Hour"/>
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sourcetypename="Combination Long-haul Truck"/>
                        <onroadvehicleselection fueltypeid="2" fueltypedesc="Diesel Fuel" sourcetypeid="61"
sourcetypename="Combination Short-haul Truck"/>
                        <onroadvehicleselection fueltypeid="2" fueltypedesc="Diesel Fuel" sourcetypeid="32"
sourcetypename="Light Commercial Truck"/>
                        <onroadvehicleselection fueltypeid="2" fueltypedesc="Diesel Fuel" sourcetypeid="54"
sourcetypename="Motor Home"/>
                        <onroadvehicleselection fueltypeid="2" fueltypedesc="Diesel Fuel" sourcetypeid="21"
sourcetypename="Passenger Car"/>
                        <onroadvehicleselection fueltypeid="2" fueltypedesc="Diesel Fuel" sourcetypeid="31"
sourcetypename="Passenger Truck"/>
                        <onroadvehicleselection fueltypeid="2" fueltypedesc="Diesel Fuel" sourcetypeid="51"
sourcetypename="Refuse Truck"/>
                        <onroadvehicleselection fueltypeid="2" fueltypedesc="Diesel Fuel" sourcetypeid="53"
sourcetypename="Single Unit Long-haul Truck"/>
                        <onroadvehicleselection fueltypeid="2" fueltypedesc="Diesel Fuel" sourcetypeid="52"
sourcetypename="Single Unit Short-haul Truck"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="61"
sourcetypename="Combination Short-haul Truck"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="32"
sourcetypename="Light Commercial Truck"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="54"
sourcetypename="Motor Home"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="11"
sourcetypename="Motorcycle"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="21"
sourcetypename="Passenger Car"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="31"
sourcetypename="Passenger Truck"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="51"
sourcetypename="Refuse Truck"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="53"
sourcetypename="Single Unit Long-haul Truck"/>
                        <onroadvehicleselection fueltypeid="1" fueltypedesc="Gasoline" sourcetypeid="52"
sourcetypename="Single Unit Short-haul Truck"/>
```

```
		</onroadvehicleselections>
		<offroadvehicleselections>
		</offroadvehicleselections>
		<offroadvehiclesccs>
		</offroadvehiclesccs>
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			<roadtype roadtypeid="2" roadtypename="Rural Restricted Access" modelCombination="M1"/>
			<roadtype roadtypeid="3" roadtypename="Rural Unrestricted Access" modelCombination="M1"/>
			<roadtype roadtypeid="4" roadtypename="Urban Restricted Access" modelCombination="M1"/>
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processname="Running Exhaust"/>
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processname="Start Exhaust"/>
			<pollutantprocessassociation pollutantkey="58" pollutantname="Aluminum" processkey="15"
processname="Crankcase Running Exhaust"/>
			<pollutantprocessassociation pollutantkey="58" pollutantname="Aluminum" processkey="16"
processname="Crankcase Start Exhaust"/>
			<pollutantprocessassociation pollutantkey="58" pollutantname="Aluminum" processkey="17"
processname="Crankcase Extended Idle Exhaust"/>
			<pollutantprocessassociation pollutantkey="58" pollutantname="Aluminum" processkey="90"
processname="Extended Idle Exhaust"/>
			<pollutantprocessassociation pollutantkey="58" pollutantname="Aluminum" processkey="91"
processname="Auxiliary Power Exhaust"/>
			<pollutantprocessassociation pollutantkey="30" pollutantname="Ammonia (NH3)" processkey="1"
processname="Running Exhaust"/>
			<pollutantprocessassociation pollutantkey="30" pollutantname="Ammonia (NH3)" processkey="2"
processname="Start Exhaust"/>
			<pollutantprocessassociation pollutantkey="30" pollutantname="Ammonia (NH3)" processkey="15"
processname="Crankcase Running Exhaust"/>
			<pollutantprocessassociation pollutantkey="30" pollutantname="Ammonia (NH3)" processkey="16"
processname="Crankcase Start Exhaust"/>
			<pollutantprocessassociation pollutantkey="30" pollutantname="Ammonia (NH3)" processkey="17"
processname="Crankcase Extended Idle Exhaust"/>
			<pollutantprocessassociation pollutantkey="30" pollutantname="Ammonia (NH3)" processkey="90"
processname="Extended Idle Exhaust"/>
			<pollutantprocessassociation pollutantkey="30" pollutantname="Ammonia (NH3)" processkey="91"
processname="Auxiliary Power Exhaust"/>
```

