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Amal Ghamrawi
University of Windsor

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MODELING THE FEASIBILITY AND BENEFITS OF ADOPTING CNG TECHNOLOGY IN TRUCKS: AN APPLICATION TO THE GREATER TORONTO AND HAMILTON AREA

By

Amal Ghamrawi

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MODELING THE FEASIBILITY AND BENEFITS OF ADOPTING CNG TECHNOLOGY IN TRUCKS: AN APPLICATION TO THE GREATER TORONTO AND HAMILTON AREA

by

Amal Ghamrawi

APPROVED BY:

W. Anderson
Department of Political Science

C. Lee
Department of Civil and Environmental Engineering

J. Tofflemire
Department of Civil and Environmental Engineering

H. Maoh, Advisor
Department of Civil and Environmental Engineering

April 2nd, 2018

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ABSTRACT

Heavy-duty commercial vehicles play an integral role in goods movement. Most these vehicles are powered by diesel and are high emitters of pollution in areas with high congestion due to longer travel times and idling. This is concerning from an environmental and social perspectives as diesel exhaust contributes to global warming, has negative health effects and is likely carcinogenic. The use of alternative fuels, like Compressed Natural Gas (CNG), could have the potential to counter these negative effects. However, one of the major drawbacks in fleets transitioning towards CNG is the lack of available refueling infrastructure.

To overcome this obstacle, establishing a natural gas virtual pipeline in the form of a hub-and-spoke network to provide on-site refueling at truck yards via mobile refuelling tractor-trailers is proposed. A basic and transferable framework is established to determine the location of potential hubs. The estimated number of potential CNG trucks per traffic analysis zone is set as the demand to establish the market for CNG fueling. Location-allocation modeling is then used to propose optimal CNG station (i.e. hub) locations.

To quantify the benefits of CNG adoption, traffic flow was predicted and EPA's MOVES software was used to estimate emission factors for diesel heavy-duty trucks under different scenarios of CNG adoption. A Multi-Criteria Decision Analysis was then conducted to determine the potential savings associated with CNG adoption. The results from the conducted analysis suggest that CNG is a more sustainable fuel for heavy duty trucks. Further, one CNG hub is recommended for initial CNG conversion in the study area.

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LIST OF ABBREVIATIONS

AF	Alternative Fuel
AFV	Alternative Fuel Vehicle
APEI	Air Pollutant Emission Inventory
AW	Assigned Weights
CAC	Criteria Air Contaminants
CD	Census Division
CDM	County Data Manager
CMA	Census Metropolitan Area
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalent
CRT	Continuously Regenerating Trap
CVS	Commercial Vehicle Survey
DGE	Diesel Gallon Equivalent
EPA	Environmental Protection Agency
ER	Emission Rate
FTG	Freight Trip Generation
GGE	Gasoline Gallon Equivalent
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GPS	Global Positioning System
GREET® Model	The Greenhouse gases, Regulated Emissions, and Energy Usage in Transportation Model
GTA	Greater Toronto Area
GTHA	Greater Toronto and Hamilton Area
GWP	Global Warming Potential
HC	Hydrocarbons
HDCV	Heavy-Duty Commercial Vehicle
IARC	International Agency for Research on Cancer
IPF	Iterative Proportion Fitting
ITE	Institute of Transportation Engineers’
LAM	Locational-Allocation Modelling
LCA	Lifecycle Assessment
LDCV	Light-Duty Commercial Vehicle
LNG	Liquefied Natural Gas
LP	Linear Programming
MAUP	Modifiable Aerial Unit Problem
MCDA	Multi-Criteria Decision Analysis
MDCV	Medium-Duty Commercial Vehicle
MITL	McMaster Institute for Transportation and Logistics

MOVES	Motor Vehicle Emissions Simulator
MTARTS	Metropolitan Toronto and Regions Transport Study
NAICS	North American Industry Classification System
NCFRP 25	National Cooperative Freight Research Program Project 25
NGV	Natural Gas Vehicles
NMHC	Non-methane Hydrocarbons
NO_x	Nitrogen Oxide
OD	Origin-Destination
PAHs	Polycyclic Aromatic Hydrocarbons
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
PV	Passenger Vehicle
QRFM	Quick Response Freight Manual
RMSE	Root Mean Square Error
SAW	Simple Additive Weighting
SI	Sustainability Indicator
TA	Trip or Traffic Assignment
TAZ	Traffic Analysis Zone
THC	Total Hydrocarbons
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TSP	Total Suspended Particulate Matter
TTS	Transportation Tomorrow Survey
UE	User Equilibrium
UTMS	Urban Transportation Modeling System
WCV	Waste Collection Vehicle
WHO	World Health Organization
WTW	Well-to-Wheel
VHT	Vehicle Hours Traveled
VKT	Vehicle Kilometers Traveled
VMT	Vehicle Miles Traveled

1. INTRODUCTION

1.1 Overview

The invention of the automobile at the beginning of the 20th century has propelled society into modernization and has resulted in a significant increase in personal travel activities. Containerization and globalization has further increased the volume of commercial truck activities over the past three decades. Heavy-duty commercial vehicles (HDCVs) are commonly used in freight transportation as they can transfer high volumes of goods in their trailers. These trucks also play a major role in intermodal freight transportation by transferring containers to their destination or between modes.

Longer periods of commercial vehicle operation have been associated with higher volumes of harmful emissions. Based on the United States Federal Highway Administration classification, heavy-duty trucks weigh more than 26,001 pounds and are classified as Class 7 and 8 vehicles. These trucks are of greater concern than lighter commercial vehicles and passenger cars when it comes to air pollution as most these vehicles are powered by diesel (97.5%, 2009 Canadian Vehicle Survey) and on average travel long distances. In 2015, these vehicles contributed to 13% of Canada-wide nitrogen oxides (NO_x) emissions and 19% of Canadian-wide transportation-related particulate matter (PM) emissions, (Environmental and Climate Change Canada, 2017). Diesel exhaust has both negative environmental and health implications, including reduction of visibility and pulmonary health (Llyod and Cackette, 2001; Sydbom et al., 2001).

For fleet operators and owners, diesel is a financial concern when the price of oil is high as "*fuel cost is typically the second highest operating cost…[and] lifetime fuel costs are nearly five times that of the original purchase price of the vehicle*." (National Petroleum Council, 2012). If the price of oil continues to rise, the cost of goods movement will in turn increase.

To combat the negative aspects that are associated with the use of diesel, the use of an alternative fuel is suggested. Compressed natural gas (CNG) has been introduced as an alternative fuel source during the energy crisis in the 1970s (Yeh, 2007). According to the literature, CNG emits less nitrogen oxides (NO_x) and particulate matter (PM) emissions than diesel powered vehicles, therefore have less impact on human health and the environment. Also, if the price of oil and diesel increases or stays consistently high, natural gas will be a cheaper alternative.

1.2 Statement of Problem

Alternative fuels like CNG have the potential to offer both environmental and economic benefits. However, one of the major drawbacks of transitioning to alternative fuels for truck fleets is the lack of existing refueling infrastructure. The accessibility to and availability of refueling stations is essential to enable continuous and long-distance freight movement. However, the availability of reliable refueling infrastructure across major goods movement networks is crucial to make CNG a feasible alternative fuel. On the other hand, fleets that return to truck yards on a nightly basis or operate regionally are ideal for the first stages of fuel conversion. These fleets can be refueled overnight at their existing truck yards. On-site refueling can be carried out using mobile refueling trucks. These refueling trailers will originate from sites that have access to and the potential to store large quantities of natural gas. The problem then becomes where and how many of these "CNG Hubs" must be created to service regions in which fleets are likely to convert to or adopt the use of CNG.

Estimating CNG demand, the number and location of CNG Hubs is required to provide adequate refueling coverage in the region. Establishing the feasibility of CNG use in heavy commercial fleets is the first step in the case for transitioning towards CNG, however the potential environmental and economic benefits must be quantified. All the pollutants associated with CNG and diesel exhaust emissions must be compared to ensure that CNG truly is a cleaner burning fuel. The economic benefit must be quantified in terms of costs associated with conversion, refueling and potential maintenance.

1.3 Objectives

The primary objectives of this project are:

1) To establish a framework for selecting sites for CNG fueling hubs,
2) To determine the feasibility of establishing a CNG-refueling network in the Greater Toronto and Hamilton Area (GTHA),

3) To quantify the environmental benefits for adopting CNG by heavy-duty trucks in the GTHA and
4) To conduct a Multi-Criteria Decision Analysis (MCDA) to gain an in-depth understanding of the different benefits and costs of using CNG technology to power heavy-duty trucks.

1.4 Thesis Outline

The remainder of this thesis is organized as follows. The next chapter provides a literature review that details the various factors associated with the transition to alternative fuels, the comparison of CNG- and diesel-powered vehicles, previous studies discussing freight trip generation and past studies evaluating the cost-benefit between different fuel types. The third chapter introduces the study area and the data used in the analysis. This is followed by a discussion of the methods of analysis utilized for the different stages of the project. The fourth chapter presents and discusses the achieved results. The final chapter provides a conclusion of conducted research. It also highlights the limitations of the current work and offers recommendations for future steps. A list of references follows the conclusion and proceeds the appendices with additional information referenced throughout the thesis.

2. LITERATURE REVIEW

2.1 Diesel and Alternative Fuels

2.1.1 Diesel Vehicles

Rudolf Diesel invented the diesel engine in the late nineteenth century and it rose in popularity after the 1920s. Diesel engines boast low fuel consumption and high reliability, both of which are attractive features for fleet operators. Diesel fuel is a "*mixture of various petroleum-derived components, including paraffins, isoparaffins, napthenes, olefins, and aromatic hydrocarbons*" (Reynolds, 2007). Diesel exhaust is made up of a unique mixture of both gases and particles, many of which are toxic air pollutants (Kagawa, 2002). These pollutants include carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), nitrogen oxides (NO_x), black carbon and sulfur dioxide (SO_2). Black carbon is an indicator of diesel-related traffic emissions of PM (Krzyzanowski et al., 2005). The most problematic of these are PM and NO_x due to the quantity generated and their associated negative environmental and health impacts. In 2015, diesel HDCVs contributed to 13% of total Canadian NO_x emissions and 19% of total Canadian transportation PM emissions (Government of Canada, 2017). Diesel exhaust is a major source of fine and ultrafine particles, 90% of PM is smaller than 1 micrometre in diameter (Reşitoğlu, 2015). These particles can become deposited into lungs and respiratory tracts potentially causing health issues. Approximately 40-70% of worldwide NO_x emissions are generated from road transport and diesel vehicles are the largest contributors (Reşitoğlu, 2015).

Diesel exhaust degrades environmental quality and produces adverse health effects. Diesel exhausts cause haze or visibility degradation, form smog, contribute to global warming, contribute to acid rain formation, alter radiative properties of clouds and cloud lifetime thus affecting rainfall (Lloyd and Cackette, 2001). Exposure to diesel exhaust has various health effects including increased hospital admissions and mainly health effects associated with the respiratory system. Susceptible populations include children, elderly and those with pre-existing respiratory problems. Exposure can exacerbate existing allergies and asthma symptoms (Ris, 2007) and can potentially cause individuals to develop allergies and asthma. Short-term exposures have the potential to cause acute irritation and inflammatory symptoms in nose, eyes and of the airways, in addition to respiratory changes, headache, fatigue and nausea (Ris, 2007; Sydbom et al., 2001). Chronic symptoms of exposure to diesel exhaust include cough, bronchitis, lung function decrements, sputum production, breathlessness and the impairment of pulmonary function (Sydbom et al., 2001; Morgan et al., 1997; Ris, 2007). Additionally, exposure can increase the susceptibility to respiratory infections (EPA, 2016). "*Long-term inhalation exposure is likely to pose a lung cancer hazard to humans as inferred from epidemiologic and animal studies*," (Ris, 2007) which implies diesel exhaust is likely carcinogenic. Additionally, diesel exhaust is classified by the International Agency for Research on Cancer (IARC) as probably carcinogenic to humans (Turrio-Baldassarri et al., 2006). Effects on reproductive health are inconsistent and the results were mainly based on animal studies, however the European World Health Organization (WHO) believes there is some evidence that exposure to diesel exhaust has the potential to produce negative reproductive outcomes. Exposure to particulate matter from diesel exhaust can contribute to irregular heartbeats, nonfatal heart attacks, and premature death in individuals with existing heart or lung decrements (EPA, 2017). To combat these health effects, fuels with lower levels of pollutants should be explored.

2.1.2 Alternative Fuels

Alternative fuel vehicles (AFVs) rose in popularity amongst governments after the 1970's energy crisis (Yeh, 2007). AFVs have the potential to reduce environmental impact. The use of alternative fuels diversifies the fuel supply which decreases the dependence on fossil fuels (i.e. petroleum). Alternative fuels include: biodiesel, electricity, ethanol, hydrogen, natural gas and propane. Biodiesel and ethanol are both renewable, made from vegetable oils, animal fats or recycled cooking grease and corn or other animal materials respectively. AFs used in Canada include propane, natural gas, electricity and ethanol. However, these are all used to power passenger vehicles. In Canada, heavy-duty trucks have the least diversity in energy source, as they primarily rely on diesel. This is not only problematic from an environmental and health points of view but also from an economic perspective. More specifically, if oil prices were to substantially increase, fleet operation costs will in turn dramatically increase when using diesel as the main source to power trucks.

Hwang et al. (2015) found that "*due to insufficient AF infrastructure on most road networks, logistics companies hesitate to replace their traditional fuel trucks with AF trucks for their over-the-road trucking business*" (p. 171). Therefore, a reliable refueling network is an essential requirement to encourage fleets to transition from diesel to an alternative fuel.

2.1.3 Natural Gas Vehicles

Natural gas is a hydrocarbon with methane forming 85 to 99 percent of its chemical structure (Faiz et al, 1996). This gas is cheap since it is abundant in nature in various places around the globe. Natural gas has a low carbon-to-hydrogen ratio, which results in lower emissions of carbon dioxide (CO_2). Thus, it can be considered as a cleaner source of energy than diesel. According to Yeh (2007), natural gas vehicles (NGV) can also produce less harmful emissions (i.e., PM, NO_x, CO, etc.).

NGV can be fueled in the form of Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG). CNG has been used in the past in Canada and currently greater compression of NG reduces the volume by a factor of three-hundred or more (Natural Gas Use in Transportation Roundtable, 2010). NGVs are operated using a pressure regulator that transports the gas into a spark-ignited or compression engine. The preference of CNG over LNG is due to its availability through existing natural gas pipelines using compression equipment. CNG is nearly free of sulfur and Krzyzanowski et al. (2005) report that CNG contains no toxic components, have low cold-start emissions and low smog-forming potential. The reduction of these emissions has the potential to improve air quality and in-turn public health.

Natural gas powers about 15.2 million vehicles worldwide (U.S. Department of Energy, 2014) and approximately 20,000 NGVs in Canada (Natural Resources Canada, 2015). NGVs in Canada consist of: urban transit buses, school buses, light-duty cars and trucks, forklifts and ice-resurfacers. Canada is one of the world's largest producers of natural gas and is expected to have a supply to last at least one hundred years (Natural Gas Use in Transportation Roundtable, 2010). A benefit associated with NGV is the potential to decrease the reliance on imported oil by utilizing the existing natural gas stores, thus diversifying the fuel supply.

CNG vehicles are generally filled at compressor refueling stations that are bound to natural gas pipelines. These stations can deter drivers from their planned route, which brings about additional costs. There are two methods for CNG refueling: fast-fill and time-fill. Fast-fill is a method normally used at retail stations and the required time is similar to a diesel or gasoline fill. Time-fill is generally used for fleets that can be refueled overnight at a central location as fueling can take several minutes to an hour. The longer fuel time is advantageous as it allows for a fuller fill since the fueling rate is lower. An increase in fueling rate causes an increase in fuel temperature, which in turn causes the fuel to expand and become less dense. The lower density is associated with less energy per unit volume at the fuel systems rated pressure. Therefore, a time-fill will be able to fill more CNG than a fast-fill (U.S. Department of Energy, 2014).

