Development and Applications of an Emissions Micro-Simulation Tool for Transportation Infrastructure Design

by

Daniel Handford

A thesis submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy.

Department of Mechanical Engineering
University of Alberta

ABSTRACT

Transportation emissions constitute a significant portion of overall emissions inventories, and contribute to air quality health concerns. Reductions in transportation emissions can be achieved through efficient design of infrastructure, effective policy and regulation, and informed planning decisions. However, current transportation emissions models cannot accomplish all of these goals efficiently, and as a result such reduction opportunities are missed. This work presents a transportation micro-simulation tool that resolves emissions at the link level and efficiently models the effects of traffic congestion, traffic shifting, and mode shifting. This tool can be used for iterative design studies using conventional computing hardware. The model is described in detail, and a confidence assessment tests the model credibility. Several application studies illustrate the usefulness of the approach, and a comparison to an interaction-based micro-simulation demonstrates the efficiency and limitations of the approach.

Acknowledgements

There are many people who have supported and encouraged me throughout this journey. First and foremost, I would like to thank Professor David Checkel and Professor Jason Olfert for their guidance and support. I would not have been able to complete this undertaking, nor would I have gained as much, without their mentorship and kindness. I would also like to thank the other members of the committee - Dr. Fraser, Dr. Lipsett, Dr. Qiu, Dr. Kostiuk, Dr. Kumar, and Dr. Lange - for their insight and feedback.

Many, many thanks to my family - especially my beautiful wife Nicole, who endured the late nights and long hours and encouraged me when I most needed it.

To all of the friends I have made along the way - Mark, Ali, Masoud, Jason, Darren, Mike, Dallin, Tyler, and the many others that I cannot hope to list - thank you for enriching the graduate student life and helping to make it fruitful and enjoyable.

I also thank all of the staff in Mechanical Engineering, who are outstanding; the knowledge gained from working with Bernie Faulkner and Rick Conrad in particular is invaluable.

Table of Contents

List of Tables

LIST OF FIGURES

LIST OF NOMENCLATURE

List of Acronyms

AESO	Alberta Electric System Operator
AQHI	Air Quality Health Index
AQI	Air Quality Index
CARB	California Air Resources Board
CO	Carbon Monoxide
CO_2	Carbon Dioxide
FTP	Federal Test Procedure
GHG	Green House Gas
GPS	Global Positioning System
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
NMHC	Non-Methane Hydrocarbon

LIST OF NOMENCLATURE

NMOG	Non-Methane Organic Gases
NO_x	Oxides of Nitrogen
NRCan	Natural Resources Canada
O_3	Ozone
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter less than 2.5 μm in aerodynamic diameter
TDM	Travel Demand Model
US EPA	United States Environmental Protection Agency
VKT	Vehicle Kilometers Travelled

List of Symbols

$P_{tractive}$	Tractive power [kW]
$F_{tractive}$	Tractive force [kN]
v	Vehicle speed [m/s]
M	Vehicle Mass [kg]
R	Rolling force [kN]
D	Drag force [kN]
r_0	First coefficient of rolling resistance
r_1	Second coefficient of rolling resistance
C_R	Coefficient of rolling resistance
C_D	Coefficient of drag
A	Frontal area [m^2]
ρ	Air density
S	Slope resistance
g	Acceleration due to gravity [m/s^2]
θ	Slope [radians]
$\dot{m}$	Mass flow rate [g/s]
M_X	Molar mass of species X [g/mol]

Chapter 1

Introduction

Transportation emissions form a significant portion of overall air quality inventories. Infrastructure can be designed to reduce transportation emissions if they can be quantified. A simplified transportation micro-simulation is proposed that will enable micro-simulation fuel and emissions modelling of whole transportation networks.

1.1 Air Quality and Transportation Emissions

The health costs associated with air quality in Canada are estimated at billions of dollars per year, in addition to the less tangible social costs borne by Canadians [1]. As a result of air quality concerns, particularly in urban areas, Canadian health agencies have revised the air quality reporting system and created a new metric for air quality: the Air Quality Health Index (AQHI), which replaces the Air Quality Index (AQI). The AQHI system is defined numerically on a scale of 1-10+, and qualitatively in four ratings. The first rating corresponds to scale numbers 1-3, and represents a “Low Health Risk”. The second rating corresponds to scale numbers 4-6, and indicates a “Moderate Health Risk”; the third rating corresponds to scale numbers 7-10 and represents a ”High Health Risk”. Scale numbers greater than 10 correspond to a “Very High Health Risk”. The AQHI scale number is calculated based on the concentration of three outdoor air contaminants: ozone, particulate matter less than 2.5 microns in diameter, and nitrogen dioxide. Equation 1.1 is used to calculate the scale number as follows, with ozone (O_3) and nitrogen dioxide (NO_2) in units of parts per billion (ppb) and $PM_{2.5}$ in units of $\mu g/m^3$ [2, 3].

$$AQHI = \frac{10}{10.4} \cdot 100 \cdot [(e^{0.000871 \cdot NO_2} - 1) + (e^{0.000537 \cdot O_3} - 1) + (e^{0.000487 \cdot PM_{2.5}} - 1)] \quad (1.1)$$

Both particulate matter and oxides of nitrogen are products of combustion processes. Ozone occurs in the troposphere when it is produced through the reactions of its precursors, and when it is transported downwards from the upper atmosphere where it occurs naturally. The precursors to the production of ozone, hydrocarbons and oxides of nitrogen, are both products of combustion. All three contributors to the AQHI are direct or indirect products of combustion, and are emitted by the vast majority of transportation sources powered by combustion engines.

While there are many sources of combustion products, transportation accounts for an estimated 15% of the oxides of nitrogen and 16% of the particulate matter released in Alberta respectively, and is the third largest contributing source in both cases [4]. Given the significant contributions of transportation emissions to air pollution, reducing transportation emissions is a logical avenue to pursue in the overall effort to improve outdoor air quality.

1.2 Quantifying Transportation Emissions

There are several ways that transportation emissions can be reduced: through technological advances to vehicles and engines, by reducing their use, and by using them more efficiently. While progress is certainly being made in all three ways, it is important to be able to quantify that progress and identify further improvement opportunities.

Transportation infrastructure is important because it has a significant influence on how efficient transportation is, and because its capital cost and longevity project its impacts far into the future. Designing infrastructure to reduce emissions requires the ability to measure or model the effects of potential designs. Modelling emissions rather than measuring them has several advantages: it allows infrastructure designers to consider the effects of designs that are not yet built, and it is generally faster and less costly.

1.3 Proposed Simplified Transportation Micro-Simulation Tool

This dissertation presents the development and applications of a simplified micro-simulation and transportation emissions modelling tool. Four-step transportation demand modelling results are used to describe the network and traffic, capturing both traffic shifting and mode shifting effects. The simplified micro-simulation models the effect of driving behaviour using an efficient approach that remains practical for large regions. Large models are simulated quickly, allowing for analysis of multiple design concepts and design iterations. The result is an emissions tool that responds to driving behaviour, traffic and mode shifting, and can be used to analyze large traffic models such as metropolitan regions. AQHI modellers could use the NO_x, PM, and hydrocarbon estimates produced by the tool as inputs to ozone production models and AQHI estimates. This is especially useful since the transportation emissions tool is localized and time-sensitive, which is important for estimating ozone production.

1.4 Dissertation Contents

The following chapter describes the state of the art in transportation emission modelling. Chapter 3 presents and details the model proposed here and describes the simplified micro-simulation, while chapter 4 presents a confidence assessment of the tool. Policy, infrastructure design, and traffic control applications are shown in chapter 5. Conclusions regarding the model are drawn in chapter 6.

Chapter 2

Transportation Emission Models Review

This chapter introduces the classification of emissions models used in this dissertation and discusses the characteristics of current transportation emission models and methodologies. The need for an emissions micro-simulation tool that captures the effects of traffic congestion and can be practically used to model large regions is identified through this review of current literature. Partial content of this chapter was published in 2011 [5].

The intent of this thesis project is to develop a tool that can predict emissions for projects that are in the planning and design stages. This requires a modelling approach. Hence, this review of literature is limited in scope to transportation emissions modelling efforts. It is presented in two main categories: Vehicle Kilometers Travelled (VKT) models, and micro-simulation models. An additional section of relevant applications of transportation emissions models describes current uses of transportation emission models.

Throughout this chapter and dissertation, models will be described as either micro-simulations or macro-simulations. Micro-simulations are models which operate at the level of individual units; in the case of transportation emission models, they operate at the vehicular level. Macro-simulations are models that operate at any level of aggregation that precludes them from being micro-simulations.

2.1 VKT Models

Transportation emissions macro-simulations are often referred to as VKT models (for Vehicle Kilometres Travelled). In its simplest form, a VKT model is the multiplication of some distance travelled (the VKT) and an emission factor. The result of this multiplication is an inventory, or an amount of pollutant that is emitted. VKT models thus respond to changes in two variables: the distance travelled and the emission factor. In practice, the distance travelled is fixed by transportation demand, and any sophistication built into a VKT model is built in through the emission factor. Generally, VKT models use emission factors that depend on few variables. Average speed is often a variable, and sometimes traffic situation or facility type is used as a modal variable [6]. VKT models are well-suited to large geographic scales and are often regional or national in scope, because their runtime depends on the complexity of their emission factor calculation and not the number of vehicles or roads.

The aggregation of traffic behaviour within a given region must be valid for a VKT model to be valid in that region. The traffic behaviour must also be similar to the traffic behaviour that the emission factors are intended to model.

VKT models use aggregate fleet and traffic characteristics to generate emission factors, typically for each vehicle class. The total emissions for a vehicle or fleet can then be calculated as the product of the emission factors and the corresponding vehicle-kilometres travelled (VKT). The emission factors are typically based on experimental datasets, and are intrinsically calibrated to the conditions under which the datasets were recorded. For example, the US EPA uses emission measurements recorded over the Federal Test Procedure (FTP) driving cycle to calculate emission factors for its MOBILE VKT models. The driving cycle has an effect on the emissions, thus VKT models that are based on data for a given driving cycle are intrinsically calibrated to that driving cycle. In general, the assumption made by VKT models is that the driving behaviour of the test cycle will be representative of the region of study if it is sufficiently large and is aggregated. However, driving behaviour that is not well-represented by the driving cycle is called “off-cycle” and must be dealt with carefully.

VKT models often use correction factors to account for off-cycle traffic behaviour. These differences in behaviour include the mean traffic speed, the aggressiveness or acceleration rates, and the congestion level or type of facility. Differing traffic patterns are not accurately modelled, and VKT models are generally considered inappropriate for studies in which the traffic differs significantly from that of the model datasets. On-road vehicle emissions are dependent on more than average traffic speed [7, 8] and correction factors are generally not sufficient to capture their dynamic nature.

Four widely used VKT models are the US EPA’s MOBILE and MOVES models, the California Air Resources Boards EMFAC model, and the European COPERT model. MOBILE6.2 is the last version of the US EPAs series of MOBILE models. It replaces and improves upon MOBILE5. MOBILE5 used the average speed to calculate emission factors; this is inherently flawed. For example, traffic flowing at an average of 40 km/hr on a low-speed arterial is likely much less congested than traffic on a high-speed freeway that is flowing at the same 40 km/hr average speed. The main improvement in MOBILE6.2 is the introduction of facility classifications, which are intended to allow it to model the effects of congestion. MOBILE6.2 uses facility classifications and average speeds to model the effects of traffic congestion.

MOBILE6.2 is known to overestimate CO emissions [9], and to be less sensitive to average traffic speeds (and the associated congestion level) than more detailed simulations suggest [6]. MOBILE6.2 is approved for the State Implementation Plans (SIPs) and is commonly used for conformity studies in the United States; however, it is being succeeded by the US EPA’s MOVES models.

MOVES2010A is the latest version of the US EPAs MOtor Vehicle Emissions

Simulator (MOVES). It replaces MOBILE6.2 and NONROAD, and is approved for conformity studies in the United States (excluding California). Strictly speaking, MOVES is a power-based modal regression model. It is based on a binning approach, such that the traffic behaviour on a link, corridor, or network is binned, and the resultant emission model is aggregated at the level of choice of the user. MOVES is thus appropriate for much smaller regions than typical VKT models; in fact, it can be useful for facility-level studies if used in project mode with appropriately detailed inputs.

MOVES can also be used to post-process micro-simulation results [10], however, this is generally not practical for regional-scale simulations as the storage and post-processing requirements for micro-simulation data for even a small region tends to be prohibitive. MOVES has been found to be computationally intensive when used to estimate emissions for transportation micro-simulation output [11]. MOVES does have the capability to work with micro-simulation generated data, however, because it cannot generate micro-simulation, it is not by itself a traffic emission micro-simulation.

MOVES is designed to expand upon the spatial and temporal capabilities of MOBILE6.2. While MOBILE6.2 is best suited to regional simulations over long periods of time (typically 24 hours), MOVES is capable of simulating temporal scales from seconds to hours, and individual vehicles as well as fleets. Emission rates are calculated using a binning approach based on vehicle specific power (VSP) and speed [12]. MOVES is expected to be more sensitive to average speed and congestion than MOBILE6.2 [13]. MOVES2010A includes a well-to-tank analysis [10], which is an important contribution to the overall greenhouse gas (GHG) contribution of a vehicle inventory.

Lin et al. [14] integrated the US EPA's MOVES model with DynusT, a dynamic traffic assignment model, to compare the use of MOVES default drive schedules with the more detailed operating mode distribution data provided by DynusT. The authors found that MOVES underestimated emissions in congested conditions, particularly for heavy duty vehicles. In fact, MOVES did not provide emissions estimates for links on which heavy duty vehicles (HDVs) averaged less than 5 mph (8 km/hr) or on which light duty vehicles (LDVs) average less than 2.5 mph (4 km/hr). It was concluded that in highly congested situations, more detailed traffic data should be used in place of the MOVES drive cycles.

The California Air Resources Board (CARB) created the EMFAC models for on-road emissions inventory [15]. It is used in lieu of MOBILE6 for conformity purposes in California. EMFAC2007 is a VKT model, and makes use of speed correction factors to account for off-cycle driving behaviour. The unified cycle (UC) driving cycle is used as the basis for the EMFAC2007 database, with unified correction cycles (UCC) used to correct emission rates for off-cycle driving behaviour [16].

Fujita et al. [17] compared the MOVES2010a, MOBILE6.2, and EMFAC2007 models with traffic tunnel measurements. They found that evaporative emissions were underestimated by all three models in hot conditions, as was the NMHC/NOx ratio that is a key factor in smog production. They also found that MOVES was highly sensitive to operating modes, and emphasize the importance of selecting appropriate operating modes for project-level analysis in MOVES. This is not surprising, as the primary criticism of macro-scale models such as these is that they are reliable only if the driving cycle data on which the model estimates are based is representative of the real-world driving behaviour they attempt to model.

The COPERT series of models are developed for use in Europe. Hot running, cold start, and evaporative emission factors are estimated [18]. COPERT emission factors are based data collected over standardized driving cycles. Like MOBILE6.2 and EMFAC, COPERT implicitly takes congestion into account, but it would require an improved congestion handling algorithm to be applicable to project-level emission predictions [6]. The aggregated network characteristics used by VKT models can work well for large regions, but are not well suited to micro-simulation [16, 19, 6, 20]. In a micro-simulation environment, the importance of vehicle activity on the emissions should be considered [21]. In essence, VKT models should only be used for studies in which the aggregation of traffic behaviour is sensible.

ARTEMIS is a modal VKT model, developed by 50 participants in 17 European countries to characterize the emission characteristics of European vehicles and traffic [22, 23]. It uses several hundred traffic situations (modes) that are a function of the facility type, congestion, and speed limit. These modes are intended to capture the effects of traffic conditions on vehicle emissions and are an improvement on aggregated traffic condition models; however, congestion is not modelled directly.

The Mobile Emissions Assessment System for Urban and Regional Evaluation (MEASURE) is a modal VKT model that estimates CO, HC, and NOx for on-road vehicles [24]. It expanded upon the explanatory power of MOBILE5a by introducing vehicle category and condition information. It captures off-cycle emissions in greater detail than MOBILE5a. MOBILE6.2 deals with congestion at a more detailed level, however, the handling and description of vehicle technology and condition in MEASURE is more expansive and is explicit.

A modal VKT model was developed by Matzoros and Van Vliet [25, 26] which uses constant emission factors for each mode of vehicle behaviour (cruise, deceleration, queuing, and acceleration). The model is based on the “shock wave” theory of traffic flow and focused on accounting for the spatial variability of emissions resulting from queuing. Emissions on links are allocated to the beginning and end of links where the effects of acceleration, deceleration, and queuing are most significant.

Zegeye et al. [27] integrated the METANET macroscopic traffic flow model with the microscopic emission and fuel consumption model VT-Micro to study model based traffic control strategies. This implementation uses a macroscopic traffic model to generate speed estimates for each link segment in the network. Acceleration is not modelled by METANET and Zegeye et al. derived an estimator to provide acceleration to VT-Micro. The METANET model is generally used for motorways with discretized link segments of 500 metres [28]. This approach is limited by the constraint that each link segment must be of sufficient capacity and flow that the speed and acceleration change in a limited and linear fashion on every segment. Hence, it is most suitable for motorways and would be difficult to implement in a metropolitan core.

GHGenius is a life-cycle inventory of greenhouse gases developed for Natural Resources Canada [29]. It includes both well-to-tank and vehicle life cycle VKT-based estimates for a comprehensive set of greenhouse gases, vehicle types, and fuels [30]. Criteria pollutants are not modelled by GHGenius. The life cycle emissions estimate aggregates traffic behaviour over the life of the vehicle; it is not clear how congestion or other traffic parameters are accounted for. For this reason, GHGenius emission estimates should really only be applied to the life cycle of a vehicle.

The United States Department of Energy developed the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) models [31], which are a set life-cycle inventory tools for greenhouse gases. GREET creates VKT-based estimates for a set of greenhouse gases, vehicle types, and fuels [30]. Like GHGenius life cycle emission factors, those calculated by GREET should only be applied to a vehicle's entire life cycle.

Delucchi's life-cycle emissions model (LEM) is a life-cycle inventory tool for a comprehensive set of greenhouse gases, vehicle types, and fuels [30, 32]. LEM includes both well-to-tank and vehicle life-cycle greenhouse gas emission rates, and should only be applied as life cycle emission factors.

Mandavilli et al. [33] used the aaSidra 2.0 micro-analytical transportation model to investigate the environmental impact of modern roundabouts. The aaSidra model, which has been further developed into Sidra Intersection 6, [34] uses a modal representation of vehicle drive cycles to estimate emissions. The relevance of this methodology to the problem at hand depends on the similarity between the drive cycle used and the real driving behaviour of the vehicles that are being modelled. This is therefore not a micro-simulation, and the driving cycle should be calibrated to each system that is modelled.

2.2 Micro-simulations

Micro-simulations provide more detail and are useful for transportation infrastructure design. They are typically used to analyze corridors, intersections, or small sections of infrastructure. However, micro-simulations generally require significant computational resources, and modelling large regions is not practical for day-to-day design studies. This also makes it difficult to resolve the effects of infrastructure design options on the larger networks that they are a part of. Traffic often shifts between routes and even modes (i.e. from personal vehicles to public transit) when infrastructure changes are implemented, which can have a far-reaching impact on the transportation network as a whole. Micro-simulations limited in scope by their computational demands may not be able to model a large enough area to capture the effects of route shifting, and generally do not account for mode shifting.

Vehicle speed and acceleration must be modelled in sufficiently small time steps throughout a micro-simulation; generally a second-by-second time base is used. However, smaller time steps may be required of transportation micro-simulations to produce acceleration data that is realistic enough to be used for emissions estimates [35]. At the geographic level, each facility in a transportation micro-simulation must have its own vehicle speed and acceleration profile. Typical interaction-based micro-simulations create a unique speed and acceleration profile for each vehicle in the simulation, and use a great deal of computational resources doing so. Micro-simulations are appropriate for any scale because they model traffic behaviour explicitly. They are the most detailed, and often the most reliable solution for the analysis of alternative operational projects because they are able to capture the effects of instantaneous speed and acceleration levels [36].

Typical interaction-based micro-simulations can be used in two ways to model on-road emissions. For simulations of small spatial and temporal scales, the individual vehicle speed traces can be stored, and emissions traces can be created in post-processing and stored or aggregated. For longer or larger simulations, the storage requirements of this method are impractical, and the emissions are more effectively calculated in parallel with the micro-simulation and aggregated at runtime rather than in post-processing. These results are stored in an aggregated format for practicality.

Xie et al. [37] integrated the PARAMICS micro-simulation with the MOVES inventory method. Their case study of a section of freeway demonstrated that fleet emission rates respond in a linear fashion to changes in the market shares of alternative fuel vehicles. This method involves simulating the traffic in PARAMICS to generate second-by-second speed traces, and then loading them into a MOVES run specification, which can take considerable computational time. It is posited that lookup tables generated by MOVES could be used directly by PARAMICS to speed the process considerably.

Pelkmans et al. [38] developed Vehicle Transient Emission Simulation Software (VeTESS), a highly detailed micro-simulation tool to calculate fuel consumption and emissions of individual vehicles. While it can be applied to multiple vehicles, the authors found that the model parameters depend strongly on the model of vehicle in question, and recommended that the model should be calibrated to each vehicle using an engine dynamometer. They further recommended for large fleets, especially when microscopic traffic data is unavailable, that more aggregated models should be used to estimate emissions and fuel consumption.

AIMSUN is a traffic modelling tool which includes micro-simulation, among other types of simulation. It includes an emissions calculator which Smit et al. [39] note must be calibrated to the vehicle fleet that is being modelled, or substantial differences in emissions can result.

Hirschmann et al. [40] integrated the traffic micro-simulation VISSIM with the emission micro-simulation PHEM. The model was used to investigate a traffic network in Graz, Austria. The study noted that microscopic methods are required to analyze traffic related emissions and fuel consumption in urban areas. Kraschl-Hirschmann et al. [41] used the same method towards a further calibration study; a city highway was observed with GPS-instrumented test vehicles to calibrate the VISSIM model. The results of the test drives and of the VISSIM model of the observed network were then post-processed and analyzed with the PHEM emissions models. Additionally, power-based emission and fuel consumption functions were created based on PHEM calibration results and applied to the VISSIM model results. The three methods (test data + PHEM, VISSIM + PHEM, and VISSIM + functions) showed good correlation. The authors state that engine-map based instantaneous emission calculations are computationally intensive and limit the number of traffic control scenarios as motivation for simplifying the emission calculation.

Song et al. [42] studied the applicability of micro-simulation models to vehicle emissions estimates and found that vehicle specific power (VSP), a popular variable for instantaneous vehicle emission models, is indeed a reliable indicator of emissions. However, they found that VISSIM-simulated VSP distributions were considerably different than real-world VSP distributions and concluded that it could not represent real-world vehicle dynamics. This is an important result; micro-simulations should not be automatically accepted as appropriate for instantaneous emissions calculations simply because of their level of detail. The vehicle dynamics produced by any micro-simulation need to be validated against real-world data to ensure that emissions estimates are reliable.

Hatzopoulou and Miller [43] linked TASHA, an activity-based travel demand model with MOBILE6.2C, the Canadian version of the US EPA's MOBILE6 model. To extend this effort to micro-simulation, Hao et al. [44] integrated the TASHA activity micro-simulation with the MATSim transportation micro-simulation and MOBILE6.2C-derived emission factor look-up tables. The authors reported that the model was sensitive to congestion, which is an improvement on the conventional VKT-based approach typically used with MOBILE6.C. However, the use of an average-speed based emissions model inherently assumes that the driving behaviour of the system is similar to the drive cycle on which MOBILE6.2C is based.

Researchers at the University of California Riverside developed the Comprehensive Modal Emissions Model (CMEM), which is a physical power-demand modal emissions micro-simulation [16]. CMEM calculates light-duty car and light-duty truck second-by-second emission rates based on the vehicle mode (cruise, acceleration, idle, etc.) and tractive power demand. While CMEM is comprehensive in terms of light-duty vehicle types, operations (cold start, warm start, off-cycle driving, etc.), and technologies [45], it does not model transit vehicles, and does not calculate particulate matter emissions [8].

CMEM has been paired the traffic micro-simulator VISSIM, with the intent of optimizing signal timing to reduce fuel consumption [46]. This type of analysis was reported to be impractical for widespread signal timing optimization due to the lengthy computation time required.

The POLY emissions model has been used in parallel with the KTH-TPMA traffic micro-simulation [19, 47]. POLY was developed by researchers at the Polytechnic University of New York and Texas Southern University [48]. It is a regression model that estimates emissions for light-duty cars and trucks based on speed, acceleration, grade, and vehicle class.

The VERSIT model was developed by Smit et al., [6, 49, 50]. It is intended to model hot running emissions of light-duty traffic at a variety of spatial scales. VERSIT is designed to be sensitive to vehicle dynamics and to capture the effects of emission control technologies. It is most reliable when driving patterns are recorded in the region of interest and supplied to the model as input [49]. Traffic patterns generated through micro-simulation can also be used, however, the quality of these micro-simulation based models must be considered as they can produce excessive acceleration rates and unnatural speed fluctuations during constant speed driving [49].

Researchers at the Virginia Tech Transportation Institute developed the VT-Micro model. VT-Micro is a non-linear regression model based on dynamometer data from the Oak Ridge National Laboratory [51]. It was implemented in the INTEGRATION software and calculates emission rates based on instantaneous speed and acceleration levels for light duty cars and light duty trucks. VT-Micro does not model road grade directly, however, the instantaneous acceleration rate can be adjusted to account for it [52]. VT-Micro models fuel consumption, NO, HC, CO, and CO_2 [36], but does not calculate particulate matter emissions [31].

TRANSIMS is an open-source traffic simulation suite which includes an emissions module that is based on the CMEM model [53]. While it does interact with a true micro-simulation, the emissions module is not sensitive to technology or policy changes [54]. It is a useful tool for verifying the relative emissions of two network options; however, it is not appropriate for forecasting and conformity purposes. CO, NO, non-methane organic gases (NMOG), and fuel consumption are modelled; particulate matter and CO_2 among other pollutants of interest are not.

Busawon and Checkel [55, 56] presented an emissions micro-simulation that creates traffic motion models based on travel demand modelling. It uses link parameters including maximum allowable speed, volume delay function, link length and grade, as well as the average speed, number of vehicles, and cold start fraction for each vehicle class. A driving pattern which satisfies the link parameters is created, and power-based fuel consumption and emission rates are calculated on a second-by-second basis. The emission rates are functions of vehicle power, speed, and acceleration, and are based on dynamometer data. They are calibrated against the MOBILE6 emission rates to produce an inventory in line with North American fleet characteristics.

Table 2.1 summarizes the current models discussed and their characteristics.

2.3 Relevant Applications and Studies of Transportation Emission Modelling

Smit et al. [57] point out that validation efforts for transportation emission models should be increased, and recommends the development of clear guidelines with respect to model accuracy. They also emphasize the importance of uncertainty analysis for emissions predictions.

Papson et al. [58] used MOVES2010 to analyze emissions at congested and uncongested intersections, and found that emissions were more sensitive to control delay than to congestion. Roundabouts were found to produce lower emissions than signalized intersections because vehicles may yield rather than stop completely, and therefore accelerate less to return to the free speed.

Panis et al. [59] studied the environmental impacts of speed reduction on urban streets with both a macro-simulation (COPERT/MEET) and a micro-simulation (VeTESS). The macro-simulation predicted a moderate increase in particulate matter, while the micro-simulation predicted a substantial decrease. The authors conclude that policy makers should not rely exclusively on macro-simulations for decisions related to speed management policies.

Madireddy et al. [60] used the PARAMICS micro-simulation with the VERSIT+ emissions model of Smit et al. [49] to assess the impact of speed limit reduction

Model	Type	Criteria Assessed	Sources
MOVES2010A	Modal, VSP-based Regression	Fuel Consumption, GHG, CO, NO_x, SO_x, HC, PM, air toxics	Hot and cold running, evaporative, brake and tire, well to tank
MOBILE6.2	VKT	Consumption, GHG, CO, NO_x, SO_x, HC, PM, air toxics	Hot and cold running, evaporative, brake and tire
EMFAC2007	VKT	Fuel Consumption, GHG, CO, NO_x, SO_x, HC, Lead, PM, air toxics	Hot and cold running, evaporative
COPERT	VKT	Fuel Consumption, GHG, CO, NO_x, SO_x, HC, Lead, PM, air toxics	Hot and cold running, evaporative
GHGenius	VKT	GHG components, CO, NO_x, SO_x PM, HC	Life cycle, aggregated over vehicle service life
GREET	VKT	GHG components, CO, NO_x, SO_x PM, HC	Life cycle, aggregated over vehicle service life
LEM	VKT	GHG components, CO, NO_x, SO_x PM, HC	Life cycle, aggregated over vehicle service life
ARTEMIS	Modal,VKT	Fuel Consumption, GHG, CO, NO_x, SO_x, HC, PM, air toxics	Hot and cold running, evaporative
MEASURE	VKT	CO, NO_x, HC	Hot running
Matzoros/Van Vliet	Modal, VKT	CO, NO_x, HC, Lead	Hot running
CMEM	Micro-sim, Modal Regression	Fuel consumption, CO, NO_x, HC	Hot and cold running
POLY	Micro-sim, Regression	CO, NO_x, HC	Hot running
VERSIT+LD	Micro-sim, Regression	Fuel consumption, CO, NO_x, HC, PM	Hot and cold running
VT-MICRO	Micro-sim, Regression	Fuel consumption, CO, NO_x, HC, CO_2	Hot and cold running
TRANSIMS	Micro-sim	Fuel consumption, CO, NO_x, NMOG	Hot running
CALMOB6	TDM-based Micro-sim	Fuel consumption, CO, NO_x, HC, PM	Hot and cold running

Table 2.1: Summary of current transportation emission models

and traffic signal coordination on vehicle emissions. The study demonstrated that in a small area (roughly 0.5 square kilometres) of Antwerp, Belgium, CO_2 and NO_x emissions could be reduced by reducing the speed limit and a using a green wave signal coordination scheme. The simulation time for this study was set at one hour; this was a relatively small area and time period.

Ahn et al. [61], investigated the environmental impacts of high-speed roundabouts using two micro-simulation models (INTEGRATION and VISSIM), and two emissions models (VT-Micro and CMEM).

Smit et al. [39] published a technical note describing the need for emissions models to be calibrated to the fleet that is being modelled. This was particularly important for their study of Australian vehicles, which differed from the vehicles on which the AIMSUN micro-simulation's emission model is based. The differences can be substantial; in their case, NO_x was underestimated by a factor of 20, HC by a factor of 1.5, and CO_2 by a factor of 4 on freeways and by a factor of 1.3 on non-freeways.

Jackson et al. [62] performed a study to determine whether Vehicle Specific Power (VSP) was a good explanatory variable for traffic emissions, and how lead-driving behaviour is influenced by road grade and curvature. They emphasize the importance of road grade and drivers' response to road grade as important factors in traffic micro-simulations, particularly for lead vehicles in interaction-based models. They also emphasize the importance of accurate road grade and acceleration data which have a strong influence on VSP and thus emissions and fuel consumption estimates.

Zegeye et al. [27] used a model-based predictive traffic control approach to study emissions reductions. The model consisted of a microscopic traffic simulation model paired with the COPERT III traffic emissions macro-simulation. The approach demonstrated that reducing total time spent on the traffic network (which is generally the priority of transportation planners) does not necessarily reduce emissions. However, their model predictive control strategy reduced emissions and average travel time. In 2009, they presented a similar study that used the VT-Micro traffic emissions micro-simulation [63] and were again able to balance the reduction of emissions and fuel consumption, and travel time spent on the network.

Wang et al. [64] presented a method of estimating acceleration, fuel consumption, and emissions from macroscopic traffic flow data. Vehicle trajectories are reconstructed based on dual-loop detector data using an innovative filtering technique. This method thus requires extensive empirical data and analysis. While the ability to reduce congestion was demonstrated, the acceleration profile predicted by the method was smoothed and would be sharper in reality, and they noted that such methods should be carefully designed if they are to be used to reduce emissions and fuel consumption.

2.4 Review Synthesis

This review focused on transportation emissions modelling efforts. The two major model categories discussed are VKT (for Vehicle Kilometers Travelled) models and micro-simulation. Relevant applications of current transportation emissions models are also discussed.

VKT models are well-suited to large geographic areas but are limited in their sophistication and detail. Emission factors can be adjusted for variables such as average speed or facility. The aggregation of traffic behaviour within a region of study must be valid for the VKT model to be valid, and the traffic behaviour must be similar to that of the underlying emission factors. Ultimately VKT models are typically not suitable for project-level analyses.

Micro-simulations are more detailed and are generally used for analyses of smaller scale. For a given region, they generally require greater computational effort than VKT models. In fact, the scope of the analysis is often limited in part by the computational resources available. The time steps of micro-simulations which model vehicle interactions must be small enough to produce realistic acceleration behaviour. Achtymichuk [35] suggested that 0.2 second time steps were the largest that could be used with VISSIM to produce vehicle speed records that were acceptable for tractive power and emissions calculations. There are numerous micro-simulations available, and some emissions models that either interact with them or can make use of their results. However, they are limited in scope by their computational and calibration requirements. Additionally, they generally do not account for the effects of traffic shifting and mode shifting even if they are large in scope. The vehicle dynamic behaviour of micro-simulations should be validated for use with emissions models. Studies have shown that while power is a reliable indicator of emissions, micro-simulations do not necessarily produce reliable power distributions.

Ideally, transportation emissions should be modelled over large regions. Models should respond to travel demand and account for traffic shifting and mode shifting.. It would also be useful for the models to respond to congestion, so that it would be resolved at a link-level and could be used for project-scale analyses. One way to do this is to use travel demand model results to define the transportation network and link-by-link traffic, and micro-simulate this traffic on each link.

CHAPTER 3

MODEL DESCRIPTION

This chapter describes the structure of the simplified transportation micro-simulation tool and details the calibration, micro-simulation, and emissions modelling modules. The classification and unique features of the tool are also discussed.

The goal of the simplified transportation micro-simulation tool is to provide a large-scale, physics-based emissions model. The tool should efficiently simulate large transportation networks, and use micro-simulation to respond to road grade, driving behaviour, and traffic congestion. Four-step models, such as the travel demand modelling tool EMME, produce results that describe traffic on large scale networks. These results are formatted for use in the design tool. Vehicle trajectories are micro-simulated on each link and used to calculate instantaneous power, fuel consumption, and emission rates. These criteria are then integrated over each trajectory to produce a link-by-link inventory. The results are stored for each link, and in a summary for the entire network and any defined sub-areas. Cold start, evaporative, crankcase, and refuelling emissions are modelled in addition to the running fuel consumption and emissions. Alternative fuels and hybrid technologies can be modelled, including emissions that result from use of electrical grid power. Additionally, a post-processor based on the work of Achtymichuk [65] can be used to generate KML files to display simulated results in Google Earth.

3.1 Model Structure

The simplified transportation micro-simulation tool consists of five modules. The user interface is used to define how the simulation should run, and initiate the simulation. The simplified micro-simulation module uses link-average traffic network parameters (average speed, average vehicle flow, etc.) to generate quasi-realistic vehicle trajectories. The fuel consumption and emissions module uses a physics-based instantaneous tractive power analysis for each vehicle trajectory, and then uses a power-based model to estimate fuel consumption and emissions. The calibration module uses the MOBILE6.2 database to generate and apply calibration factors for the vehicle fleet that is being modelled. The inventory module writes files for the link results, simulation parameters, and inventory summaries.

The model flow chart in figure 3.1 shows the module interactions for a typical micro-simulation of traffic emissions of a transportation demand model. Alternatively, the tool can analyze vehicle speed traces that might be produced by a third-party micro-simulation (such as VISSIM) or by an experimental study of vehicles in traffic.

The following sections of this chapter describe each module of the simplified transportation micro-simulation tool in detail.

3.2 User Interface

The transportation emissions tool uses a series of graphical user interface windows to define the simulation parameters and report its progress. The following sequence of windows prompts users to provide information for the simulation:

- an introduction window briefly describes the program
- a region window allows users to select their geographic location (i.e. Edmonton, or Calgary, etc.)

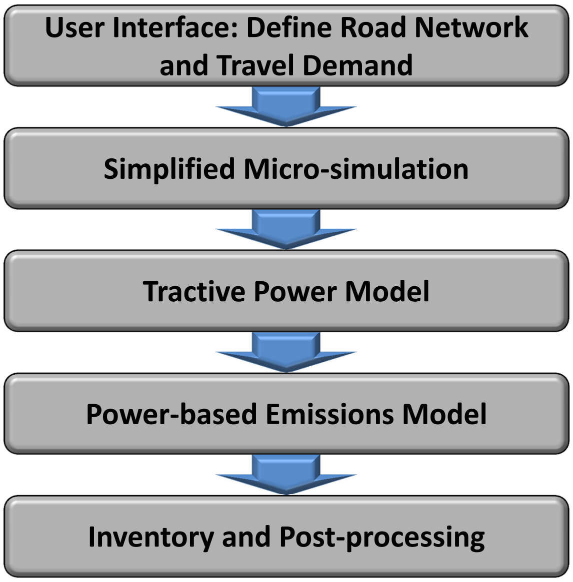


Figure 3.1: Model structure for simulation of four-step model results

Input Parameter (from TDM, i.e. EMME)	Parameter is used for...
Link location	Post processing
Link length	Simplified MS, inventory
Link free speed	Simplified MS
Link slope	Tractive power analysis
Vehicle volumes	Simplified MS, inventory
Average speeds	Simplified MS
Cold starts	Calibration, fuel and emissions, inventory

Table 3.1: TDM-based inputs for simplified micro-simulation

- a classification window to specify custom link types and fleet divisions (discussed in section 3.5)
- a main window to enter the simulation period, ambient temperature and atmospheric pressure, vehicle fleet composition, cold start and evaporative emissions parameters, and input files derived from transportation demand models, micro-simulations, driving cycles, or experimental data.

There are additional windows that can be accessed from the main window to view and modify the simulation definition parameters. The graphical user interface is described in more detail in Appendix A. A user guide also includes sample simulation runs that demonstrate the user interface [66].

3.3 Simplified Emissions Micro-simulation

The simplified emissions micro-simulation module uses link-level transportation simulation results, such as those produced by a four-step model like EMME, to simulate vehicle trajectories for each class of vehicle on each link. The input parameters are shown in table 3.1.

The average speed and cold start fraction for each class of vehicle as well as the link parameters (location, length, free speed, and grade are among the required inputs.

Given these inputs, the simplified micro-simulation creates a vehicle trajectory for each vehicle class. The algorithm attempts to conserve the link behaviour defined by the input and is representative of real driving behaviour. The simulation algorithm is designed to the following priorities:

1. Each vehicle trajectory must complete a distance that is equal to the link length so that all network travel is fulfilled.

2. Vehicle trajectories begin and end at the input-defined free speed for continuity, except in zones. Half of the vehicles in zones begin from a stop and the other half end at a stop. On congested links, the free speed may be reduced by the micro-simulation.

3. Each time a vehicle comes to a complete stop, it may idle for a period of time. The idle period is limited to a maximum of 30 seconds. If more delay is required to match the input-defined average speed additional stops or a reduction of the free speed are used.

4. The average speed of the vehicle trajectory is equal to the input-defined average speed on the link, unless the average speed must be reduced so that the trajectory is within the limitations of the vehicle powertrain.

The first priority ensures that the trips simulated by a four-step model are all completed, by ensuring that the required distance is travelled. The second priority ensures that trips begin from a stop and ends at a stop, and that vehicle trajectories transition from link to link in a continuous manner. The third priority ensures that vehicles that stop will idle for a reasonable period of time, such as one would at a stop light. The fourth priority ensures that, whenever possible, the average speed of the vehicle trajectories matches the input-defined link average speed. This requires that the four-step model results do not specify traffic movements that are outside of the limitations of the vehicles that follow them. An example is a steep uphill link; if the four-step model allows heavy-duty trucks to travel this link they could be limited in their top speed and acceleration on the link. The simplified micro-simulation will reduce their free speed, and if necessary average speed, to complete the link distance within the limitations of their powertrain. A flow chart of the simplified micro-simulation algorithm is shown in Figure 3.2 with sample vehicle trajectories for increasing levels of congestion. Appendix B shows a more detailed series of vehicle trajectories for increasing levels of congestion.

3.3.1 Acceleration Profiles

The simplified micro-simulation uses a combination of cruise (steady travel at the free speed), one or more stops or a partial stop, and idling to generate vehicle trajectories that satisfy the distance and average speed specified by the model input. Analytical methods are used to solve for the free speeds, minimum speeds, cruise time, and idle time that satisfy the time and distance requirements of acceleration and deceleration events. The simplified micro-simulation makes use of acceleration profiles that define representative acceleration as a function of vehicle speed. The criteria for choosing acceleration functions are that they must fit experimental data and yield analytical solutions to the first order autonomous differential equation that defines acceleration as a function of vehicle speed:

$$a = \frac{dv}{dt} = f(v) \tag{3.1}$$

This equation is separable, so it is easily solved by rearranging into the following integral form, provided a solution exists for the integrand.

$$t = \int \frac{dv}{f(v)} + C \tag{3.2}$$

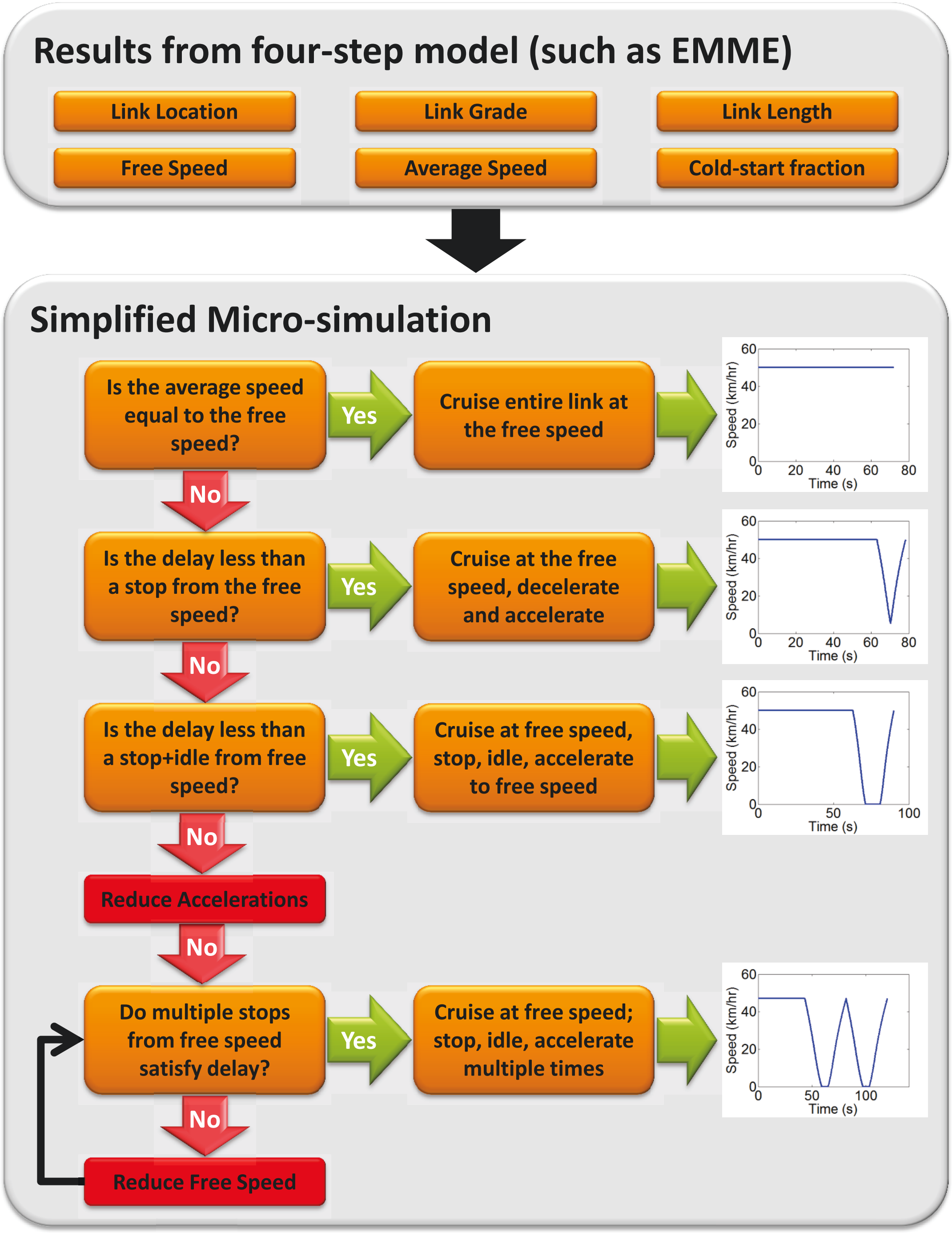


Figure 3.2: Simplified micro-simulation flow chart.