```
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processname="Running Exhaust"/>
                <pollutantprocessassociation pollutantkey="36" pollutantname="Ammonium (NH4)" processkey="2"
processname="Start Exhaust"/>
                <pollutantprocessassociation pollutantkey="36" pollutantname="Ammonium (NH4)" processkey="15"
processname="Crankcase Running Exhaust"/>
                <pollutantprocessassociation pollutantkey="36" pollutantname="Ammonium (NH4)" processkey="16"
processname="Crankcase Start Exhaust"/>
                <pollutantprocessassociation pollutantkey="36" pollutantname="Ammonium (NH4)" processkey="17"
processname="Crankcase Extended Idle Exhaust"/>
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processname="Extended Idle Exhaust"/>
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processname="Auxiliary Power Exhaust"/>
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processname="Running Exhaust"/>
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processname="Start Exhaust"/>
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processname="Extended Idle Exhaust"/>
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processname="Auxiliary Power Exhaust"/>
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processkey="1" processname="Running Exhaust"/>
                <pollutantprocessassociation pollutantkey="121" pollutantname="CMAQ5.0 Unspeciated (PMOTHR)"
processkey="2" processname="Start Exhaust"/>
                <pollutantprocessassociation pollutantkey="121" pollutantname="CMAQ5.0 Unspeciated (PMOTHR)"
processkey="15" processname="Crankcase Running Exhaust"/>
                <pollutantprocessassociation pollutantkey="121" pollutantname="CMAQ5.0 Unspeciated (PMOTHR)"
processkey="16" processname="Crankcase Start Exhaust"/>
                <pollutantprocessassociation pollutantkey="121" pollutantname="CMAQ5.0 Unspeciated (PMOTHR)"
processkey="17" processname="Crankcase Extended Idle Exhaust"/>
                <pollutantprocessassociation pollutantkey="121" pollutantname="CMAQ5.0 Unspeciated (PMOTHR)"
processkey="90" processname="Extended Idle Exhaust"/>
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processkey="91" processname="Auxiliary Power Exhaust"/>
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processname="Running Exhaust"/>
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processname="Start Exhaust"/>
```

```
                <pollutantprocessassociation pollutantkey="98" pollutantname="CO2 Equivalent" processkey="90"
processname="Extended Idle Exhaust"/>
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processname="Auxiliary Power Exhaust"/>
                <pollutantprocessassociation pollutantkey="55" pollutantname="Calcium" processkey="1"
processname="Running Exhaust"/>
                <pollutantprocessassociation pollutantkey="55" pollutantname="Calcium" processkey="2"
processname="Start Exhaust"/>
                <pollutantprocessassociation pollutantkey="55" pollutantname="Calcium" processkey="15"
processname="Crankcase Running Exhaust"/>
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processname="Crankcase Start Exhaust"/>
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processname="Crankcase Extended Idle Exhaust"/>
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processname="Auxiliary Power Exhaust"/>
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processname="Running Exhaust"/>
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processname="Start Exhaust"/>
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processname="Crankcase Running Exhaust"/>
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processname="Crankcase Start Exhaust"/>
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processname="Auxiliary Power Exhaust"/>
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processname="Running Exhaust"/>
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processname="Start Exhaust"/>
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processname="Crankcase Running Exhaust"/>
                <pollutantprocessassociation pollutantkey="51" pollutantname="Chloride" processkey="16"
processname="Crankcase Start Exhaust"/>
```

```
			<pollutantprocessassociation pollutantkey="51" pollutantname="Chloride" processkey="17" processname="Crankcase Extended Idle Exhaust"/>
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			<pollutantprocessassociation pollutantkey="118" pollutantname="Composite - NonECPM" processkey="90" processname="Extended Idle Exhaust"/>
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```

```
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			<pollutantprocessassociation pollutantkey="119" pollutantname="H2O (aerosol)" processkey="16" processname="Crankcase Start Exhaust"/>
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			<pollutantprocessassociation pollutantkey="119" pollutantname="H2O (aerosol)" processkey="90" processname="Extended Idle Exhaust"/>
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			<pollutantprocessassociation pollutantkey="59" pollutantname="Iron" processkey="2" processname="Start Exhaust"/>
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```

```
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processname="Running Exhaust"/>
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			<pollutantprocessassociation pollutantkey="35" pollutantname="Nitrate (NO3)" processkey="16"
processname="Crankcase Start Exhaust"/>
			<pollutantprocessassociation pollutantkey="35" pollutantname="Nitrate (NO3)" processkey="17"
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			<pollutantprocessassociation pollutantkey="35" pollutantname="Nitrate (NO3)" processkey="90"
processname="Extended Idle Exhaust"/>
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processname="Auxiliary Power Exhaust"/>
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processname="Running Exhaust"/>
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processname="Start Exhaust"/>
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processname="Crankcase Running Exhaust"/>
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			<pollutantprocessassociation pollutantkey="79" pollutantname="Non-Methane Hydrocarbons" processkey="16" processname="Crankcase Start Exhaust"/>
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**Figure B.1 – MOVES runspec file (Baseline Scenario)**