NGVs can either be factory-built or retrofitted vehicles. Factory-built NGVs are designed to provide similar horsepower to their diesel counterparts. There are three main types of natural gas vehicles: dedicated, bi-fuel and dual-fuel. A dedicated NGV is powered solely by natural gas. NGV use on-board CNG in high-pressure cylinders at a pressure of 3,000 to 3,600 psi. These fuel systems are robust and maintain integrity during operation. A bi-fuel NGV operates on two separate fueling systems providing the user the flexibility of switching from natural gas to another fuel source, however it only uses one fuel at a time. A dual-fuel NGV runs on natural gas and diesel or another fuel is used for ignition. Dedicated NGVs have been demonstrated to be more efficient than bi-fuel vehicles. This is the case because firstly, dedicated NGVs allow for a higher cargo capacity as the weight of the additional fuel and fueling system associated with the bi-fuel vehicle is eliminated in a dedicated system and can be used for cargo. Secondly, dedicated NGVs engines are optimized for CNG-use.

Unlike Europe, Latin American, Africa and the Asia-Pacific Region, North America is the only region that has experienced a decline in NGV growth. In Canada, public CNG refueling stations have declined in quantity from 134 in 1997 to 72 in 2010 (Natural Gas Use in Transportation Roundtable, 2010). This decline can be due to several disadvantages associated with the use of natural gas. Higher vehicle costs are associated with NGVs than traditional diesel heavy-duty trucks. It is estimated that natural gas engine options for new medium- and heavy-duty trucks have an additional cost approximately ranging from \$35,000 to \$100,000 (Canadian Dollar) and conversions approximately range from \$26,000 to \$46,000 (Canadian Dollar) (Natural Gas Use in Transportation Roundtable, 2010; Omnitek Enginering, 2013; Berg, 2012; Groom, 2013). Without federal support or incentives, fleets may not be willing to spend the extra upfront costs associated with the purchase of new vehicles. Additionally, the energy content of natural gas is lower than diesel and a larger tank size is required to meet energy demands. As mentioned earlier, the lack of existing refueling infrastructure dissuades fleets from conversion. The lack of reliable NG refueling infrastructure and the lower driving range of CNG vehicles has primarily led to the adoption of CNG amongst regional fleets, such as transit and school buses and waste collection vehicles. The lack of recent experience with CNG in Canada could also deter fleet conversion.

Fracking is required for the extraction of natural gas which has negative environmental impacts such as the potential contamination of groundwater, use of water resources, degradation of air quality and the potential for fracking-induced earthquakes. However, developments and improvements to drilling technology, pollution prevention and water treatment and recycling can reduce the negative environmental impacts. The future use of renewable natural gas or biomethane can reduce the need for fracking. Biogas is produced in municipal landfills and sewage treatment's anaerobic digestion process. This biogas can be upgraded to meet the standards of supplying natural gas pipelines (Natural Gas Use in Transportation Roundtable, 2010).

The outlook on diesel and natural gas will primarily depend on fuel price as the sensitivity analysis demonstrated in Maimoun et al. (2016) and several other sources have found that natural gas will be a better fueling option than diesel if the price of the latter increases over time.

2.1.4 NGV in Canada

Major deterrents of the transition to NGVs in Canada during the 1980s were provided and discussed in Flynn (2002). NG was touted as a better alternative to gasoline as it was more economic and provided substantial environmental benefits. One of the economic advantages of NG over oil-based fuels was primarily due to the elimination of NG retail taxes at a Federal level and amongst most provinces. Lack of refueling infrastructure, especially public stations was a major retardant in NGV adoption. The lack of development of support infrastructure and refueling stations was due to lack of return on investment (Flynn, 2002). AFV consumers may not consider the transition if there are no convenient refueling options. This, according to Flynn (2002), becomes a "*chicken and egg*" problem. That is, "*without refueling facilities, no one invests in vehicles using the new fuel, and without sufficient customers for the fuel, no one invests in [establishing] refueling stations,*" (Flynn, 2002). The development of alternative fuel stations becomes a tricky supply vs. demand problem. If there is insufficient demand, both fuel and vehicle suppliers will have no economic incentive to invest in supplying AFs and AFVs. The profitability of refueling stations is an essential factor in ensuring a reliable supply and motivating consumers to transition to NG.

Flynn's opinion is that exaggerated claims of both the economic and environmental benefits of NG in the 1980s may have swayed the public and commercial fleet operators away from NGV. NG enthusiasts and promoters firmly believed that the NG prices are bound to drop and used this notion to promote the conversion, however this drop never occurred. A major reason why NG was marketable in the 1980s was due to the government grants per vehicle conversion and NG service station. However, these grants were only made available up to a certain quantity of NGVs and stations and these grants were used in the quantification of potential economic savings.

2.1.5 Comparison of Diesel and Natural Gas Vehicles Emissions

There are many studies that have quantified or tested the difference of exhaust emissions between diesel and natural gas vehicles. However, the reported results are conflicting. Some studies have found substantial emission reductions associated with NGVs over diesel-powered vehicles whilst others only found minimal benefits or trade-offs associated with emission outputs. For example, less PM is released when CNG is used instead of diesel, however more hydrocarbons are emitted as a result. This is likely due to differences in fuel composition, the presence of exhaust after-treatment systems or emission control devices. According to the Natural Gas Use in Transportation Roundtable, 2010 CNG emits less greenhouse gas (GHG) emissions than diesel at a life cycle level. This encompasses the emissions associated with resource recovery, refining, shipping and vehicle operation. Upstream, CNG is only processed to remove impurities and this process requires lower amounts of energy than the diesel refining process.

A study on diesel and natural gas buses for the same location and study time in Slovenia found that average elemental or black carbon concentrations were three times lower in the case of the natural gas buses (Krzyzanowski et al., 2005). A PM emission study reported 80% lower emissions from the CNG-powered heavy-duty vehicle than the diesel-powered heavy-duty vehicle, (Krzyzanowski et al., 2005).

A study conducted in California by Ayala et al. (2002) and Kado et al. (2006) compared the emissions from CNG and diesel transit buses. These studies conducted analysis on various vehicles with and without exhaust after-treatment devices that have the potential to reduce emissions. The CNG bus had no oxidation catalyst in place and was tested and then retested after three months of use. These emission results were compared to the emissions of a diesel bus with first a catalyzed muffler and second a Johnson Matthey Continuously Regenerating Trap (CRT) in place of the muffler. Four driving cycles were explored and tested on a chassis dynamometer, one cycle was steady-state and the rest were transient.

The CRT Diesel vehicle had the lowest PM emissions in all but one driving cycle, however both CNG tests have significantly lower PM emissions than diesel in the transient driving cycles. Both CNG tests showed higher levels of carbon monoxide emissions, volatile organic carbons, and non-methane hydrocarbons. CNG had slightly lower CO_2 emissions than the diesel configurations and both diesel configurations were outperformed by the CNG vehicles in terms of NO_x emissions. However, the CNG re-test in comparison to the original test, yielded almost double the NO_x emissions. This variation in emissions has been observed in other studies but no causation has been determined. One plausible explanation that Kado et al. (2006) offered is that the natural gas used for the re-test was below specifications.

The inconsistencies in emission levels will further deter conversion to natural gas. However, the results from the California study by Kado et al. (2006) were not corrected for tunnel background pollutant levels. From the results, the different driving cycles (representing varied vehicle operation) influenced the quantity of emissions released. Therefore, driving conditions caused by variations in traffic characteristics because of congestion, traffic signaling operation or the nature of the vehicles routes could impact the overall emission results. From this study, exhaust after-treatment devices should be further examined on all types of vehicles to reduce harmful emissions.

Contrasting the previous study, Turrio-Baldassarri et al. (2006) reported that even though the use of after-treatment devices such as PM traps or oxidant catalysts in experimental studies have shown to reduce emissions, very limited applications in heavy-duty engines have been applied. Turrio-Baldassarri et al. (2006) compared a CNG-fueled bus engine coupled with a three-way catalyst with an equivalent diesel engine fueled with diesel and a diesel-biodiesel blend (20% vegetable oil). Emissions were determined using an eddy current dynamometer coupled with the engine. CNG emissions demonstrated lower emissions than the equivalent diesel engine. With reductions of THC (total hydrocarbons) (67%), NO_x (98%) and PM (96%), polycyclic aromatic hydrocarbons (PAHs) (98%) emissions. Additionally, a 20- to 30-fold reduction of genotoxic activity was demonstrated. The improved results associated with this study can potentially be attributed to the exhaust after-treatment.

Ristovski et al. (2004) retrofitted a six-cylinder sedan dedicated petrol passenger car to a bi-fuel CNG and petrol-powered vehicle. Emission measurements were taken before conversion, at conversion, and up to a period of three months after conversion leading to a final test of using petrol and CNG. The notable advantages of CNG over the unconverted petrol include lower levels of total PAHs, formaldehyde, and NO_x emissions. The average global warming potential (GWP) was calculated for both fuel types based on the gaseous emissions. The average GWP was estimated to be lower for CNG vehicles at high vehicle speeds and loads. These reductions reduce health risks and environmental impact. Ristovski et al. (2004) observed a decrement in the performance of petrol after the conversion to bi-fuel petrol/CNG with respect to CO and particle number and mass emissions.

Fontaras et al. (2012) studied four waste compactor trucks, one of which was diesel-powered and equipped with an oxidation catalyst and was fueled with 25% biodiesel and the other three were CNG-fueled. An on-road and in-operation study was conducted with a CNG-fueled truck equipped with a three-way catalyst and a diesel truck. These two vehicles were tested on the same route on the same day of the week to control for the amount of waste collected as it will impact overall weight. A portable emission measurement system (PEMS) was used to measure exhaust emissions while the speed of the vehicle was measured by means of a GPS system. The results of the on-road tests coincide with previous studies with lower levels of PM (75% reduction) and NO_x (86% reduction) emissions. However, they reported higher levels of CO_2, HC and CO emissions associated with CNG over diesel. HC and CO are sensitive to any exhaust after-treatment devices in use, this can potentially explain the inconsistencies associated with these emissions. Most of the emitted hydrocarbons from CNG vehicles are methane which has a higher 100-year GWP (21) than CO_2 (1). Black carbon, a component of PM, is reduced with the use of CNG. Black carbon is reported to have a GWP ranging from 350 to 1,500; therefore, this reduction can contribute to reduction of the total GHG emissions. However, methane emissions were higher with the use of CNG fuel which can increase total GHG emissions.

The second experiment carried out by Fontaras et al. (2012) was a controlled operation of two CNG-powered waste collection vehicles on a closed track. CO emissions associated with the test-track results were lower than both vehicles associated with real-world operation. Therefore, CO emissions associated with CNG use can potentially be reduced when vehicles are operating at less transient conditions, therefore making it a better application for vehicles that do not stop as often as buses. Results showed some inconsistencies as one vehicle showed higher NO_x than the diesel vehicle and HC emissions greater than the other two CNG vehicles examined. These results emphasize the "*high variability that can be observed in the performance of [CNG] vehicles*," (Fontaras et al., 2012).

From these studies, it is evident that many factors play a role in the level of emissions. These factors include the driving cycle and traffic conditions, vehicle condition, quality and type of the fuel. The use of CNG fuel consistently reduced NO_x and PM emissions, which are the most problematic pollutants associated with diesel. However, there is some inconsistency with other harmful pollutants emitted from NGVs. In theory, CNG engines are clean when operated under optimized conditions and "*deliver 1.6 times more energy* *from the same amount of CO_2 emission*," (Shahraeeni et al., 2015). Therefore, CNG engine efficiency will continue to increase with advances in technology, which will lead to a decrease of emissions. For both CNG and diesel powered vehicles, exhaust treatment play a crucial role in reducing vehicular emissions and should be considered with both fuels. Also, factory built NGVs are likely to be more energy efficient than converted NGVs and in turn emit less pollutants which is also an important factor to consider when comparing the two fuels. Table 2-1 provides a summary of the studies discussed in this section and in later sections.

Table 2-1: Summary of CNG vs. Diesel Emissions

Study (*Location*)	**Vehicles Studied**	**CNG compared to Diesel***
Turrio-Baldassarri et al. (2006) (*Italy*)	• Heavy-Duty Urban Bus Engine *Fueled by*: • Diesel • Diesel with 20% Vegetable Oil • CNG with a Three-Way Catalyst	• Lower PAHs, formaldehyde, PM and NO_x • 20 to 30 times reduction of genotoxic activity was estimated
Fontaras et al. (2012) (*Italy*)	• Waste Collection Trucks *Fueled by*: • Diesel (25% v/v biodiesel) • CNG (3 trucks)	• Lower PM and NO_x • Higher CO_2, HC and CO
Ayala et al. (2002) and Kado et al. (2005) (*United States*)	• Transit Bus (40-passenger) *Fueled by*: • Diesel with (1) a catalyzed muffler (2) a CRT in the place of the muffler • CNG	• Lower NO_x and slightly lower CO_2 in all configurations and driving cycles • Lower PM only with respect to the catalyzed muffler • Higher CO, THC/NMHC, VOCs AND carbonyls
Ristovski et al. (2004): (*Australia*) **compared to petrol*	• Six-Cylinder Sedan Car *Bi-fueled by*: • CNG and Petrol	• Decrease in NO_x, total PAHs and formaldehyde emissions • PM was only significantly lower when the vehicle was operating at a speed of 80 km/h

2.2 Refueling Infrastructure

2.2.1 Locating Refueling Infrastructure

Selecting the optimal location for refueling stations is an essential step to ensure that the public has sufficient access to fuel and the owners are profiting. Optimization models have been used in past studies to determine the location of fueling stations. Optimization models are used to achieve effective coverage in a region or on highways and major roadways. Location-allocation models can be used to determine optimal locations based on various objectives. Some objectives include maximizing attendance and minimizing travel time or distance. The former will locate optimal stations from a group of potential locations such that more individuals or fleets are served, while the latter aims to minimize travel time or distance between the supply and target consumers.

Both Yeh (2007) and Hwang et al. (2015) stressed the importance of establishing reliable refueling stations to encourage the shift to AF vehicles. Further, refueling must become convenient with respect to location and fueling time. Various studies have reported that the approximate amount of refueling stations to meet a new AF market is ten to thirty percent of gasoline stations (Nicholas and Ogden, 2006).

Hwang et al. (2015) proposed a mathematical model for locating AF refueling stations on highways. The proposed model incorporated constraints and considered driving direction, as some stations may only be accessible to one-way traffic. To achieve this a 0-1 integer linear programming (LP) model was used to optimize the location and number of fueling stations while maximizing coverage along the highway (Hwang et al., 2015, p. 177). The model used was path-based, limiting the driving range of LNG vehicles, and it assumed that candidate locations can be either one-way or two-way access facilities.

Nicholas and Ogden (2006) used a p-median problem to minimize travel time between one's home and proposed hydrogen refueling stations. A major assumption made for this model was the general preference of public refueling near the home over at-home refueling. It was further assumed that all regions were the same with the amount of time individuals were willing to drive to refuel. Further, existing gasoline stations were used as possible AF refueling locations. Census tracts were the zones of analysis used to break down the population. ESRI software was used to compute the free-flow driving times on the road network.

Results from Hwang et al. (2015) showed that more highway truck trips could be serviced with a high number of stations and a higher vehicle driving range. The results lacked convexity, after the optimal number of stations is reached the effective coverage plateaus. Thus, the results establish that additional stations past the optimal station value does not provide additional coverage. Nicholas and Ogden (2006) found that as the desired travel time decreased the number of stations required substantially grew. For example, for the Metropolitan region of Los Angeles, a desired travel time of seven minutes, five minutes and three minutes warranted 26, 61 and 228 stations respectively. From these studies it is further emphasized that the location and number of refueling stations are essential in optimizing the performance of refueling stations.

2.2.2 Alternative Refueling Approach: Virtual Pipeline

As discussed earlier, the major roadblock to the adoption of alternative fuels is the lack of existing refueling infrastructure. To overcome this, a virtual-pipeline can be implemented. A "*virtual-pipeline is an alternative method of transporting natural gas to places where there are no pipeline networks available*" (Udaeta et al., 2012). Virtual-pipelines are advantageous in areas where the "*presence of complex underground infrastructure and complex structure of private properties in cities and suburbs make it inordinately expensive or complicated to build a pipeline system*" (Chrz and Emmer, 2007). The feasibility of virtual LNG pipelines has been demonstrated in Europe and the United States. In Norway for example, LNG has been delivered in large vacuum insulated tanks and trailers. Transporting LNG via trailers on the road network allowed LNG to travel approximately 20% longer distances than pipelines as it does not require transport recompression.