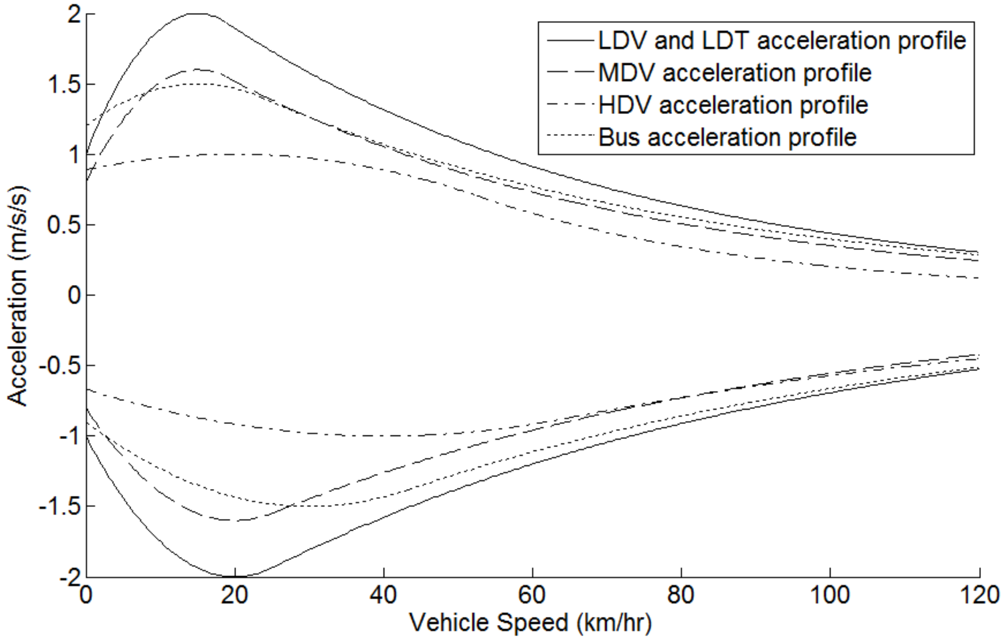


Figure 3.3: Simplified micro-simulation acceleration profiles.

The shape of typical acceleration profiles can be described using two functions: a quadratic function for low speeds, and an exponential decay for high speeds. The two functions are joined such that they, and their first derivatives, are continuous. Since both of these functions are analytically integrable as first-order autonomous differential equations, they are mathematically convenient in addition to being well-suited to the definition of acceleration profiles for vehicles. It is also possible to solve for the distance travelled in addition to the travel time. The two functions are defined below, up to and above the transition speed v_s:

$$a(v) = \begin{cases} c_1 \cdot v^2 + c_2 \cdot v + c_3 & v \leq v_s \\ \alpha \cdot \exp^{-\lambda \cdot v} & v \geq v_s \end{cases} \tag{3.3}$$

The acceleration functions used in the model are fit to large datasets of Canadian vehicle traces in metropolitan areas. These functions and their fits are discussed further in Appendix C. The default acceleration functions are shown in figure 3.3.

This approach to modelling acceleration captures its dependence on speed. It also allows for numerically efficient analytical solutions to the traffic constraints imposed by most travel demand model links. Short and highly congested links require some iteration to find a suitable reduced free speed, however, the number of iterative calculations and the simulation times are significantly reduced in comparison to previous versions of this micro-simulation [67].

3.4 Instantaneous Power, Fuel Consumption, and Emission Module

This module consists of two models: an instantaneous tractive power model, and an instantaneous power-based emissions and fuel consumption model.

3.4.1 Tractive Power Model

This module calculates the tractive power at each time step in each of the vehicle trajectories supplied by the simplified micro-simulation. Tractive power is the product of the tractive force required to drive the vehicle, and its speed.

$$P_{tractive} = F_{tractive} \cdot v \tag{3.4}$$

There are a variety of methods used to calculate the tractive force of vehicles, however, the model described by Sovran and Bonn [68] is used in this model. This method is based on a physical interpretation of vehicle traction and, with an additional term for link grade, can be applied to vehicle characteristics, trajectory, and link grade. The model of Sovran and Bonn includes rolling resistance, aerodynamic drag resistance, and acceleration terms:

$$F_{tractive} = M\frac{dv}{dt} + R + D \tag{3.5}$$

The rolling resistance term described by Sovran and Bonn consists of two terms:

$$R = M(r_0 + r_1 \cdot v) \tag{3.6}$$

Many models assume that rolling resistance is not a function of speed and set r_1 equal to zero [69, 70]. This assumption is appropriate up to and including highway speeds and is used in the tractive power model. Equation (3.6) is then reduced to:

$$R = M \cdot C_R \cdot v \tag{3.7}$$

The aerodynamic drag term, D, is described as:

$$D = C_D \cdot A \cdot \frac{v^2}{2} \cdot \rho \tag{3.8}$$

An additional term must be added to account for slope resistance:

$$S = M \cdot g \cdot \sin(\theta) \tag{3.9}$$

The final form of the tractive force model used in the model is then combined from equations (3.5) and (3.7) to (3.9):

$$F_{tractive} = M\left(\frac{dv}{dt} + C_R \cdot v + g \cdot \sin(\theta)\right) + C_D \cdot A \cdot \frac{v^2}{2} \cdot \rho \tag{3.10}$$

Hence, given a vehicle's physical characteristics, its speed, and its acceleration, the instantaneous tractive force is calculated as shown in the above derivation.

3.4.2 Power-based Fuel Consumption and Emissions Model

Fuel consumption and emission rates are calculated for each time step of every vehicle trajectory. The functions used are based on correlations to chassis dynamometer testing done at the University of Alberta [56, 71, 72]. The functions return instantaneous fuel consumption and emission rates given inputs of power and vehicle speed. The fuel consumption and emission functions for gasoline vehicles are shown in equations 3.11 to 3.15. The complete set of functions is documented in Appendix D. Carbon dioxide is calculated based on the mass conservation of carbon in the fuel and the exhaust, and idle consumption and emissions rates are the second values shown in the maximum functions.

$$\dot{m}_{gasoline} = \mathbf{max}\left[\frac{1}{3.6}\cdot e^{(-0.476\log(P_{tractive})+0.602)} - 0.148 + 0.00262\cdot v\cdot P_{tractive}, 0.496\right] \tag{3.11}$$

$$\dot{m}_{NO_x} = \mathbf{max}\left[0.001\cdot 0.675\cdot(-0.9121 + 1.778\cdot P_{tractive}), 0.00544\right] \tag{3.12}$$

$$\dot{m}_{NMHC} = \mathbf{max}\left[\frac{1}{3600}\cdot e^{(-0.595\log(P_{tractive})+3.234)}\cdot P_{tractive}, 0.00933\right] \tag{3.13}$$

$$\dot{m}_{CO} = \mathbf{max}\left[\frac{1}{3600}\cdot e^{(-0.439\log(P_{tractive})+4.64)}\cdot P_{tractive}, 0.0213\right] \tag{3.14}$$

$$\dot{m}_{CO_2} = \left[\frac{M_{C_n}}{M_{C_nH_{2n}}}\cdot(\dot{m}_{gasoline} - \dot{m}_{NMHC}) - \frac{M_C}{M_{CO}}\cdot m_{CO}\right]\cdot\frac{M_{CO_2}}{M_C} \tag{3.15}$$

3.5 Calibration

The transportation emissions tool uses power-based fuel consumption and emissions functions. These are derived from experimental studies performed on several vehicles and engines at the University of Alberta [56, 71]. The raw fuel consumption and emission estimates calculated by the tool must be calibrated to represent the fleet that is being modelled. The calibration module generates calibration factors for each vehicle sub-class modelled that are passed to the power-based fuel consumption and emissions model. Running, starting, and fugitive emissions are calibrated to the MOBILE6.2 model. Fuel consumption is calibrated to the NRCan transportation database [73]. Electrical energy drawn from the grid to power battery electric and plug-in hybrids is also calibrated. The Alberta Electrical System Operator (AESO) market share projections are used along with LCA-based emission factors for each electricity generation technology. Appendix E is a detailed description of the calibration calculations and their application to fuel consumption and emission estimates.

The calibration factors for a given vehicle type depend on the following:

- simulation year, ambient temperature, and barometric pressure
- vehicle fleet composition
- electrical grid properties
- hybrid and electric vehicle market shares

The calibration is defined for each of the 21 vehicle types in table 3.2, according to one of the two schemes shown in the second and third columns.

The default vehicle classes are divided differently than the MOBILE6.2 vehicle classes because of their sensitivity to mass and drag within the micro-simulation framework. The LDV class is divided into mini, economy, and large cars since there are considerable differences in their fuel consumption and emissions. Additionally, the LDT1 and LDT2 classes are treated as LDVs in traffic since they behave more like LDVs than the heavier light trucks. (LDT1 and LDT2 classes include vehicles like the Toyota RAV4, Chevrolet Equinox, and Volvo XC70 which are used more like passenger vehicles than light trucks.) Heavy duty trucks are subdivided into Medium-heavy Duty (MDVs) and Heavy-heavy Duty Vehicles (HDVs) since the lighter medium duty vehicles are not only used differently, but also have different capabilities. The

	Vehicle Classes	Model Divisions	MOBILE6 Divisions
1	LDV - Mini	LDV	LDV*
2	LDV - Economy		
3	LDV - Large		
4	LDT1		LDT
5	LDT2		
6	LDT3	LDT	
7	LDT4		
8	HDV2b	MDV	HDV
9	HDV3		
10	HDV4		
11	HDV5		
12	HDV6	HDV	
13	HDV7		
14	HDV8a		
15	HDV8b		
16	Small School Bus	Bus	Bus
17	Large School Bus		
18	New Transit Bus		
19	Old Transit Bus		
20	Short Transit Bus		
21	Long Transit Bus		

*MOBILE6 does not differentiate the LDV class

Table 3.2: Vehicle Fleet Class Definitions

Vehicle Class	Mass kg	Frontal Area m^2	Drag Coefficient	Rolling Coefficient
LDV - Mini	1005	1.900	0.300	0.013
LDV - Economy	1295	1.951	0.327	0.013
LDV - Large	1735	2.118	0.313	0.013
LDT1	1606	2.346	0.360	0.013
LDT2	2120	2.633	0.368	0.013
LDT3	2676	3.122	0.390	0.013
LDT4	3025	3.126	0.410	0.013
HDV2b	3260	3.655	0.410	0.010
HDV3	3655	3.800	0.500	0.010
HDV4	4175	3.900	0.600	0.010
HDV5	5025	4.000	0.700	0.010
HDV6	6490	4.200	0.800	0.010
HDV7	8210	4.500	0.900	0.010
HDV8a	18100	4.960	0.900	0.010
HDV8b	23800	5.160	0.900	0.010
Small School Bus	3600	4.718	0.550	0.010
Large School Bus	11000	5.712	0.550	0.010
New Transit Bus	13595	6.370	0.550	0.010
Old Transit Bus	10955	5.933	0.550	0.010
Short Transit Bus	3750	4.520	0.550	0.010
Long Transit Bus	19945	6.370	0.550	0.010

Table 3.3: Vehicle characteristics by class

buses are also further divided into six classes. The six classes represent bus usage and characteristics more closely than the MOBILE6.2 divisions, which differ only by fuel type (gasoline or Diesel). The physical characteristics of the 21 vehicle classes which are used to calculate power are shown in Table 3.3.

3.6 Inventory Module

The inventory module compiles the simulation results and writes them to files. Raw results are stored for detailed analysis and further post-processing. An overall simulation summary is stored, which contains a record of the simulation definition and summaries for the whole fleet and for each division of the fleet. If a custom link classification scheme is used, summaries are stored for each link classification, and for unclassified links. Evaporative and refuelling emissions breakdowns are summarized in the same manner. Finally, the fleet age distribution used in the simulation is recorded in a format that can be used as input in subsequent simulation runs. The files that are created as output for a simulation run are described in Appendix F.

The inventory module also includes a series of calculations that provide additional functionality to the transportation emissions tool. Adjustments for high-emitters and alternative fuels are made and non-running fuel consumption and emissions are calculated. Non-running fuel consumption and emissions include those that result from cold start, evaporative, crankcase, and refuelling. These emissions are calculated according the methodology used in the US EPA's MOBILE6.2 model and are discussed further in Appendix E.

3.7 Classification of the Simplified Transportation Micro-simulation Tool

The simplified transportation micro-simulation is a micro-simulation of vehicle traffic based on travel demand model (TDM) results. While it does not model the capacity of transportation networks like many transportation micro-simulations, it operates at the vehicular level. Hence, it satisfies the popular definition of a micro-simulation as one which operates at the level of individual units.

3.8 Unique Features of the Simplified Transportation Micro-simulation

The simplified transportation micro-simulation tool has several features that on their own are not uncommon, but in combination are rare. The most important feature is the capability to micro-simulate emissions on large-scale networks with conventional computational resources. For example, a 24-hour EMME model of the Capital Region of Alberta (94,210 links) can be micro-simulated in 147 minutes on a 32-bit Windows

XP computer with a 3 GHz Intel Core 2 Duo E8400 processor and 3 Gb of RAM (using both processors). Currently, a transportation micro-simulation (such as VISSIM or PARAMICS) modelling a network of this scale would be impractical as it would require a supercomputer, a large cluster, or an excessive simulation time.

Another important feature of this tool is that it is physics-based, rather than regression-based. This lends predictability and explanatory power to the model; changing vehicle parameters such as mass or frontal area will result in predictable changes to emissions and fuel consumption. Regression models are inherently less reliable at responding appropriately to conditions that differ from those of the data that was used to generate the regression.

Finally, the simplified emissions micro-simulation module models traffic congestion continuously (rather than in bins) and over a wide range of conditions. It differs from the project-level mode of MOVES2010 in the way that congestion is modelled on the links. The simplified micro-simulation uses free speed and average speed to respond to congestion in a continuous manner, while MOVES2010 uses the facility type (i.e. freeway, arterial, etc.) and average speed. Appendix G further investigates the difference between the simplified micro-simulation approach and the MOVES approach.

CHAPTER 4

MODEL CONFIDENCE ASSESSMENT

This chapter presents confidence assessment studies for the simplified micro-simulation module and for the transportation emissions inventory tool.

4.1 Confidence Assessment Overview

The credibility of the simplified transportation micro-simulation is assessed using confidence assessment techniques described by Knepell and Arangno [74]. Several methods are used to perform an operational validation of the model. At the micro-simulation level the model is compared to two experimental datasets. At the aggregate level, the fuel sales in the Edmonton metropolitan region are compared to the fuel consumption estimate of the inventory tool.

4.2 Simplified Vehicle Trajectory Micro-simulation Model Validation

The goal of this section is to determine whether the simplified vehicle trajectory micro-simulation model predicts fuel consumption and emissions that agree with other emissions predictions for the traffic that it models. This is a fairly specific test that makes use of more than one of the model modules but tests only the simplified vehicle trajectory micro-simulation, i.e. the module that creates vehicle trajectories based on link-averaged parameters described in section 3.3. The tractive power model and the power-based fuel consumption and emissions model are also used in these validation activities, but are not tested.

The question that this section aims to answer is this: *Do the vehicle trajectories generated by the simplified micro-simulation produce: 1) acceleration and tractive efficiency estimates, and 2) fuel consumption and emission estimates that are similar to the estimates for measured vehicle trajectories with the same link-averaged parameters?* Furthermore, any differences in the estimates will be analyzed.

4.2.1 Comparison to Edmonton Data

A study at the University of Alberta collected second-by-second driving data from light duty vehicles used in Edmonton traffic. The dataset is compared to the inventory tool model for the Edmonton metropolitan region. This data is used to compare the driving behaviour generated by simplified micro-simulation to the driving behaviour of the Edmonton data. Descriptive statistics of this dataset are shown in table 4.1. The Edmonton dataset was recorded between September 5 and October 9 of 2008, almost exclusively on weekdays. It is worth noting that 38% of the recording time was spent idling. Vehicles were considered idling if their speed was less than 2.5 km/hr.

The Edmonton dataset is used to compare the acceleration and tractive efficiency of the simplified vehicle trajectory micro-simulation. The dataset is compared to the City of Edmonton traffic model. This comparison is appropriate because the dataset was recorded in Edmonton and on weekdays in the fall, which matches the City of Edmonton traffic model.

Figure 4.1 shows histograms of instantaneous speed for both the simplified micro-simulation and the measured Edmonton driving data. There are three noticeable differences between the two histograms. It is apparent that drivers spend more time idling than the simplified micro-simulation model accounts for; about 40% of driving time is spent idling in the Edmonton data, while the simplified micro-simulation

Number of Vehicles	4
Vehicle Hours	350
VKT	10,198
Average Speed (km/hr)	29.1
Idle Hours	134
Average Speed without idle (km/hr)	47.1
Weekday Hours	348
Weekend Hours	1.53
Weekday VKT	10,166
Weekend VKT	32

Table 4.1: Edmonton Dataset Summary

predicts about 10% of time is spent idling. This can be partly attributed to real-world drivers spending some time just idling rather than travelling anywhere; the four-step transportation model that is used as input to the simplified micro-simulation models trip time without consideration of idling periods at the start and end of each trip. The simplified micro-simulation assumes that trips begin and end in zones with 30 seconds of idling time, but this does not account for the large amount of time spent idling in the real world. The lower idle fraction can also be partly attributed to the simplified micro-simulation's maximum idling time of 30 seconds; if a vehicle must stop and idle for more than 30 seconds to achieve the desired link speed, the simulation instead models congested traffic with a reduced free speed and multiple stops. This 30 second maximum idling time is intended to correspond to typical traffic signal timings for the region of study, and assumes that traffic congestion is always related to traffic signals. The second difference between the two histograms is that the simplified micro-simulation favours common free speeds. This is because the model assumes that drivers generally accelerate steadily to and maintain the designated free speed (i.e. speed limit) unless they are limited by traffic signals or congestion. The third difference is that average speeds are higher in the simplified micro-simulation as a consequence of the lower idle time than the real driving data. However, the average

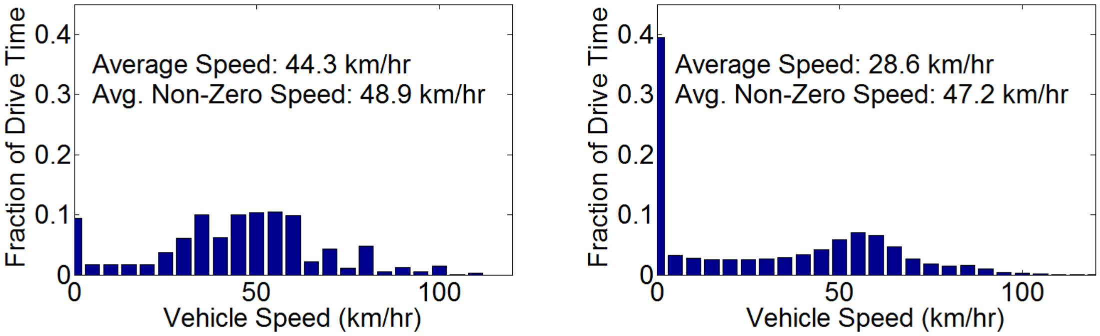


Figure 4.1: Instantaneous speed histogram for simplified micro-simulation of Edmonton metropolitan region (left) and Edmonton dataset (right)

non-zero speeds, i.e. the average speeds without idle, are very similar (50 km/hr for the simplified micro-simulation and 47.2 km/hr for the real driving data). Hence the actual driving data is comparable to the simplified micro-simulation data, with the major difference being the time spent idling and the minor difference that the simplified micro-simulation favours common free speeds and shows a less continuous distribution.

These differences in the model speed distribution propagate into the tractive energy and fuel consumption estimates produced by the inventory tool from each set of inputs. Figure 4.2 shows the distributions of tractive energy and fuel energy use with vehicle speed. The trends from the histograms of figure 4.1 are repeated in a distorted fashion in figure 4.2; since more energy is required at higher speeds, the distributions maintain the location of their peaks, but grow in magnitude as speed increases. The overall tractive efficiency implied by the modelled tractive energy demand and fuel consumed is displayed in the top right corner of each graph; the simplified micro-simulation yields a tractive efficiency of 19.7%, while the Edmonton data is estimated to be 16.5% efficient. This difference is a product of the greater time spent idling, since fuel is consumed at idle but no tractive energy is used.

Acceleration is an important aspect of driving behaviour, especially at lower speeds

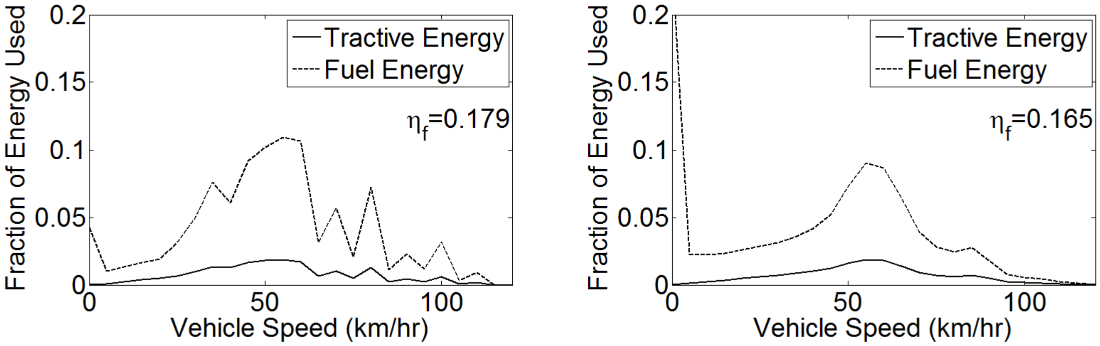


Figure 4.2: Tractive efficiency profile for simplified micro-simulation of Edmonton metropolitan region (left) and Edmonton dataset (right)

where acceleration contributes heavily to the required vehicle tractive power. Acceleration also tends to be a function of speed, since at higher speeds more tractive power is required to overcome rolling resistance and drag. Figures 4.3 and 4.4 show histograms of acceleration for the simplified micro-simulation and for the real driving data. These histograms break down the speed ranges of the data to show the effect of speed on acceleration.

The simplified micro-simulation uses higher accelerations than those calculated from the real world driving data, especially at low speeds. The simplified micro-simulation does capture the reduction of acceleration as speed increases; this is evident in figure 4.3 where the histograms on the right show lower acceleration levels for higher speed ranges.

The Edmonton data in general shows lower acceleration levels than the simplified micro-simulation, but more time is spent at these lower acceleration levels. The real-world driving data is also more symmetrical (i.e. deceleration levels are about equal to acceleration levels) at higher speeds; this is intuitive since drivers tend to apply less braking power at high speeds.

Figures 4.5 and 4.6 show the histograms of fuel and tractive energy with acceleration, and have the overall tractive efficiency for each speed range printed to the right

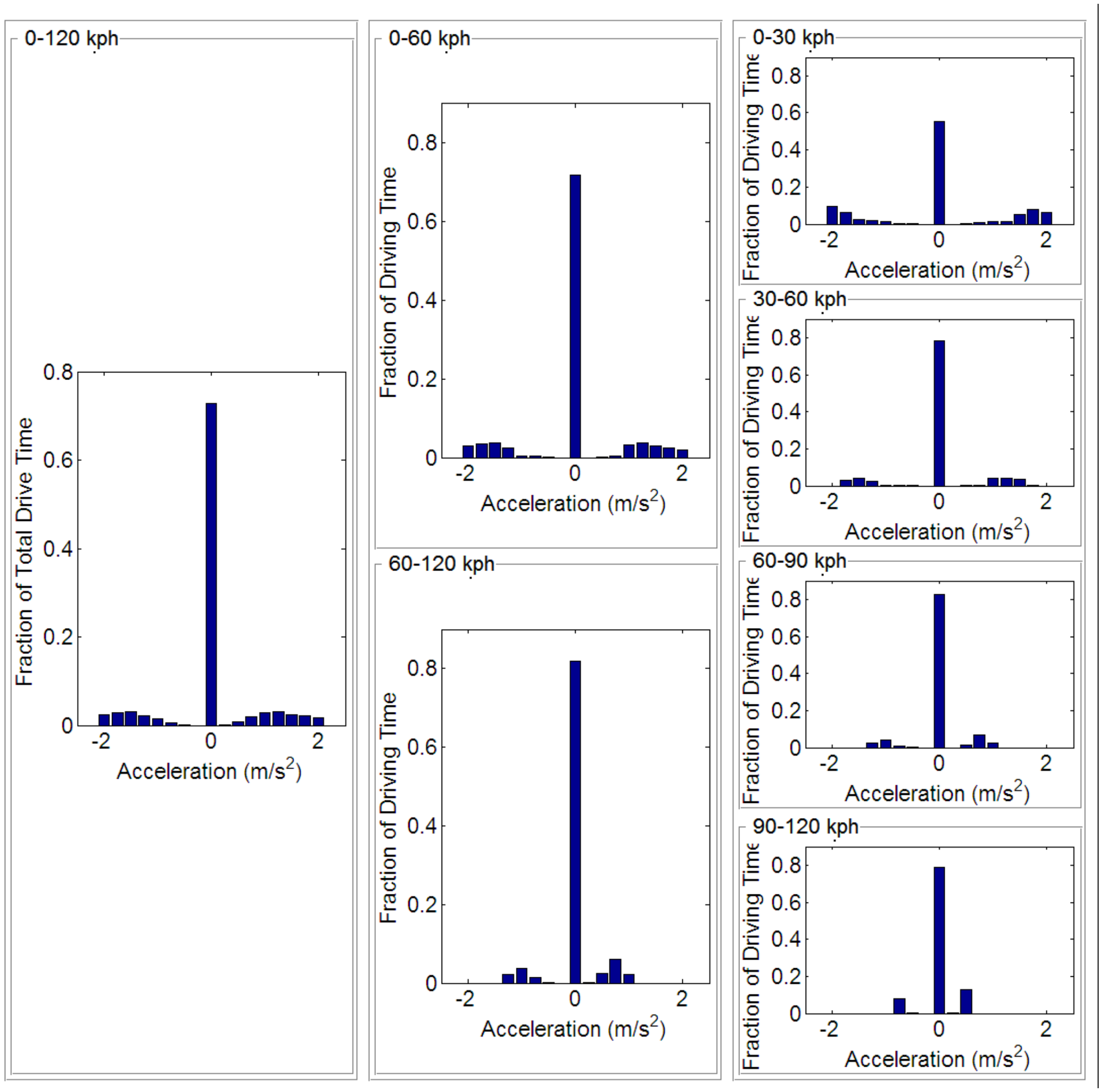


Figure 4.3: Acceleration histograms for simplified micro-simulation of the Edmonton metropolitan region.

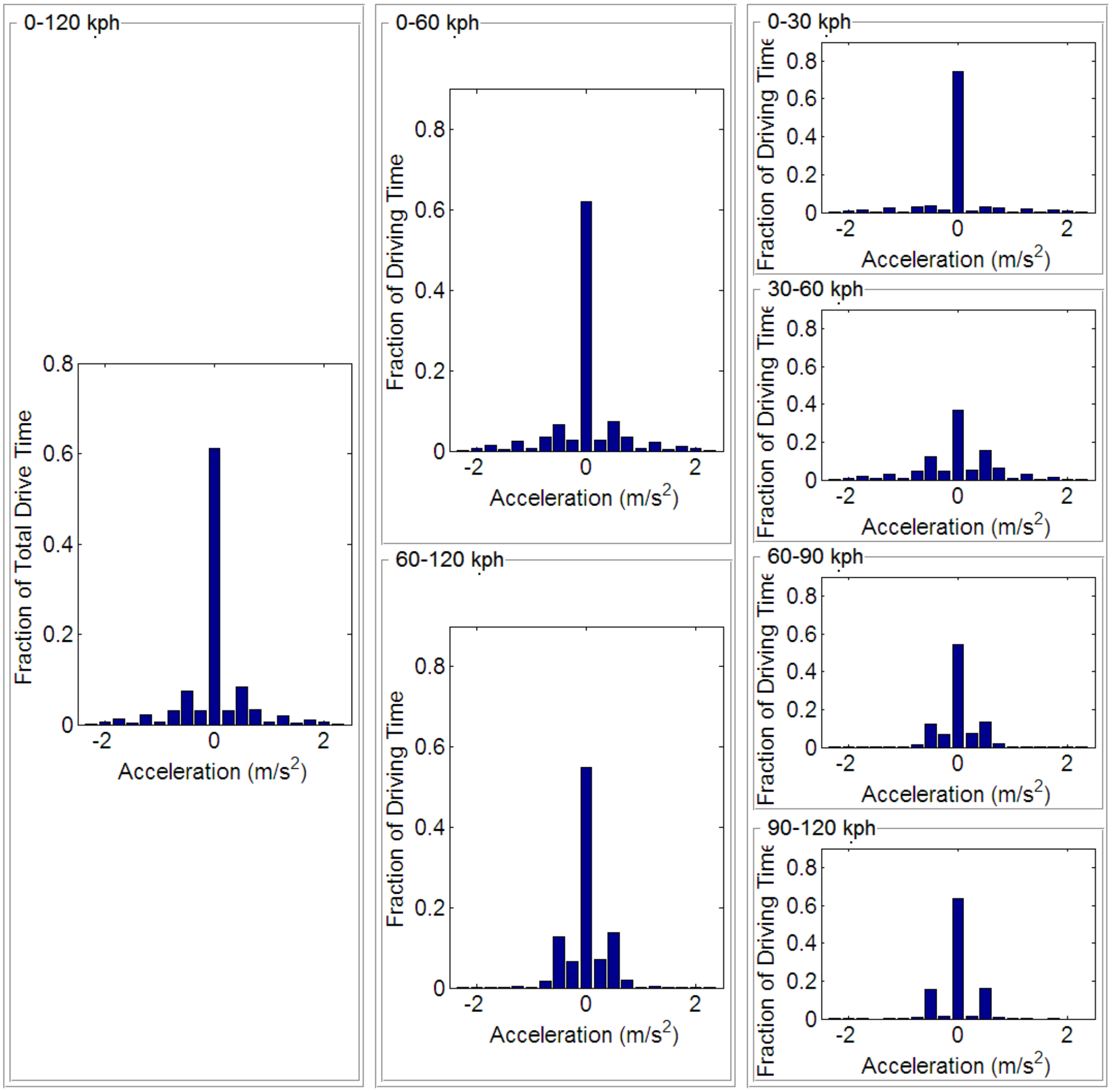


Figure 4.4: Acceleration histograms for Edmonton dataset.

of each histogram. As expected, little tractive power is required during deceleration, although some fuel energy is used to idle the engine. The differences between the acceleration histograms for the Edmonton data and simplified micro-simulation model carry into the energy histograms. The overall tractive efficiency in each speed range changes considerably for the Edmonton data; the lowest speed range, which includes the idling time, has an efficiency of only 6.5%, while the highest speed range of 90–120 km/hr has a tractive efficiency of 29.6%. This is expected, since tractive efficiency at idle is zero, and since engine efficiency generally increases with tractive power for moderate power levels. It is notable that the overall tractive efficiency is dramatically affected by idling; reducing the amount of time spent idling would increase tractive efficiency considerably. The change in tractive efficiency across the speed ranges is not as significant for the simplified micro-simulation. This can be partly attributed to the lower time spent idling, which results in a higher tractive efficiency for the 0–30 km/hr range. Also, the 90–120 km/hr range shows a tractive efficiency of only 21.5%, compared to 29.6% for the Edmonton data. This discrepancy is a result of the lower acceleration at higher speeds in the Edmonton data, which reduces the tractive power and increases efficiency.

4.2.2 Comparison to Winnipeg Dataset

A research study conducted by Bibeau et al. [75] of the University of Winnipeg resulted in a large database of real-world driving records. This database has several features that make it particularly useful for validating the simplified emissions micro-simulation: it contains differential[1] GPS records, vehicle speed, and most importantly, speed limit. The sampling rate is 1 Hz, which is well-suited to tractive energy analysis and emissions estimates. A suitable subset of this dataset was used for the analysis

---

[1] The GPS coordinates were zeroed at the beginning of each trip to protect the privacy of the participating drivers.

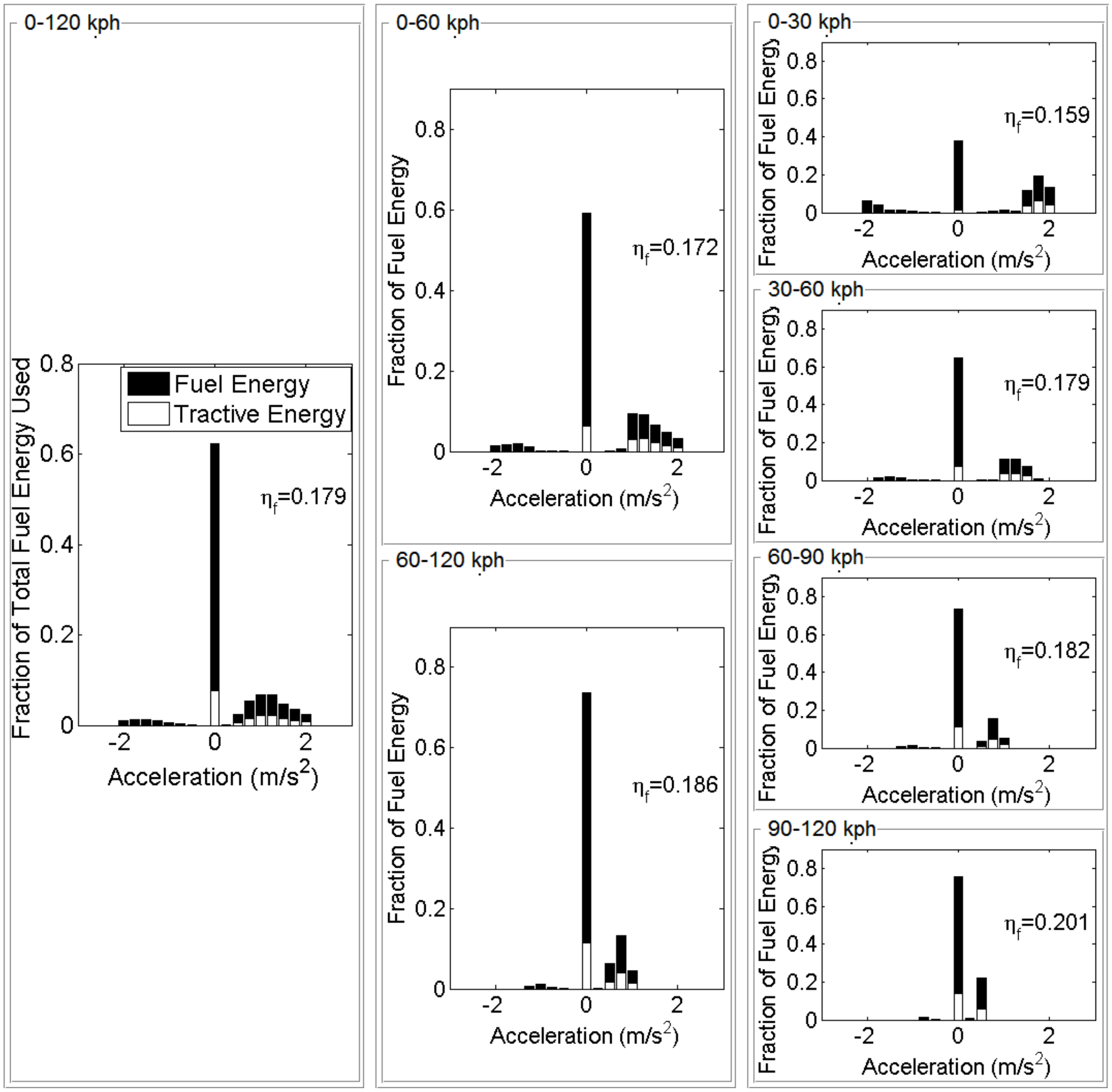


Figure 4.5: Tractive efficiency histograms for simplified micro-simulation of the Edmonton metropolitan region.

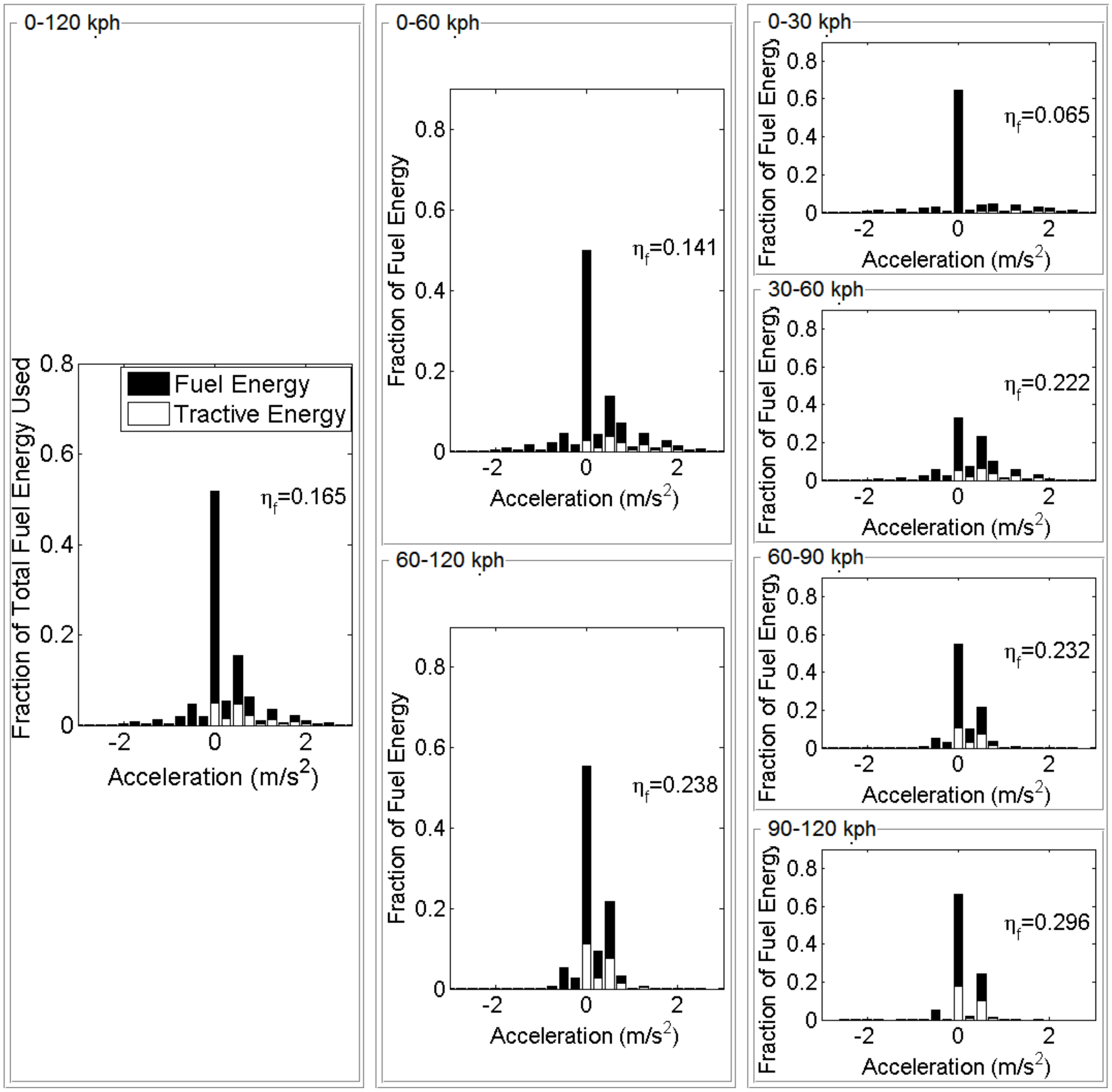


Figure 4.6: Tractive efficiency histograms for simplified micro-simulation for Edmonton dataset.

	Winnipeg Dataset	Subset Used
Number of Vehicles	75	75
Vehicle Hours	12,821	9,966
VKT	394,530	269,120
Average Speed (km/hr)	30.8	26.9
Idle Hours	3,769	2,862
Average Speed without idle (km/hr)	43.6	37.7
Weekday Hours	9,006	7,059
Weekend Hours	3,815	2,935
Weekday VKT	272,580	189,800
Weekend VKT	121,940	79,316

Table 4.2: Winnipeg Dataset Summary

in this section. Table 4.2 contains descriptive statistics for this dataset and for the subset that was used. Data records that did not have a valid speed limit, or exceeded the speed limit by more than 10 km/hr were not used for this analysis. Vehicles were considered idling if their speed was less than 2.5 km/hr.

The dataset was analyzed by splitting the trips into sections of constant speed limit, and then further dividing these sections into link-like entities that occur in between cornering events. Since the database does not include complete GPS coordinates it isn't possible to detect every intersection, it is only possible to detect those at which the vehicles turned. This is a source of uncertainty in the analysis because vehicles driving on multiple links without turning (i.e. going straight through intersections) must be assumed to be driving on a single long link since there is no information to indicate otherwise. The energy, fuel consumption, and emissions for the link-like sections of data were calculated using the inventory tool to generate the point clouds, mean data trends, and 95% confidence intervals presented in this section. The emissions shown represent those of a fleet-average economy-size LDV in 2006, based on the default fleet age distribution for Edmonton shown in Appendix E.

The Winnipeg dataset is used to compare the effects of traffic congestion on energy, emissions, and fuel consumption. It is uniquely well-suited to this because it includes speed limit data, which allows for a direct comparison with the link parameters used by the simplified vehicle trajectory micro-simulation.

Energy, fuel consumption, and emissions estimates for the Winnipeg data and the inventory tool are presented in sections 4.2.2.1 to 4.2.2.6.

4.2.2.1 Energy Consumption Estimates

Figure 4.7 shows the distance-specific energy consumption calculated for trips isolated from the Winnipeg data, and for trips modelled using the simplified emissions micro-simulation. The mean and 95% confidence interval trends for the Winnipeg data, calculated in 5 km/hr bins using a windowing approach, are also plotted in red on those graphs which contain sufficient data for their estimation. The mean and 95% confidence interval were calculated for each speed bin which had at least thirty data points. The data points that exist outside of the 95% confidence intervals are outliers that would be less common in a smaller dataset. Each individual graph in the figure shows the distance-specific energy consumption estimates (in units of kWh/km) as a function of average speed on the link. It is interesting to note that distance-specific energy consumption does not seem to vary significantly with free speed, i.e. the data are clustered within similar ranges in each column of graphs. The mean trend of the Winnipeg data is also consistent in each row of graphs, indicating that the mean distance-specific energy trend does not vary significantly with link length.

The simplified micro-simulation model estimates remain within the 95% confidence intervals in most of the graphs. The model underestimates energy consumption for longer links, and overestimates energy consumption for shorter links. All of the micro-simulation trends overestimate energy consumption for conditions of extreme congestion, where the average speed on the link is less than 20% of the free speed. The simplified micro-simulation energy trends show step changes (increases) in energy as congestion increases, as a result of the algorithm increasing the number of complete stops made as the time spent on the link increases with congestion. This response is discussed in further detail in Appendix B.

4.2.2.2 Gasoline Consumption Estimates

Figure 4.8 shows the distance-specific fuel consumption calculated for the Winnipeg data. The mean and 95% confidence interval trends for the Winnipeg data, calculated in 5 km/hr bins using a windowing approach, are also plotted in red. The estimates of the simplified emissions micro-simulation are plotted in black. There is considerably less scatter in the gasoline data than the energy data of figure 4.7, because gasoline fuel is still consumed during periods of negative tractive power demand, i.e. idle periods, and because spark ignition engines that consume gasoline become more efficient as power increases. Hence, the gasoline fuel consumption data collapses towards its mean value because there is considerably less variation between the lowest and highest fuel consumption rates than there is between the lowest and highest power demand.

The gasoline fuel consumption estimated by the simplified emissions micro-simulation is within the 95% confidence interval of the Winnipeg data on all of the graphs in figure 4.8, and is close to the mean values.