# Appendix C – Parameter Development

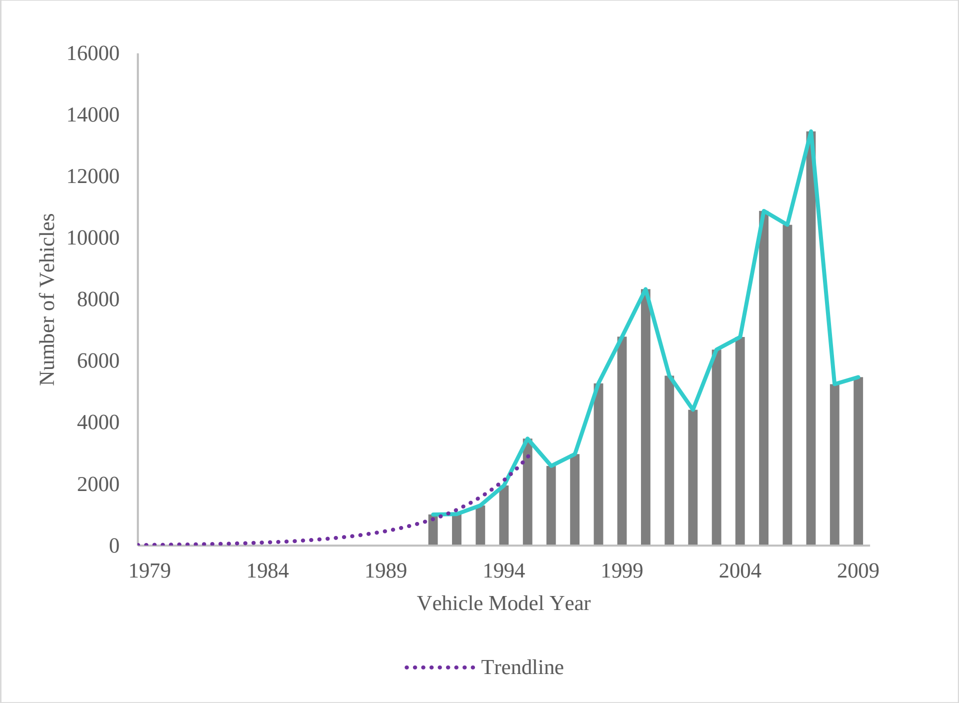

Figure C.1 – Trendline for HDV age extrapolation

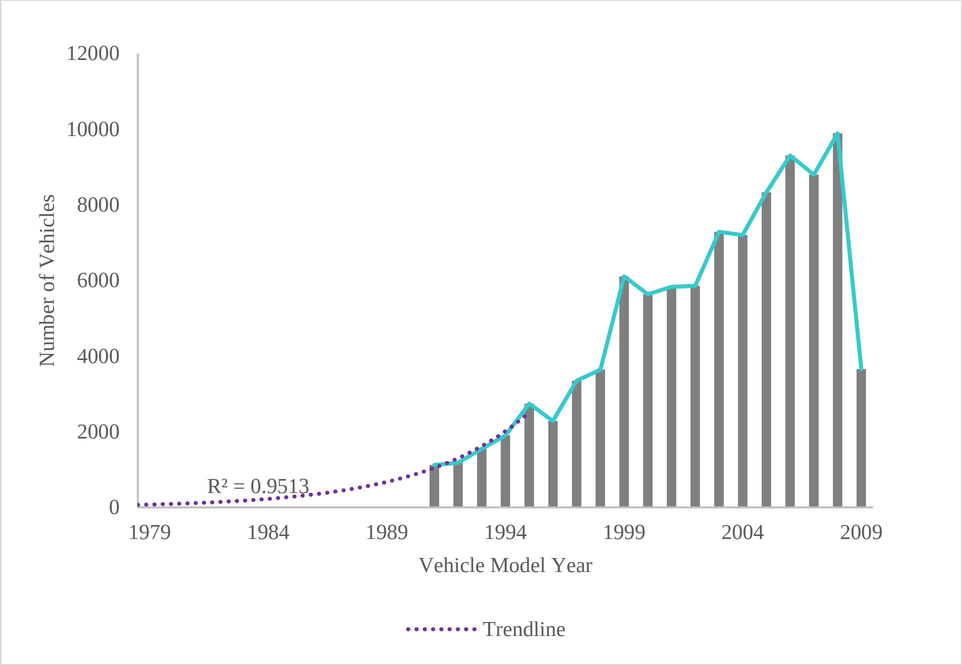

Figure C.2 – Trendline for MDV age extrapolation

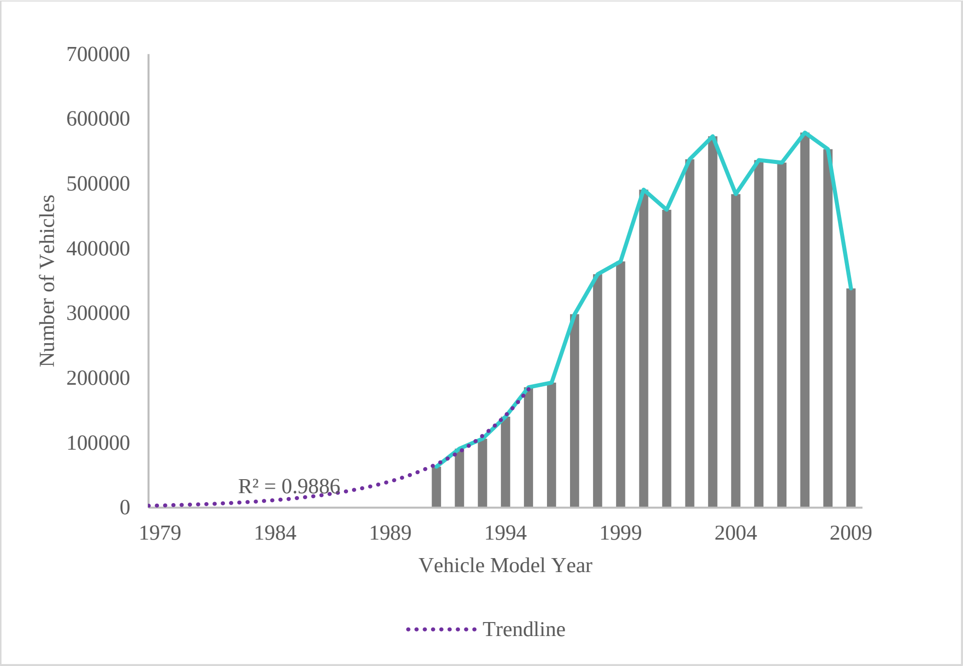