Implementing a virtual-pipeline to refuel CNG trucks can reduce travel costs for the fleet operator and can ensure a "fuller" fill as overnight refueling will allow for a time-fill of the fleets. A virtual-pipeline is an attractive option at the infancy of CNG conversion as it may reduce the infrastructure required. There are also several considerations for a virtual pipeline for CNG refueling, the carrying capacity of CNG tractor-trailers will depend on local regulations. Additionally, there are associated safety concerns with pressurized CNG, which differ than traditional gasoline or diesel fuel tanks. These guidelines and requirements will need to be further evaluated in the GTHA context.

2.3 Trip Generation Modeling

2.3.1 Passenger Trip Modeling

Passenger trip modeling is concerned with explaining and predicting the number of trips made by passenger vehicles. Individuals make trips to travel to and/or from work, school, social or shopping locations. These trips have varying departure times and trip durations. Also, route choice will vary based on the driver's preference. This complexity makes passenger trip modeling challenging. There are many approaches taken to perform passenger trip modelling, such as generating trips by purpose, like work and social trips or estimated trips by period, for example AM peak, PM peak, and Off peak or even combining both methods. The resulting predicted trips are usually validated with trip count data.

The most commonly used approach to model passenger trips is the four-stage modeling system (Ortúzar and Willumsen, 2011). Trip generation estimates the number of trips occurring in a region. Trip generation consists of two components – trip production and trip attraction. Trip production accounts for the trips leaving a zone, whilst trip attraction accounts for the number of trips destined to a zone. Trip generation models can be estimated separately by mode, by a persons' socio-economic and/or demographic attributes, trip purpose, time of day, and household and zonal variables. The most common modeling approaches for trip generation include: linear regression modeling, cross-classification models, growth-factor modeling,, and trip frequency or discrete choice models. However, the most commonly used technique is regression modeling. Typically, the number of trip attractions and productions are determined using a linear function and zonal and/or household characteristics.

Trip distribution is "*the process of converting the production and [attraction] estimates from trip generation into trip flows…between zones*," (Kuzmyak, J.R., 2008, p. 20). Trip distribution is heavily dependent on spatial interaction between the traffic analysis zones. A region may attract more work trips due to the presence of jobs. A residential area will produce more home-to-work trips in the morning, and attract many home-bound trips in the evening. Additionally, the ease of movement in terms of travel time, distance or cost between two zones is another factor that can motivate travelers to visit one zone while avoiding another. The most common approach for trip distribution is the gravity model. The gravity model used in trip distribution is adapted from Newton's Law of Gravitation and was first used by Ravenstein (1889). The parallels drawn are provided in the following equation.

$$F_{ij}=G\frac{m_i m_j}{d_{ij}^2} \rightarrow T_{ij}=k\frac{P_i P_j}{d_{ij}^2}$$

Where F_{ij} is the gravitational force between bodies i and j and T_{ij} represents the number of trips originating from zone i and destined to zone j. The gravitational constant, G is replaced in the trip distribution gravity model by k which is a constant which defines characteristics related to trip distribution. The distance between the two bodies in Newton's law of gravity is replaced with the distance between the two zones of interest. The mass of the bodies in the gravitational model is replaced by the population of the two zones. There are several forms of the gravity model which can constrain trip attractions and/or productions. Additional modeling techniques include entropy maximization and the iterative proportional fitting (IPF) method or the Fratar Method. These models are essential in determining the flow of trips between zones.

Elmi et al. (1999) examined the temporal transferability of work-trip distribution models by determining the travel time parameter β from transportation survey results in Toronto. The datasets analyzed come from three study years and two sources the 1964 Metropolitan Toronto and Regions Transport Study (MTARTS) and the 1986 and 1996 Transportation Tomorrow Survey (TTS). The TTS is a travel survey conducted in the Greater Toronto and the Greater Golden Horseshoe area and has been conducted every five years since 1986. The study area during the examined time frame experienced significant changes in both socioeconomic and spatial distribution. Most notably, the Toronto region adopted a multicentered urban structure in the late 1970s. Elmi et al. (1999) used the reported trips from both studies to develop six different trip distribution models. Two of the models were derived by maximizing the entropy function with trip production and attraction constraints which resulted in a doubly constrained entropy model. The second model is improved by subjecting the entropy function to a travel time cost constraint. Models 3 to 6 were derived "*after stratification of the trip data by a person or household* *variable*," (Elmi et al., 1999). Each of these six models were developed for the three study years and were used to estimate trips in other years.

The estimated model for 1964 was used to model both 1986 and 1996 trips and the 1986 model was used to test the 1996 data to determine temporal transferability. The Transfer Index is: "*a relative performance measure, which indicates how well a transferred model performs in prediction in the application context relative to a locally estimated model in application context*," (Elmi et al., 1999). This index was found to be above 80 percent for all models which suggests that the derived models are temporally transferrable. The Root Mean Square Error (RMSE) was obtained to examine the errors associated with model transfer. The RMSE for Model 2 was the lowest when the 1986 models were used to predict 1996 trips and second lowest when the 1964 models were used to predict the latter years. Elmi et al. (1999) found that Models 3 to 6 provided better predictions than the second model when transferring models temporally, however the percentage improvements from Model 2 ranged from 0.03% to 1.36%. This result suggests that Model 2 is a sufficient model to transfer for future years as the other models did not provide a significant advantage.

After trip distribution, mode choice is generally conducted to delineate which trips are carried out by which method of transportation. Mode choice is generally implemented with the use of discrete choice models and is applied to the total trip count produced. However, some trip generation models are already broken down by mode, eliminating the need to use these models. Trip assignment predicts the routes taken by the estimated trips and there are various algorithms available to determine the flow and travel times on the road network.

2.3.2 Commercial Trip Modeling

In the context of this thesis, freight trip generation (FTG) modeling will be required to determine the demand and commercial vehicle flow. That is, one of the requirements for assessing the feasibility of adopting CNG is to determine the number of trucks that will engage in travel activities in the study area. Typically, the number of freight trips could be used to verify truck counts since the two are expected to be highly correlated. The latter is true since every truck has the potential of producing trips. While the count of trucks across the traffic analysis zones could be modeled, existing literature has been solely focused on modeling trips.

In general, freight trips are more difficult to model than passenger trips. Commercial vehicles do not follow standard routes every day. Also, several factors including truck capacity, variable delivery window times, and heterogeneity of industries play a role in producing or attracting commercial trips (Muñuzuri et al., 2012). It is usually a challenge to obtain the necessary information required from businesses and firms to develop predictive FTG models. According to Madar (2014), the associated information with delivery patterns and route design can aid the competition and therefore is kept confidential.

Holguín-Veras et al. (2013) attempted to enhance existing FTG models to allow for better predictions and the utility outside of the study area in which these models were derived in. Three major FTG models were assessed by Holguín-Veras et al. (2013): (1) the National Cooperative Freight Research Program Project 25 (NCFRP 25) "Freight Trip Generation and Land Use", (2) Quick Response Freight Manual (QRFM) and (3) the Institute of Transportation Engineers' Trip Generation Manual (ITE)). The NCFRP 25 Model was derived from freight trips generated by 362 establishments in New York City, New York. Most of the produced models rely on employment counts and the square footage of an establishment. The QRFM was developed in Phoenix, Arizona using the results of a freight origin-destination survey. The model provides freight trip rates for light-, medium- and heavy-duty commercial vehicles based on employment and population counts. The ITE's Trip Generation Manual presents a collection of FTG models submitted by researchers from many different groups such as public agencies, consulting firms, developers and universities. Some of these models are based on land use, whilst others are directly related to the counts of freight-generating markets such as furniture, hardware and paint stores. These models were tested for their predictive ability using data obtained from different industries of varying sizes and various geographical regions. Through comparing the modeled results with the data, it was found that NCFRP 25 tended to perform better than the other models and had a smaller range of associated RMSE. The authors found that the QRFM tended to overestimate FTG for larger businesses. However, a major advantage of the QRFM was that the model allowed for relatively easy estimations of commercial trips.

Roorda et al. (2010) developed a trip-based freight model for the Greater Toronto Area (GTA). The initial rates were based on the Region of Peel Commercial Travel Survey (2007) and then calibrated to correspond to the observed traffic counts of crossing cordons in the GTA and modeled assigned traffic. These calibrated rates are based on land use, employment industry and truck type. Land use in the model is classified to differentiate between: Rural and Suburban zones, and between urban zones and the Central Business District (CBD). The trip generation model results were compared with observed traffic counts that were available for the AM and PM peak hours. The modeled results were sensible and the matched aggregate totals (Roorda et al., 2010). Overall, the estimated model for the GTA provided good estimates in the GTHA for freight trips.

The reviewed papers concluded that further research is required to effectively predict FTG and produce accurate models. The importance of obtaining more data on freight flows and demand patterns is emphasized for future research. Additionally, truck count data and road counts of truck traffic are required to verify results.

2.4 Environmental Impact and Benefit Estimation

Emissions from transportation has been consistently the largest contributor of overall greenhouse gases (GHG) in Canada. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most significant GHGs (Shahraeeni et al., 2015). Exposure to vehicular emissions can increase the risk of death. It can also increase the risk of acquiring respiratory symptoms and diseases, increase the risk of developing allergies and exacerbate these symptoms among asthmatics (Krzyzanowski, 2005). Fortunately, the volume of these emissions can be estimated using emission models. The most popular model in North America is the United States Environmental Protection Agency’s (EPA) Motor Vehicle Emission Simulator (MOVES). MOVES is an “*emission modeling system that estimates emission for mobile sources at national, county, and project level for criteria air pollutants, greenhouse gases and air toxics*,” (EPA, 2017). MOVES2014a is current version of the software. MOVES is extensively used throughout the United States and Canada. MOVES’ default database is based on American data, therefore users must take caution when using any default data for modeling exercises outside of the United States. MOVES requires several inputs like traffic flow, vehicle population characteristics, meteorology and road characteristics of the study area to estimate emission factors or an emission inventory.

Several Canadian studies have used MOVES to estimate vehicular emissions. The McMaster Institute for Transportation and Logistics (MITL) modelled traffic flow in the Toronto and Hamilton areas and used the results as the required traffic input for MOVES. Since their study was not in the United States, most of the required inputs had to be obtained from other sources. Historical temperature and relative humidity data was obtained from Environment Canada. Information on the vehicle population, age and fuel-type was obtained R. L Polk and Company's Vehicles in Operation Data. Shorshani and Hatzopoulou (2016) used data from an automobile insurance company to determine vehicle age distribution. MITL (2014) used INRIX Historical Flow Data to determine the speed distribution on different roads while Shorshani and Hatzopoulou (2016) used driving cycles from a dynamic microscopic traffic model that was built in the PTV VISSIM software. The two Canadian studies showed that emission inventory by vehicle type per pollutant can be quantified by using a combination of transportation modelling results and derived MOVES emission rates.

2.5 Sustainability Indicators and MCDA

Introducing new changes to a regional or an urban system (e.g., implementing a new process, utilizing a new fuel, or introducing new infrastructure) can potentially have positive and/or negative environmental benefits. On the other hand, new changes can cause financial strain on the involved parties or have negative repercussions on society. Typically, several factors should be evaluated to be able to make informed decisions. Also, it is vital to examine the long-term impacts (i.e. sustainability) of the proposed changes. Here, sustainability indicators (SIs) could be generated and used in the decision-making process. The general approach would be to generate standardized measures that can be used to evaluate a targeted goal (Maoh and Kanaroglou, 2009). The indicators are generated to examine the three pillars of sustainability: Economy, Environment and Society. The objective is to minimize the negative environmental and societal impacts whilst maximizing economic benefits for a proposed change or policy. Multi-Criteria Decision

Analysis (MCDA) is applied to the generated standardized indicators to allow the decision-maker to assess various criteria to select the best alternative.

Maimoun et al. (2016) conducted a multi-level multi-criteria analysis to determine which alternative fuel was a better option both financially and environmentally compared to the existing conventional diesel for waste collection vehicles (WCVs). The study was based on North American fleet and conditions. Maimoun et al. (2016) established a multi-level multi-criteria approach to determine the ideal fuel, this approach is presented in Figure 2-1. The analysis considered various factors under both the economic and environmental pillars of sustainability. The economic pillar considers both direct costs such as fuel price and vehicle costs and indirect costs such as a fueling station availability. As aforementioned, the access to fueling station is an extremely important factor when considering the transition to an alternative fuel. The lack of refueling stations can cause additional planning and travel costs to refuel. The environmental pillar expands its focus as the analysis covers not only the negative environmental impacts associated with operation but also considers the overall environmental implications of the entire life cycle of the fuel.

Like the trucking industry, "*fuel cost has been the driving factor for the waste industry*," (Maimoun et al., 2016) and waste management fleets have started taking advantage of the lower priced natural gas in comparison to conventional diesel. Two MCDA methods, Simple Additive Weighting (SAW) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) were used to rank nine alternative fuels. These two methods (discussed in section 3.6.4) were used at each level of the analysis and ranked for use at the next level of analysis. Environmental results with all the included criteria suggested that waste collection vehicles were best fueled with fossil fuels. Financially, diesel ranked better than CNG since CNG was affected by the lack of fueling stations. The overall ranking placed diesel as the ideal fuel for WCVs. A sensitivity analysis was conducted to examine the impact of removing specific Level 2 criteria from the analysis. North American sourced CNG outperformed diesel when the economic category was adjusted to exclude fuel price stability and fueling station availability, which both had a deterrent impact on CNGs economic viability. Various other studies have made efforts to compare CNG, diesel and other alternative fuels, however the majority of these studies focused on transit buses or waste collection vehicles.

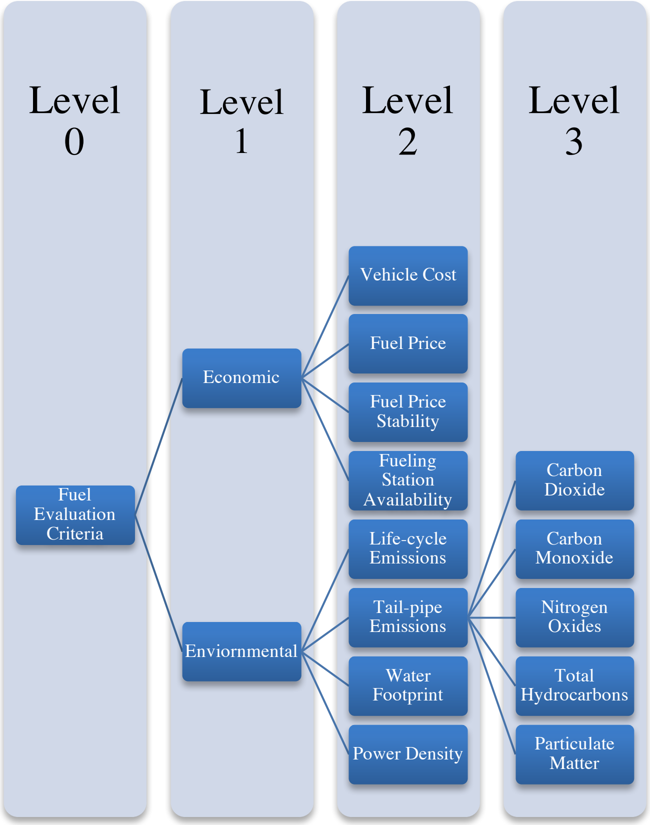


Figure 2-1: Maimoun et al. (2016) Multi-Level MCDA

In an effort to decrease harmful pollutants at both the global and local levels, Yedla et al. (2005) performed predictions for twenty years with the use of an optimization model that minimized total costs of new vehicles and operation and maintenance of new and existing vehicles. This model was used to determine if the adoption of mixed fuels and/or technologies have the potential to save energy, reduce emissions and economic expenditure. From this analysis, the results suggested that CNG cars should replace diesel cars, however CNG buses should not replace diesel buses due to the high capital costs of CNG buses. The effect on other emissions when the objective was to reduce one particular emission via optimizing the vehicular fuel and technology mix was also examined. The three emissions of interest were CO_2, total suspended particulate matter (TSP) and hydrocarbons (HC). Yedla et al. (2005) found that when the objective of reducing the three emissions of interest was included in the optimization model, CNG buses and three-wheelers were introduced to the future vehicle population. From this study, it is interesting to note that CNG offers an environmental advantage in this study but does not possess an economic advantage for buses which can translate to heavy-duty trucks.

