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A Methodology for Estimating Greenhouse Gas Emissions from Heavy Duty Diesel Trucks Used for Road Transportation in the Construction Sector

by

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Abstract

A large growth in the number of Heavy Duty Diesel Vehicles (HDDVs) is one of the main causes that Greenhouse Gas (GHG) emissions from the road transportation experienced a significant increase since 1990. With 97.5% of the total fleet used for delivery being HDDVs, these vehicles play an important role in Canada's freight transportation. Latest statistics show that 17% of the heavy trucks operate in the construction sector. The objective of this study is to develop a methodology to estimate emissions from a single HDDV used in construction road transportation. The developed methodology showed −14% difference with on-road measurements, which suggests a reasonable accuracy in comparison with similar methods in the literature. This methodology can be used to address increasing GHG emissions from road transportation through implementing behavioural changes such as route planning and load factor management. It can also be also used by the construction suppliers to track and control their share of GHG emissions.

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Dedication

With respect and love to:

My lovely parents, Ebrahim & Farideh, my beautiful sisters, Nasibeh & Nafiseh and my wonderful brother in law Siamak who have made the happiest moments of my life

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List of Abbreviations

Abbreviation	**Definition**
AAWT	Annual Average Weekday Traffic
AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
Cal/EPA	California Environmental Protection Agency
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon Dioxide
CO_2 eq.	Carbon Dioxide equivalent
DfT	Department for Transport
DOE	U.S. Department of Energy
DTSC	Directional Traffic Count Summary
EEM	GHG Emission Estimation Methodology
EM	Elemental Model
EMFAC	California Air Resources Board's EMission FACtors
EPA	U.S. Environmental Protection Agency
FCM	Fuel Consumption Model
FCR	Fuel Consumption Rate
F-gases	Fluorinated gases
g CO_2 /L	gram of Carbon Dioxide per Litre
GHG	Greenhouse Gas
GHGRP	GHG Emissions Reporting Program
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HC	Hydrocarbons
HDDV	Heavy Duty Diesel Vehicle
HDV	Heavy Duty Vehicle
HGV	Heavy Goods Vehicle
IFEU	Institute for Energy and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
LDGT	Light Duty Gasoline Trucks
LDV	Light Duty Vehicle
LEM	Lifecycle Emission Model
LF	Load Factor
MOBILE	Mobile Source Emission Factor Model
MOVES	Motor Vehicle Emission Simulator
Mt of CO_2 eq.	Megatonnes of Carbon Dioxide equivalent
N_2O	Nitrous Oxide
NIR	National Inventory Report
NRCan	Natural Resources Canada
O/D	Origin/Destination

Abbreviation	**Definition**
ORNL	Oak Ridge National Laboratory
PARAMICS	Parallel Microscopic Simulation
RGF	Road Gradient Factor
PTV	Planung Transport Verkehr
RTM	Regional Transportation Model
STM	Signal Timing Summary
TCR	Traffic Count Report
TD	Total Delay
TMSD	Turning Movement Summary Diagram
TS	Total Stops
TT	Total Travel
U.S.	United States
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VISSIM	Verkehr In Städten-SIMulationsmodell
VIUS	Vehicle Inventory and Use Survey
VKT	Vehicle Kilometres Travelled
VOE	Vehicle Operation Emissions
VTF	Vehicle Type Factor

CHAPTER 1: INTRODUCTION

1.1 Background

Human activities such as burning fossil fuels release Greenhouse Gases (GHG) into the atmosphere (Cubasch, et al. 2013). GHGs absorb infrared radiation. This behaviour increases the surface temperature of the Earth. This in turn alters the Earth's energy balance and makes the planet warmer. This is called "Global Warming," which causes the "Climate Change." Global warming perturbs the climate and leads to extreme weather events e.g. drought, floods and heat waves. It also changes the environmental parameters such as precipitation, glaciers and sea level. Consequently, climate change may have an irrecoverable impact on the environment, economy and human life e.g. experiencing 2003 heat wave in Europe and 2008 Midwestern flooding in the United States (U.S.) (Haines, et al. 2006, Holmes, Koenig and Karstensen 2010, Cubasch, et al. 2013). Climate change may also have adverse health effects through causing infectious diseases, malnutrition, extreme weather-related injuries and fatalities (Haines, et al. 2006).

1.1.1 GHGs from Vehicle Operation

The main GHGs emitted by human activities are Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O). CO_2 accounts for 77% of the total GHG emissions and it is the largest emission source at the global level (IPCC 2007). Burning fossil fuels is the primary source of emitting this GHG and it accounts for 90% of the total CO_2 emissions (JRC/PBL 2011). Vehicle operation emissions stem from burning fossil fuels. Vehicle fossil fuel consumption has made transportation one of the main causes of CO_2 emissions (IPCC 2007, EPA.GD 2013). CH_4 places second by contributing to 14% of the total GHG emissions (IPCC 2007). Fertilizer use and burning fossil fuels are the primary emission sources of this GHG (IPCC 2007, EPA.GD 2013). N_2O accounts for 8% of the GHG emissions. Vehicle fossil fuel consumption also releases N_2O into the air (EPA.GD 2013, SC.HAE 2008). Fluorinated gases (F-gases) contribute to only 1% of the total global GHG emissions (EPA.GD 2013, SC.HAE 2008, IPCC 2007). Burning fossil fuel due to vehicle operation is the emission source for the top three important GHGs (CO_2, CH_4 and N_2O) and it does not include F-gases. In this dissertation, the term “GHG” refers to GHG emitted from vehicle operation and includes CO_2, CH_4 and N_2O.

1.1.2 Current Status of the GHG Emissions

Statistics on GHG emissions continues to demonstrate an increasing trend at global level since the pre-industrial era (i.e. since 1750) (NEAA 2012, Cubasch, et al. 2013). In 2011, CO_2 CH_4 and N_2O emissions reached a 40%, 150% and 20% growth, in comparison with the pre-industrial levels (Cubasch, et al. 2013). These increasing trends led to the establishment of different policies. Implementing these policies has shown potentials for improving the status of GHG emissions around the world and stabilizing the GHG emission levels of different countries (OCDE/IEA 2003, EPO 2005, LP 2008, CAPCOA 2009, EC.CA 2013). While implementing these policies effected sustainable development positively; studies show that without additional policies and a strict supervision on their implementation, it would be very difficult to reduce the global growth in GHG emissions and meet the established targets (Hughes and Scott 1997, IPCC 2007, Hofman and Li 2009, Yang, et al. 2009, Liimatainen and Pollanen 2010, Morrow, et al. 2010). Figure 1-1 shows CO_2 emissions from burning fossil fuels and industrial processes classified by countries of the world (CDIAC 2009).

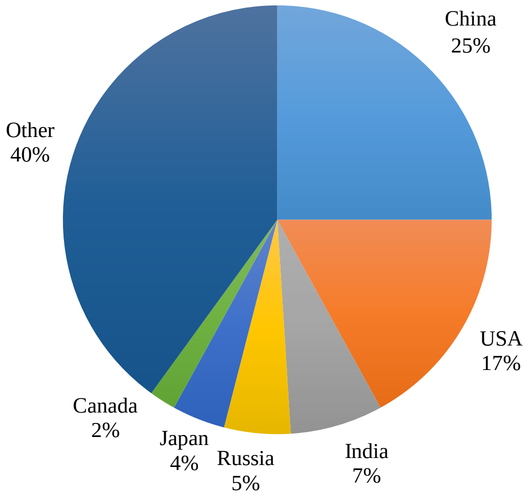


Figure 1-1 Global CO_2 emission from burning fossil fuels, cement production and gas flaring classified by world's countries (CDIAC 2009)

Similar to the global trend, U.S. and Canada also have experienced an increasing trend in GHG emissions. These countries have similar issues with stabilizing their GHG emission levels and meeting their established targets (Hughes and Scott 1997, Hofman and Li 2009, Yang, et al. 2009, Morrow, et al. 2010). In 2011, the total GHG emissions in the U.S. were estimated at 6,702 megatonnes (Mt) of carbon dioxide equivalent (CO_2 eq.). The overall GHG emission trend between 1990 and 2011 shows 0.4% increase on average (EPA.IR 2012). The most recently released statistics for Canada demonstrate that the total GHG emissions in 2011 are equal to 702 Mt of CO_2 eq. This is a 19% increase since 1990 (EnvC.NGE 2013). Figure 1-2 shows the total GHG emissions in Canada between 1990 and 2011 with Canada's established target for 2020. Canada's low population density along with its large contribution to the global GHG emissions, place Canadians among the highest per capita emitters (EnvC.NGE 2013). Based on the Copenhagen Accord signed by Canada in December 2009, Canada needs to reduce its total GHG emissions level to 607 Mt of CO_2 eq. by 2020 (CA 2009, CA.RCP 2009). However, projections from current levels of GHG emissions in Canada suggest 720 Mt of CO_2 eq. emissions in 2020; which is 113 Mt of CO_2 eq. above the aforementioned target (EnvC.ET 2012).

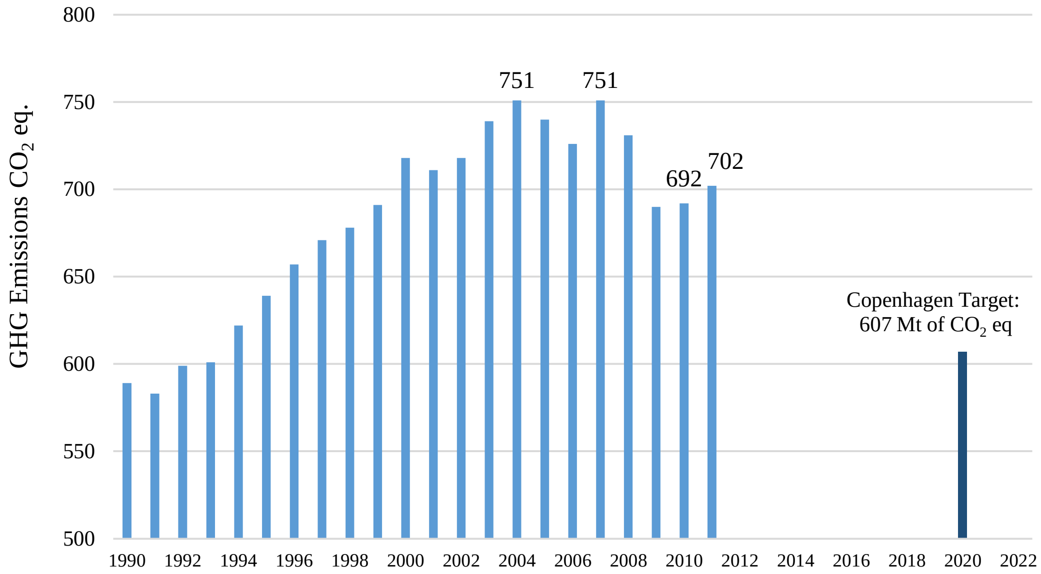


Figure 1-2 Total GHG emission (Mt of CO_2 eq.) in Canada 1990-2011 (EnvC.NGE 2013)

1.1.3 Main Contributors to the GHG Emissions

GHG emission is caused by economic activities. Categorizing the causes of GHG emission by economic sector attributes the total emission to seven key areas of the economy. Energy supply contributes to 26% of the total GHG emission mainly through burning fossil fuels and it places first among economic sectors in releasing GHGs. Industry places second, being responsible for 19% of the emissions. Forestry (17%), agriculture (14%), transport (13%), buildings (8%) and waste (3%) are the next causes of GHG emissions, respectively (IPCC 2007). Among the above causes, transportation has the second largest increase with 120% growth, between 1970 and 2004 at the global level (IPCC 2007). When it comes to North America the share of the transportation sector is even larger, reaching, 27.3% in U.S. and 24.2% in Canada (NIR.CA 2013, NIR.US 2013). Figure 1-3 demonstrates the seven major causes of GHG emission by economic sector and their respective contributions to GHG emissions in Canada. As can be seen in Figure 1-3, in Canada transportation places first among the economic sectors in releasing GHGs into the atmosphere. Emissions from this sector have led to 49% of the total GHG emission growth from 1990 to 2011 (NIR.CA 2013).

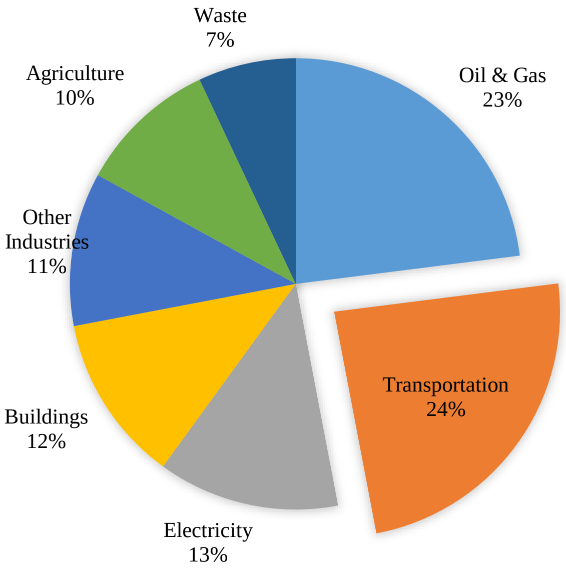


Figure 1-3 Canada's GHG emission by economic sectors 1990-2011 (NIR.CA 2013)

1.2 Problem Definition

1.2.1 GHG Emissions from the Transportation Sector

The fast growth of the transportation network around the world has facilitated quick access to various locations. However, this growing trend has an adverse impact on the global warming due to vehicle fossil fuel consumption that emits pollutants into the atmosphere. This growth has been associated with the increasing levels of GHG emissions in the transportation sector (Leonardi and Baumgartner 2004, Hickman and Banister 2007, Kamakate and Schipper 2009, Yang, et al. 2009, Liimatainen and Pollanen 2010, Morrow, et al. 2010, Nealer, Matthews and Hendrickson 2012). Based on the latest National Inventory Report (NIR) submitted to the United Nations (UN) by Canada, the transportation sector emitted 170 Mt of CO_2 eq. of the total 702 Mt of CO_2 eq. (NIR.CA 2013). This amounts to a large portion (24.2%) of Canada's total GHG emissions, and places this sector first amongst the economic sectors in releasing harmful gases into the atmosphere (see Figure 1-3).

Transportation activities are divided into four major sectors: road, aviation, railways and marine. Out of these four, road transportation is responsible for 79.4% of the emissions released in the transportation sector and plays the main role in the increasing levels of GHG emissions in this sector (EPA.GHGS 2013, NIR.CA 2013). This means the road transportation accounts for 19.2% of Canada's total GHG emissions. Road transportation experienced a significant growth between 1990 and 2011 (NIR.CA 2013). This increasing trend is mainly caused by a large growth in the number of Light Duty Gasoline Trucks (LDGT) and Heavy Duty Vehicles (HDV), especially Heavy Duty Diesel Vehicles (HDDV) (NIR.CA 2013). The number of HDVs experienced a 24.2% growth between 2000 and 2009 (NRC.VS 2009). Moreover, the emissions from the HDDVs increased by 109% between 1990 and 2011 (NIR.CA 2013).

1.2.2 GHG Emissions from the HDDVs

Due to the major role of HDVs in Canada’s trade, export and import and in other word Canada’s freight transportation, they cannot be eliminated from the transportation sector (EPS.TE 2001, Steenhof, Woudsma and Sparling 2006). Because of the important role of HDVs in the economy on one hand and their contributions to GHG emissions on the other hand, regulation for HDVs was recently established in Canada and is effective as of model year 2014 (LT.R 2010, HD.R 2013). The engine of the HDVs is designed to operate with both gasoline and diesel fuels. However, diesel is the desired fuel due to its higher efficiency. Therefore, 97.5% of the HDVs operate with diesel fuel; i.e. they are HDDVs (NRC.VS 2009). Hence, previous research has associated stabilizing the emissions from road transportation through addressing GHG emissions from HDDVs (Steenhof, Woudsma and Sparling 2006, Nealer, Matthews and Hendrickson 2012, NIR.CA 2013). The latest Vehicle Inventory and Use Survey (VIUS) shows that 17% of the HDVs operate in the construction sector (VIUS 2002). This study focuses on GHG emissions from road transportation in this sector.

1.3 Research Objective and Methodology

The objective of this study is to develop a GHG emission estimation methodology that can calculate GHG emissions from an individual HDDV used in the construction sector for road transportation. In order to estimate GHG emissions from individual HDDVs, first a traffic micro-simulation network is developed to capture the impact of traffic-related indicators on GHG emissions. The output from the traffic micro-simulation is then combined with the remainder of GHG emission indicators to calculate fuel consumption rate and GHG emission for individual HDDVs.

A tool is developed to automatically compute the fuel consumption and the GHG emitted from an individual vehicle using the output from the developed micro-simulation network. The following steps were taken in this study to develop the proposed methodology:

Literature Review:

1. Review the existing GHG emission calculators for road transportation and their GHG estimation approaches.
2. Identify indicators that affect GHG emissions from the road transportation.

Develop and Implement the Methodology:

3. Propose a GHG Emission Estimation Methodology (EEM) to estimate the GHG emission from an HDDV as it travels between the manufacturing plant and the construction site.
4. Develop a traffic micro-simulation network with static assignment using Verkehr In Städten-SIMulationsmodell (VISSIM - German for: traffic in cities - simulation model).
5. Develop a GHG emission estimator tool in Visual Studio using C-sharp (C#) programming language.

Validation:

6. Conduct a real-world case study to compare the output from the micro-simulation with on-road measurements to examine the reliability of the developed micro-simulation network

7. Conduct a real-world case study to compare the estimation from the developed methodology with on-road measurements to examine its accuracy and capabilities of the EEM.

The developed EEM can assist in managing GHG emissions in construction road transportation. It can be used by the construction material suppliers to track and control their share of GHG emissions, which is important for environmental reporting purposes. Due to the importance of accurate tracking of the GHG emissions, the Government of Canada has established a mandatory GHG Emissions Reporting Program (GHGRP) since March 2004. Reporting the GHG emissions provides the opportunity to evaluate and improve the governmental strategies and policies (EnvC.GHGRP 2014). It also helps in preparing a more precise National Inventory Report (NIR), which Canada is obligated to submit to the United Nations Framework Convention on Climate Change (UNFCCC) annually (EnvC.In 2014).

The developed EEM can be also used to implement behavioural changes such as route planning and load factor management. These in turn will contribute to more efficient and sustainable operations of the HDDVs in construction road transportation by reducing the fuel consumption rates. The lower fuel consumption rates not only help in decreasing the environmental impacts of the construction sector, but it also lowers the operational expenses through less fuel consumption.

1.4 Scope of the Study

The scope of this research focuses on the key GHGs (CO_2, CH_4 and N_2O) and does not consider other pollutants emitting from the vehicle operation like Nitrogen (N_2) or Particulate Matter (PM). This study estimates the GHG emissions from the running exhaust. Hence, emission from other parts of the vehicle like start exhaust and tire wear are out of the scope of this research. This study focuses on estimating GHG emissions from HDDVs used in the construction sector and does not consider other vehicle types in the methodology section.

1.5 Thesis Layout

This thesis includes six chapters. Chapter 2 provides a review of the literature. It summarizes available GHG emission calculators and highlights their capabilities and limitations. In this chapter, the indicators affecting GHG emissions from the vehicle operation are identified. The proposed methodology is described in Chapter 3. Chapter 4 describes how the proposed methodology was implemented using the micro-simulation network developed in VISSIM (micro-simulation environment) and the GHG emissions estimator tool programmed in Visual Studio. In chapter 5, a real-world case study is conducted to first examine the reliability of the developed micro-simulation network and second identify the functionality and accuracy of the developed methodology. Finally, Chapter 6 offers concluding remarks of this study including a summary of the developed methodology, contributions, limitations and recommendations for future work.

CHAPTER 2: REVIEW OF THE LITERATURE

2.1 Overview of GHG Emission Calculators

This section summarizes publicly available calculators for measuring GHG emits from road transportation. This research identifies 33 GHG emission calculators. These calculators were found by in depth study of research papers on transportation GHG emission and by searching for GHG emission calculators. The calculator is a general term used in this section and refers to a tool that calculates emission or offers a method for calculating GHG emissions. A summary of these calculators is presented in Table 2-1. This table provides information on the comprehensive name, abbreviation, the publisher of the calculator and the format that the calculator is working with. Furthermore, vehicle types and the GHG emission indicators that are considered in each calculator approach. In this study, indicators are factors that affect GHG emissions from the vehicle operation. Finally, emission type and output of each calculator are extracted and presented in Table 2-1. Capabilities and limitations of these calculators and the identified gaps are discussed in the following sections.

Table 2-1 Summary of the GHG emission calculators for road transportation

Calculator	Organization Publisher/Supporter	Format	Vehicle Type	Indicators (Vehicle Operation)	Emission Type	Outputs
Urban Transportation Emission Calculator (UTEC) (UTEC 2012, UTEC.UG 2012)	Transport Canada	Online	Personal vehicle: (< 6000 lbs.) -Car -Light truck Commercial vehicles: -Light-duty (< 8500 lbs.) -Medium-duty (85001-33000 lbs.) -Heavy-duty (> 3001 lbs.) Public Transit: -Bus -Light & heavy rail -Metro	Kilometres travelled Fuel type Traffic condition: -Peak hour -Average daily Driving condition: -City Driving -Highway driving	Life Cycle Analysis (LCA)	Annual GHGs & key air pollutants emission
MOtor Vehicle Emission Simulator (MOVES) (EPA.UG 2012, EPA.UM 2012)	EPA's Office of Transportation and Air Quality (OTAQ)	Software (MySQL & JAVA)	Motorcycle Passenger car Passenger truck Light commercial truck Intercity bus Transit bus Refuse truck Single unit short-haul/long-haul truck Motor home Combination short-haul/long-haul truck	Kilometres travelled Scale: -National (USA) -Specific country -Specific roadway Time span: -Hour -Day -Month -Year Fuel type Speed Road gradient Engine situation (e.g. cold start, idle) Vehicle model year Traffic condition: -Weekdays -Weekends Driving condition: -Urban -Rural -Off network (e.g. parking lot)	LCA Rates per unit of activity	GHGs & air pollutants emission Energy usage

Table 2-1 Summary of the GHG emission calculators for road transportation (cont.)

Calculator	Organization Publisher/Supporter	Format	Vehicle Type	Indicators (Vehicle Operation)	Emission Type	Outputs
Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) -Fuel cycle model -Vehicle cycle model -Fleet footprint calculator -Travel Carbon calculator (ANL.DA 2006, ANL.FC 2007, ANL.GREET 2010)	Argonne National Laboratory (Transportation Technology R&D Center), US Department of Energy	Spreadsheet in Excel	Passenger car (< 6000 lbs.) Light truck #1 (< 6000 lbs.) Light truck #2 (6001-8500 lbs.)	Kilometres travelled Vehicle combustion technology Fuel type Fuel economy Vehicle model year Driving condition: -Urban -Non-urban	LCA	GHGs & air pollutants emission Energy usage
Life Cycle Emission Model (LEM) (Delucchi 2002, ITS.LEM 2003)	Mark A. Delucchi, Institute of Transportation Studies, University of California	Spreadsheet in Lotus software	Light-duty passenger car Full-size buses Mini-buses Mini-cars Motor scooters Bicycles Heavy-rail transit Light-rail transit Medium-duty trucks Heavy-duty trucks Diesel train Tanker Cargo ship Barge	Location Kilometres travelled Fuel type Fuel economy Engine type Vehicle model year Vehicle weight Urban	LCA	GHGs & air pollutants emission Energy usage
GHGenius A model for lifecycle assessment of transportation fuels (GHGenius 2004)	Natural Resources Canada (NRCan)	Spreadsheet in Excel	Light-duty vehicle Medium-duty trucks Heavy-duty trucks Bus	Location Fuel type Engine type Vehicle model year Kilometres travelled Driving condition: -City driving -Highway driving	LCA	GHGs & air pollutants emission Energy usage
CALMOB 6 (Busawon 2006)	Roshan Busawon	Software (MATLAB)	Light-duty vehicle (passenger car) Light-duty truck Heavy-duty vehicle Bus	Location Urban Kilometres travelled Fuel economy Fuel type Road gradient Temperature Air pressure Speed Idling Number of stops Cold start Vehicle model year	Vehicle operation	GHGs & air pollutants emission Energy usage

Table 2-1 Summary of the GHG emission calculators for road transportation (cont.)

Calculator	Organization Publisher/Supporter	Format	Vehicle Type	Indicators (Vehicle Operation)	Emission Type	Outputs
The California Air Resources Board's EMission FACtors (EMFAC) -EMFAC-LDV passenger VEHICLES module -EMFAC-HD heavy trucks and buses module -EMFAC-SG scenario assessment module (EMFAC.UG 2011, EMFAC 2013)	California Environmental Protection Agency, Air Resources Board	Software (Visual Basic)	Passenger car Light-duty truck Light-heavy-duty trucks Motorcycle Medium-duty truck Motor home Medium-heavy duty truck Heavy-heavy duty truck Power take off Motor coach Bus	Location Kilometres travelled Speed Fuel type Vehicle technology Vehicle model year Fuel economy Speed Weather condition: -Winter -Summer	Vehicle operation	GHGs & air pollutants emission
Transport Emission Evaluation Models for Projects (TEEMP) -TEMP-roads -Rural Roads Improvement -Urban Road Improvement (TEEMP 2013)	Clean Air Initiative Asia (CIA Asia) Institute for Transportation & Development Policy (ITDP) Asian Development Bank (ADB) United Nations Environment Programme (UNEP) Cambridge Systematics, Inc.	Spreadsheet in Excel	Passenger car 2-wheeler 3-wheeler Bus LCV/HCV Bicycle Bullock cart Cycle rickshaw	Kilometres travelled Vehicle model year Loading/Occupancy Driving condition: -Urban -Rural	LCA	GHGs & air pollutants emission Emission intensity
CCAP Transportation Emission Guidebook -Land use, Transit & Travel Demand Management -Vehicle Technology & Fuels (CCAP 2013, CCAP.GB 2013)	Center for Clean Air Policy (CCAP)	Spreadsheet in Excel	Car Transit Bicycle	Kilometres travelled Fuel economy Vehicle model year Vehicle technology Fuel type Driver behaviour Idling Speed	Vehicle operation	GHGs & air pollutants emission Energy usage Cost
The Greenhouse Gas Protocol (GHG Protocol) -GHG emission from transport or mobile sources (GHG.P 2012)	World Resources Institute (WIR) World Business Council for Sustainable Development (WBCSD)	Spreadsheet in Excel	Passenger car Bus Motorbike Light Goods Vehicle Heavy Duty Vehicle	Location Kilometres travelled Fuel consumed Fuel type Vehicle model year	Vehicle operation	GHG emissions
Clean Air and Climate Protection Software Tools (CACP) (CACP 2009)	International Council for Local Environmental Initiatives (ICLEI)	Software	Not available to the public		Vehicle operation	Annual GHGs & air pollutants emission Energy usage

Table 2-1 Summary of the GHG emission calculators for road transportation (cont.)