**Figure C.3 – Trendline for LDV age extrapolation**

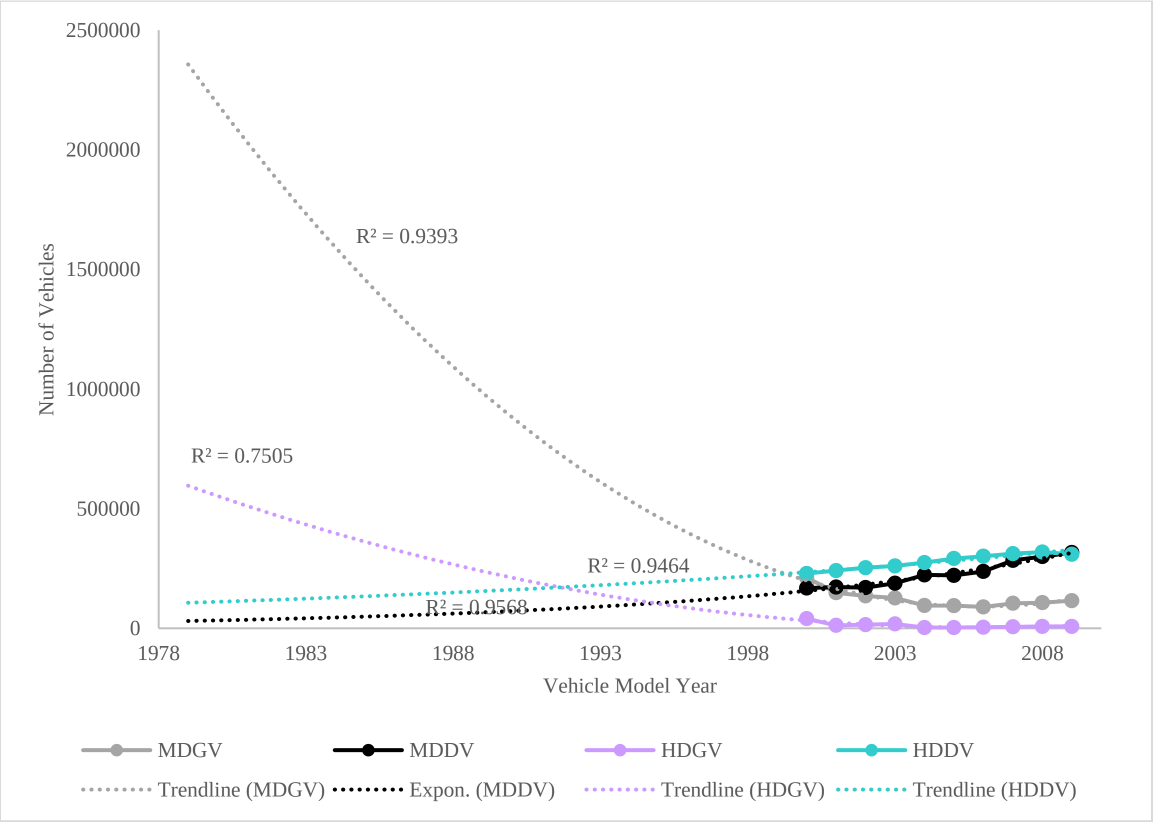

**Figure C.4 – Trendlines for MDV and HDV fuel usage type by vehicle age**

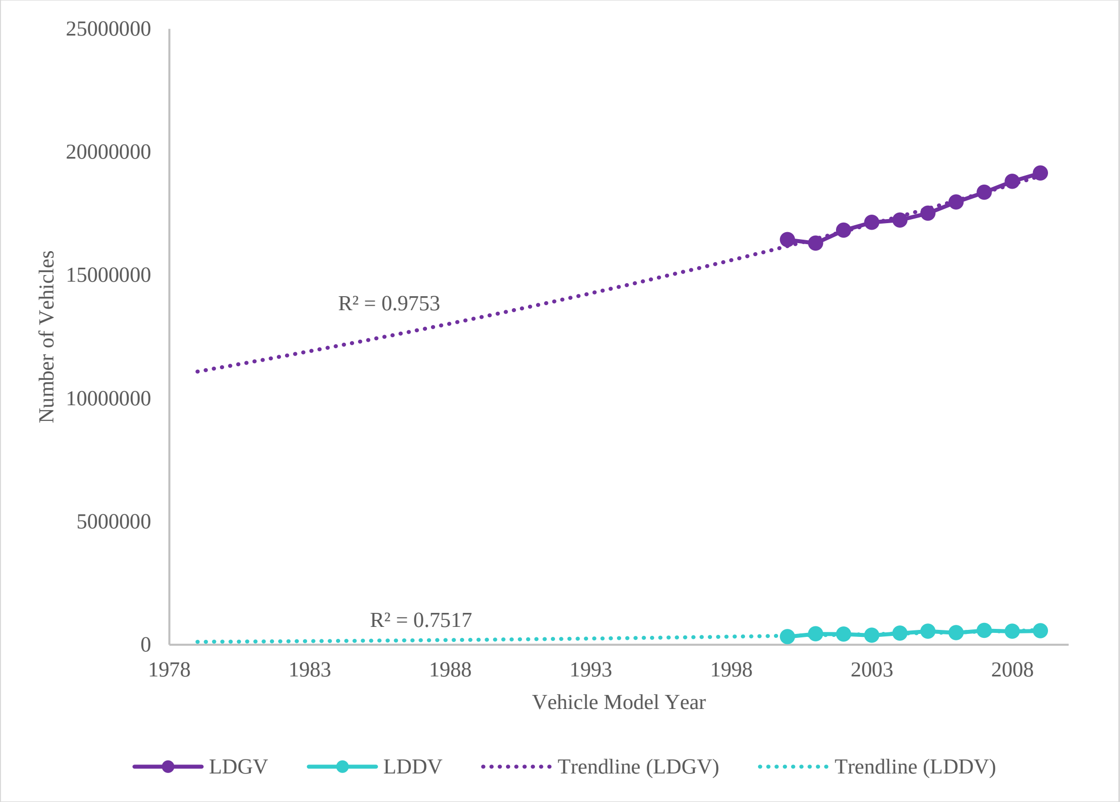