4.2.2.3 CO Emissions Estimates

Carbon monoxide emissions also tend to collapse onto their mean in comparison to the energy consumption data. The slope of the curve that represents CO emissions as a function of power decreases as power increases, as shown in figure 4.9. CO is also emitted when tractive power is at or below an idle value, thus the variation between the highest and lowest value of CO is less than that of the energy and there is less scatter in the data. This is evident in the Winnipeg data of figure 4.10; the mean and 95% confidence intervals are again plotted in red, with the simplified emissions

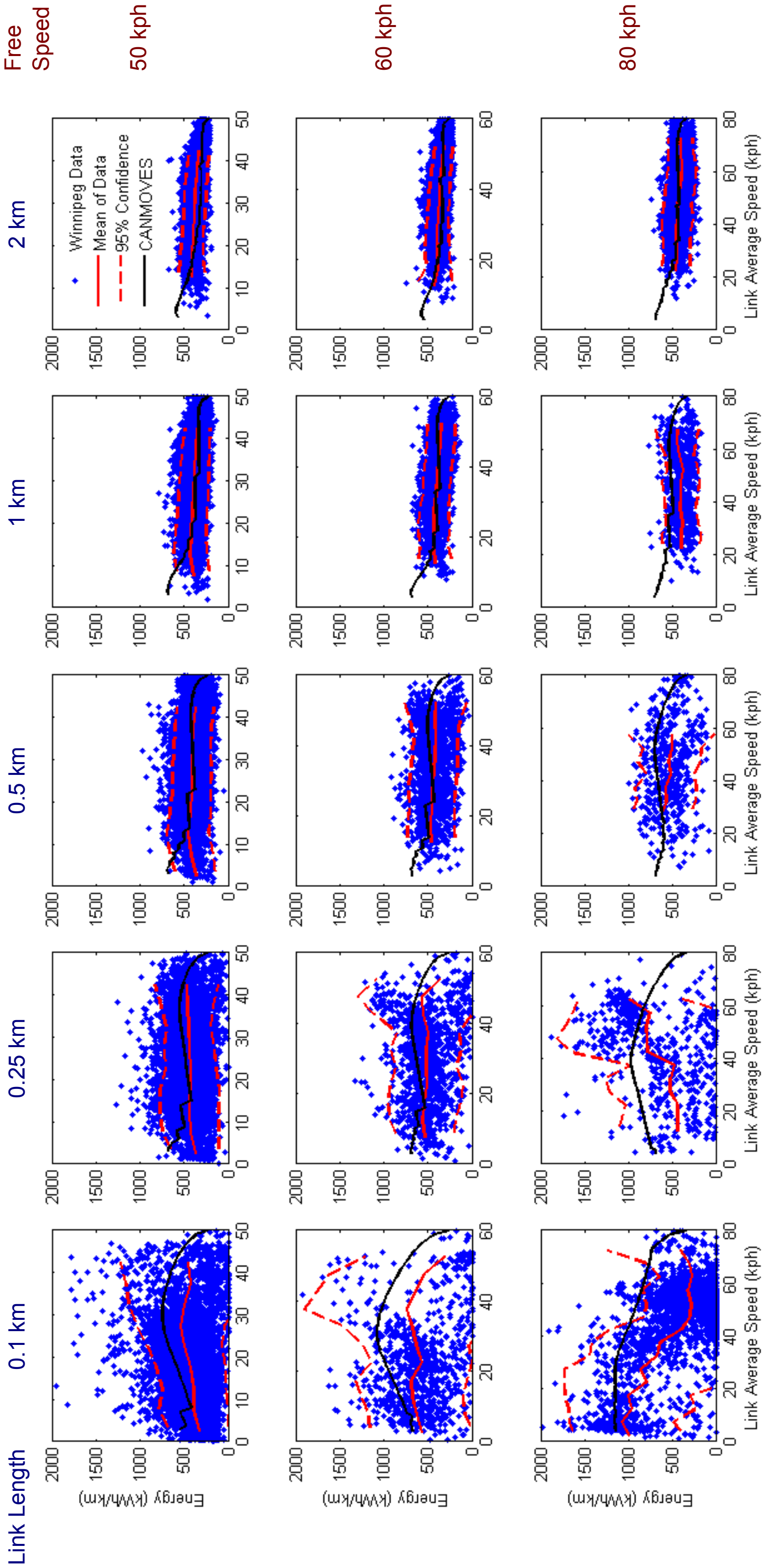


Figure 4.7: Comparison of distance-specific energy consumption calculated for Winnipeg dataset and for simplified emissions micro-simulation model

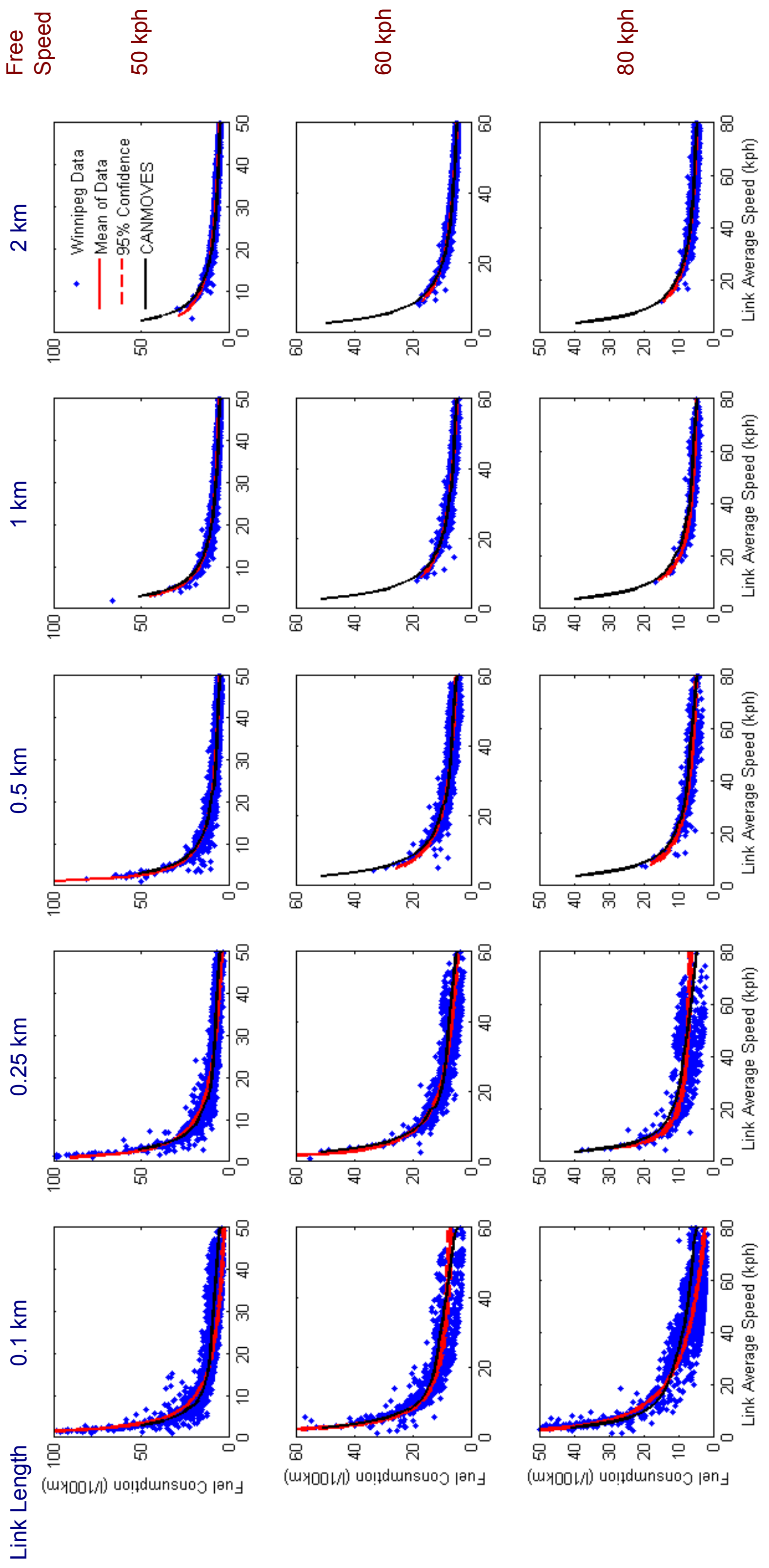


Figure 4.8: Comparison of distance-specific fuel consumption calculated for Winnipeg dataset and for simplified emissions micro-simulation model

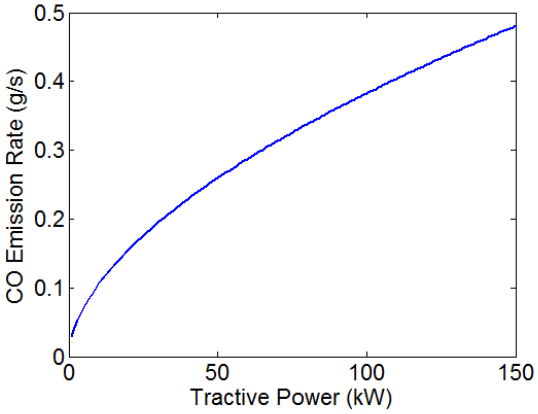


Figure 4.9: Carbon monoxide emissions as a function of tractive power.

micro-simulation estimate trend plotted in black. The micro-simulation estimates are within the 95% confidence intervals and generally follow the mean trends closely on all of the graphs.

4.2.2.4 NMHC Emissions Estimates

Non-methane hydrocarbon (NMHC) emissions follow a power trend with little scatter compared to the energy data. The NMHC emissions calculated for the Winnipeg data are shown in figure 4.11; the mean and 95% confidence intervals are also plotted in red, with the simplified emissions micro-simulation estimate trend plotted in black. The micro-simulation estimates follow the mean trends of the data closely in all of the graphs.

4.2.2.5 NO$_x$ Emissions Estimates

NO$_x$ emissions are strongly dependant on power, and thus behave similarly the energy estimates. Figure 4.12 shows more scatter in the calculated NO$_x$ emissions for the Winnipeg data than for CO and NMHC emissions; however, there is still less scatter than the energy estimates because of the minimum idle value of NO$_x$ emissions. The

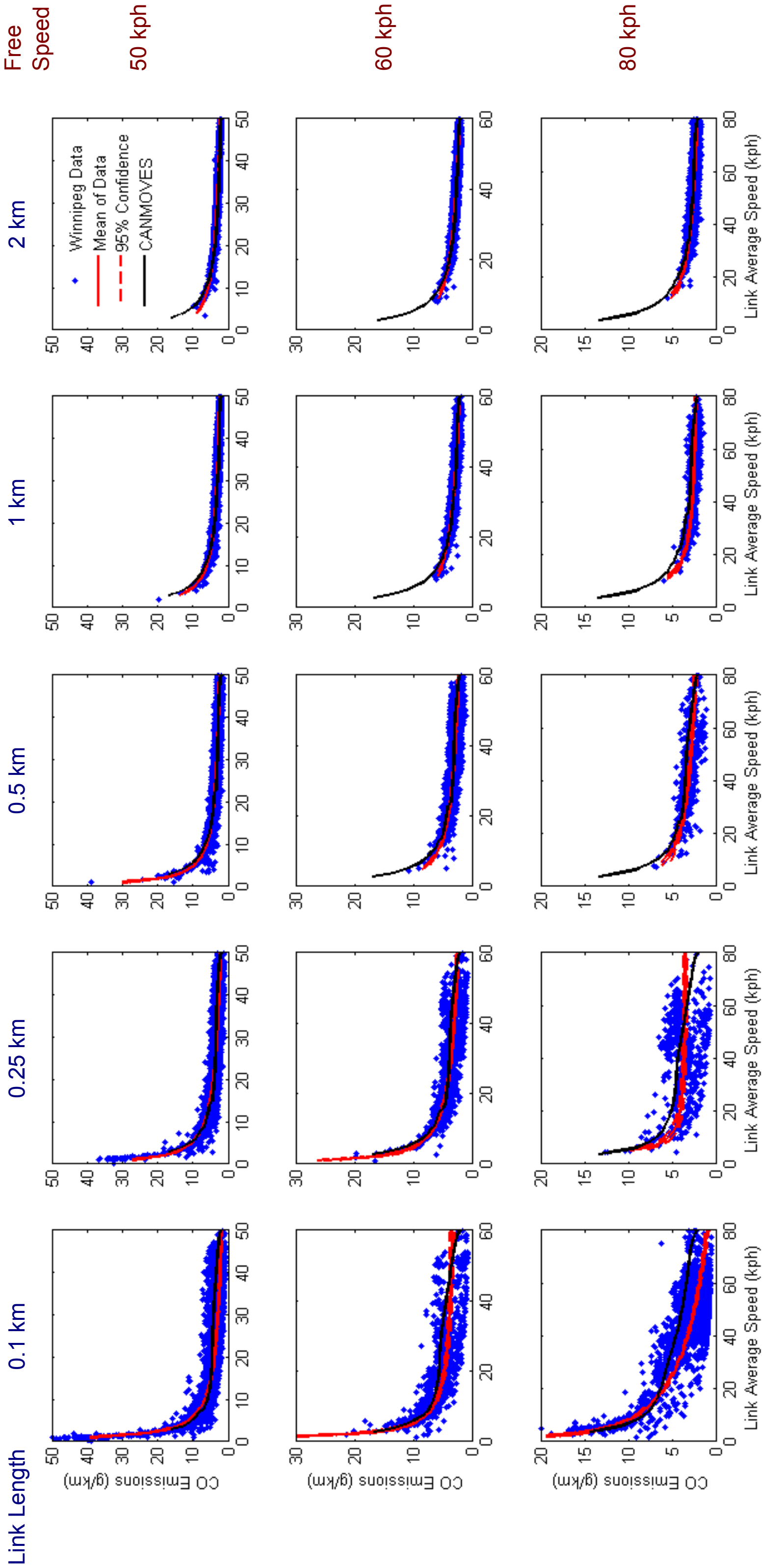


Figure 4.10: Comparison of distance-specific CO emissions calculated for Winnipeg dataset and for simplified emissions micro-simulation model

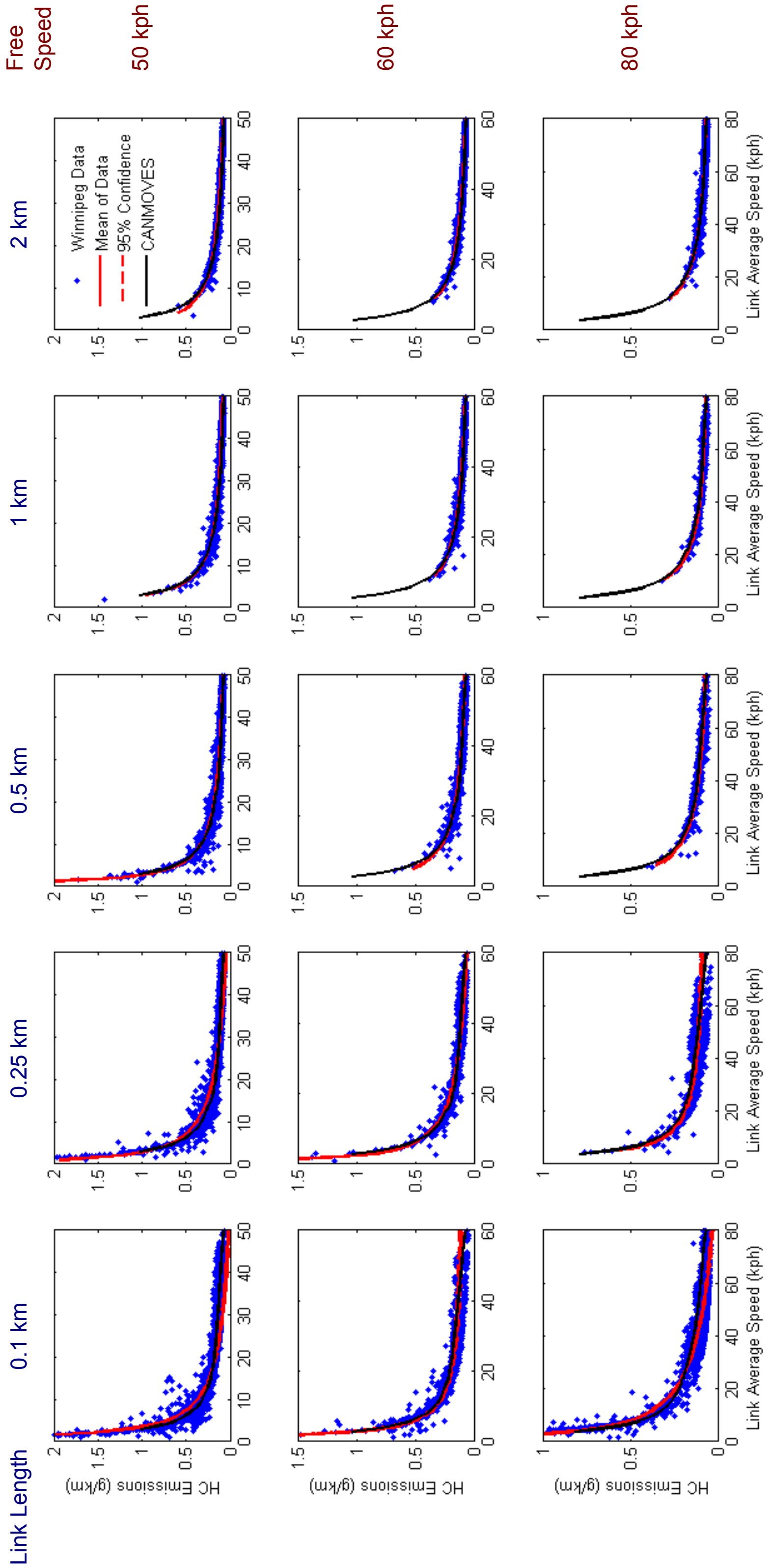


Figure 4.11: Comparison of distance-specific NMHC emissions calculated for Winnipeg dataset and for simplified emissions micro-simulation model

micro-simulation trends overestimate NO_x emissions for highly congested links, where the link average speed is less than 20% of the free speed.

The simplified emissions micro-simulation trends resemble the Winnipeg data mean trends in most of the graphs of figure 4.12. The model results are further from mean values for shorter links, and in some cases are outside the 95% confidence intervals.

4.2.2.6 $PM_{2.5}$ Emissions Estimates

$PM_{2.5}$ emissions are plotted in figure 4.13 and show considerable scatter. The scatter is due to the strong correlation of particulate emissions to tractive power. The simplified emissions micro-simulation trends remain within the 95% confidence interval of the emissions calculated for the Winnipeg data for most conditions; however, like the energy estimate data there is more scatter for shorter links and the micro-simulation trends are underestimated for longer links and overestimated for shorter links. The micro-simulation trends also tend to overestimate $PM_{2.5}$ emissions for highly congested links, where the link average speed is less than 20% of the free speed.

4.3 Aggregate Level Inventory Comparisons

The previous section dealt with the validation of the simplified emissions micro-simulation model for individual links. This section assesses the performance of the whole transportation emissions inventory tool over a large region of 94,210 links. Annual fuel sales estimates for the City of Edmonton in 2006 are compared to the simulation model for the Edmonton Metropolitan Region.

The City of Edmonton records annual fuel sales and has provided their estimates of the fuel sold in Edmonton in 2006. Gasoline fuel sales totalled 1,182,142,000 litres, and Diesel fuel sales totalled 572,428,000 litres. The fuel sold in Edmonton is not

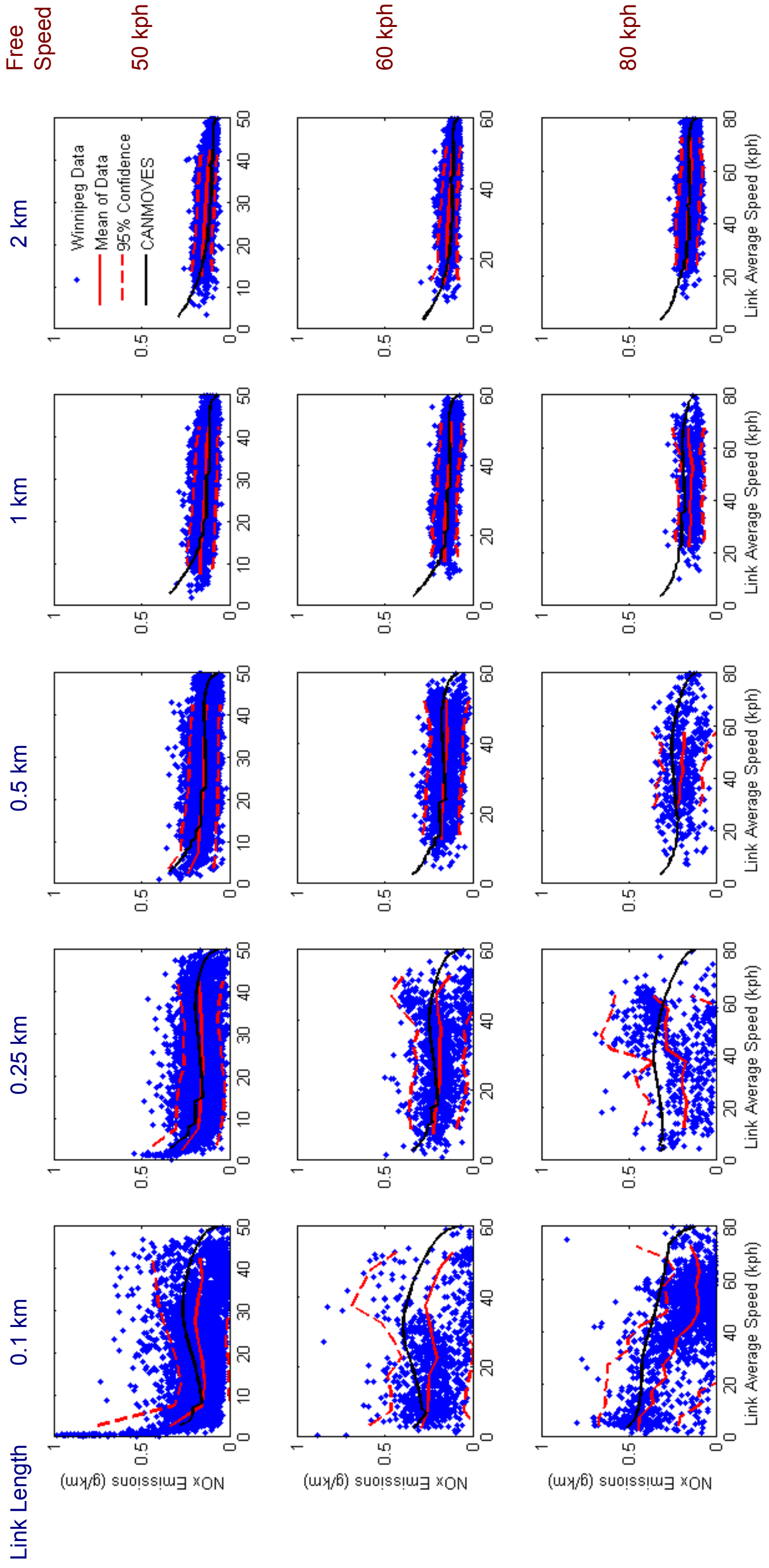


Figure 4.12: Comparison of distance-specific NO_x emissions calculated for Winnipeg dataset and for simplified emissions micro-simulation model

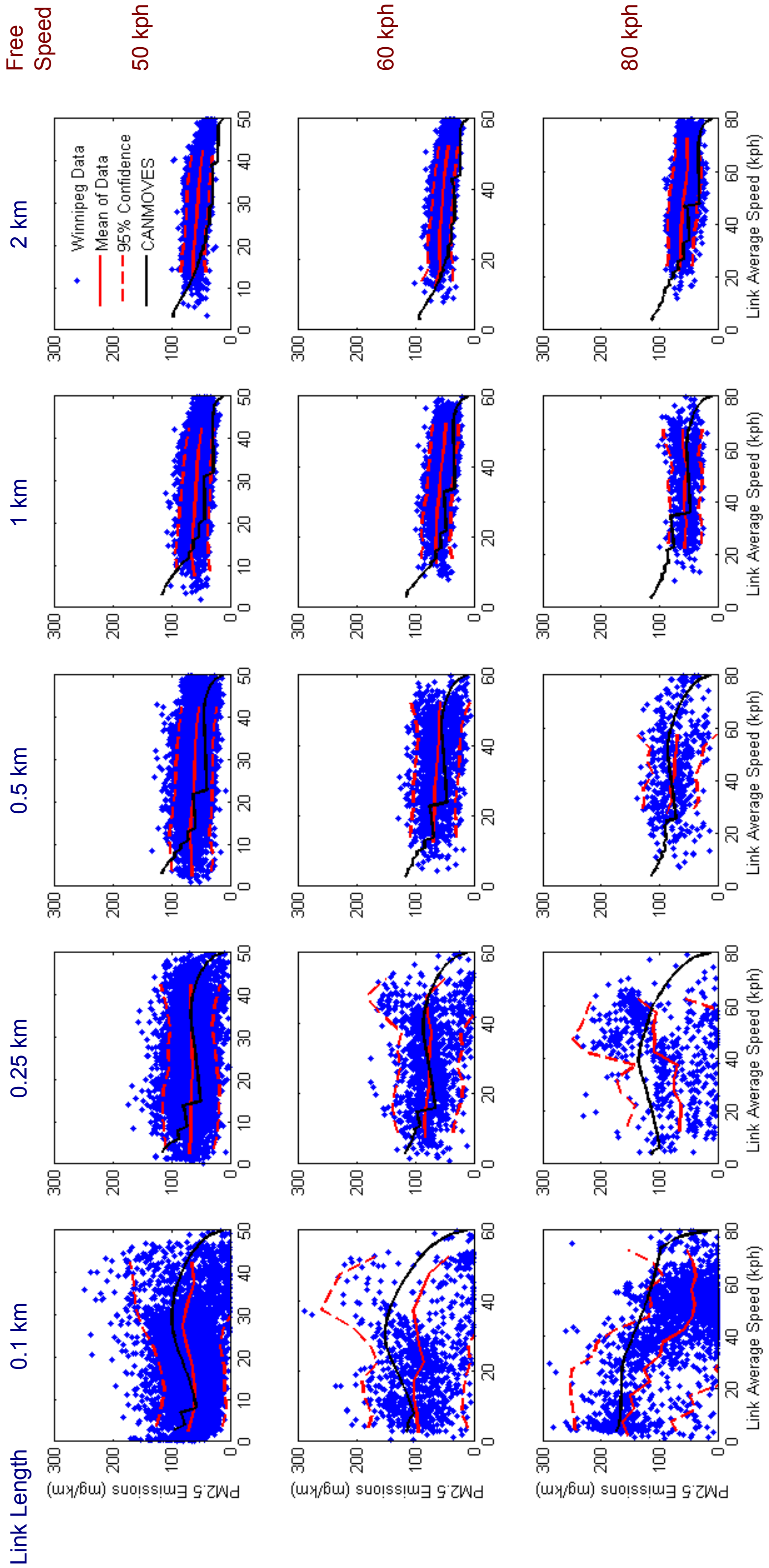


Figure 4.13: Comparison of distance-specific $PM_{2.5}$ emissions calculated for Winnipeg dataset and for simplified emissions micro-simulation model

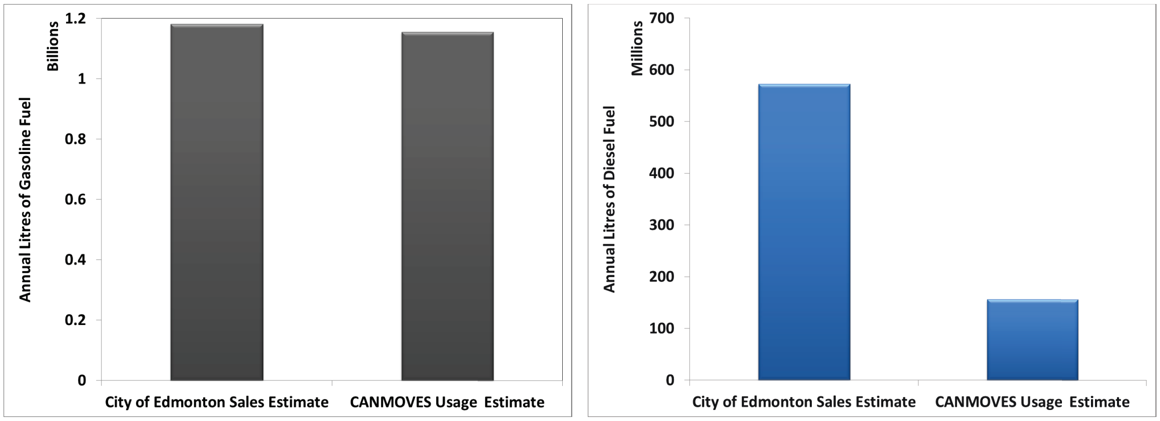


Figure 4.14: Comparison of 2006 Gasoline and Diesel Fuel Sales to the Inventory Tool Annual Fuel Consumption Estimates

necessarily consumed in Edmonton, and not all of the fuel consumed in Edmonton is necessarily purchased in Edmonton so the comparison between the fuel sales and the simulation for the Edmonton Metropolitan Region is not exact. However, the fuel sales should still be representative of the amount of fuel that is consumed in Edmonton.

The comparison between the inventory tool simulation for the Edmonton Metropolitan Region and the fuel sales estimate is shown in figure 4.14. The model estimate is 7% higher than the gasoline fuel sales estimate and the inventory tool gasoline usage estimate. The model only captures 22% of the Diesel fuel sales estimate. The inventory tool predictions indicate that 86% of Diesel fuel is consumed by class 6 to class 8b heavy duty trucks; these trucks are likely used for long-distance highway travel and it is possible that they tend to arrive in the Metropolitan Region with a partial fuel tank, refill, and depart the Region again. Much of the Diesel fuel may be consumed off-road or delivered outside the region; however, further investigation would be required to determine how much of the difference could be attributed to this.

4.4 Confidence Assessment Summary

This chapter aimed to provide insight into the performance of the transportation emissions inventory tool, and the simplified emissions micro-simulation. The inventory tool fuel consumption estimates are similar to the annual fuel sales estimate for the Edmonton Metropolitan Region in 2006.

The simplified emissions micro-simulation trends fit within the 95% confidence ranges of the estimates made using the Winnipeg data for the gasoline fuel consumption, CO emissions, and NMHC emissions. There is considerably more scatter in the Winnipeg data for energy use, NO_x emissions, and $PM_{2.5}$ emissions, and the simplified micro-simulation overestimates these criteria for shorter links.

Chapter 5

Application Studies

This chapter uses several application studies to emphasize the uses of the simplified transportation micro-simulation model. Studies of policy, infrastructure design, and traffic control are presented. The simplified micro-simulation model is also compared to an interaction-based micro-simulation in a design study application. Partial content of this chapter was published in a chapter of the book Mitigating Climate Change: The Emerging Face of Modern Cities *[76].*

The simplified transportation micro-simulation tool has many uses for transportation policy analysts, planners, and infrastructure designers. Policy analysts can use the forecasting and fleet modelling capabilities to inform regulatory and resource allocation decisions. Infrastructure designers can use the tool to compare the energy, fuel consumption, and emissions performance of multiple design options. Examples of such applications are presented in the following sections. The simplified emissions micro-simulation is also compared to VISSIM, a third-party interaction-based micro-simulation, in an infrastructure design study.

Transportation demand model results were used for the policy application, infrastructure design, and traffic control studies. These were EMME models created by municipal planning staff for the sole purpose of exploring the capabilities of the simplified micro-simulation model. The models used represent a real traffic network but the scenarios presented are hypothetical and not official planning models.

5.1 Policy Application Study

This policy study considers the use of incentive programs to reduce greenhouse gas (GHG) emissions from the light-duty vehicle fleet. GHG emissions are calculated as the weighted sum of CO_2 and CH_4 emissions (by mass) based on the 100-year GWP (global warming potential) of 25 for CH_4 specified in the IPCC's Fourth Assessment Report [77]. The calculation for GHG is shown in equation 5.1. Two scenarios are compared to the baseline estimates. The first scenario uses incentives to encourage scrapping old vehicles (10 years or older) in favour of new vehicles; the second considers the use of similar incentives to encourage the purchase of hybrid vehicles rather than conventional gasoline vehicles. The two scenarios both model three-year programs beginning in a major Canadian municipality (Edmonton) in 2013, with an incentive of $3,000 per vehicle. A limited number of drivers are given the incentive if they choose to participate in the program by purchasing a new vehicle that has a smaller GHG footprint than their current vehicle. The programs are assumed to have an incentive budget of $45,000,000 and thus provide incentives to 15,000 vehicle owners, distributed evenly over the three years to 5,000 vehicle owners per year. These scenarios are hypothetical and are only intended to demonstrate the usefulness of the micro-simulation model in making an informed policy decision.

$$GHG = CO_2 + 25 \cdot CH_4 \tag{5.1}$$

The base case for both scenarios is a travel demand model (TDM) for the Capital Region of Alberta. It is estimated that there are approximately 746,000 active light duty vehicles in the Capital Region and that 37,300 of those are new vehicles. The traffic demand is assumed to increase at a rate of 2% per year. However, this analysis

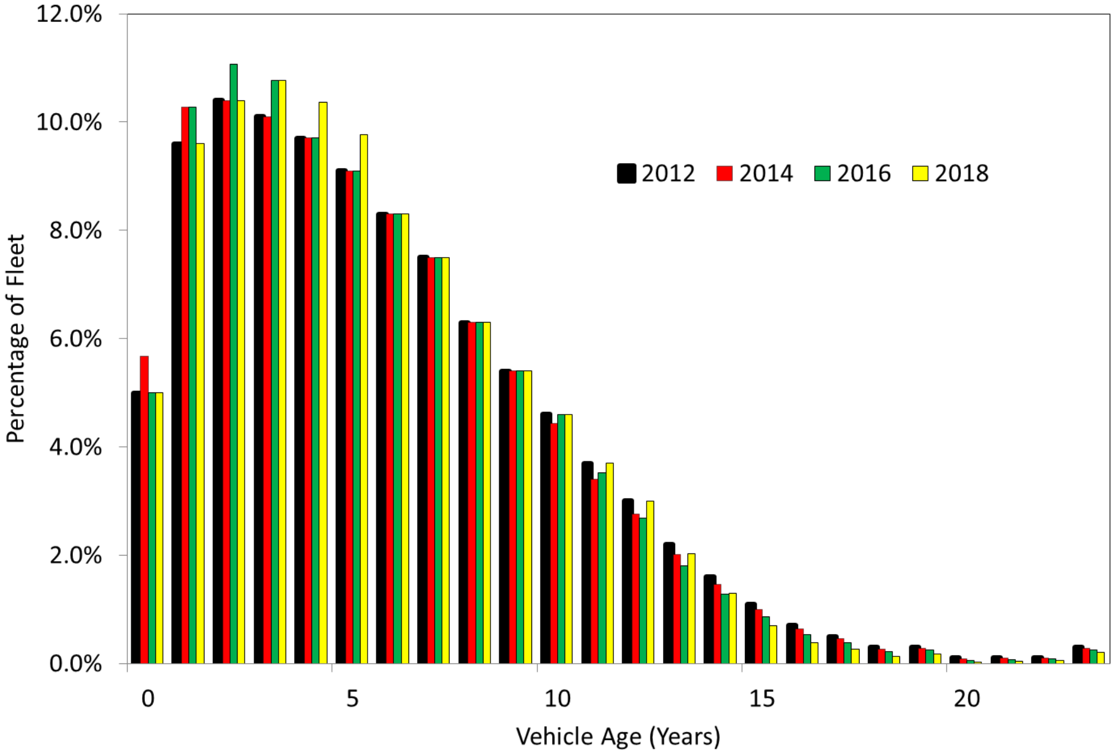


Figure 5.1: Fleet age distribution evolution for incentive programs

does not account for any increases in road capacity or traffic congestion.

The first incentive model involves accelerating scrappage[1] rates using new vehicle purchase incentives. For each of the three program years (2013 - 2015), an additional 5,000 new vehicles are introduced into the fleet, and 5,000 vehicles aged more than 10 years are retired. It is assumed that there would be sufficient demand for the incentives. Figure 5.1 shows the evolution of the fleet age distribution from the base year through to 2018.

The second incentive model is a hybrid technology program. In this scenario, the fleet age distribution remains unchanged, but for each of the three years of the program (2013 to 2015), the number of new hybrids brought into the fleet is increased

---

[1] Scrappage refers to removing a vehicle from the fleet by changing the title status from active to salvage, and often recycling it.

by 5,000 as a result of the incentive program. This program does not remove additional older vehicles from the fleet, it simply increases the number of new hybrid vehicles purchased and reduces the number of new conventional vehicles purchased accordingly.

The results of these incentive program models are shown in figure 5.2. The introduction of more efficient technologies with fleet turnover is expected to lower GHG emissions for a fixed amount of traffic but the baseline case shows that this is overcome by the anticipated 2% yearly increase in traffic demand. Both the scrappage and hybrid incentive programs reduce the overall GHG emissions over the three year program period. For the parameters chosen, the hybrid incentive program has a greater effect on GHG emissions than the scrappage program. The anticipated end of the programs in 2015 results in an upward inflection in their emission trends as the fleet continues to turn over and age with fleet purchasing decisions reverting to the baseline conditions.

In general the objective of policy makers is to mitigate the largest quantity of GHG possible for their given budget. This type of analysis lends itself well to this goal; the program budget and emissions mitigated can be used to calculate the cost of reducing GHGs on a $/tonne basis, and then compared to alternative projects. For these hypothetical programs, the cost effectiveness of the incentive scenario is $382 per tonne and is more effective than the scrappage incentive scenario at $498 per tonne. However, both programs are relatively expensive compared to typical carbon prices ranging around $15 per tonne based on energy conservation programs. The ability to estimate the emissions savings and cost effectiveness of potential GHG reduction programs allows policy makers to quantify the effects of their concepts and identify the most efficient ways to use their budgets.

The simplified transportation micro-simulation model gives policy makers a micro-simulation tool that can be used to rapidly evaluate, compare, and optimize policy

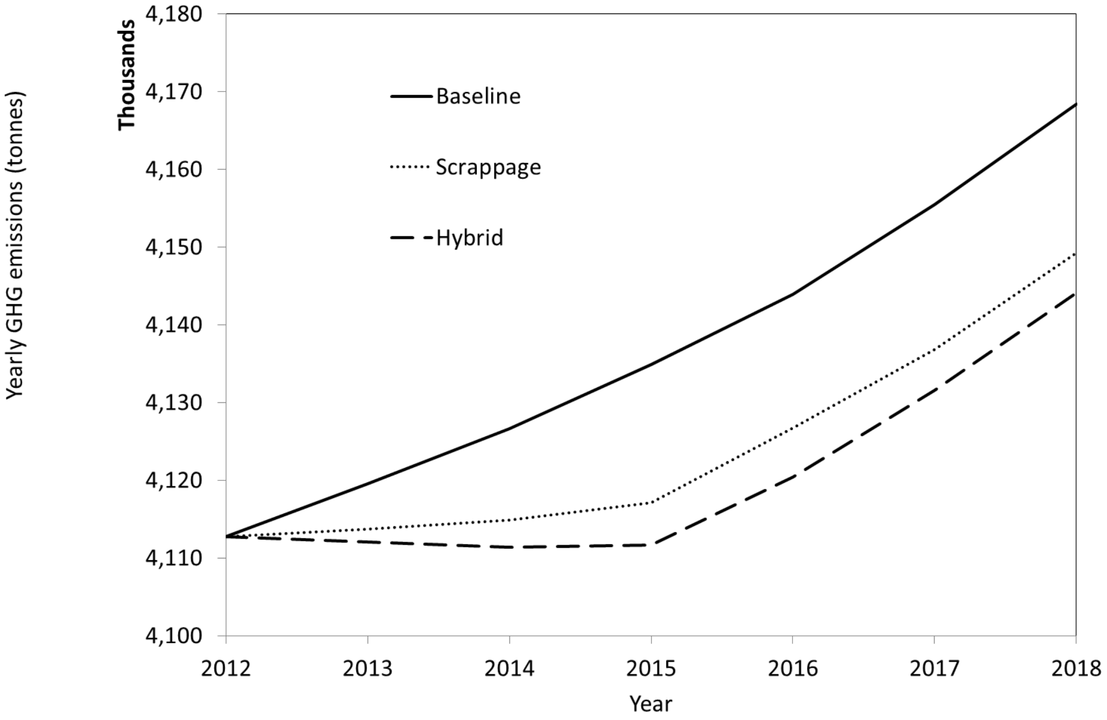


Figure 5.2: GHG emission horizons for baseline model and scrappage and hybrid incentive programs

concepts.

5.2 Infrastructure Design Study

This case demonstrates the effects of infrastructure changes on emissions by modelling the closure of a major urban bridge. The importance of large-scale simulations that capture traffic shifting effects as well as local congestion is emphasized.

The bridge that is closed is a major artery into the down town area of Edmonton, Canada. Figure 5.3 shows distance-specific GHG emission maps for the baseline case and bridge closure case. The bridge closure causes traffic to shift to alternate river crossings, and increases congestion at these alternate crossings. Some mode-shifting is likely to occur as well; that is, some travellers will choose alternate methods such as public transit and there will be fewer vehicles on the network. Figure 5.4 shows that average speeds decrease in the vicinity of the bridge, as do VKT. GHG emissions are lower, however, the distance-specific GHG rate increases in the vicinity of the bridge, indicating that traffic is less efficient. This illustrates the importance of traffic shifting and the necessity of large-scale modelling. While the regional model does not show a significant increase in traffic, travel time, or GHG emissions, the traffic volumes within a 0.5 km to 1 km radius of the bridge are significantly lower, and vehicle travel is both slower and less efficient. The results indicate that, for this case, a minimum radius of 2.5 to 5 km from the closed bridge would be required to capture the effectors of traffic to alternate crossings. (This radius would be different for other cases depending on the traffic volume crossing the bridge and the capacity and proximity of alternative routes). In this case, the displacement of some vehicle trips to light rail transit roughly balanced the increased distance travelled by vehicles detouring around the closed bridge so, on a city-wide basis, changes in vehicle mileage and GHG emissions were minimal. This result would have been difficult to foresee and to confidently predict without the capability to model both traffic and emissions on a whole-network basis.

This case study demonstrates that the effects of traffic shifting and mode shifting can be modelled using the simplified transportation micro-simulation model with transportation demand model results. This approach can be used to evaluate the results over a large area, and determine to what extent local changes in the transportation network affect the surrounding areas.

5.3 Traffic Control Study

The following two scenarios relate to traffic control measures; increasing the speed limit on a major freeway, and changing from signalized intersections to free flowing interchanges on a ring road. Each of these case studies includes a baseline case and the altered case in which the capacity of a major artery is increased and traffic is likely to shift towards that artery. These case studies demonstrate the advantages of large-scale micro-simulation models for a complete understanding of the transportation issues being modelled.

5.3.1 Freeway Speed Limit Increase

In the first case study, a major suburban freeway crosses a metropolitan region outside the inner core in the East-West direction. The speed limit is 80 km/hr baseline and might be increased to 90 km/hr. With lower travel time on the freeway, some traffic that would otherwise use nearby roads is attracted to the faster flowing freeway. The problem is studied using three boundaries to demonstrate the importance of large-scale modelling. The narrowest boundary is only the freeway, the second includes roads in the immediate vicinity, and the largest includes the entire metropolitan region. The three boundaries are shown graphically in figure 5.5. Figure 5.5 also

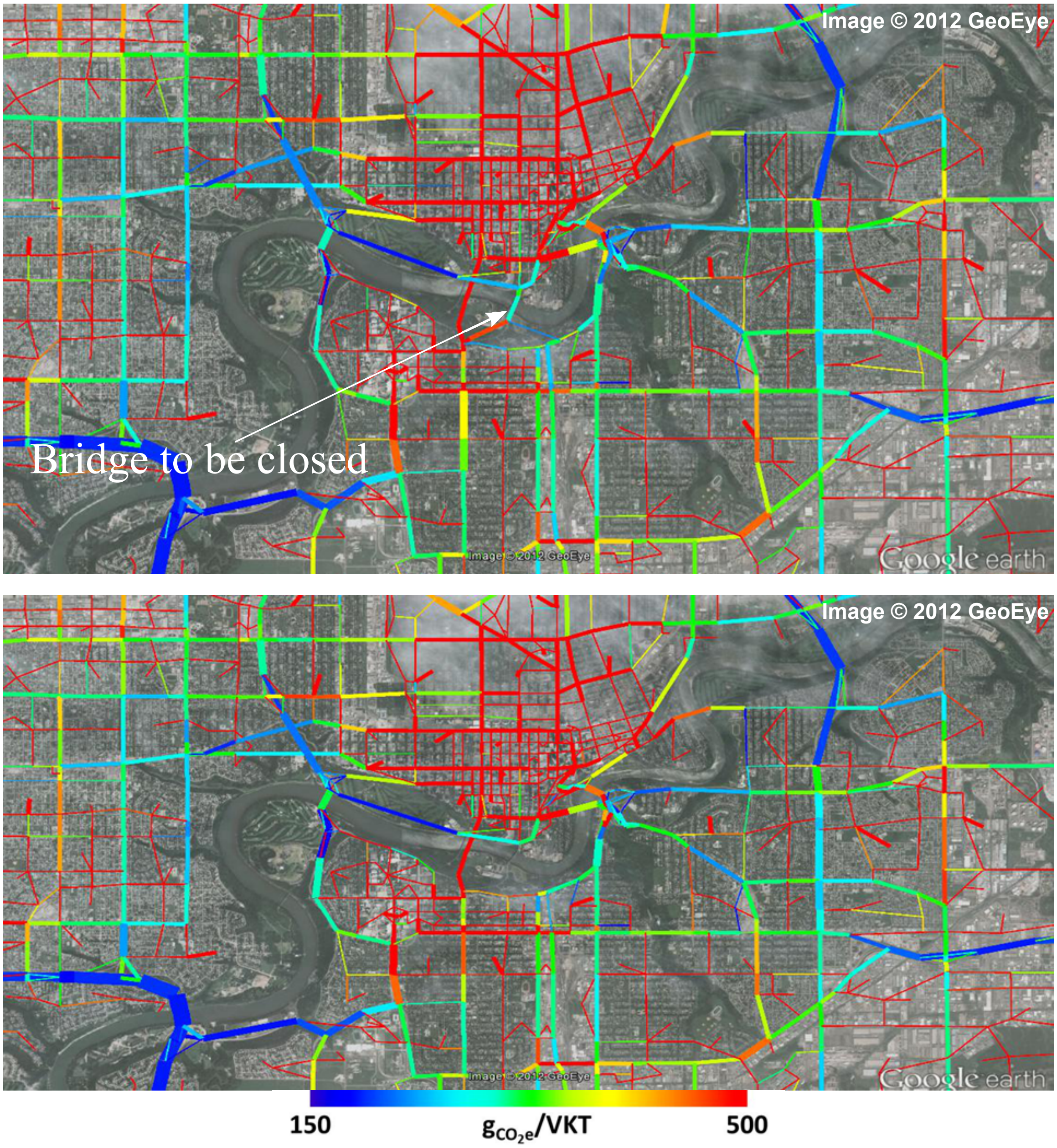


Figure 5.3: Distance-specific GHG emissions for baseline (top) and bridge closure model (bottom)

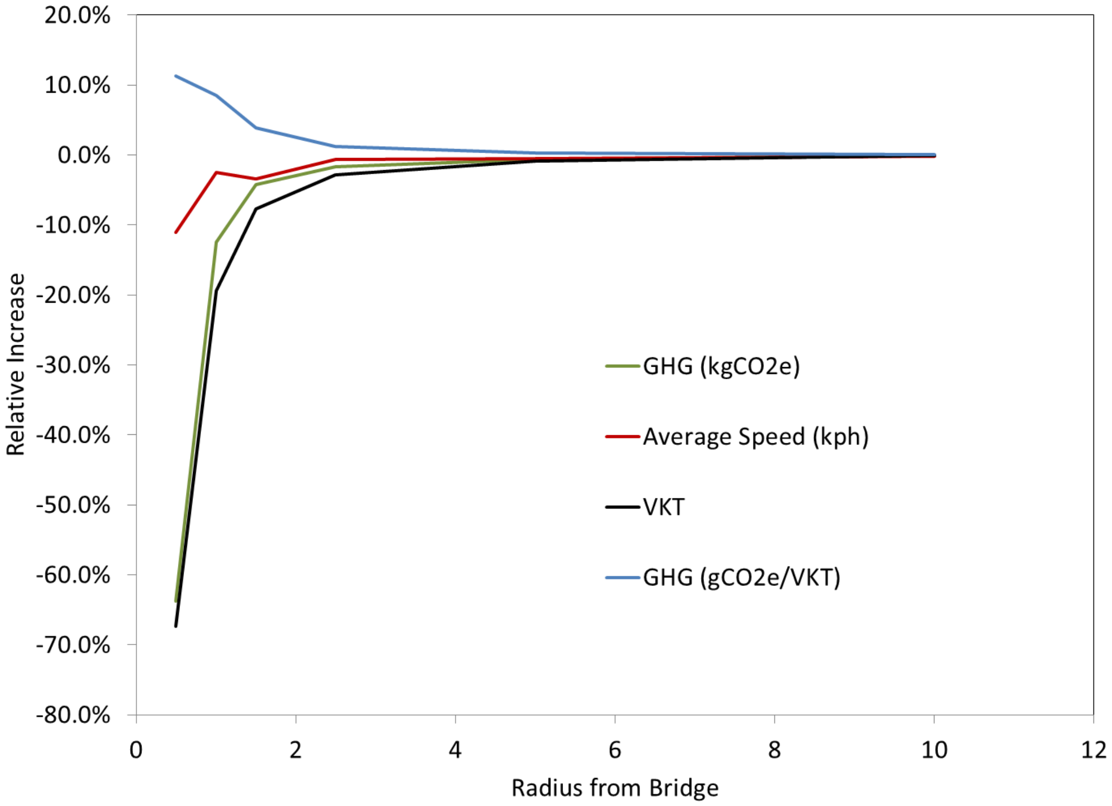


Figure 5.4: Correlation of changes in traffic and emissions with distance from bridge

illustrates the resulting link traffic volumes (as line width) and the specific GHG emission rates (as line colour). Figure 5.6 shows the relative changes in GHG emissions and traffic for the three different boundaries.