Shahraeeni et al. (2015) conducted a lifecycle assessment (LCA) to determine if CNG is more cost-effective than diesel for Light-Duty Commercial Vehicles (LDCVs). A LCA assesses the environmental and economic impacts associated with every stage of a material from “cradle-to-grave”. With regards to a vehicle LCA, the fuel lifecycle must also be analyzed as both the vehicle and fuel are joined during operation. The fuel lifecycle consists of stages from harvesting the feedstock to its production and transportation and finally the production and distribution of the fuel. The vehicle lifecycle consists of the stages from material production and transportation to vehicle assembly followed by vehicle distribution and vehicle use, where both the fuel and vehicle lifecycles meet. The vehicle lifecycle ends with vehicle disposal, some studies have found that both NGVs and conventional diesel vehicles have the same impact at this stage. Shahraeeni et al. (2015) utilized GHGenius tool to assess lifecycle emissions, this tool uses MOBILE6.2C to model vehicular emissions.

The lifecycle CO_2-equivalent (CO_2eq) GHGs emission associated with the CNG-powered LDCVs were found to be 34% lower than their diesel counterparts. CNG only emits more CO_2eq emissions than diesel for only three stages of the LCA, which are the fuel distribution and dispensing and vehicle material production stage. The lifecycle energy use for CNG LDCVs was found to be 2% higher than diesel LDCVs with the greatest difference between the two found during the vehicle operation phase. The emissions of five Criteria Air Contaminants (CACs) were analyzed at a lifecycle level and Shahraeeni et al. (2015) noted that the vehicle operation stage was where the greatest quantity of emissions in the total fuel and vehicle lifecycle were released. So much so that this stage determines which fuel has higher overall lifecycle emissions. Oxides of nitrogen emissions were found to be higher with CNG powered vehicles, which contradicts the results from previously discussed studies in Section 2.1.5.

Shahraeeni et al. (2015) discussed that recent studies have found that NO_x will only decrease if proactive measures are taken to ensure CNG engines are working efficiently. The overall results present that a 64% increase in CAC emissions with the use of CNG LDCVs over their diesel-powered counterparts. This result exhibited the opposite trend of results from a study carried out by the same research group focusing on WCVs equipped with a three-way catalyst, which found a 54% overall reduction in CAC emissions for CNG-powered WCVs (Rose et al., 2013). Therefore, it is important to further assess the lack of consistency of the CNG NO_x advantage before converting to CNG use. Additionally, the cost-effectiveness of CNG was determined using the lifecycle cost of vehicles, their operation and maintenance, and fuel price which was then normalized to the GHG emission reduction. Shahraeeni et al. (2015) found that the use of CNG in LDCVs results in a lifetime cost reduction and a 60% savings on overall lifetime fuel costs.

Rose et al. (2013) also used GHGenius and a LCA approach to assess the difference between WCVs using diesel and CNG. They found no net gain in energy use and approximately a 24% decrease in CO_2eq GHG emissions. The use of CNG was found to save \$650 and \$330 CDN per realized tonne of CO_2 reduction with and without diesel tax respectively. This study utilized operational data as inputs for the GHGenius model. These inputs include the average daily distance traveled, the number of stops per day, maximum operational lifetime and travel distance, tare and maximum mass, and the capital cost of both CNG and diesel WCVs. Using real-world data was useful as Rose et al. (2013) report that their work features more frequent stops than previous works.

McKenzie and Durango-Cohen (2012) conducted a LCA for the costs and GHG emissions of transit buses which was also subjected to a sensitivity analysis to examine the effect of fuel price. A hybrid input-output model was used in the study to examine the differences between alternative fuels and technology. The study included ultra-low sulfur diesel and CNG. The end-of-life stage was not considered in this study as there was minimal differences between the different bus types. An interesting feature of this study was that the data was based on buses operating on existing transit routes in four different American states spread across a five-year study period. The collected data included statistics on operation, maintenance and performance and their respective costs. CNG transit bus per mile operating costs were found to be 9 cents cheaper and the GHG emissions per mile were also found to be lower than their diesel counterparts. However, the passenger capacity of CNG transit bus was found to be lower, carrying twenty less passengers than the diesel transit bus. This is an important consideration in the freight and waste collection industry as any decrease in carrying capacity can increase the number of trips which can potentially counteract any potential savings.

The emissions are examined at a well-to-wheels (WTW) scale and these emissions are converted to their CO_2eq. From the LCA the higher costs and GHG emissions associated with manufacturing CNG transit buses created a higher present value cost but lower GHG emissions for CNG buses with respect to diesel buses, due to the lower operational costs both financially and environmentally. The bulk of the lifecycle emissions (74-85%) occurred whilst the running of the vehicle. Of the alternative fuel vehicles considered, it was found CNG had the smaller marginal costs and the larger emission reduction per unit cost during the operation phase than diesel. However, when the entire lifecycle is considered, diesel is more cost-effective and it becomes the best alternative fuel or technology examined. When the cost and emissions associated with the construction of the fueling infrastructure were considered in the analysis, the "*marginal costs of GHG reductions increase[d] by a factor of two*" (McKenzie and Durango-Cohen, 2012).

Based on these results the payback period of refueling infrastructure must be considered when assessing AFVs. Fuel price is one of the major drivers of the operational cost. The operational cost of powering vehicles is also reliant on the fuel economy. The ideal mixture is a low fuel price and a high fuel economy; the lower the fuel economy the more sensitive the operational costs to variation in fuel prices. It was demonstrated that a 50% increase in CNG fuel costs causes a sevenfold increase in the costs required for GHG reduction. The same dataset was later examined in 2017 by Durango-Cohen and McKenzie. An economic input-output analysis with linear programming was used to conduct a sensitivity analysis. The objective of this study was to determine the transit fleet mix that minimize acquisition, operation and disposal costs and meet passenger demand and LOS constraints. These constraints were considered when examining five different scenarios, in three scenarios environmental constraints were considered. In a scenario in which the objective is to reduce GHG and NO_x emissions, 11.7% of the fleet was converted to CNG without a significant increase to the life cycle cost.

Table 2-2 presents a summary of the reviewed studies. The results do not conclusively state that CNG is an ultimately better option than diesel, however these particular studies do suggest if some of the economic and operational hurdles are dealt with, CNG can then potentially be the more sustainable option. The economic and operational hurdles in question that can be controlled for include fueling station availability, conversion and/or vehicle costs. Governments should consider incentives for vehicle conversions to encourage the shift if environmental impacts of CNG are determined to be lower than diesel. It is also essential that governments and industry work together to provide safe, reliable and convenient CNG fueling options to produce a reliable refueling network. The greater uncertainty associated with oil prices in contrast to natural gas in Canada also plays a role in fluctuating the price differential between CNG and diesel, which can in turn make CNG less appealing. Governments can potentially counteract this uncertainty as it has done in the past by reducing taxes on NG.

Table 2-2: Summary of MCDAs Reviewed

Source	Study Region	Study Vehicle	Comparison Method	Results
Cohen, J.T., Hammitt, J.K. and Levy, J.I., 2003.	United States	Transit Bus	Cost-Effectiveness (CE) and Quality Adjusted Life Years (QALYs)	CNG provided larger health benefits than diesel and emission controlled diesel vehicles
Durango-Cohen, P.L. and McKenzie, E.C., 2017.	United States	Transit Bus	Economic Input-Output Analysis with Linear Programming for Sensitivity Analysis	When the objective is to reduce PM and NO_x, CNG transit buses are introduced to the all-diesel fleet.
Maimoun, M., Madani, K. and Reinhart, D., 2016	United States	Waste Collection Vehicles	Multi-level multi-criteria analysis	Overall analysis suggests conventional diesel is best option; removal of fueling station availability and fuel price stability criteria from analysis suggests CNG is a better option.
McKenzie, E.C. and Durango-Cohen, P.L., 2012.	United States	Transit Bus	Hybrid Input-Output Model and LCA	CNG reduces operating costs and emissions, but increase life cycle costs. Additional costs associated with required infrastructure and reduced passenger capacity are incurred with CNG.
Rose, L., Hussain, M., Ahmed, S., Malek, K., Costanzo, R. and Kjeang, E., 2013.	Canada	Waste Collection Vehicles	Cost-Effectiveness, LCA (GHGenius)	CNG WCVs were found to reduce environmental impact and also found to be cost-effective.
Shahraeeni, M., Ahmed, S., Malek, K., Van Drimmelen, B. and Kjeang, E., 2015.	Canada	Light Duty Commercial Vehicles	Life Cycle Cost of Vehicles Fuel, operation and Maintenance Normalized to reduction of GHG emission. Cost-Effectiveness of LCA.	CNG was more cost-effective than diesel (Lower CO_2eq, slightly higher energy use, 2/5 CACs lower with CNG).
Yedla, S., Shrestha, R.M. and Anandarajah, G., 2005.	India	Various Vehicles	Optimization Model: Objective - minimize total costs of new vehicles and operating costs of all vehicles	CNG cars were preferred over diesel cars whilst diesel buses were preferred over CNG buses

3. METHODS OF ANALYSIS

This chapter will start by presenting the study area for which the analysis is conducted. This will be followed by a detailed description of the different phases of analysis. Furthermore, the chapter will present and discuss the methods used to address the research questions of this thesis and fulfill the objectives listed in Chapter 1.

3.1 Study Area

Ontario has the highest number of heavy-duty trucks in the country (Natural Resources Canada Office of Energy Efficiency, 2007). The province's economy "*thrives through its unique combination of resources, manufacturing expertise, [and] exports*." (Government of Ontario, 2016). Additionally, Ontario is home to fourteen Canada-U.S. road border crossings. As such, most of Canada's exports to the United States originates from Ontario. Due to its economy and trading patterns, Ontario attracts and produces a large volume of freight movement. The Greater Toronto and Hamilton Area (GTHA) was selected as the study area due to its extensive freight activity and its role in Ontario's economy. The GTHA hosts the largest market in Canada. According to the Canadian Census, the GTHA had a population of 6.66 million people in 2011. The total number of households and jobs in that census year were 2.4 million and 2.9 million, respectively. In 2016, the population grew to a total of 7.05 million. On the other hand, households and jobs grew to a total of 2.57 million and 3.54 million, respectively. In addition to the population size and the vast number of jobs, commercial vehicle movement is prevalent in this area due to the many warehouse and distribution centers located in the area (especially in the Peel region) and their access to major Ontario highways such as the Highway 401. Increasing congestion in urban areas like the GTHA has the potential to increase vehicular emissions. Therefore, transitioning to CNG heavy trucks can potentially improve Ontario's air quality and public health.

The study area can be delineated through both Census Metropolitan Areas (CMAs) and Census Divisions. The GTHA is comprised of the following Census Divisions (CDs): Durham, Halton, Hamilton, Peel, Toronto and York; and the three CMAs of Toronto, Hamilton and Oshawa. The study area was further centralized to incorporate only regions of the GTHA that have census tracts. Statistics Canada defines census tracts as areas found in CMAs that are relatively stable and small, with populations usually ranging between 2,500 and 8,000 persons. Census tracts are only located in CMAs and Census agglomerations that have a core population of 50,000 or more (Statistics Canada, 2011). There are 1,326 census tracts in the study area. These tracts, which represent the traffic analysis zones (TAZs), are shown in Figure 3-1.

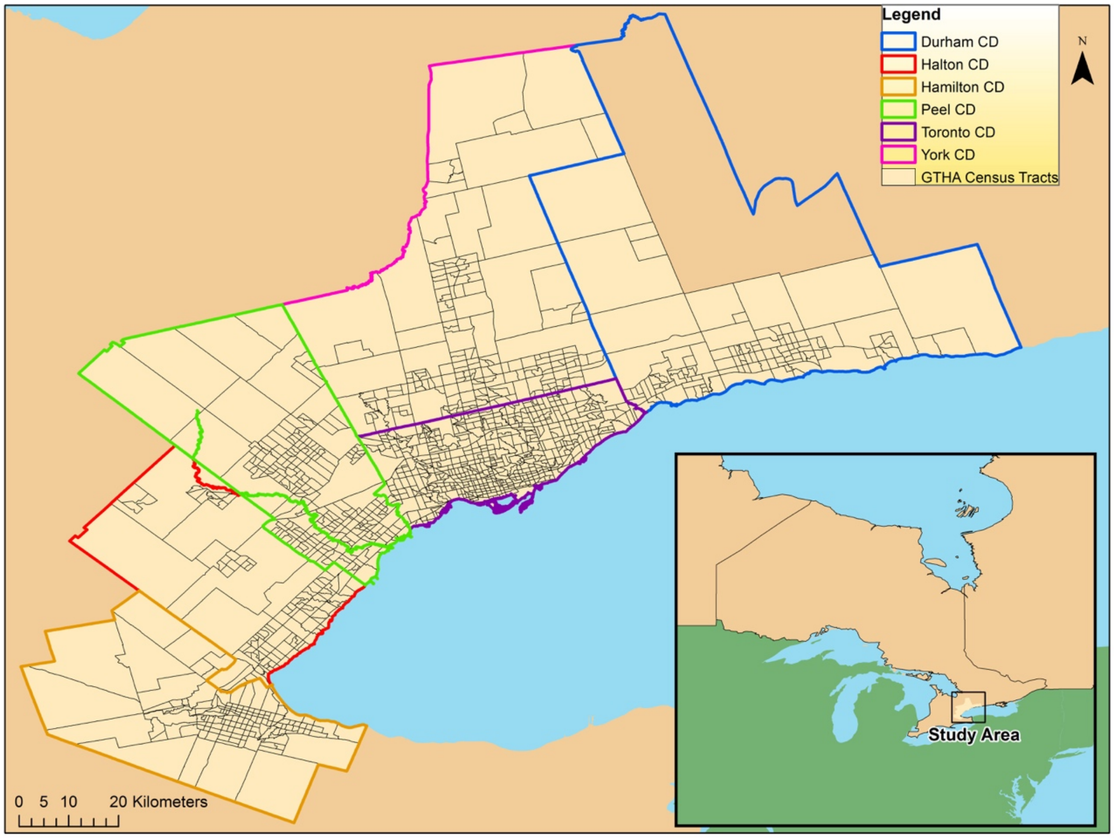


Figure 3-1: Study Area - GTHA

3.2 Analysis Phases

To achieve the objectives listed in Chapter 1, the analysis was broken into four major phases, as shown in Table 3-1. Phase 1 is concerned with establishing a framework for selecting optimal sites for locating CNG fueling hubs in the GTHA. This phase is also focused on determining the feasibility of establishing a CNG fueling network. A location-allocation modeling (LAM) exercise is performed to fulfil the first two objectives of the proposed research.