**Figure C.5 – Trendlines for LDV fuel usage type by vehicle age**

# Appendix D – Provincial Benefits map (Alternative Scenarios)

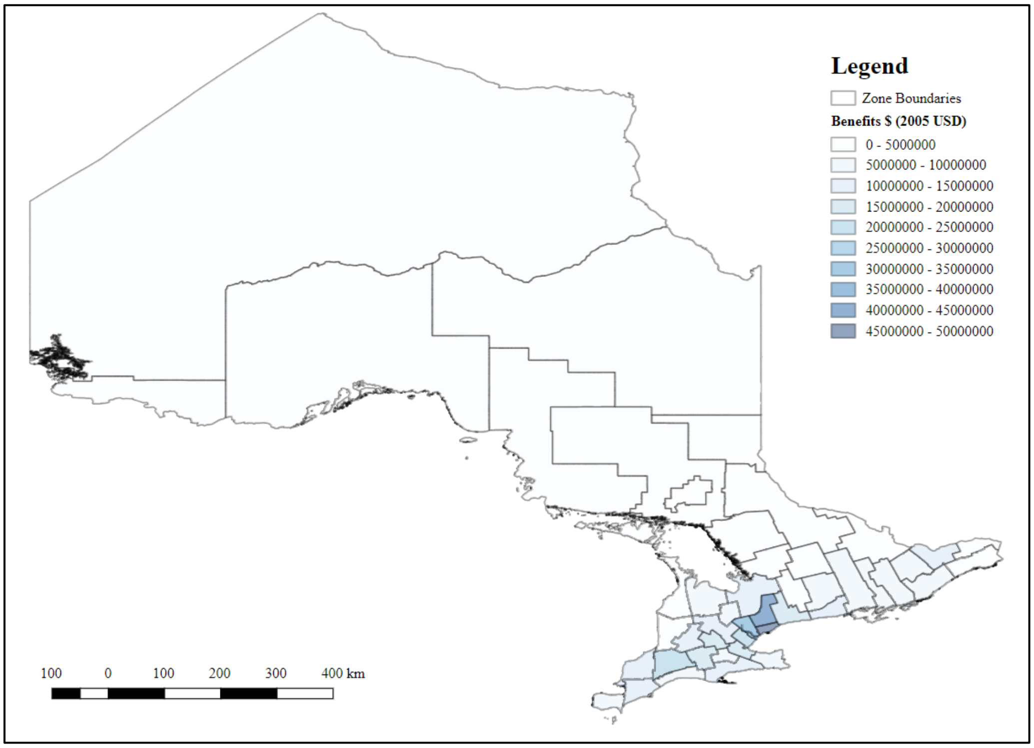

**Figure D.1 – Ontario provincial annual marginal benefits under 25% ZEV Adoption in 2012**