Considering only the freeway, a higher speed limit produces faster travel (by 5%) and a marginally lower specific GHG emission rate (by 1%) because of vehicle efficiency and smoother flow. However, the increased traffic on the link (up by 7%) raises overall GHG emissions along the freeway by 6%.

The extra traffic using the freeway is displaced from lower-speed, less-efficient links but must also drive further to access the freeway. Hence, it is necessary to study a larger region to determine whether the greater efficiency of the freeway outweighs the resulting increase in vehicle kilometres travelled. The study is repeated with broader boundaries to capture the effects of traffic displacement. At the freeway + vicinity level, overall travel rises by 2% with a corresponding 1% increase in GHG emissions. This now covers about 3 times as much travel as the freeway itself and the result is interpreted to indicate that the extra travel of getting vehicles to/from the freeway still provides an overall increase in GHG emissions. However, at the urban region level, (encompassing 19 times as much travel as the freeway), the effect of reduced demand on other links across the region becomes apparent. As a result, the overall travel distance and overall GHG emissions still increase by a marginal amount but less than indicated by the freeway vicinity itself.

This case illustrates the advantages of using a micro-simulation in tandem with a travel demand model. The simplified transportation micro-simulation captures the increase in efficiency that results from the change to the freeway, and the transportation demand model results that are used to generate the micro-simulation ensure that the traffic increase is modelled.

Another interesting result of this study was the change in oxides of nitrogen (NO_x) in relation to the area that was modelled. Figure 5.7 shows the relative changes in

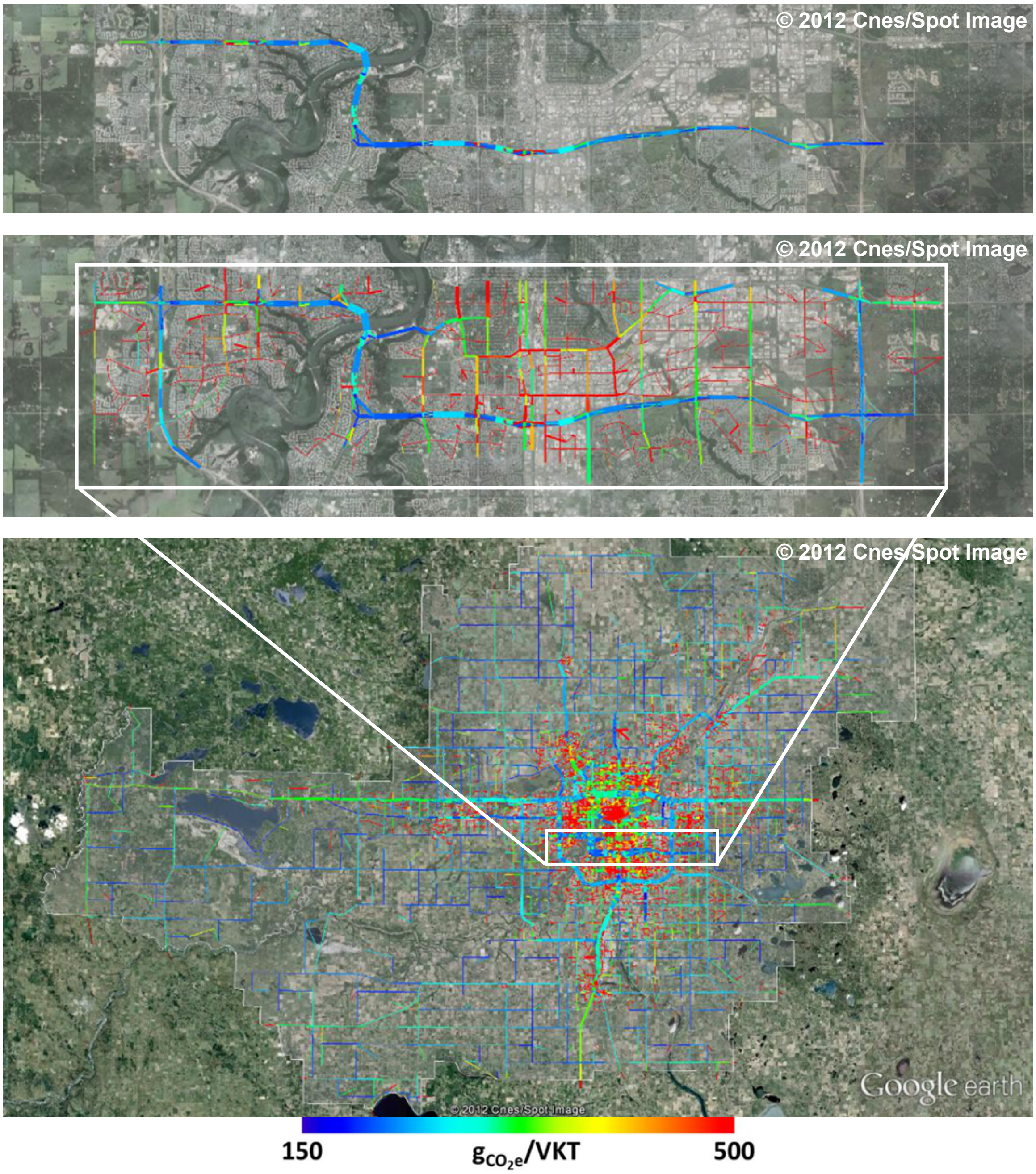


Figure 5.5: Freeway study model boundaries. Top: freeway only. Centre: freeway and immediate vicinity. Bottom: metropolitan region

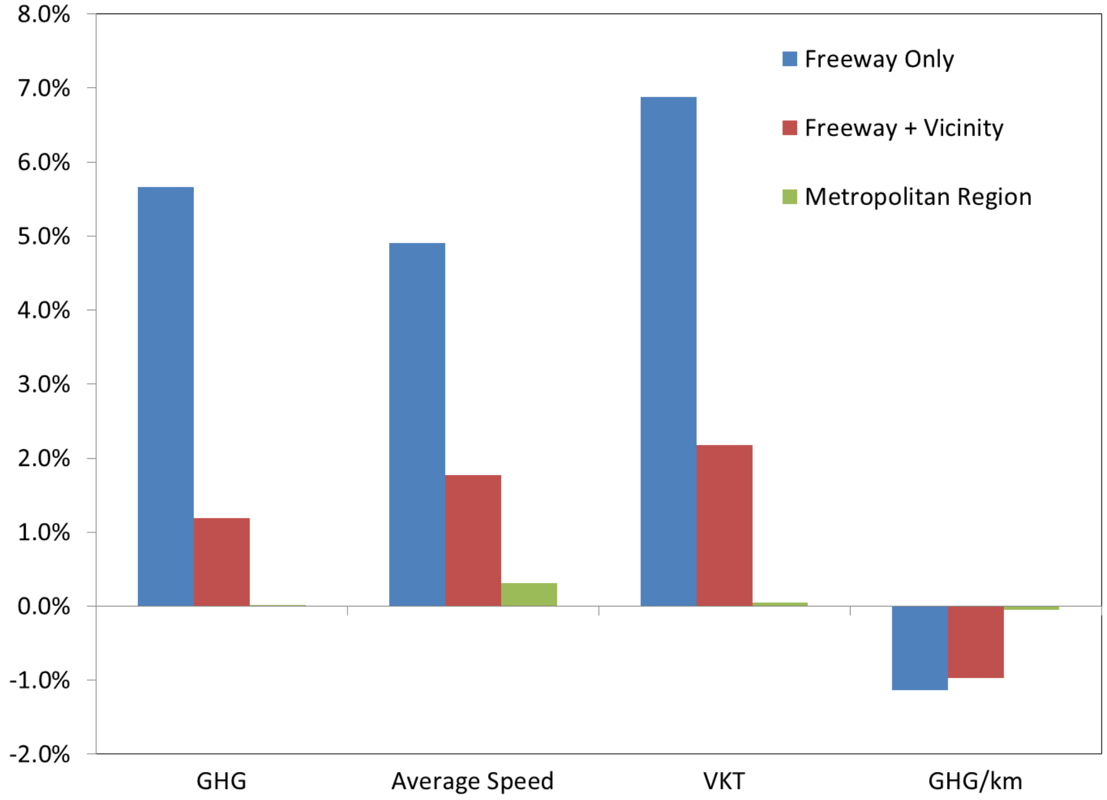


Figure 5.6: Correlation of changes in traffic and GHG emissions and model area

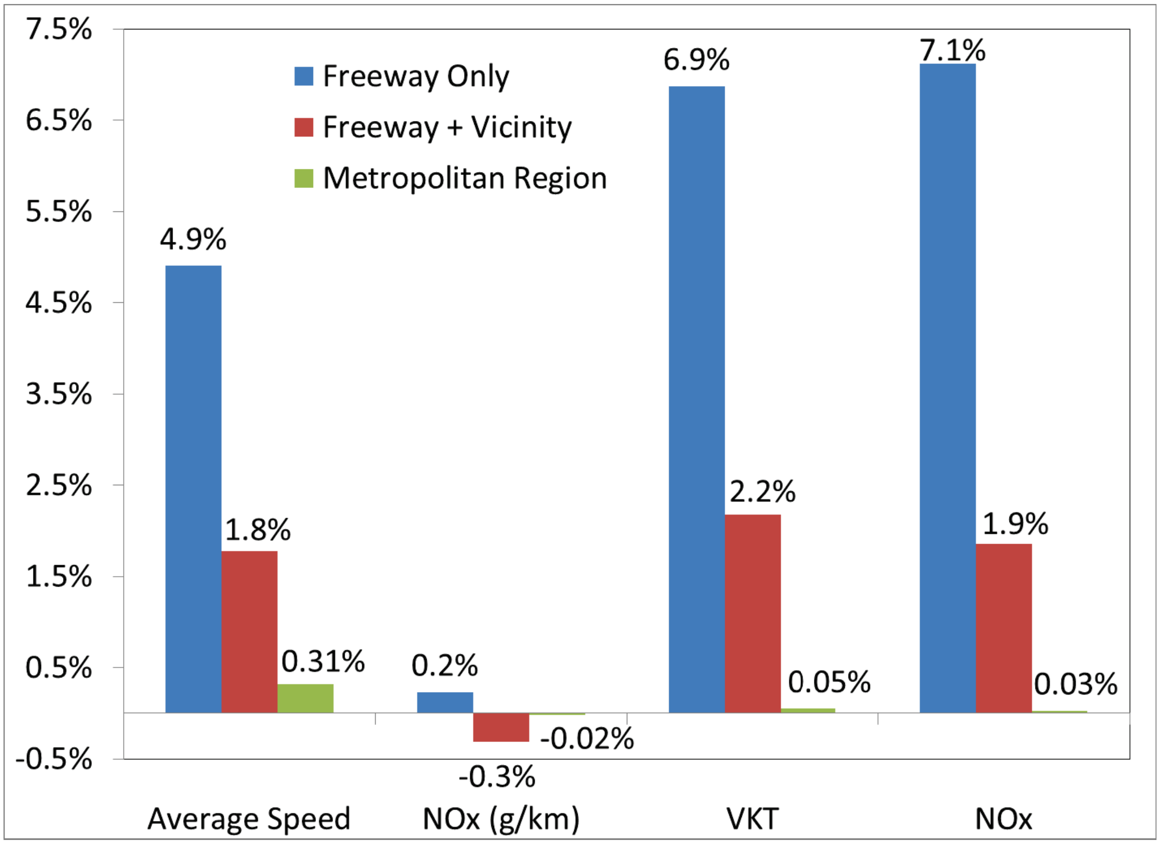


Figure 5.7: Correlation of changes in traffic and NO_x emissions and model area

NO_x emissions compared with the relative changes in traffic (VKT) and average speed. The higher speed on the freeway demands more engine power, and results in a higher per kilometre rate of NO_x emissions. However, when accounting for the roads in the vicinity of the freeway and for the whole region, there are net decreases in the per kilometre rate of NO_x emissions. Ultimately this means that the increased speed limit results in a more concentrated increase of NO_x emissions on the freeway than over the whole region. This result is only captured by a model that can simulate a large region and makes use of a realistic emissions model that responds to changes in vehicle power. If the whole region were modelled without responding to power appropriately, the NO_x emissions on the freeway would be underestimated.

5.3.2 Ring Road Signalization

The second scenario in traffic control measures examines changing a section of a major outer ring road from signalized intersections to free flowing interchanges. The distance specific GHG emission maps are shown in figure 5.8 and the change in traffic and emissions in the vicinity of the road and within the metropolitan are shown in figure 5.9. This type of development on a high-speed outer ring road is expected to improve travel times and figure 5.9 confirms the average speed improvement both locally (5% for the ring road and vicinity) and over the whole metropolitan region (0.6%, which is significant considering the relatively small area receiving interchanges). The efficiency of the vehicles on the network also improves as is indicated by reduced distance-specific GHG emissions (3.2% lower in the vicinity and 0.3% averaged over the entire region). However, given the peripheral nature of the outer ring road, vehicle mileage increases significantly to access that increased capacity and thus overall traffic volume (measured by vehicle kilometres travelled) increases significantly (by 6% for the vicinity and 1% over the urban region).

Ultimately this case study shows that increasing the capacity and average speed of the ring road on this network results in a significant increase in overall GHG emissions. This presents a dilemma for transportation planners; the increases in capacity and average speed are desirable but the increase in GHG emissions is not. It is likely that increasing demand as a result of a growing population and urban footprint would have caused an increase in congestion in the future. This would be partially alleviated by the improvement in capacity and average speed, and could lead to lower GHG emissions in future scenarios. The simplified transportation micro-simulation can efficiently evaluate multiple present and future scenarios and help to inform decisions that have long-lasting effects.

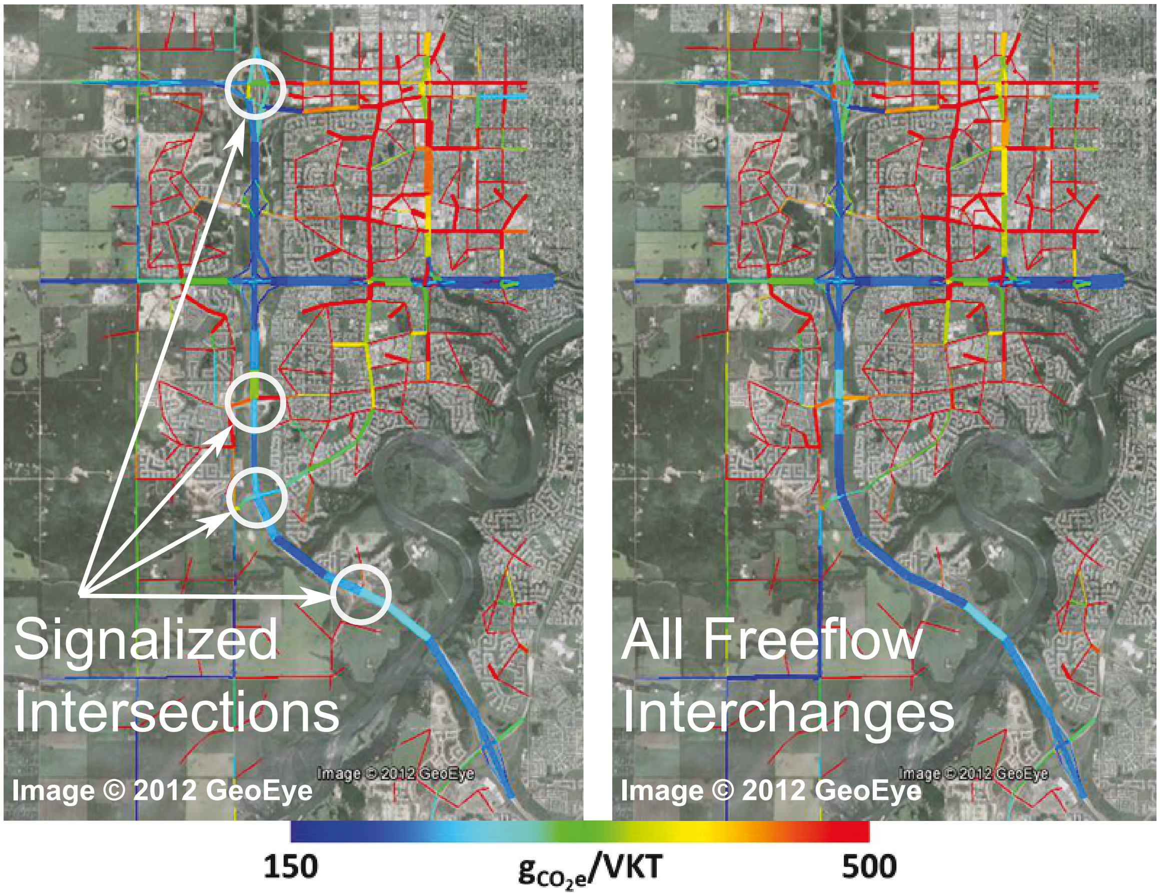


Figure 5.8: Distance specific emissions for the ring road study

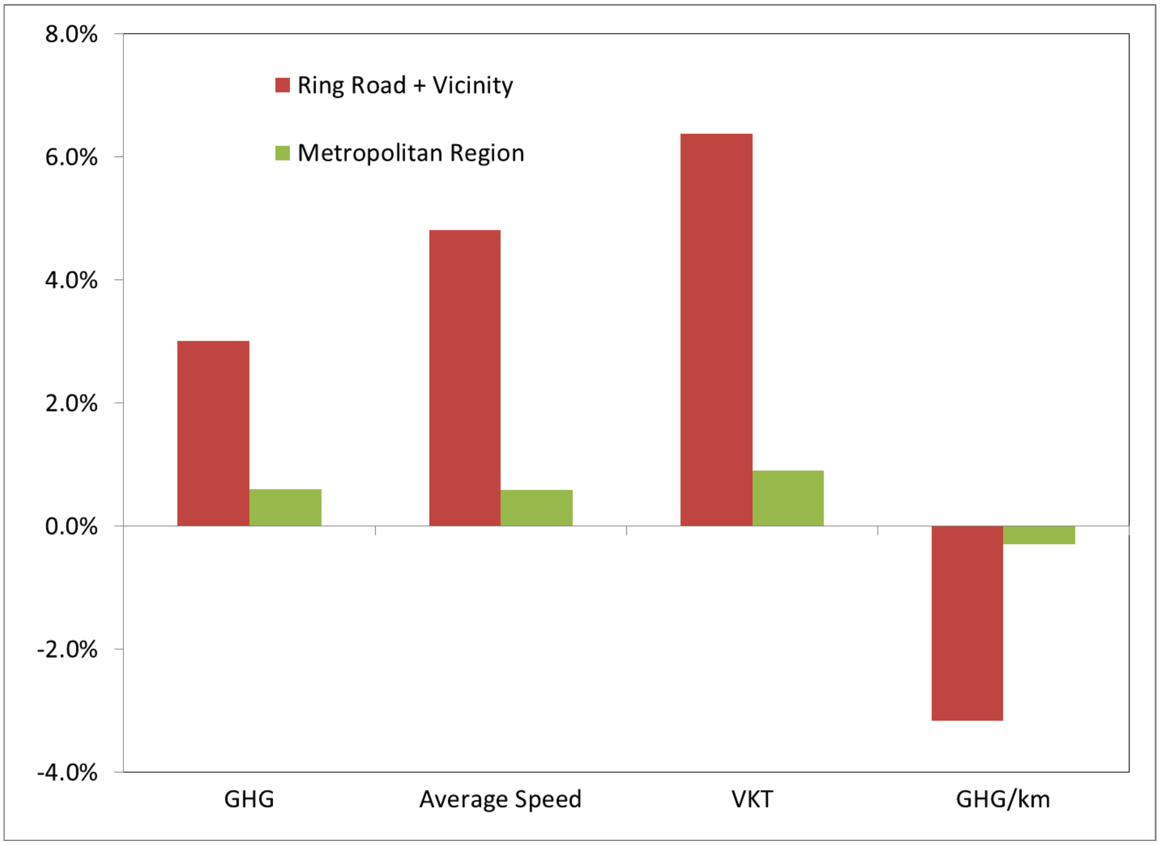


Figure 5.9: Correlation of changes in traffic and emissions and distance from bridge

5.4 Comparison of Simplified Emissions Micro-simulation to Third-party Interaction-based Micro-simulation

The case study used to compare the effectiveness of the simplified micro-simulation to the interaction-based VISSIM micro-simulation is one in which traffic turning onto a large urban arterial is causing congestion (Design Option 1) and the alternative design would re-route that traffic to a larger, more efficient neighbouring intersection (Design Option 2). The case study in this paper aims to answer two questions; (1) "how does the change in infrastructure design impact the emissions at the link level when modelled with VISSIM, and with the simplified micro-simulation?", and (2) "is the simplified micro-simulation capable of generating equally useful results at the link and network level"?

The main simulation parameters for the two design options and both micro-simulations are shown in table 5.1 below. Because the simplified micro-simulation does not generate trips, but rather generates trajectories based on supplied link characteristics, it requires no warm-up time to fill the network. For the VISSIM simulations a "warm-up time" of 3000 seconds was used to fill the network with a stable traffic flow, based on the United States Federal Highway Association's recommendation that the minimum warm-up time for such micro-simulations be no less than twice the time required for a vehicle to traverse the network unhindered by traffic [78]. The micro-simulation results eventually showed that this free-flow travel time was approximately 1400 seconds, making a 3000 second warm-up time slightly conservative. The total road length changes little between the two design options, since the change to the network is small and localized at a single intersection. The number of links (which includes connectors in VISSIM) is around five times higher for the more detailed VISSIM model which includes individual lanes and ramps; the average link length for the simplified micro-simulation is 0.5 km in contrast with the aver-

	Design 1		Design 2	
	simplified micro-simulation	VISSIM	simplified micro-simulation	VISSIM
Simulation period*	6000 s	9000 s	6000 s	9000 s
Runtime** (h:mm:ss)	0:01:06	3:48:18	0:01:05	3:52:25
Number of Links	199	1173	200	1177
Total VKT	247,573		249,168	
Average Speed (km/hr)	37.6		40.1	

*VISSIM model includes 3000 s warm-up to fill network

**Time for micro-simulation only using Windows XP 32-bit, 3 GHz Intel Core 2 Duo E8400, 3 Gb RAM

Table 5.1: Micro-simulation parameters for micro-simulations applied to two intersection design options

age VISSIM link length of 0.09 km. The total VKT and average speed are slightly higher for Design Option 2, presumably due to the increase in network efficiency. The run times for the simplified micro-simulation are significantly lower than for VISSIM: about one minute for the simplified micro-simulation compared to nearly 4 hours for VISSIM.

The results of the case studies are presented at both aggregate and localized levels. The aggregated inventory shows the potential improvement of the studied design options within the complete domain. The localized graphical results show the improvement in local GHG emissions.

5.4.1 Overall Tractive Energy and GHG Emission Results

Table 5.2 shows the energy and GHG emission results of both design options. Both the simplified micro-simulation and VISSIM micro-simulations show a slight increase in tractive energy requirements from Design Option 1 to Design Option 2, presumably because of the increase in average speeds. (Aerodynamic drag increases with the square of velocity, giving a non-linear increase in tractive effort as speeds rise.) However, the energy increases are very small (less than 0.4%) and both modelling ap-

	simplified micro-simulation		VISSIM	
	Design 1	Design 2	Design 1	Design 2
Tractive Energy (kWh)	43,919	43,951	34,007	34,019
GHG Emissions (kg)	55,561	54,403	47,419	46,351
Relative Tractive Energy	1.00		1.00	
Relative GHG Emissions	0.98		0.98	

Table 5.2: Micro-simulation results for two intersection design options

proaches show that GHG emissions decrease by 2% from Design Option 1 to Design Option 2. This apparently contrary result arises because vehicles travelling closer to the free speed with less congestion are able to operate at higher efficiency. These results indicate that the simplified micro-simulation provides an equivalent prediction of the environmental impact of micro-scale design features when compared to a more detailed interaction-based micro-simulation such as VISSIM. It is notable that the simplified micro-simulation estimates for tractive energy and GHG emissions are 21% and 12% higher than those for VISSIM respectively; however, the relative increases modelled between design options are similar.

5.4.2 Tractive Energy and GHG Emissions by Vehicle Class

The improvement in tractive energy and GHG emissions is more pronounced for small light duty vehicles (MOBILE6 classes LDV, LDT1, and LDT2) than for larger light duty vehicles (MOBILE6 classes LDT3 and LDT4), as the results in tables 5.3 and 5.4 show. In fact, while the tractive energy used and GHG produced by small light duty vehicles decreases for Design Option 2 in both simulations, the tractive energy usage for large light duty vehicles increases.

	simplified micro-simulation		VISSIM	
	Design 1	Design 2	Design 1	Design 2
Tractive Energy (kWh)	41,211	41,243	32,475	32,469
GHG Emissions (kg)	52,240	51,133	45,372	44,300
Relative Tractive Energy	1.00		1.00	
Relative GHG Emissions	0.98		0.98	

Table 5.3: Micro-simulation results for LDV, LDT1, and LDT2 vehicles for two intersection design options

	simplified micro-simulation		VISSIM	
	Design 1	Design 2	Design 1	Design 2
Tractive Energy (kWh)	2,708	2,709	1,532	1,550
GHG Emissions (kg)	3.321	3,270	2,047	2,050
Relative Tractive Energy	1.00		1.01	
Relative GHG Emissions	0.98		1.00	

Table 5.4: Micro-simulation results for LDT3 and LDT4 vehicles for two intersection design options

5.4.3 Localized Graphical Results

Figure 5.10 shows emission maps of the intersection from which turning traffic is rerouted to the neighbouring intersection. The improvement in the network is immediately apparent on several of the short VISSIM links, which change from red (high emission rate) to orange (moderate emission rate). The improvement is also apparent in the simplified micro-simulation representations shown in the bottom plots; however, it is less apparent since fewer links are modelled and the resulting changes are averaged over fewer, larger links. The more detailed VISSIM model can serve to pinpoint not only relatively large links, but also individual lanes and connectors which are particularly high emitting. While the simplified micro-simulation is likely a good candidate for many studies, there is still a need for more detailed micro-simulations if such fine detail is required in the results. It is for this reason that third-party micro-

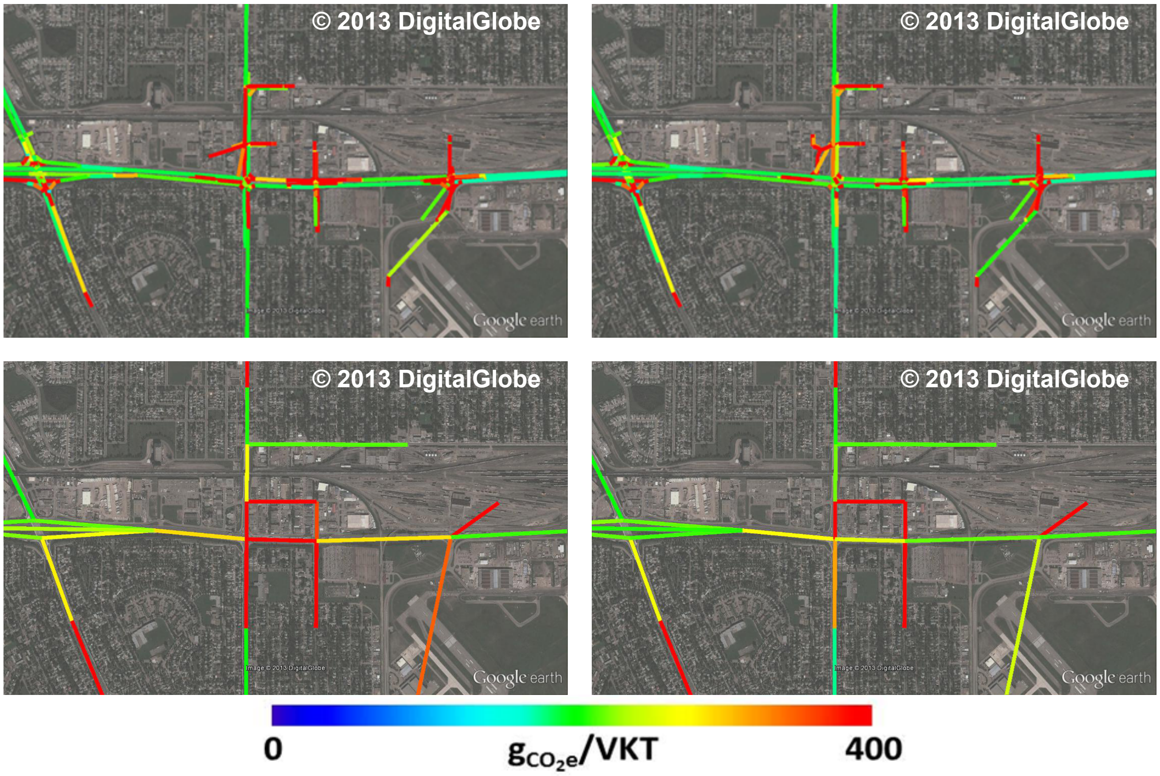


Figure 5.10: VISSIM (top) and simplified micro-simulation (bottom) visualizations for design option 1 (left) and design option 2 (right)

simulation results can be analyzed by the inventory tool described in this dissertation.

The simplified transportation emissions micro-simulation can be used to model the effects of changes to infrastructure such as the intersection redesign shown in this case study. This key capability gives transportation infrastructure designers a tool that can be used to focus on local projects, and still model large regions to ensure that traffic shifting, mode shifting, and other effects that affect larger areas are not overlooked.

CHAPTER 6

CONCLUSION

This dissertation presents the development of a simplified transportation emissions micro-simulation tool and its uses for transportation design and planning. Transportation emissions are a substantial contributor to overall air pollution and are costly in terms of financial burden and quality of life. Hence, it is important to reduce transportation emissions through informed policy decisions, planning activities, and infrastructure design. The effects of proposed transportation plans, policies, and infrastructure projects can be predicted using appropriate transportation models. Ideally, large-scale transportation micro-simulation models can be used while also resolving the important effects of traffic congestion and driving behaviour. Current transportation micro-simulations are too detailed and computationally expensive for large-scale models such as metropolitan regions. This work presents the development of a simplified transportation micro-simulation integrated into an inventory tool that is capable of efficiently modelling metropolitan regions and resolving the effects of traffic congestion and driving behaviour. The performance of the model was investigated using confidence assessment techniques, and application studies were used to demonstrate the utility of the tool. The following sections outline specific contributions of this dissertation.

6.1 Development of the Simplified Emissions Micro-simulation

The simplified micro-simulation explicitly models congestion on a link-by-link basis. One vehicle trajectory is generated for each class of vehicle on each link. This approach efficiently models link-by-link emissions without the complexity of vehicle interactions. The simplified micro-simulation algorithm includes acceleration rates that vary as a function of vehicle speed, and is analytical rather than iterative. This acceleration model is based on real-world driving data. The analytical vehicle movements are efficiently solved and reduce the iteration required to define driving behaviour on each link. The simplified micro-simulation has also been coded for task-parallel processing of links, further improving run times on multi-threaded systems.

6.2 Confidence of the Simplified Emissions Micro-simulation Approach

The confidence assessment carried out in this study indicated several notable differences between the traffic generated by the simplified micro-simulation for the Edmonton Metropolitan Region transportation model and a dataset of recorded driving behaviour in the same region (the Edmonton dataset). First, the simplified micro-simulation underestimates the amount of time that vehicles spend idling. Second, it also tends to favour common free speeds that are associated with the common speed limits in the model (30, 50, 60, 70, 80, 90, and 100 km/hr). Lastly, the simplified micro-simulation does not capture the intermediate levels of acceleration that are seen in real traffic, as vehicles are either cruising (zero acceleration) or accelerating at an average level.

The simplified micro-simulation was then compared to a large database of driving data from a major Canadian municipality (the Winnipeg dataset). The tractive energy, gasoline fuel consumption, CO, NO_x, HC, and $PM_{2.5}$ emissions were calculated using the tractive power and emissions models built into the inventory tool. This dataset includes speed limit data, and allows for a comparison between energy, fuel consumption and emissions estimates for real driving data and for the simplified micro-simulation. The comparison showed that the gasoline fuel consumption and CO and HC emissions estimates for the simplified micro-simulation fit the mean trends of the Winnipeg dataset within the 95% confidence ranges. The tractive energy and NO_x and $PM_{2.5}$ emissions were within the 95% confidence intervals of the mean trends of the Winnipeg dataset and generally exhibited similar trends. The simplified micro-simulation algorithm results in small step changes in the tractive energy trend as congestion increases on links. As a result the NO_x and $PM_{2.5}$ emissions, which are strongly dependent on engine power, also show these step changes.

This part of the confidence assessment revealed certain limitations of the simplified emissions micro-simulation. In particular, the energy, NO_x emissions, and $PM_{2.5}$ emissions are overestimated for congested links with an average speed that is less than 20% of their free speed. This level of congestion is extreme, and should be rare in a transportation model. The study also indicated that these criteria may be overestimated for shorter links, and the limitations of the data available for the assessment introduced some uncertainty into the comparison for longer links. A database that includes complete GPS coordinates that can be matched to a transportation demand model would resolve this source of uncertainty.

In the final confidence assessment study, the inventory tool as a whole is compared with the City of Edmonton fuel sales estimates. The model estimate is 8% higher than the sales estimate for gasoline fuel. Considering the uncertainty inherent of both estimates, their similarity is encouraging in terms of overall model validation.

In addition to the confidence assessment studies, the simplified micro-simulation was also compared to the VISSIM micro-simulation. The simplified micro-simulation estimates of tractive energy and tailpipe CO_2 emissions were 9% and 19% higher than those of the more detailed VISSIM micro-simulation. However, both the simplified micro-simulation and the VISSIM micro-simulation predicted similar changes in CO_2 emissions for simulations which compared two intersection designs. This result demonstrated the ability of the simplified micro-simulation to resolve localized changes in transportation infrastructure.

6.3 Simplified Transportation Micro-simulation as a Design Tool

The application studies presented in chapter 5 demonstrate several key features of the simplified transportation micro-simulation approach and of the inventory tool. The simplified transportation micro-simulation approach is differentiated from tools currently used to model transportation emissions by its ability to micro-simulate large-scale models using conventional computers quickly enough to be useful for design studies[1]. The simplified micro-simulation was over 200 times faster than the commercial interaction-based micro-simulation VISSIM on a model with 250,000 VKT, and this advantage would increase with model size.

The inventory tool presented in this work can be used to rapidly evaluate, compare, and optimize policy concepts. This is made possible by the sensitivity of the model to fleet changes including the technology level and age of vehicles, and by the efficiency of the simulation. It is practical with the simplified micro-simulation approach to evaluate several policy cases for an entire metropolitan region, and over several time periods (for example present-day, 10-year, and 35-year horizon studies).

The effects of traffic shifting and mode shifting that are captured by a transportation demand model can be simulated using the simplified transportation micro-simulation model. Emissions and energy and fuel consumption can be evaluated over a large area, and used to determine to what extent infrastructure changes affect the

---

[1] The model for the Capital Region of the province of Alberta, Canada contains 94,210 links and is simulated in 59 minutes using a 32-bit Windows XP computer with a 3 GHz Intel Core 2 Duo E8400 processor and 3 Gb of RAM.

surrounding transportation network. Using transportation demand modelling results also ensures that any increase in demand that results from changes to the transportation network is captured. This is important for environmental inventory since increases in transportation efficiency often results in increased of use those facilities. Hence, an improvement to the transportation network may result in an increase in emissions and fuel consumption despite an improvement of travel efficiency.

Traffic congestion and driving behaviour are captured by the simplified micro-simulation. This means that it can be used to model a large area, but still resolve localized changes in traffic and driving behaviour. The simplified micro-simulation is able to model the combined effects of traffic shifting, mode shifting, traffic congestion, and driving behaviour in a single and efficient simulation step.

The simplified transportation emissions micro-simulation can be used to model the environmental effects of potential infrastructure designs. This capability gives transportation infrastructure designers a tool that can be used to evaluate localized projects, and ensure the larger-scale effects of traffic shifting, mode shifting, and increasing demand are not overlooked.

6.4 Future Research

This study has highlighted several areas that merit further investigation to improve the performance of this model, and to enhance the development and calibration of this model and other transportation emissions models.

Validation studies would be beneficial towards the development of this model, and for transportation emission models in general. There are two validation studies in particular that would provide insight for modellers and model developers: studies of driving behaviour to validate the vehicle movements predicted by micro-simulations, and bulk emission measurements that would yield a validation of the model against real-world emissions. While both of these types of studies are complex and challenging, there are current methods that can achieve them.

Tunnel studies are often used to measure emissions in a defined and closed space. This is useful for emissions modelling because it isolates vehicle emissions from other sources. An additional level of detail that would allow for a complete validation of transportation emissions micro-simulations would be to also capture the instantaneous speeds of vehicles traversing the tunnel, as well as their make, model, and age.

Building a database of second-by-second driving records from cars in traffic that includes, at minimum: GPS coordinates, vehicle speed, and speed limit (or free speed) would allow for improved calibration of simulation models. Additional useful data would include coolant temperature, fuel flow rate, and accelerator pedal position (notably, these parameters are broadcast by the on-board computers of most modern North American vehicles). Such a database could be used to calibrate and validate:

1. the acceleration behaviour of micro-simulation models,
2. fuel consumption models, and
3. the link-average performance of the simplified micro-simulation model.

This most unique feature of this database would be the inclusion of the speed limit (or free speed), which can be done with roadside transmitters and in-car receivers, or can be done off-line by post-processing GPS coordinates. Both methods present unique challenges; however, the benefits to transportation emission models are considerable. Many models use a facility type (i.e. freeway or arterial) and average speed to determine the level of congestion, and would benefit from a more rigorous determination of congestion. The free speed and average speed are much more powerful variables in terms of determining congestion, and should be pursued further as parameters that can improve estimation of congestion effects on transportation emissions and fuel consumption. Recording data that can be used to study the interaction of these parameters is an important step in this regard.

There have been considerable efforts made to model the transportation emissions of metropolitan areas, and to some extent the Census Divisions in Alberta. However, a province-wide model would provide an informative comparison to provincial inventories of transportation emissions. Provincial inventories can be estimated based on vehicle registration data and VKT models, and a province-wide emissions micro-simulation would help inform policy decisions regarding the allocation of provincial transportation resources to most effectively reduce emissions. Modelling an entire province is not beyond the capability of this micro-simulation. Congested links, which occur mainly in the metropolitan regions currently modelled, require considerably more computational effort than the typically free-flowing rural links that make up the majority of the province.

Finally, particulate emissions regulations and measurement are rapidly evolving and with the information that is becoming available with these advancements, it is important to update the particulate emissions models that are in use. Regulations are moving towards both mass and number restrictions on particles and as vehicle technology changes as a result of these regulations it will be important to capture relevant and accurate estimates in transportation emission models.

BIBLIOGRAPHY

[1] Ec.gc.ca, “Environment canada - air - 4.4.2 - human health costs.” online, 2013. Available at :http://www.ec.gc.ca/air/default.asp?lang=En&n=085A22B0-1.

[2] S. Daley, “Analysis of the air quality health index in canadian urban centres,” tech. rep., Prepared for Envrionment Canada, 2010.

[3] H. Chen and R. Copes, “Review of air quality index and air quality health index,” tech. rep., Public Health Ontario, 2013.

[4] “Alberta air emissions trends and projections,” tech. rep., Alberta Environment Air Policy Branch, 2008.

[5] D. I. Handford and M. D. Checkel, “Emissions inventories for transportation planning and environmental purposes,” in *TRANSLOG 2011, McMaster Institute for Transportation and Logistics*, (Hamilton, ON), 2011.

[6] R. Smit, A. L. Brown, and Y. C. Chan, “Do air pollution emissions and fuel consumption models for roadways include the effects of congestion in the roadway traffic flow?,” *Journal of Environmental Modelling and Software*, vol. 23, pp. 1262–1270, 2008.

[7] K. Zhang, S. Batterman, and F. Dion, “Vehicle emissions in congestion: Comparison of work zone, rush hour, and free-flow conditions,” *Atmospheric Environment*, vol. 45, pp. 1929–1939, 2011.

[8] Q. Gan, J. Sun, W. Jin, and J. Saphores, "Incorporating vehicular emissions into an efficient mesoscopic traffic model: An application to the alameda corridor," tech. rep., University of California Transportation Center, UC Berkeley, 2011.

[9] D. D. Parrish, "Critical evaluation of us on-road vehicle emission inventories," *Atmospheric Environment*, vol. 40, pp. 2288–2300, 2006.

[10] United States Environmental Protection Agency, *Motor Vehicle Emission Simulator (MOVES) 2010 User Guide*, 2009.

[11] B. Liu and H. C. Frey, "Development of a simplified version of moves and application to iterative case studies," in *Proceedings, 106th Annual Meeting of the Air & Waste Management Association*, 2013.

[12] R. A. Giannelli, E. K. Nam, K. Helmer, T. Younglove, G. Scora, and M. Barth, "Heavy-duty diesel vehicle fuel consumption modeling based on road load and power train parameters," No. 2005-01-3549 in SAE Technical Paper, 2005.

[13] S. Bai, D. Eisinger, and D. Niemeier, "Moves vs. emfac: A comparison of greenhouse gas emissions using los angeles county," Transportation Research Board 2009 Annual Meeting, 2009.

[14] J. Lin, Y. Chiu, S. Vallamsundar, and S. Bai, "Integration of moves and dynamic traffic assignment models for fine-grained transportation and air quality analyses," in *Integrated and Sustainable Transportation Systems, 2011 IEEE Forum*, pp. 176–181, 2011.

[15] California Air Resources Board, *EMFAC2007: Calculating emission inventories for vehicles in California*, 2007.

[16] M. Barth, C. Malcolm, T. Younglove, and N. Hill, "Recent validation efforts for a comprehensive modal emissions model," *Transportation Research Record: Journal of the Tranpsortation Research Board*, vol. 1750, pp. 13–23, 2001.

[17] E. M. Fujita, D. E. Campbell, B. Zielinska, J. C. Chow, C. E. Lindhjem, A. Den-Bleyker, G. A. Bishop, B. G. Schuchmann, D. H. Stedman, and D. R. Lawson, "Comparison of the moves2010a, mobile6.2, and emfac2007 mobile source emission models with on-road traffic tunnel and remote sensing measurements," *Journal of the Air & Waste Management Association*, vol. 62, pp. 1134–1149, 2012.

[18] L. Ntziachristos and Z. Samaras, "Copert iii computer program to calculate emissions from road transport," Tech. Rep. Technical Report 49, European Environmental Agency.