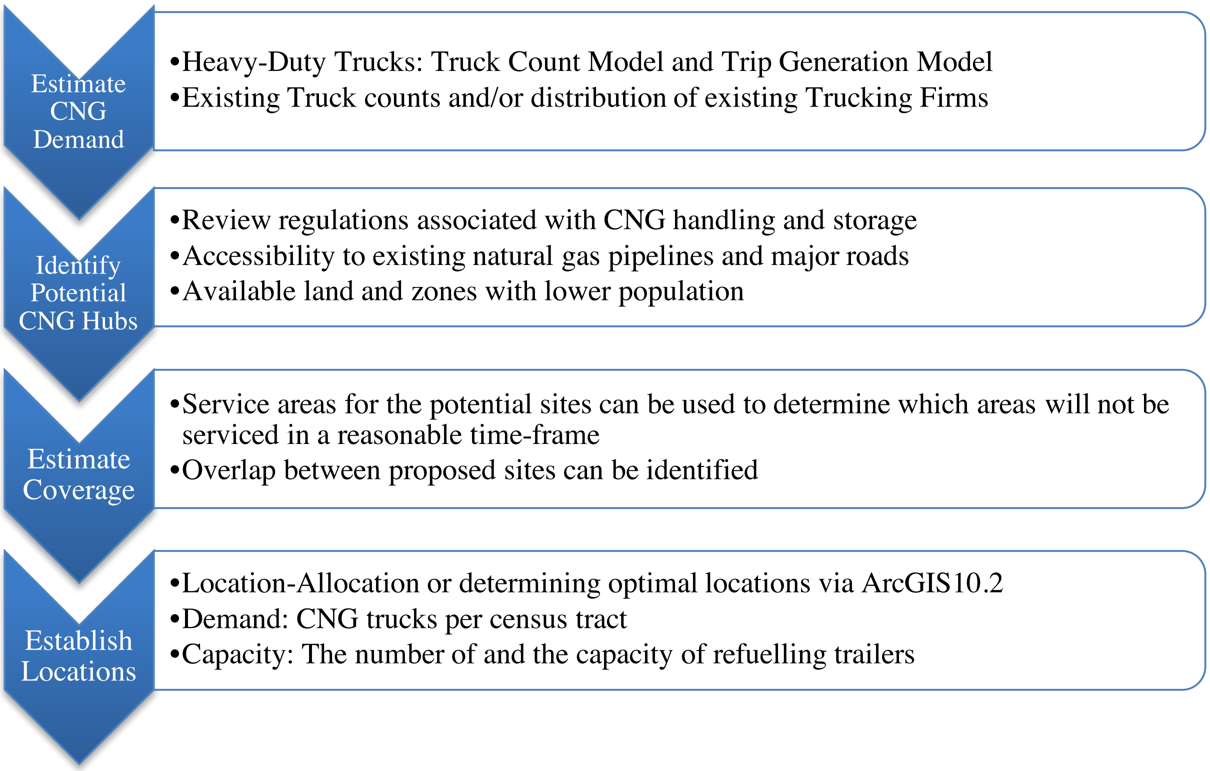
To support the transition towards CNG and to verify the potential benefits of adopting CNG to fuel heavy-duty trucks, a four-stage travel demand modeling and emission quantification analysis will be required. Therefore, the second phase of the analysis (i.e. Phase 2) is focused on estimating traffic flows on the road network in the GTHA. The purpose is to estimate traffic flows under a status quo scenario (i.e. when all trucks are diesel powered) and compare that to CNG scenarios in which certain percentage of trucks in the GTHA are using CNG instead of diesel. Assigned traffic flows from Phase 2 are used as input to Phase 3. The latter is focused on estimating traffic related emissionsbased on emission factors that are derived from the MOVES emissions model. Finally, the fourth and final phase of the analysis is concerned with conducting a multi-criteria decision-making analysis (MCDA) to compare and evaluate the benefits of CNG relative to diesel.

Table 3-1: Phases Associated with Objectives

Corresponding Phase	**Objective**
Phase 1: Location-Allocation Modeling (LAM)	To establish a framework for selecting sites for alternative fueling hubs.
	To determine the feasibility of establishing a CNG-refueling network in the proposed study area.
Phase 2: Transportation Modeling	To quantify the environmental benefits from adopting CNG by heavy-duty trucks in the GTHA.
Phase 3: Emissions Quantification	
Phase 4: Multi-Criteria Decision Analysis	A MCDA of the transition to CNG technology by heavy-duty trucks.

3.3 Locational-Allocation Modelling (LAM)

A framework is to be proposed to establish the potential feasibility of a virtual-pipeline in the GTHA. The framework will allow for transferability between study areas and can be applied to other vehicle types—not only heavy-duty vehicles and other alternative fuels. The proposed framework is summarized in Figure 3-2. A hub-and-spoke model as presented in Figure 3-3 represents the proposed flow of CNG between CNG hubs or facilities to existing truck yards.


Estimate CNG Demand

- Heavy-Duty Trucks: Truck Count Model and Trip Generation Model
- Existing Truck counts and/or distribution of existing Trucking Firms

Identify Potential CNG Hubs

- Review regulations associated with CNG handling and storage
- Accessibility to existing natural gas pipelines and major roads
- Available land and zones with lower population

Estimate Coverage

- Service areas for the potential sites can be used to determine which areas will not be serviced in a reasonable time-frame
- Overlap between proposed sites can be identified

Establish Locations

- Location-Allocation or determining optimal locations via ArcGIS10.2
- Demand: CNG trucks per census tract
- Capacity: The number of and the capacity of refuelling trailers

Figure 3-2: Framework for Establishing an Alternative Fuel

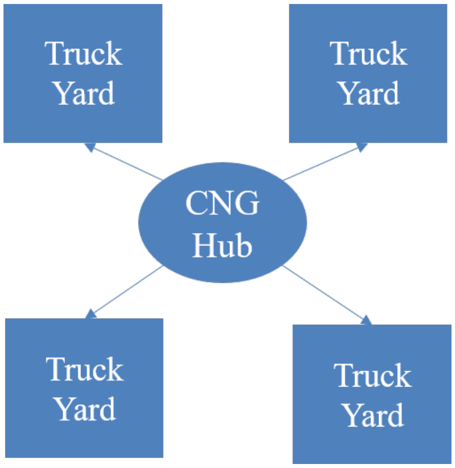


Figure 3-3: Hub-and-Spoke Network

3.3.1 Estimate CNG Demand

The demand for transportation fuel is directly associated to the number of vehicles in the study area. Therefore, to determine the demand, either the number of heavy-duty truck trips or heavy-duty trucks is required. As mentioned earlier on, truck and associated trip counts have the potential to be compared as trucks represent the capacity to produce trips. For the purposes of this analysis, two models will be used to estimate heavy-duty truck trips. Also, a model will be developed to estimate heavy-duty truck counts at the census tract level. The results pertaining to the three models will then be compared to identify the best option to represent the demand side in the LAM exercise.

The two models that will be used to predict heavy truck trips are the QRFM and the Roorda et al. (2010) model. The Quick Response Freight Manual provides trip generation models for different vehicle classes and is based on origin-destination data from Phoenix, Arizona. The QRFM model inputs include employment per industry and households per zone. Holguín-Veras et al. (2013) found that the QRFM overestimated freight trip generation, however it allows for a quick estimation of commercial trips. Appendix A presents these two models.

To use the model Roorda et al. (2010) developed, each census tract in the study area must be assigned a land use class. The Central Business District was selected based on the knowledge of business activities in the downtown Toronto area. The urban and rural and suburban land uses were then identified based on the size (i.e. sq. km) of the census tract. The area of each census tract was calculated in ArcGIS 10.2. Census tracts with values below or equal to 2.1 km^2 are classified as Urban and any census tract with an area above 2.1 km^2 is classified as Rural and Suburban Division.

The Roorda et al. (2010) model provides 12.5-hour trip generation rates. These 12.5-hour totals must be scaled up to a 24-hour rate to be able to compare the estimated values with the QRFM values. Figure 3-4 presents hourly commercial trip fractions for the GTHA (CVS, 2006), which can then be used to obtain the hourly rates. The Roorda et al. (2010) model predicts trips from 7 am to 6 pm. That 12-hour modeled trip generation accounts for 65.92% of daily commercial trips. Therefore, the remaining daily fraction can be used to estimate the hourly trips for the rest of the day (i.e. 24-hours).

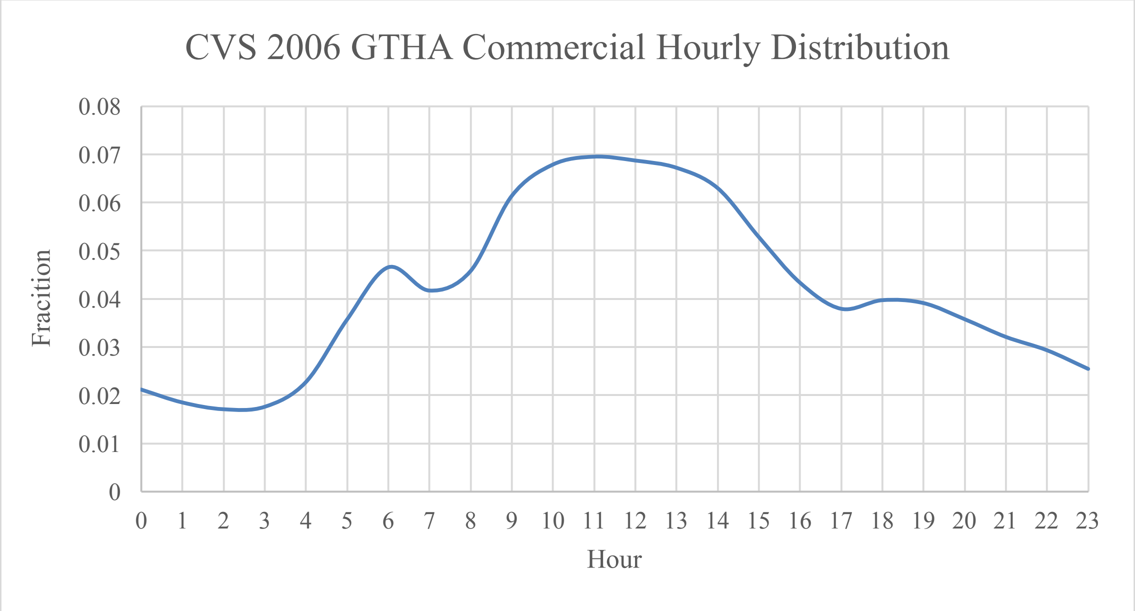


Figure 3-4: Hourly Distribution used for HDCVs

Existing truck counts per TAZ in the GTHA were obtained from R. L. Polk and Co. A scatter diagram suggested a strong linear relationship between the number of jobs and the obtained truck counts. Therefore, a linear regression model was specified and then used to model the number of trucks at the zonal level in the GTHA. Next, the heavy truck trips and counts were compared to examine the validity of estimates before proceeding to the main analysis. Although, the 2012 Polk truck count data for the GTHA was used to represent the demand, the truck count model is presented as a tool for future predictions. In the LAM analysis, the centroid of each census tract is used to spatially represent the demand points.

CNG heavy-duty trucks have an estimated driving range of approximately 1,000 km (Union Gas correspondence with the Cross-Border Institute). To ensure that the truck has enough CNG to drive back to the truck yard, it is assumed the truck must not travel a distance more than 500 km from its originating point. This distance is the direct distance between the origin and destination of the trip. It is assumed that trucks meeting the driving constraints have the potential for CNG conversion. Truck movement data represented by trips originating from the GTHA were utilized in the analysis. These trips were derived from a large GPS database that was acquired from Shaw Tracking Communication. The trips represented the movement of a sample of Canadian trucks (approximately 20%) for the month of March 2016. The truck trips originated from within the GTHA and contains the exact location of the origin and destination of the trucks. The trips were processed by the Cross-Border Institute (CBI) of the University of Windsor. Origin-destination information was used to obtain the Euclidean distance for each trip. According to the GPS data, approximately 36,040 trips originated from the GTHA. These trips were geo-referenced by census tracts, and a ratio of trips that were less than or equal to 500 km was determined. Census tracts that did not have any trips originating from it, used the average of neighbouring census tracts. This fraction was then applied to the existing truck count to determine the number of potential CNG trucks.

3.3.2 Identify Potential CNG Storage Locations

A set of possible sites for CNG refueling and storage stations must be identified in order to determine the optimal locations with respect to truck demand. A suitability mapping model can find potential sites for these centralized CNG Hubs based on pre-defined criteria. For this, multi-criteria decision analysis (MCDA) in a spatial context is applied to identify potential sites. Several factors could be considered when determining suitable locations. In this analysis, five factors were considered. Figure 3-5 provides a conceptual model of the suitability criteria for CNG Hubs.

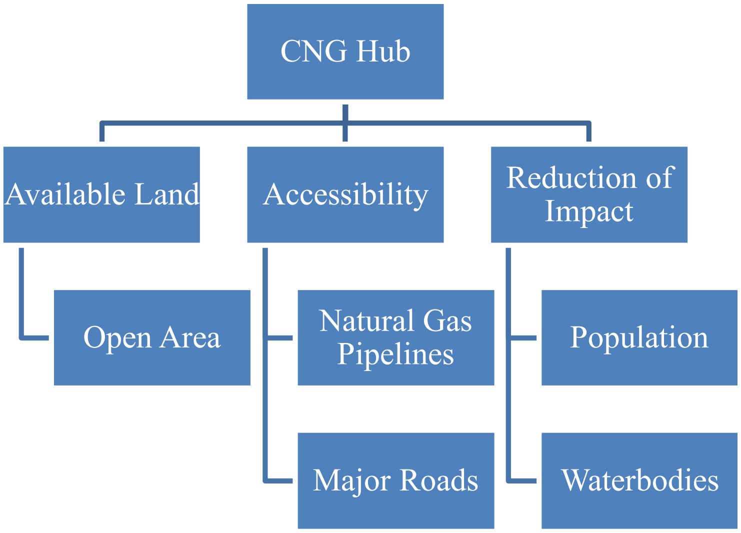


Figure 3-5: CNG Hub Suitability Criteria

In the proposed framework, proximity to a major road network enhances accessibility to the market and reduces vehicular emissions. Also, locating the stations in census tracts with lower population will minimize any risks and concerns associated with the natural gas storage. Open area was assumed to be land that can be purchased, as land-ownership data was not readily available. However, this is likely an overestimation, as the "Open area" land use may be currently owned. Areas with waterbodies cannot be used to establish CNG hubs to protect these waterbodies. The same goes to the surrounding areas of these waterbodies. Finally, locations with access to natural gas pipelines are ideal sites for CNG hubs, other things being equal.

The spatial distribution and locations of the population, road network, water bodies, existing natural gas pipelines and open areas were collected from various sources many of which were accessible via the Scholars GeoPortal. The datasets were available as Geographic Information Systems (GIS) Shapefile layers. Census tract level population figures were obtained from the 2011 National Household Survey. Further, the major road network for the study was derived from the DMTI Ontario Route Logistics Geospatial Database. The existing natural gas pipeline and land use data was also derived from the DMTI Geospatial database, which was accessible via the Scholars Geoportal.

Table 3-2 details the classification procedure used to determine sites of higher suitability per criteria. The common scoring system that is used for all factors ranges from least suitable (assigned value 1) to most suitable (assigned value 9). The weight for each factor dictates its significance and its overall impact in selecting a site. The larger the weight, the higher the influence that factor has on site suitability. The two most important factors are the availability of open area and zonal population, each assigned a weight of 0.30. This ensures that suitable and available sites will have lower population. The presence of existing natural gas pipelines is assigned a weight of 0.20 as the existence of natural gas pipeline infrastructure will reduce cost. Proximity to road networks have a weight of 0.15 since it is not as important as the other factors and is not integral to the operation of the virtual pipeline, however still beneficial. The waterbodies variable is assigned a weight of 0.05.

Table 3-2: Weights and Scoring Classification for Criterion

Criteria	Weight	Classification of Scoring
Open Area	0.30	Sites that have a land use of open area were given a suitability of 5, whereas all other sites were given a not suitable classification.
Zonal Population, P	0.30	$0 \leq P \leq 2000$: 1 $2000 < P \leq 3000$: 2 $3000 < P \leq 4000$: 3 $4000 < P \leq 5000$: 4 $5000 < P \leq 6000$: 5 $6000 < P \leq 7000$: 6 $7000 < P \leq 8000$: 7 $8000 < P \leq 9000$: 8 $9000 < P \leq 10000$: 9 $P > 10{,}000$: Not suitable
Waterbodies	0.05	Sites with waterbodies were given a not suitable classification, other sites were given a suitability of 5.
Natural Gas Pipelines	0.20	The closer a site is to major roads and pipelines the higher the suitability. Euclidean distance is the direct distance to a point. A raster grid was created with each cell representing distance from (1) major roads and (2) pipelines. Closer distances were assigned higher suitability values.
Major Roads	0.15	

All the discussed criteria were converted to raster grids (i.e. spatial layers) with the same classification scheme such that the higher the assigned rank the more suitable the site. The Raster Calculator of the Spatial Analyst Extension of ArcGIS was used to apply the weights detailed in Table 3-2 to generate a suitability surface or map. The following equation details the Raster Calculators execution.

$$S_g = \sum_{i=1}^{n} w_i x i_g$$

Where S_g is the suitability of gridcell g, w_i is the weight of factor i and xi_g is the criterion score of factor i in gridcell g. As will be shown in the next Chapter, the site suitability analysis resulted in a total of fifteen potential locations to establish CNG fueling stations.

3.3.3 Estimate Coverage

Service areas visually represent the locations that can be reached within a pre-specified driving time window, as shown in Figure 3-6. Service areas are useful when establishing additional branches of banks, new fire and gas stations as they ensure that the all individuals are serviced in a specific region. Service areas ranging from five to twenty minutes of driving time were produced for the potential sites serving the estimated CNG demand. The service areas are created using the ArcGIS Network Analyst Extension. The creation of the service areas was restricted to the study area and it is assumed that that if a major road is a one-way there is a minor road that is close in proximity where one can traverse to reach the target destination.