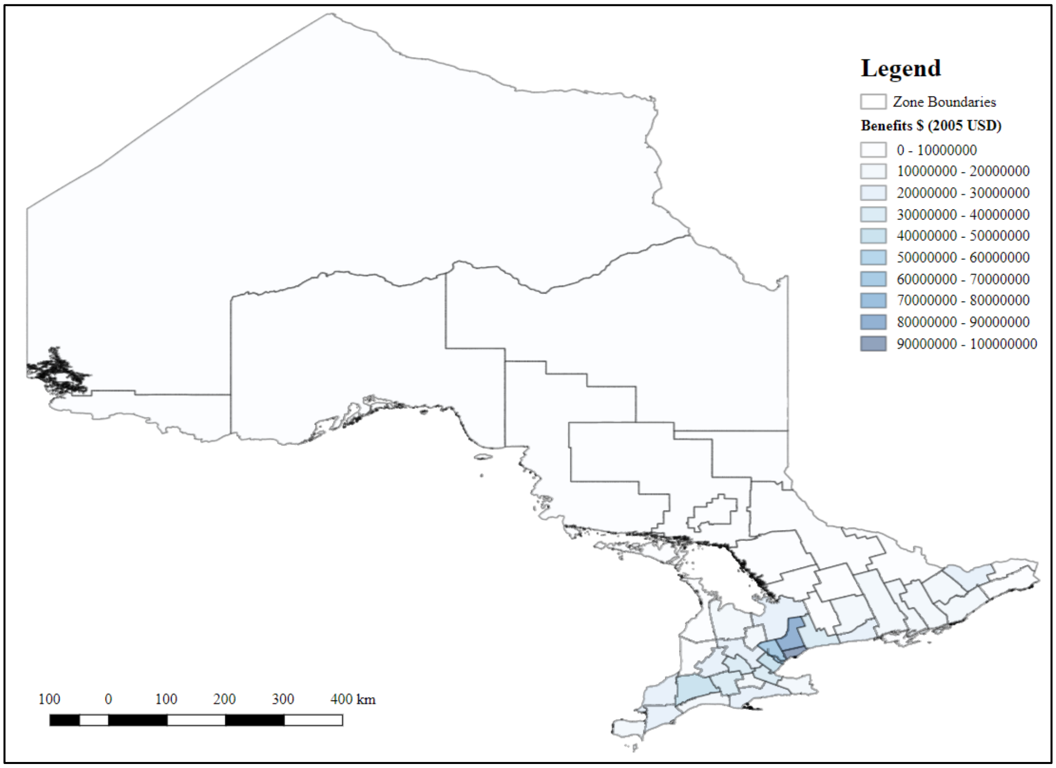

**Figure D.2 – Ontario provincial annual marginal benefits under 50% ZEV Adoption in 2012**

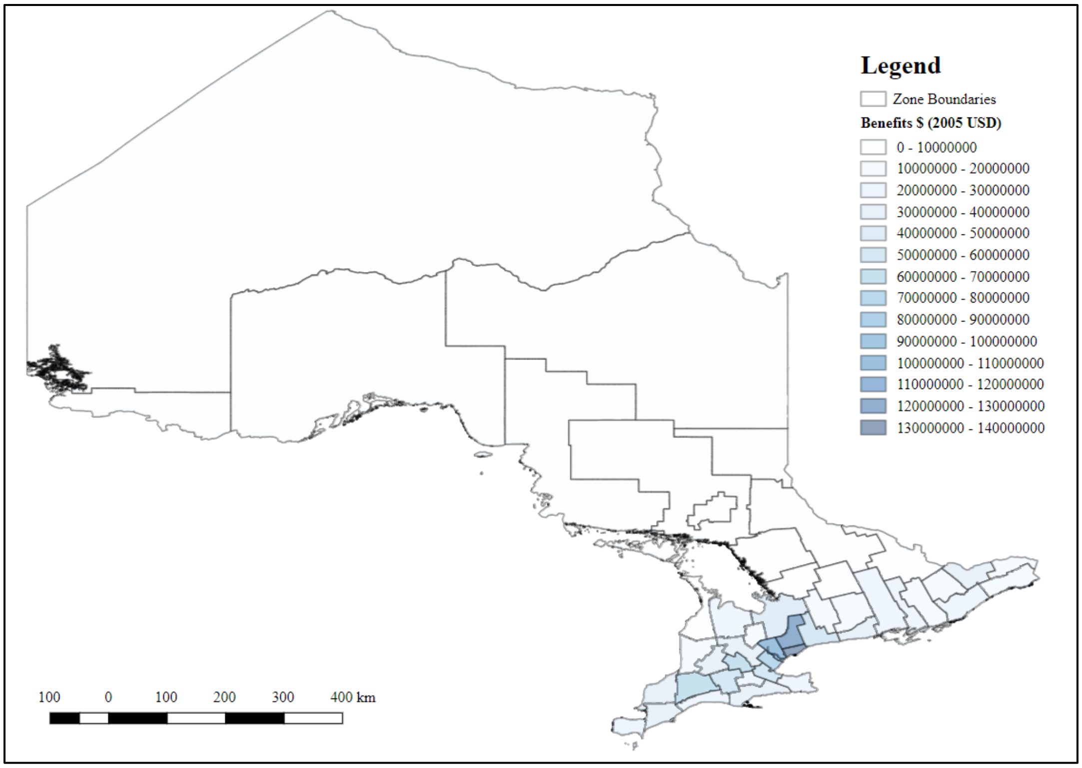

**Figure D.3 – Ontario provincial annual marginal benefits under 75% ZEV