[19] Z. Huang and X. Ma, "Integration of emission and fuel consumption computing with traffic simulation using a distributed framework," in *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems.*

[20] H. C. Frey, K. Zhang, and N. M. Rouphail, "Vehicle-specific emissions modeling based upon on-road measurements," *Environmental Science and Technology*, vol. 44, pp. 3594–3600, 2010.

[21] S. D. Shah, K. C. Johnson, J. W. Miller, , and D. R. C. III, "Emission rates of regulated pollutants from on-road heavy-duty diesel vehicles," *Atmospheric Environment*, vol. 40, pp. 147–153, 2006.

[22] *ARTEMIS: Assessment and reliability of transport emission models and inventory systems: final report.*

[23] M. Andre, M. Keller, A. Sjodin, M. Gadrat, and I. McCrae, "The artemis european tools for estimating the pollutant emissions from road transport and their application in sweden and france," in *Proceedings of the 17th International Symposium Transport and Air Pollution*, 2008.

[24] I. Fomunung, S. Washington, R. Guensler, , and W. Bachman, "Validation of the measure automobile emission model: A statistical analysis," *Journal of Transportation and Statistics*, 2000.

[25] M. A. and D. V. Vliet, "A model of air pollution from road traffic, based on the characteristics of interrupted flow and junction control: Part i model description," in *Transportation Research Part A: Policy and Practics*, vol. 26, pp. 315–330, 1992.

[26] M. A. and D. V. Vliet, "A model of air pollution from road traffic, based on the characteristics of interrupted flow and junction control: Part ii model results," in *Transportation Research Part A: Policy and Practics*, vol. 26, pp. 331–355, 1992.

[27] S. Zegeye, B. De Schutter, H. Hellendoorn, and E. Breunesse, "A model-based predictive traffic control approach for the reduction of emissions," in *Proceedings of the 10th TRAIL Congress 2008 - TRAIL in Perspective - Selected Papers*, October 2008.

[28] M. Papageorgiou, I. Papamichail, A. Messmer, and Y. Wang, *Fundamentals of Traffic Simulation*, ch. Traffic Simulation with METANET. Springer, 2010.

[29] S. C. Inc., "2008 ghgenius update," tech. rep., Prepared for Natural Resources Canada, Office of Energy Efficiency, 2008.

[30] B. A. Weigel, F. Southworth, and M. D. Meyer, “Calculators to estimate greenhouse gas emissions from public transit vehicles,” *Transportation Research Record: Journal of the Transportation Research Board*, no. 2143, pp. 125–133, 2010.

[31] Argonne National Laboratories, United States Department of Energy, *Development and use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies*, 2001.

[32] M. A. Delucchi, *A Lifecycle Emission Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials.* Institute of Transportation Studies, University of California, Davis, California, 2003.

[33] S. Mandavilli, M. J. Rys, and E. R. Russell, “Environmental impact of modern roundabouts,” *International Journal of Industrial Ergonomics*, vol. 38, pp. 135–142, 2008.

[34] R. Akcelik, “Lane-by-lane modelling of unequal lane use and flares at roundabouts and signalised intersections: the sidra solution,” *Traffic Engineering & Control*, vol. 38, pp. 388–399, April 1997.

[35] D. Achtymichuk, “Investigating the effects of transportation infrastructure development on energy consumption and emissions,” Master’s thesis, University of Alberta.

[36] K. Ahn and H. Rakha, “The effects of route choice decisions on vehicle energy consumption and emissions,” in *Transportation Research Part D*, vol. 13, pp. 151–167, 2008.

[37] Y. Xie, M. Chowdhury, P. Bhavsar, and Y. Zhou, "An integrated modeling approach for facilitating emission estimations of alternative fueled vehicles," *Transportation Research Part D*, no. 17, pp. 15–20, 2012.

[38] L. Pelkmans, P. Debal, T. Hood, G. Hauser, and M. Delgado, "Development of a simulation tool to calculate fuel consumption and emissions of vehicles operating in dynamic conditions," in *Modeling for SI & Diesel Engines*, Fuels & Lubricants Meeting & Exhibition, Toulouse, France, SAE International, June 8-10 2004.

[39] R. Smit and J. McBroom, "Technical note: Use of microscopic simulation models to predict traffic emissions," *Road & Transport Research*, vol. 18, pp. 49–54, June 2099.

[40] K. Hirschmann, M. Zallinger, M. Fellendorf, and S. Hausberger, "A new method to calculate emissions with simulated traffic conditions," in *2010 13th International IEEE Annual Conference on Intelligent Transportation Systems*, pp. 33–38, September 2010.

[41] K. Kraschl-Hirschmann, M. Zallinger, R. Luz, M. Fellendorf, and S. Hausberger, "A method for emission estimation for microscopic traffic flow simulation," in *2011 IEEE Forum on Integrated and Sustainable Transportation Systems*, pp. 300–305, 2011.

[42] G. Song, L. Yu, and Y. Zheng, "Applicability of traffic microsimulation models in vehicle emissions estimates," *Transportation Research Record: Journal of the Transportation Research Board*, no. 2270, pp. 132–141, 2012. Transportation Research Board of the National Academies.

[43] M. Hatzopoulou and E. J. Miller, "Linking an activity-based travel demand model with traffic emission and dispersion models: Transports contribution to

air pollution in toronto," *Transportation Research Part D*, no. 15, pp. 315–325, 2010.

[44] J. H. Hao, M. Hatzopoulou, and E. J. Miller, "Integrating an activity-based travel demand model with dynamic traffic assignment and emission models," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2176, pp. 1–13, 2010. Transportation Research Board of the National Academies.

[45] A. Spence, S. Turksma, A. Schelling, T. Benz, J. Medevielle, I. McCrae, J. Jaaskelainen, and E. Boethius, "Methodologies for assessing the impact of its applications on co2 emissions," tech. rep., EC-METI Task Force, 2009.

[46] A. Stevanovic, J. Stevanovic, K. Zhang, and S. Batterman, "Optimizing traffic control to reduce fuel consumption and vehicular emissions," *Journal of the Transportation Research Board*, no. 2128, pp. 105–113, 2009.

[47] Z. Huang, "Dynamic emission prediction platform and its integration with microscopic traffic simulation," Master's thesis, Department of Information Technology, Uppsala University, 2009.

[48] Y. Qi, H. Teng, and L. Yu, "Microscale emission models incorporating acceleration and deceleration.," *Journal of Transportation Engineering*, vol. 130, no. 3, pp. 348–360, 2004.

[49] R. Smit, R. Smokers, and E. Rabe, "A new modelling approach for road traffic emissions: Versit+," *Transportation Research Part D*, vol. 12, pp. 414–422, 2007.

[50] R. Smit, M. Poelman, and J. Schrijver, "Improved road traffic emission inventories by adding mean speed distributions," *Atmospheric Environment*, vol. 42, pp. 916–926, 2008.

[51] H. Rakha, K. Ahn, and A. Trani, "Development of vt-micro model for estimating hot stabilized light duty vehicle and truck emissions," *Transportation Research Part D*, vol. 9, pp. 49–74, 2009.

[52] I. El-Shawarby, K. Ahn, and H. Rakha, "Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions," *Transportation Research Part D*, vol. 10, pp. 13–30, 2005.

[53] M. Jeihani, K. Ahn, A. G. Hobeika, H. D. Sherali, and H. A. Rakha, "Comparison of transims light duty vehicle emissions with on-road emissions measurements," *Journal of the Transportation Research Forum*, vol. 45, no. 1, pp. 87–89, 2006.

[54] A. Hobeika, "Transims fundamentals," tech. rep., Virginia Polytechnic University, 2005.

[55] R. Busawon and M. D. Checkel, "Calmob6: A fuel economy and emissions tool for transportation planners," in *2006 Annual Conference of the Transportation Association of Canada*, 2006.

[56] R. Busawon and M. Checkel, "Predicting on-road veicle emissions inventories," in *Association Quebecoise du Transport et des Routes (AQTR)*, (Quebec).

[57] R. Smit, L. Ntziachristos, and P. Boulter, "Validation of road vehicle and traffic emission models e a review and meta-analysis," *Atmospheric Environment*, vol. 44, pp. 2943–2953, 2010.

[58] A. Papson, S. Hartley, and K. Kuo, "Analysis of emissions at congested and uncongested intersections with motor vehicle emission simulation 2010," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2270, pp. 124–131, 2012. Transportation Research Board of the National Academies.

[59] L. I. Panis, C. Beckx, S. Broekx, I. De Vlieger, L. Schrooten, B. Degraeuwe, and L. Pelkmans, "Pm, nox and co2 emission reductions from speed management policies in europe," *Transport Policy*, vol. 18, pp. 32–37, 2011.

[60] M. Madireddy, B. De Coensel, A. Can, B. Degraeuwe, B. Beusen, I. De Vlieger, and D. Botteldooren, "Assessment of the impact of speed limit reduction and traffic signal coordination on vehicle emissions using an integrated approach," *Transportation Research Part D*, no. 16, pp. 504–508, 2011.

[61] K. Ahn, N. Kronprasert, and H. Rakha, "Energy and environmental assessment of high-speed roundabouts," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2123, pp. 54–65, 2009. Transportation Research Board of the National Academies.

[62] E. Jackson and L. Aultman-Hall, "Analysis of real-world lead vehicle operation for modal emissions and traffic simulation models," *Transportation Research Record: Journal of the Transportation Research Board*, no. 2158, pp. 44–53, 2010. Transportation Research Board of the National Academies.

[63] S. K. Zegeye, B. De Schutter, H. Hellendoorn, and E. Breunesse, "Model-based traffic control for balanced reduction of fuel consumption, emissions, and travel time," tech. rep., Delft University of Technology, 2009.

[64] M. Wang, W. Daamen, S. Hoogendoorn, and B. van Arem, "Estimating acceleration, fuel consumption, and emissions from macroscopic traffic flow data,"

Transportation Research Record: Journal of the Transportation Research Board, no. 2260, pp. 123–132, 2011. Transportation Research Board of the National Academies.

[65] D. Achtymichuk, "Weighing a bus using grey-box system identification," tech. rep., University of Alberta, 2009.

[66] D. Handford, "Canmoves user manual," tech. rep., University of Alberta, 2013.

[67] R. Busawon, "A software model for transportation emission inventories," Master's thesis, University of Alberta, 2006.

[68] G. Sovran and M. Bonn, "Formulae for the tractive-energy requirements of vehicles driving the epa schedules," *SAE Transactions*, no. 810184, 1981.

[69] J. B. Heywood, *Internal Combustion Engine Fundamentals.* New York: McGraw-Hill, 1988.

[70] *Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques*, vol. 1 of *2003 SAE Handbook*, ch. SAE Recommended Practice J1263, pp. 580–606. SAE International, February 1996. Section 26.

[71] M. Checkel, "Vehicle emissions project the city of edmonton transportation master plan," tech. rep., Prepared for the City of Edmonton, 1996.

[72] M. Checkel, "Truck and bus engine emissions the city of edmonton transportation master plan," tech. rep., Prepared for the City of Edmonton, 1996.

[73] N. R. Canada, "Comprehensive energy use database 1990-2010," tech. rep., Government of Canada Office of Energy Efficiency, 2011.

[74] P. Knepell and D. Arangno, *Simulation Validation: A Confidence Assessment Methodology.* John Wiley and Sons, 1993.

[75] S. S., E. L. Bibeau, and S. Filizadeh, “Statistical development of a new duty cycle for plug-in electric vehicles in a typical north american urban setting,” *IEEE Transactions on Vehicular Technology*, vol. 59, no. 8, pp. 3710–3719, 2010.

[76] D. I. Handford and M. D. Checkel, *Mitigating Climate Change*, ch. Emissions Models as a Design Tool for Urban Transportation Planners. Springer, 2013.

[77] I. P. on Climate Change, *Fourth Assessment Report: Climate Change 2007: The AR4 Synthesis Report*. Geneva: IPCC, 2007.

[78] Federal Highway Administration, *Guidelines for Applying Traffic Microsimulation Modeling Software*, vol iii ed. http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol3/sectapp_c.htm. Accessed July 27, 2012.

[79] *Variability of Heavy-Duty Vehicle Operating Mode Frequencies for Prediction of Mobile Emissions*, Air and Waste Management Association Annual Meeting, 1998.

[80] J. M. Kern, “Inventory and prediction of heavy-duty diesel vehicle emissions,” Master’s thesis, West Virginia University, 2000.

[81] D. K. D. B. H. Pelkmans, L. and G. Lenaers, “Influence of vehicle test cycle characteristics on fuel consumption and emissions of city buses,” International Spring Fuels & Lubricants Meeting, SAE International, 2001. SAE paper 2001-01-2002.

[82] N. H. T. S. Administration, “Historical cafe regulations,” tech. rep., Government of the United States of America. Last access August 8, 2013: http://www.nhtsa.gov/cars/rules/CAFE/HistoricalCarFleet.htm.

[83] S. C. Davis and S. W. Diegel, "Transportation energy data book: Edition 26," tech. rep., Oak Ridge National Laboratory, 2007.

[84] E. I. Administration, "Annual energy review 2008," tech. rep., United States Department of Energy, June 2009. Available at: http://www.eia.gov/totalenergy/data/annual/archive/038408.pdf.

[85] M. Weilenmann, P. Soltic, C. Saxer, A.-M. Forss, and N. Heeb, "Regulated and nonregulated diesel and gasoline cold start emissions at different temperatures," *Atmospheric Environment*, vol. 39, no. 13, pp. 2433 – 2441, 2005. 12th International Symposium, Transport and Air Pollution.

[86] I. ARCADIS Geraghty & Miller, "Update heavy-duty engine conversion factors for mobile6," tech. rep., United States Environmental Protection Agency, 2002. Report No. M6.HDE.004.

[87] M. Beardsley, D. Brzezinski, and V. Rao, "Mobile6 estimates of exhaust emissions for 1994 and later light duty diesel cars and trucks," tech. rep., United States Environmental Protection Agency, 2001. Report No. M6.EXH.011.

[88] D. Brzezinski and J. Gilmore, "Basic exhaust emission rates of open loop vehicles for mobile6," tech. rep., United States Environmental Protection Agency, 2001. Report No. M6.EXH.005.

[89] P. Enns, E. Glover, and P. Carey, "Determination of running emissions as a function of mileage for 1981-1993 model year light-duty cars and trucks," tech. rep., United States Environmental Protection Agency, 2002. Report No. M6.EXH.001.

[90] E. L. Glover and J. Koupal, "Determination of co basic emission rates, obd and i/m effects for tier 1 and later ldvs and ldts," tech. rep., United States Environmental Protection Agency, 2001. Report No. M6.EXH.009.

[91] J. Koupal and D. Brzezinski, "Update to the accounting for the tier 2 and heavy-duty 2005/2007 requirements in mobile6," tech. rep., United States Environmental Protection Agency, 2003. Report No. M6.EXH.013.

[92] J. W. Koupal, "Accounting for the tier 2 and heavy-duty 2005/2007 requirements in mobile6," tech. rep., United States Environmental Protection Agency, 2001. Report No. M6.EXH.004.

[93] J. W. Koupal and E. L. Glover, "Determination of nox and hc basic emission rates, obd and i/m effects for tier 1 and later ldvs and ldts," tech. rep., United States Environmental Protection Agency, 2001. Report No. M6.EXH.007.

[94] C. Lindhjem and T. Jackson, "Update of heavy-duty emission levels (model years 1988-2004+) for use in mobile6," tech. rep., United States Environmental Protection Agency, 1999. Report No. M6.HDE.001.

[95] J. D. Hawirko, "Modeling vehicle emission factors determined with an in-use & real-time emission measurement system," Master's thesis, University of Alberta, 2002.

[96] D. Handford, "Evaporative emissions in canmoves," tech. rep., University of Alberta, 2011.

[97] D. Handford, "Crankcase emissions in canmoves," tech. rep., University of Alberta, 2011.

[98] D. Handford, "Refuelling emissions in canmoves," tech. rep., University of Alberta, 2011.

[99] L. Gagnon, C. Belanger, and Y. Uchiyama, "Life-cycle assessment of electricity generation options: The status of research in year 2001," *Energy Policy*, vol. 30, pp. 1267–1278, 2002.

[100] P. of Alberta, "Emissions trading regulation," in *Environmental Protection and Enhancement Act*, Alberta Queen's Printer. Alberta Regulation 33/2006.

Appendix A

Graphical User Interface

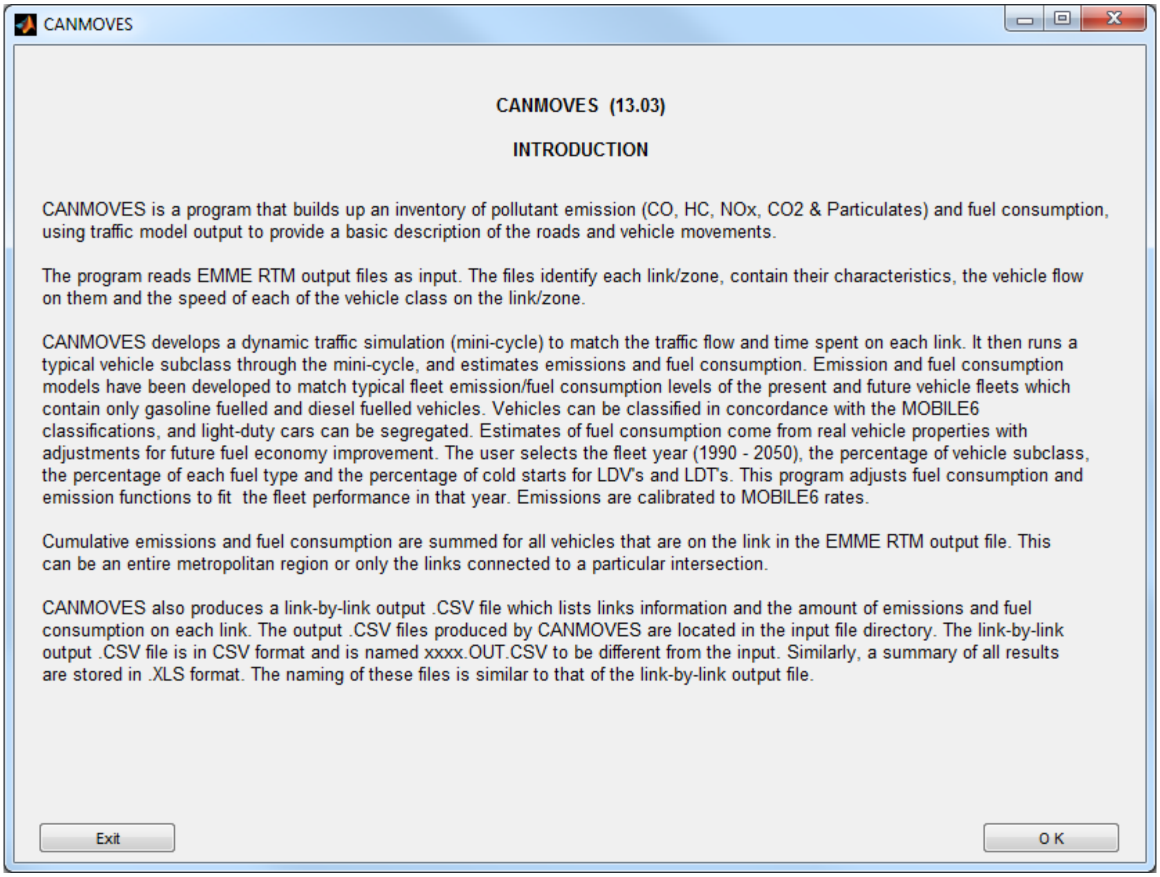
This appendix introduces the graphical user interface of the simplified micro-simulation inventory tool. The model inputs are shown in a brief description of the main simulation description windows.

A.1 Introduction Window

A model run is started by opening CANMOVES.exe. The introductory screen which gives a brief overview of the model appears, and is shown below. The user continues by selecting "OK" or cancels the simulation by selecting "Exit". Selecting "OK" will close the Introduction window and open the VDF Region window.

A.2 VDF Region Window

The VDF Region window allows users to select their region. This selection determines the set of default environmental conditions that can be selected later on in the simulation definition, as well as the Volume Delay Function (VDF) identifier for zones. The VDF zone identifier is used to differentiate zones from links: by default it is 99; for the City of Edmonton it is 99; and for the City of Calgary the VDF zone identifier is 40. Select "Edmonton" for this example, and then select "OK" to close the VDF Region window and open the Output Classification and Categorization window.



CANMOVES (13.03)

INTRODUCTION

CANMOVES is a program that builds up an inventory of pollutant emission (CO, HC, NOx, CO2 & Particulates) and fuel consumption, using traffic model output to provide a basic description of the roads and vehicle movements.

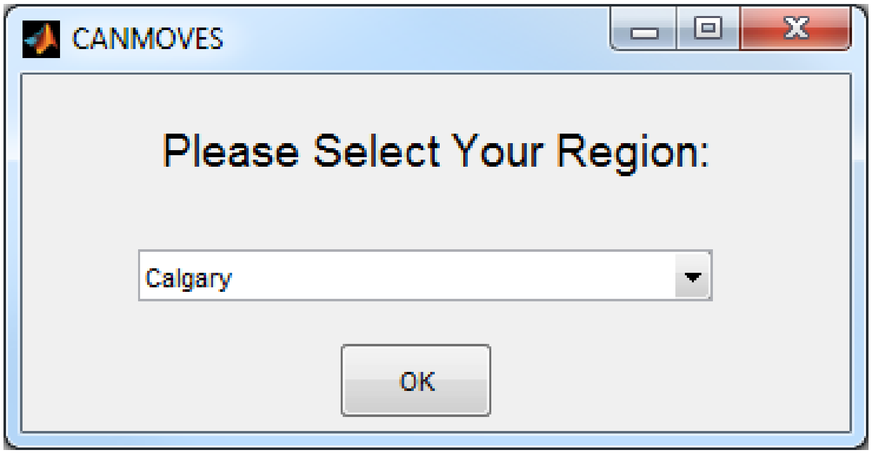
The program reads EMME RTM output files as input. The files identify each link/zone, contain their characteristics, the vehicle flow on them and the speed of each of the vehicle class on the link/zone.

CANMOVES develops a dynamic traffic simulation (mini-cycle) to match the traffic flow and time spent on each link. It then runs a typical vehicle subclass through the mini-cycle, and estimates emissions and fuel consumption. Emission and fuel consumption models have been developed to match typical fleet emission/fuel consumption levels of the present and future vehicle fleets which contain only gasoline fuelled and diesel fuelled vehicles. Vehicles can be classified in concordance with the MOBILE6 classifications, and light-duty cars can be segregated. Estimates of fuel consumption come from real vehicle properties with adjustments for future fuel economy improvement. The user selects the fleet year (1990 - 2050), the percentage of vehicle subclass, the percentage of each fuel type and the percentage of cold starts for LDV's and LDT's. This program adjusts fuel consumption and emission functions to fit the fleet performance in that year. Emissions are calibrated to MOBILE6 rates.

Cumulative emissions and fuel consumption are summed for all vehicles that are on the link in the EMME RTM output file. This can be an entire metropolitan region or only the links connected to a particular intersection.

CANMOVES also produces a link-by-link output .CSV file which lists links information and the amount of emissions and fuel consumption on each link. The output .CSV files produced by CANMOVES are located in the input file directory. The link-by-link output .CSV file is in CSV format and is named xxxx.OUT.CSV to be different from the input. Similarly, a summary of all results are stored in .XLS format. The naming of these files is similar to that of the link-by-link output file.

Figure A.1: Introduction Window



Please Select Your Region:

Calgary

Figure A.2: Region Selection Window

A.3 Output Categorization and Vehicle Classification and Window

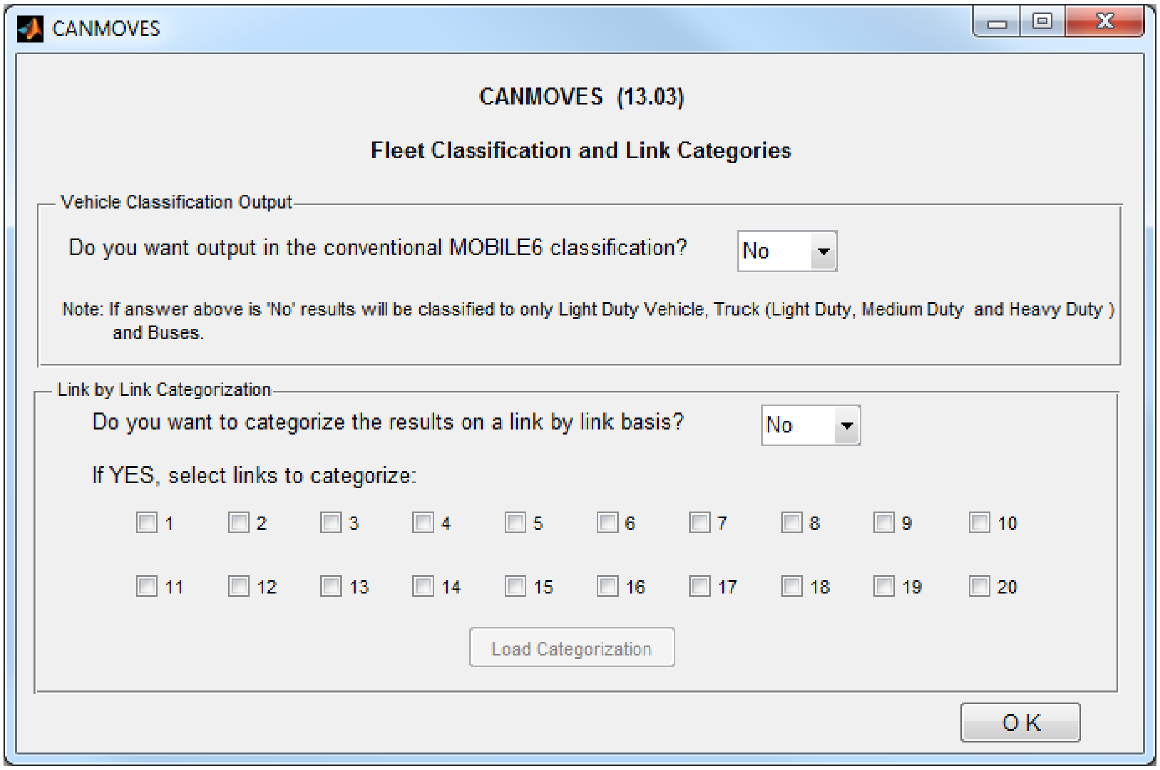
There are two options for vehicle classification: conventional MOBILE6 classification or the default inventory tool classification. MOBILE6 includes Mini, Economy, and Large cars in the LDV class, and LDT1-4 in the LDT class. The default inventory tool classification moves LDT1 and LDT2 into the LDV category. This better reflects the car-like driving behaviour of the smaller light duty trucks (LDT1 and LDT2, which include minivans, crossovers, small SUVs, and some large cars). This classification is used to model fleet behaviour in greater detail.

Link-by-link categorization allows the creation of separate results summaries for different kinds of links specified in a single transportation demand model (TDM) output file. This is useful to analyze specific geographic regions or time periods. For example, all links in the downtown core of the city could be identified as link category 1, and the AM peak period could be identified as link category 2. An overall results file will be created in addition to the two files defined for categories 1 and 2. This option will be discussed later in Model Parameters (Options) and Defaults. Selecting "OK" will close this window and open the Simulation Definition window.

A.4 Simulation Definition Window

The simulation definition window is used to define the time, environmental conditions, fleet characteristics, and output file for the run. The temperature will change automatically as a function of the simulation month and city, and can also be manually set. Atmospheric pressure is a function of elevation and can be manually set.

To run a simulation, a fleet file must be specified by selecting the "Browse" button and choosing a properly formatted fleet file. The fleet files contain the distribution of vehicles by class and fuel type, as well as the fraction of full and mild hybrids in the fleet. A TDM output file must also be specified by selecting the "Browse"



CANMOVES (13.03)

Fleet Classification and Link Categories

Vehicle Classification Output

Do you want output in the conventional MOBILE6 classification? No

Note: If answer above is 'No' results will be classified to only Light Duty Vehicle, Truck (Light Duty, Medium Duty and Heavy Duty) and Buses.

Link by Link Categorization

Do you want to categorize the results on a link by link basis? No

If YES, select links to categorize:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

☐ 11 ☐ 12 ☐ 13 ☐ 14 ☐ 15 ☐ 16 ☐ 17 ☐ 18 ☐ 19 ☐ 20

Figure A.3: Vehicle Categorization and Link Classification Window button and choosing a properly formatted TDM output file. This file defines the network parameters (link location, grade, length, free speed, vehicle flows, average speeds, cold start percentage, VDF identifier, etc.). An important note here is that the TDM output files are created with a cold start distance specified during the TDM run. To fully capture the effects of cold starts, the cold start distance in the TDM run should be 4.5 km. This cold start distance must match the one in the Cold Start Distance drop-down list. If it does not, the cold start fractions may be discounted and concentrated improperly. Selecting the “Run” button will start the simulation. A progress box will appear and the calibration routines will run for roughly a minute (depending on the computer), followed by the link analysis.

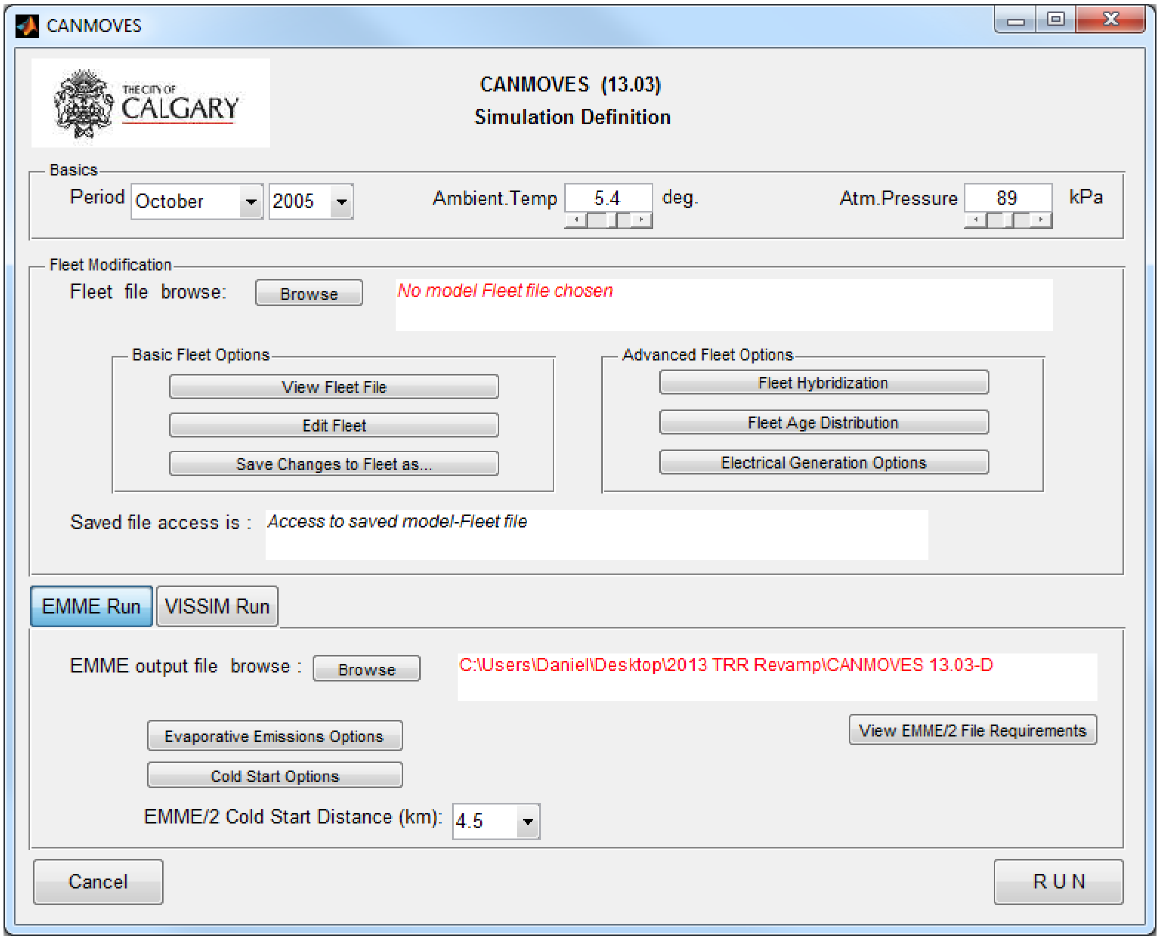
A.4.1 Fleet Options

The composition of the vehicle fleet can be modified by selecting the “Edit Fleet” button. The current composition can also be viewed by selecting the “View Fleet File” button. Note that to access either of these functions a fleet file must have already been selected through the “Browse” buttons dialog box. The fleet that is specified in the simulation can also be saved by selecting the “Save Changes to Fleet as...” button. Selecting the “Edit Fleet” button will bring up the Fleet Editing window, shown in figure A.5.

The fleet subclasses can then be modified by selecting the appropriate “Edit” buttons, or can be left out of the simulation by selecting the appropriate “Ignore” checkbox.

A.4.2 Fleet Age Distribution Window

Selecting the “Fleet Age Distribution” button will open the Fleet Age Distribution Modifications window. This window is used to change the age distribution of the fleet, either by directly modifying the age percentages in the edit boxes or by selecting the



CANMOVES (13.03)

Simulation Definition

Period: October 2005

Ambient.Temp: 5.4 deg.

Atm.Pressure: 89 kPa

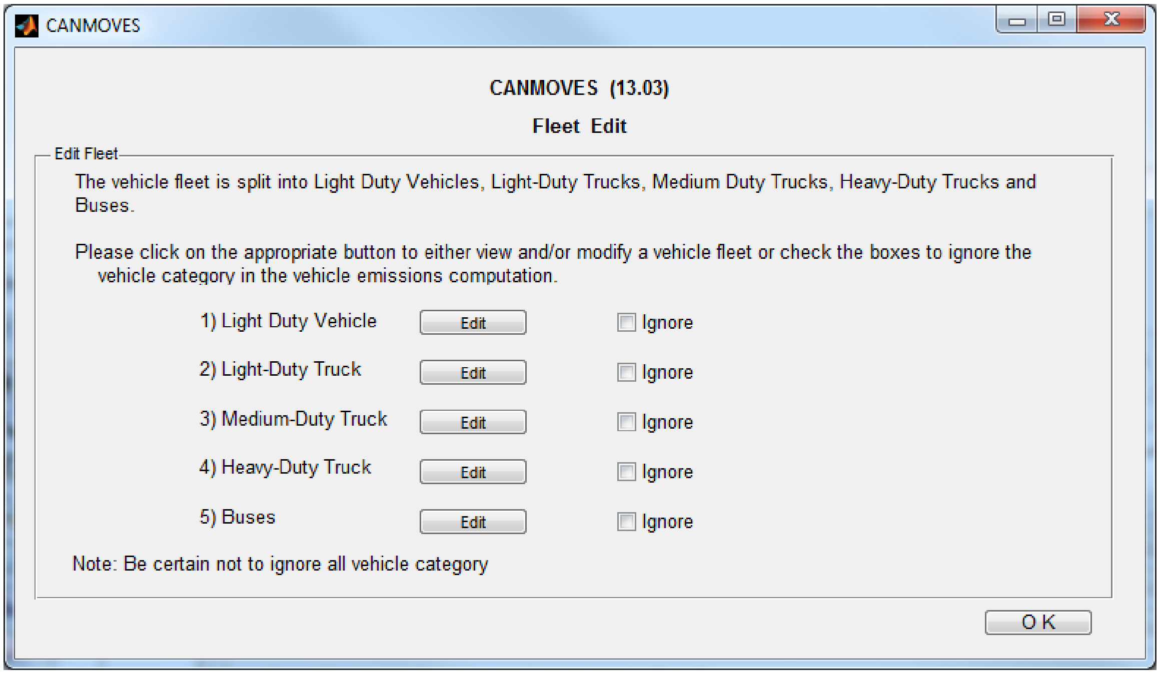
Fleet file browse: No model Fleet file chosen

Saved file access is : Access to saved model-Fleet file

EMME output file browse : C:\Users\Daniel\Desktop\2013 TRR Revamp\CANMOVES 13.03-D

EMME/2 Cold Start Distance (km): 4.5

Figure A.4: Simulation Definition Window



The vehicle fleet is split into Light Duty Vehicles, Light-Duty Trucks, Medium Duty Trucks, Heavy-Duty Trucks and Buses.

Please click on the appropriate button to either view and/or modify a vehicle fleet or check the boxes to ignore the vehicle category in the vehicle emissions computation.

1) Light Duty Vehicle [Edit] ☐ Ignore
2) Light-Duty Truck [Edit] ☐ Ignore
3) Medium-Duty Truck [Edit] ☐ Ignore
4) Heavy-Duty Truck [Edit] ☐ Ignore
5) Buses [Edit] ☐ Ignore

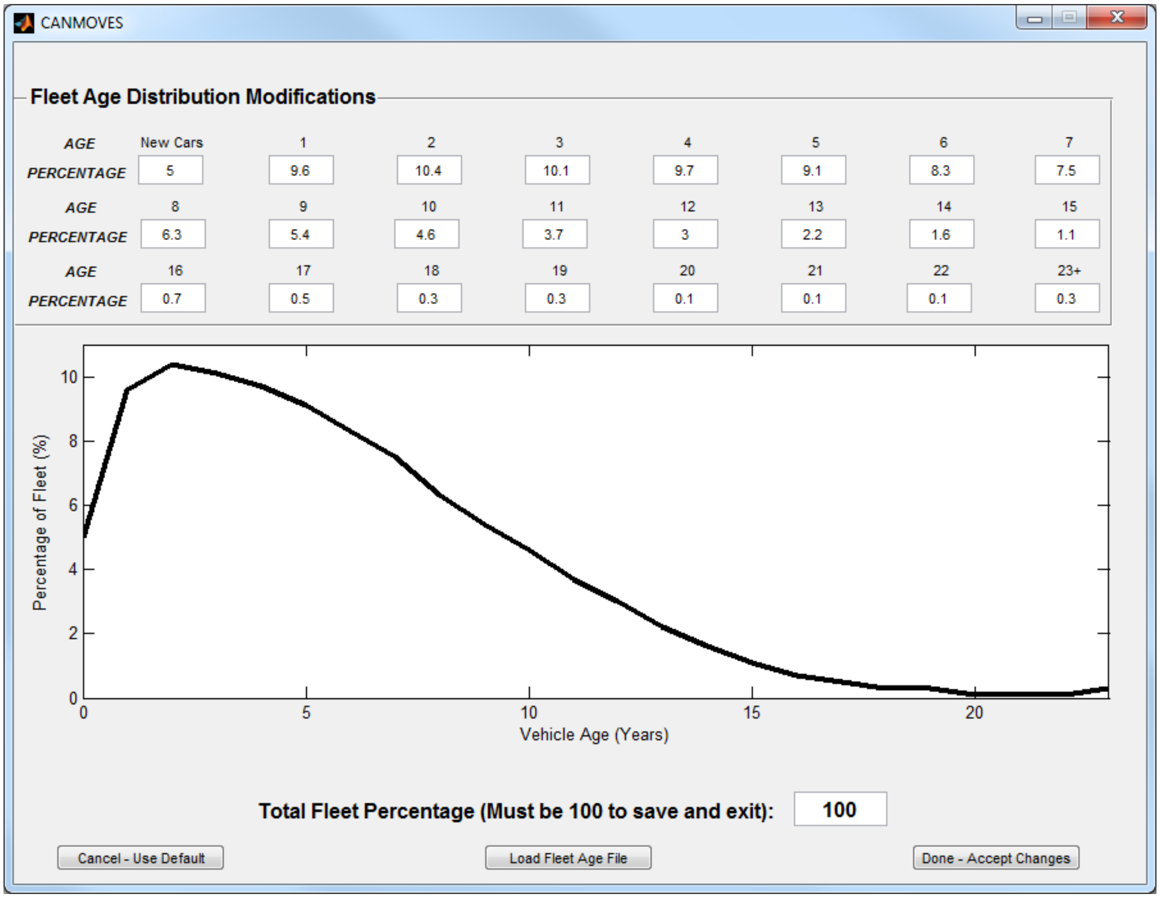
Note: Be certain not to ignore all vehicle category

Figure A.5: Fleet Editing Window

"Load Fleet Age File" button. Changing the fleet manually in the edit boxes requires that the sum of age distribution percentages is equal to 100. Selecting the "Cancel" button will return the fleet age distribution to its default. The default fleet age distribution is based on 2006 vehicle registration data from the City of Edmonton Region. The distribution is assumed to be the same across all classes of vehicles. It can be modified, however, to reflect different age distributions for any class of vehicle. The bus fleet distribution, for example, is quite different for the City of Edmonton than the default distribution shown below and changes with simulation year. Using the "Load Fleet Age File" button and a set of pre-determined fleet age distribution files to model this is an effective approach to capture the dynamic bus fleet.

A.4.3 Fleet Hybridization Options

The Fleet Hybridization options allow for simulation of the effects of increased hybrid technology in the vehicle fleet. Selecting the "Done" button will return to the Sim-



CANMOVES

Fleet Age Distribution Modifications

AGE	New Cars	1	2	3	4	5	6	7
PERCENTAGE	5	9.6	10.4	10.1	9.7	9.1	8.3	7.5
AGE	8	9	10	11	12	13	14	15
PERCENTAGE	6.3	5.4	4.6	3.7	3	2.2	1.6	1.1
AGE	16	17	18	19	20	21	22	23+
PERCENTAGE	0.7	0.5	0.3	0.3	0.1	0.1	0.1	0.3

Total Fleet Percentage (Must be 100 to save and exit): 100

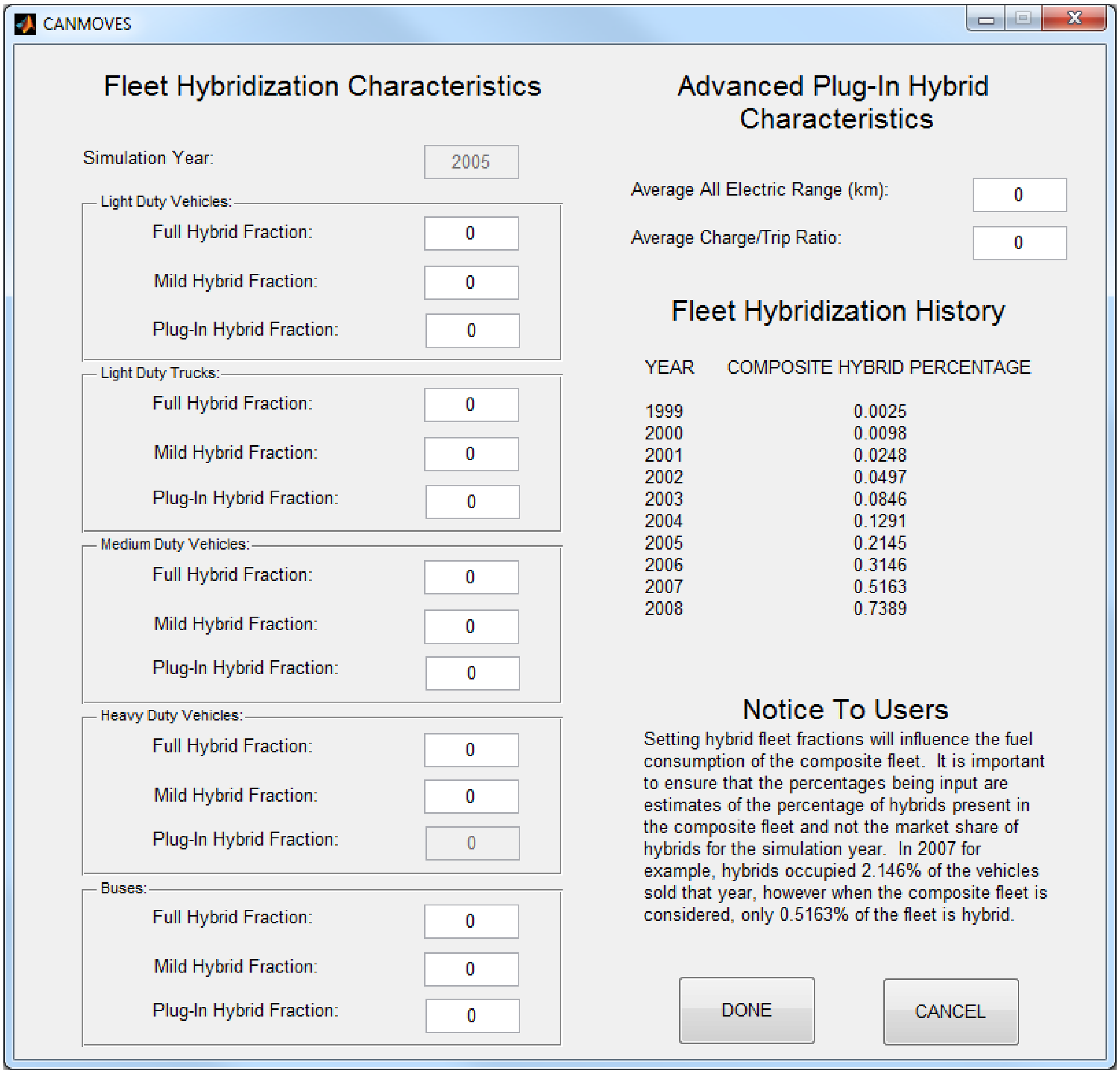
Figure A.6: Fleet Age Distribution Window ulation Definition window. Selecting the “Run” button in the Simulation Definition window will run the simulation. The progress bar will appear.