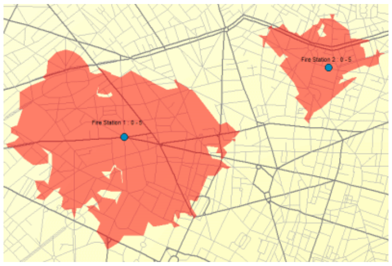


Figure 3-6: Example of Service Area Polygon (Source: ArcGIS 10.4 Online Help)

3.3.4 Establish Facility Locations

The final locations chosen for any business venture can lead to either surplus profits or additional expenses. Therefore, selecting the optimal facility locations is key in the LAM exercise. Several types of normative models could be solved to establish the optimal CNG Hubs based on the potential sites identified in the previous section. All models share the following two constraints: (1) only a pre-specified number or the optimal number of facilities (i.e., CNG Hubs) will be located, and (2) every demand will receive CNG fuel from the closet facility. Four methods are used and summarized in Table 3-3.

The analysis was conducted under the assumption that CNG fueling trucks will be traveling from the facility (i.e., virtual fueling network) to the demand, which in this study are the centroids of the census tracts. As the major road network is used for analysis, one-way roads are neglected. The free-flow travel time is used as the travel impedance as it is assumed that the trips will be occurring overnight (i.e., during off-peak periods). The four models presented in Table 3-3 will be implemented and the results will be compared.

Table 3-3: Locational Problems and their Characteristics

Problem Type	Objective: Select locations that….	Characteristics of Solution
P-Median	Minimize total distance traveled or travel time.	Facilities are located at a weighted center of the majority of the demand.
Maximize Attendance	Maximize attendance or access to demand for the facility with respect to a time constraint.	Facilities are located closer to zones with highest demands. Past the time constraint, attendance is likely zero.
Maximize Coverage	Maximize the level of demand that falls within a time constraint.	A demand point is covered when it is within the time constraint. The objective is to maximize demand coverage, not optimize distance traveled or trip times.
Minimize Facilities	Minimize the number of facilities required to service the highest level of demand within a time constraint.	Facilities are located such that within the time-constraint applied the maximum number of demand is serviced.

Model 1: P-Median

To minimize fixed and transportation costs of the fueling facility, a p-median problem will be applied to optimize the refueling of the maximum number of trucks with the optimal number and location of facilities. The CNG demand per truck was assumed to be 90 Diesel Gallon Equivalent (DGE), which is the average capacity of a CNG truck (J.B. Hunt, 2014). DGE is used to rate CNG vehicle storage. To determine the capacity of the plant, the capacity of the refueling fleet is required. The capacity of a CNG refueling trailer was not readily available, therefore a ratio between the capacity of a LNG refueling trailer (12,000 gallons) and a LNG truck tank (200 gallons) was determined and this ratio (60) was then scaled to the capacity of a CNG truck tank to determine an approximate value for CNG capacity. The number of refueling trucks assigned per station varied based on scenario, therefore changing a facility’s capacity. Five scenarios were examined in which each potential facility had: 10, 15, 20, 25 or 30 refueling trucks and enough refueling trucks to service the entire GTHA demand. Each “refueling truck scenario” was analyzed with the establishment of only one facility up to all fifteen facilities.

Models 2 and 3: Maximize Attendance and Maximize Coverage

These two problem types are solved with the same approach. The travel time cut-off used ranged from 10 minutes to 30 minutes using intervals of five minutes. For each time cut-off, the number of facilities to be established were varied from the minimum one to the maximum fifteen potential sites.

Model 4: Minimize Facilities

The least number of facilities required to cover the maximum number of facilities possible were obtained for travel time constraints ranging from five minutes to sixty minutes at every 5-minute interval. This model was evaluated for a greater time range to assess the time required to service the GTHA and to examine the sensitivity of the supply to demand travel time. Using the set of potential CNG Hubs previously identified, the ArcGIS 10.2 Network Analyst is used along with the Location-Allocation solver to determine the optimal locations of the potential sites.

For the conducted analysis, the following statistics were obtained: the number of demand points serviced, the minimum, mean, maximum and standard deviation of the travel time from the facility to the centroid of the zonal demand. Further the spatial selection of facilities was noted.

3.3.5 Validations

To ensure that the selected facilities obtained from the previous analysis will provide sufficient coverage in the GTHA, the location of existing trucking firms in the GTHA were obtained from the Yellow Pages. The coverage of these 1,588 trucking firms was evaluated at 5, 10, 15, 20, 25 and 30-minute driving times with frequently selected CNG hubs. This validation measure ensures that the selected sites based on the estimated demand is also suitable to service the existing trucking firms in the GTHA.

3.4 Transportation Modeling

The Urban Transportation Modeling System (UTMS) is used to determine the traffic flows on the existing road network in the GTHA for both passenger cars and commercial trucks. The standard approach consists of four inter-linked stages: (1) trip generation, (2) trip distribution, (3) mode choice, and (4) trip assignment. One can begin the trip generation by identifying the types of trips generated by vehicle type. In this research, differentiating between light-, medium-, and heavy-duty commercial trips is done since the amount of emissions vary depending on the size of the vehicle. The four vehicles of interest are passenger vehicles (PVs), and the three commercial vehicles: light-, medium-, and heavy-duty commercial vehicles (LDCVs, MDCVs, and HDCVs, respectively).

3.4.1 Passenger Trip Generation

Passenger trip generation was first performed using the parameters shown in Table 3-4. These parameters for trip production (O_i) and attraction (D_j) were estimated using an aggregated zonal regression model in Calgary, Alberta (Maoh et al., 2009). The passenger models have high explanatory power, with an adjusted R^2 ranging from 0.785 to 0.903 for each regression model. Further detailed statistics on these models are provided in Appendix B. These models are based on employment and population counts per zone and provide trip generation estimates for three periods: AM Peak, PM Peak and Off Peak. The Calgary models were applied to the GTHA as there was no readily available TAZ level model to use in this study. The data available to us from the Transportation Tomorrow Survey (2011) provided morning and daily total trips aggregated at the census division level. However, this level of data aggregation is too large to determine traffic flows on the road network. Therefore, the Maoh et al. (2009) models were used to estimate trip generation at the TAZ level in the study area.

Table 3-4: Passenger Trip Generation Initial Parameters

Period	Parameter	O_i	D_j
AM Peak	Population	0.289371	0.134942
	Employment	0.014047	0.269245
PM Peak	Population	0.207640	0.337230
	Employment	0.295264	0.085506
Off Peak	Population	1.133041	1.061202
	Employment	0.740940	0.720359

An hourly distribution of passenger trips obtained from the 2006 Commercial Vehicle Survey stations in the GTHA was used to identify the hourly trip rates. This hourly distribution is shown in Figure 3-7 in which the peaks were broken down as follows: AM Peak (6:00 am to 9:00 am), PM Peak (3:00 pm to 6:00 pm) and the remaining eighteen hours were considered to be Off Peak. The CVS hourly fractions were then used to determine the hourly fractions per peak to obtain the hourly trip productions and attractions per zone. This procedure is outlined in the following equation, where the Peak O_i or D_j is obtained using the models provided in Table 3-4 and the Σ *Peak Fraction* is the sum of all the hourly fractions for all the hours in the peak which hour *h* occurs during.

$$O_i \text{ or } D_j \text{ for Hour } [h] = \text{Peak } O_i \text{ or } D_j \times \frac{\text{CVS Hourly Fraction of Hour } [h]}{\sum \text{Peak Fraction}}$$

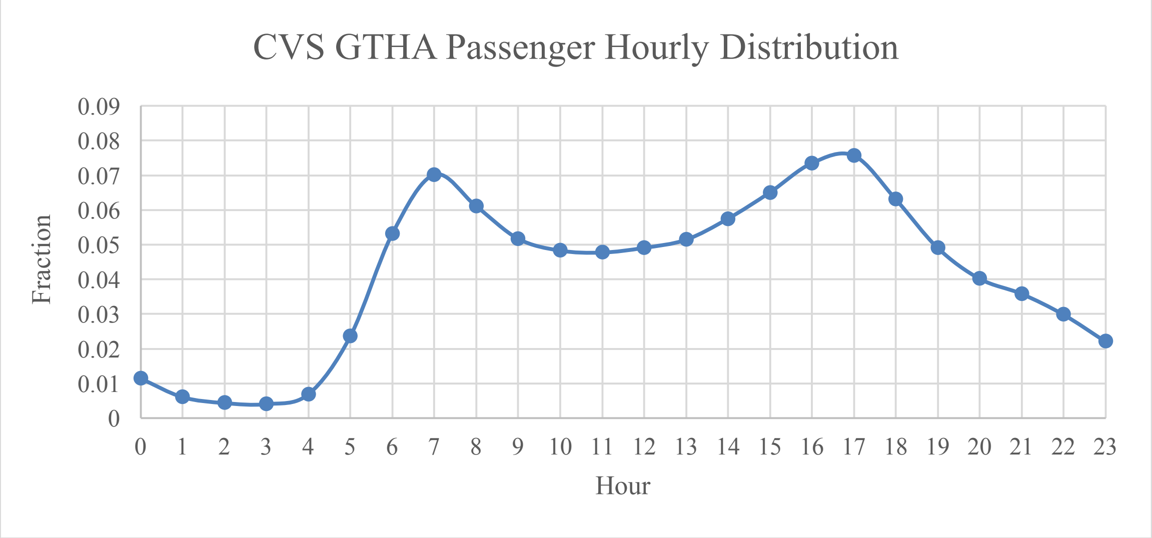


Figure 3-7: GTHA Passenger Trips Hourly Distribution

The passenger trip generation values were then validated with information obtained from the 2011 Transportation Tomorrow Survey. The 2011 TTS data provide total daily origin-destination (OD) trips and AM peak OD trips (6 to 9 am) for all purposes in the GTHA at a census division level (see Appendix D for more information about the TTS data). The AM Peak OD matrix was transposed to approximate the PM Peak OD matrix. The assumption made here is that most the trips that occurred in the morning are work trips (i.e. home-to-work trip) and as such work-to-home trips (i.e. transpose of home-to-work OD) will occur in the PM peak since workers must go home at the end of the day. Both the transposed OD matrix and the AM Peak OD matrix were subtracted from the total daily OD trips to determine the remainder of the daily trips. The estimated peak zonal totals are then compared with the TTS AM Peak, inverted AM Peak (i.e. PM Peak) and the remaining 18 hours. Correlations and percentage difference will be computed using the following equation.

$$\text{Census Division Percent Difference} = \frac{\left|\text{Predicted } O_i \text{ or } D_j - \text{2011 TTS } O_i \text{ or } D_j\right|}{\frac{1}{2}\left(\text{Predicted } O_i \text{ or } D_j + \text{2011 TTS } O_i \text{ or } D_j\right)}$$

If there is a significant difference between the estimated and the observed trip generation values the estimates will need to be improved. In such case, the ratio between the observed and estimated values will be used to rescale the trip productions and attractions at the census division level. The following equation defines the scaling factor used to modify census tract trip productions and attractions.

$$\mathit{Scale\ Factor\ for\ Peak\ h\ (per\ CD)} = \frac{\mathit{2011\ TTS}\ O_i \ \mathit{or}\ D_j \ \mathit{for\ Peak\ h}}{\mathit{Predicted}\ \ O_i \ \mathit{or}\ D_j \ \mathit{for\ Peak\ h}}$$

3.4.2 Commercial Trip Generation

Commercial trip generation for light-, medium- and heavy-duty vehicles is carried out using the previously discussed modeling approach documented in Roorda et al. (2010). The model is applied based on the three zone classifications (CBD, urban, rural and suburban) for each census tract and then scaled up as the Roorda at al. model only provides 12.5-hour predictions.

3.4.3 Trip Distribution

The trip distribution is the second stage in the UTMS. The implementation of a trip distribution model usually relies on some form of a gravity model. Such model relies on three inputs: trip productions O_i, trip attractions D_j and impedance t_{ij} which reflect the cost of moving between i and j. Typically, congested travel time is used in the UTMS to represent the impedance t_{ij}. However, the starting point is a free-flow travel time matrix that is used as a first step into an iterative procedure, as shown in Figure 3-8. The free-flow matrix was generated using the Network Analyst of ArcGIS 10.2.

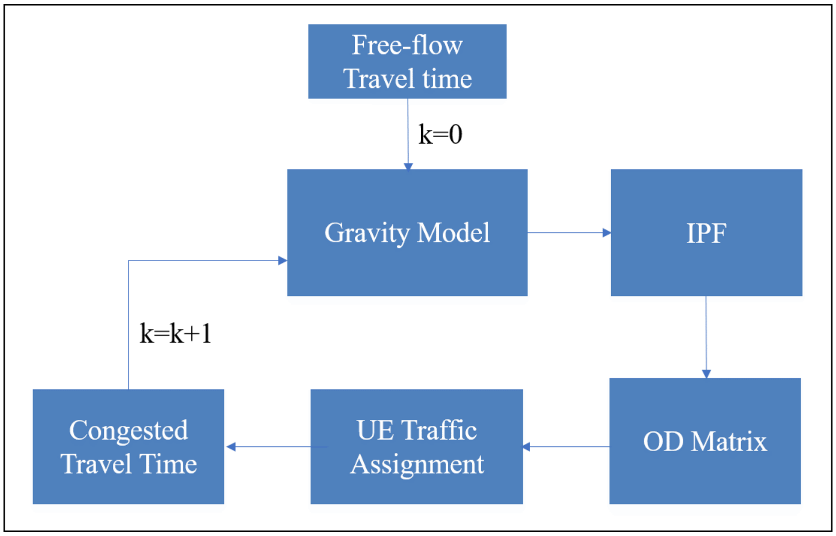


Figure 3-8: Procedure to estimate OD-Matrices

In the case of passenger trips, the following gravity model is employed to produce a seed matrix, $T_{ij}(0)$:

$$T_{ij}(0)=O_i \frac{D_j \, exp\left(-\beta t_{ij}\right)}{\sum_j D_j \, exp\left(-\beta t_{ij}\right)}$$

Where:

T_{ij}: the number of trips originating from zone *i* and destined to zone *j*

O_i: the number of trips originating from zone *i*

D_j: the number of trips destined to zone *j*

t_{ij}: the travel time from zone *i* to zone *j*

The $\boldsymbol{\beta}$ parameter is based on the results reported in Elmi et al. (1999), as shown in Table 3-5.

Table 3-5: Elmi et al. (1999) Trip Distribution Model

Auto Travel Time Model	
Travel Time Parameter, β	-0.07876
T-statistic	-1.26
Log-Likelihood$\times 10^7$	-1.5748

Next, matrix $T_{ij}(0)$ was used as input in doubly-constrained balancing procedure to create the needed OD matrix. The balancing procedure used the Iterative Proportional Fitting (IPF) Method, also known as Fratar method. The procedure uses the seed matrix along with the trip productions and attractions of the required OD matrix as input. After several iterations, the procedure will produce an OD matrix with marginal totals being within a 5% error tolerance of the used trip productions and attractions. A custom IPF OD Estimation Tool was used for the derivation of these passenger OD matrices.

To obtain congested travel times, a stochastic user equilibrium traffic assignment procedure was utilized. However, to ensure the assigned passenger trips only present automobile trips, the estimated OD from the IPF procedure was modified using automobile driver and passenger trip fractions. The latter were based on the 2011 TTS Data obtained from the Data Management Group's iDRS Database. These fractions are based on the daily trips reported at the census division level (see Appendix D). There are 36 fractions representing all potential 36 trip origins and destinations (6 census divisions × 6 census divisions). This matrix is applied to the study area producing a 1326 x 1326 matrix with the 36 fractions assigned to each cell based on its respective origin and destination. This matrix is then multiplied by all the hourly passenger OD matrices to determine the automobile only OD matrices.

OD matrices for commercial trips were also estimated in a similar fashion to the passenger trips. However, the β parameters used in the commercial trip distribution models were based on the work reported in Roorda et al (2010). These parameters, as shown in Appendix A, vary for light, medium and heavy commercial vehicles. To calculate the congested travel time, all trips were assigned to the network in one run. For that, all non-passenger trips were converted to their passenger car equivalent units (PCUs). That is, commercial vehicle trips were scaled up to represent their passenger equivalency using the factors of 1.5, 2 and 2.5 for light, medium and heavy-duty commercial vehicles, respectively. In order to obtain the congested travel times, all of the studied vehicles were presented in PCUs and then assigned to the network in one step using the stochastic user equilibrium model.