Adoption in 2012**

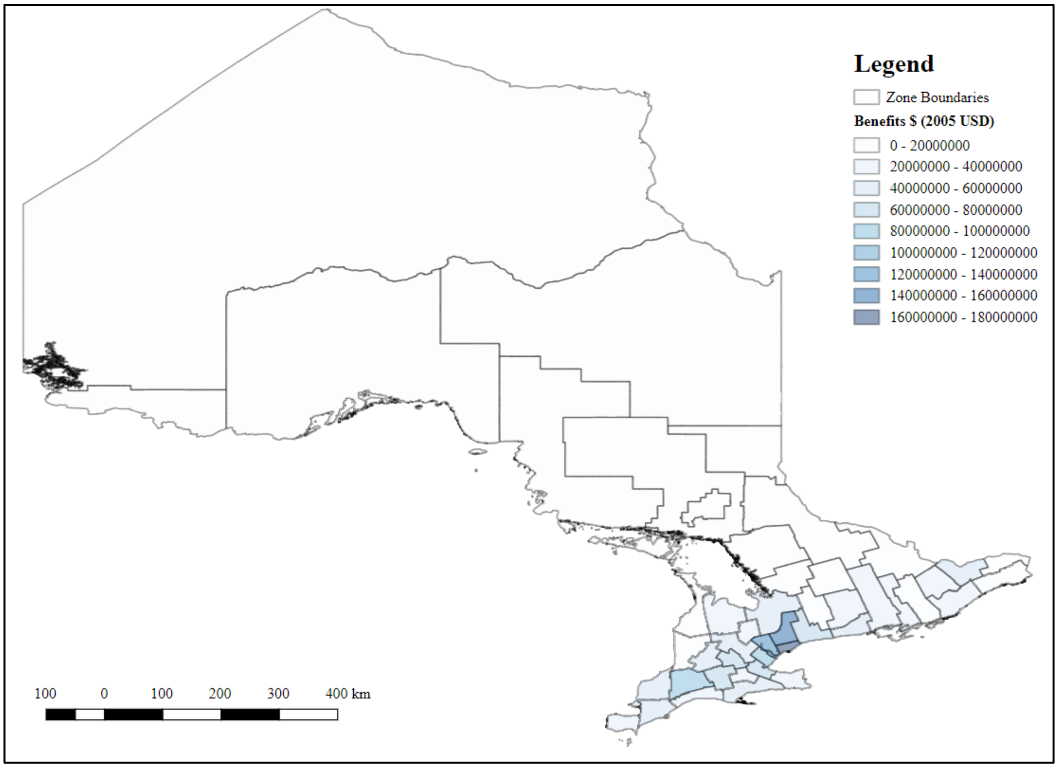

**Figure D.4 - Ontario provincial annual marginal benefits under 95% ZEV Adoption in 2012**

# Appendix E – Sensitivity analysis distribution profile plots

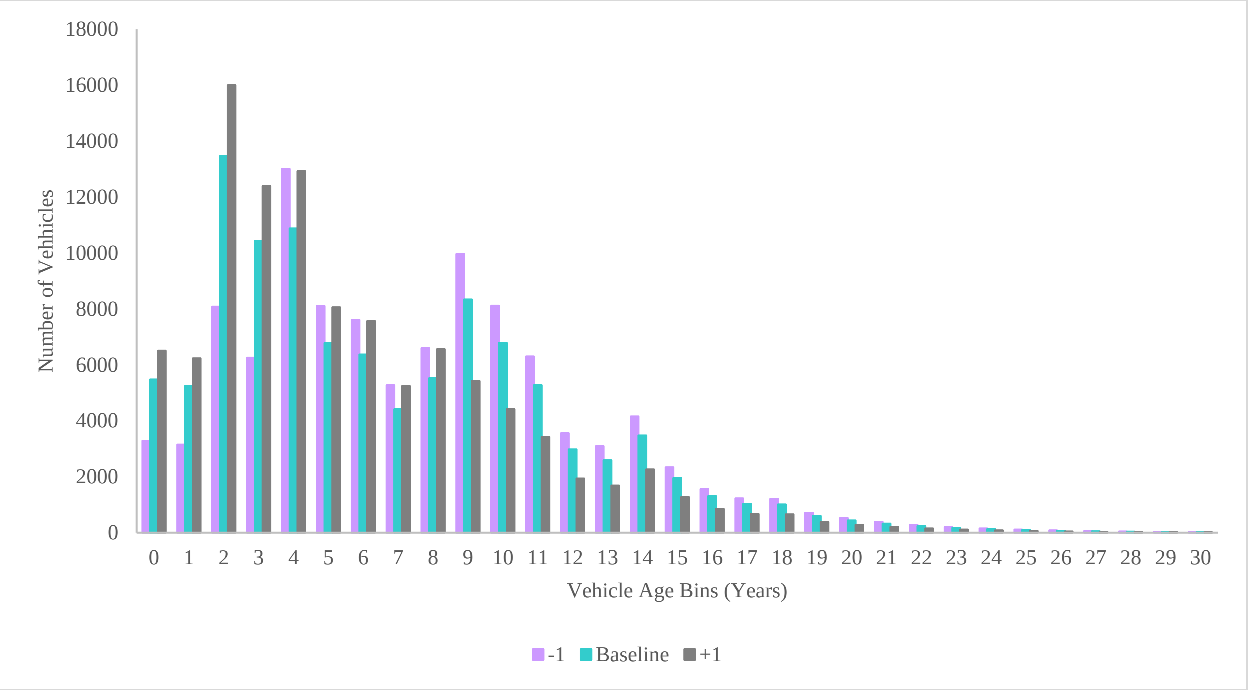