A.4.4 Electrical Generation Options

The electrical generation options allow for modifications to the sources of grid energy that is used to power electric and plug-in hybrid vehicles. There are a number of generation options available, as shown in figure A.8. The default values are also shown, and are based on the Alberta Electrical System Operator’s database for the Alberta grid. This provides an opportunity to investigate the effect of using electric vehicles, as well as the impact of changing the source of electricity used for electric vehicles.

A.4.5 Evaporative Emissions Options

The Evaporative Emissions Options window allows detailed modelling of evaporative emissions and the effects of certain driving behaviour parameters on evaporative emissions. The defaults shown in figure A.9 are based on a typical simulation run by the City of Edmonton. The duration is the time in hours that the simulation is intended to cover, and is generally 24 to represent a full day’s traffic. The number of trips per day is based on the 2005 Edmonton Household Travel Survey and is the average number of one-way trips throughout the day for each vehicle simulated. The default average trip length of 14.5 km is also based on the 2005 Edmonton Household Travel Survey. The default ratio of resting to active vehicles is based on the number of vehicles used during the day and the total registration numbers for the City of Edmonton Region. Additionally, the duration of stops tends to vary between weekday and weekend travel, so the time of week should be specified using the radio buttons. By default, the simulation will calculate evaporative emissions for weekday travel.



Fleet Hybridization Characteristics

Simulation Year: 2005

Light Duty Vehicles:
Full Hybrid Fraction: 0
Mild Hybrid Fraction: 0
Plug-In Hybrid Fraction: 0

Light Duty Trucks:
Full Hybrid Fraction: 0
Mild Hybrid Fraction: 0
Plug-In Hybrid Fraction: 0

Medium Duty Vehicles:
Full Hybrid Fraction: 0
Mild Hybrid Fraction: 0
Plug-In Hybrid Fraction: 0

Heavy Duty Vehicles:
Full Hybrid Fraction: 0
Mild Hybrid Fraction: 0
Plug-In Hybrid Fraction: 0

Buses:
Full Hybrid Fraction: 0
Mild Hybrid Fraction: 0
Plug-In Hybrid Fraction: 0

Advanced Plug-In Hybrid Characteristics

Average All Electric Range (km): 0
Average Charge/Trip Ratio: 0

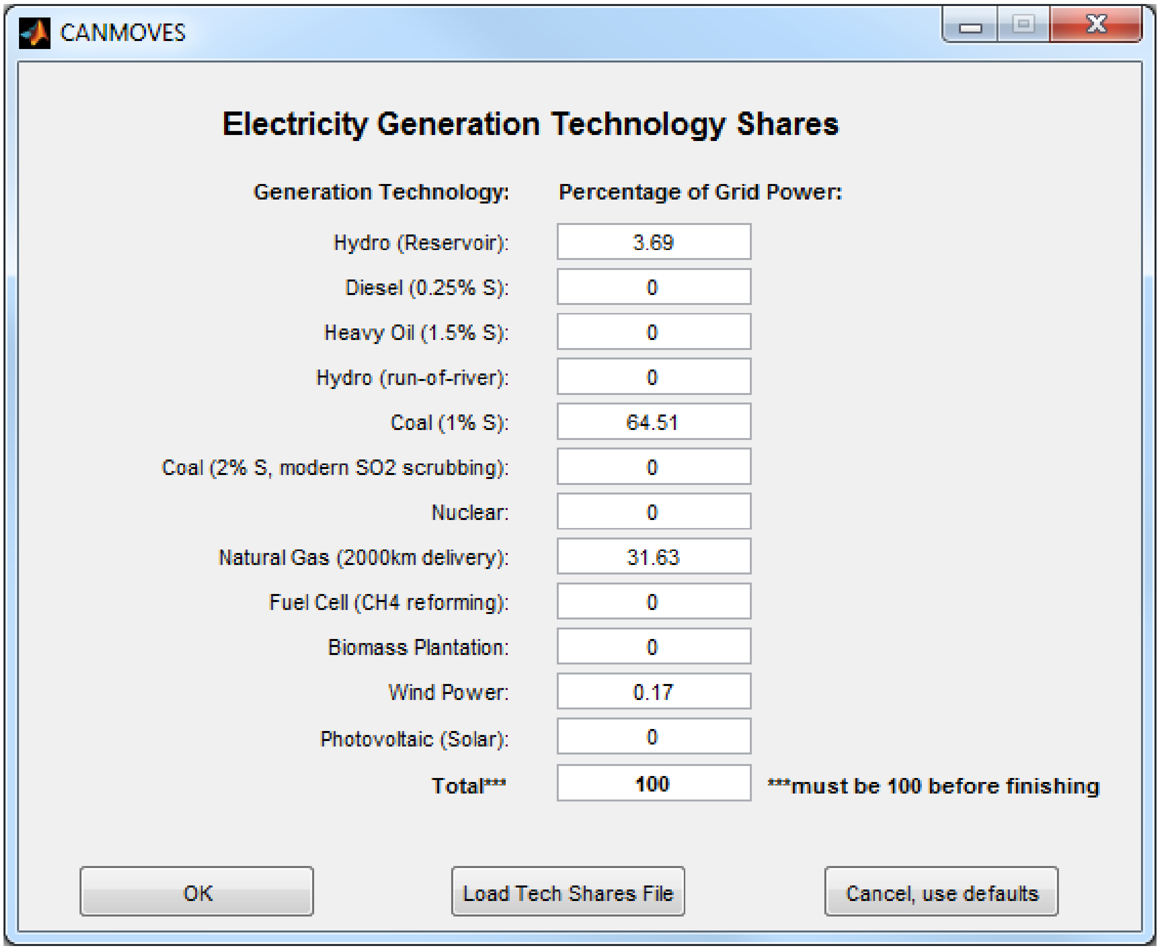
Fleet Hybridization History

YEAR	COMPOSITE HYBRID PERCENTAGE
1999	0.0025
2000	0.0098
2001	0.0248
2002	0.0497
2003	0.0846
2004	0.1291
2005	0.2145
2006	0.3146
2007	0.5163
2008	0.7389

Notice To Users

Setting hybrid fleet fractions will influence the fuel consumption of the composite fleet. It is important to ensure that the percentages being input are estimates of the percentage of hybrids present in the composite fleet and not the market share of hybrids for the simulation year. In 2007 for example, hybrids occupied 2.146% of the vehicles sold that year, however when the composite fleet is considered, only 0.5163% of the fleet is hybrid.

Figure A.7: Fleet Hybridization Window

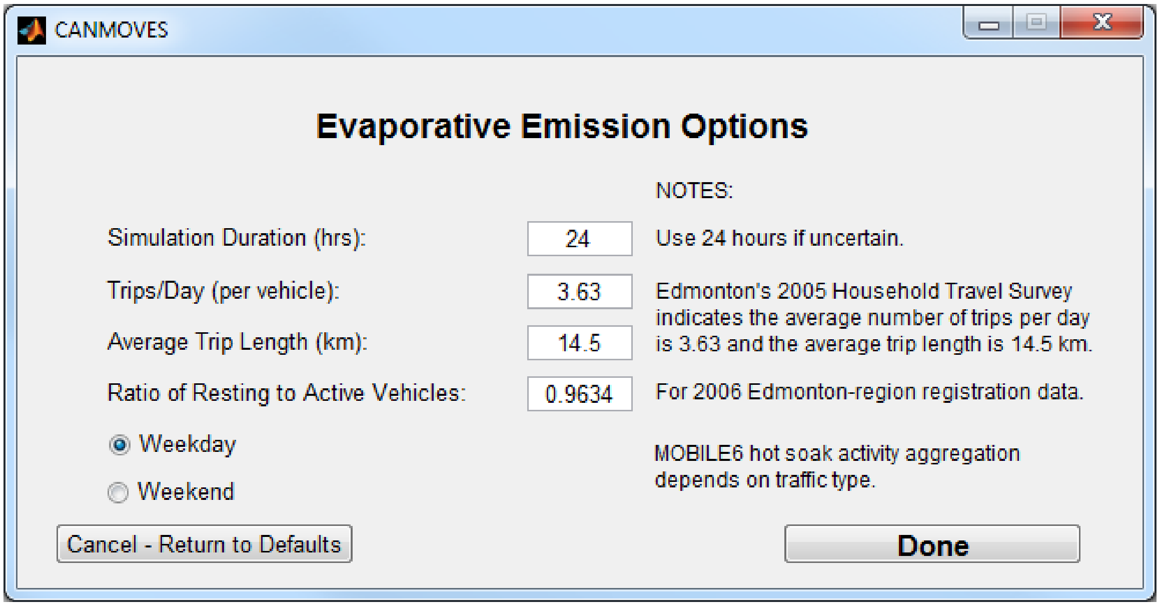


Electricity Generation Technology Shares

Generation Technology:	Percentage of Grid Power:
Hydro (Reservoir):	3.69
Diesel (0.25% S):	0
Heavy Oil (1.5% S):	0
Hydro (run-of-river):	0
Coal (1% S):	64.51
Coal (2% S, modern SO2 scrubbing):	0
Nuclear:	0
Natural Gas (2000km delivery):	31.63
Fuel Cell (CH4 reforming):	0
Biomass Plantation:	0
Wind Power:	0.17
Photovoltaic (Solar):	0
Total* **	**100**

*****must be 100 before finishing**

Figure A.8: Electrical Generation Options Window



Evaporative Emission Options

NOTES:

Simulation Duration (hrs): 24 — Use 24 hours if uncertain.

Trips/Day (per vehicle): 3.63

Average Trip Length (km): 14.5

Edmonton's 2005 Household Travel Survey indicates the average number of trips per day is 3.63 and the average trip length is 14.5 km.

Ratio of Resting to Active Vehicles: 0.9634 — For 2006 Edmonton-region registration data.

● Weekday

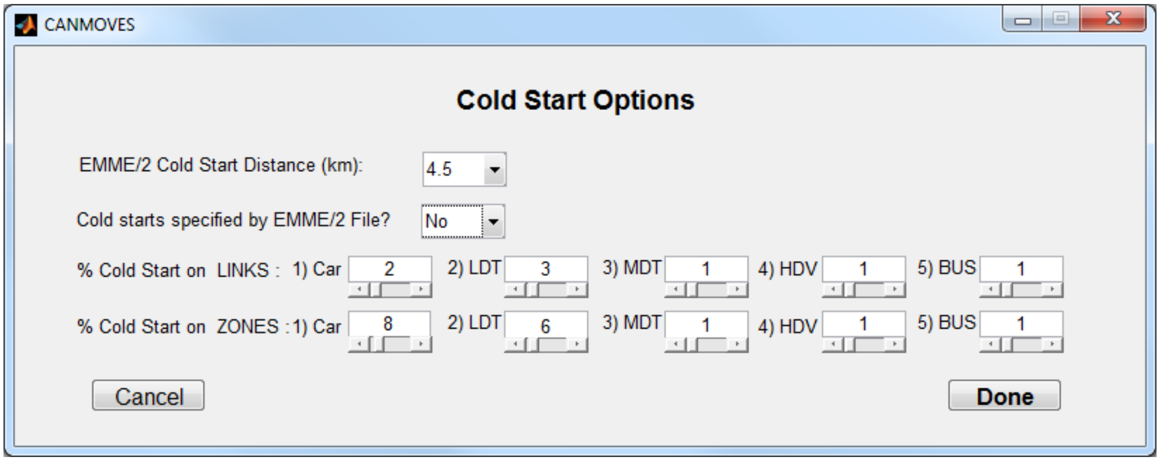
○ Weekend

MOBILE6 hot soak activity aggregation depends on traffic type.

Figure A.9: Evaporative Emissions Options Window

A.4.6 Cold Start Options

The cold start options are used to specify the percentage of cold start vehicles on each link manually, and to change the Cold Start Distance. Manually setting the cold start percentages is only recommended for runs in which the cold start percentages are not available in the transportation demand model (TDM) output file. An important note here is that the TDM output files are created with a cold start distance specified during the TDM run. To fully capture cold start effects, the cold start distance in the transportation demand model (TDM) run should be 4.5 km. This cold start distance must match the one in the Cold Start Distance drop-down list. If it does not, the cold start fractions may be discounted and concentrated improperly.



EMME/2 Cold Start Distance (km): 4.5

Cold starts specified by EMME/2 File? No

% Cold Start on LINKS : 1) Car 2 2) LDT 3 3) MDT 1 4) HDV 1 5) BUS 1

% Cold Start on ZONES : 1) Car 8 2) LDT 6 3) MDT 1 4) HDV 1 5) BUS 1

Figure A.10: Cold Start Options Window

Appendix B

Simplified Micro-simulation Congestion Response

This appendix is a detailed analysis of the response of the simplified micro-simulation to congestion. It is intended to provide some insight into the energy trends that emerge as congestion is increased on a single link with a fixed length and fixed speed limit.

B.1 Test Link Description

The test link chosen to demonstrate the energy trend is 0.5 km long, and has a speed limit of 50 km/hr. The energy trend is plotted at the top of figure B.1, with numbers indicating the average link speeds at which seven speed traces are plotted below the energy trend. As the link average speed decreases (and congestion increases) the energy trend develops as follows as a result of the simplified micro-simulation logic:

1. The link average speed is equal to the speed limit, so vehicles will cruise through the link at the speed limit.
2. The link average speed is slightly lower than the speed limit; vehicles slow momentarily but there is not enough delay to justify a complete stop.
3. There is now enough delay to come to a complete stop; vehicles may also idle

to satisfy the average delay on the link.

4. The vehicle now idles for nearly 30 seconds, presumably at a stop light; the energy has decreased slightly from the previous speed trace because the free speed on link decreases with average link speed, and idling requires no tractive energy.
5. The delay on the link now exceeds a complete stop and 30 seconds of idle, so two complete stops are made with idle periods; there is a step change in energy to this point since the additional stop requires additional tractive energy.
6. The idle periods during the two stops increase to nearly 30 seconds, and the free speed continues to decrease with link average speed.
7. A third stop is added to the speed trace to produce the required delay without exceeding the 30 second idle period limit, and there is another step change in energy to this point as a result.

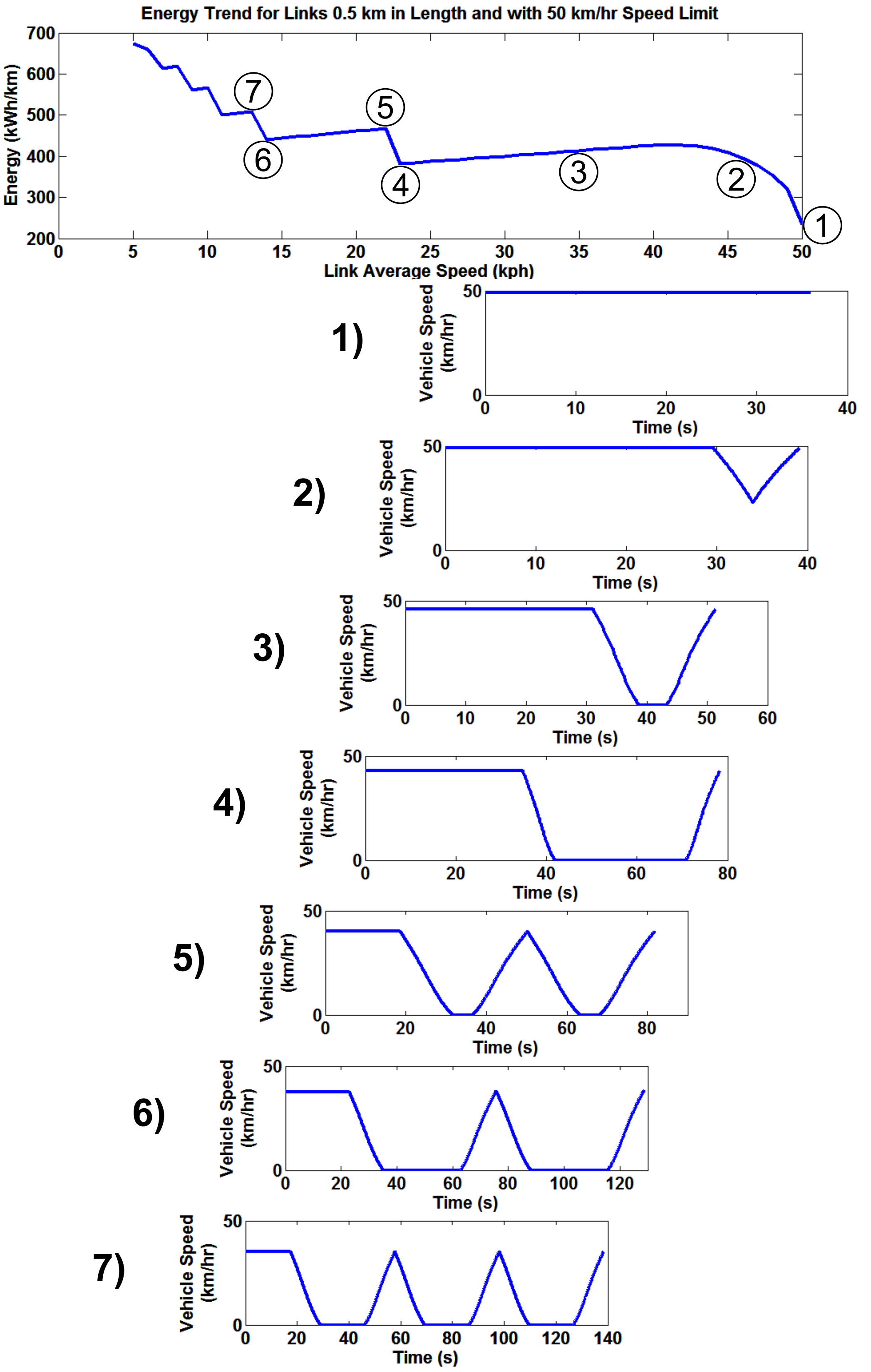


Figure B.1: Energy Trend and Vehicle Speed Traces for Links 0.5 km long and with 50 km/hr Speed Limit

APPENDIX C

ACCELERATION FUNCTIONS

This appendix describes the acceleration functions used in the simplified micro-simulation model. The dataset used to define their shape and the methods used to fit the data are documented.

The acceleration profiles used in this model are described using two functions: a quadratic function for low speeds, and an exponential decay for high speeds. The two functions are joined such that they, and their first derivatives, are continuous. The form of the acceleration profiles is shown in equation C.1. This form is useful since it can approximate the acceleration distributions observed in real-world driving data, and can be analytically solved in the simplified micro-simulation. The following sections detail the data used to estimate acceleration profiles for each class of vehicle modelled by the simplified micro-simulation.

$$a(v) = \begin{cases} c_1 \cdot v^2 + c_2 \cdot v + c_3 & v \leq v_s \\ \alpha \cdot \exp^{-\lambda \cdot v} & v \geq v_s \end{cases} \tag{C.1}$$

Number of Vehicles	75
Vehicle Hours	12,821
VKT	394,530
Average Speed (km/hr)	30.8
Idle Hours	3,769
Average Speed without idle (km/hr)	43.6
Weekday Hours	9,006
Weekend Hours	3,815
Weekday VKT	272,580
Weekend VKT	121,940

Table C.1: Winnipeg Data Summary

C.1 Acceleration Data and Profile Fitting

C.1.1 LDV and LDT Acceleration

The acceleration profiles used in the simplified micro-simulation define the default acceleration of all vehicles in the model. For links with congestion that require a reduction in free speed and acceleration, a multiplier less than one is applied to the acceleration profile. Hence it is important that the default acceleration profiles are representative of average acceleration values in free flowing traffic.

The Winnipeg study provides the most appropriate data for estimating the acceleration profile of light-duty vehicles. It includes a variety of light-duty vehicles (both LDVs and LDTs), a variety of drivers, and is recorded over a sufficient range of vehicle speeds. It is assumed that both LDVs and LDTs have similar acceleration profiles since they are generally driven in similar conditions and have similar acceleration capabilities. Table C.1 summarizes the characteristics of this data. This data is plotted in figure C.1.

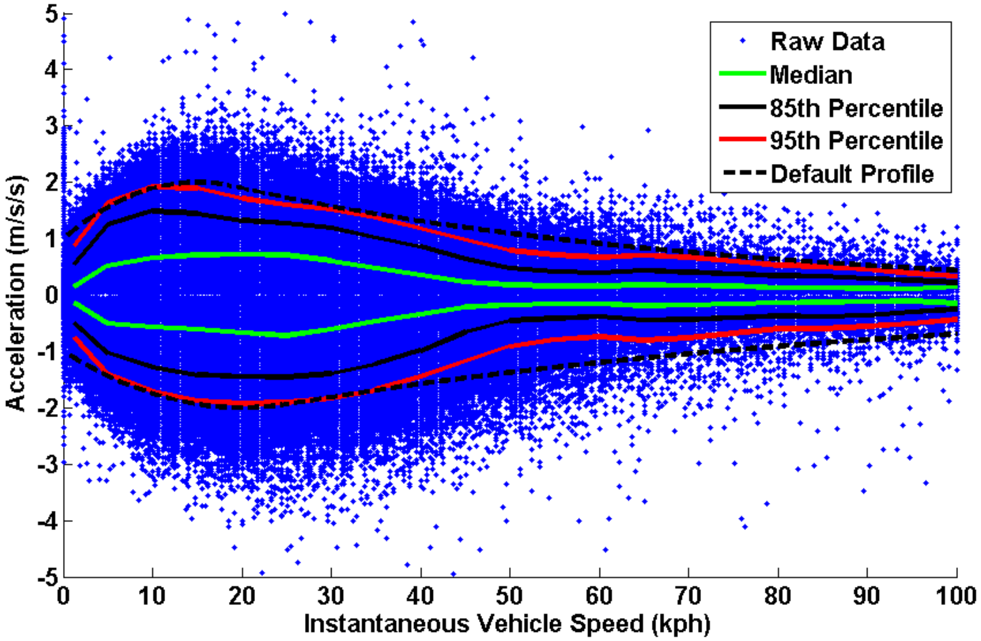


Figure C.1: Winnipeg study acceleration data, mean, 85^{th} and 95^{th} percentile, plotted with the Default Acceleration Profile for the simplified micro-simulation.

C.1.2 MDV Acceleration

There are no datasets currently available to estimate MDV acceleration profiles. Since MDVs are generally similar to LDTs while being both heavier and larger, it is assumed that MDVs accelerate at 80% of the acceleration level of LDVs.

C.1.3 HDV Acceleration

There are several North American studies that show the acceleration capabilities of heavy duty vehicles. However, since the data has not been made publicly available, the prior research has been analyzed to estimate reasonable acceleration limits for heavy duty vehicles. The acceleration profile is defined to adhere to these limits. The first study that was analyzed was that of Grant, Guensler, and Meyer [79]. This study reported that among the heavy duty fleet, heavier vehicles had lower acceleration limits, and that road characteristics and driver behaviour had a significant influence on acceleration characteristics of heavy duty vehicles. The data presented in the study include speeds from 10 mph (16 km/hr) to 50 mph (80 km/hr). It does not cover all of speed range that the simplified micro-simulation is capable of modelling; hence there are indicators of limits in the data shown but not enough to estimate a complete acceleration profile up to 120 km/hr. The data that is presented indicates that the maximum acceleration for heavy duty vehicles is 2 – 3 mph/s (0.888 – 1.33 m/s^2) at a speed of 30 mph (50 km/hr).

The second study that was analyzed is that of Kern [80]. This data was recorded on a single tractor truck powered by a 435 hp Cummins N14 engine with No. 2 diesel fuel over three test routes, at a simulated weight of 46,400 lbs (21,090 kg). This study shows data recorded up to 60 mph (100 km/hr), and indicates that the maximum acceleration for the truck was 2.5 mph/s (1.11 m/s^2) up to 20 mph (32 km/hr), and the minimum acceleration was -2 mph/s (0.888 m/s^2) up to about 30 mph (48 km/hr).

C.1.4 Bus Acceleration

Pelkmans et al. [81] recorded the acceleration capability of a stoichiometric CNG bus, a lean-burn CNG bus, and a diesel bus under similar conditions. The simplified micro-simulation profile has been defined to be comparable to the Diesel bus. As such it peaks at about 1.5 m/s^2 at 10 km/hr and decays through 0.2 m/s^2 at 70 km/hr. The acceleration level from a stop is set at 0.8 m/s^2 based on this study.

Data collected from two Diesel buses in Edmonton agrees with these observations, although some higher accelerations at lower speeds were observed. The vehicle speed was recorded from the CAN-bus through the SAE J1939 socket on the buses. Figure C.2 shows the acceleration profile for buses defined to adhere to these limitations. The data from the Edmonton buses is also presented as a point cloud, and the mean and 95% confidence ranges calculated using a windowing approach are also plotted.

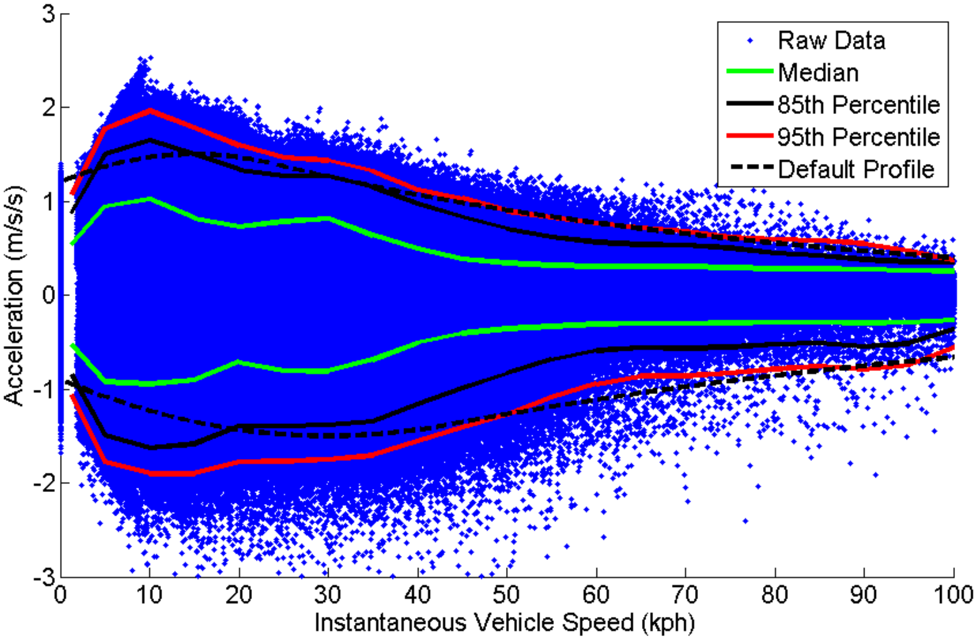


Figure C.2: Bus default acceleration profile for simplified micro-simulation

C.2 Default Acceleration Profiles

Figure C.3 shows the acceleration profiles for each class of vehicle modelled by the simplified micro-simulation.

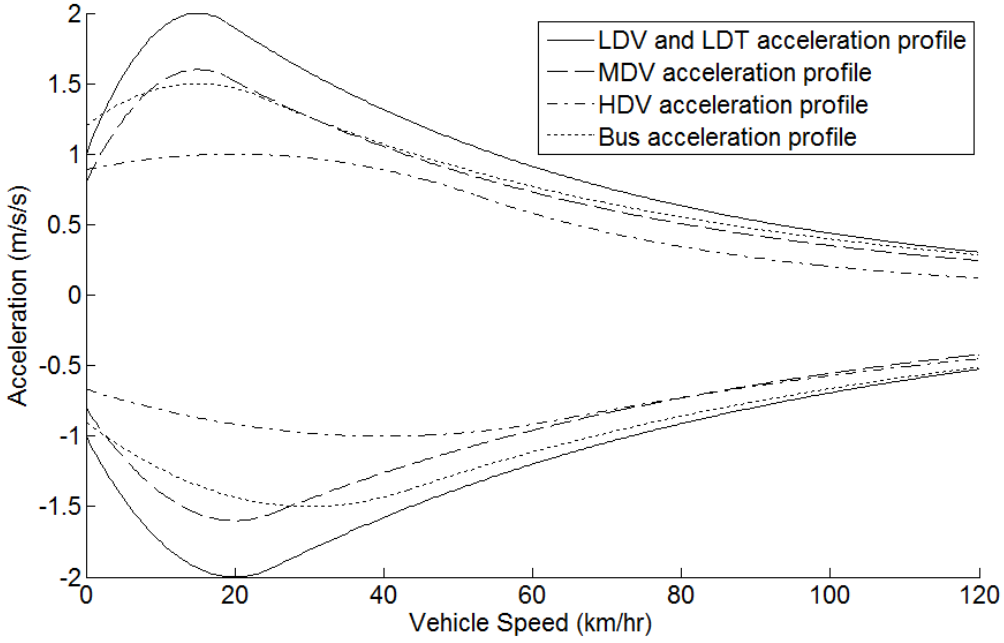


Figure C.3: Default acceleration profiles for simplified micro-simulation

Appendix D

Power-based Fuel Consumption and Emission Model

The advantages of micro-simulation rely on instantaneous fuel consumption and emission rates. This appendix describes the instantaneous, power-based fuel consumption and emission functions used in the simplified micro-simulation inventory tool.

D.1 Gasoline Vehicle Fuel Consumption and Emissions Functions

The fuel consumption function for gasoline vehicles in equation D.1 is the work of Checkel [71]. The emissions function in equations D.2 to D.4 are the work of Busawon [67] and are correlations to engine dynamometer data.

Carbon dioxide emissions are calculated with the carbon balance described by equation D.5. It is assumed that gasoline has a hydrogen to carbon ratio of 2 and is approximated as C_nH_{2n}. It is also assumed that any carbon not emitted in the form of CO_2, CO, and non-methane hydrocarbons is negligible.

$$\dot{m}_{gasoline} = \begin{cases} 0.496 & \text{if idling} \\ \frac{1}{3.6} \cdot e^{(-0.476 \log(P_{tractive}) + 0.602)} - 0.148 + 0.00262 \cdot v \cdot P_{tractive} & \text{otherwise} \end{cases} \tag{D.1}$$

$$\dot{m}_{NO_x} = \begin{cases} 0.00544 & \text{if idling} \\ \frac{0.675}{1000} \cdot (-0.9121 + 1.778 P_{tractive}) & \text{otherwise} \end{cases} \tag{D.2}$$

$$\dot{m}_{NMHC} = \begin{cases} 0.00933 & \text{if idling} \\ \frac{1}{3600} \cdot e^{(-0.595 \log(P_{tractive}) + 3.234)} \cdot P_{tractive} & \text{otherwise} \end{cases} \tag{D.3}$$

$$\dot{m}_{CO} = \begin{cases} 0.0213 & \text{if idling} \\ \frac{1}{3600} \cdot e^{(-0.439 \log(P_{tractive}) + 4.64)} \cdot P_{tractive} & \text{otherwise} \end{cases} \tag{D.4}$$

$$\dot{m}_{CO_2} = \left[\frac{M_{C_n}}{M_{C_nH_{2n}}} \cdot (\dot{m}_{gasoline} - \dot{m}_{NMHC}) - \frac{M_C}{M_{CO}} \cdot m_{CO} \right] \cdot \frac{M_{CO_2}}{M_C} \tag{D.5}$$

D.2 Diesel Vehicle Fuel Consumption and Emissions Functions

The fuel consumption function for Diesel vehicles in equation D.6 is the work of Checkel [72]. The emissions function in equations D.7 to D.10 are the work of Busawon [67] and are correlations to measured emissions data.

The fuel consumption and emissions functions for Diesel vehicles depend on their rated power P_{max} and their idle fuel consumption rate $\dot{m}_{Diesel,idle}$. Table D.1 shows the rated power and idle fuel consumption rate for each class of Diesel vehicle modelled.

Carbon dioxide emissions are calculated with the carbon balance described by equation D.11. It is assumed that Diesel also has a hydrogen to carbon ratio of 2 and is approximated as C_nH_{2n}, and that any carbon not emitted in the form of CO_2, CO, and non-methane hydrocarbons is negligible.

Vehicle Class	Rated Power	Idle Fuel Consumption Rate
	kW	g/s
LDV-Mini	120	0.0995
LDV-Economy	120	0.13236
LDV-Large	120	0.16515
LDDT1	150	0.16515
LDDT2	150	0.2143
LDDT3	150	0.277
LDDT4	150	0.290
HDVG2b	250	0.290
HDVG3	250	0.290
HDVG4	250	0.290
HDVG5	250	0.290
HDVG6	250	0.404
HDVG7	250	0.404
HDVG8a	375	0.404
HDVG8b	375	0.404
Small School Bus	225	0.290
Large School Bus	210	0.404
New Transit Bus	210	0.404
Old Transit Bus	170	0.404
Short Transit Bus	225	0.290
Long Transit Bus	210	0.404

Table D.1: Diesel vehicle rated power and idle fuel consumption rates

$$\dot{m}_{Diesel} = \begin{cases} \dot{m}_{Diesel,idle} & \text{if idling} \\ \dot{m}_{Diesel,idle} + 0.05895 P_{tractive} + 0.00008537 P_{tractive}^2 & \text{otherwise} \end{cases} \tag{D.6}$$

$$\dot{m}_{NO_x} = \begin{cases} 0.007 & \text{if idling, otherwise} \\ e^{\left(1.5475 - 0.030471 \log\left(\frac{P_{tractive}}{P_{max}}\right)\right)} & \text{if } a \leq 0 \\ P_{tractive} \cdot \left(20.8531 - 40.2396 \frac{P_{tractive}}{P_{max}} + 25.0789 \left(\frac{P_{tractive}}{P_{max}}\right)^2\right) & \text{if } a > 0 \end{cases} \tag{D.7}$$

$$\dot{m}_{NMHC} = \begin{cases} 0.0072917 & \text{if idling, otherwise} \\ P_{tractive} e^{\left(-1.12321 - .7738 \log\left(\frac{P_{tractive}}{P_{max}}\right)\right)} & \text{if } a \leq 0 \\ P_{tractive} \cdot \left(1.41 - 3.376 \frac{P_{tractive}}{P_{max}} + 2.458 \left(\frac{P_{tractive}}{P_{max}}\right)^2\right) & \text{if } a > 0 \end{cases} \tag{D.8}$$

$$\dot{m}_{CO} = \begin{cases} 0.0085 & \text{if idling, otherwise} \\ P_{tractive} e^{\left(0.6612 - 0.78959 \log\left(\frac{P_{tractive}}{P_{max}}\right)\right)} & \text{if } a \leq 0 \\ P_{tractive} \cdot \left(22.04 - 8.526 \frac{P_{tractive}}{P_{max}}\right) & \text{if } a > 0 \end{cases} \tag{D.9}$$

$$\dot{m}_{PM_{10}} = \begin{cases} 0.000025389 & \text{if idling, otherwise} \\ P_{tractive} e^{\left(-2.82697 - 0.515982 \log\left(\frac{P_{tractive}}{P_{max}}\right)\right)} & \text{if } a \leq 0 \\ P_{tractive} \cdot \left(1.32556 - 1.17628 \frac{P_{tractive}}{P_{max}}\right) & \text{if } a > 0 \end{cases} \tag{D.10}$$

$$\dot{m}_{CO_2} = \left[\frac{M_{C_n}}{M_{C_nH_{2n}}} \cdot (\dot{m}_{diesel} - \dot{m}_{NMHC}) - \frac{M_C}{M_{CO}} \cdot m_{CO}\right] \cdot \frac{M_{CO_2}}{M_C} \tag{D.11}$$

Appendix E

Fuel Consumption and Emissions Calibration

This appendix describes the methodology used to calibrate the simplified micro-simulation inventory tool to the NRCan fuel consumption database and the US EPA's MOBILE6.2C model.

E.1 Fuel Consumption

Fuel consumption estimates are calibrated based on historical data from the Natural Resources Canada (NRCan) fuel consumption database [73] and on forecast constraints derived from the work of Heywood et al. [69]. This section details the methods used to calibrate fuel consumption and includes the Light Duty Vehicle (LDV) calibration trends as an example. The complete set of calibration functions is then reported for the LDT, MDV, and HDV classes along with any differences in the methodology and additional data sources.

E.1.1 NRCan Historical Fuel Consumption

Natural Resources Canada (NRCan) maintains the Comprehensive Energy Use Database, which includes yearly statistics-based estimates of the average fuel consumption of Canadian vehicles. The NRCan data goes back to 1981 and is supplemented by historical corporate average fuel economy characteristics published by the National

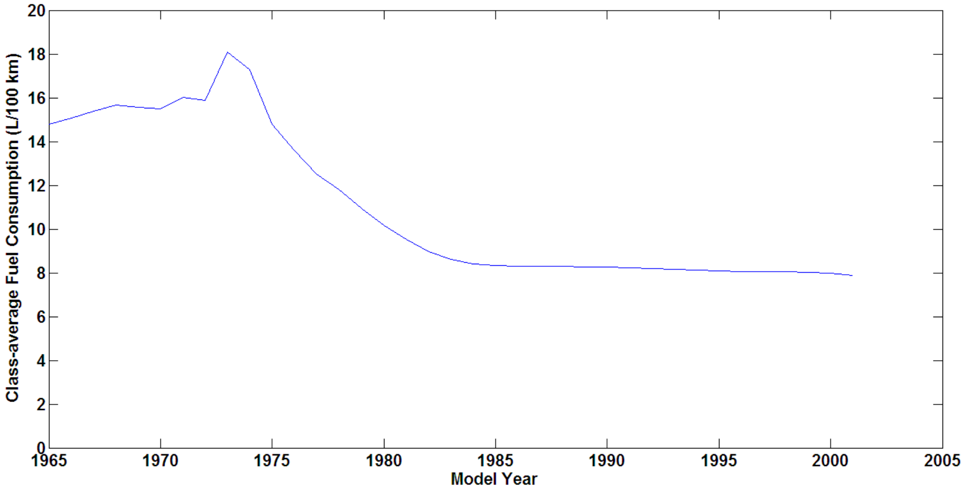


Figure E.1: Light Duty Vehicle (LDV) Historical Gasoline Fuel Consumption Trend

Highway Traffic Safety Administration [82] and in the Transportation Energy Data Book [83] to extend historical fuel consumption estimates back to 1967 [1]. Interpolation was used for years for which the fuel consumption data was unavailable. The historical fuel consumption trend for light duty vehicles is shown in figure E.1.

E.1.2 Fuel Consumption Forecasting Methodology

Fuel consumption is forecast from 2002 to 2050 simulation years by extending the historical fuel consumption trend based on the improvement predicted by Heywood et al. [69], and on the minimum fuel consumption that can be expected given reasonable engine efficiency limits. The forecasting function is thus constrained by the following:

- the forecast function must predict the same fuel consumption as the last historical data point, which in the case of LDVs is the year 2001
- fuel consumption is expected to improve by 41% between 2001 and 2020 [69]

---

[1] Vehicle fleets from 1990 to 2050 can be modelled, with a maximum age of 23 years (all vehicles older than 23 years are assumed to be 23 years old; this is typically less than 0.5% of the vehicle fleet). Hence, annual fuel consumption estimates that date back to 1967 are necessary to calculate composite fleet fuel consumption from 1990 onwards.

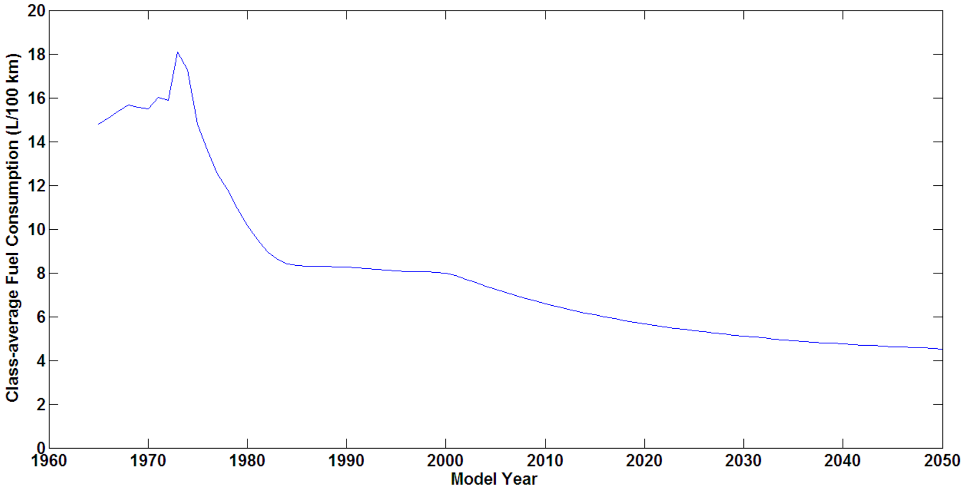


Figure E.2: Light Duty Vehicle (LDV) Class-average Gasoline Fuel Consumption

- the minimum fuel consumption that can be expected far into the future for internal combustion engines is calculated assuming a maximum tractive efficiency of 35%

An exponential decay that passes through the points of the first and second constraint, and has an offset equal to the horizontal asymptote predicted by the third constraint, results in the fuel consumption forecast for the LDV fleet described by equation E.1 and shown with the historical data in figure E.2.

$$FC = 4.16 + 3.9008e^{-0.04745\cdot(year-2000)} \quad \forall \quad year = [2001, \ \ 2050] \tag{E.1}$$

E.1.3 Fleet Composite Fuel Consumption Calibration Functions

The vehicle fleet for a simulation is defined as a combination of new vehicles and vehicles aged up to 23 years. This combination is called the fleet age distribution, and can be user-modified as discussed in Appendix A. The default fleet age distribution,

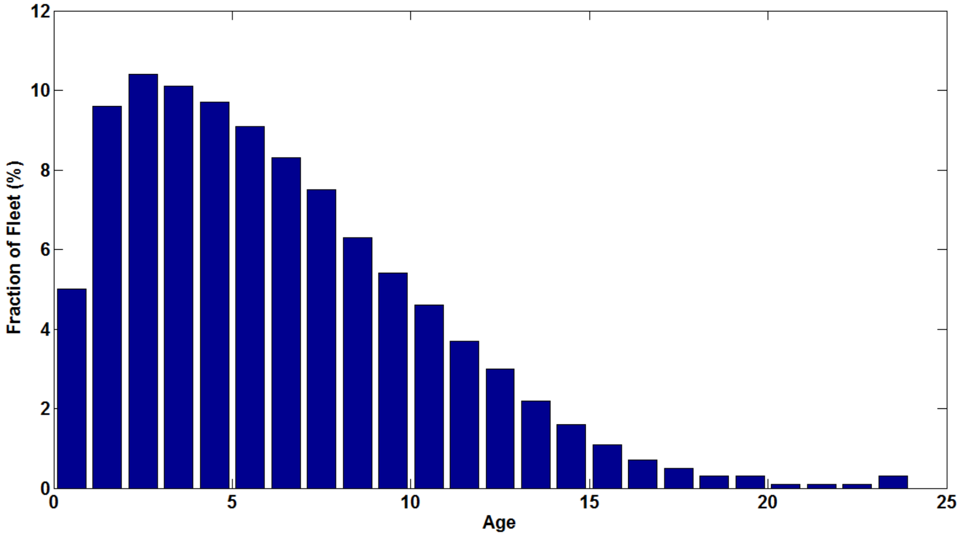


Figure E.3: Light Duty Vehicle Default Fleet Age Distribution

which is based on 2005 vehicle registration data for the city of Edmonton, Alberta, is shown in figure E.3.

The fleet composite fuel consumption, calculated with the default fleet age distribution, is shown in figure E.4. The fleet age distribution can be redefined by the user, and the fleet composite fuel consumption is calculated at runtime based on the fleet age distribution selected. The fleet composite fuel consumption function in figure E.4 is for the default fleet age distribution and is shown here purely for reference.

The final step in calibrating fuel consumption is to calculate the fuel consumption factors for each sub-class of the fleet. In the case of LDVs, factors are required to calibrate the fuel consumption for Mini, Economy, and Large LDVs. Class-average fuel consumption for the sub-classes was estimate by a survey of model year 2001 vehicles. The sub-class fuel consumption factors are calculated as shown in equation E.2 where the index SC denotes the sub-class (Mini, Economy, or Large).

$$FCF_{SC} = \frac{Average\ Fuel\ Consumption_{SC}(2001)}{Fuel\ Consumption\ Function(2001)} \tag{E.2}$$

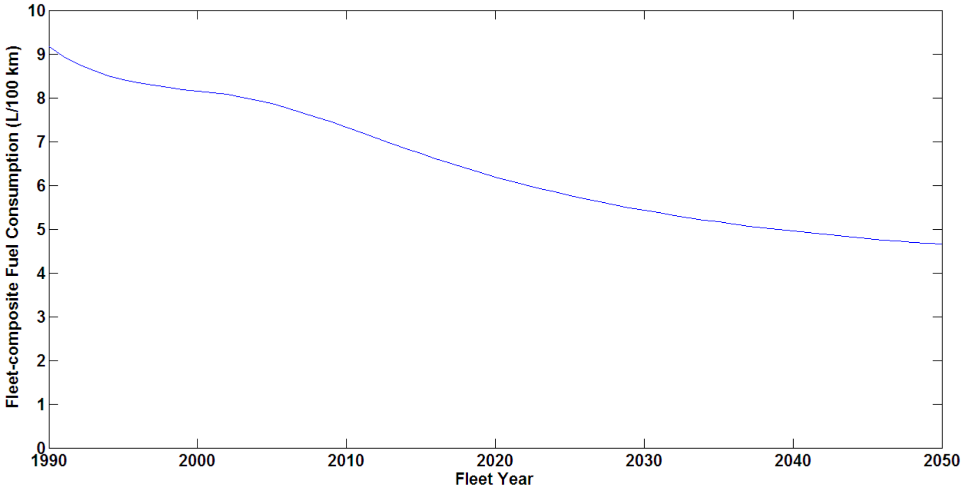


Figure E.4: Light Duty Vehicle (LDV) Fleet-composite Gasoline Fuel Consumption

The result of the calibration of each sub-class, using the default fleet age distribution, is shown in figure E.5. The sub-class calibration factors for gasoline and Diesel fuelled vehicles of all classes are shown in table E.1. It is assumed that Diesel vehicles follow the same trend as gasoline vehicles. This assumption relies on the mass, area, and drag and rolling coefficients being similar, and on similar technological improvements to powertrain efficiency for vehicles of both fuel types.