Calculator	Organization Publisher/Supporter	Format	Vehicle Type	Indicators (Vehicle Operation)	Emission Type	Outputs
COmputer Program to Calculate Emissions from Road Transport (COPERT) (COPERT 2011)	European Environment Agency (EEA)	MS Windows s oftware program	Passenger car Light-duty vehicle Heavy-duty vehicle Bus Moped Motorcycle	Kilometres travelled Location Fuel economy Fuel type Temperature Speed Road type Cruising Idling Driving condition -Urban -Rural	Vehicle operation	GHGs & air pollutants emission
(Perez Cajilema 2009)	Alex Daniel Perez Cajilema	MS Windows s oftware program	Passenger car	Location Cruising Acceleration/deceleration Speed Vehicle model year Engine size Road gradient Driving Condition: -Urban -Rural	Vehicle operation	CO_2 & air pollutants emission
Nova Scotia GHG Emissions Calculator -Personal Transportation/Commuting Calculator (NS.EC 2010, CCM.NS 2010)	Nova Scotia Environment Prepared by: - Canadian Standard Association (CSA)	Online calculator	Passenger car: -Car -Light-truck Public transportation	Fuel consumed Kilometres travelled	Vehicle operation	Annual GHG emissions
Transit Planning Emission Calculator (TPEC 2013)	Travel Matters, Center for Neighborhood Technology Sponsored by: -Federal Transit Administration -Transportation Research Board -American Public Transportation Association	Online calculator	Transit vehicle	Location Fuel consumed Fuel economy Fuel type Vehicle model year Temperature Humidity Road gradient Rural	Vehicle operation	GHGs & air pollutants emission -Annual -Grams per mile

Table 2-1 Summary of the GHG emission calculators for road transportation (cont.)

Calculator	Organization Publisher/Supporter	Format	Vehicle Type	Indicators (Vehicle Operation)	Emission Type	Outputs
Individual Emission Calculator (IEC 2013)	Travel Matters, Center for Neighborhood Technology Sponsored by: -Federal Transit Administration -Transportation Research Board -American Public Transportation Association	Online calculator	Personal vehicle	Kilometres travelled Vehicle model year Vehicle make Vehicle model Driving condition: -Stop & go -Highway driving	Vehicle operation	GHGs & air pollutants emission per month in lbs.
Household Carbon Footprint Calculator (HCFC 2013)	United Estates Environmental Protection Agency (EPA)	Online calculator	Personal Vehicle: -Car -Light truck	Number of household vehicles Kilometres travelled Fuel economy	Vehicle operation	Annual GHG emissions
Carbon Calculator (FTA.CC 2013)	US Department of Transportation Federal Transit Administration	Online calculator	Passenger cars Light truck	Kilometres travelled Fuel economy	Vehicle operation	GHG emissions
Carbon Savings Calculator (PT.CSC 2013)	American Public Transportation Association	Online calculator	Passenger cars Light truck	Kilometres travelled Fuel economy	Vehicle operation	CO_2 emission
Personal GHG Emission Calculator (PTC.GD 2009, PTC 2013)	Green Registry: -Manitoba's climate change - Canadian Climate Exchange -Canadian Standard Association (CSA)	Online calculator	Passenger car Public transit Bicycle Motorcycle Telework Airplane	Kilometres travelled Vehicle model	Vehicle operation	GHG emissions
Lifecycle Carbon Calculator -Auto (BC.CC 2013)	Live Smart British Colombia (BC)	Online calculator	Passenger cars Light truck	Kilometres travelled Fuel type Fuel economy	Vehicle operation	Annual GHG emissions
Carbon Calculator (UK.CC 2013)	United Kingdom (UK) Government	Online calculator	Passenger car Motorcycle Train Taxi Ferry Coach Metro Air plane	Location Kilometres travelled Fuel type Engine size Fuel economy Driver behaviour Maintenance Driving condition: -Urban -Rural	Vehicle operation	CO_2 emission

Table 2-1 Summary of the GHG emission calculators for road transportation (cont.)

Calculator	Organization Publisher/Supporter	Format	Vehicle Type	Indicators (Vehicle Operation)	Emission Type	Outputs
Fleet Emission Calculator (FC 2010)	Environmental Defense Fund (EDF) Business	Online calculator	Passenger car Light-duty truck Van SUV Medium-duty vehicle Heavy-duty vehicle	Fuel consumption Fuel type	LCA	GHG emissions
Greenhouse Gas Emissions Calculator -Transportation (WYI 2013)	What's your impact? (WYI) Non-profit organization Montreal, Canada	Online calculator	Passenger cars Light truck Air plane	Location Kilometres travelled Fuel economy	Vehicle operation	GHG emissions
CO_2 Emission Calculator (Sco.EC 2013)	Traffic Scotland Real time and future traffic information for Scotland	Online calculator	Car Coach Rail Motorbike	Kilometres travelled Fuel type Engine size Loading/Occupancy	Vehicle operation	CO_2 emission
Manual for Calculating Greenhouse Gas Benefits for Global Environment Facility Transportation Projects (GEF 2010)	Global Environment Facility (GEF)	Guideline report	Car 2-wheeler 3-wheeler Bus Jeepney/RTV Bicycle LRT	Kilometres travelled Fuel type Speed	LCA	GHG emissions
General Reporting Protocol -Direct emission from mobile combustion (GRP 2013)	The Climate Registry (TCR)	Guideline report	Passenger car Light-duty truck Heavy-duty truck Bus Train Ship Air plane Tractor Forklift	Kilometres travelled Fuel economy Fuel type Vehicle model year Vehicle make Vehicle model Driving condition: -City driving -Highway driving	Vehicle operation	GHG emissions
International Local Government GHG Emissions Analysis Protocol (IEAP) (IEAP.MP 2009)	International Council for Local Environmental Initiatives (ICLEI)	Guideline report	Government fleet	Tier 1: Kilometres travelled in average Fuel used in average National defaults Tier 2: Kilometres travelled Fuel economy Local data Tier 3: Kilometres travelled Fuel type, Driving condition Vehicle model year, Vehicle technology	Vehicle operation	GHG emissions

Table 2-1 Summary of the GHG emission calculators for road transportation (cont.)

Calculator	Organization Publisher/Supporter	Format	Vehicle Type	Indicators (Vehicle Operation)	Emission Type	Outputs
Quantification of Greenhouse Gas Produces by the Road Transportation Sector in Alberta Using a Traffic Volume Methodology (AB.GHG 2003)	Alberta Infrastructure and Transportation	Guideline report	Passenger vehicle Recreational vehicle Bus Single unit trucks Tractor-trailer combination	Kilometres travelled Fuel consumption	Vehicle operation	GHG emissions
Direct Emissions from Mobile Combustion Sources (EPA.DE 2009)	United Estates Environmental Protection Agency (EPA) Climate Leaders	Guideline report	Passenger car Light-duty trucks Heavy-duty trucks	Kilometres travelled Fuel consumption Fuel type Vehicle model year	Vehicle operation	GHG emissions
Guidance on measuring and reporting Greenhouse Gas (GHG) emissions from freight transport operations (DfT.G 2009, Defra 2009)	United Kingdom (UK) Government Department for Transport (DfT)	Guideline report	Heavy-duty trucks Train Ship	Fuel consumption Kilometres travelled Fuel economy Vehicle load	Vehicle operation	GHG emissions
Guidelines for measuring and managing CO_2 emission from freight transport operations (Cefic 2011)	The European Chemical Industry Council (cefic)	Guideline report	Heavy-duty truck Train Ship	Kilometres travelled Fuel consumption Vehicle load Vehicle efficiency Speed Driving behaviour Traffic condition Road gradient Road type	Vehicle operation	CO_2 emission
GHG emissions calculation methodology and GHG audit -Requirements for the calculation of GHG emissions from transport (ISCC 2010)	International Sustainability and Carbon Certification (ISCC)	Guideline report	Depends on transport mode (e.g. Heavy-duty trucks)	Kilometres travelled Fuel economy Vehicle load	LCA	GHG emissions
Emission Facts -Greenhouse Gas Emissions from a typical passenger vehicle (EF.PV 2005, EF.KFF 2005)	United Estates Environmental Protection Agency (EPA) Office of Transportation and Air Quality	Fact sheet	Passenger car Light trucks	Kilometres travelled Fuel economy	Vehicle operation	GHG emissions

2.1.1 LCA Calculators versus VOE Calculators

GHG emission calculators vary based on their ability to account for different types of inputs and analysis. Given the types of analysis, they can be divided into two main categories (Table 2-1 “Emission Type” column). The first group of calculators considers fuel upstream, vehicle upstream, vehicle downstream and vehicle operation emissions in their calculations. The upstream cycle has fuel production (well to pump) and vehicle production process while the vehicle material recovery and vehicle disposal emissions are covered by the downstream cycle. The upstream and downstream cycles with vehicle operation (pump to wheel) emission calculations create a Life Cycle Analysis (LCA) calculator. LCA traces fuel and vehicle environmental impact from origin to end and tries to analyze different mitigation scenarios (Ayres 1995, Russo 2008). Hence, it benefits both environment and industry (Ayres 1995). The second group of calculators focuses on emissions released directly from vehicle use. The Vehicle Operation Emission (VOE) calculators are most suitable for travel demand management, fleet management and following the established standards (DfT.G 2009). It also helps households and individuals to track and reduce their emissions. Calculating direct vehicle emissions is beneficial when considering travel impact indicators such as vehicle characteristics and traffic, driving and ambient conditions (TRB 2013).

2.1.2 Calculators Format

The majority of household and individual emission calculators are available in online format while calculators that are more comprehensive are in the form of downloadable software or spreadsheet. Moreover, the guideline reports make an emission calculation manual available to the partners and organizations to report their emissions and follow standards. The format for each calculator is presented in Table 2-1 under the "Format" column.

2.1.3 Calculation Procedures

These calculators cover emissions from various sources (e.g. building energy use and transportation) and different scope of calculations like LCA or exclusive vehicle operation. However, this study focuses on transportation and vehicle operation emissions. The majority of VOE calculators use fuel consumption/emission factor method to calculate emissions from vehicle operation. In this method, energy usage from vehicle's activity is estimated using specified emission indicators as inputs. Once the fuel consumption is found, the amount of GHG emission can be calculated using relevant emission factors. Emission factors mostly depend on the fuel type like gasoline or diesel. Fuel type varies based on the type of the vehicle (Cefic 2011, EnvC.FC 2013). Vehicle type also affects the fuel economy as a major emission indicator. Table 2-1 shows types of vehicle considered in each calculator under "Vehicle Type" column. The basic logic is that the key air pollutants can be estimated based on vehicle's fuel consumption using the appropriated emission factors. The emission from the most important GHG (CO_2) is also following the above procedure and it happens in direct proportion to the Fuel Consumption Rate (FCR) (Ericson 2001b, Gajendran and Clark 2003, ICF 2006).

Despite CO_2, estimating N_2O and CH_4 needs taking into account, emission control technologies of the vehicle (ICF 2006). Therefore, N_2O and CH_4 emission has to be quantified using default emission factors that consider the vehicle type, fuel type and emission control technology (Lipman and Delucchi 2002). Unites States (U.S.) Environmental Protection Agency (EPA) established different class of emission control standards each effective for specific vehicle model years (EPA.FES 2012). Canada also legislated specific emission factors for the fuel combustion arises from different vehicle type (EnvC.FC 2013). For Heavy Duty Diesel Vehicles (HDDVs), vehicle technology is separated by advanced controlled, medium controlled and uncontrolled (EnvC.FC 2013). The emission factor for CO_2 is equal for all three classes of technology; however, for N_2O and CH_4 the factor varies for each technology type (EnvC.FC 2013). Integrated collaboration between U.S. and Canada has led to a vast range of aligned on-road and off-road regulations that follow the same procedures (EPS.TE 2001, EnvC.T4 2012, EPA.T3 2013, EnvC.HDV 2013).

2.1.4 Calculation Principles

Three classes of principles are defined by the Intergovernmental Panel on Climate Change (IPCC) based on level of detail needed in applying emission indicators and data (IPCC 2006). Tier 1 standard represents a simple emission calculation method. It takes global and country level defaults and statistics for estimations (IPCC 2006). Tier 2 takes more level of details into account such as local-specific factors, fuel economy and kilometres travelled. Therefore, Tier 2 makes it possible to measure and track emissions at the local level (IEAP 2009). Tier 3 represents more complex approaches and tries to involve as many as indicators and detailed information available (IPCC 2006). Tier 3 is recommended for calculating GHG emission (IEAP 2009). It considers the impact of various indicators such as kilometres travelled, fuel type, vehicle technology and driving condition (IEAP 2009). In other words, indicators that address vehicle characteristics, traffic and driving condition, which have significant impact on GHG emissions (IEAP 2009). Indicators applied by each calculator extracted under "Indicators for Vehicle Operation Emissions" column of Table 2-1. When a calculator includes more than one computing method, all indicators are collectively entered in Table 2-1. The importance of the details in estimating GHG emissions from the vehicle operation can be derived from the above-mentioned argument.

2.1.5 Commonly used Calculators

EPA's MOtor Vehicle Emission Simulator (MOVES) and U.S. Department of Energy's (DOE) Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) are the most commonly referenced GHG emission calculators: e.g. Oliver and Stasko 2009, Tan, et al. 2011, Xie, et al. 2012, Abou-Senna and Radwan 2013, Ramos Pereira and Coelho 2013, Strecker, Hausmann and Depcik 2013. They considered a wide range of vehicle-related indicators as well as traffic and driving condition indicators when comparing to other simpler calculators (ICF 2006). These commonly used calculators are described in the following sections:

MOVES: The earlier version of MOVES is called Mobile Source Emission Factor Model 6.2 (MOBILE) and it has been replaced by MOVES since 2010 (EPA.UM 2012). MOVES2010b released in April 2012 is the latest version of the MOVES available to the public (EPA.UM 2012). MOVES currently is used across the U.S. except California (EPA.UM 2012). California Environmental Protection Agency

(Cal/EPA) developed an exclusive emission model called The California Air Resources Board’s EMission FACtors (EMFAC) (EMFAC 2013).

GREET: The first version of GREET was released in 1996 and the current GREET versions are GREET 1 2012 for fuel-cycle analysis and GREET 2.7 for vehicle-cycle analysis (ANL.DA 2006, ANL.GREET 2010). VOE calculations are covered in the fuel-cycle analysis (ANL.FC 2007). GREET calculators include a wide range of new fuels and advanced vehicle technologies (ANL.FC 2007, ANL.GREET 2010).

Emission indicators and emission factors need to be defined specifically for the location that vehicle activity occurs. Both MOVES and GREET are based on U.S. national and local defaults. The majority of the calculators in Table 2-1 also represent calculation methods for a specific location. Moreover, if calculators include estimations for other regions, specific factors shall be added for those locations, or the users are allowed to customize the calculator, for example, MOVES (EPA.UG 2012).

GHGenius: GHGenius is an LCA model defined specifically with Canada’s national and local factors. This model is developed for Natural Resources Canada (NRCan) based on Delucchi’s Lifecycle Emission Model (LEM) in 1998. GHGenius 4.03 is the latest version of this model released by the NRCan.

2.1.6 Identifying the Gap

Consistency in Applied Emission Indicators and Factors*:* The majority of the calculators in Table 2-1 follow the same calculation procedure and are built based on each other. However, each of these calculators applies different indicators and factors to estimate GHG emissions. Having a wide range of values, that each can be used in GHG emission calculation led to different estimation results (McKinnon and Piecyk 2009). This delivers the importance of being consistent in terms of indicator, factor and probably the procedure at least at the national level (EF.PV 2005, EF.KFF 2005, McKinnon and Piecyk 2009). To address this problem, EPA published a series of fact sheets to bring consistency in assumptions and practices (EF.PV 2005, EF.KFF 2005).

Level of Detail in Applied Emission Indicators*:* Beside the common and comprehensive tools mentioned above, the majority of the remained calculators, especially the online tools, take the simple method of multiplying the fuel consumed by the related emission factor using available statistics. This way, they try to give a rough estimation of GHG emitted and they do not consider the impact of other important indicators on GHG emissions.

Level of Detail in Output Data: Although each of these calculators has its own advantages, however, all of them fail to track a specific vehicle through a defined route. This provides investigating the scenarios that may happen to the vehicle as it is travelling through that route for multiple times (Hao, Hatzopoulou and Miller 2010). These scenarios vary based on the numbers of stops, idling and speed that the vehicle experiences during each trip. The scenarios with different numbers of stops, idling and speed make GHG emission value different for each trip. Estimating GHG emission for each trip helps to figure out, which scenario happens commonly to make it the base for further actions. This is also helpful when multiple trips are unavoidable, for instance, construction material transportation.

Section 2.2 covers GHG emission indicators. These indicators influence emissions from the vehicle operation. This section reviews role of these indicators in fuel consumption and GHG emissions and tries to extract the important indicators with significant impact on GHG emissions.

2.2 Indicators Affecting GHGs from VOE

VKT, Fuel Consumption and Fuel Economy: As presented in Table 2-1 the majority of the calculators take Vehicle Kilometres Travelled (VKT) and vehicle fuel economy to calculate fuel consumption or they directly use fuel consumption value to estimate GHG emissions using related emission factors. These three indicators (VKT, fuel consumption and fuel economy) are initial requirements for calculating the GHG emissions. Calculators that are more comprehensive try to involve other important indicators to estimate GHG emissions. Aforementioned calculators along with previous literature list the influential indicators affecting GHG emissions from the vehicle operation as presented in Table 2-2. These indicators can be classified into four main groups: vehicle-related, driver-related, traffic-related and environment-related.

Location: Location is an independent indicator that affects the emission factors. It shows whether the selected emission factor is related to the location of the study.

Table 2-2 Indicators affecting GHG emissions from the vehicle operation

Indicator	Reference (Calculators)	Reference (Literature)
Location*	(Delucchi 2002) (AB.GHG 2003) (GHGenius 2004) (EF.PV 2005) (Busawon 2006) (ANL.FC 2007) (EPA.DE 2009) (DfT.G 2009) (PTC.GD 2009) (Perez Cajilema 2009) (CCM.NS 2010) (Cefic 2011) (COPERT 2011) (EMFAC.UG 2011) (EPA.UG 2012) (GHG.P 2012) (UTEC.UG 2012) (BC.CC 2013) (FTA.CC 2013) (HCFC 2013) (IEC 2013) (PT.CSC 2013) (Sco.EC 2013) (TPEC 2013) (UK.CC 2013) (WYI 2013)	(Kean, Harley and Kendall 2003) (Leonardi and Baumgartner 2004) (El-Shawarby, Ahn and Rakha 2005) (Wang, et al. 2008) (McKinnon and Piecyk 2009) (Yang, et al. 2009) (Nazelle, et al. 2010) (Liimatainen and Pollanen 2010)
Vehicle		
Vehicle Kilometres Travelled (VKT)*	(Delucchi 2002) (AB.GHG 2003) (GHGenius 2004) (EF.PV 2005) (Busawon 2006) (ANL.FC 2007) (DfT.G 2009) (EPA.DE 2009) (IEAP.MP 2009) (PTC.GD 2009) (CCM.NS 2010) (GEF 2010) (Cefic 2011) (EMFAC.UG 2011) (COPERT 2011) (EPA.UG 2012) (GHG.P 2012) (UTEC.UG 2012) (BC.CC 2013) (CCAP.GB 2013) (FTA.CC 2013) (GRP 2013) (HCFC 2013) (IEC 2013) (PT.CSC 2013) (Sco.EC 2013) (TEEMP 2013) (UK.CC 2013) (WYI 2013)	(Kean, Harley and Kendall 2003) (El-Shawarby, Ahn and Rakha 2005) (Steenhof, Woudsma and Sparling 2006) (McKinnon and Piecyk 2009) (Yang, et al. 2009) (Nazelle, et al. 2010) (Liimatainen and Pollanen 2010) (Demir, Bektas and Laporte 2011)
Fuel Consumption*	(AB.GHG 2003) (Busawon 2006) (DfT.G 2009) (EPA.DE 2009) (CCM.NS 2010) (FC 2010) (Cefic 2011) (GHG.P 2012) (TPEC 2013)	(Kean, Harley and Kendall 2003) (Leonardi and Baumgartner 2004) (Steenhof, Woudsma and Sparling 2006) (Yang, et al. 2009) (Nazelle, et al. 2010) (Zhang, Batterman and Dion 2011)
Vehicle Type* Engine Size	(Delucchi 2002) (AB.GHG 2003) (GHGenius 2004) (EF.PV 2005) (Busawon 2006) (ANL.FC 2007) (DfT.G 2009) (EPA.DE 2009) (PTC.GD 2009) (Perez Cajilema 2009) (CCM.NS 2010) (FC 2010) (GEF 2010) (Cefic 2011) (EMFAC.UG 2011) (COPERT 2011) (EPA.UG 2012) (GHG.P 2012) (UTEC.UG 2012) (BC.CC 2013) (CCAP.GB 2013) (FTA.CC 2013) (GRP 2013) (HCFC 2013) (IEC 2013) (PT.CSC 2013)(Sco.EC 2013) (TPEC 2013) (UK.CC 2013) (WYI 2013)	(Ericson(b) 2001) (Brodrick, et al. 2002) (Gajendran and Clark 2003) (Kean, Harley and Kendall 2003) (El-Shawarby, Ahn and Rakha 2005) (Ericsson, Larsson and Brundell-Freij 2006) (Frey, Rouphail and Zhai 2008) (Wang, et al. 2008) (McKinnon and Piecyk 2009) (Yang, et al. 2009) (Nazelle, et al. 2010) (Liimatainen and Pollanen 2010) (Demir, Bektas and Laporte 2011) (Zhang, Batterman and Dion 2011) (Abou-Senna and Radwan 2013)
Fuel Economy* Vehicle Efficiency	(Delucchi 2002) (EF.PV 2005) (Busawon 2006) (ANL.FC 2007) (DfT.G 2009) (IEAP.MP 2009) (PTC.GD 2009) (ISCC 2010) (EMFAC.UG 2011) (COPERT 2011) (BC.CC 2013) (CCAP.GB 2013) (FTA.CC 2013) (GRP 2013) (HCFC 2013) (IEC 2013) (PTC.GD 2009) (PT.CSC 2013) (TPEC 2013) (UK.CC 2013) (WYI 2013)	(Leonardi and Baumgartner 2004) (Brundell-Freij and Ericsson 2005) (El-Shawarby, Ahn and Rakha 2005) (Steenhof, Woudsma and Sparling 2006) (McKinnon and Piecyk 2009) (Liimatainen and Pollanen 2010) (Demir, Bektas and Laporte 2011)
Fuel Type*	(Delucchi 2002) (GHGenius 2004) (ANL.FC 2007) (Busawon 2006) (EPA.DE 2009) (IEAP.MP 2009) (FC 2010) (GEF 2010) (EMFAC.UG 2011) (COPERT 2011) (EPA.UG 2012) (GHG.P 2012) (UTEC.UG 2012) (BC.CC 2013) (CCAP.GB 2013) (GRP 2013) (Sco.EC 2013)(TPEC 2013) (UK.CC 2013)	(Steenhof, Woudsma and Sparling 2006) (Frey, Rouphail and Zhai 2008) (Searchinger, et al. 2008) (Campbell, Lobell and Field 2009) (Yang, et al. 2009) (Arteconi, et al. 2010) (Hertel, et al. 2010)
Vehicle Load* Vehicle Weight Vehicle Occupancy	(Delucchi 2002) (DfT.G 2009) (ISCC 2010) (Cefic 2011) (Sco.EC 2013) (TEEMP 2013)	(Gajendran and Clark 2003) (Leonardi and Baumgartner 2004) (Liimatainen and Pollanen 2010) (Demir, Bektas and Laporte 2011)
Vehicle model year -Age -Technology*	(Delucchi 2002) (GHGenius 2004) (Busawon 2006) (ANL.FC 2007) (EPA.DE 2009) (IEAP.MP 2009) (Perez Cajilema 2009) (EMFAC.UG 2011) (EPA.UG 2012)(GHG.P 2012) (CCAP.GB 2013) (GRP 2013) (TEEMP 2013) (TPEC 2013)	(Brodrick, et al. 2002) (Gajendran and Clark 2003) (Kean, Harley and Kendall 2003) (Wang, et al. 2008)
Vehicle Accessory Load	(Cefic 2011)	(Brodrick, et al. 2002) (Demir, Bektas and Laporte 2011)
Maintenance	(UK.CC 2013)	-

Table 2-2 Indicators affecting GHG emissions from the vehicle operation (cont.)

Indicator	Reference (Calculators)	Reference (Literature)
Driver		
Driving Behaviour	(CCAP.GB 2013) (UK.CC 2013)	(Ericson(a) 2000) (Ericson(b) 2001) (Leonardi and Baumgartner 2004) (Brundell-Freij and Ericsson 2005) (El-Shawarby, Ahn and Rakha 2005) (Liimatainen and Pollanen 2010)
Traffic		
Traffic Condition* -Time of the day -Weekday or weekend -Rush hour	(Cefic 2011) (EPA.UG 2012) (UTEC.UG 2012)	(Ericson(b) 2001) (Ericson(a) 2000) (Kean, Harley and Kendall 2003) (Leonardi and Baumgartner 2004) (Ericsson, Larsson and Brundell-Freij 2006) (Smit, Brown and Chan 2008) (Wang, et al. 2008) (Figliozzi 2011) (Zhang, Batterman and Dion 2011)
Driving Condition* -City driving (Urban) -Highway driving (Rural)	(Delucchi 2002) (GHGenius 2004) (Busawon 2006) (ANL.FC 2007) (IEAP.MP 2009) (Perez Cajilema 2009) (COPERT 2011) (EPA.UG 2012) (UTEC.UG 2012) (GRP 2013) (IEC 2013) (TEEMP 2013) (TPEC 2013)	(Ericson(a) 2000) (Ericson(b) 2001) (Brundell-Freij and Ericsson 2005) (Liimatainen and Pollanen 2010) (Figliozzi 2011)
Engine Situation -Cold start -Cruising* -Idling* -Acceleration/Deceleration*	(Busawon 2006) (Perez Cajilema 2009) (COPERT 2011) (EPA.UG 2012) (CCAP.GB 2013)	(Ericson(a) 2000) (Ericson(b) 2001) (Brodrick, et al. 2002) (Kean, Harley and Kendall 2003) (Rakha and Ding 2003) (El-Shawarby, Ahn and Rakha 2005) (Demir, Bektas and Laporte 2011) (Zhang, Batterman and Dion 2011) (Abou-Senna and Radwan 2013)
Speed*	(Busawon 2006) (Perez Cajilema 2009) (GEF 2010) (Cefic 2011) (COPERT 2011) (EMFAC.UG 2011) (EPA.UG 2012) (CCAP.GB 2013)	(Ericson(a) 2000) (Ericson(b) 2001) (Kean, Harley and Kendall 2003) (Rakha and Ding 2003) (El-Shawarby, Ahn and Rakha 2005) (Frey, Rouphail and Zhai 2008) (Wang, et al. 2008) (Demir, Bektas and Laporte 2011) (Zhang, Batterman and Dion 2011) (Abou-Senna and Radwan 2013)
Number of Stops*	(Busawon 2006)	(Ericson(b) 2001) (Rakha and Ding 2003) (Wang, et al. 2008)
Road Type*	(Cefic 2011) (COPERT 2011)	(Jensen 1995) (Ericson(a) 2000) (Brundell-Freij and Ericsson 2005)
Environment		
Road Gradient*	(Busawon 2006) (Perez Cajilema 2009) (Cefic 2011) (EPA.UG 2012) (TPEC 2013)	(Kean, Harley and Kendall 2003) (El-Shawarby, Ahn and Rakha 2005) (Wang, et al. 2008) (Demir, Bektas and Laporte 2011) (Abou-Senna and Radwan 2013)
Weather -Temperature - Condition	(Busawon 2006) (EMFAC.UG 2011) (TPEC 2013)	(Kean, Harley and Kendall 2003) (El-Shawarby, Ahn and Rakha 2005) (Abou-Senna and Radwan 2013)

*Indicators included in methodology section of this study

2.2.1 Vehicle-Related Indicators

Vehicle Type: Under the vehicle-related group of indicators vehicle type and engine size place beside each other. Either the calculators account for the type of the vehicle or they divide vehicles by class and involve engine size to separate different vehicle types in a specific vehicle class. For example, Heavy Duty Vehicle (HDV) class includes light heavy-duty engine, medium heavy-duty engine and heavy heavy-duty engine (see Table 2.3).