**Figure E.1 – Vehicle age distribution profiles for Baseline and alternative Scenarios (HDV)**

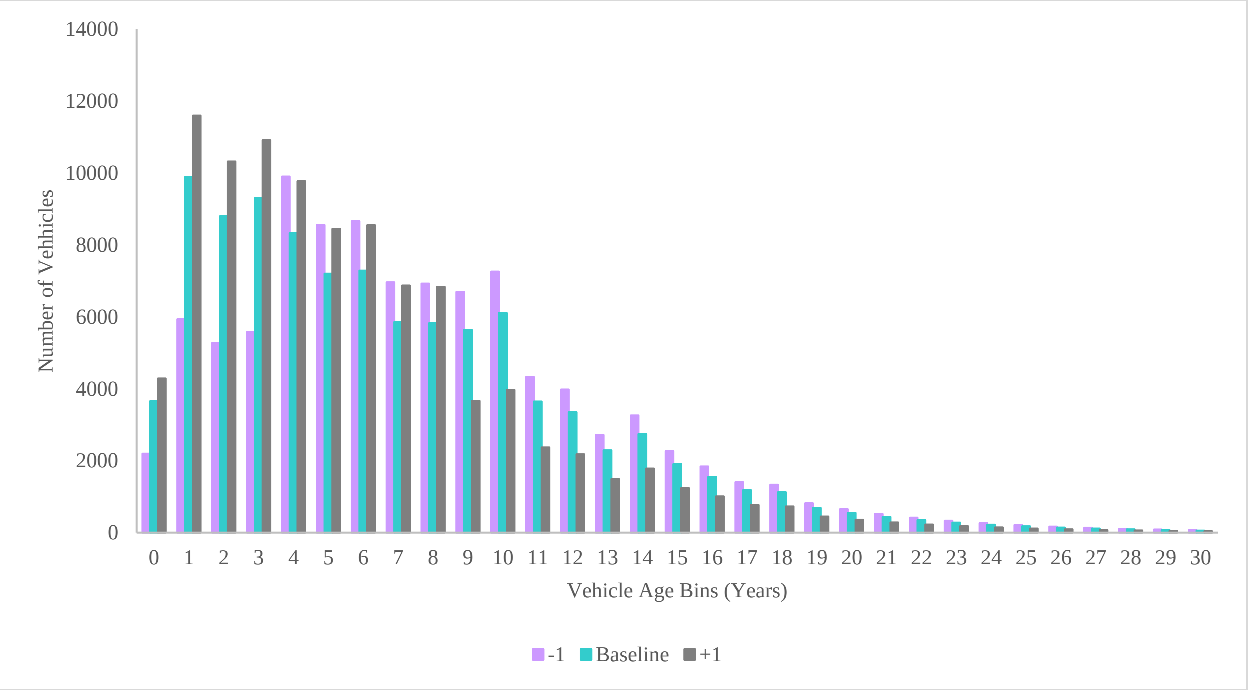

**Figure E.2 – Vehicle age distribution profiles for Baseline and alternative Scenarios (MDV)**