The output of the traffic assignment is an updated (i.e. congested) travel time matrix that accounts for the effect of traffic on the road network. The resulting congested travel time matrix was then used as the impedance for the creation of updated passenger and commercial origin-destination matrices. These updated OD matrices were then used in a second iteration as in Figure 3-8. The iterative procedure continued until the congested travel times stabilized. The result is then used to calculate the final OD-matrices. In total, three congested travel time matrices representing each peak were generated. In each peak case, the hour pertaining to the highest trip production levels was used in the traffic assignment (AM Peak: 7 am, PM Peak: 5 pm and Off Peak: 6 pm). Hourly OD matrices were then calculated by using the peak-specific congested travel time matrix for which an hour belongs.

3.4.4 Traffic Assignment

Using the hourly OD matrices, traffic assignment was performed on an hourly basis for all modes. Pseudo-links were created to connect the census tract centroid with the GTHA road network. The road network used was derived from Ontario's major road network dataset. Trip assignment (TA) was conducted using a stochastic user equilibrium model. A multi-class traffic assignment was employed to assign the four classes of trips (passenger, light-, medium-, and heavy-duty trucks) individually to the network. The multi-class TA is an iterative procedure that calculates the travel time t_l^k on each road link *l* per iteration *k* after assigning the four classes of vehicles to the network. For any two consecutive iterations *k* and *k*+1, the following condition is examined to verify if the travel time has stabilized in which case the multi-class TA achieved convergence:

$$max\left|t_l^{k+1} - t_l^k\right| \leq \varepsilon$$

Where ε is the convergence tolerance and usually set to a small value like 3 minutes. In each iteration *k*, the TA starts by assigning the passenger and light-duty commercial vehicles on the road network and using the assigned flows to update the travel time for the subsequent vehicles to be assigned. Then, the MDCVs are assigned and the network and then the travel time for each link is readjusted prior to assigning the HDCVs. Upon assigning the HDCVs, road link travel time t_l^k is re-calculated taking into consideration the assigned flows from the four vehicle classes.

The parameters used for the assignment routine are provided in Table 3-6. The link performance function used to adjust the travel time as traffic is introduced to the road is also provided. When the flow on link a, v_a is greater than the design capacity, the travel time is updated for the link with the existing traffic flow on the road. The traffic assignment and free-flow adjustments are carried out using an in-house traffic assignment software.

Table 3-6: Trip Assignment Parameters

Parameter	***Passenger and Light***	***Medium and Heavy***
α (arterial)	0.15	0.15
α (freeway)	0.15	0.15
β (arterial)	4	4
β (freeway)	4	4
θ	-0.16	-10
traffic convergence criterion	100	100
Maximum Number of iterations	200	200

$$t_a(v_a)=t_a^0\left[1+\alpha\left(\frac{v_a}{C_a}\right)^\beta\right]$$

Where:

C_a= design capacity of road link a

t_a^0= free-flow travel time which corresponds to design capacity

v_a= volume assigned to road link a

It should be noted that while passenger and light-commercial trips were subjected to a stochastic user equilibrium assignment (θ = -0.16), the medium and heavy commercial trips were derived using a deterministic user equilibrium assignment (θ = -10). θ is a parameter associated with the travel time variable in the multinomial logit model used in the stochastic user equilibrium procedure. This θ captures the variation in taste when it comes to route choice. In the case of MDCVs and HDCVs, θ was set to a large negative value (i.e. -10) to allow the trip assignment algorithm to capture the more deterministic behaviour associated with the route choice of these trucks. Here, the majority of trucks favour the shortest path over any other path making their route choice more predictable (i.e. deterministic) compared to smaller vehicles. In other words, in the case of MDCVs and HDCVs, the stochastic user equilibrium model collapses to a deterministic user equilibrium model. By comparison, a θ value of -0.16 enables the traffic assignment to account for variation in taste in the intra-urban passenger and light commercial trips (Si et al., 2010).

To validate the simulated traffic flows, the 2006 Commercial Vehicle Survey (CVS) traffic counts were used. Fifteen count stations fall within the study area. It is assumed that links falling in proximity with a count station and links heading in the specified direction are included in the count. Also, hourly Vehicle Kilometers Traveled (VKT) based on the simulated flows were calculated and compared to the MITL Study (2014) as their study area is roughly similar to ours.

Appendix D presents a visual summary of the procedure used for the analysis.

3.5 Emissions Quantification

EPA's MOVES2014a is chosen to obtain emission rates (ER) needed to determine the emission inventories of the five scenarios presented in Table 3-7. A county scale analysis was conducted to quantify the emissions during a typical weekday at 12 pm. To evaluate seasonal differences, emission rates were generated for both of January and August. MOVES2014a does not currently have the capacity to model CNG Heavy-Duty Trucks, however it is capable of modelling CNG Transit Bus. The proposed analysis will model both a CNG and diesel transit bus based on a heavy-duty fleets' fuel characteristics and heavy-duty truck driving cycle then scale the outcomes to heavy-duty trucks.

Table 3-7: Fleet Scenarios

Regime	**Criteria**
A. Status Quo	No adoption of CNG
B. CNG Adoption	Low CNG Adoption (10%)
	Medium CNG Adoption (30%)
	High CNG Adoption (60%)
	All CNG Adoption (100%)

Emission rates per mass units and energy consumption per energy unit of activity will be estimated for the varying CNG adoption scenarios. A county scale analysis will be conducted to quantify the emissions from the existing truck fleet and with proposed CNG adoption. The emissions for an hour with higher traffic flows on a weekday in January and in August will be quantified to evaluate seasonal differences. MOVES2014a does not currently have the option to model Heavy-Duty Trucks using CNG, however it allows for the modelling of a CNG Transit Bus. The proposed analysis will model both a CNG and diesel transit bus based on a heavy-duty fleets' fuel characteristics and heavy-duty truck driving cycle then attempt to scale these findings to heavy-duty trucks.

3.5.1 MOVES Input

The emissions inventory for several pollutants will be obtained from running MOVES. The following is the list of pollutants for which emission inventories will be estimated: Total Gaseous Hydrocarbons (HC), Carbon Monoxide (CO), Oxides of Nitrogen (NO_x), Methane (CH_4), Formaldehyde, Acetaldehyde, Arcolein, Ammonia (NH_3), Non-methane Hydrocarbons (NMHC), Volatile Organic Compounds (VOCs), Atmospheric CO_2, CO_2 Equivalent, Primary Exhaust Particulate Matter (PM2.5 and PM10), Organic Carbon, Elemental Carbon, and Sulfate Particulate. These emissions cause a wide variety of negative environmental and health effects such as smog, global warming and increased respiratory and cardiac illnesses. A full list of pollutants and some of their effects and are presented in Appendix E. Additionally, the total energy consumption of the fleet will be computed.

MOVES reports emissions for several vehicle operating processes, such as running and start emissions. Process emissions are dependent on the pollutants examined. The current analysis provides results for the following emission processes: running exhaust, start exhaust, brakewear, tirewear, crankcase running and start exhaust, refueling displacement vapour loss and refueling spillage loss. Running exhaust are the tailpipe emissions released during vehicle operation on the road network with a fully heated up engine. Start exhaust include the emissions from the engine while it is heating up both on- and off-road network. The use and eventual wear down of brakes and tires emit PM, which constitute the brakewear and tirewear emissons. These emissions should be the same for both fuel types as they are not related or associated to the engine. Crankcase running and start emissions *"represent the gases that are not combusted in the engine pistons which subsequently leak into the atmosphere*" (MITL, 2014). Emission rates are either provided as a rate per vehicle (for start, crankcase start and a portion of the refueling losses) or a rate per distance (for running exhaust, brakewear, tirewear, crankcase running exhaust, and refueling losses).

Table 3-8 summarizes the data required as input for MOVES. Most of the required information is source (or vehicle) type and/or road type dependent. For example, the average speed distribution per vehicle type varies per road type. The MOVES Run Specification is an XML file which outlines the criteria to be examined for the specific analysis. The current analysis will be a county-wide analysis modelling a custom domain.

Appendix E provides all the criteria and selections detailed in the Run Specification and additional data used for the analysis.

The MOVES source or vehicle types that were used in the analysis are: Transit Buses and Combination Short-Haul Trucks. Vehicle count and age distribution of heavy-duty trucks was obtained from the 2012 GTHA Polk Data count. These properties were also applied to transit buses to allow for consistency when scaling. In the absence of readily available and complete Canadian data sources, default MOVES data were utilized. The average speed distribution is assessed on a per hour basis and accounts for the duration of time a vehicle spends in each of the sixteen MOVES Speed Bins (see Appendix E). The average speed distribution for a HDCV in the GTHA was not readily available. The TomTom Traffic Index measures congestion worldwide. The congestion level as defined by TomTom, is a percent increase of flow conditions from a free flow situation. Miami, Florida has comparable daily, morning and evening peak congestion levels to Toronto, Ontario. Due to the similarities, the Miami-Dade County average speed distribution profile for HDCVs was used for analysis in the GTHA. The American default fuel formulation was used in the place of Canadian values, since the MOVES User Manual stresses the importance of ensuring that the relationships between the different fuel properties examined are accurate.

MITL (2014) reports a thirty-year average of Environment Canada's hourly temperature and relative humidity records for the GTHA. These averages were used as meteorological inputs for this study. MOVES utilizes four major road types that can be classified based on access (restricted or unrestricted) and road type (rural or urban). Where restricted roads are only accessible by on-ramps. A procedure, relying on the existing road network and census tracts, was devised to classify the road network into urban and rural. A census tract was considered rural if it was not in the city core or did not have any major highways. Road links that were in these areas were considered rural roads.

Table 3-8: Required Input Data for MOVES

Data Required	Level of Detail	Potential Source	Source Used
Age Distribution, Source Type Distribution	Fraction of vehicles that are new to 30 years old based on source type (ie. Heavy-duty truck, Passenger Car). The population of each source type/vehicle.	• Polk Data • Auto Insurers • MOVES Default Data (US)	• GTHA Polk Data
Average Speed Distribution	Average speed per vehicle type per time of day per road type. The average fraction the vehicle spends in the average speed bins defined by MOVES. (Road Type, Day and Vehicle Type)	• GPS Data • INRIX Data (MITL, 2014) • MOVES Default Data (US)	• Default MOVES Data
Fuel Formulation	Properties for the fuels based on existing formulations.	• MOVES Default • Further research	• Default MOVES Data
Meteorology	Temperature and Relative Humidity at an hourly level based on month of study	• Environment Canada	• MITL, 2014 Summary
Ramp Fraction	Fraction of freeway VHT occurring on ramps (fraction of time not distance) as compared to the total time on restricted roadways and ramps.	• Traffic Assignment Results	• MOVES Default of 0.08
Road Type	The assignment of roads following the classifications: • Rural or Urban Restricted Access • Rural or Urban Unrestricted Access	• Existing Road Shapefiles	• Shapefile and distinguish based on speeds or area location
Road Type Distribution	The VMT fraction each vehicle type spends on each road type.	• Traffic Counts and Studies	• Traffic Assignment Results
Start Information	Starts by source type per age category by hour and day.	• GPS Data • Associate with trip or truck count • MOVES Calculation	• MOVES Calculates it
VMT	VMT (Vehicle Miles Traveled) fraction per hour per road type	• Traffic Assignment Results per vehicle type	• Traffic Assignment Results per vehicle type

Figure 3-9 presents a map of this delineation and the resulting rural and urban roadway classifications. Links identified as Freeways or Highways were classified as restricted while links identified as Arterials were classified as unrestricted. Ramps were classified as restricted if at least one end is connected to a freeway or highway or connected to a ramp with “highway” in its name, while unrestricted ramps are usually connected to two arterials. These classifications are presented in Table 3-9.

Based on the previously discussed methodology, most of the links in the GTHA are urban unrestricted. With these road type classifications, the proportions of assigned traffic on each road type is used to determine the Road Type Distribution. The VMT of HDCVs is obtained from the previous section, although the results require conversion from kilometres to miles.

MOVES only has the capability of modeling hoteling emissions for long-haul combination trucks. Since the current analysis only focuses on short-haul combination trucks, hoteling will not be considered in this study. Providing the number of starts in MOVES is optional, if no input is provided MOVES computes the number of starts per vehicle and the related emissions.

Table 3-9: Roadway Classification Results

Road Classification	Ramps	Links	Total	Percentage
Rural Restricted	117	0	117	1%
Rural Unrestricted	34	1005	1039	13%
Urban Unrestricted	324	3482	3806	49%
Urban Restricted	1409	1461	2870	37%

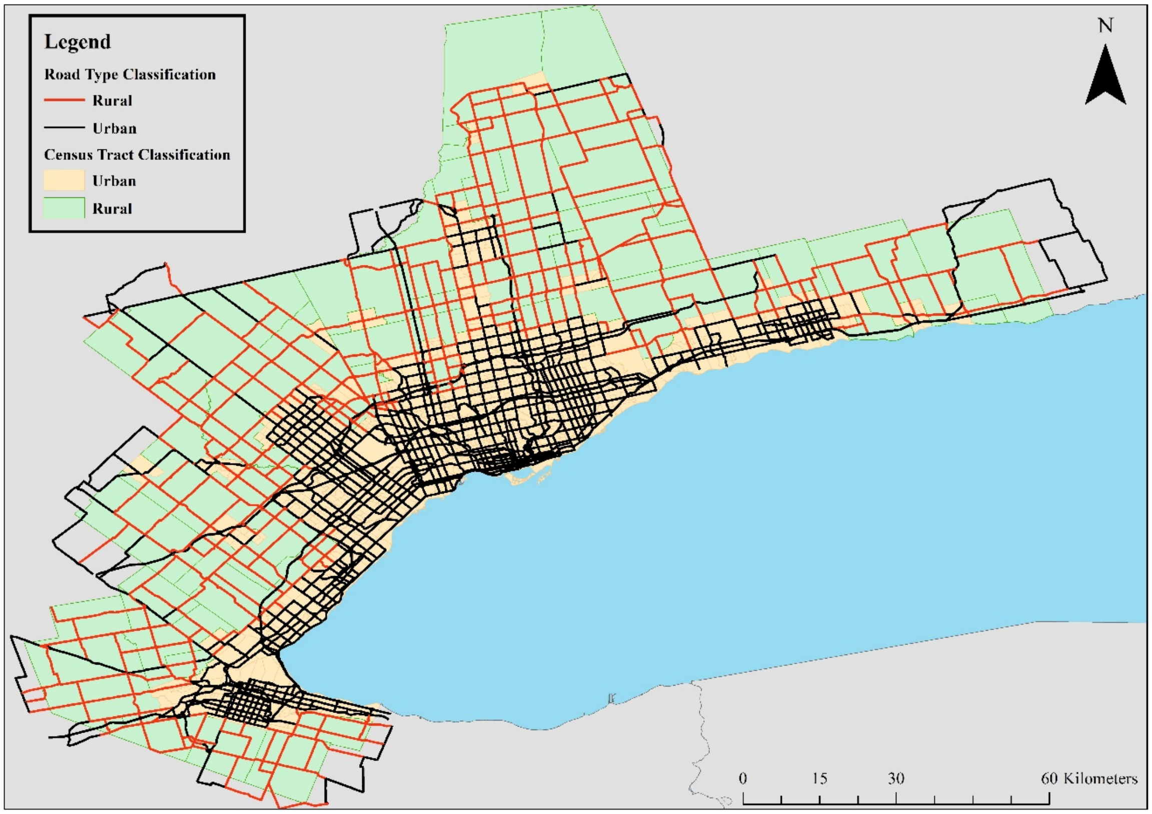


Figure 3-9: Census Tract and Road Type Classification

3.5.2 Processing MOVES Output

A MOVES post-processing script produced output tables with the emission rates. The results are then retrieved through the MySQL Workbench and exported to Microsoft Excel. The two MOVES output rate tables used in this study were “rateperdistance” and “ratepervehicle”. The *rateperdistance* rates provide the running emissions whilst the *ratepervehicle* table provides emission rate associated with starting a vehicle. The following equation is used to obtain emission rate (ER) estimates for CNG HDCVs:

$$ER\ (CNG_{HDCV}) = ER\ (Diesel_{HDCV}) \times \frac{ER\ (CNG_{TransitBus})}{ER\ (Diesel_{TransitBus})}$$

Running Emissions

The running rates for this analysis were specified in the units of grams per vehicle-kilometre. These rates are given for each road type, speed bin and MOVES process. To facilitate the computation of the running emissions, the HDCV traffic results were prepared using two approaches. The first involves summing all the VKT for each speed bin and road type and placing these results in a matrix (speed bin by road classification) and just simply multiplying this total with the respective emission rate. Whilst the second approach involves interpolating emission rates for each specific link based on its speed. These two approaches are used in this study and compared.