Gross Vehicle Weight (GVW) is the basic parameter for distinguishing vehicle classes in Canada. GVW consists of both vehicle mass and vehicle payload and it is the maximum weight that the vehicle is allowed to have. In regulations, Government of Canada defines vehicle classes as described in Table 2.3. As the vehicle becomes heavier, the Fuel Consumption Rate (FCR) experiences a substantial increase, which is mainly because of the vehicle weight (Demir, Bektas and Laporte 2011). For instance, based on U.S. vehicle classification, a passenger car (class 1c) travels 7-9.5 L/100km on average but an HDV (class 8b) travels only 31-56 L/100km (TR 2004, NRC.R 2010). The difference shows a range of 4-6 times more fuel consumption for the HDV class (NRC.R 2010).

Table 2-3 Canada’s vehicle classification (RC 2003)

Class	Gross Vehicle Weight Ratings (GVWR), kg (lbs.)
Motorcycle	≤ 793 kg (1,749)
Light-Duty Vehicle	≤ 3,856 (8,500)
Light-Duty Truck - light light-duty truck - heavy light-duty truck	≤ 3,856 (8,500) - ≤ 2,722 (6,000) - > 2,722-3,856 (> 6,000-8,500)
Medium-Duty Passenger Vehicle	3,856- < 4,536 (8,500- < 10,000)
Complete Heavy-Duty	3,856-6,350 (8,500-14,000)
Heavy-Duty Vehicle/Heavy-Duty Engine - light heavy-duty engine - medium heavy-duty engine - heavy heavy-duty engine	> 3,856 (8,500) - <8,847 (19,500) - 8,847-14,971 (19,500-33,000) - >14,971 (33,000)

Fuel Type: Fuel carbon content, defined as coefficient or a fraction of the fuel type has direct influence on CO_2 emissions (EPA.DE 2009). The majority of HDVs consume diesel fuel as it has a higher carbon content and therefore, higher fuel efficiency per litre of fuel (NRC.VS 2009, NRC.EI 2013). This caused diesel fuel to emit higher levels of CO_2 compared to gasoline trucks (NRC.EI 2013). Applying fuel alternatives rather than diesel in HDVs is a possibility of reducing emissions (EPS.TE 2001). The problem with this replacement is that usually using other fuel types (e.g. natural gas, ethanol, biodiesel and hydrogen) are associated with higher cost and needs advance technology (EPS.TE 2001). A study that compared diesel versus biodiesel fuel concluded that both fuels emit the same level of CO_2. However, in that study loaded trucks consumed more biodiesel (36%) than diesel (34%) fuel in comparison with the unloaded vehicles (Frey, Rouphail and Zhai 2008). The problems associated with biofuels are the efficiency of land-use and GHGs that are being emitted from growing the feedstock (Searchinger, et al. 2008, Campbell, Lobell and Field 2009, Hertel, et al. 2010).

Load: Load plays a leading role in the content of GHG emissions from freight transportation. A study regarding emissions from HDDVs found that vehicle's load has a significant impact on FCR and emissions. This study shows that there is a linear increase in CO_2 emissions, as the load changes from zero to 100 % (Gajendran and Clark 2003). Other research tried to quantify the impact of load on GHG emissions. European sources suggest that GHG emissions should be calculated for the loaded vehicle based on the ton-km unit. For instance, Deutsche Bahn, Charterway-Daimler and Institute for Energy and Environmental Research (IFEU), jointly calculate a load factor to estimate CO_2 emission per "ton-km" for three different transport modes (Truck 40 tons, Ship 1,200 tons, and Train 1,000 tons) (VDA 2006). They found a range of 53 g/tons-km to 43 g/tons-km generated CO_2 for the load factor range of 70 % to 85% for Truck 40 tons which is roughly equivalent in average to 21 tons cargo (1 United Kingdom (UK) ton equals 1,016.047 kg) (VDA 2006). Furthermore, British sources measured the impact of payload on truck's FCR. UK Department for Transport (DfT) conducted a real on-road truck test and concluded that FCR changes 0.05 km/L (2000 L/100km) as a 1 ton increase in payload for 38 and 40 ton trucks (1 metric ton equals 1,000 kg) (DfT 2007). Similarly, North American sources present other norms and figures in the context of the load impacts on fuel consumption and GHG emissions. Table 2.4 outlines the impact of the load on fuel consumption in HDVs according to a set of on-road or simulated truck test cycles in North America.

Table 2-4 Impact of Load on Fuel Consumption Rate in Heavy Duty Vehicles

Study	GVWR	Load Impact	Comments
(Strimer, et al. 2005)	9.4 - 36.1 tons 20,740 - 79,700 lbs.	1. 1% km/L per 0.5 ton 2. 1.6% km/L per 0.5 ton	1. Level terrain (-1% to 1%) 2. Stop and go
(Capps, et al. 2008)	8.6 - 35.8 tons 19,000 - 79,000 lbs.	0.7-1% km/L per 0.5 ton	Level terrain (-1% to 1%) Highway driving
(Cooper, et al. 2009)	29.5 - 36.3 tons 65,000 - 80,000 lbs.	0.5% km/L per 0.5 ton	Highway driving
(Delorme, Karbowski and Sharer 2009)	15.7 - 36.3 tons 35,000 - 80,000 lbs.	0.6% km/L per 0.5 ton	Steady state speed
(NRC.R 2010)	15 - 36.3 tons 33,001 - 80,000 lbs.	0.03 km/L per 0.5 ton	Average for a typical class 8 truck
(Franzese and Davidson 2011)	9 - 36.3 tons 20,000 - 80,000 lbs.	0.02 km/L per 0.5 ton	At 105 km/h

Vehicle Model Year: Vehicle model year indicator tries to consider the impact of time on the deterioration of the emission factor through changes in vehicle and fuel efficiency. It also captures the effect of technology on vehicle and fuel efficiency for current model years. The recent vehicle model years expected to emit at lower levels in comparison with older vehicles (Kean, Harley and Kendall 2003). Based on the recent Canadian vehicle survey, trucks more than 13 years old are significantly less fuel efficient than the newer vehicles. Moreover, 71% of the distance travelled by the heavy trucks was operated with vehicles younger than 5 years old and trucks older than 9 years contribute to only 7% of the distance travelled (6-9 years old (22%), > 9 years old (7%)) (NRC.VS 2009).

Vehicle Accessory Load and Maintenance: Vehicle accessory load and maintenance were mentioned in a few studies, as it is difficult to capture the impact of these indicators. Therefore, as can be seen in Table 2-2 these indicators are typically considered as negligible (Kean, Harley and Kendall 2003, Demir, Bektas and Laporte 2011).

2.2.2 Driver-Related Indicators

Driving Behaviour: Driving behaviour is a human related indicator and therefore; it is hard to quantify its impact in a model. Efforts on improving the driving behaviour include promoting efficient driving training programs and motivational plans. Seeing that it is beneficial to minimize the impact of driver on vehicle efficiency and FCR (Leonardi and Baumgartner 2004, Brundell-Freij and Ericsson 2005, Liimatainen and Pollanen 2010)

2.2.3 Traffic-Related Indicators

Traffic Condition: Traffic condition, mainly congestion, affects vehicle speed, acceleration/deceleration and it creates idling during vehicle’s operation. Moreover, disrupting driving pattern of the vehicle leads to significant changes in FCR and GHG emissions (Zhang, Batterman and Dion 2011).

Driving Condition and Engine Situation: Fuel Consumption Models (FCMs) usually divide vehicle operation stage to different phases based on the engine situation. This separation depends on whether the vehicle travels in rural (speed is over or at least 55 km/h) or urban (speed is less than 55 km/h) areas (Evans, Herman and Lam 1976a). Rural driving cycles work around the cruising phase, but when it comes to urban driving, idling and acceleration/deceleration phase become important (Perez Cajilema 2009, Demir, Bektas and Laporte 2011, Davis, et al. 2013). Rural FCMs were formulated based on cruise speed and steady state condition, which often happens under highway driving cycle (Vincent, Mitchell and Robertson 1980, Post, et al. 1981). The Elemental Model (EM) can be named as one of the initial urban FCMs developed since 1976. The main indicator affecting FCR in this model is the average speed (Chang, et al. 1976a, Evans, Herman and Lam 1976a, Evans and Herman 1978b, Chang and Herman 1981b). However, speed changes known as acceleration/deceleration and idling play major roles in FCR and emission rate (Ericson 2001b, Frey, Rouphail and Zhai 2008, Wang, et al. 2008). Akcelik, 1981 and 1983 proposed a model that takes into account all three phases of urban driving cycle including cruising, idling and acceleration/deceleration as independent variables affecting FCR (Akcelik 1981a, Akcelik 1983b). Another model developed by Watson and co-workers incorporates initial and final speed and changes in positive kinetic energy during acceleration to estimate the FCR (Watson, Milkins and Marshal 1980). The cold start emissions happen when the vehicle is not operating for over a significant time. A large proportion of Hydrocarbons (HC) emissions (60% to 80%) happen during cold start. Beside HC, Carbon monoxide (CO) also is a product of the cold start in HDVs with diesel engines. This excess emission can be reduced with the help of technology improvements (Heck and Farrauto 2001).

Speed and Number of Stops: Speed and number of stops both are positively correlated with vehicle FCR and emission rate (Rakha and Ding 2003, Wang, et al. 2008). However, different speed levels change vehicle FCR more than the vehicle stops

(Rakha and Ding 2003). Various studies tried to find and optimum FCR as the vehicle is cruising at different speed levels (El-Shawarby, Ahn and Rakha 2005, Wang, et al. 2008, Abou-Senna and Radwan 2013). They suggested different speed intervals such as 60 and 90 km/h, 50 and 70 km/h for Light Duty Vehicle (LDV) class and 88.5 and 97 km/h for the composition of LDVs and HDVs (0% to15%) in a highway corridor (El-Shawarby, Ahn and Rakha 2005, Wang, et al. 2008). For the HDV class, fuel economy decreases as speed increases (EPS.TE 2001, Franzese and Davidson 2011). A study conducted by Oak Ridge National Laboratory (ORNL) found that at speeds under 113 km/h HDVs has a higher fuel economy when comparing VKT with FCR (Franzese and Davidson 2011). Implementing strict control on road speed limits can lead to 1% to 4% reduction in trucks fuel consumption and respectively their emissions (EPS.TE 2001).

Road Type: Road type (e.g. street, arterial and highway) influences the driving pattern and therefore it affects FCR and consequently the emissions (Jensen 1995, Ericson 2000a, Brundell-Freij and Ericsson 2005). Road characters such as speed limits and density of traffic lights affect the FCR and emissions (Brundell-Freij and Ericsson 2005). Ericson, 2000 found that road type effect is even more than the influence that the driver behaviour has on FCR.

2.2.4 Environment-Related Indicators

Road gradient: Table 2-2 shows that environment-related indicators, especially the road gradient also caught attention when estimating GHG emission from vehicle operation. Slope or grade of the road that the vehicle is travelling on affects the FCR and GHG emission rates. FCR increases if the road is positively sloped and it decreases with a negatively sloped road (Perez Cajilema 2009, Demir, Bektas and Laporte 2011, Franzese and Davidson 2011). A study about the effect of road grade on HDVs found that fuel economy falls to 60% for extreme positive slopes (>4%) and it rises to 221% when the same HDV travels on an extreme negative slope (<-4%) in comparison with the level terrain (-1% to 1%) (Franzese and Davidson 2011).

Weather: Other studies also tried to investigate the weather contribution to GHG emissions from the vehicle operation. Weather temperature usually affects GHG emissions indirectly through its impact on vehicle's accessory load (Kean, Harley and Kendall 2003, Abou-Senna and Radwan 2013). A study investigated the effect of cold weather (-10 °C) on GHG emissions from HDVs in Canada (Graham, et al. 2008). This study found that considering diesel fuel, cold temperature increases CO_2 emissions slightly (5%). However, CH_4 emissions tend to decrease and N_2O emissions tend to increase by 40% (Graham, et al. 2008).

2.2.5 Summary of the Indicators

Section 2.2 summarized GHG emissions indicators based on GHG emission calculators reviewed in Section 2.1 and an extra literature survey. Indicators with significant impact on fuel consumption and GHG emissions were also identified in this section. Indicators involved in the methodology section were distinguished with an asterisk symbol (*) in Table 2-2. The effect of age, accessory load, maintenance, driving behaviour, cold start and weather are not considered in developing an emission estimation method in this study. As shown in Section 2.2, Traffic-related indicators have considerable impact on GHG emissions especially in urban areas. Use of micro-simulation environments becomes important when capturing the effect of traffic-related indicators. Beside real on-road tests, which are prohibitively expensive, the closest to the real world are the traffic micro-simulation tools, which produce output regarding driving cycle and actual driving pattern of the vehicle (Cappiello 2002, Lee, et al. 2009, Hao, Hatzopoulou and Miller 2010). Section 2.3 describes common commercially available micro-simulation tools.

2.3 Traffic Simulation Environments

As described in Section 2.2 the use of micro-simulation environment becomes important when it comes to the impact of traffic-related indicators. Parallel Microscopic Simulation (PARAMICS) and Verkehr In Städten-SIMulationsmodell (VISSIM - German for traffic in cities - simulation model) are the most advanced and complete micro-simulation tools commercially available today based on their control strategies and algorithms. These tools are able to address managing the road logistics, demand, traffic, parking, public transport, freight and fleet, provide traffic and travel information in detail, perform vehicle control and track in both urban and rural areas (Algers, et al. 1998, Choa, Milam and Stanek 2003, Golly 2006).

PARAMICS: PARAMICS developed by The Edinburgh Parallel Computing Centre and Quadstone, companies from Scotland. This tool provides parallel microscopic road traffic simulation in large scale with unlimited number of links, connectors and vehicles; however, it only supports dynamic traffic assignment using Origin/Destination (O/D) matrices.

VISSIM: VISSIM developed by a German company named Planung Transport Verkehr (PTV). VISSIM is a microscopic time step and a behaviour base simulation model. VISSIM not only provides unlimited number of links, connectors, vehicles and intersection approach legs but also gives the ability to do both dynamic and static assignments (Cameron and Duncan 1996, Algers, et al. 1998, Golly 2006, VISSIM.UG 2008). VISSIM works with two main components, the traffic simulator along with the signal state generator. The traffic simulator controls the vehicle's behaviour such as traffic flow and lane change logic and the signal state generator provides signal control status information in a specific time step and sends it to the traffic simulator (VISSIM.UG 2008).

Both PARAMICS and VISSIM output detailed data for links, connectors, network and each vehicle type. They provide data on vehicle's VKT, travel time, idling, number of stops, cruise speed and acceleration/deceleration rates as the vehicle is travelling through a specific route. The user also has the ability to explore the vehicle's different routing alternatives between certain origin and destination (Golly 2006, VISSIM.UG 2008). Both PARAMICS and VISSIM are suitable for the purpose of this study; however, VISSIM was selected for this study based on its availability.

2.4 Summary

In this chapter, the GHG emission indicators were extracted from available emission calculators and literature review. Section 2.1 presented an overview of the available GHG emission calculators for road transportation (see Table 2-1). Types and formats of the calculators were extracted along with their calculation procedures and principles were studied. Section 2.2 investigated GHG emission indicators, which affect road transportation emissions. These indicators can be classified by their causes, which are vehicle, driver, traffic and environment. GHG emission indicators extracted from studying GHG emission calculators and reviewing the literature and summarized in Table 2-2. This study includes the effect of location, VKT, fuel consumption, vehicle type, fuel economy, fuel type, vehicle load, vehicle model year, traffic condition, driving condition, engine situation, speed, number of stops, road gradient and road type to develop a GHG Emission Estimation Methodology (EEM) in Chapter 3. Section 2.3 introduced VISSIM, which is one of the advanced traffic micro-simulation environments. VISSIM outputs detailed data for links, connectors, network and each vehicle type. They provide data on vehicle’s VKT, travel time, idling, number of stops, cruise speed and acceleration/deceleration rates. VISSIM was selected to develop a traffic micro-simulation network and capture the effect of the traffic-related indicators.

CHAPTER 3: METHODOLOGY

3.1 The GHG Emission Estimation Methodology

As discussed in Section 2.1, the common procedure for calculating GHG emissions from road transportation is to estimate the fuel consumption as the first step and then convert the fuel consumption value to GHG emissions using appropriate emission factors. The difference between various GHG emission calculators that use the same method is in the specific indicators used to calculate the Fuel Consumption Rate (FCR), as well as the source used for the emission factors. Generally, the more indicators considered, the more precise the model should become. These indicators were extracted based on reviewing existing emission calculators and the literature (see Table 2.2). A GHG Emission Estimation Methodology (EEM) is developed to estimate the GHG (CO_2, CH_4 and N_2O) emission from the trucks as they deliver construction materials to specific destinations in an urban area. Emission indicators that are covered in the developed methodology are location, Vehicle Kilometres Travelled (VKT), fuel consumption, vehicle type, fuel economy, fuel type, vehicle load, vehicle model year, traffic condition, driving condition, engine situation (cruising, idling and acceleration/deceleration), speed, number of stops, road gradient and road type. The overview of the developed EEM is illustrated in Figure 3-1. As can be seen in the figure, EEM is conducted in two phases. Phase 1 develops a traffic micro-simulation network and collects traffic-related indicators. The collected indicators are used to estimate the initial FCR from the truck's journey in phase 2. Moreover, phase 2 considers other emission indicators to estimate GHG emissions.

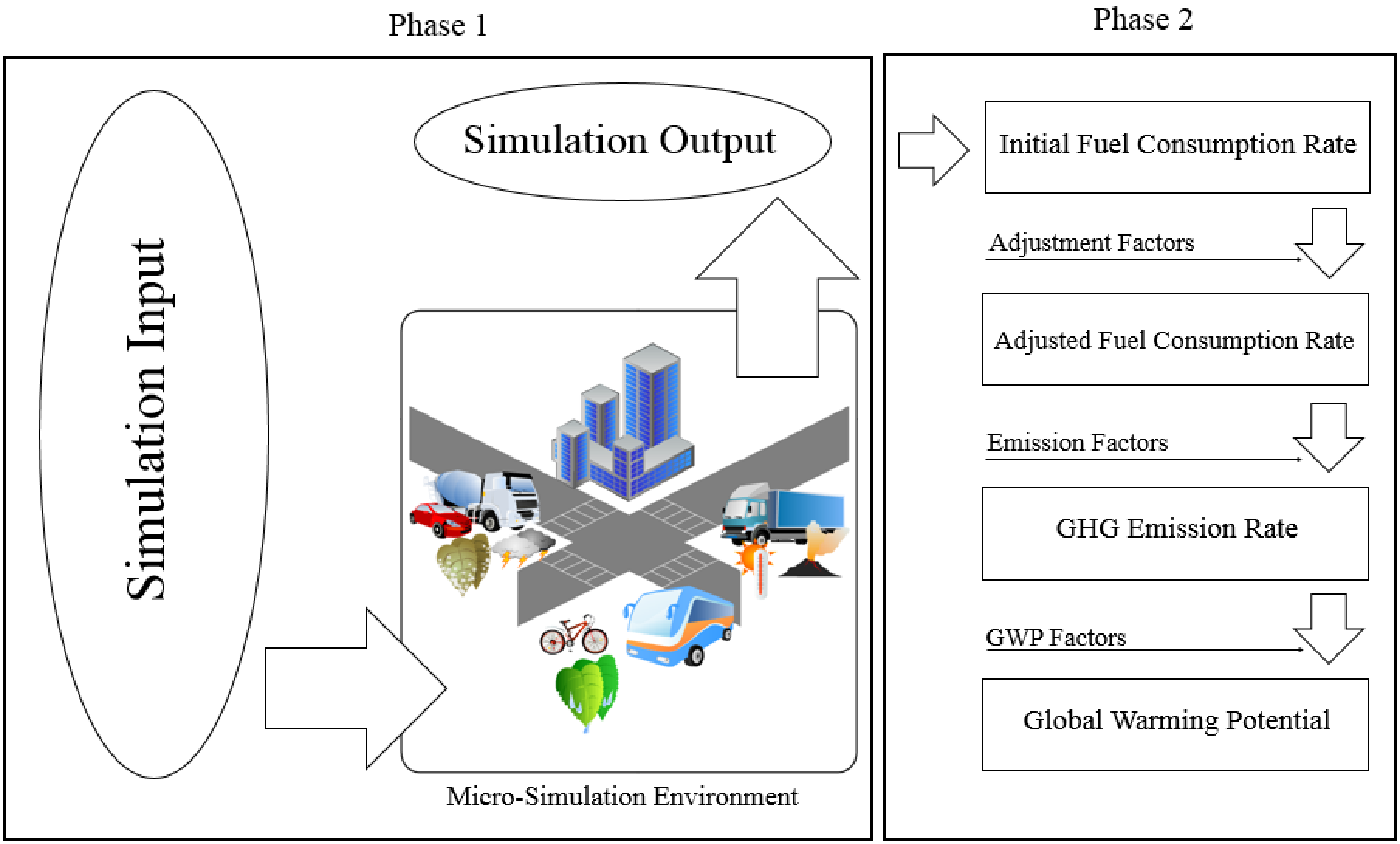


Figure 3-1 Overview of the proposed EEM

The first step of the proposed EEM is to develop a traffic micro-simulation network to capture the effect of the traffic-related indicators. Different steps are required to create an effective traffic micro-simulation network in a micro-simulation environment. Section 3.1.1 describes the role and details of the micro-simulation phase (phase 1). The micro-simulation output data will be used to calculate the initial FCR in phase 2. A Fuel Consumption Model (FCM) needs to be selected based on the indicators desired to be included in the EEM. The selected FCM may miss some of the important vehicle-related and environment-related indicators. The next step is to refine the estimates from the selected FCM using adjustment factors. After calculating the adjusted FCR, the GHG emission rate can be estimated using the relevant emission factors. Finally, the estimated emissions need to be converted to the amount of the heat that can be trapped using the Global Warming Potential (GWP) factors. The following sections describe each step of the EEM in details.

3.1.1 Micro-simulation

As demonstrated in Figure 3-1, the EEM developed in this study requires the traffic micro-simulation output to calculate the initial FCR. This section provides an overview of developing a typical static traffic micro-simulation network. Chapter 4 gives details about traffic micro-simulation network with static assignment. It also describes developing the micro-simulation network as implemented in this study. Micro-simulation plays an important role in considering the effect of traffic-related indicators including traffic condition and driving condition. Moreover, it gives detailed output about idling, acceleration/deceleration, speed and number of stops. Beside traffic-related indicators, the micro-simulation also captures VKT, travel time and provides the ability to include the effect of the road type in the calculations. The overall logic of developing a static traffic micro-simulation network in a micro-simulation environment indicated in Figure 3-2.

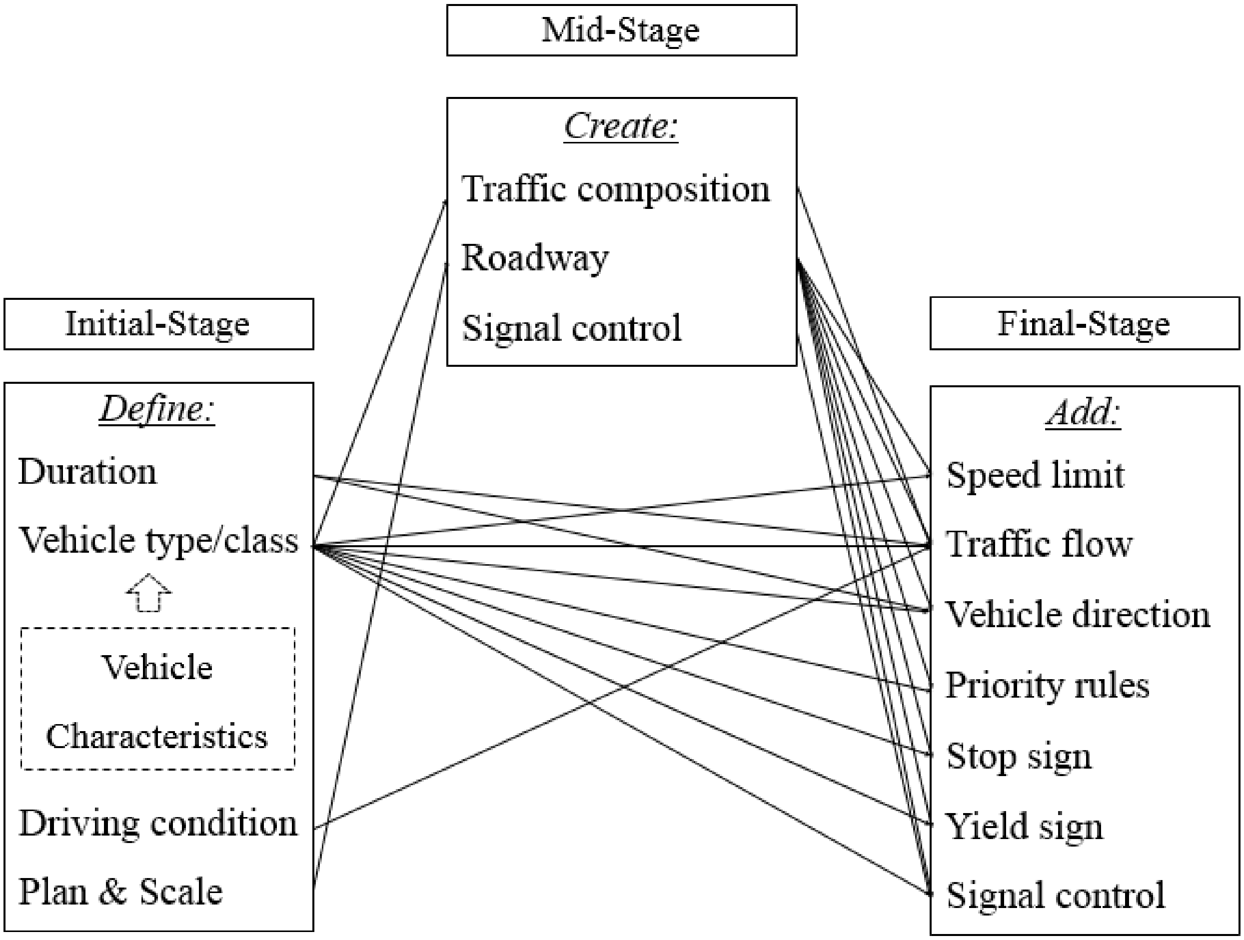


Figure 3-2 Overall logic of developing a static traffic micro-simulation network

In general, the network characteristics need to be defined before taking further steps. Duration specifies when the simulation is taking place and how many hours it covers. Simulation environments usually have a list of common vehicle types/classes available by default. However, they also allow the user to define a desired vehicle within a specific vehicle class. Furthermore, the characteristics of the new added vehicle can be changed by various functions and distributions in the simulation environment (e.g. acceleration/deceleration, speed, power and weight). Defining the traffic condition and uploading a clear map of the desired location are subsequent steps of the initial-stage. Traffic condition affects the behaviour of the traffic flow throughout the network. The background map is required for creating the roadways. Moreover, certain scaling ratios have to be defined for the simulation network based on the ratio between distance on the uploaded map and the corresponding distance on the real-world location. Creating the roadways happens at the mid-stage level along with creating the traffic compositions and signal controls. Completing the roadways is essential for starting the final-stage. Afterwards, speed limits can be added for each roadway. Traffic flow need to be placed for each network entry and traffic directional movement is required for each intersection. Data for vehicle entry and vehicle direction need to be entered precisely in order for traffic volume to be accurate. In addition, relevant stop or yield sign needs to be added for non-signalized intersections and specific signal control has to be placed for signalized intersections. Moreover, for both non-signalized and signalized intersections proper priority rules need to be entered into the network based on driving rules established for the desired location.