This methodology is also used to create gasoline fuel consumption functions for the light duty truck (LDT), medium duty vehicle (MDV), and heavy duty vehicle (HDV) classes. The resulting fleet-composite gasoline fuel consumption trends are shown in figures E.6, E.7, and E.8. The MDV and HDV historical data was projected backwards from 1990 to 1967 using the fuel consumption of trucks relative to their 1990 fuel consumption reported by the United States Energy Information Administration [84]. The MDV and HDV Diesel fuel consumption functions are generated independently from the gasoline fuel consumption functions as their market shares are significant and there is sufficient data available to do so. The default fleet composite fuel consumption trends for MDV and HDV classes are shown in figures E.9 and E.10.

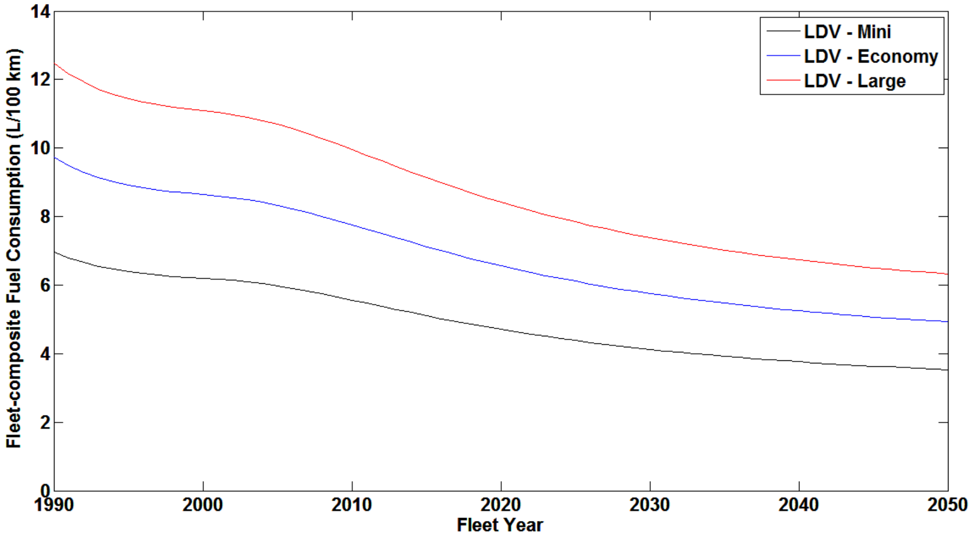


Figure E.5: Light Duty Vehicle (LDV) Fleet-Composite Gasoline Fuel Consumption for Sub-classes

Sub-class	Gasoline Calibration	Diesel Calibration
LDV - Mini	0.761	0.546
LDV - Economy	1.06	0.761
LDV - Large	1.36	0.977
LDT1	0.913	0.723
LDT2	1.23	0.974
LDT3	1.45	1.15
LDT4	1.50	1.19
HDV2b	0.893	0.843
HDV3	0.963	0.937
HDV4	0.976	1.05
HDV5	1.11	1.10
HDV6	1.12	1.23
HDV7	1.21	1.40
HDV8a	0.660	0.855
HDV8b	0.699	0.906

Table E.1: Sub-class fuel consumption calibration factors

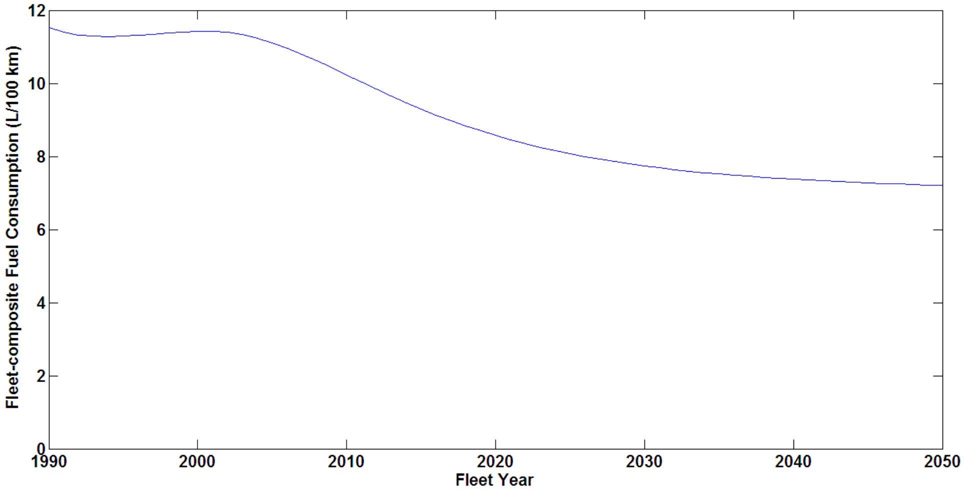


Figure E.6: Light Duty Truck (LDT) Fleet-composite Gasoline Fuel Consumption

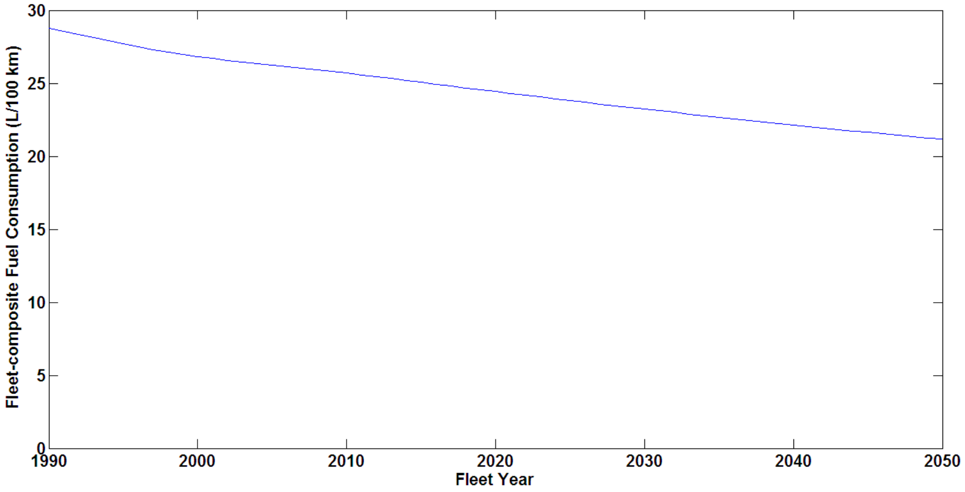


Figure E.7: Medium Duty Vehicle (MDV) Fleet-composite Gasoline Fuel Consumption

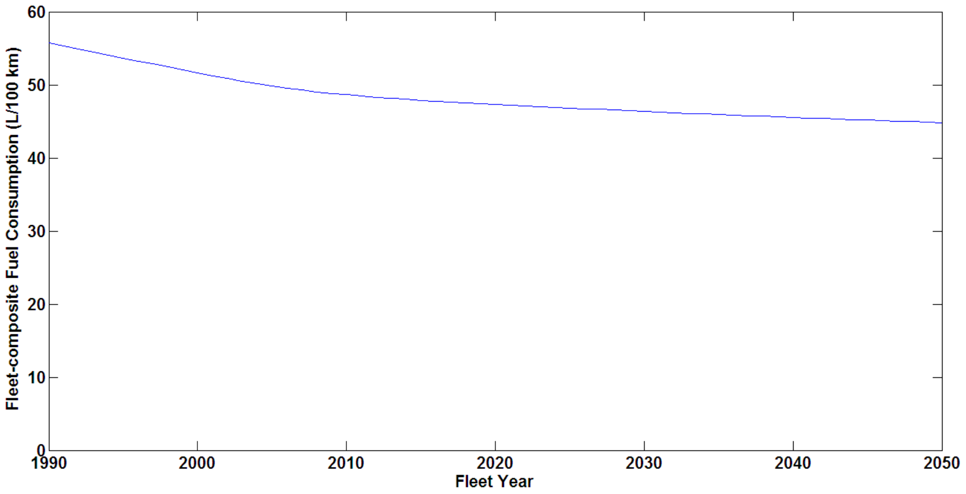


Figure E.8: Heavy Duty Vehicle (HDV) Fleet-composite Gasoline Fuel Consumption

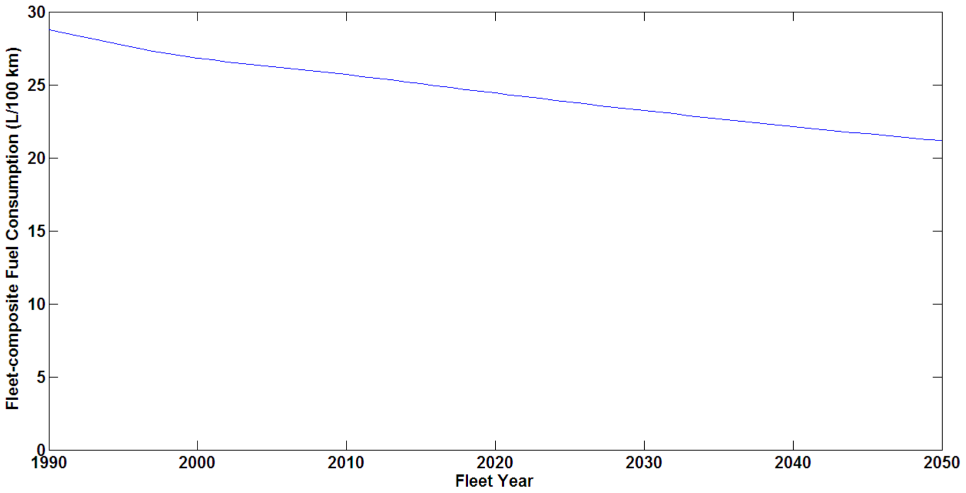


Figure E.9: Medium Duty Vehicle (MDV) Fleet-composite Diesel Fuel Consumption

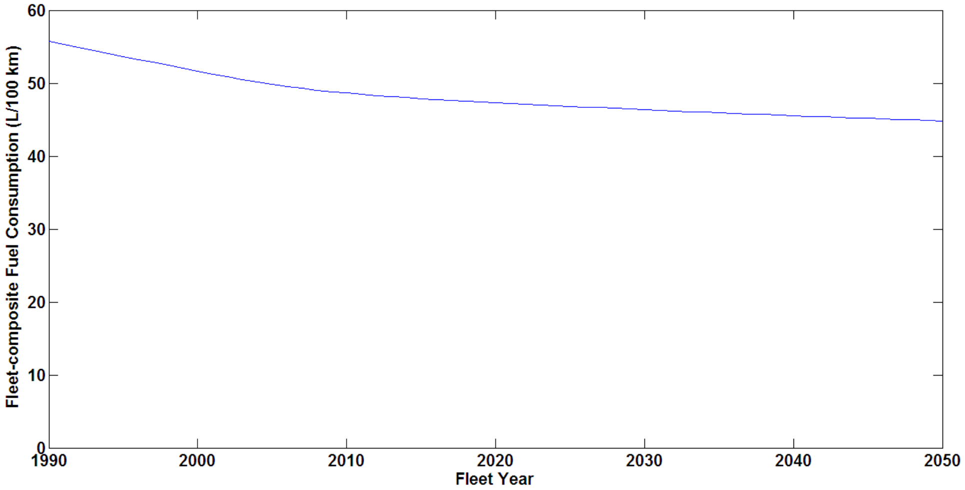


Figure E.10: Heavy Duty Vehicle (HDV) Fleet-composite Diesel Fuel Consumption

E.1.4 Cold-start Fuel Consumption Temperature Correction

Cold-start fuel consumption increases as ambient temperature decreases; the amount of fuel required for a cold start at temperatures below 22° Celsius is multiplied by the temperature dependent correction factors based on the work of Weilenmann et al. [85] and shown in figure E.11.

E.2 Tailpipe Emissions

Tailpipe emissions are calibrated to the US EPA's MOBILE6.2C model. MOBILE6.2C is a Canadian version of MOBILE6.2, which is based on a vast number vehicle emissions tests that were performed using the standardized federal test procedure (FTP) cycle. Tailpipe emissions are calculated in two parts; cold-start emissions for vehicles that have not completed the distance of a cold start, and hot-running emissions for vehicles which have completed their cold-start distance.

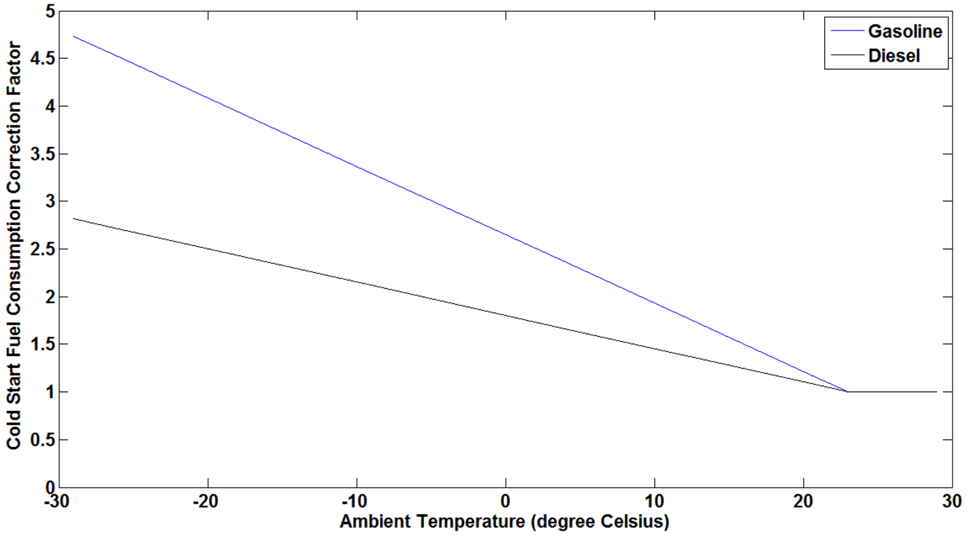


Figure E.11: Cold Start Fuel Consumption Temperature Correction Functions

E.2.1 Hot Running Emissions

Hot running emissions are calibrated using the MOBILE6.2C basic emission rates (BERs) and calibration factors for the power-based emission functions.

E.2.1.1 MOBILE6.2C Base Emission Rates

The Base Emission Rate (BER) of each class of vehicle is calculated based on the MOBILE6.2C model. The BERs depend on the simulation year and the fleet age distribution. A typical BER calculation is shown in equation E.3.

$$BER = ZML + DR \cdot M \tag{E.3}$$

In equation E.3, ZML is the Zero Mile Level of emission, or the emission rate of a new vehicle for the specified simulation year; DR is the deterioration rate of the vehicle, or the rate at which the emissions increase as the vehicle ages. The deterioration rate is multiplied by M, the mileage of the vehicle, which is specified in the MOBILE6 model based on the vehicle age and class. BERs are calculated for new vehicles as well as those aged between 1 and 23 years. It is assumed that vehicles older than 23 years are a small fraction of the fleet that emit similarly to those 23 years of age, and their fraction of the fleet is included in the fraction of vehicles 23 years old. Base Emission Rates are calculated according to the MOBILE6.2 documentation [86, 87, 88, 89, 90, 91, 92, 93, 94].

The fleet age distribution is then applied to calculate the fleet composite BER for each vehicle class. The fraction of each age of vehicle in the fleet is multiplied by its corresponding BER and summed to produce the composite BER for each vehicle class.

$$Composite\ BER = \sum_{i=0}^{23} BER(i) \cdot f(i) \tag{E.4}$$

$Composite\ BER$ is the fleet composite BER for a particular vehicle class, $BER(i)$ is the BER for a vehicle of that class and age i and $f(i)$ is the fraction of vehicles of that age in the fleet.

The composite BERs for each vehicle class are stored in calibration factors for use in the program when the emissions have been calculated based on vehicle micro-simulation.

The BER calculation shown in equation E.4 is adjusted for high altitude simulations by a factor described in the MOBILE6 model. The high altitude criterion for MOBILE6 is set at 4000 feet above sea level; simulations that specify atmospheric pressures indicating higher altitudes are subject to the high altitude correction.

E.2.1.2 Calibration Factors

The base emission rates (BERs) discussed in section E.2.1.1 are the distance-specific emission rates expected of vehicles driven through the hot-running sections of an

FTP cycle. To produce calibration factors a direct, uncalibrated simulation of the hot-running bags of the FTP cycle is performed, and compared to the result that is predicted by the MOBILE6.2C model. The calibration factors are the ratio of the MOBILE6.2C model and the uncalibrated model, shown below in equation E.5.

$$CF = \frac{MOBILE6.2C\ BER}{Uncalibrated\ FTP\ Emissions} \tag{E.5}$$

These calibration factors are then applied to all running emissions estimates made by the power-based emissions model to yield calibrated results, as shown in equation E.6.

$$Calibrated\ Hot\ Running\ Emission\ Rate\ = CF \cdot Uncalibrated\ Emission\ Rate \tag{E.6}$$

E.2.2 Cold-start Emissions

Cold start emissions are defined in MOBILE6.2C similarly to base emission rates; there is a zero mile level (ZML) and a deterioration rate (DR). Cold start emissions are estimated by taking the difference between the cold-start bag 1 of the FTP cycle and the hot-start bag 3 of the FTP cycle, which are shown in figure E.12. Hence, cold-start emissions are defined as a mass (in grams) of pollutant rather than a distance-specific emission rate. There is therefore no calibration necessary for cold-start emissions, as the mass of pollutant predicted by MOBILE6.2C can be applied directly to each vehicle that cold-starts in a simulation.

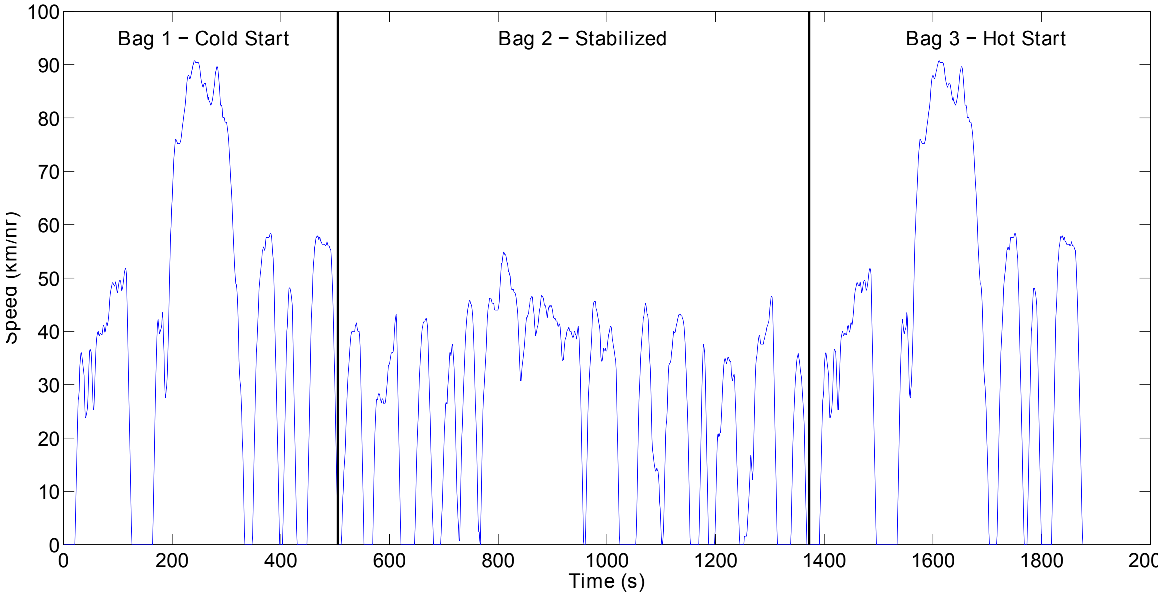


Figure E.12: Federal Test Procedure (FTP) cycle. Cold-start emission amounts are the difference between what is emitted on bag 3 and on bag 1.

E.2.2.1 Cold-start Emissions Temperature Correction

Cold-start emissions increase with lower temperature, and cold-start emissions are corrected based on the work of Hawirko [95]. Hydrocarbon and carbon monoxide emissions increase as ambient temperature decreases due to lower combustion efficiency. Oxides of nitrogen do not tend to increase as they depend more on combustion temperature rather than combustion efficiency. The temperature correction factors are shown in figure E.13.

E.3 Fugitive Emissions

Fugitive emissions are modelled based on the MOBILE6.2C model. Fugitive emissions include evaporative, crankcase, and refuelling emissions. These are hydrocarbon emissions that escape the vehicle through a variety of mechanisms. Evaporative emissions sources include:

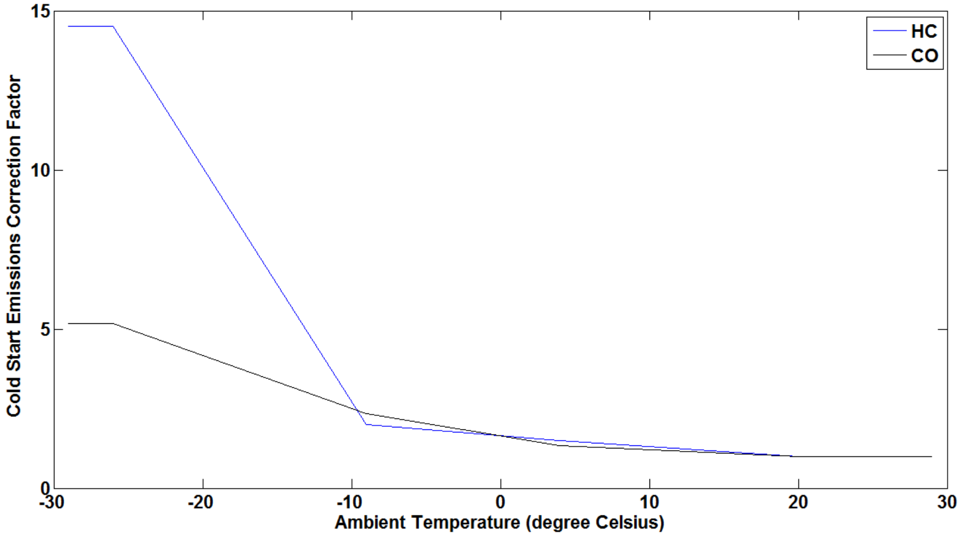


Figure E.13: Cold Start Emissions Temperature Correction Functions

- resting losses: hydrocarbons that escape the vehicle while it is at rest, and independently of temperature changes (e.g. through permeation of a plastic fuel tank)

- diurnal losses: hydrocarbons that escape the vehicle due to the change in temperature throughout the course of the day (e.g. through venting of the fuel tank as the fuel warms with ambient temperature)

- running losses: hydrocarbons that escape the vehicle while it is moving (e.g. through leaks in pressurized fuel lines)

- hot soak losses: hydrocarbons that escape the vehicle within one hour of being shut off

The evaporative emission sources and their implementation are described in more detail in the inventory tool documentation [96].

Crankcase emissions are hydrocarbons that escape the crankcase of the engine. These emissions are particularly important for vehicles that have failed positive crankcase ventilation (PCV) valves. The inventory tool documentation provides further description of the crankcase emissions model [97].

Refuelling emissions are hydrocarbons that are lost during refuelling events, such as drips from fuel nozzles. The refuelling emissions model is also described in the inventory tool documentation [98].

E.4 Alternative Fuels and High-Emitters

Alternative fuels and high-emitters were modelled in CALMOB6, an earlier version of the inventory tool, and are described by Busawon [67]. The fuels that are modelled include gasoline, Diesel fuel, compressed natural gas (CNG), liquefied petroleum gas (LPG), M85 methanol and E85 ethanol. Electric and hybrid vehicles also modelled.

E.4.1 Electrical Generation Emissions

The transportation emissions inventory tool uses life cycle assessment (LCA) based emission factors to calculate the emissions that result from electricity drawn from the grid to power electric and plug-in hybrid vehicles. The emission profiles of electrical grids are specific to the technologies used to generate the energy within the region of interest. For this reason, the grid generation technology shares can be user-modified to suit the region of interest. Table E.2 lists the generation technologies that are modelled by the inventory tool, and the emissions estimates for each technology based on a review of life-cycle assessments [99], and the Alberta regulations regarding emissions trading [100]. The default market shares of each of these technologies for 2013 is shown in table E.3 and is based on historical data and future projections of the Alberta Electrical System Operator.

Technology	CO_2 (kg/kWh)	SO_2 (kg/kWh)	NO_x (kg/kWh)
Hydro (reservoir)	0.015	0.000007	0
Diesel (0.25% S)	0.778	0.001285	0.006
Heavy Oil (1.5% S)	0.778	0.008013	0.0015
Hydro (run-of-river)	0.002	0.000001	0
Coal (1% S, no scrub)	1.05	0.00072*	0.000621*
Coal (2% S, scrubbed)	0.96	0.00072*	0.000621*
Nuclear	0.015	0.000003	0
Natural Gas (2000 km deliv.)	0.443	0.000314	0.0007
Fuel Cell (H2 from CH4)	0.664	0.00047	0
Biomass Plantation	0.118	0.000026	0.002
Wind Power	0.009	0.000069	0
Solar Photovoltaic	0.013	0.000024	0

*Based on regulatory limits in Alberta [100]

Table E.2: Emission factors for electrical generation technologies

Hydro (with reservoir)	2.97
Diesel	0
Heavy Oil	0
Hydro (run-of-river)	0
Coal (1% S)	55.99
Coal (2% S, scrubbed)	0
Nuclear	0
Natural Gas	40.9
Fuel Cell	0
Biomass plantation	0
Wind power	0.14
Photovoltaic	0

Table E.3: Market Share Percentages of Electrical Generation Technologies in Alberta in 2013

Appendix F

Simulation Output Files

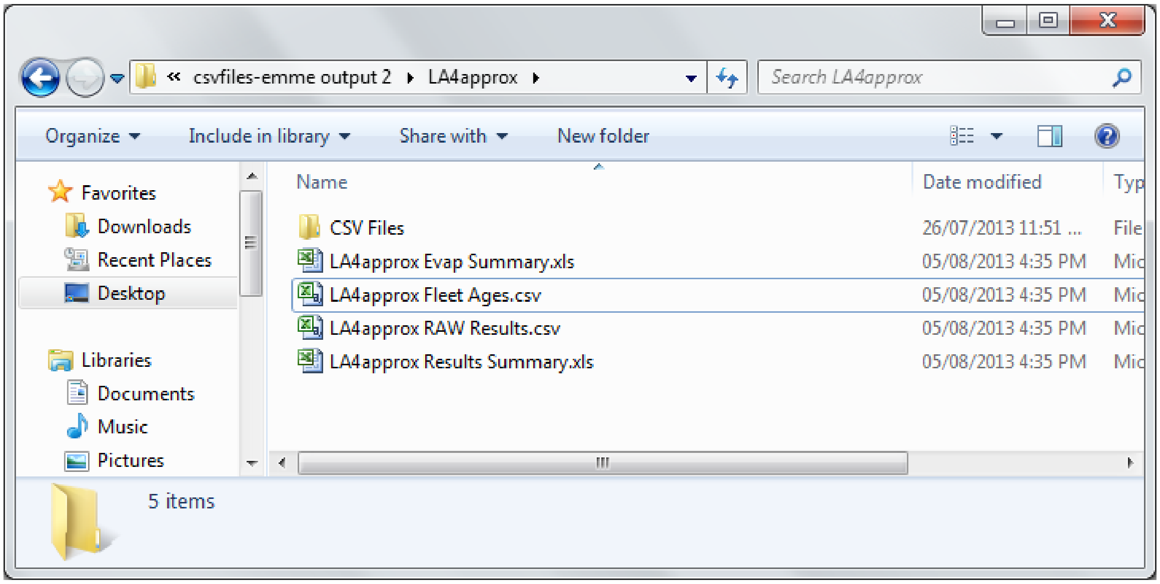
This appendix describes the output files that are created with each run of the simplified transportation micro-simulation tool.

F.1 Results Directories

Simulation results are stored in a folder created (or overwriting a previous results folder) in the directory containing the EMME Output file. The folder will contain four files and a folder titled CSV Files, as shown below. The Evap Summary and Results Summary contain the evaporative emissions results and overall inventory results respectively. The fleet age distribution is documented in the Fleet Ages file, and the RAW Results file contains raw simulation for documentation and further post-processing. The CSV Files directory contains link-by-link results for the simulations and can also be used for further post-processing.

F.2 Overall Results Summary

The overall results summary is saved in the "Results Summary.xls" file and contains an introduction sheet that summarizes the run parameters and is shown below. It also has a worksheet for each major type of vehicle (Car, LDT, MDV, HDV, and Bus), an overall summary worksheet, and three appendices.

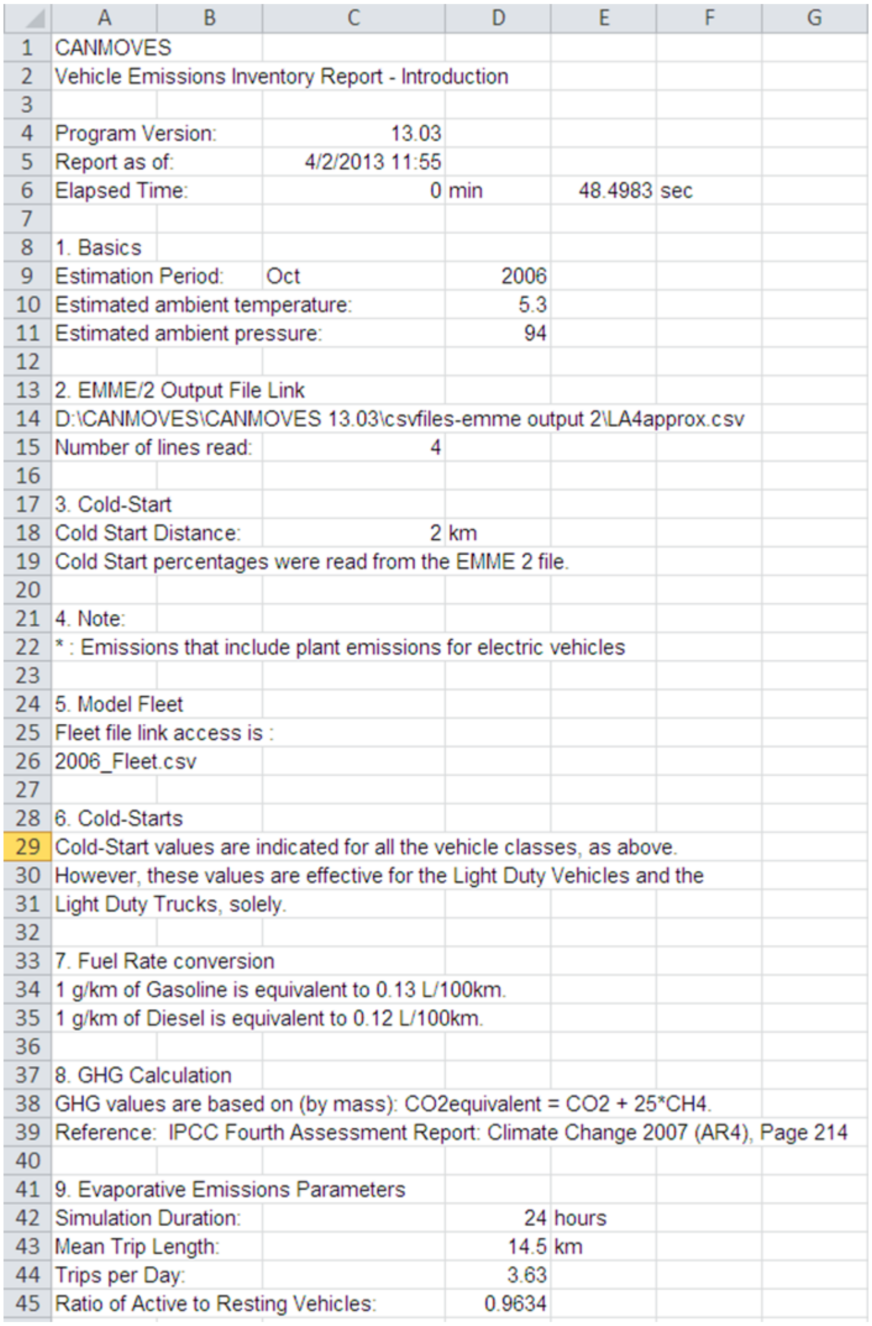


Name	Date modified	Typ
CSV Files	26/07/2013 11:51 ...	File
LA4approx Evap Summary.xls	05/08/2013 4:35 PM	Mic
LA4approx Fleet Ages.csv	05/08/2013 4:35 PM	Mic
LA4approx RAW Results.csv	05/08/2013 4:35 PM	Mic
LA4approx Results Summary.xls	05/08/2013 4:35 PM	Mic

Figure F.1: Results Directory for EMME input file titled “LA4Approx.csv”

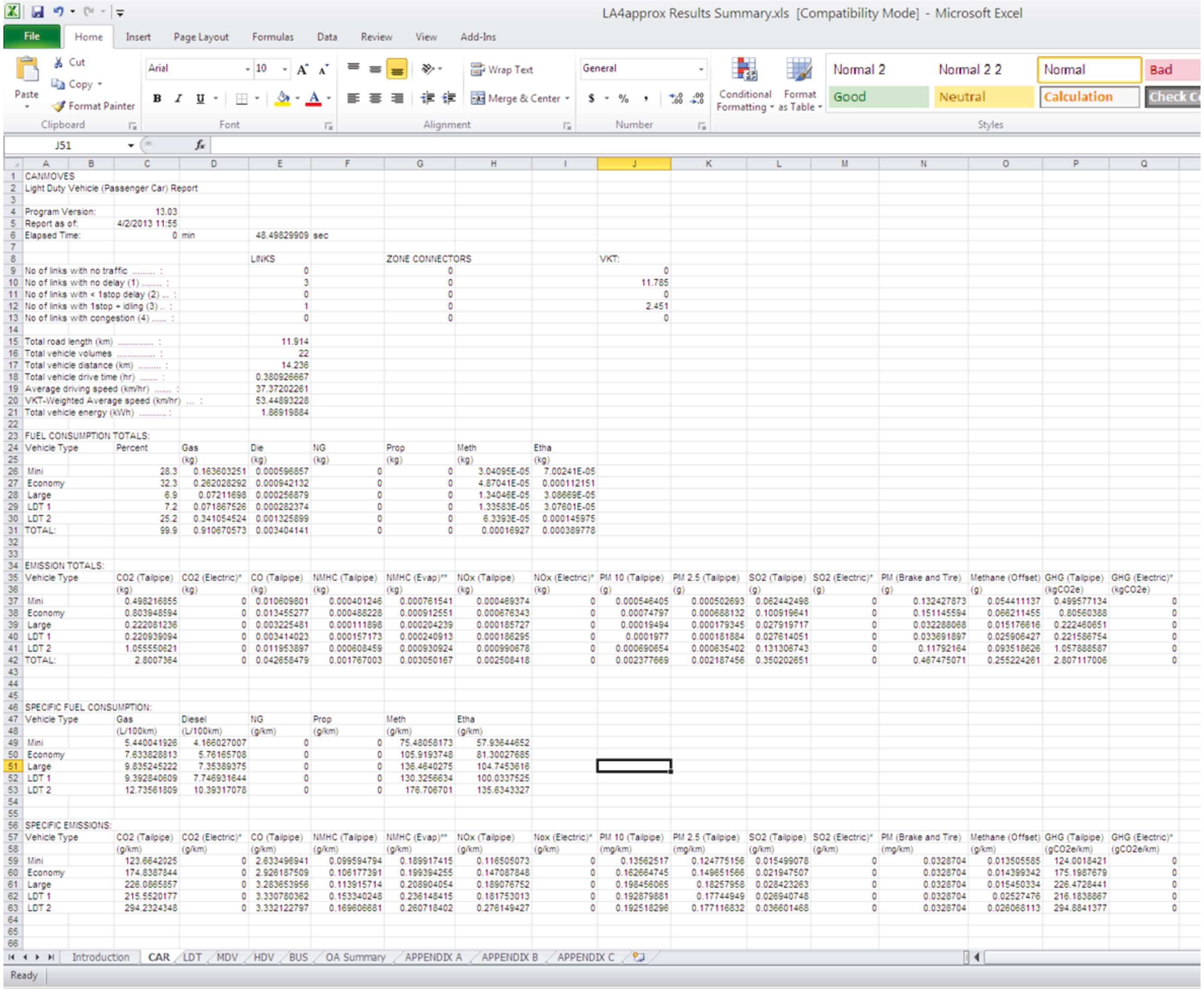
The LDT worksheet shown below is similar to the car (LDV), MDV, HDV, and Bus sheets. Fuel consumption and emissions are reported both in gross emission (grams or kilograms) and emission rate (grams per vehicle kilometre) for each vehicle subclass. Note that for this example, no electric, propane, or natural gas vehicles were modelled and the associated fuel consumption and emissions are zero.

The OA (OverAll) Summary worksheet gives a report of the entire simulation; all vehicles are summarized on this sheet. The sheet has been rearranged to show on one screen, and is shown below. Again, both the gross emissions and the emission rates are summarized. Appendix A contains information regarding the vehicle classification used, and Appendix B contains the fleet file information. Appendix C records any links on which the vehicle power limit was exceeded and the link speed was reduced or the link was simply omitted from the simulation. This may occur when, for example, a heavy duty truck is climbing a hill and does not have enough power to do so at the average speed dictated by the link parameters.



	A	B	C	D	E	F	G
1	CANMOVES						
2	Vehicle Emissions Inventory Report - Introduction						
3							
4	Program Version:		13.03				
5	Report as of:		4/2/2013 11:55				
6	Elapsed Time:		0	min	48.4983	sec	
7							
8	1. Basics						
9	Estimation Period:		Oct	2006			
10	Estimated ambient temperature:			5.3			
11	Estimated ambient pressure:			94			
12							
13	2. EMME/2 Output File Link						
14	D:\CANMOVES\CANMOVES 13.03\csvfiles-emme output 2\LA4approx.csv						
15	Number of lines read:		4				
16							
17	3. Cold-Start						
18	Cold Start Distance:		2	km			
19	Cold Start percentages were read from the EMME 2 file.						
20							
21	4. Note:						
22	* : Emissions that include plant emissions for electric vehicles						
23							
24	5. Model Fleet						
25	Fleet file link access is :						
26	2006_Fleet.csv						
27							
28	6. Cold-Starts						
29	Cold-Start values are indicated for all the vehicle classes, as above.						
30	However, these values are effective for the Light Duty Vehicles and the						
31	Light Duty Trucks, solely.						
32							
33	7. Fuel Rate conversion						
34	1 g/km of Gasoline is equivalent to 0.13 L/100km.						
35	1 g/km of Diesel is equivalent to 0.12 L/100km.						
36							
37	8. GHG Calculation						
38	GHG values are based on (by mass): CO2equivalent = CO2 + 25*CH4.						
39	Reference: IPCC Fourth Assessment Report: Climate Change 2007 (AR4), Page 214						
40							
41	9. Evaporative Emissions Parameters						
42	Simulation Duration:			24	hours		
43	Mean Trip Length:			14.5	km		
44	Trips per Day:			3.63			
45	Ratio of Active to Resting Vehicles:			0.9634			

Figure F.2: Introduction sheet of Results Summary



CANMOVES

Light Duty Vehicle (Passenger Car) Report

Program Version: 13.03

Report as of: 4/2/2013 11:55

Elapsed Time: 0 min 48.49829909 sec

	LINKS	ZONE CONNECTORS	VKT:
No of links with no traffic .... :	0	0	0
No of links with no delay (1) .... :	3	0	11.785
No of links with < 1stop delay (2) ... :	0	0	0
No of links with 1stop + idling (3) .. :	1	0	2.451
No of links with congestion (4) ...... :	0	0	0

Total road length (km) .... :	11.914
Total vehicle volumes .... :	22
Total vehicle distance (km) .... :	14.236
Total vehicle drive time (hr) .... :	0.380926667
Average driving speed (km/hr) .... :	37.37202261
VKT-Weighted Average speed (km/hr) ... :	53.44893228
Total vehicle energy (kWh) .... :	1.86919884

FUEL CONSUMPTION TOTALS:

Vehicle Type	Percent	Gas (kg)	Die (kg)	NG (kg)	Prop (kg)	Meth (kg)	Etha (kg)
Mini	28.3	0.163603251	0.000596857	0	0	3.04095E-05	7.00241E-05
Economy	32.3	0.262028292	0.000942132	0	0	4.87041E-05	0.000112151
Large	6.9	0.07211698	0.000256879	0	0	1.34046E-05	3.08669E-05
LDT 1	7.2	0.071867526	0.000282374	0	0	1.33583E-05	3.07601E-05
LDT 2	25.2	0.341054524	0.001325899	0	0	6.3393E-05	0.000145975
TOTAL:	99.9	0.910670573	0.003404141	0	0	0.00016927	0.000389778

EMISSION TOTALS:

Vehicle Type	CO2 (Tailpipe) (kg)	CO2 (Electric)* (kg)	CO (Tailpipe) (kg)	NMHC (Tailpipe) (kg)	NMHC (Evap)** (kg)	NOx (Tailpipe) (kg)	NOx (Electric)* (kg)	PM 10 (Tailpipe) (g)	PM 2.5 (Tailpipe) (g)	SO2 (Tailpipe) (g)	SO2 (Electric)* (g)	PM (Brake and Tire) (g)	Methane (Offset) (g)	GHG (Tailpipe) (kgCO2e)	GHG (Electric)* (kgCO2e)
Mini	0.498216855	0	0.010609801	0.000401246	0.000761541	0.000469374	0	0.000546405	0.000502693	0.062442498	0	0.132427873	0.054411137	0.499577134	0
Economy	0.803948594	0	0.013455277	0.000488228	0.000912551	0.000676343	0	0.00074797	0.000688132	0.100919641	0	0.151145594	0.066211455	0.80560388	0
Large	0.222081236	0	0.003225481	0.000111898	0.000204239	0.000185727	0	0.00019494	0.000179345	0.027919717	0	0.032288068	0.015176616	0.222460651	0
LDT 1	0.220939094	0	0.003414023	0.000157173	0.000240913	0.000186295	0	0.0001977	0.000181884	0.027614051	0	0.033691897	0.025906427	0.221586754	0
LDT 2	1.055550621	0	0.011953897	0.000608459	0.000930924	0.000990678	0	0.000690654	0.000635402	0.131306743	0	0.11792164	0.093518626	1.057888587	0
TOTAL:	2.8007364	0	0.042658479	0.001767003	0.003050167	0.002508418	0	0.002377669	0.002187456	0.350202651	0	0.467475071	0.255224261	2.807117006	0

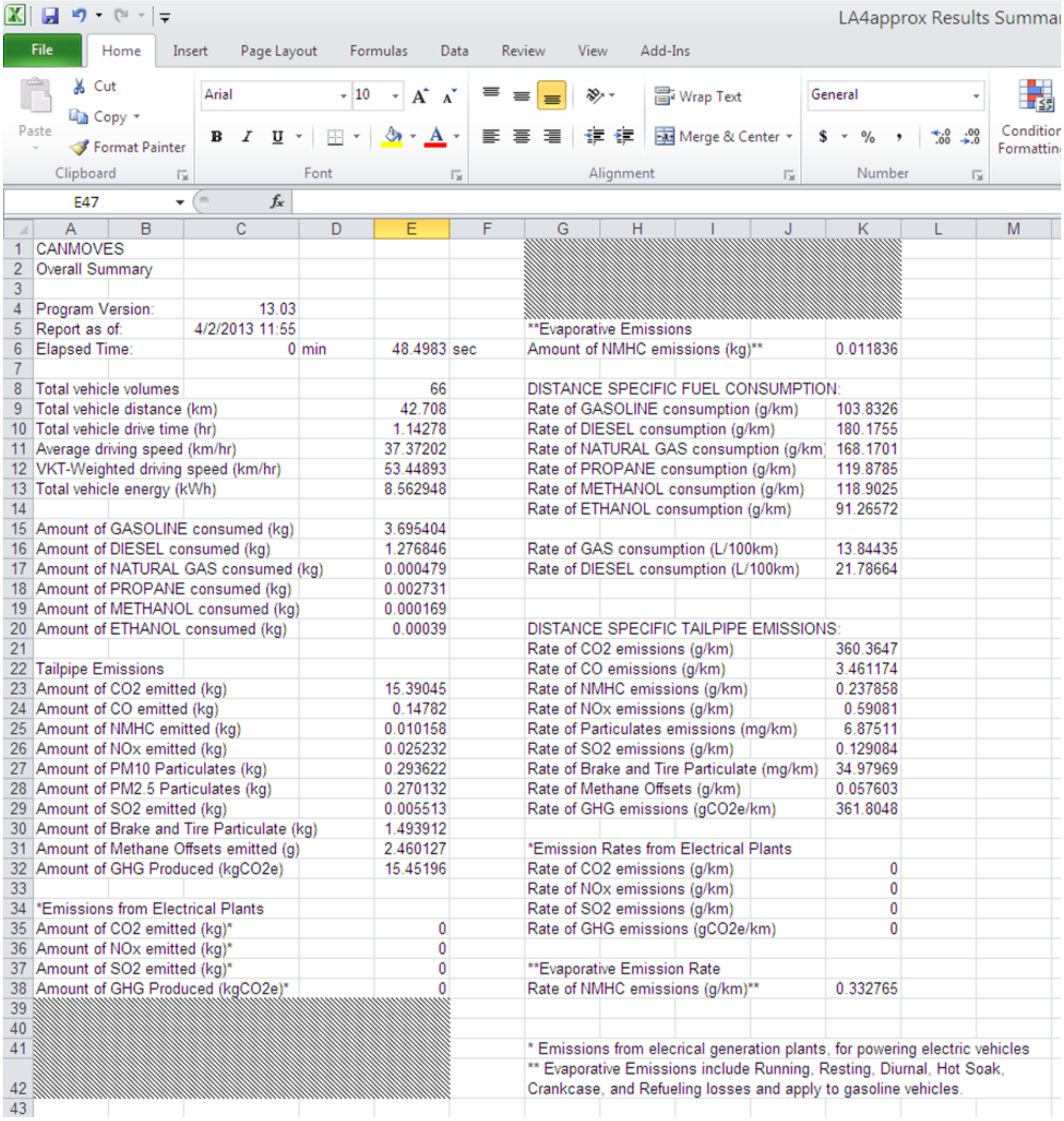
SPECIFIC FUEL CONSUMPTION:

Vehicle Type	Gas (L/100km)	Diesel (L/100km)	NG (g/km)	Prop (g/km)	Meth (g/km)	Etha (g/km)
Mini	5.440041926	4.166027007	0	0	75.48058173	57.93644652
Economy	7.633828813	5.76165708	0	0	105.9193748	81.30027685
Large	9.835245222	7.35389375	0	0	136.4640275	104.7453616
LDT 1	9.392840609	7.746931644	0	0	130.3256634	100.0337525
LDT 2	12.73561809	10.39317078	0	0	176.706701	135.6343327

SPECIFIC EMISSIONS:

Vehicle Type	CO2 (Tailpipe) (g/km)	CO2 (Electric)* (g/km)	CO (Tailpipe) (g/km)	NMHC (Tailpipe) (g/km)	NMHC (Evap)** (g/km)	NOx (Tailpipe) (g/km)	Nox (Electric)* (g/km)	PM 10 (Tailpipe) (mg/km)	PM 2.5 (Tailpipe) (mg/km)	SO2 (Tailpipe) (g/km)	SO2 (Electric)* (g/km)	PM (Brake and Tire) (mg/km)	Methane (Offset) (g/km)	GHG (Tailpipe) (gCO2e/km)	GHG (Electric)* (gCO2e/km)
Mini	123.6642025	0	2.633496941	0.099594794	0.189917415	0.116505073	0	0.13562517	0.124775156	0.015499078	0	0.0328704	0.013505585	124.0018421	0
Economy	174.8387844	0	2.926187509	0.106177391	0.199394255	0.147087848	0	0.162664745	0.149651566	0.021947507	0	0.0328704	0.014399342	175.1987679	0
Large	226.0865857	0	3.283653956	0.113915714	0.208904054	0.189076752	0	0.198456065	0.18257958	0.028423263	0	0.0328704	0.015450334	226.4728441	0
LDT 1	215.5520177	0	3.330780362	0.153340248	0.236148415	0.181753013	0	0.192879881	0.17744949	0.026940748	0	0.0328704	0.02527476	216.1838867	0
LDT 2	294.2324348	0	3.332122797	0.169606681	0.260718402	0.276149427	0	0.192518296	0.177116832	0.036601468	0	0.0328704	0.026068113	294.8841377	0

Figure F.3: LDT sheet of Results Summary



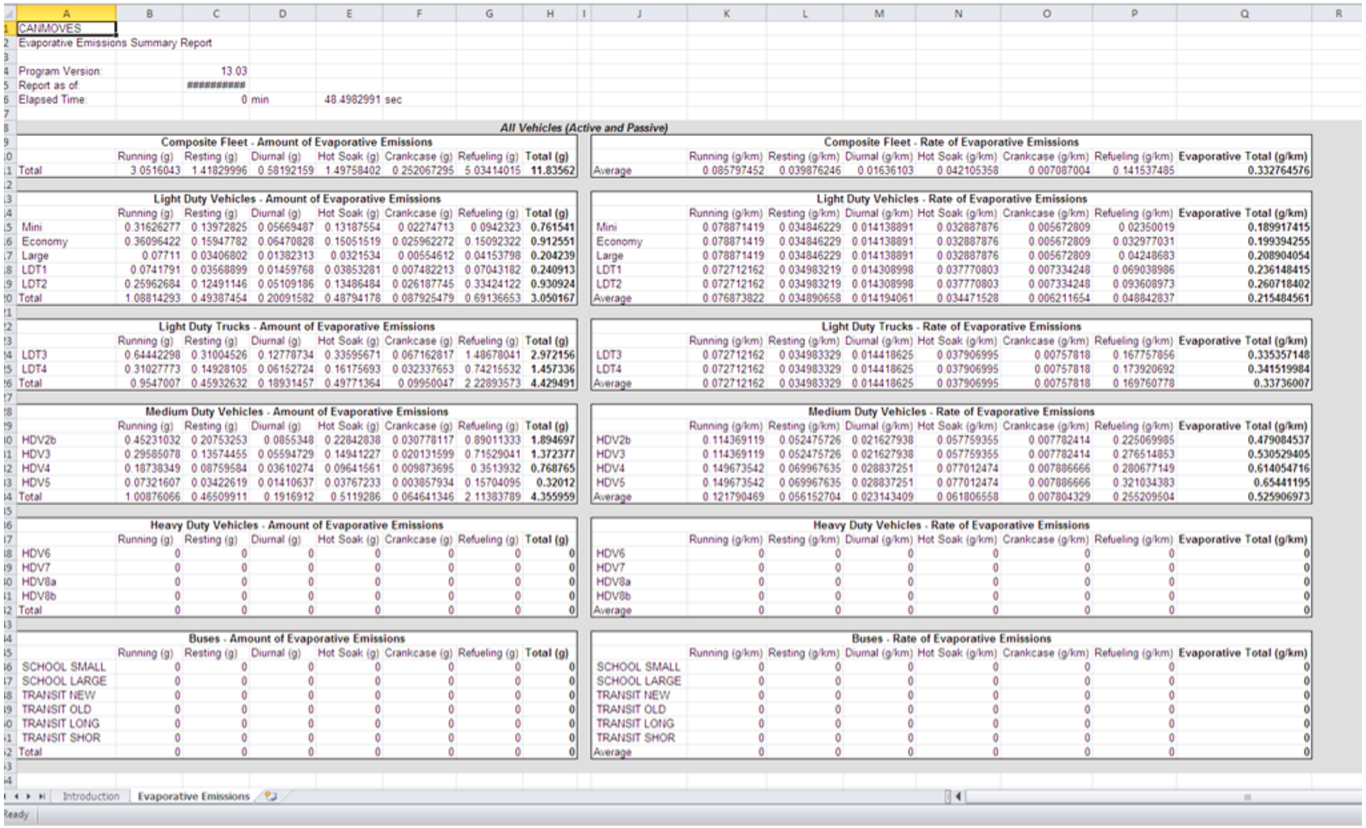
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	CANMOVES												
2	Overall Summary												
3													
4	Program Version:		13.03										
5	Report as of:		4/2/2013 11:55				**Evaporative Emissions						
6	Elapsed Time:		0	min	48.4983	sec	Amount of NMHC emissions (kg)**				0.011836		
7													
8	Total vehicle volumes				66		DISTANCE SPECIFIC FUEL CONSUMPTION:						
9	Total vehicle distance (km)				42.708		Rate of GASOLINE consumption (g/km)				103.8326		
10	Total vehicle drive time (hr)				1.14278		Rate of DIESEL consumption (g/km)				180.1755		
11	Average driving speed (km/hr)				37.37202		Rate of NATURAL GAS consumption (g/km				168.1701		
12	VKT-Weighted driving speed (km/hr)				53.44893		Rate of PROPANE consumption (g/km)				119.8785		
13	Total vehicle energy (kWh)				8.562948		Rate of METHANOL consumption (g/km)				118.9025		
14							Rate of ETHANOL consumption (g/km)				91.26572		
15	Amount of GASOLINE consumed (kg)				3.695404								
16	Amount of DIESEL consumed (kg)				1.276846		Rate of GAS consumption (L/100km)				13.84435		
17	Amount of NATURAL GAS consumed (kg)				0.000479		Rate of DIESEL consumption (L/100km)				21.78664		
18	Amount of PROPANE consumed (kg)				0.002731								
19	Amount of METHANOL consumed (kg)				0.000169								
20	Amount of ETHANOL consumed (kg)				0.00039		DISTANCE SPECIFIC TAILPIPE EMISSIONS:						
21							Rate of CO2 emissions (g/km)				360.3647		
22	Tailpipe Emissions						Rate of CO emissions (g/km)				3.461174		
23	Amount of CO2 emitted (kg)				15.39045		Rate of NMHC emissions (g/km)				0.237858		
24	Amount of CO emitted (kg)				0.14782		Rate of NOx emissions (g/km)				0.59081		
25	Amount of NMHC emitted (kg)				0.010158		Rate of Particulates emissions (mg/km)				6.87511		
26	Amount of NOx emitted (kg)				0.025232		Rate of SO2 emissions (g/km)				0.129084		
27	Amount of PM10 Particulates (kg)				0.293622		Rate of Brake and Tire Particulate (mg/km)				34.97969		
28	Amount of PM2.5 Particulates (kg)				0.270132		Rate of Methane Offsets (g/km)				0.057603		
29	Amount of SO2 emitted (kg)				0.005513		Rate of GHG emissions (gCO2e/km)				361.8048		
30	Amount of Brake and Tire Particulate (kg)				1.493912								
31	Amount of Methane Offsets emitted (g)				2.460127		*Emission Rates from Electrical Plants						
32	Amount of GHG Produced (kgCO2e)				15.45196		Rate of CO2 emissions (g/km)				0		
33							Rate of NOx emissions (g/km)				0		
34	*Emissions from Electrical Plants						Rate of SO2 emissions (g/km)				0		
35	Amount of CO2 emitted (kg)*				0		Rate of GHG emissions (gCO2e/km)				0		
36	Amount of NOx emitted (kg)*				0								
37	Amount of SO2 emitted (kg)*				0		**Evaporative Emission Rate						
38	Amount of GHG Produced (kgCO2e)*				0		Rate of NMHC emissions (g/km)**				0.332765		
39													
40													
41							* Emissions from elecrical generation plants, for powering electric vehicles						
42							** Evaporative Emissions include Running, Resting, Diurnal, Hot Soak, Crankcase, and Refueling losses and apply to gasoline vehicles.						
43													

Figure F.4: OA Summary sheet of Results Summary

F.3 Evaporative Emissions Summary

Evaporative emissions are hydrocarbons (fuel vapour) that escape the vehicle without passing through the engine. These emissions are summarized in the Evap Summary.xls file. An introduction sheet identical to that of Figure F.2 summarizes the simulation definition parameters. The Evaporative Emissions sheet describes the evaporative emissions by vehicle class and source (crankcase, running loss, etc.) and is shown in Figure F.5.

The Evaporative Emissions worksheet breaks down the evaporative emissions by source and vehicle class, and contains both the gross emissions (in grams of pollutant) and the emission rate (in grams of pollutant per vehicle kilometre). The composite fleet is reported at the top and is the overall emission rate of the fleet. This data is presented for all vehicles, and is broken down in to active and passive vehicles in lower cells of the worksheet. Active vehicles are those which make one or more trips during the simulation and passive vehicles are those which remain parked during the simulation.



CANMOVES

Evaporative Emissions Summary Report

Program Version: 13.03

Report as of: ##########

Elapsed Time: 0 min 48.4982991 sec

All Vehicles (Active and Passive)

Composite Fleet - Amount of Evaporative Emissions

	Running (g)	Resting (g)	Diurnal (g)	Hot Soak (g)	Crankcase (g)	Refueling (g)	**Total (g)**
Total	3.0516043	1.41829996	0.58192159	1.49758402	0.252067295	5.03414015	**11.83562**

Composite Fleet - Rate of Evaporative Emissions

	Running (g/km)	Resting (g/km)	Diurnal (g/km)	Hot Soak (g/km)	Crankcase (g/km)	Refueling (g/km)	**Evaporative Total (g/km)**
Average	0.085797452	0.039876246	0.01636103	0.042105358	0.007087004	0.141537485	**0.332764576**

Light Duty Vehicles - Amount of Evaporative Emissions

	Running (g)	Resting (g)	Diurnal (g)	Hot Soak (g)	Crankcase (g)	Refueling (g)	**Total (g)**
Mini	0.31626277	0.13972825	0.05669487	0.13187554	0.02274713	0.0942323	**0.761541**
Economy	0.36096422	0.15947782	0.06470828	0.15051519	0.025962272	0.15092322	**0.912551**
Large	0.07711	0.03406802	0.01382313	0.0321534	0.00554612	0.04153798	**0.204239**
LDT1	0.0741791	0.03568899	0.01459768	0.03853281	0.007482213	0.07043182	**0.240913**
LDT2	0.25962684	0.12491146	0.05109186	0.13486484	0.026187745	0.33424122	**0.930924**
Total	1.08814293	0.49387454	0.20091582	0.48794178	0.087925479	0.69136653	**3.050167**

Light Duty Vehicles - Rate of Evaporative Emissions

	Running (g/km)	Resting (g/km)	Diurnal (g/km)	Hot Soak (g/km)	Crankcase (g/km)	Refueling (g/km)	**Evaporative Total (g/km)**
Mini	0.078871419	0.034846229	0.014138891	0.032887876	0.005672809	0.02350019	**0.189917415**
Economy	0.078871419	0.034846229	0.014138891	0.032887876	0.005672809	0.032977031	**0.199394255**
Large	0.078871419	0.034846229	0.014138891	0.032887876	0.005672809	0.04248683	**0.208904054**
LDT1	0.072712162	0.034983219	0.014308998	0.037770803	0.007334248	0.069038986	**0.236148415**
LDT2	0.072712162	0.034983219	0.014308998	0.037770803	0.007334248	0.093608973	**0.260718402**
Average	0.076873822	0.034890658	0.014194061	0.034471528	0.006211654	0.048842837	**0.215484561**

Light Duty Trucks - Amount of Evaporative Emissions

	Running (g)	Resting (g)	Diurnal (g)	Hot Soak (g)	Crankcase (g)	Refueling (g)	**Total (g)**
LDT3	0.64442298	0.31004526	0.12778734	0.33595671	0.067162817	1.48678041	**2.972156**
LDT4	0.31027773	0.14928105	0.06152724	0.16175693	0.032337653	0.74215532	**1.457336**
Total	0.9547007	0.45932632	0.18931457	0.49771364	0.09950047	2.22893573	**4.429491**

Light Duty Trucks - Rate of Evaporative Emissions

	Running (g/km)	Resting (g/km)	Diurnal (g/km)	Hot Soak (g/km)	Crankcase (g/km)	Refueling (g/km)	**Evaporative Total (g/km)**
LDT3	0.072712162	0.034983329	0.014418625	0.037906995	0.00757818	0.167757856	**0.335357148**
LDT4	0.072712162	0.034983329	0.014418625	0.037906995	0.00757818	0.173920692	**0.341519984**
Average	0.072712162	0.034983329	0.014418625	0.037906995	0.00757818	0.169760778	**0.33736007**

Medium Duty Vehicles - Amount of Evaporative Emissions

	Running (g)	Resting (g)	Diurnal (g)	Hot Soak (g)	Crankcase (g)	Refueling (g)	**Total (g)**
HDV2b	0.45231032	0.20753253	0.0855348	0.22842838	0.030778117	0.89011333	**1.894697**
HDV3	0.29585078	0.13574455	0.05594729	0.14941227	0.020131599	0.71529041	**1.372377**
HDV4	0.18738349	0.08759584	0.03610274	0.09641561	0.009873695	0.3513932	**0.768765**
HDV5	0.07321607	0.03422619	0.01410637	0.03767233	0.003857934	0.15704095	**0.32012**
Total	1.00876066	0.46509911	0.1916912	0.5119286	0.064641346	2.11383789	**4.355959**

Medium Duty Vehicles - Rate of Evaporative Emissions

	Running (g/km)	Resting (g/km)	Diurnal (g/km)	Hot Soak (g/km)	Crankcase (g/km)	Refueling (g/km)	**Evaporative Total (g/km)**
HDV2b	0.114369119	0.052475726	0.021627938	0.057759355	0.007782414	0.225069985	**0.479084537**
HDV3	0.114369119	0.052475726	0.021627938	0.057759355	0.007782414	0.276514853	**0.530529405**
HDV4	0.149673542	0.069967635	0.028837251	0.077012474	0.007886666	0.280677149	**0.614054716**
HDV5	0.149673542	0.069967635	0.028837251	0.077012474	0.007886666	0.321034383	**0.65441195**
Average	0.121790469	0.056152704	0.023143409	0.061806558	0.007804329	0.255209504	**0.525906973**

Heavy Duty Vehicles - Amount of Evaporative Emissions

	Running (g)	Resting (g)	Diurnal (g)	Hot Soak (g)	Crankcase (g)	Refueling (g)	**Total (g)**
HDV6	0	0	0	0	0	0	**0**
HDV7	0	0	0	0	0	0	**0**
HDV8a	0	0	0	0	0	0	**0**
HDV8b	0	0	0	0	0	0	**0**
Total	0	0	0	0	0	0	**0**

Heavy Duty Vehicles - Rate of Evaporative Emissions

	Running (g/km)	Resting (g/km)	Diurnal (g/km)	Hot Soak (g/km)	Crankcase (g/km)	Refueling (g/km)	**Evaporative Total (g/km)**
HDV6	0	0	0	0	0	0	**0**
HDV7	0	0	0	0	0	0	**0**
HDV8a	0	0	0	0	0	0	**0**
HDV8b	0	0	0	0	0	0	**0**
Average	0	0	0	0	0	0	**0**

Buses - Amount of Evaporative Emissions

	Running (g)	Resting (g)	Diurnal (g)	Hot Soak (g)	Crankcase (g)	Refueling (g)	**Total (g)**
SCHOOL SMALL	0	0	0	0	0	0	**0**
SCHOOL LARGE	0	0	0	0	0	0	**0**
TRANSIT NEW	0	0	0	0	0	0	**0**
TRANSIT OLD	0	0	0	0	0	0	**0**
TRANSIT LONG	0	0	0	0	0	0	**0**
TRANSIT SHOR	0	0	0	0	0	0	**0**
Total	0	0	0	0	0	0	**0**

Buses - Rate of Evaporative Emissions

	Running (g/km)	Resting (g/km)	Diurnal (g/km)	Hot Soak (g/km)	Crankcase (g/km)	Refueling (g/km)	**Evaporative Total (g/km)**
SCHOOL SMALL	0	0	0	0	0	0	**0**
SCHOOL LARGE	0	0	0	0	0	0	**0**
TRANSIT NEW	0	0	0	0	0	0	**0**
TRANSIT OLD	0	0	0	0	0	0	**0**
TRANSIT LONG	0	0	0	0	0	0	**0**
TRANSIT SHOR	0	0	0	0	0	0	**0**
Average	0	0	0	0	0	0	**0**

Figure F.5: Evaporative Emissions sheet of Evap Summary

APPENDIX G

COMPARISON OF MOVES2010B TO THE SIMPLIFIED MICRO-SIMULATION INVENTORY TOOL

This chapter compares the MOVES2010B emission inventory to the simplified micro-simulation emissions inventory tool.

G.1 MOVES2010b inventory methods

The US EPAs MOVES2010b model is the latest version of the MOVES model, which replaces the macro-scale MOBILE model. In addition to macro-scale National and County modes, the Project mode in MOVES includes two options for smaller scale emissions calculations. The Project mode allows for transportation demand model type input (i.e. link length, average speed, and roadway type), and for driving schedule input. When the link average speed is specified, built-in driving cycles are used to simulate each link in the network. These driving cycles assign a distribution of vehicle-specific power (VSP) and speed bins to each link, and MOVES2010b applies bin-average emission rates to calculate the link emissions. Alternatively, second-by-second driving cycles (such as micro-simulation data, dynamometer schedules, or real driving data) can be input directly into a MOVES2010b project-level simulation, and the vehicle specific power and emissions are calculated at each second of each cycle to generate the inventory.

The approach used in MOVES differs from the approach used in the simplified micro-simulation inventory tool in the following ways:

- MOVES uses VSP, while the inventory tool uses tractive power analysis
- Emissions are calculated based on the vehicle speed and VSP
- MOVES calculates emissions using a binning approach, while the inventory tool uses continuous functions
- MOVES uses five facility types to describe the link, while the inventory tool uses the speed limit
- When using link average speeds in the project mode, MOVES will interpolate between the two closest driving cycles, while the inventory tool generates a cycle matching the link average speed exactly

In terms of congestion modelling, the MOVES model is considerably different than the inventory tool. The five facility types modelled by MOVES are off-network, rural restricted, rural unrestricted, urban restricted, and urban unrestricted. The off-network links are used to model parking lots, restricted facilities are those with traffic signals, and unrestricted facilities are freeways. Using these definitions is somewhat restrictive in terms of how a road is described. For example, a large arterial with a speed limit of 70 km/hr cannot be distinguished from a small feeder link with a speed limit of 50 km/hr. This is problematic since the two roads are not equally congested if their average speed is 40 km/hr. However, MOVES will estimate the same emissions on both links since their description within the simulation definition is identical.

The following sections describe a series of simulations designed to show the differences between the modelling approaches used in MOVES2010b and the inventory tool.

Mass (kg)	1478.8
Frontal Area (m^2)	1.951
Drag Coefficient	0.327
Rolling Resistance Coefficient	0.00765

Table G.1: LDV properties used to simulate a MOVES passenger car (class 21)

G.2 Vehicle definition

To generate comparable simulations, a vehicle class was defined in simplified micro-simulation inventory tool that would require similar power to the MOVES default passenger car up to 120 km/hr. The physical characteristics of this vehicle class are shown in table G.1. The tractive power calculated by the inventory tool and the vehicle specific power (VSP) calculated by MOVES are compared in figure G.1; the largest difference between the two power curves is 0.768 kW. For the comparisons in the following sections, the MOVES simulations model a default passenger car (class 21), while the inventory tool simulations model a light-duty vehicle with the physical characteristics shown in table G.1.

G.3 Comparison of the inventory tool to MOVES2010b Project mode with average speeds

This set of simulations compares the response of the simplified micro-simulation tool and of MOVES2010b to link average speed. The MOVES estimate of CO_2 emissions for the Urban Restricted facility type are compared to the inventory tool results for links with speeds limits between 50 and 80 km/hr in figure G.2. The MOVES estimate increases smoothly as link speed decreases, while the inventory tool estimates increase with slight steps as the number of stops that vehicles make on the link is incremented. The inventory tool estimate of CO_2 emissions for an average speed of 50 km/hr is 54% higher for a link with a speed limit of 80 km/hr than it is for a link with a speed limit

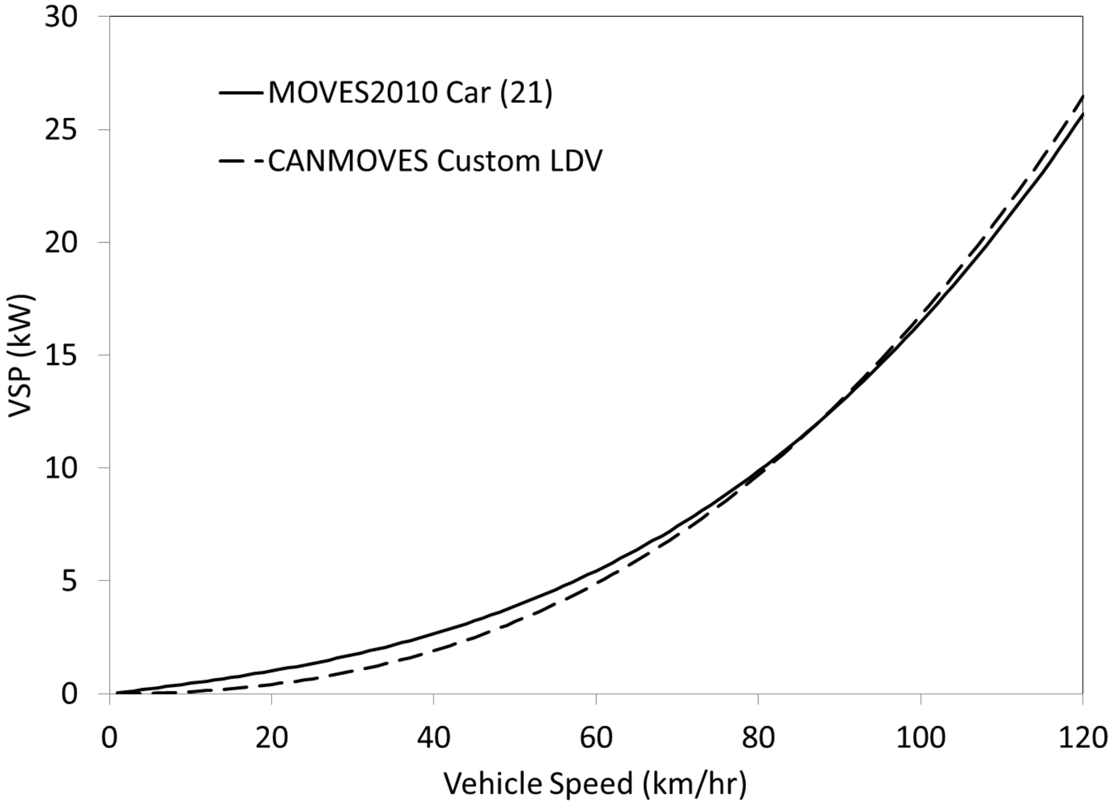


Figure G.1: MOVES Passenger Car Vehicle Specific Power (VSP) and LDV-Custom Tractive Power for comparison simulations

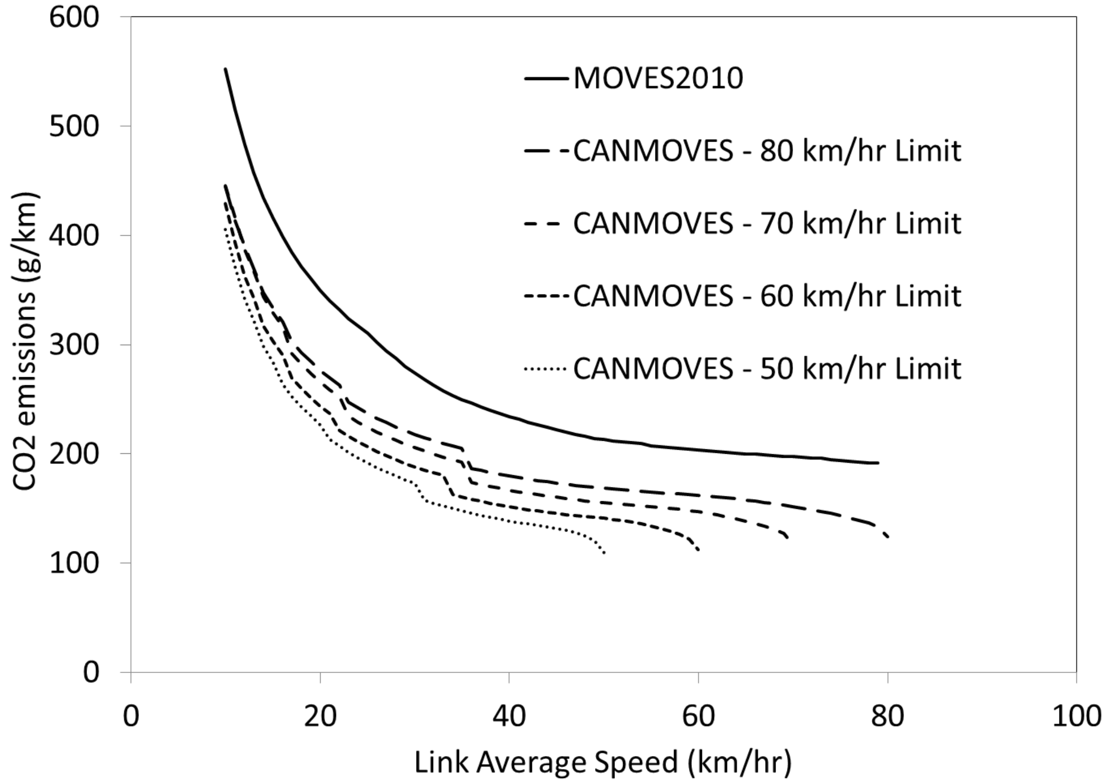


Figure G.2: CO2 emissions estimated for MOVES2010 Urban Restricted facility and simplified micro-simulation links with 50 - 80 km/hr speed limits

of 50 km/hr. Since MOVES does not differentiate city links beyond the restricted and unrestricted classification, it cannot capture the difference between these links when the project mode is used with average link speeds.

Figure G.3 shows a similar comparison for the Urban Unrestricted MOVES facility type and simplified micro-simulation links with speed limits of 90 - 110 km/hr. The same observation applies: MOVES cannot capture the difference between links with different speed limits. It is notable that MOVES predicts higher emissions than the inventory tool in these two simulations. The following section compares the two inventories more directly by using the simplified micro-simulation drive schedules to simulate the same traffic in both models.

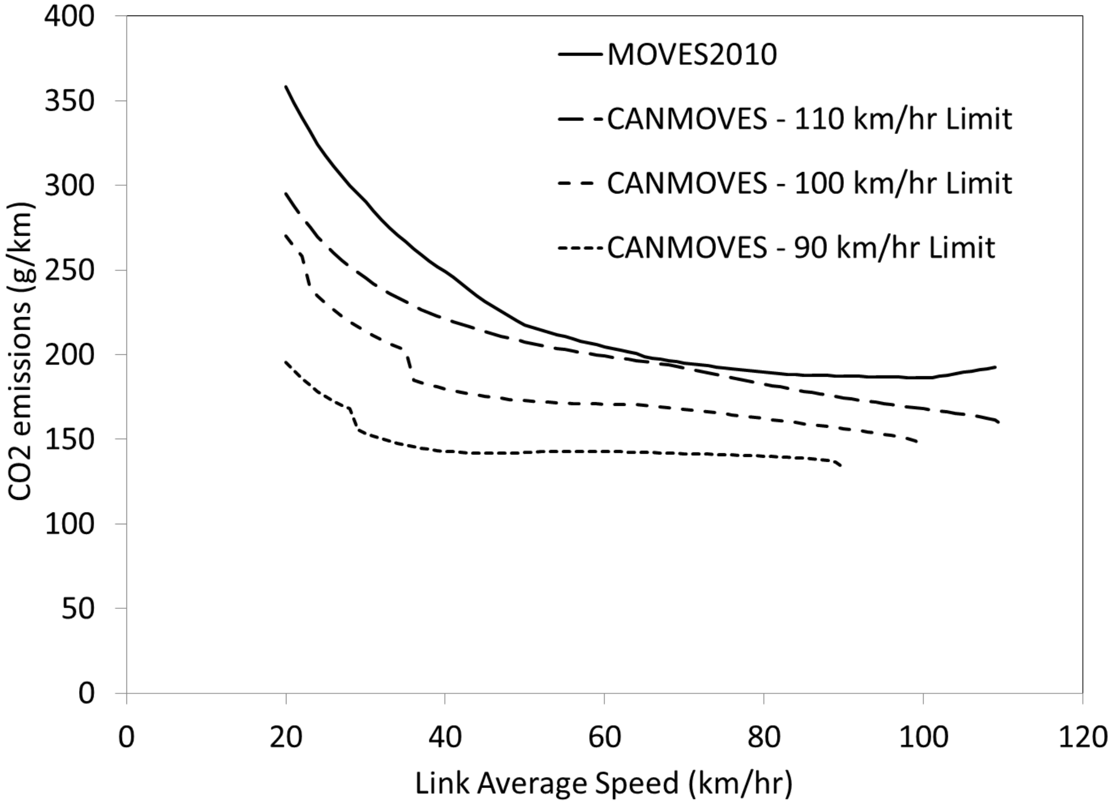


Figure G.3: CO2 emissions estimated for MOVES2010 Urban Unrestricted facility and simplified micro-simulation links with 90 - 110 km/hr speed limits

G.4 Comparison of the inventory tool to MOVES2010b Project mode using simplified micro-simulation drive schedules

The drive schedules generated by the simplified micro-simulation are used as input for MOVES simulations in the following comparisons. This means that the traffic patterns used by the two models are the same and the emissions predictions are compared. Figure G.4 shows the CO_2 emissions predictions for MOVES for the drive schedules generated by the simplified micro-simulation at speed limits of 50 - 80 km/hr. These trends overlap and cross over each other, which is detrimental to a micro-simulation because link-by-link results will not be consistent: it is possible that a link with higher congestion will be modelled with lower emissions by MOVES. This makes the use of results at the link level questionable since the model must be sufficiently aggregated to produce a consistent result.

The simplified micro-simulation inventory tool CO_2 emission results are shown for the same simulation data in figure G.5. The trends do have slight steps as congestion increases to the point that vehicles must make multiple stops, but the model consistently shows that higher congestion levels result in higher CO_2 emissions; consequently the use of the simplified micro-simulation inventory tool results at the link level can be expected to model congestion consistently.

Figure G.6 shows a similar set of simulation results for speed limits between 80 and 110 km/hr, and the inconsistency of the trends is further exaggerated at these speeds. The corresponding simplified micro-simulation inventory tool results are shown in figure G.7 and once again show that consistent results are expected at the link level.

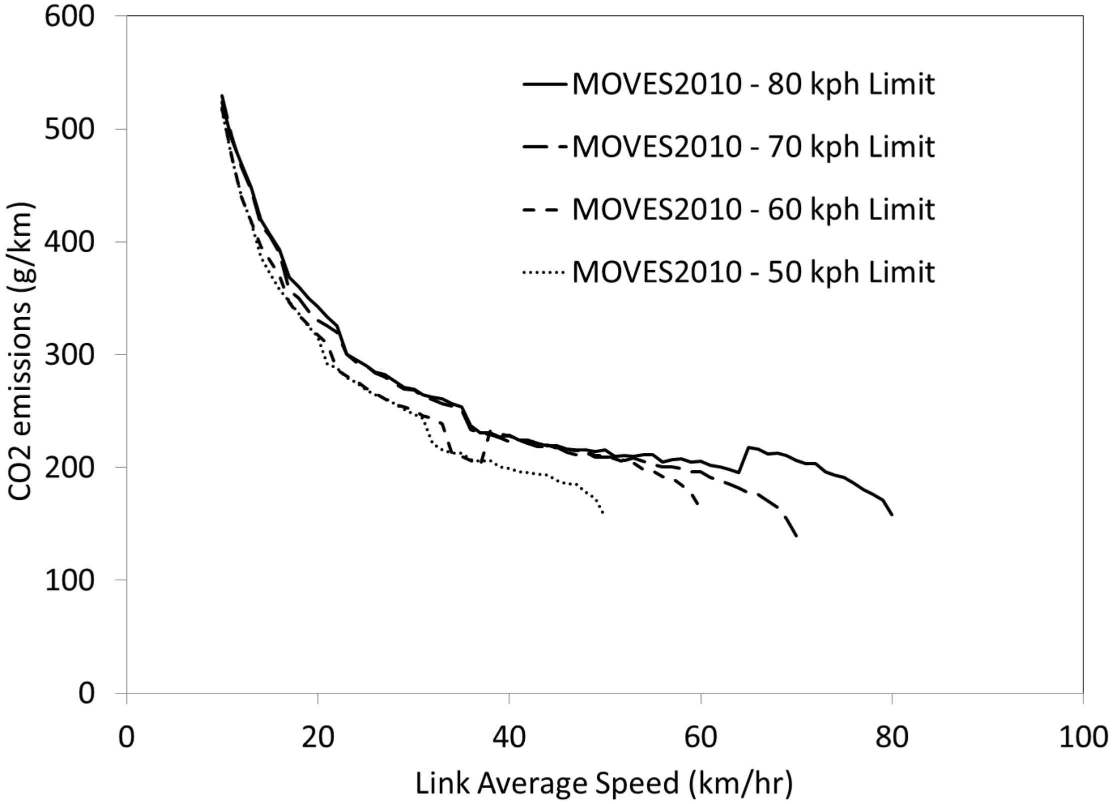


Figure G.4: CO2 emissions estimated for MOVES2010b Urban Restricted facility with drive schedules simulated by the simplified micro-simulation

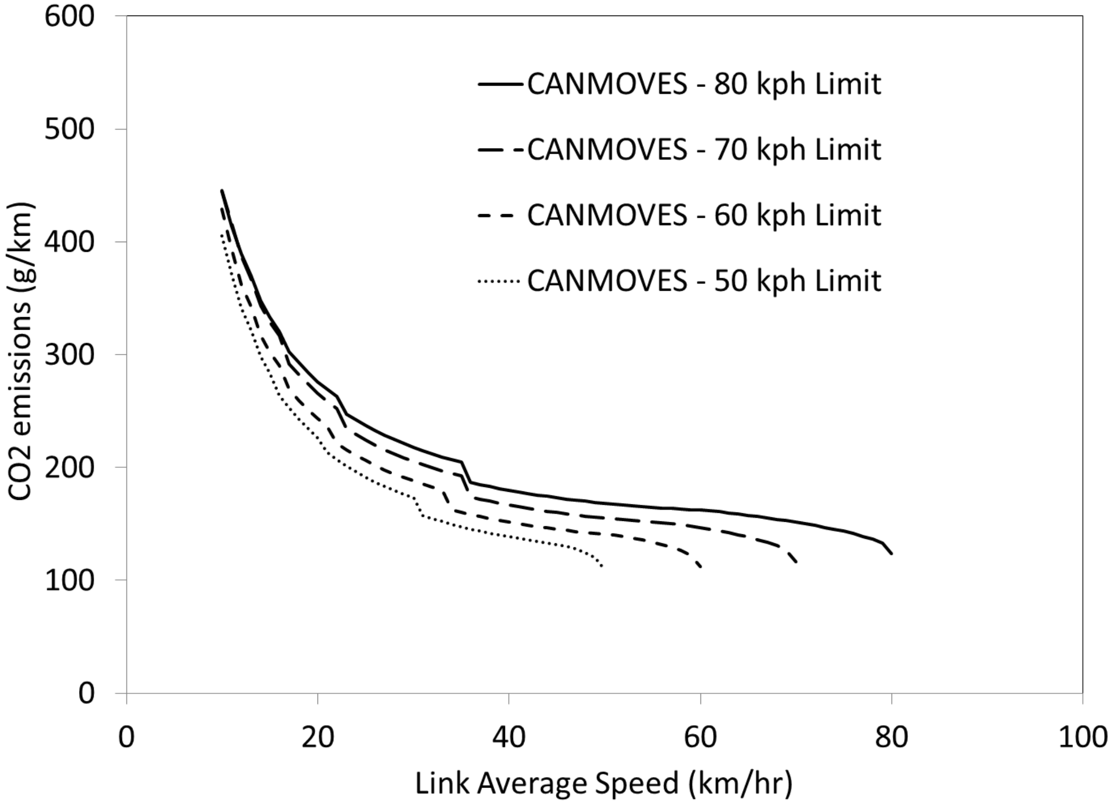


Figure G.5: CO2 emissions estimates for simplified micro-simulation links with 50 - 80 km/hr speed limits

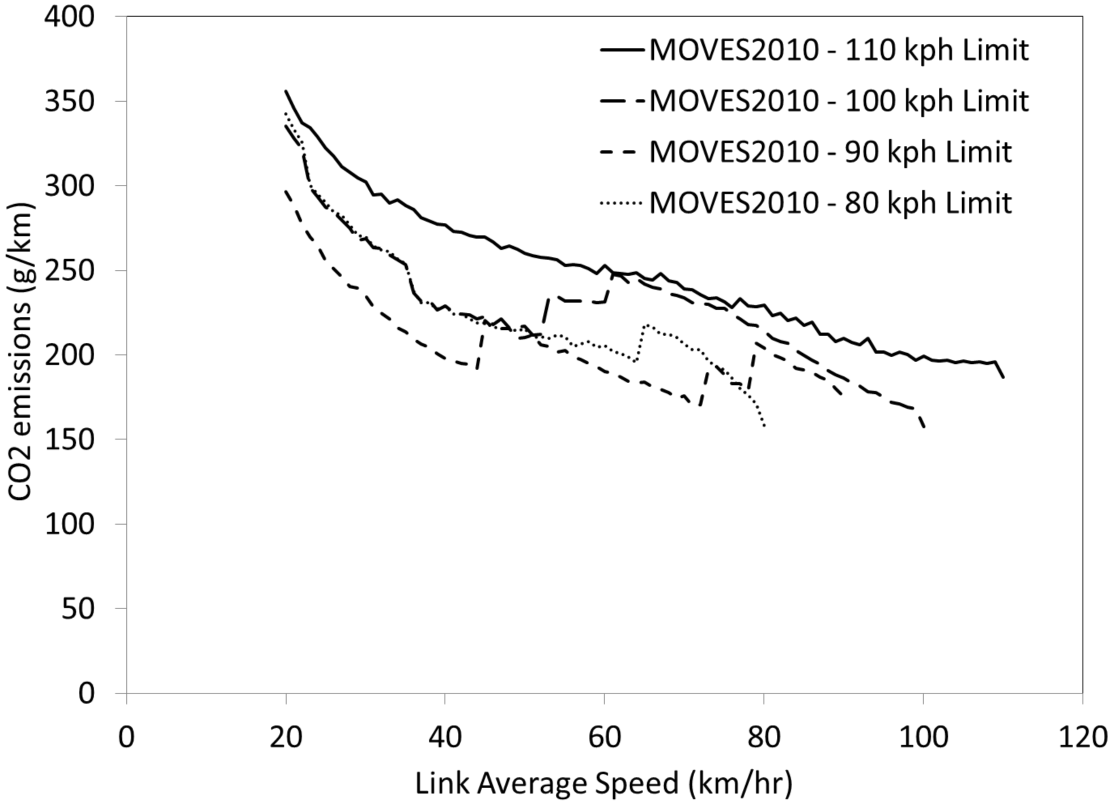


Figure G.6: CO2 emissions estimated for MOVES2010b Urban Unrestricted facility with simplified micro-simulation drive schedules

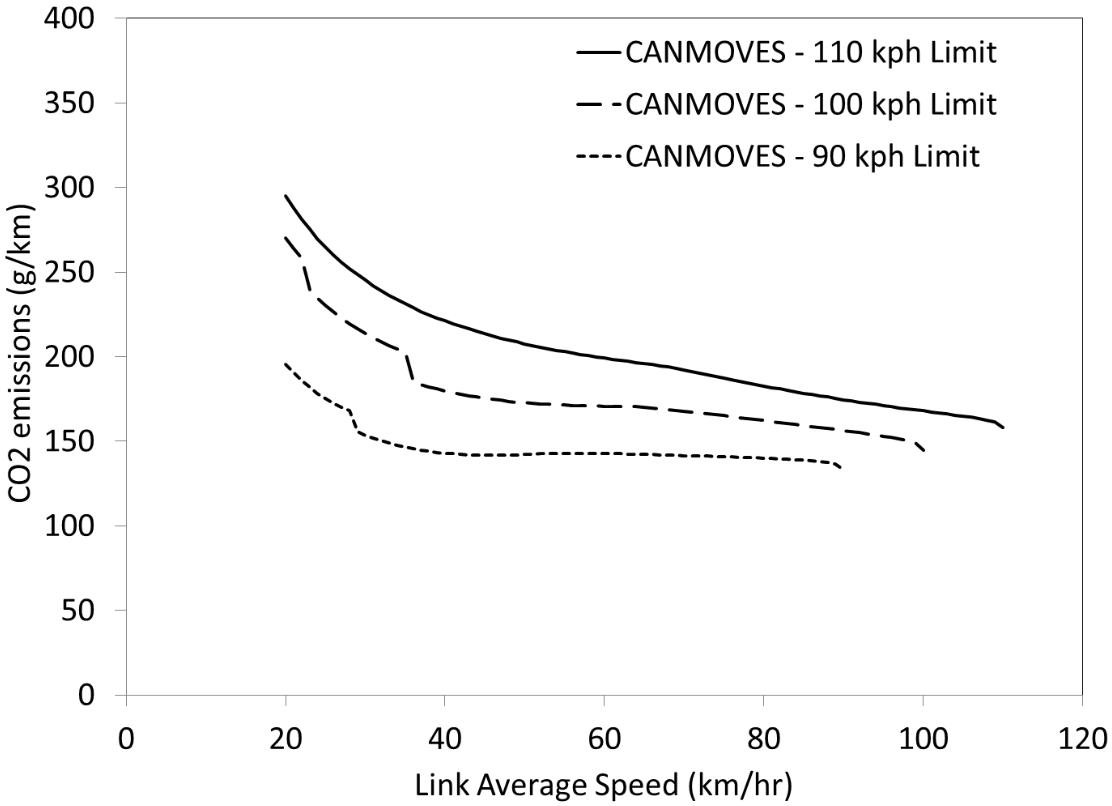


Figure G.7: CO2 emissions estimates for simplified micro-simulation links with 90 - 110 km/hr speed limits