3.1.2 Initial Fuel Consumption Calculation

An initial FCR can be calculated by using the traffic micro-simulation output. Different models for calculating the FCR under urban, steady and non-steady state conditions have been proposed since 1976. These models take into consideration different traffic-related indicators to calculate the fuel consumption such as cruising, acceleration/deceleration, idling, speed and number of stops. In addition, they include VKT, vehicle type and fuel economy into their methodology. Change in fuel consumption due to other indicators is assumed negligible in these models. However, the model output can be adjusted to compensate for the effect of important indicators such as vehicle load and road gradient (Chang, et al. 1976a, Evans, Herman and Lam 1976a, Evans and Herman 1978b, Watson, Milkins and Marshal 1980, Akcelik 1981a, Chang and Herman 1981b, Akcelik 1983b, Ardekani, Hauer and Jamei 1992). Comparing fuel consumption estimation from a number of models for road freight transportation indicates that, when comparing the model output with the real on-road measurements, the reliability of the output varies by changing indicators like speed and vehicle weight. Moreover, in rare cases the output aligned with the real on-road measurements (Demir, Bektas and Laporte 2011). One possible explanation could be the large number of input data that these freight transportation models were needed to calculate the fuel consumption. This may have increased the possibility of having errors in the model estimation.

This study adopts the urban FCM developed by Akcelik, 1981 and Akcelik, 1983 to calculate the initial FCR (Akcelik 1981a, Akcelik 1983b). This model estimates fuel consumption during cruising, idling and acceleration/deceleration, which are the three main phases of an urban driving cycle (Ardekani, Hauer and Jamei 1992). The model calculates the average fuel consumption per vehicle (F) in ml through considering VKT, fuel economy, speed, delay time and number of stops and is expressed as follows:

$F = k_1 . X_s + k_2 . d_s + k_3 h_s$ Equation 3.1

where:

cruising phase: $k_1 . X_s$
k_1= fuel consumption rate while cruising (ml/km)
X_s= total section distance (km)

idling phase: $k_2 . d_s$
k_2= fuel consumption rate while idling (ml/s)
d_s= average delay time per vehicle (idling time) (sec)

acceleration/deceleration phase: $k_3 h_s$
k_3= excess fuel consumption per vehicle stop (ml)
h_s = average number of stops per vehicle

The equation coefficients (k_1, k_2 and k_3) which vary with changes in the vehicle speed were calibrated based on the United States (U.S.) fleet characteristics (Wallace, et al. 1984). The following formulas are the calibrated model that calculates the fuel consumed (F) in gallons (gal):

$F = (k_1 \times Total\ Travel) + (k_2 \times Total\ Delay) + (k_3 \times Total\ Stops)$ Equation 3.2

where:

cruising phase: $k_1 \times Total\ Travel$
$k_1 = 0.075283 - 0.0015892 \times Speed + 0.000015066 \times Speed^2$ Equation 3.3
$Total\ Travel$= vehicle miles traveled (mile)
$Speed$ = Cruise speed in mile per hour (mph)

idling phase: $k_2 \times Total\ Delay$
$k_2 = 0.7329$
$Total\ Delay$= total signal delay in hours (h)

acceleration/deceleration phase: $k_3 \times Total\ Stops$
$k_3 = 0.0000061411 \times Speed^2$ Equation 3.4
$Total\ Stops$= total stops in vehicles per hour (veh/h)
$Speed$ = Cruise speed in mile per hour (mph)

The calibrated model presented above has been broadly used in research (Wallace, et al. 1984, Hogan 2000, WSU 2007, Cobian, et al. 2009). The model does not consider the effect of a number of major emission indicators namely load and road gradient. The initial FCR estimates from the above model can be adjusted to account for the missing emission indicators (Ardekani, Hauer and Jamei 1992, Stevanovic 2009a, Stevanovic, et al. 2009b).

3.1.3 Adjusted Fuel Consumption Calculation

The aforementioned FCM (Equation 3.2) does not account for the effect of the vehicle type. As this study focuses on road transportation in the construction sector and deals with Heavy Duty Diesel Vehicles (HDDV), it is essential to account for this indicator. The other two necessary adjustments are the load and the road gradient effects.

3.1.3.1 HDDVs Effect

This study focuses on heavy heavy-duty engine class (class 8b based on U.S. vehicle classification) which has the Gross Vehicle Weight (GVW) larger than 14,971 kg (see Table 2.3), with diesel as the primary fuel. The aforementioned FCM (Equation 3.2) calculates the GHG emission for Light Duty Vehicles (LDV). Hence, a correction coefficient is needed to account for fuel consumption differences between LDVs and HDDVs. This study applies the "base city fuel consumption data" from the GHGenuis emission model released by the Natural Resources Canada (NRCan). This model is specifically developed for Canada and uses Canada's national and local fuel economy and emission factors. According to the GHGenuis, HDDVs consume 4.16 times more fuel than LDVs in an urban area in Canada. This is due to the HDDVs weight, engine technology and the combustion efficiency (GHGenius 2004, EPA.FF 2012). Table 3.1 shows the data used for calculating the adjustment factor for the vehicle type indicator in detail.

Table 3-1 Effect of vehicle type on fuel consumption rate (GHGenius 2004)

Vehicle Type	**Canada Fuel Consumption Parameters** **Base CITY fuel consumption for 2000 (L/100km)**
LDGV Light Duty Gas Vehicle	10.72
HDDV Heavy Duty Diesel Vehicle	44.63
Adjustment factor	$44.63 \div 10.72 = 04.16$

3.1.3.2 Load Effect

The HDDV's load affects the GHG emission level significantly. Construction material delivery trucks are typically only loaded during one of the trip legs. They carry the cargo from the manufacturing plant to the construction site and then they travel back empty to load the next delivery. Hence, in construction material delivery, the truck is either loaded or empty. Studies show that higher load factors lead to higher fuel efficiencies for delivery of a specific volume of load. Consequently, companies try to keep high proportions of load levels and efficiently match the truck's capacity with the load (Leonardi and Baumgartner 2004, McKinnon, 2005, Delorme, Karbowski and Sharer 2009, Kamakate and Schipper 2009, Liimatainen and Pollanen 2010). Personal communications with industry practitioners also confirmed that when delivering construction materials, the HDDV would be fully loaded, unless a "route load capacity ban" exists throughout the truck's route or the load volume is less than the truck's total capacity. Therefore, this study assumes that the trucks are fully loaded when they are delivering the construction materials to the construction site.

According to the U.S. Department of Energy (DOE) "2012 vehicle technologies and market report data", which were extracted from U.S. 2010 National Research Council report, typical fuel consumption of a class 8b combination truck is 0.015 Litres per ton-kilometres (L/ton-km) (NRC.R 2010, DOE.MR 2012). This value is used to calculate the difference in fuel consumption due to the changes in the truck's weight. For example, for an HDDV with GVW of 36.6 tons and payload volume of 7.5 cubic meters (m^3) of concrete, which roughly equals 17.31 tons load capacity, when the truck is empty it weighs 19.29 tons (36.6 tons−17.31 tons=19.29 tons) and consumes 0.29 L/km fuel (19.29 tons×0.015 L/ton-km=0.29 L/km). Moreover, when this truck is fully loaded it weighs 36.6 tons and its fuel usage increases to 0.55 L/km (36.6 tons×0.015 L/ton-km=0.55 L/km), an increase of approximately 90%. The initial FCR needs to be increased by 90% to account for the load effect.

Based on Canadian vehicle survey summary report, fuel consumption of the HDDVs is approximated 33.4 L/100 km (NRC.VS 2009). A study on transporting ready-mix concrete in Greater Toronto Area (GTA), Canada, found that loaded HDDVs consume 62.5 L/100 km on average (58-67 L/100 km) (Artenian, Sadeghpour and Teizer 2010). The ratio between the aforementioned FCRs returns 1.9 (62.5 L/100km ÷ 33.4 L/ 100 km = 1.87 ~ 1.9) as the load factor adjustment. The fuel consumption rises by 90%, similar to the ratio estimated above, applying information available in "2012 vehicle technologies and market report data."

3.1.3.1 Road Gradient Effect

As discussed in Section 2.2.4 road gradient also have an important effect on the fuel consumption, and consequently on vehicle's GHG emissions. An uphill grade increases the fuel consumption; conversely, a downhill grade leads to a decrease in vehicle's fuel consumption level. Road gradient adjustments vary with the slope of the road and clearly, it does not need to be applied when the truck is travelling through a flat terrain. Based on the DOE 2012 energy transportation data book effect of the road gradient on class 8 truck fuel economy can be found in Table 3-2.

Table 3-2 Effect of road gradient on the fuel economy of class 8 truck - DOE 2012 energy transportation data book (Davis, Diegel and Boundy 2012)

Slope Type	Trucks Fuel Economy (km/L)	Gradient Adjustment Factor
Severe upslope (>4%)	1.23	2.5
Mild upslope (1% to 4%)	1.85	1.7
Flat terrain (-1% to 1%)	3.12	1
Mild downslope (-4% to -1%)	6.42	0.5
Severe downslope (<-4%)	9.99	0.3

3.1.4 Estimating GHG Emission Rate

The emission rates for the main GHGs (CO_2, CH_4 and N_2O) can be estimated by applying emission factors to the adjusted FCR. The emission factor for CO_2 depends closely on the location and the fuel type and it has a linear relationship with the FCR (see Section 2.3.1). As this model is developed for the purpose of transportation in the context of the Canadian construction industry and deals with HDDVs, the emission factors for diesel fuel in Canada are needed. Table 3-3 shows the latest Canadian CO_2 emission factor defaults for transport fuels in gram per litre of the fuel consumed (g CO_2 / L) based on 2013 Canada's National Inventory Report (NIR).

Table 3-3 CO_2 emission factor defaults for transport fuels in Canada (NIR.CA, 2013)

Fuel Type	CO_2 Emission Factor (g CO_2 / L)
Gasoline	2289
Diesel	2663
Propane	1510
Light Fuel Oil	2725
Heavy Fuel Oil	3124
Aviation Gasoline	2342
Ethanol	1494
Biodiesel	2449

As can be seen in Table 3-3 diesel fuel contains 2663 g CO_2 per one litre of fuel. For CH_4 and N_2O emission factor, beside location and fuel type, vehicle type, engine technology and vehicle model year also have to be taken into account (see Section 2.3.1). The CH_4 and N_2O emission factors for HDDVs by engine technology and vehicle model year are in Table 3-4 as prescribed by Canada's NIR report.

Table 3-4 Emission Factors for Energy Mobile Combustion Sources (NRC.R 2010)

HDDVs Engine Technology	Vehicle Model Year	Emission Factor (g / L)	
		CH_4	N_2O
Advanced Control	2004-2009	0.11	0.151
Moderate Control	1994-2003	0.14	0.082
Uncontrolled	1980-1995	0.15	0.075

3.1.5 Estimating Global Warming Potential

The GWP is an indication of how much heat can be trapped in the atmosphere by the emitted GHGs. The atmospheric lifetime and heat-trapping potential of each of the aforementioned GHGs differ based on the mass of each specific gas. The GWP makes it possible to compare the heat-trapping abilities relative to the mass of the CO_2 (CO_2 equivalent (eq.)) over a specific time. Table 3-5 shows the GWP values for CO_2, CH_4

and N_2O over a hundred-year time horizon published in the latest Intergovernmental Panel for Climate Change (IPCC) climate change report (AR5).

Table 3-5 Global warming potentials (GWP) - 100-Year Time Horizon (Myhre, et al. 2013)

Greenhouse Gas	**Formula**	**GWP_{100}**
Carbon dioxide	CO_2	1
Methane	CH_4	34
Nitrous oxide	N_2O	298

GWP represents the CO_2 amount with the same heat-trapping effect as the specific GHG over the specified time horizon, known as the carbon dioxide equivalent (CO_2 eq.). The GWP in CO_2 eq. can be estimated using the following equation and values presented in Table 3-5:

$$GWP_X = (Em(CO_2)_X \times 1) + (Em(CH_4)_X \times 34) + (Em(N_2O)_X \times 298) \qquad \text{Equation 3.5}$$

Where:

$GWP_X =$ Global Warming Potential for Route $_X$ in CO_2 eq.
$Em(CO_2)_X =$ CO_2 emitted from traveling through route $_X$ in kg
$Em(CH_4)_X =$ CH_4 emitted from traveling through route $_X$ in kg and
$Em(N_2O)_X =$ N_2O emitted from traveling through route $_X$ in kg.

Figure 3-3 demonstrates the overall view of the developed EEM after determining, which FCM is appropriate for this study (Equation 3.2), which adjustments are required to be added and, what values should be used as the emission and GWP factors. In the figure, FIn is the initial FCR, TT is the Total Travel, TD is the Total Delay (idling) and TS is the Total Stops. The adjustment factors are presented as VTF, LF and RGF, which are Vehicle type, Load and Road Gradient Factors, respectively.

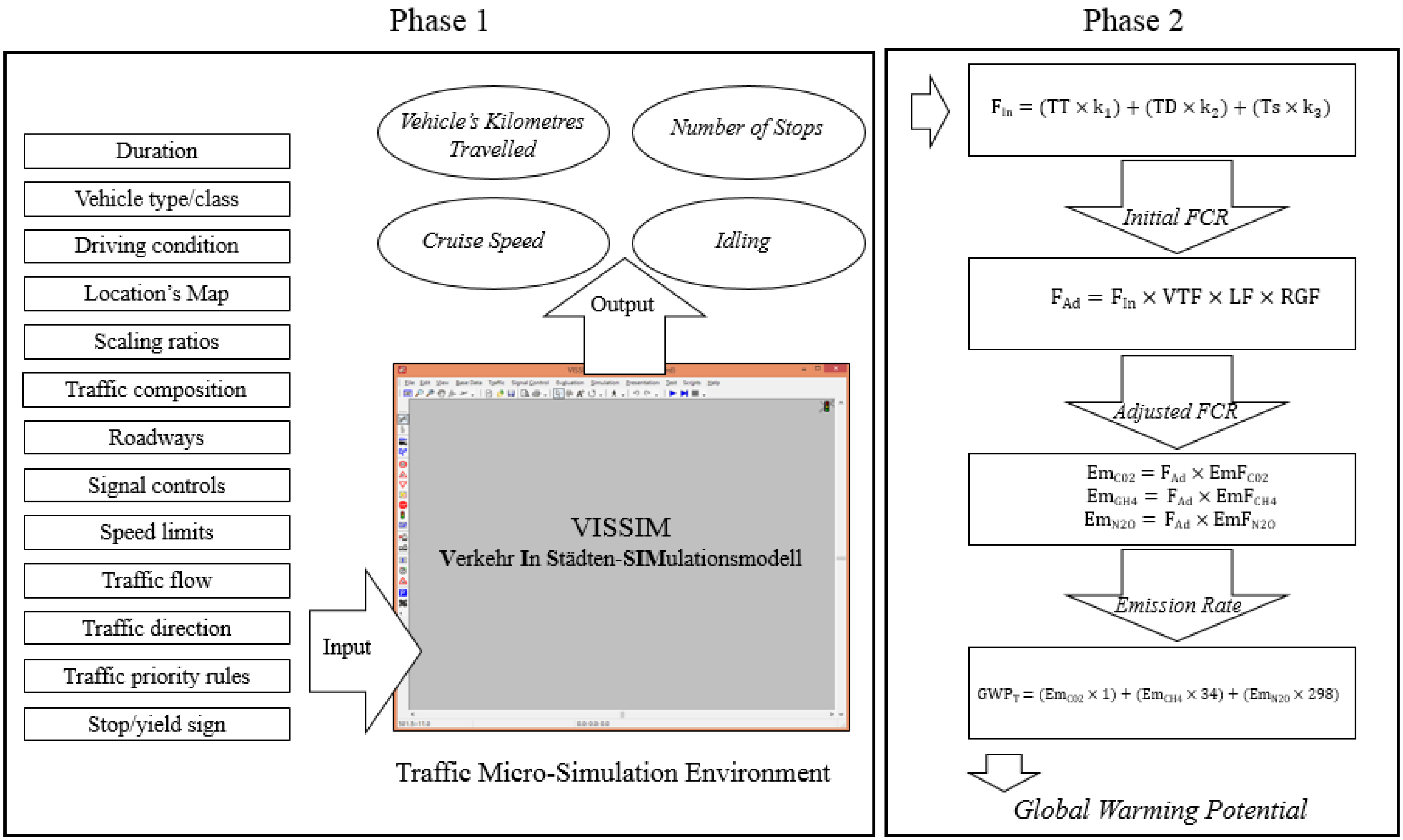


Figure 3-3 Developed methodology (EEM) in the current study

3.2 Summary

The developed EEM for calculating GHG emissions from the HDDVs was described in this chapter. The developed methodology used traffic micro-simulation to capture the impact of the traffic-related indicators. The micro-simulation output was used to calculate an initial FCR. The initial FCR was adjusted for the missing GHG emission indicators, which were vehicle type, load and road gradient. The adjusted FCR was then; used to calculate GHG emissions and GWP (see Figure 4.8). Chapter 4 will describe how the EEM is implemented using traffic micro-simulation and a GHG emission estimator tool.

CHAPTER 4: IMPLEMENTATION

4.1 Phase 1: Traffic Micro-Simulation

This study utilizes Verkehr In Städten-SIMulationsmodell (VISSIM - German for traffic in cities - simulation model) to derive traffic-related indicators needed for the proposed GHG Emission Estimation Methodology (EEM). VISSIM provides a suitable tool for environmental impact studies as it allows for most of the important emission indicators that were identified in Chapter 2 to be considered in this study, including traffic and driving conditions, speed, number of stops, delay time, Vehicle Kilometres Travelled (VKT) and road type. There are two types of traffic assignment in developing a traffic micro-simulation network: dynamic and static. The difference is that the dynamic assignment predicts the behaviour of the traffic over time. This study used static traffic assignment because it aims to calculate GHG emission from a single truck and not to do predictions about the behaviour of the traffic. VISSIM provides static traffic assignment for developing a traffic micro-simulation network. Figure 3.2 summarized the logic for developing a static traffic micro-simulation network. Table 4-1 summarizes steps and data required to implement the logic showed in Figure 3.2.

Table 4-1 Steps utilized for developing a traffic micro-simulation network with static assignment

Step	VISSIM Action	Data Required
Initializing the micro-simulation	Define simulation hours	Traffic condition, Desired time of the study
	Define driving condition (urban/rural)	Driving condition, Area of the study
Vehicle characteristics	Define vehicle type/class	Desired vehicle type
	Define power distribution	Desired vehicle characteristics
	Define weight distribution	Desired vehicle characteristics
Roadways	Upload plan	Location's map
	Scale the plan	Real-world scaling ratios
	Create roadways	Number of lanes, Road type
	Add speed limits	Road type Regional Transportation Model (RTM)
Traffic composition & traffic flow	Create traffic compositions	Volume of each vehicle type existing in the traffic flow
	Add traffic flow	Average Annual Daily Traffic , Traffic counts reports
Traffic direction	Add vehicle direction	Turning Movement Summary Diagram (TMSD) Traffic Count Reports (TCR)
Non-signalized intersection	Add traffic priority rules	Traffic priority rules, Type of the intersection
	Add stop or yield sign	Type of the intersection
Signalized intersection	Create signal controls	Signal timing summaries
	Add signal controls	Type of the intersection
Finalizing the micro-simulation	Specify output file	Desired output parameters

The following sections describe the steps summarized in Table 4.1 to develop a micro-simulation network in VISSIM. These steps are explained in the context of an example. This example is an area located in Southeast (S.E.) Calgary, Canada. S.E. Calgary was selected because of the large number of construction projects in progress in that area due to development of the new communities. In addition, the new vehicle defined for VISSIM (see Section 4.1.2) is based on the characteristics of the vehicle that used in the case study in Chapter 5.

4.1.1 Initializing the Micro-Simulation

The basic simulation characteristics need to be defined for VISSIM to start a traffic micro-simulation network. The main characteristic of the simulation including the simulation hours, specific date and time can be defined through the simulation parameters. For the purpose of this study, an eight-hour simulation that starts from 8:00 a.m. and ends until 4:00 p.m. was defined using the simulation parameters. The eight-hour simulation represents 28,800 ($8h\times60(min/h)\ \times60(s/min)\ =28{,}800$) simulation seconds in VISSIM. Since construction material suppliers avoid delivery during rush hours, simulation output data were collected from the off-peak period, which belongs to 9:00 a.m. until 3:00 p.m. The simulation was also conducted for two extra hours outside the off-pick period: from 8 a.m. to 9 a.m. to warm up the network before delivery trucks enter the roadways; and from 3 p.m. to 4 p.m. to let the trucks complete their trip and end up at their destination. Driving condition of the simulation network can be changed in VISSIM using the Driving Behaviour tool. For this study, the urban (motorized) driving behavior was selected, as the selected location is an urban area (S.E. Calgary).

4.1.2 Vehicle Characteristics

It is important to define the specific type of vehicle, for which the GHG emission needs to be calculated. Usually, micro-simulation tools contain common vehicle types and vehicle classes. For instance, VISSIM includes car, HGV (Heavy Goods Vehicle), bus, tram, pedestrian and bike. In VISSIM, vehicle types with similar characteristics and driving behaviours gather under the same vehicle class. For this study the specific characteristics of the HGV, namely type and class were changed based on the vehicle used in the case study in Chapter 5. For the newly defined HGV two subclasses were created: a fully loaded vehicle (named GHGV) and an empty vehicle (named EHGV) to collect data when the fully loaded Heavy Duty Diesel Vehicle (HDDV) transports construction materials from the manufacturing plant to the construction site and accordingly returns back empty. For the newly defined vehicle, width, weight and power range were added in VISSIM.

4.1.3 Roadways

To start creating the roadways for the micro-simulation network, a plan of the desired location (S.E. Calgary) needs to be added as the background image. The background image should be a picture map of the specific location that shows roads and intersections clearly. Google Maps was used to upload a background image from S.E. Calgary and to scale the image with real-world gauges using the Distance Measurement Tool of the Google Maps. Calgary's truck routes were simulated in VISSIM because trucks are permitted to travel on certain routes throughout the city. This study updated the current S.E. Calgary truck routes map with the forecasted 2019 truck routes plan to consider future expansions within the micro-simulation (FTRM 2014). Figure 4-1 illustrates the S.E. section of the City of Calgary 2019 truck routes plan.

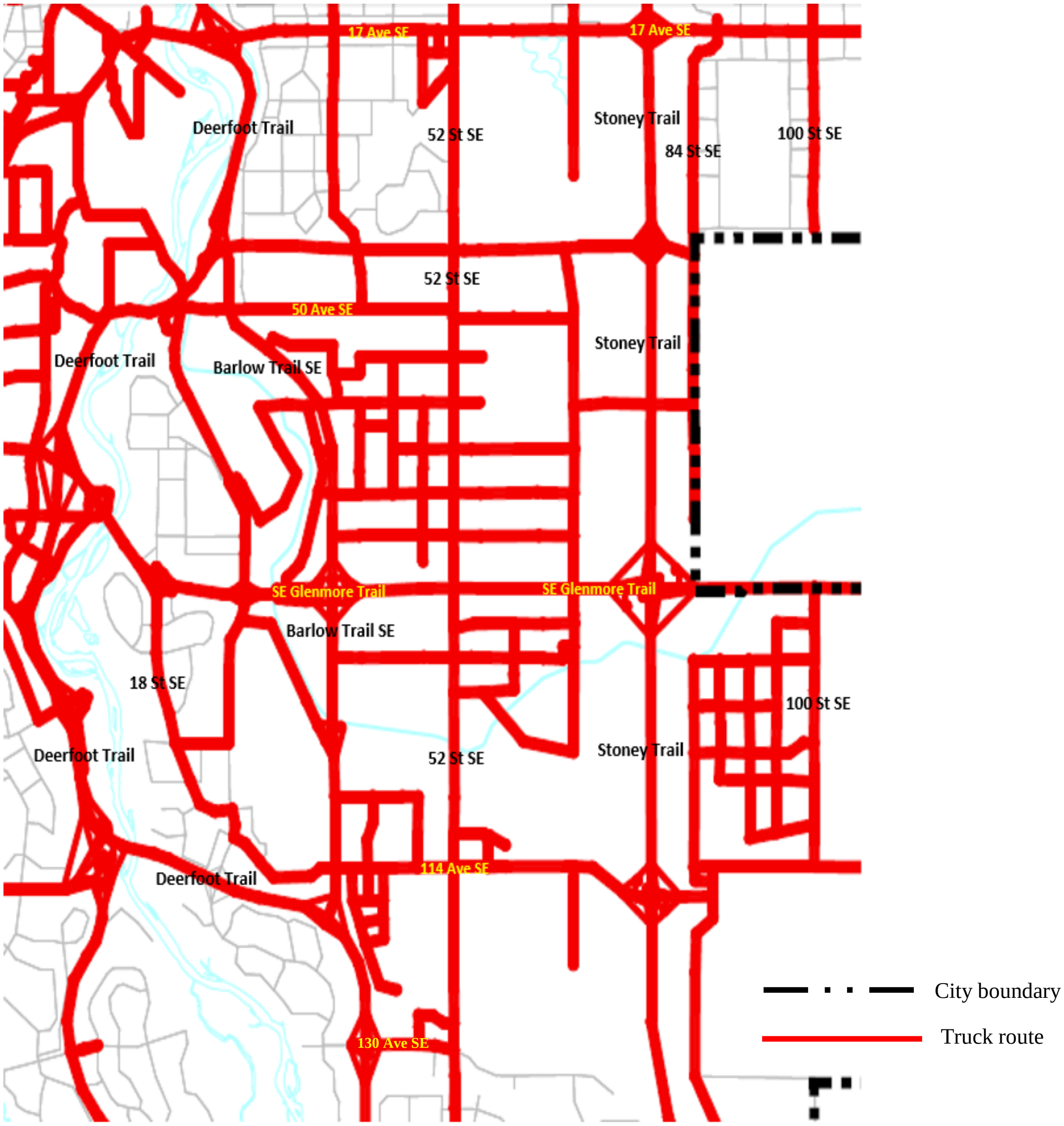


Figure 4-1 Routes where trucks are permitted to travel through in S.E. Calgary area

The simulated roadways consist of 1,383 links and 2,461 connectors representing S.E. Calgary truck routes in VISSIM. Deerfoot Tr., 17 Ave. S.E., 100 Ave. S.E. and 130 Ave. S.E. are respectively east, north, west and south boundaries of the roadway network (see Figure 4-1). In addition to the plan of the desired location, posted speed limits for each roadway should be added to the network. Speed limits were extracted from Calgary Regional Transportation Model (RTM) map for the "posted speed limits" (FTRM 2014). In total, 1,361 speed limits were added for the roadways exist in the network. Figure 4-2 depicts the complete roadways of S.E. Calgary truck routes simulated in VISSIM. This figure also shows examples of the network entries, which are needed for the next step.

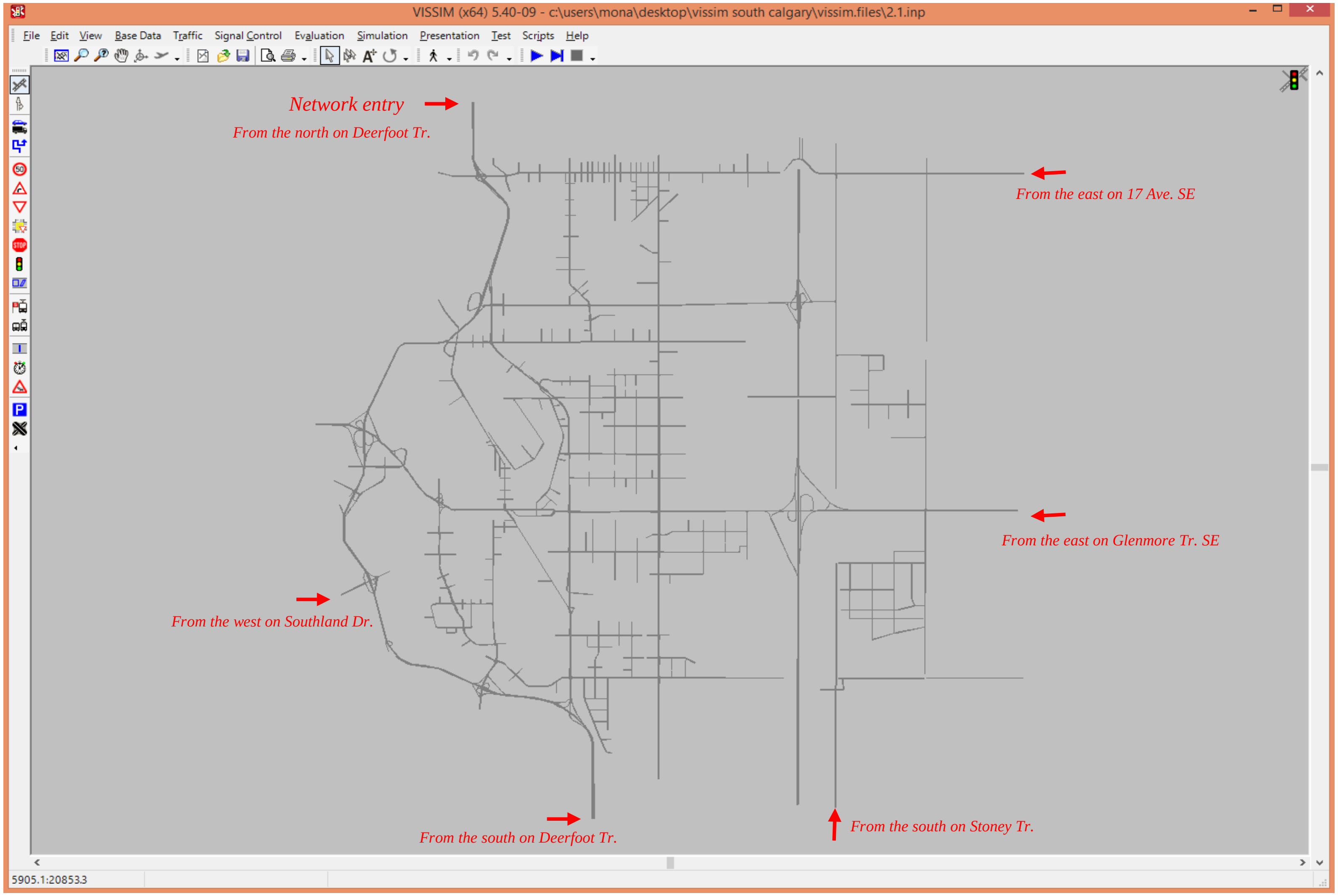
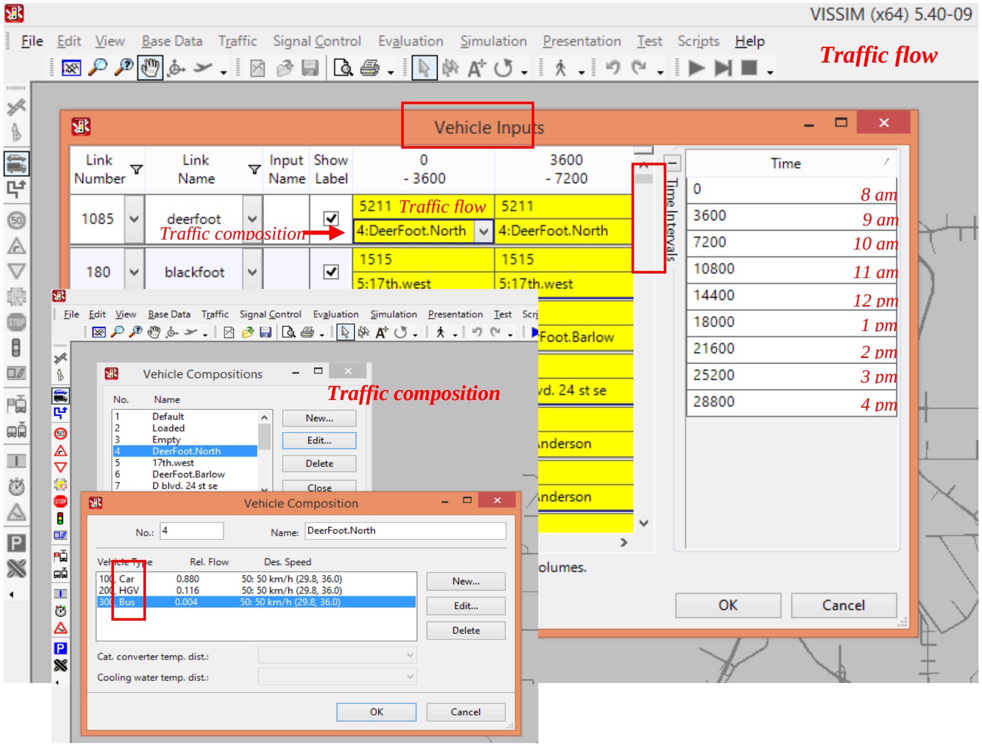


Figure 4-2 Complete roadways network of the S.E. Calgary truck routes simulated in VISSIM

4.1.4 Traffic Composition and Traffic Flow

When developing a static traffic micro-simulation network, traffic flow and traffic composition need to be defined for each network entry (see Figure 4-2). This data can be extracted from real traffic counts available online or by contacting municipal transportation divisions of the desired location. In this study, data for Alberta’s provincial Highways (e.g. Deerfoot Trail) were available online through the provincial website (ABgov 2014). Data for Calgary region were obtained from the Transportation Data division of the Transportation Planning Department in the City of Calgary. Traffic compositions and traffic flows were defined based on Directional Traffic Count Summary (DTCS) and Traffic Count Report (TCR) data obtained from the above sources. Figure 4-3 shows traffic compositions and traffic flows defined for VISSIM based on S.E. Calgary traffic characteristics.



Vehicle Inputs

Link Number	Link Name	Input Name	Show Label	0 - 3600	3600 - 7200
1085	deerfoot		☑	5211 4:DeerFoot.North	5211 4:DeerFoot.North
180	blackfoot		☑	1515 5:17th.west	1515 5:17th.west

Time	
0	8 am
3600	9 am
7200	10 am
10800	11 am
14400	12 pm
18000	1 pm
21600	2 pm
25200	3 pm
28800	4 pm

Vehicle Compositions

No.	Name
1	Default
2	Loaded
3	Empty
4	DeerFoot.North
5	17th.west
6	DeerFoot.Barlow
7	D blvd. 24 st se

Vehicle Composition

No.: 4

Name: DeerFoot.North

Vehicle Type	Rel. Flow	Des. Speed
100, Car	0.880	50: 50 km/h (29.8, 36.0)
200, HGV	0.116	50: 50 km/h (29.8, 36.0)
300, Bus	0.004	50: 50 km/h (29.8, 36.0)

Cat. converter temp. dist.:

Cooling water temp. dist.:

Figure 4-3 S.E. Calgary traffic compositions and traffic flows added to VISSIM

Table 4.2 shows an example of the DTCS data, which includes 9:00 a.m. to three 3:00 p.m. traffic counts divided in 15 minutes count intervals. The traffic composition consists of the following vehicles: passenger vehicle (A), recreation vehicle (B), bus (C), single unit truck (D) and tractor-trailer combination (E). Data collected in 15 min count intervals for each hour were added up to obtain the hourly traffic flow. For instance, between 9:00 a.m. and 10:00 a.m., which corresponds to 3,600 and 7,200 simulation seconds in VISSIM (see Figure 4-3), 5,211 vehicles traveled through Deerfoot Trail from the north. The determined hourly traffic flow was entered in VISSIM as vehicle inputs and related traffic composition was assigned to it (see Figure 4-3). For instance, the 4:DeerFoot.North traffic composition was created for this traffic flow and was assigned to it as can be seen in Figure 4-3. The following are the calculations for determining the 4:DeerFoot.North traffic composition, based on data presented in Table 4-2.

A: Passenger vehicle
B: Recreation vehicle
$\text{Total (A, B)} = 1251 + 1 + 22278 + 135 + 4897 + 14 = 28{,}576$
$\text{Total} = 1251 + 1 + 6 + 63 + 11 + 22278 + 135 + 96 + 1620 + 1405 + 489 + 14 + 28 + 485 + 198 = 32{,}488$
% Car (A, B) = $28{,}576 \div 32{,}488 = 0.87958 \times 100 = 87.96$ % ~ $\mathbf{88}$ %

C: Bus
$\text{Total (C)} = 6 + 96 + 28 = 130$
% Bus (C) = $130 \div 32{,}488 = 0.00400 \times 100 = \mathbf{0.4}$ %

D: Single-unit truck
E: Tractor-trailer combination
$\text{Total (D, E)} = 63 + 11 + 1620 + 1405 + 485 + 198 = 3{,}782$
% HGV (D, E) = $3{,}782 \div 32{,}488 = 0.11641 \times 100 = \mathbf{11.6}$ %

Table 4-2 Sample DTSC data used for creating the traffic compositions and adding the traffic flows

Time Intervals	**Count Intervals**	**Approaching Intersection : From the North on Deerfoot Trail**															**Total (Veh/h.)**
		Left					**Through**					**Right**					
		A	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	
9:00-10:00	9:00 - 9:15	48			3		1000	8	3	88	60	171	2		9	9	5211
	9:15 - 9:30	51			2	1	950	9	5	90	72	211		2	16	13	
	9:30 - 9:45	46			4	1	830	6	4	64	70	156		3	8	4	
	9:45 - 10:00	49			2	1	840	5	5	75	55	148		1	7	4	
10:00-11:00	10:00 - 10:15	38			2		730	3	6	69	55	159			4	7	4856
	10:15 - 10:30	61			4		870	3	4	65	50	162	1	2	11	4	
	10:30 - 10:45	53		1	1	1	860	1	2	71	57	248	1	2	21	8	
	10:45 - 11:00	47		1	1		770	3	1	65	74	215			28	14	
11:00-12:00	11:00 - 11:15	46			1		840	4	10	69	66	192	1	2	26	12	5402
	11:15 - 11:30	58			3	1	870	6	1	66	54	267	1	3	24	11	
	11:30 - 11:45	52			3		860	2	2	66	54	235		1	20	9	
	11:45-12:00 p.m.	65		1	3		970	3	2	66	57	267	2	1	20	7	
12:00-1:00	12:00 - 12:15	42			2		930	8	1	67	58	194	1	3	24	9	5341
	12:15 - 12:30	45		1	1		920	9	3	68	74	194			22	4	
	12:30 - 12:45	64			1		800	7	1	72	66	238		1	24	12	
	12:45 - 1:00	63			5	1	930	8	3	62	52	219	1	1	20	10	
1:00-2:00	1:00 - 1:15	54			2		895	8	2	67	63	211	1	1	23	9	5672
	1:15 - 1:30	58			2		892	7	4	70	62	226		1	22	9	
	1:30 - 1:45	47		1	3	1	1090	6	4	57	51	185		1	26	7	
	1:45 - 2:00	53			4	1	1086	6	7	61	51	200	1	1	26	7	
2:00-3:00	2:00 - 2:15	54			4		1055	4	4	70	53	209			19	8	6006
	2:15 - 2:30	52	1		5	2	1070	8	8	47	51	201	2	1	17	12	
	2:30 - 2:45	57			2	1	1110	6	6	71	52	214			31	6	
	2:45 - 3:00	48		1	3		1110	5	8	54	48	175		1	37	3	
Total		**1251**	**1**	**6**	**63**	**11**	**22278**	**135**	**96**	**1620**	**1405**	**4897**	**14**	**28**	**485**	**198**	**32488**

This traffic composition was calculated via categorizing passenger vehicles (A) and recreation vehicles (B) under Car group in VISSIM, buses (C) as Bus and single unit trucks (D) and tractor-trailer combinations (E) under HGV vehicle type group in VISSIM. The proportions of the vehicle composition change roughly for each hourly time interval. Therefore, one unique value was estimated considering all 6 hours in aggregate. The traffic approaching Deerfoot Trail from the north consists of 88% Car, 11.6% HGV and 0.4% Bus, which corresponds to the created 4:DeerFoot.North vehicle composition in VISSIM (see Figure 4-3). If data were missing for a specific network entry, estimated values for nearby entries with similar traffic characteristics were used. In total, 245 Vehicle Inputs were added throughout the micro-simulation. Traffic compositions for other network entries were calculated using the same procedure. In addition to the default vehicle composition available in VISSIM, 15 extra vehicle compositions were created to consider S.E. Calgary traffic characteristics.

4.1.5 Traffic Direction

Traffic direction required to be added to each intersection in the micro-simulation network. It distributes the traffic flow based on the real-world proportions while the traffic flow approaches these intersections. Routing Decision and Direction Decision tools make it possible to define traffic directional movement at each intersection bound, which includes north, south, east and west bounds with straight, left and right directional movements. Routing Decision functions better with Single lane Roadways while Direction Decision is applicable for multi-lane roadways. Traffic directional movements were extracted from Turning Movement Summary Diagram (TMSD), DTCS and TCR data. For provincial highways (e.g. Deerfoot Trail) TMSD and DTSC are available online through government of Alberta website (ABgov 2014). For urban areas within Calgary's boundaries, TCR data were obtained from The Transportation Data Division of the Transportation Planning Department in the City of Calgary. Table 4.3 shows an example of the TCR data used to create proper traffic directional movement for each intersection to control vehicles' distribution close to each intersection. It shows the intersection of the 17th Ave. S.E. and 68th St. S.E. and includes 6 hours intersection count. The data cover 2 hours from the morning peak (7:00 a.m. to 9:00 a.m.), 2 hours from the off-peak period (11:00 a.m. to 1:00 p.m.) and 2 hours from the evening peak period (4:00 p.m. to 6:00 p.m.) with 15 minutes count intervals. Data collected during the off-peak period were used to determine the traffic directional movement.

Table 4-3 Sample TCR data used for adding traffic directional movement to the intersections

17th Ave. S.E. & 68th St. S.E.												
Count intervals	**North**			**South**			**East**			**West**		
	North Left	North Straight	North Right	South Left	South Straight	South Right	East Left	East Straight	East Right	West Left	West Straight	West Right
11:00:00	20	8	74	13	2	3	3	107	24	49	83	9
11:15:00	25	3	69	8	6	2	1	128	27	54	94	5
11:30:00	31	8	48	8	5	2	4	122	34	61	104	9
11:45:00	30	7	52	7	2	6	4	124	29	51	106	6
12:00:00	24	9	47	7	4	1	4	154	24	61	109	9
12:15:00	26	8	56	8	4	3	1	127	20	60	110	9
12:30:00	19	3	91	3	4	6	3	125	24	73	121	9
12:45:00	34	2	53	7	6	5	1	124	23	53	115	16
Total	**209**	**48**	**490**	**61**	**33**	**28**	**21**	**1011**	**205**	**462**	**842**	**72**

The following are the calculations for determining the traffic directional movement for the intersection of 17th Ave. S.E. and 68th St. S.E., based on data shown in Table 4-3.

$\text{Total (North)} = 209 + 48 + 490 = 747$
% north left = $209 \div 747 = 0.27978 \times 100 = 27.98\,\% \sim \mathbf{28}\,\%$
% north straight = $48 \div 747 = 0.06425 \times 100 = \mathbf{6.4}\,\%$
% north right = $490 \div 747 = 0.65595 \times 100 = \mathbf{65.6}\,\%$

$\text{Total (South)} = 61 + 33 + 28 = 122$
% south left = $61 \div 122 = 0.5 \times 100 = \mathbf{50}\%$
% south straight = $33 \div 122 = 0.27049 \times 100 = 27.05\,\% \sim \mathbf{27}\,\%$
% south right = $28 \div 122 = 0.22950 \times 100 = 22.95\,\% \sim \mathbf{23}\,\%$

$\text{Total (East)} = 21 + 1011 + 205 = 1237$
% east left = $21 \div 1237 = 0.01697 \times 100 = \mathbf{1.7}\,\%$
% east straight = $1011 \div 1237 = 0.81729 \times 100 = \mathbf{81.7}\,\%$
% east right = $205 \div 1237 = 0.16572 \times 100 = \mathbf{16.6}\,\%$

$\text{Total (West)} = 462 + 842 + 72 = 1376$
% west left = $462 \div 1376 = 0.33575 \times 100 = \mathbf{33.6}\,\%$
% west straight = $842 \div 1376 = 0.61191 \times 100 = \mathbf{61.2}\,\%$
% west right = $72 \div 1376 = 0.05232 \times 100 = \mathbf{5.2}\,\%$

As can be seen in the above calculations, from 747 vehicles approaching the intersection from the north, 209 vehicles turned left, 48 vehicles traveled straight and 490 vehicles turned right. Therefore, $209 \div 747 = 0.27978 \times 100 \sim 28\,\%$ of the vehicles turned left, 6.4% went straight and 65.6% turned left. A total of 379 Routing Decisions and 937 Direction Decisions were added to the micro-simulation network to direct vehicles as they are approaching the intersections.

4.1.6 Non-Signalized Intersections

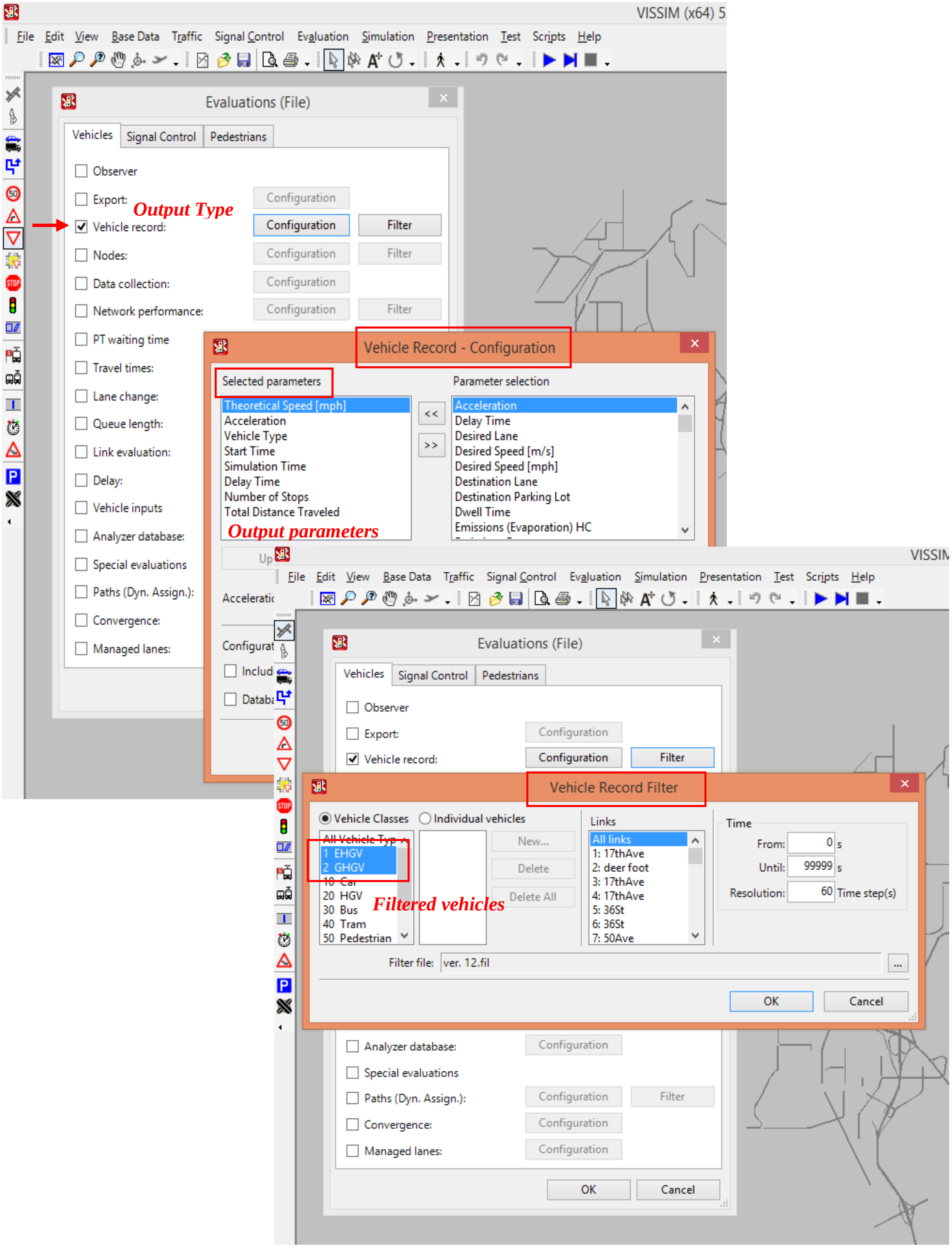
For non-signalized intersections, a set of traffic priority rules associate with stop or yield signs needs to be defined. Priority rules can be assigned to non-signalized intersections using Conflict Areas tool. Priority rules and stop or yield signs complete each other when dealing with non-signalized intersections in VISSIM. Therefore, in addition to the conflict areas, based on the intersection type a stop or yield sign was placed at the intersection to control the traffic. Alberta’s intersections and turns rules were used to set appropriate priority rules in the micro-simulation network (TSA 2013). A total of 184 stop signs and 20 yield signs were set throughout the micro-simulation network. Moreover, each non-signalized intersection needed up to 30 priority rules to follow the traffic rules properly.

4.1.7 Signalized Intersections

Specific signal controls need to be defined for signalized intersections. Signal Timing Summary (STM) data were obtained from the City of Calgary, Roads Operation Center, Traffic Division, Roads. Forty-eight signal controls were created in VISSIM using the STM data obtained from the City of Calgary for the S.E. area. STM includes location of the intersection, intersection number, date that the intersection is coded and installed, timing plan number and start and end time, cycle length and green and yellow cycle time for each timing plan. Timing plan number 211 was used because it covers 9:00 a.m. to 3:00 p.m. time interval for weekdays. If data were missing for a specific signalized intersection, a signal control for a nearby intersection with similar traffic characteristics was used. Sections 4.1.6 and 4.1.7 were also applied for existing 3-way intersections through the micro-simulation network.

4.1.8 Finalizing the Micro-Simulation

Desired outputs can be specified using the Evaluation tool. Without determining the output file, VISSIM would not provide any output data after running the simulation. Vehicle record is the type of output that is needed for this study. Within the vehicle record, the following parameters were selected: theoretical speed, vehicle type, start time, simulation time, delay time (idling), number of stops and total distance travelled were selected. Moreover, the vehicle classes were filtered to GHGV and EHGV under the Filter tab. Hence, VISSIM only collects the specified parameters for the GHGVs and EHGVs. Figure 4-4 shows finalizing the micro-simulation network in VISSIM. Eventually, data obtained through VISSIM output file were applied in phase 2 of the developed EEM as described in Section 4.2. Figure 4-5 shows the generated output file and the simulation multi-run tool used to run the developed micro-simulation.



Evaluations (File) – Vehicles: ☐ Observer, ☐ Export, ☑ Vehicle record, ☐ Nodes, ☐ Data collection, ☐ Network performance, ☐ PT waiting time, ☐ Travel times, ☐ Lane change, ☐ Queue length, ☐ Link evaluation, ☐ Delay, ☐ Vehicle inputs, ☐ Analyzer database, ☐ Special evaluations, ☐ Paths (Dyn. Assign.), ☐ Convergence, ☐ Managed lanes

Vehicle Record - Configuration

Selected parameters:
- Theoretical Speed [mph]
- Acceleration
- Vehicle Type
- Start Time
- Simulation Time
- Delay Time
- Number of Stops
- Total Distance Traveled

Parameter selection:
- Acceleration
- Delay Time
- Desired Lane
- Desired Speed [m/s]
- Desired Speed [mph]
- Destination Lane
- Destination Parking Lot
- Dwell Time
- Emissions (Evaporation) HC

Vehicle Record Filter

● Vehicle Classes ○ Individual vehicles

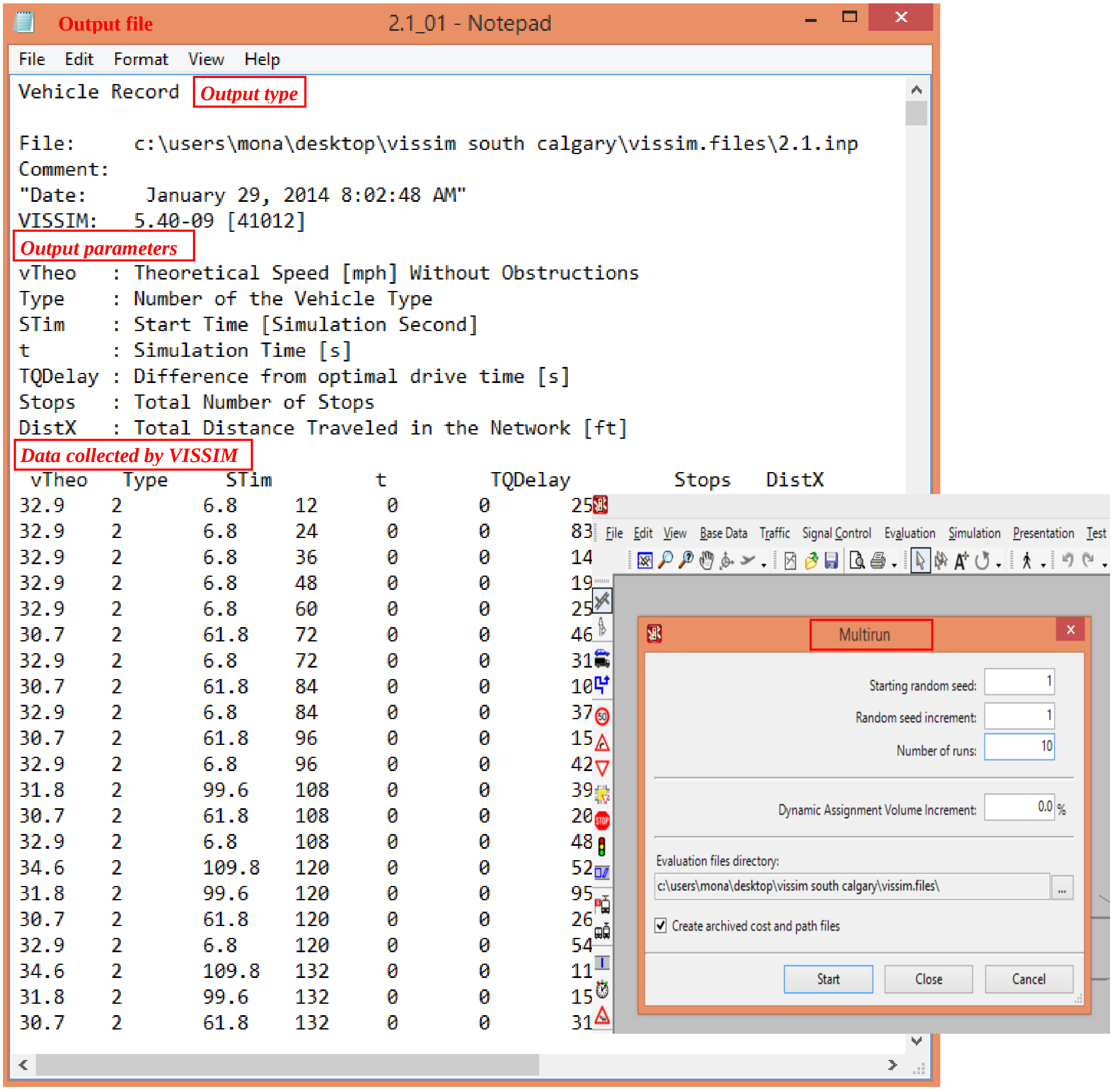
Vehicle classes: All Vehicle Typ; 1 EHGV (selected); 2 GHGV (selected); 10 Car; 20 HGV; 30 Bus; 40 Tram; 50 Pedestrian

Links: All links (selected); 1: 17thAve; 2: deer foot; 3: 17thAve; 4: 17thAve; 5: 36St; 6: 36St; 7: 50Ave

Time – From: 0 s; Until: 99999 s; Resolution: 60 Time step(s)

Filter file: ver. 12.fil

Figure 4-4 Finalizing the developed traffic micro-simulation in VISSIM



```
Vehicle Record

File:     c:\users\mona\desktop\vissim south calgary\vissim.files\2.1.inp
Comment:
"Date:     January 29, 2014 8:02:48 AM"
VISSIM:   5.40-09 [41012]

vTheo   : Theoretical Speed [mph] Without Obstructions
Type    : Number of the Vehicle Type
STim    : Start Time [Simulation Second]
t       : Simulation Time [s]
TQDelay : Difference from optimal drive time [s]
Stops   : Total Number of Stops
DistX   : Total Distance Traveled in the Network [ft]

 vTheo   Type      STim        t        TQDelay       Stops   DistX
32.9    2       6.8     12      0       0       25
32.9    2       6.8     24      0       0       83
32.9    2       6.8     36      0       0       14
32.9    2       6.8     48      0       0       19
32.9    2       6.8     60      0       0       25
30.7    2       61.8    72      0       0       46
32.9    2       6.8     72      0       0       31
30.7    2       61.8    84      0       0       10
32.9    2       6.8     84      0       0       37
30.7    2       61.8    96      0       0       15
32.9    2       6.8     96      0       0       42
31.8    2       99.6    108     0       0       39
30.7    2       61.8    108     0       0       20
32.9    2       6.8     108     0       0       48
34.6    2       109.8   120     0       0       52
31.8    2       99.6    120     0       0       95
30.7    2       61.8    120     0       0       26
32.9    2       6.8     120     0       0       54
34.6    2       109.8   132     0       0       11
31.8    2       99.6    132     0       0       15
30.7    2       61.8    132     0       0       31
```

Starting random seed: 1
Random seed increment: 1
Number of runs: 10
Dynamic Assignment Volume Increment: 0.0 %
Evaluation files directory: c:\users\mona\desktop\vissim south calgary\vissim.files\
☑ Create archived cost and path files

Figure 4-5 Generated output file and the simulation multi-run tool used to run the micro-simulation

4.2 Phase 2: GHG Emission Estimator Tool

Figure 4-6 shows the steps for implementing phase 2 of the EEM. As can be seen in the figure, before starting the calculations for phase 2, the VISSIM output file needs to go through few reorganization steps. The output data from phase 2 calculations are: Global Warming Potential (GWP), selected parameters for each individual HDDV, and detail of the calculation in a spreadsheet format, as shown in Figure 4-6. These output data are used for analysis and reporting the results in Chapter 5.

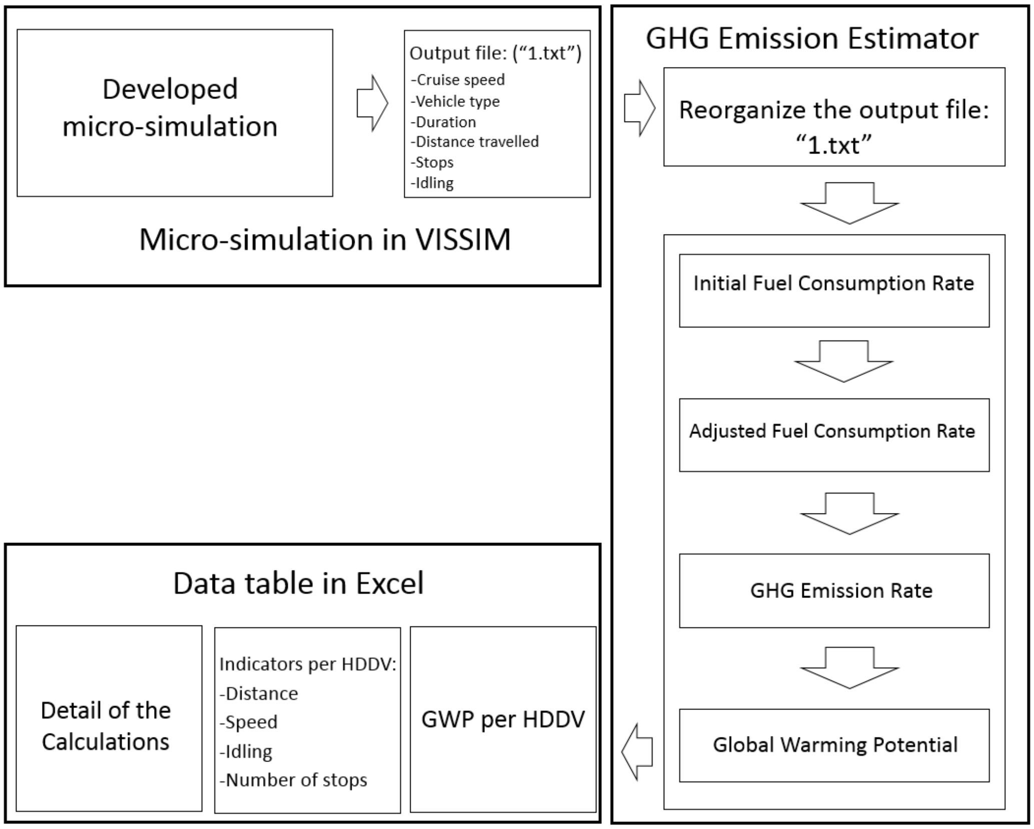


Figure 4-6 Implementation steps for phase 2 of the EEM

Based on the steps shown in Figure 4-6, a GHG emission estimator tool was developed in Visual Studio 2013 using C-sharp (C#) programming language. Figure 4-7 shows the interface of the developed estimator tool. This tool reads the VISSIM output file, reorganizes the data as required for phase 2 calculations and then, calculates the GWP value. The flowchart for coding the program is illustrated in Figure 4-8. In the flowchart, the output parameters from VISSIM are shown with Italic typeface and marked with *'Apostrophes'* and the variables used to program the estimator tool are distinguished with Italic typeface and marked with "*Quotation marks*".

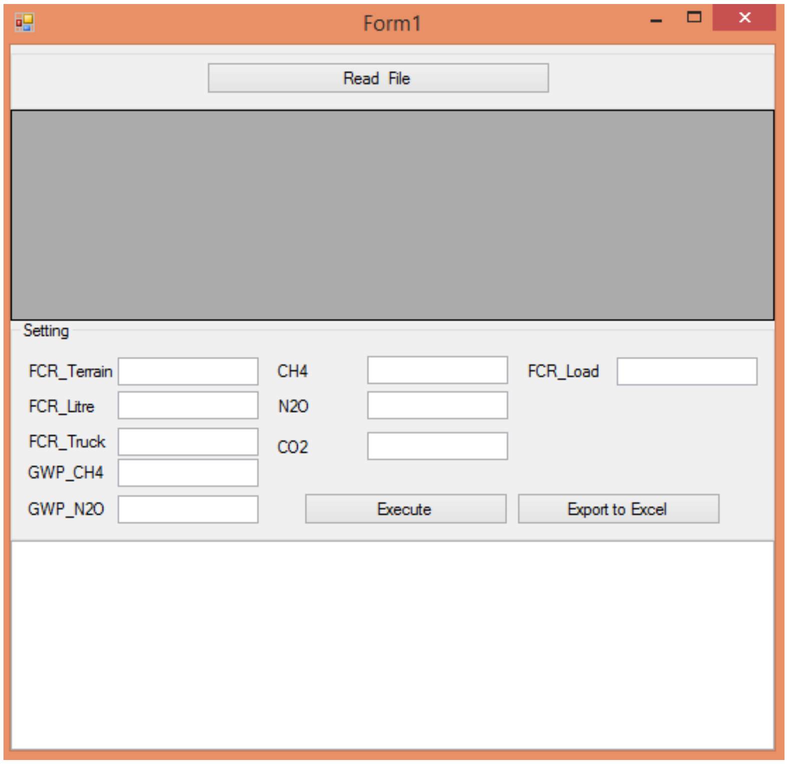


Figure 4-7 Interface window of the estimator tool developed to implement phase 2 of the EEM

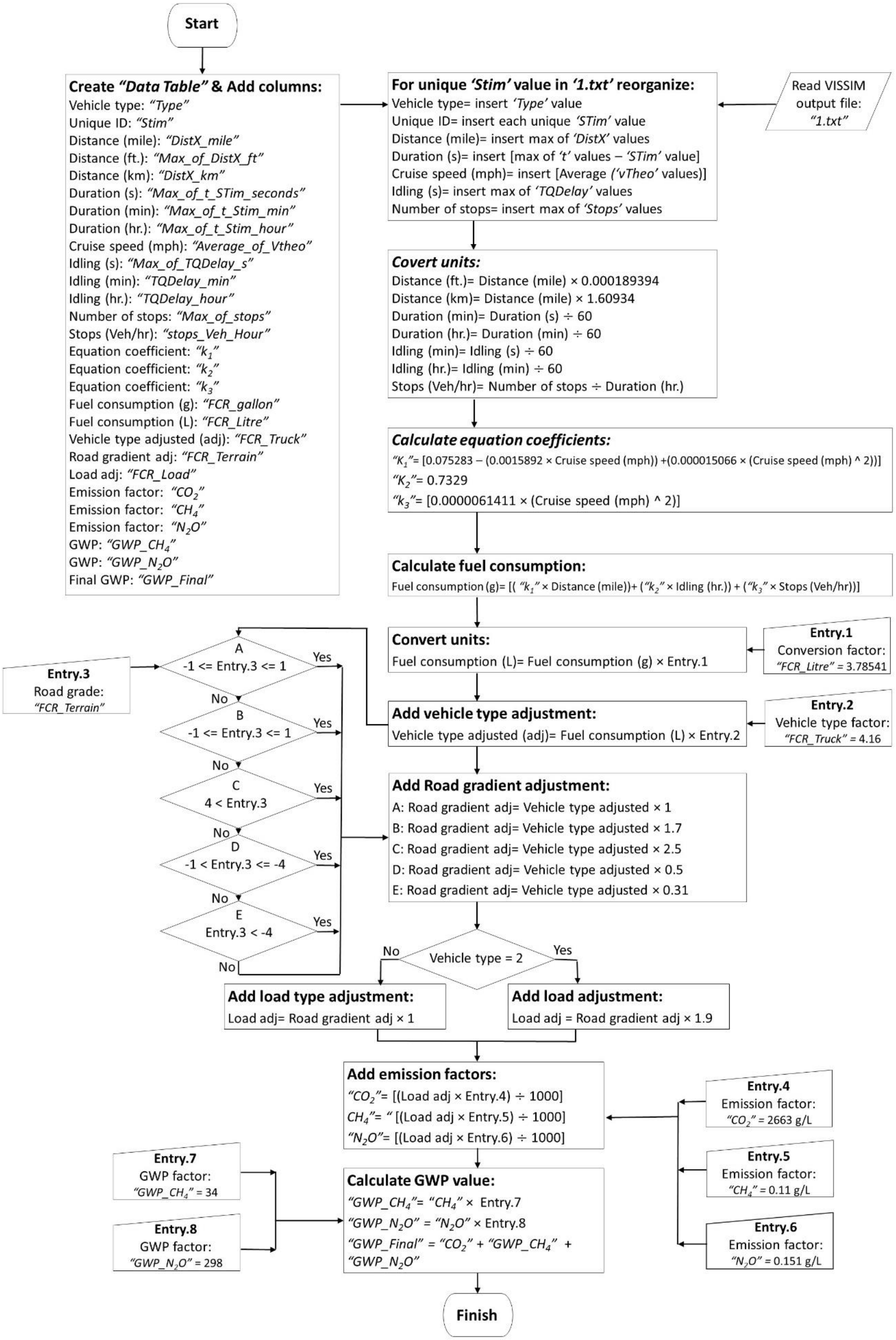
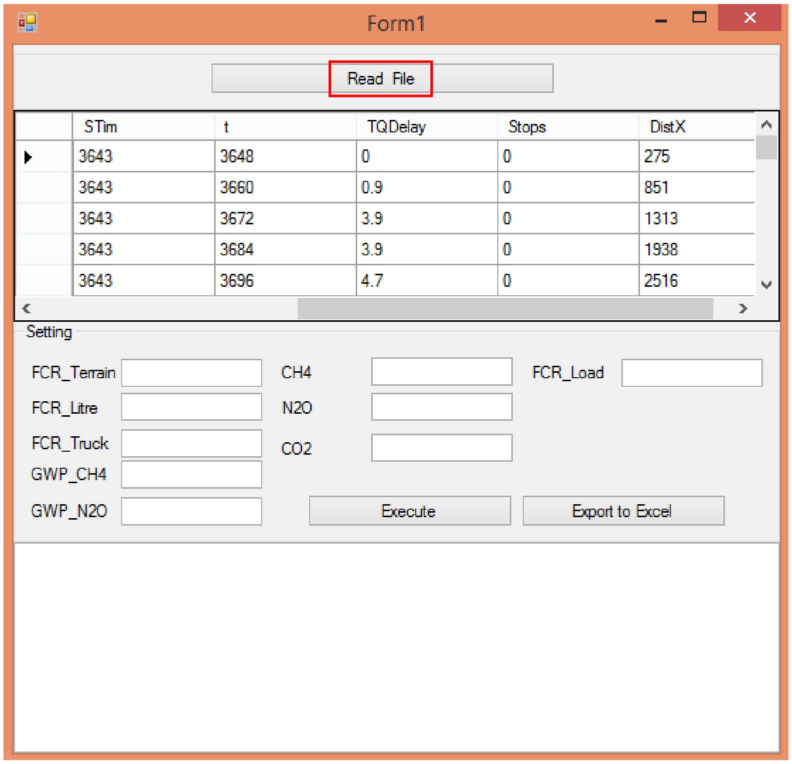


Figure 4-8 Flowchart of the developed GHG emission estimator tool

4.2.1 Reorganization

First, the estimator tool creates a *"Data Table"* and adds all the required columns with specified titles to it. This step is called "Create *"Data Table"* & Add columns*"* in Figure 4-8. Then, the tool reads the VISSM output file *"1.txt."* This step can be executed by clicking on the Read File button placed at the top of the interface window as shown in Figure 4-9.



	STim	t	TQDelay	Stops	DistX
▶	3643	3648	0	0	275
	3643	3660	0.9	0	851
	3643	3672	3.9	0	1313
	3643	3684	3.9	0	1938
	3643	3696	4.7	0	2516

Figure 4-9 Reading the VISSIM output file using the GHG emission estimator tool

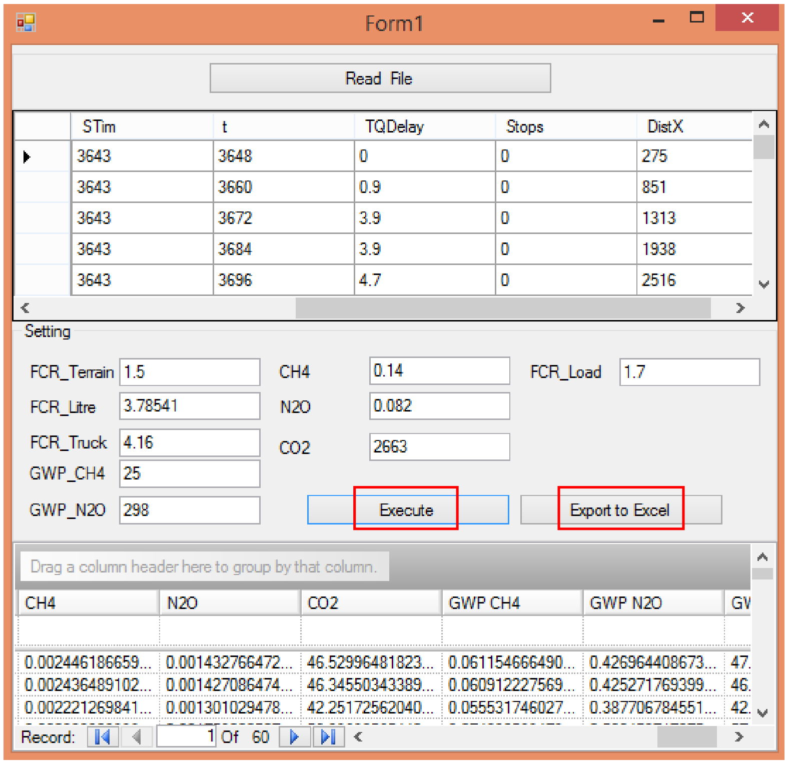
As mentioned above, the *"1.txt"* file needs to be reorganized for phase 2 calculations. The VISSIM output file is a data table format with different columns. Each column represents the data collected for each selected parameter. VISSIM generates the results (the selected parameters for each GHGV or EHGV) at specific time intervals (e.g. every 20 seconds), called as simulation time step. These results correspond to the time that the truck exists in the micro-simulation network. Moreover, The VISSIM output file includes these results for all the trucks and they are not in specific order. The records for a single truck can be distinguished with a parameter called *'STim'* [Start time (simulation second)]. This parameter shows the time that each truck entered the network in seconds. The *'STim'* value is unique for each truck during each micro-simulation analysis (run). Data required for phase 2 calculations were mainly the maximum-recorded values before the truck leaves the network. In some cases, the average for all the records was needed, e.g. the cruise speed (*'vTheo'*). For the defined GHGVs and EHGVs, the required data show the cumulative record for a specific route that each truck was travelling through prior to leaving the micro-simulation network. A macro was needed to pull out the required data for each truck. The reorganization part in the estimator tool performs as a macro inside the program, it extracts the required data and places them under specified columns created in the previous step. It uses the *'STim'* value to distinguish data recorded for each EHGV or GHGV. Table 4.4 shows VISSIM output parameters and specifies which record was extracted in the reorganization step to be used in phase 2 calculations.

Table 4-4 Data extracted from the VISSIM output file in the reorganization step

VISSIM Parameter	VISSIM Description	Indication	Required Record
'STim'	Start time (simulation second)	Simulation second that the truck entered the network Unique ID: *"Stim"*	Similar pick one
'Type'	Number of the vehicle type	Vehicle type: *"Type"*	Similar pick one 1= EHGV 2= GHGV
'vTheo'	Theoretical speed [mph] without obstructions	Cruise speed	Average of the records Cruise speed (mph): *"Average_of_Vtheo"*
't'	Simulation Time [s]	t minus the STim shows the trucks travel time	Max record Duration (s)= insert [max of *'t'* values – *'STim'* value]
'TQDelay'	Difference from optimal drive time [s]	Idling	Max record Idling (s)= insert max of *'TQDelay'* values
'Stops'	Total Number of Stops	Number of stops	Max record Number of stops= insert max of *'Stops'* values
'DistX'	Total Distance Traveled in the Network [ft]	Distance	Max record Distance (mile)= insert max of *'DistX'* values

4.2.2. Calculations

The reorganized data needs some unit conversion to be prepared for phase 2 calculations (Equation 3.2, 3.3 and 3.4). Afterwards, the data are ready to be plugged in the equation coefficient formulas (Equation 3.3 and 3.4) and the selected Fuel Consumption Model (FCM) (Equation 3.2) to obtain the initial Fuel Consumption Rate (FCR), which is in gallons (see Figure 3.3 and Section 3.1.2). After converting the initial FCR form gallons to litres, the estimator tool applies the adjustment factors to the initial FCR and computes the adjusted FCR (see Figure 3.3 and Section 3.1.3). The fuel consumption conversion factor, vehicle type and load adjustments and the percentage of the road gradient are not limited to the values determined in the current study (see Chapter 3: Methodology) and can be changed through the interface window as shown in Figure 4-10. Finally, the tool estimates the GHG emission rates and the GWPs for each truck. Emission factors for the GHGs and the GWP factors are also not limited to the values that are used in the current study and can be changed through the interface window (see Figure 4-10). All the steps except, reading the VISSIM output file, are performed by entering the corresponding values to the input boxes of the estimator tool and executing as shown in Figure 4-10. Table 4-5 shows the entry data that can be changed through the interface window. The output file of the estimator tool can be reached through bottom of the interface window. It also can be saved in excel file format by using the Export to Excel button (see Figure 4-10). The output of the estimator tool is a data table that includes the following for each truck: GWP, adjusted FCR, initial FCR, travel time, distance, number of stops, idling, cruise speed and estimated data for all the other existed variables shown in the flowchart (Figure 4-8).



STim	t	TQDelay	Stops	DistX
3643	3648	0	0	275
3643	3660	0.9	0	851
3643	3672	3.9	0	1313
3643	3684	3.9	0	1938
3643	3696	4.7	0	2516

FCR_Terrain 1.5
CH4 0.14
FCR_Load 1.7
FCR_Litre 3.78541
N2O 0.082
FCR_Truck 4.16
CO2 2663
GWP_CH4 25
GWP_N2O 298

CH4	N2O	CO2	GWP CH4	GWP N2O	GV
0.002446186659...	0.001432766472...	46.52996481823...	0.061154666490...	0.426964408673...	47.
0.002436489102...	0.001427086474...	46.34550343389...	0.060912227569...	0.425271769399...	46.
0.002221269841...	0.001301029478...	42.25172562040...	0.055531746027...	0.387706784551...	42.

Figure 4-10 Reorganization and computation performed by the estimator tool

Table 4-5 The inputs of the estimator tool

Entry Boxes	Description	Default Value
FCR_Terrain	Percentage of the road gradient	1% (see Table 3.2)
FCR_Litre	Fuel consumption conversion unit	3.78541 (gallons to litres)
FCR_Truck	Vehicle type adjustment	4.16 (see Table 3.1)
FCR_Load	Load adjustment	1.9 (see Table 5.2)
GWP_CH_4	CH_4 GWP factor	34(see Table 3.5)
GWP_N_2O	N_2O GWP factor	298 (see Table 3.5)
CH_4	CH_4 emission factor	0.11 (see Table 3.4)
N_2O	N_2O emission factor	0.151(see Table 3.4)
CO_2	CO_2 emission factor	2663 (see Table 3.3)

4.3 Summary

This chapter explained the steps to develop a static traffic micro-simulation network using VISSIM. Moreover, this chapter described the data required to complete each step and their sources. Generally, when developing a traffic micro-simulation network, the goal is to have acceptable results for the real world using the virtual environment. Therefore, it is beneficial to keep the real-world characteristics in the simulated network as much as possible. Being detail oriented and obtaining data from related sources help to improve the accuracy of the developed micro-simulation network. The micro-simulation network of S.E. Calgary was developed in this chapter to implement phase 1 of the EEM. The GHG emission estimator tool was developed according to the flowchart shown in Figure 4-8. This tool reads the VISSIM output file and implement phase 2 of the EEM. Figure 4-7 shows the interface window of the estimator tool. The micro-simulation network of S.E. Calgary is used to conduct a real-world case study in Chapter 5. Chapter 5 provides detail about the case study and the results after implementing phase 1 using the developed traffic micro-simulation network and phase 2 using the programmed estimator tool. A comparison between results from the developed EEM and real on-road measurements are presented in Chapter 5.

CHAPTER 5: CASE STUDY

5.1 Lafarge Concrete Delivery Project

In order to examine the accuracy of the GHG Emission Estimation Methodology (EEM), South East (S.E.) Calgary was selected to implement a real-world case study in collaboration with the Lafarge Cement Company. Lafarge is the largest construction material supplier in North America. It mainly produces cement, ready-mix concrete, aggregates and gypsum. This company follows specific CO_2 reduction commitment to make environmental improvements for the society. They established strategies to reduce energy consumption including “No Idling” rule for ready-mix concrete delivery trucks (Lafarge 2014). The Lafarge manufacturing plant and the construction site locations that were used for the case study are as following:

Manufacturing Plant: *Foothills - 285135 Duff Drive, Rocky View County, AB*

Construction Site: *Quarry Park - 505 Quarry Park Boulevard S.E. Calgary, AB*

Figure 5-1 shows the picture map from the Google Maps, which was used as the background image to develop S.E. Calgary traffic micro-simulation network in Chapter 4. The manufacturing plant and the construction site are tagged in the figure.

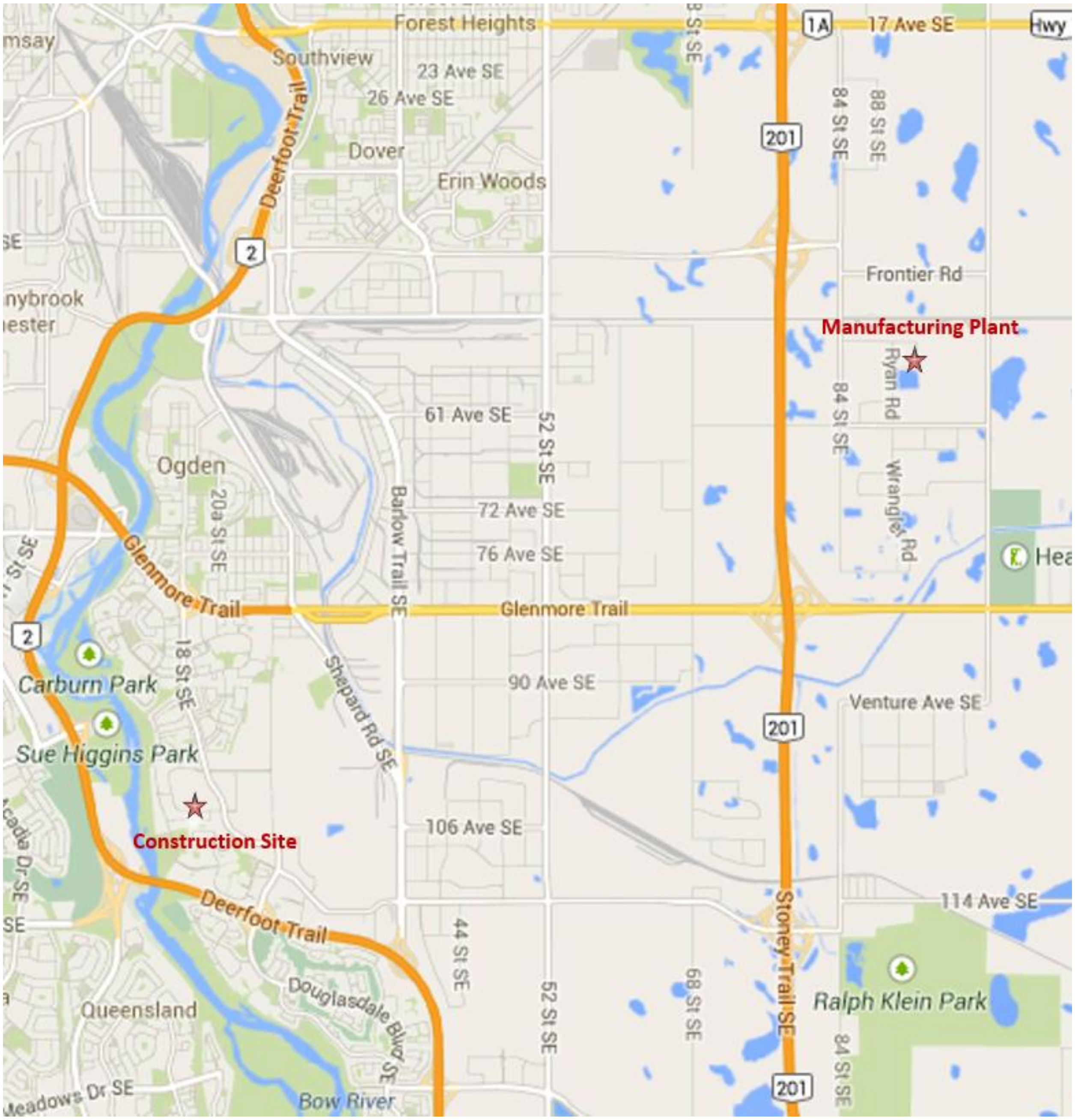


Figure 5-1 Background image used to develop the S.E. Calgary traffic micro-simulation network with labeled manufacturing plant and construction site locations

Figure 5-1 pictures entry of the Foothills manufacturing plant, cement batchers and the ready-mix trucks. The batch plant starts loading early in the morning to be able to deliver the orders on time. It takes nearly 1.5 hours for a specific ready-mix truck to get the first load and be ready to leave the batch plant. Figure 5-3 shows Quarry Park construction site, while construction workers pouring the concrete with the concrete pumpers. As mentioned in chapter 4, the developed traffic micro-simulation network consists of an eight-hour simulation representing 8:00 a.m. to 4:00 p.m. This network was developed to capture the traffic flow during a.m., noon and p.m. off-peak hours in S.E. Calgary. Through communications with the manager of the manufacturing plant, it was learned that the suppliers avoid delivery during rush hours since the ready-mix concrete has to be delivered within an hour of mixing. If forced to deliver during rush hours, drivers will try to avoid the traffic and take routes with lower traffic congestion. Similarly, Lafarge has a one-hour travel time cut off, from the manufacturing plant to the construction site location, for accepting new orders. Consequently, simulation output data were collected from the smallest traffic congestion (off-peak period), which belongs to 9:00 a.m. until 3:00 p.m. However, simulating extra two hours, which are 8:00 a.m. and 4:00 p.m. periods, will warm up the micro-simulation network before the delivery trucks (GHGV and EHGV) enter and let them end up at their destination.


a) Main entry of the Lafarge Foothills manufacturing plant

b) Batchers discharging concrete mixture

c) Concrete trucks waiting to load their first delivery early in the morning (7 a.m.)

d) Foothills plant main building and the batchers

Figure 5-2 Foothills ready-mix concrete manufacturing plant

Figure 5-3 Quarry Park construction site

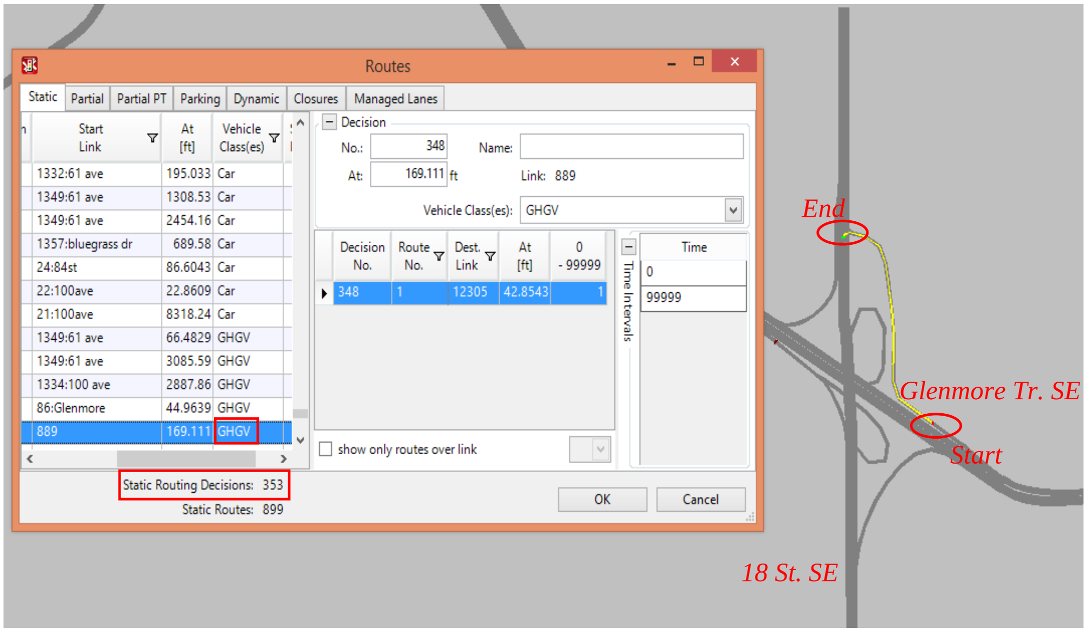
Two experiments were done in the case study to validate the developed micro-simulation network and the proposed EEM. In experiment 1, on-road measurements were compared with the output of the micro-simulation to determine the accuracy of the developed micro-simulation network of the S.E. Calgary truck routes. In experiment 2, a field study was conducted between Foothills manufacturing plant and Quarry Park construction site. During the field study, on-road measurements were collected by travelling with Lafarge ready-mix truck while it was delivering ready-mix concrete between the aforementioned locations. Then, the on-road measurements were compared to the results from the proposed EEM. Experiment 1 and experiment 2 are described in the following sections.

5.1.1 Experiment 1

An alternative route between Foothills manufacturing plant and Quarry Park construction site was selected. GHG emissions for this route were calculated using the developed EEM, to be discussed in Section 5.3.3. The route was picked based on the Google Maps direction suggestions and will be referred to as route 1 in this study. Figure 5-4 shows route 1 in the S.E. Calgary traffic micro-simulation network.

Figure 5-4 Route 1 in the S.E. Calgary micro-simulation network

S.E. Calgary micro-simulation network was customized and run specifically for route 1. In the customized micro-simulation for route 1, certain number of GHGVs flow to the network by setting a Vehicle Input at the Foothills manufacturing plant entry (see Figure 5-4). Appropriate Routing Decisions and Direction Decisions were set for the GHGVs to direct these vehicles through the distinguished route in Figure 5-4, which travels through Foothills, 100 St., Glenmore Tr., 18 St. S.E. and gets to the Quarry Park. Figure 5-5 shows one of the Routing Decisions set for the GHGVs in the delivery route (when the truck is fully loaded) of the route 1 to steer the GHGVs to turn right on 18 St. S.E. from Glenmore Tr. S.E. Nineteen Routing Decisions in combination with a number of Direction Decisions were set to control the GHGVs movement in the micro-simulation network. Another Vehicle Input was set at the Quarry Park construction site to send out the EHGVs to the micro-simulation network. Thirteen defined Routing Decisions and a number of Direction Decisions navigate the EHGVs through the return route (when truck is empty) of the route 1. Data for route 1 also were collected by travelling through this route with a passenger car. The output from the micro-simulation for route 1 is compared with the on-road measurements in Section 5.3.



Start Link	At [ft]	Vehicle Class(es)
1332:61 ave	195.033	Car
1349:61 ave	1308.53	Car
1349:61 ave	2454.16	Car
1357:bluegrass dr	689.58	Car
24:84st	86.6043	Car
22:100ave	22.8609	Car
21:100ave	8318.24	Car
1349:61 ave	66.4829	GHGV
1349:61 ave	3085.59	GHGV
1334:100 ave	2887.86	GHGV
86:Glenmore	44.9639	GHGV
889	169.111	GHGV

Static Routing Decisions: 353
Static Routes: 899

Decision
No.: 348
Name:
At: 169.111 ft
Link: 889
Vehicle Class(es): GHGV

Decision No.	Route No.	Dest. Link	At [ft]	0 - 99999
348	1	12305	42.8543	1

☐ show only routes over link

Time Intervals

Time
0
99999

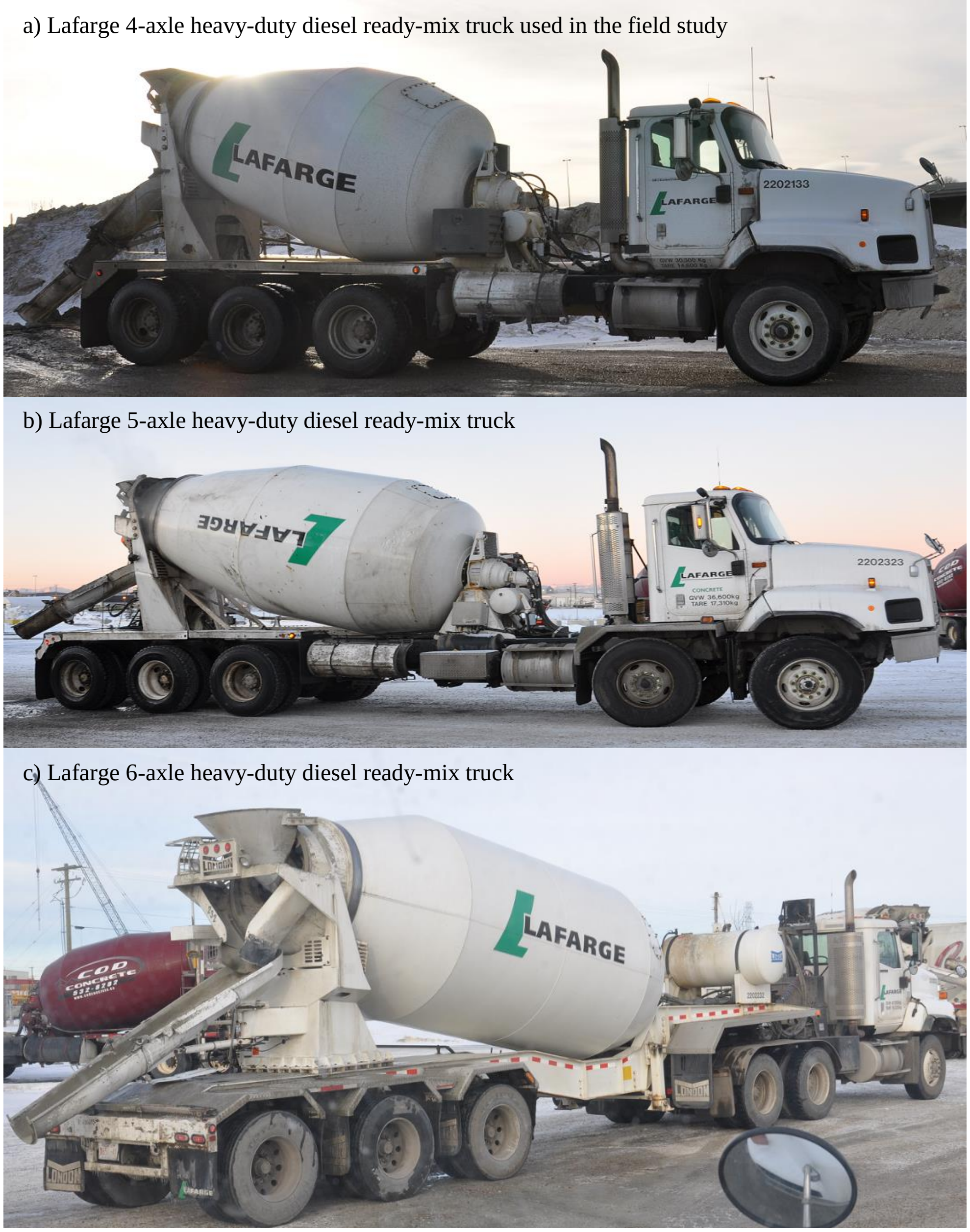
Figure 5-5 Sample of a routing decision that directs GHGVs through route 1

5.1.2 Experiment 2

A field study was conducted by travelling with Lafarge ready-mix truck when the truck was delivering ready-mix concrete between Foothills manufacturing plant and Quarry Park construction site. Heavy Duty Diesel Vehicles (HDDV) observed at Foothills manufacturing plant doing the ready-mix concrete delivery are presented in Table 5.1 and the following figure pictures these HDDVs (Figure 5-6). Personal communication with Lafarge employees also confirmed that these three HDDVs are typical trucks that Lafarge is using to deliver ready-mix concrete. The age of the trucks is ranged between 2004 and 2013 and usually they will be retired after 10 years of delivery. The field study was done by travelling with a 4-axle HDDV, 2004 model year and therefore, the characteristics of the proposed EEM were defined based on the Lafarge 4-axle ready-mix truck: e.g. GHGV weight distribution and the load adjustment factor. Defined weight distribution for 4-axle ready-mix truck can be seen in Figure 4.3 and the calculated load adjustment factor for Lafarge HDDVs is shown Table 5-2.

Table 5-1 Typical ready-mix concrete HDDVs in the case study

HDDV	Brand	Fuel	GVW (ton)	Load Capacity(ton)	Empty Weight(ton)
4-axle	International	Diesel	30.3	14.6	15.7
5-axle	International	Diesel	36.6	17.31	19.29
6-axle	International	Diesel	47.1	19.32	27.78



a) Lafarge 4-axle heavy-duty diesel ready-mix truck used in the field study

b) Lafarge 5-axle heavy-duty diesel ready-mix truck

c) Lafarge 6-axle heavy-duty diesel ready-mix truck

Figure 5-6 Typical HDDVs used to deliver ready-mix concrete

Table 5-2 Load factor calculations for the HDDVs

HDDV	GVW (ton)	Load Capacity (ton)	Empty weight (ton)	Empty FCR (L/km)	Fully Loaded FCR(g/mile)	Load Factor	FCR Increase
4-axle	30.3	14.6	15.7	15.7tons×0.015L/ton-km = 0.23 L/km	30.3tons×0.015 L/ton-km = 0.45 L/km	1.9	93%
5-axle	36.6	17.31	19.29	19.29tons×0.015 L/ton-km = 0.29 L/km	36.6tons×0.015 L/ton-km = 0.55 L/km	1.9	90%
6-axle	47.1	19.32	27.78	27.78tons×0.015 L/ton-km = 0.42 L/km	47.1tons×0.015 L/ton-km = 0.71 L/km	1.7	69%

As can be seen in Table 5-2, the calculated load factor for 4-axle ready-mix truck used in the field study (see Figure 5-6) is equal to 1.9 and shows 93% increase in fuel consumption when the truck is fully loaded. During the field study, the truck driver travelled through another route, which is called route 2 in this study. Similar to the route 1, this route was customized in S.E. Calgary micro-simulation network, and then its GHG emission was estimated using the developed EEM. The estimation from the EEM is compared with on-road measurements from the field study in Section 5.3. Figure 5-7 shows route 2 in S.E. Calgary micro-simulation network.

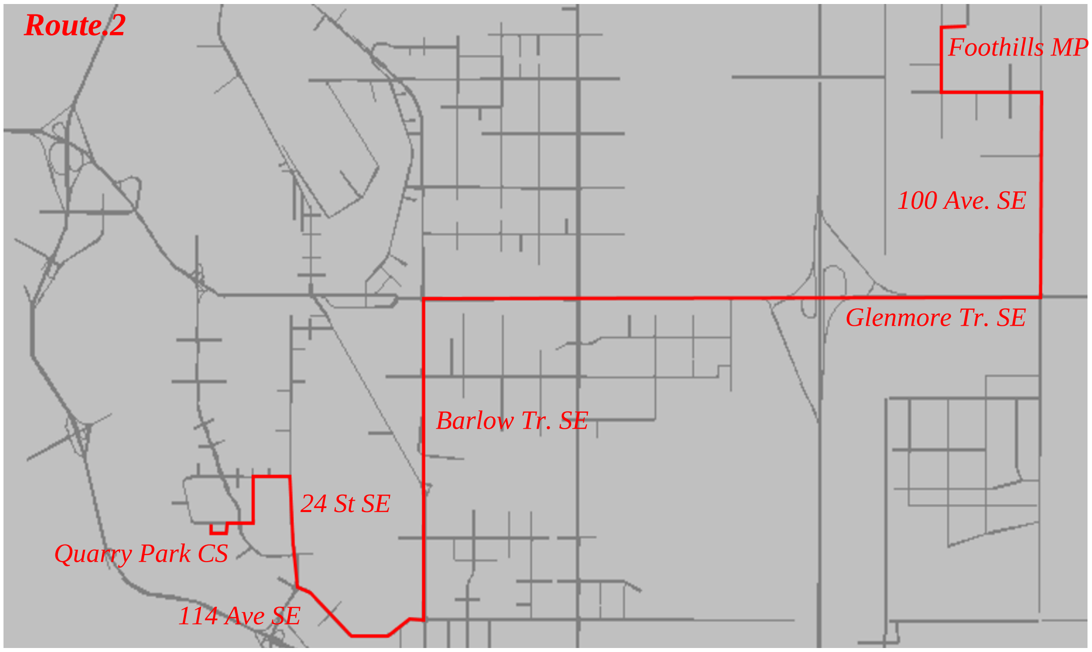
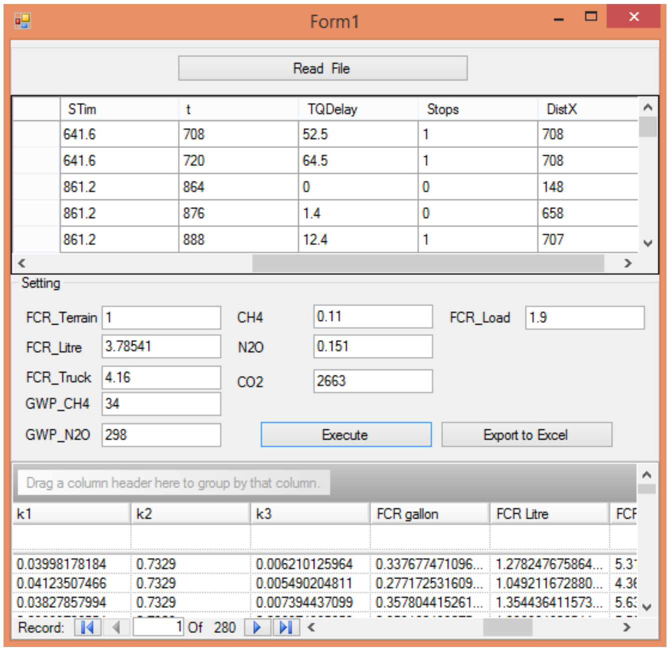


Figure 5-7 Route 2 in the S.E. Calgary micro-simulation network

The emission factor for advance control engine was used, because the truck used in the field study was a 2004 model year HDDV (see Table 3.4). The location of the case study was placed at a flat terrain area, so the terrain percentage entered as one in the estimator tool (see Figure 5-8). Finally, the customized micro-simulation for route 1 and route 2 were multi-run 40 times with 40 different seeds collectively (see Figure 4.8), which took 80 hours to be completed by VISSIM. Random seed provides various input flows from the network entries for each simulation run and leads to different output file data for each run. Running the simulation various times with a certain random seed number leads to identical input flow and identical output data. Therefore, it is beneficial to specify a unique random seed number for each simulation run. Eventually, VISSIM generated 40 output files for route 1 and route 2 to be used as the input file for the estimator tool. Figure 5-8 shows the interface window with determined entries for the current case study.



	STim	t	TQDelay	Stops	DistX
	641.6	708	52.5	1	708
	641.6	720	64.5	1	708
	861.2	864	0	0	148
	861.2	876	1.4	0	658
	861.2	888	12.4	1	707

FCR_Terrain 1
FCR_Litre 3.78541
FCR_Truck 4.16
GWP_CH4 34
GWP_N2O 298
CH4 0.11
N2O 0.151
CO2 2663
FCR_Load 1.9

k1	k2	k3	FCR gallon	FCR Litre	FCF
0.03998178184	0.7329	0.006210125964	0.337677471096...	1.278247675864...	5.3
0.04123507466	0.7329	0.005490204811	0.277172531609...	1.049211672880...	4.3
0.03827857994	0.7329	0.007394437099	0.357804415261...	1.354436411573...	5.6

Figure 5-8 Determined entries for the estimator tool based on the case study

5.2 The EEM Estimations for the Case Study

Beside GHG emission in CO_2 eq., EEM also provides usable values for distance, travel time, number of stops, idling, cruise speed and fuel consumption, which were calculated by the estimator tool. Table 5.3 shows the estimations from the EEM for the delivery route of route 1 and route 2 (referred to as D.route 1 and D.route 2, respectively). Table 5.4 shows the results for the return routes of the two examined routes (R.route 1 and R.route 2). Table 5.5 shows fuel consumptions and GHG emissions for combined delivery and return routes of the route 1 and route 2. The following section compares the results of the developed methodology with real on-road measurements.

Table 5-3 The average of the EEM estimations for the delivery routes

Delivery Route	Distance	Travel time	Number of stops	Idling	Cruise speed	Fuel consumption	GWP (CO_2 eq.)
D.route 1	16.2 km	20 min	5	5 min	66 km/h	17.1 L	46 kg
D.route 2	18 km	23 min	5	5 min	63 km/h	17.4 L	47 kg

Table 5-4 The average of the EEM estimations for the return routes

Return Route	Distance	Travel time	Number of stops	Idling	Cruise speed	Fuel consumption	GWP (CO_2 eq.)
R.route 1	16 km	19 min	6	6 min	72 km/h	10 L	27 kg
R.route 2	18 km	21 min	7	6 min	72 km/h	10.9 L	30 kg

Table 5-5 The average of the EEM estimations for combined delivery and return routes

Route	Distance	Travel time	Number of stops	Idling	Cruise speed	Fuel consumption	GWP (CO_2 eq.)
Route 1	32.2 km	39 min	11	11 min	69 km/h	27.1 L	73 kg
Route 2	36 km	44 min	12	11 min	68 km/h	28.3 L	77 kg

5.3 Comparing Method Results with On-Road Measurements

The author conducted the on-road measurements to validate the output data from the micro-simulation and the EEM estimations. On-road measurements for route 1 were collected by driving through this route with a passenger car. Data for route 2 were collected by travelling through route 2 with Lafarge 4-axle ready-mix truck (see Table 5-9), while the truck were delivering ready-mix concrete between Foothills manufacturing plant and the Quarry Park construction site as shown in Figure 5-7. Experiment 1 was used to identify the accuracy of the developed micro-simulation network of the S.E. Calgary and experiment 2 was used to identify the accuracy of the developed methodology (EEM).

5.3.1 Experiment 1: Micro-Simulation Output Comparison

In experiment 1 the output of the developed micro-simulation network was compared with the on-road measurements. The data was collected by taking 12 trips with a passenger car through route 1 (six trips on D.route 1 and six trips on R.route 1). Data related to 6 trips (rout 1) were gathered on November 23th, 2013 from 11:00 a.m. to 1:36 p.m. and the remainder of the trips for rout 1 were collected on November 24th, 2013 from 10:46 a.m. to 1:00 p.m. These data were gathered during the weekend. Therefore, to perform a valid comparison, the difference between weekend traffic and Annual Average Weekday Traffic (AAWT) was added to the developed micro-simulation network. Based on a study on the difference between weekday and weekend traffic volume in Calgary, Saturday traffic is 78% of the AAWT and Sunday traffic is

64% of the AAWT (Hunt and Atkins 2003). Therefore, the traffic flow of the micro-simulation was decreased by 30% to represent the weekend traffic.

Statistical analysis was conducted to compare the collected on-road measurements and the micro-simulation output. The “t-test” was used to test the equality of the two means and assess whether the means (μ) of the two data sets i.e. on-road measurements and the micro-simulation output, are statistically different from each other. For the t-test, the null hypothesis says that there is no difference in the means of the two data sets:

Null Hypothesis	Ho: $\mu_x = \mu_y$
Alternative Hypothesis	Ha: $\mu_x \neq \mu_y$

The test returns a p-value. At 95% confidence ($\alpha = 0.05$), if the p-value < α the Ho will be rejected, otherwise (p-value >α) this test fails to reject the null hypothesis (Ho). Microsoft Excel was used to run the t-test between on-road measurements and the micro-simulation output. The calculated p-values and the test results are indicated under the “p-value” and “t-test Results” at the far left columns of Table 5-6. This table also presents the difference (error) between on-road measurements and the output from the developed micro-simulation network.

Table 5-6 Comparison between the results from the developed micro-simulation network and on-road measurements (route 1)

Parameter	Range [Min, Max]		Average			p-value ($\alpha = 0.05$)	t-test Results
	Simulation	On-road	Simulation	On-road	Error		
Number of trips	-	-	1580 (10 seeds)	12	-		
Fuel consumption (L)	-	-	2.3	2.2	-4.5%		
Distance (km)	[15.4, 16.3]	[15, 17]	16	16	0%	$0.30 > \alpha$	Failed to reject
Travel time (minute)	[11.51, 23.13]	[17.13, 22.7]	20.18	19.5	-3.5%	$0.12 > \alpha$	Failed to reject
Number of stops	[1, 9]	[3, 8]	4.92	5.41	9%	$0.28 > \alpha$	Failed to reject
Idling (minute)	[1.2, 7.7]	[1.9, 4.22]	4.6	3	-53.3%	$0.00000039 < \alpha$	rejected

As can be seen in the table, the results from the micro-simulation show a very good correlation to the on-road measurements in terms of distance (0% error), travel time (−3.5% error), and the number of stops (9% error). For the aforementioned parameters, the t-test failed to reject the hypothesis that the mean of the micro-simulation output is equal to the mean of the on-road measurements ($\mu_x = \mu_y$). Since the p-value is greater than $\alpha = 0.05$ for distance, travel time and the number of stops, therefore, it cannot be concluded that the two data sets are different. For idling, the calculated difference (−53.3% error) is higher than that for the other parameters and the t-test rejected the hypothesis that the means of the two data sets are equal. Despite the difference between micro-simulation output and on-road measurements for idling, the difference between the fuel consumption of the two, is insignificant (−4.5% error). It should be reminded that the “simulation” fuel consumption was calculated using Equation 3.2 and the “on-road” fuel consumption was recorded from the fuel gauge of the passenger car. The reason behind this insignificant difference (−4.5% error) can be attributed to the minor role of idling in total fuel consumption for regular trips where the majority of time is spent on cruising. The fuel consumption for cruising, acceleration/deceleration and idling were separately calculated for experiment 1 (using equation 3.2) as shown in Figure 5.9.

As can be seen in the figure, cruising and the acceleration/deceleration phases have greater fuel consumption values than the idling phase. Considering the average values, the share of the cruising phase is six times higher than the idling phase. Similarly, the fuel consumption from the acceleration/deceleration phase is two and a half times higher than that for the idling phase. Therefore, despite the relatively high error for the idling values, this indicator does not have a significant impact on calculating the fuel consumption in comparison to the distance and the number of stops.

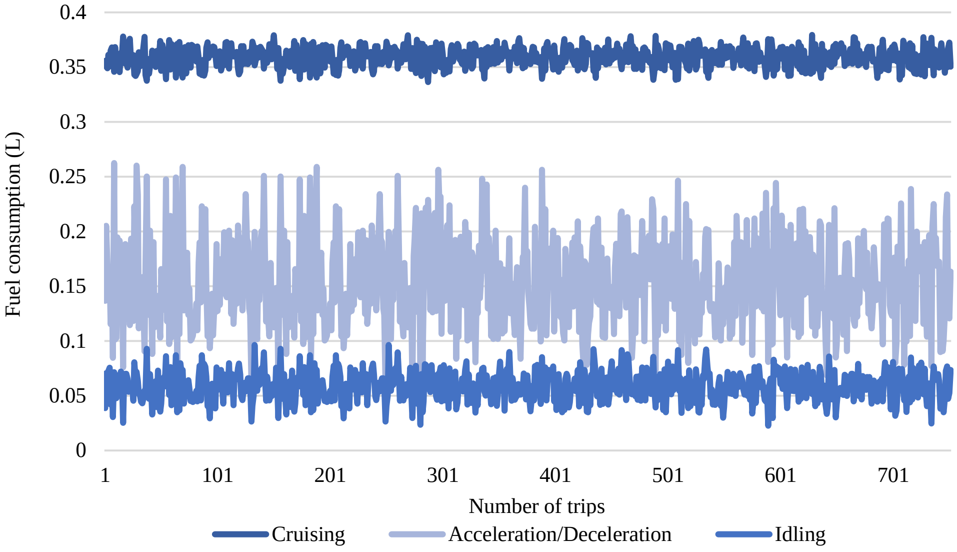


Figure 5-9 Fuel consumption for D.route 1 as separated by cruising, idling and acceleration/deceleration phases

5.3.2 Experiment 2: EEM Estimation Comparison

To examine the reliability of the developed EEM, its results were compared with on-road measurements. The on-road measurements were collected by travelling with a Lafarge HDDV while it was delivering the ready-mix concrete from Foothills manufacturing plant to the Quarry Park construction site on January 23rd, 2013, from 7:29 a.m. until 4:29 p.m. Figure 5-6a shows the 4-axle HDDV that used in the field study and Table 5.1 shows characteristics of the truck. It started the delivery at 8:40 a.m., it travelled through D.route 2 two times while it was fully loaded and once while it had 30% load. The truck travelled through R.route 2 three times while it was empty and it finished the delivery for that day at 3:53 p.m. The truck experienced half an hour idling at manufacturing plant to load the delivery and half an hour idling at the construction site to pour the ready-mix concrete at the start and end of each trip, respectively. The truck started with full fuel tank, it travelled 102 km and consumed 100.38 L diesel fuel by the end of the measurement period (see Figure 5-10).

Figure 5-10 Fuel consumed by the HDDV used in the field study

Total load delivered was equal to 15 m^3 ($6.5m^3+6.5m^3+2m^3=15m^3$), which is equivalent to 34.5 tons ready-mix concrete. To perform a comparison with EEM estimations fuel consumed by the truck in L/km is calculated and shown in Table 5-7.

Table 5-7 Fuel consumed by Lafarge HDDV in L/km

VKT(km)	FCR (L)	Load (ton)	FCR (L/km)
102	100.38	34.5	100.38/102= 0.98

The EEM estimations for route 2 were adapted based on the HDDV trip characteristics. Therefore, half hour idling were added to each trip end and one of the data sets estimated with 30% load adjustment factor (see Table 5.8). Table 5-9 compares the results from the EEM and on-road measurements for route 2.

Table 5-8 Estimation of load adjustment factor for 30% loaded HDDV in the field study

HDDV	Full Load Capacity(ton)	30% Load Capacity	Empty weight	Empty FCR	30% Loaded FCR (g/mile)	Load Factor
4-axle	14.6	14.6×0.3 = 4.38 tons	15.7 tons	15.7×0.015 = 0.23 km/h	(15.7+4.38) ×0.015 = 0.3	0.3/0.23=1.3

Table 5-9 Comparison between the EEM estimation and on-road measurements

FCR	EEM	On-road Measurements	Error
FCR(L/km)	1.12	0.98	-14%

A study done by Demir, Bektas and Laporte compared on-road measurements with six different vehicle emission models for road freight transportation (Demir, Bektas and Laporte 2011). The comparison were performed between on-road fuel consumption measurements and fuel consumption calculated by the 6 models under three different conditions (Cond.) of the vehicle weight and average speed (Demir, Bektas and Laporte 2011). Table 5-10 compares accuracy of the EEM estimations with average accuracy from the aforementioned models.

Table 5-10 Comparison between the accuracy of the EEM and accuracy of the similar emission models for road freight transportation (Demir, Bektas and Laporte 2011)

Model	Cond. 1 (%)	Cond. 2 (%)	Cond.3 (%)	Average Error
1. An instantaneous fuel consumption model	25	76	16	39%
2.A four-mode elemental fuel consumption model	6	51	39	32%
3.A running speed fuel consumption model	69	96	82	82%
4.A comprehensive modal emission model	15	42	34	30%
5.Methodology for calculating transportation emissions and energy consumption (MEET)	-37	-22	-31	− 30%
6.Computer programme to calculate emissions from road transportation (COPERT)	-21	-6	-17	− 15%
GHG Emission Estimation Methodology (EEM)				− 14%

As can be seen in the table, EEM and model 6 have better estimations in comparison with the rest of the models. Model 3 has the largest difference (82%) when comparing the results to the on-road measurements. Models 1, 2, 4 overestimate between 30% and 40% and model 5 underestimates close to 30%. Resulting 1% higher accuracy in comparison with model 6, the EEM has the smallest difference with the on-road measurements.

5.3.3 Discussion

Studies show that GHG emissions from the HDDVs can be addressed through technological and behavioural changes. Technological changes focus on the advancement of vehicles and efficient alternative fuels, while research on behavioural changes suggests that travel demand reduction, trip mode conversion, improving load factor levels and limiting the number of empty runs can facilitate reducing the GHG emission from the HDDVs (Leonardi and Baumgartner 2004, Kamakate and Schipper 2009, Yang, et al. 2009, Morrow, et al. 2010, Nazelle, et al. 2010, Nealer, Matthews and Hendrickson 2012). Due to increasing levels of travel demand (VKT), specified targets cannot be achieved by considering technological changes alone (Nealer, Matthews and Hendrickson 2012). Moreover, findings from studies in the road transportation show that changes in travel behaviours are the effective methods for decreasing GHG emissions (Chapman, L 2007, Yang, et al. 2009, Morrow, et al. 2010). Among various methods, route planning has been suggested to reduce emissions from the road transportation since route planning reduces trips with high emission rates (McKinnon 1999, Barth, Boriboonsomsin and Vu 2007, Chapman 2007, Ahn and Rakha 2008, Piecyk and McKinnon 2010). Therefore, route planning can also be applied to the road transportation in the construction sector.

Route planning is one of the capabilities of the developed EEM. Comparing the EEM estimations for routes 1 and 2 (see Table 5.5), shows lower GHGs emitted from route 1. During the field study, the truck took route 2 to deliver the load and emitted 77 kg of CO_2 eq. with 28.3 L fuel consumption. However, the truck could have emitted 4 kg of CO_2 eq. less GHGs and consumed 1.2 L less fuel by taking route 1. To put the importance of route planning in perspective, thirty-seven (37) trucks were working on the day of the field study and each of them delivered at least three loads, which led to 37×3= 111 trips on that day. In this case, route planning would lead to save 111×1.2= 133.2 L fuel and emit 111×4= 444 kg of CO_2 eq. lower GHGs for one day of delivery at Foothills manufacturing plant. These savings become important when considering the number of manufacturing plants in Calgary and at national level.

Based on the findings from this study, the traffic parameters contributing to GHG emission from road transportation can be named as the number of stops, idling and the cruise speed. Figure 5-11, Figure 5-12 and Figure 5-13 show the relationship between GHG emissions and the above parameters from 2,800 simulated trips for delivery routes (D.route) and return routes (R.route) of the routes 1 and 2. As shown in Figure 5-11, the number of stops is positively correlated with the GHG emissions. This is also suggested by Rakha and Ding 2003 that higher number of stops leads to higher levels of GHG emissions. The aggressiveness of the vehicle stop also affects the GHG emission rates positively. Stopping aggressively causes higher acceleration/deceleration levels, which leads to higher fuel consumption and GHG emissions (Rakha and Ding 2003).

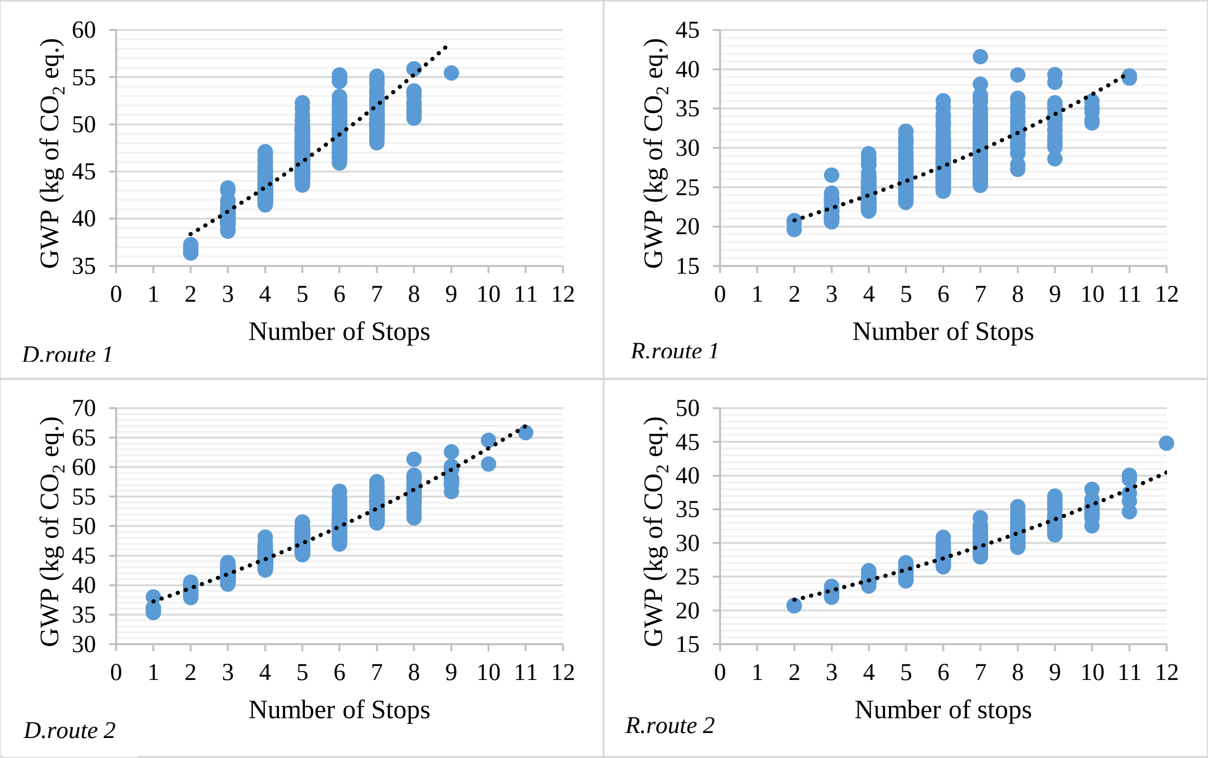


Figure 5-11 Relationship between GHG emissions (kg of CO_2 eq.) and the number of stops

As illustrated in Figure 5-12, idling showed direct relationship with GHG emissions as suggested by previous studies (Zhang, Batterman and Dion 2011, Davis, et al. 2013). Despite the fact that the lowest average fuel consumption happens during the idling phase (see Figure 5-9), idling becomes important when it comes to delivering the construction materials. For instance, during the field study, the ready-mix concrete truck experienced half an hour idling at the manufacturing plant to load the delivery and half an hour idling at the construction site to pour the ready-mix concrete (see Section 5.3.2). Adding half an hour idling at the manufacturing plant to the fuel consumption of the truck from travelling through D.route 2 (see Table 5-3), changed the FCR from 17.4 L to 28.5 L. In this case, idling increased the FCR by 64% for D.route 2.

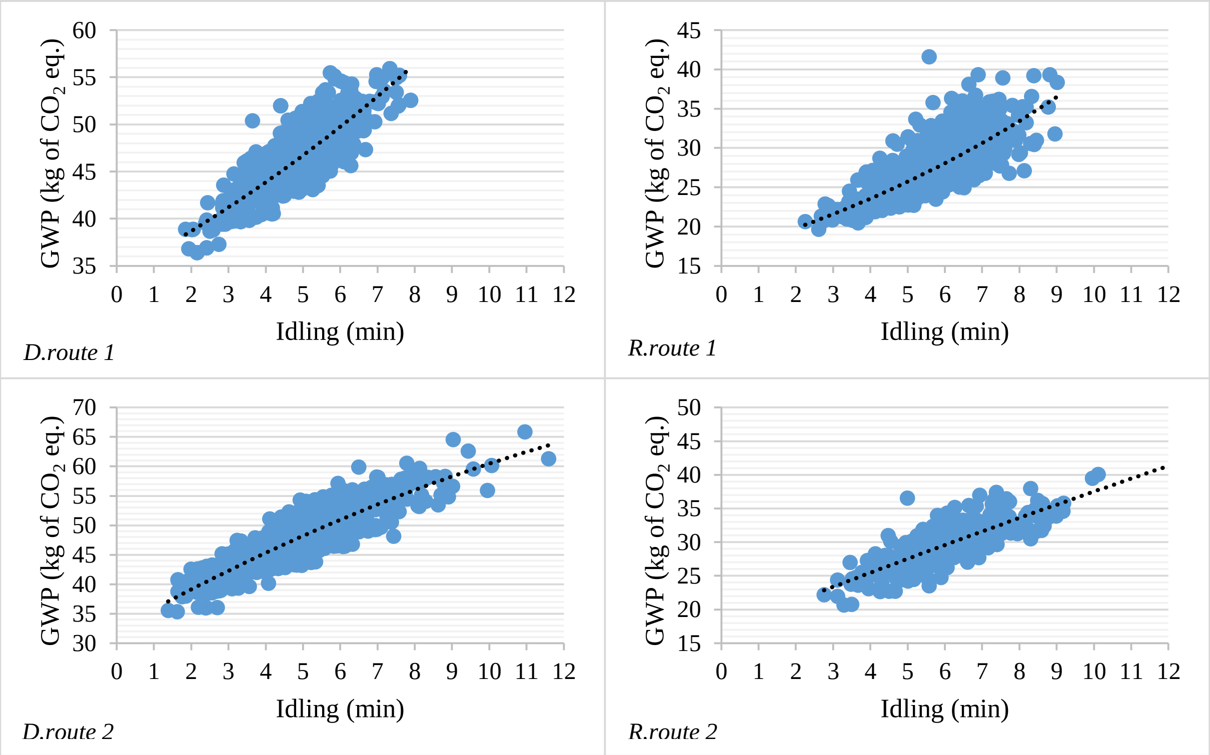


Figure 5-12 Relationship between GHG emissions (kg of CO_2 eq.) and idling (minute)

The relationship between cruise speed and GHG emission cannot be identified from data available in this study, as shown in Figure 5-13. Previous studies suggest that there is an optimum fuel economy as the vehicle travels within a specific speed range and speeds below or above this range waste the energy with no benefit (El-Shawarby, Ahn and Rakha 2005, Wang, et al. 2008, Abou-Senna and Radwan 2013). The fuel consumption is high when the cruising starts, because the vehicle's drive train is not optimized for low speeds. Fuel consumption decreases as the vehicle speed rises to the optimum speed range. The fuel consumption increases again as the speed passes the optimum speed range because aerodynamic drag increases. The GHG emissions also changes with the same pattern. Therefore, graphing GHG emissions versus speed would give a convex curve; with the bottom of the curve showing the optimum speed range (see Section 2.2.3). In Figure 5-13, speed changes between 85 km/h to 95 km/h for trips taken over routes 1 and 2. Therefore, these graphs show only a partial picture of the relationship between GHG emissions and speed. Fuel consumption at speeds lower than 85 km/h and higher than 95 km/h are needed to show the whole picture of the aforementioned convex curve. For HDVs, the fuel consumption is optimum at speeds under 113 km/h (Franzese and Davidson 2011). Therefore, graphs showed in Figure 5-13 may only present the bottom part of the curve and requires more experiments to be conducted to show the relationship between fuel consumption and GHG emissions with speed completely.

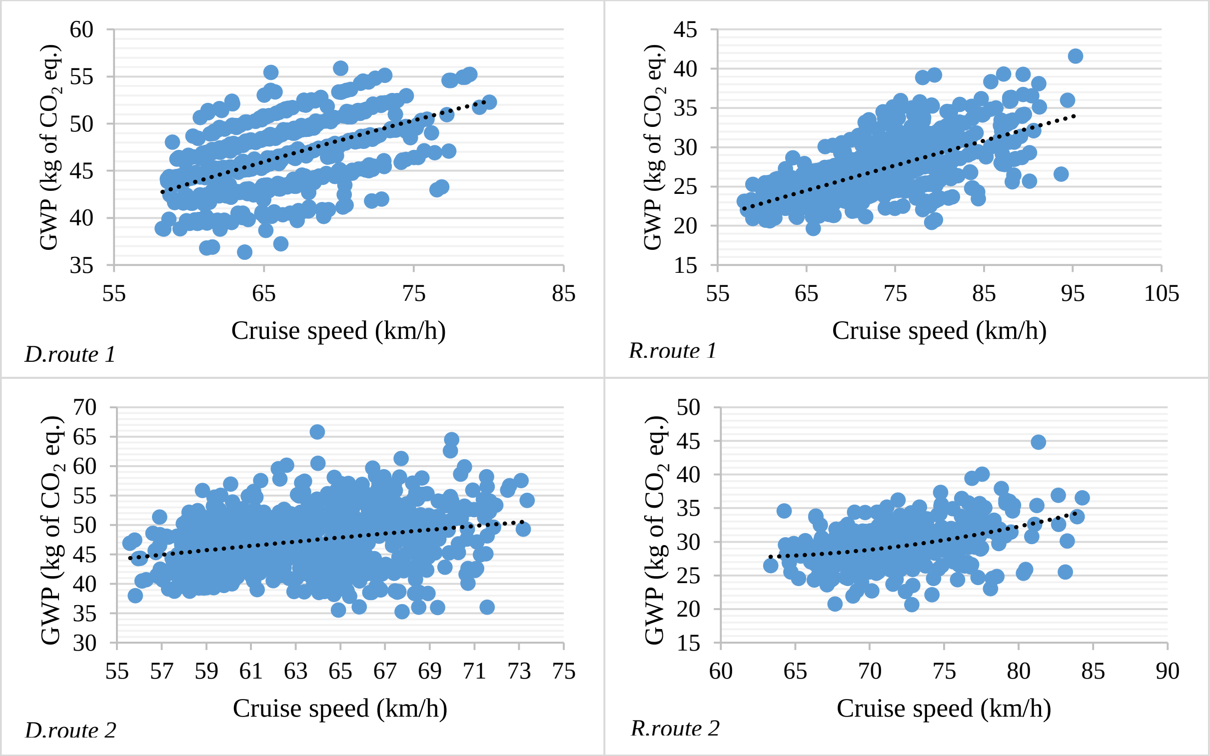


Figure 5-13 Relationship between GHG emissions (kg of CO_2 eq.) and cruise speed (km/h)

5.4 Summary

A real-world case study was conducted to validate the developed micro-simulation network of S.E. Calgary and the proposed EEM. The case study was one of the Lafarge concrete delivery projects in S.E. Calgary. An alternative path between Foothills plant and Quarry Park site was selected, named route 1. This route was simulated in the S.E. Calgary micro-simulation network. Moreover, on-road measurements for route 1 were collected by travelling through this route with a passenger car. Then, the micro-simulation output were compared with on-road measurements, which confirmed reliability of the developed network. A field study was conducted by travelling with Lafarge ready-mix truck. The truck was delivering ready-mix concrete to the Quarry park construction site. It was a 2004 model, 4-axle HDDV with 6.5 m^3 (14.6 tons) load capacity and Gross Vehicle Weight (GVW) of 30.3 tons. During the field study, the truck travelled through another route, which was named route 2. Similar to route 1, route 2 was simulated in the developed micro-simulation network. Next, the estimator tool used the simulation output to estimate the fuel consumption for route 2. The fuel consumption from the field study and the developed EEM were compared in Section 5.3. The EEM shows an average difference of -14% with the on-road measurements. Comparing the EEM accuracy with other similar models shows that except COPERT with -15% difference, the other models showed lower accuracy with an error greater than ± 30%. An example of route planning was explained to show capabilities of the developed EEM. Graphing GHG emission verses number of stops and idling showed direct relationship between these parameters. Moreover, the available data for routes 1 and 2 show the relationship between GHG emissions and speed changes partially. Further research is needed to verify the identified relationships.

CHAPTER 6: CONCLUSION

6.1 Summary of the Work

A detailed parametric review of the existing GHG emission calculators revealed that, currently there is no calculator, which is capable of tracking the GHG emissions for individual trucks. The objective of this study was to develop a simple approach for estimating GHG emissions from HDDVs used in construction road transportation in the construction sector. A methodology was developed to calculate GHG emissions from individual delivery trucks in urban areas. To develop the methodology, indicators that affect GHG emissions from the vehicle operation were identified from the literature review. This study used 15 indicators, namely: location, Vehicle Kilometres Travelled (VKT), fuel consumption, vehicle type, fuel economy, fuel type, vehicle load, vehicle model year, traffic condition, driving condition, engine situation (cruising, idling acceleration/deceleration), speed, number of stops, road gradient and road type.

The developed methodology consisted of two phases. First phase used traffic micro-simulation to capture the impact of six of the aforementioned indicators; i.e. traffic and driving conditions, speed, number of stops, VKT and road type. The output of this phase includes VKT, speed, idling and number of stops. This output was then used in the second phase to calculate an initial Fuel Consumption Rate (FCR). The impact of the remainder of the indicators; i.e. location, engine situation, fuel consumption, vehicle type, fuel economy, fuel type, vehicle load, vehicle model year and road gradient was captured in this phase. Based on the proposed methodology, a GHG emission estimator tool was developed in Visual Studio programming environment. The estimator tool takes the output data from the traffic micro-simulation, reorganizes the data (as they cannot be used in the format and structure that is generated by the micro-simulation) and calculates the GHG emissions for each HDDV.

To examine the reliability and capabilities of the developed methodology as well as the micro-simulation network, a real-world case study in S.E., Calgary, AB, was conducted. Two experiments were carried out on this case study. The first experiment was conducted to examine the reliability of the developed micro-simulation network. Experiment 2 examined the reliability and capabilities of the developed methodology. To examine the reliability of the traffic micro-simulation network, data on fuel consumption, VKT, travel time, number of stops and idling were collected; by traveling through a specific route with a passenger car. The on-road measurements were then compared with the micro-simulation output for the same route. The developed micro-simulation showed a good approximation of the reality (0% error for distance, −3.5% error for travel time, 9% error for number of stops. The error found for idling was relatively high (−53.3%), however, as it was shown it did not affect the overall calculation of the fuel consumption rate. In experiment 2, on-road measurements for fuel consumption, idling for loading and unloading, and VKT were recorded by travelling with an actual ready-mix truck. The truck carried ready-mix concrete between Lafarge Foothills manufacturing plant and a construction site located at Quarry Park community in South East (S.E.) Calgary. The measurements from this experiment were compared with the estimations made using the developed methodology. The estimations from the developed methodology showed −14% difference with the on-road measurements. Considering that the error from similar methods in the literature ranges from −15% to +82% (with the majority of them being between 30% and 40%). The error of the developed methodology can be considered reasonable.

6.2 Contribution

This study developed a GHG Emission Estimation Methodology (EEM). The developed methodology calculates GHG (CO_2, CH_4 and N_2O) emissions for an individual HDDV, while it is delivering the construction materials between the manufacturing plant and the construction site.

Measuring the GHG emission of a single truck is important in construction material transportation, as it can help in individual route planning for the vehicle’s repeated trip from the manufacturing plant to the construction site. Route planning limits the number of trips over the routes with high GHG emission rates. For example, a ready-mix concrete supplier such as Lafarge delivers around 18000 orders per year and these orders need between 1 to 40 loads of concrete delivery per day. The number of trips required to deliver these orders is equal to 50000 deliveries per year. In the case study, the delivery truck consumed 28.3 L diesel fuel and emitted 77 kg of CO_2 eq. by travelling through route 2. However, route 1 was an existing route between the same locations with lower fuel consumption rate (27.1 L) and lower emission rates (73 kg of CO_2 eq.). Taking route 1, would lead to 1.2 L saving in the fuel consumption and 4 kg of CO_2 eq. less emission.

Assuming this case study as a typical case, these numbers may not be that significant when looking at a single truck, however considering 50000 trips per year would save 1.2L ×50000=60000 L fuel. Applying average diesel price for Calgary in 2013, which is equal to 118.6 ¢/L, shows (60000L×118.6 ¢/L) ÷100=$ 71154 benefit for the construction material supplier (NRCan 2014). Considering average diesel price at the national level (Canada) in 2013 shows $6000 more savings ((60000L×128.5 ¢/L) ÷100=$ 77132) (NRCan 2014).

From an environmental point of view, emitting 4 kg of CO_2 eq. less per trip would lead to (4 kg of CO_2 eq. ×50000) ÷ 1000=200 tons of CO_2 eq. lower emissions annually. Approximately 98 trees are needed to absorb 1ton of CO_2 eq. in a year. Therefore, to offset 200t of CO_2 eq. in a year, 98×200= 19600 trees are needed (T.CA 2005). The estimations from the developed methodology in this study, not only can benefit the construction material suppliers by saving money on fuel consumption, but also, it can protect the environment and increase sustainability in construction road transportation. The developed EEM can contribute to prevent increasing levels of the GHG emission in the transportation sector.

6.3 Limitations

This study did not consider the effect of age, driver behaviour, maintenance, vehicle accessory load, cold start and weather in the development of the EEM. HDDVs used in delivery of the construction materials are usually less than 10 years old. Therefore, the effect of age would not be significant on fuel consumption and GHG emissions (see Section 2.2.1). Driving behaviour is a human related indicator, and therefore, it is hard to quantify its impact in a model. Maintenance and the vehicle accessory load were mentioned in a few studies, as it is difficult to capture the impact of these indicators.

Therefore, these indicators are typically considered as negligible. Cold temperature increases CO_2 emissions slightly (5%) and the weather temperature usually affects GHG emissions indirectly through its impact on vehicle’s accessory load.

6.4 Recommendations for future work

Improving the Developed EEM

- The EEM does not consider the effect of age, driver behaviour, maintenance, vehicle accessory load, cold start and weather. Future research is needed to account for the effect of these five indicators on truck GHG emissions.

Improving the Accuracy of the Input Data for the Developed Micro-Simulation Network

- Updating the assumptions made for missing traffic count and signal summary data would increase the accuracy of the developed micro-simulation network and consequently the estimations of the EEM.

Future Experiments

- The EEM was examined using ready-mix concrete trucks. However, it can be applied to materials with lower prices, for which the cost of the delivery could be more important such as aggregate or transporting rock and soil from excavation.
- The reliability of the EEM was examined through one field study. Conducting more field studies are needed to validate the accuracy of the EEM for variety cases.
- The real-world case study did not allow for consideration of the road gradient, because the slope was between ±1% in area of the case study. Future experiments should be done using an area with varying terrain levels.

Sensitivity Analysis

- The developed EEM suggest that load can increase the fuel consumption of the trucks from 69% up to 93%, which in turn can be translated into similar increase in GHG emission rate. Further research is needed to verify the precise effect of the load on GHG emissions from the trucks.
- The case study used in this study suggested a direct effect between the traffic-related indicators (e.g. idling and number of stops) and GHG emissions. Further research is needed to verify the direct effect of the above indicators on GHG emissions.
- The case study does not suggest any specific relation between the cruise speed and GHG emissions. Therefore, the relation between cruise speed and the GHG emission needs a set of sensitivity analysis to be identified in future research.

Future Development

- Develop a smart route planner using the Geographic Information System (GIS). The route planner would take specified origin and destination and identify optimized route in terms of the environmental impact between the two locations.

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