The congested speeds were required to determine which speed bin the road link operates in. These congested speeds were obtained using the Link Performance Function previously discussed in Section 3.2.4. The free flow time (t_a^0) of each road link a was computed using the link length l_a and the posted speed s_a. This speed was adjusted with the assigned volume v_a of PVs, LDCVs, MDCVs and HDCVs. The following equations present this process.

$$t_a^0 = \frac{l_a}{s_a}$$

$$t_a(v_a) = t_a^0 \left[1 + 0.15 \left(\frac{v_a}{C_a} \right)^4 \right]$$

$$Congested\ Speed = \frac{l_a}{t_a(v_a)}$$

The sum of HDCV VKT per MOVES speed bin and road type class were summarized in a matrix. This matrix was manipulated in preparation for the different diesel-CNG scenarios to enable a quick calculation. The *rateperdistance* table was then filtered by pollutant and process, then a *rateperdistance* matrix (road class=i, speed bins=j) was created for each fuel, pollutant, process and examined season. Each matrix was then multiplied by the VKT matrix for each studied scenario as shown in the following equation:

$$Running\ Emissions = [Running\ ER] \times [VKT]$$

The interpolation process used the adjusted speed results and the MOVES emission rates to obtain an emission rate for each specific link.

Starts Emissions

The units for Starts Rates are in grams per vehicle. The Starts inventory is obtained by multiplying the *ratepervehicle* by the vehicle population. The total GTHA HDCV population used throughout this study is 58,815. This value is applied to the All Diesel and All CNG scenario to estimate the quantity of emissions, whilst the other scenarios used the vehicle breakdown in Table 3-10 for estimation. This was done for each process where the rate was provided, and then these values were summed for each pollutant.

Table 3-10: Vehicle-Fuel Allocation

CNG Implementation	10%	30%	60%
CNG	5,881	17,645	35,289
Diesel	52,934	41,170	23,526

3.6 Multi-Criteria Decision Analysis

The multi-level multi-criteria hierarchy from Maimoun et al. (2016) (presented in section 5.2) was modified for the current analysis, as shown in Figure 3-10. The purpose is to consider and evaluate the three pillars of sustainability: economic, environmental and social. Various ranking and weighting methods will be applied to determine which fueling scenario is the most sustainable, providing the most environmental, social and economic benefit.

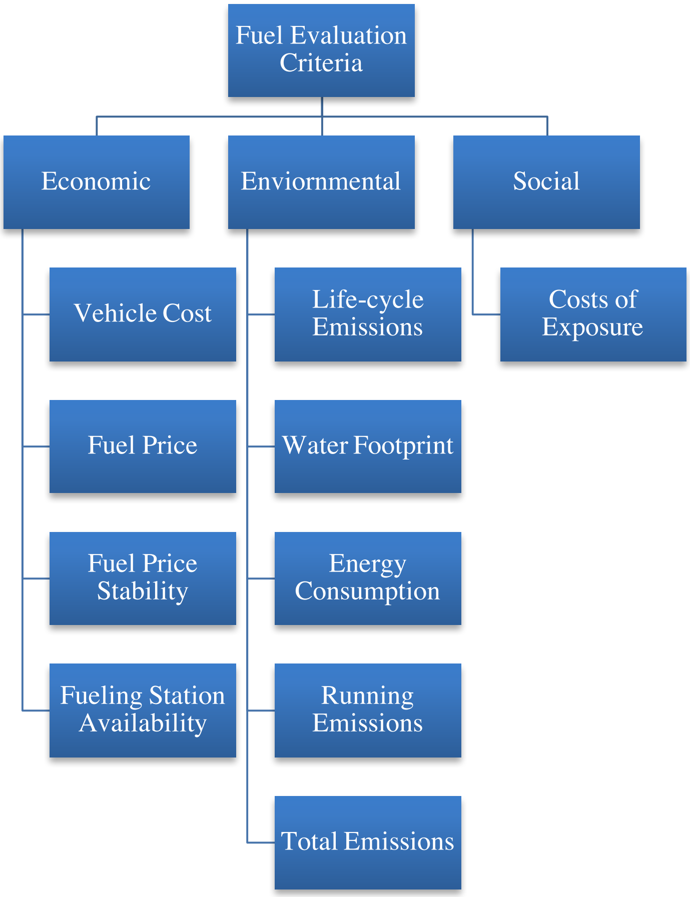


Figure 3-10: MCDA

3.6.1 Economic Pillar

The economic factors considered in this analysis include: vehicle cost, fuel price and stability, and the availability of fueling stations. The costs for both a new and converted NGV are greater than vehicle costs of a diesel truck as the latter are more in demand and the majority of the Canadian heavy-duty market is powered by diesel. Various sources, as presented in Table 3-11, have suggested lower costs associated with diesel trucks.

On the other hand, CNG fares much better with respect to fuel price and stability. Figure 3-11 presents historic diesel and CNG prices in Ontario. The price of CNG has been consistently lower and more stable than diesel for the past twenty-five years (sample standard deviation: 29.1 (diesel) vs. 13.3 (CNG)). To ensure that this trend is also reflected at an annual level, the standard deviation for the years 2011 to 2017 were examined, and are presented in Table 3-12. Again, the CNG fuel cost standard deviation was found to be lower than diesel. However, in 2014, the differential between the two standard deviations was not as substantial as exhibited in previous years. This is likely an outcome of higher CNG prices in 2014. This trend continues in 2015, 2016 and 2017. The price differential decrease is possibly related to reduction of CNG suppliers in the GTHA as some of the refueling stations have closed. Ontario fuel prices are currently in CNGs favour, however the price of CNG is per gasoline equivalent litres and does not consider CNGs lower performing fuel economy. Nevertheless, when fuel economy was considered in Maimoun et al. (2016) it is found that CNG is still a cheaper option.

Table 3-11: Additional Costs associated with CNG HDCVs

	Currency	***Average***	***Source***
Cost of Conversion	US	$25,000.00	Omnitek Corp[1]
	US	$32,500.00	Trucking Info[2]
Incremental Cost of CNG (with respect to diesel)	US	$60,000.00	Reuters[3]
	CDN	$75,000.00	Canada Gas Association[4]
	CDN[5]	$50,000.00	Marbek[7]
	CDN[6]	$70,000.00	

[1] http://www.omnitekcorp.com/projectmanage.htm
[2] http://www.truckinginfo.com/channel/equipment/article/story/2012/06/dual-fuel-conversion-saves-big-money-every-day-supplier-trucker-says.aspx
[3] http://www.reuters.com/article/us-trucks-natural-gas-idUSBRE92L07620130322
[4] http://www.cga.ca/wp-content/uploads/2016/07/2-pager-Transportation-EN-1.pdf
[5] SI (Spark Ignited) Engine
[6] HPDI (High pressure direct injection) Engine
[7] http://www.xebecinc.com/pdf/Marbek-NGV-Final-Report-April-2010.pdf

A major hurdle to alternative fuel use is the lack of refueling accessibility. The first portion of this study addresses this concern and proposes the implementation of a virtual pipeline to provide on-site refueling. Nevertheless, in 2014 there were only five public access CNG stations in Ontario (Natural Gas Use in Transportation Roundtable, 2014). Further, a Google search conducted in November 2017 found that there are thirty NG stations in Ontario, while there are more than four-hundred stations supplying diesel (approximately 428 diesel stations).

Table 3-12: Average Ontario Annual Fuel Costs and Standard Deviation (cents/L)

Year		**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017[1]**	**Min**	**Max**	**Mean**
Mean	***Diesel***	124.65	125.30	127.58	131.36	108.35	94.03	101.70	94.03	131.36	116.14
	CNG	73.59	71.47	70.74	81.24	82.89	82.00	83.69	70.74	83.69	77.94
Standard Deviation	***Diesel***	4.32	4.40	4.81	7.81	6.38	4.05	5.56	4.05	7.81	5.33
	CNG	1.32	0.73	1.20	6.03	0.60	1.22	1.38	0.60	6.03	1.78
Price Differential		51.06	53.83	56.84	50.12	25.46	12.03	18.01	12.03	56.84	38.19
[1]CNG Rates for 2017 only reflect rates from January-April 2017 as the last NG station monitored by the Ontario Ministry of Energy closed											

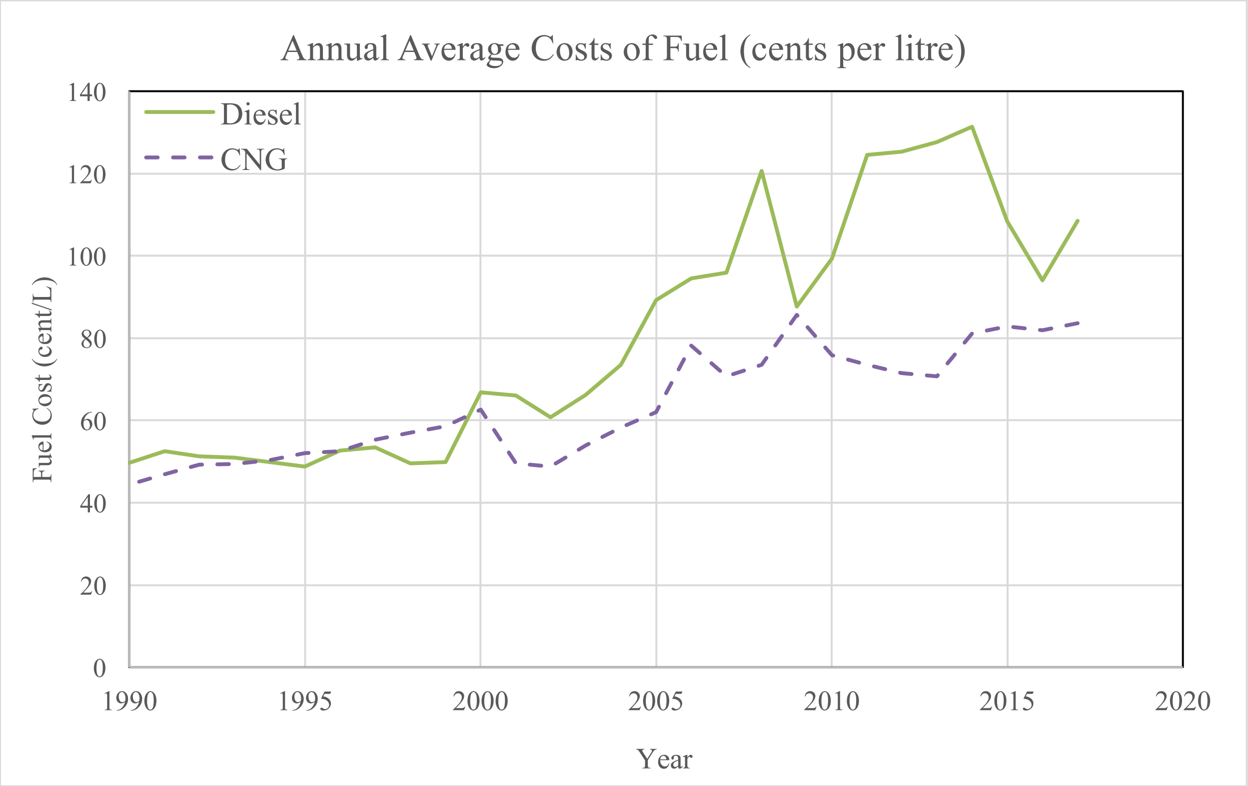


Figure 3-11: Annual Average Costs of Fuel in Ontario (Ontario Ministry of Energy)

3.6.2 Environmental Pillar

The environmental factors that were evaluated in this study include: water footprint, life cycle emissions, total energy consumption, and tailpipe emissions. Unlike Maimoun et al. (2016) the power density associated with fuel production was not evaluated for this analysis as the two fuels examined in this study were reported to have similar values.

The water footprint of a product is defined as "*the volume of freshwater used to produce the product measured over the full supply chain*" (Hoekstra et al., 2009). The water footprint value also includes consumption of surface water, groundwater and rainwater and any freshwater used to treat water to meet water quality standards. The water footprint values for both CNG and diesel fuel are obtained from Gerbens-Leenes et al. (2008) and are 0.109 m^3/GJ and 1.058 m^3/GJ, respectively.

Argonne National Laboratories developed The *Greenhouse gases, Regulated Emissions, and Energy use in Transportation* (GREET) Model to produce estimates of life cycle emissions of alternative fuels. The GREET Fleet Footprint Calculator can be used to evaluate the greenhouse gas (GHG) emissions and petroleum usage of heavy-duty vehicles on a well-to-wheels (WTW) basis. GREET outputs can be used to perform a comprehensive comparison of alternative fuels as the model evaluates GHG emissions and energy use throughout the entire fuel lifecycle, transporting the fuel to the pump and vehicle operation. Lower WTW GHG emissions and petroleum usage denotes a smaller environmental impact.

Natural Resources Canada developed the GHGenius model. GHGenius is a spreadsheet life cycle assessment model that can also be used to quantify the life cycle energy consumption and GHG generated of various fuels. This model quantifies the GHG emissions from entire life cycle starting from fuel extraction or growth to vehicle operation. The GHGenius model was used in Shahraeeni et al. (2015) while GREET was used in Maimoun et al. (2016). The former and latter studies were conducted in Canada and the United States, respectively. The two tools are assessed in this study to compare results. Discussion on these two model inputs is provided in Appendix L, for the GHGenius model, many defaults for the Ontario region were used.

Total emissions obtained from MOVES include running and start emissions. As noted earlier, start exhaust was obtained using MOVES defaults and therefore it will not be considered in all the scenarios as the starts estimated are based on MOVES average rates. The emissions obtained were discussed in the previous section and the objective of the MCDA is to reduce all types of emissions. Non-methane hydrocarbons and equivalent carbon dioxide emissions will not be included in the analysis as the NMHC's are already accounted for in the total hydrocarbon emissions and the components of CO_2eq emissions are already assessed.

3.6.3 Social Pillar

This pillar of sustainability reflects the impacts on the general population. The social effects assessed are the exposure costs of the following pollutants: $PM_{2.5}$, NH_3, SO_2, NO_x and VOCs. The Clean Air for Europe (CAFE) Programme produced average exposure cost estimates per tonne of emission for these pollutants in the European Union (2005). The impacts quantified include the cost of human exposure to $PM_{2.5}$ and ozone and the effects on health and crops due to ozone exposure. The effects of NH_3, SO_2 and VOCs are marginal in comparison to the effects of ozone and $PM_{2.5}$. Their effects however are considered when examining ozone as the formation of ozone occurs when there is sufficient sunlight and is dependent on the concentration of VOCs, NO and NO_2 in the atmosphere.

3.6.4 Ranking Approaches

Several approaches are used to rank the alternative fueling scenarios. As previously discussed there are five potential fueling alternatives. For the three sustainability pillars, every alternative must be assessed for each criterion and then must be ranked with respect to one another. A value of 1 is assigned to the best fueling scenario, whilst a value of 0 is assigned to the worst fueling scenario and the other three scenarios are ranked based on their relative rank from the worst and best scenario. The following equations present the formulas used to determine the relative ranks. Equation 1 is used when a lower value is ideal (such as cost), whilst equation 2 is used when a higher value is more beneficial (such as fueling stations).

$$\textit{Equation 1: } r_{ij} = \frac{x_{ij} - min_j}{max_j - min_j}$$

$$\textit{Equation 2: } r_{ij} = \frac{max_j - x_{ij}}{max_j - min_j}$$

Where r_{ij} is the rank of scenario *i* with respect to criteria *j* and x_{ij} is the value of scenario *i* with respect to criteria *j*. Then, weights for the criteria within a sustainability pillar are obtained. This process was accomplished using various ranking methods. The first three methods are grouped together as their premise is quite simple, weights are determined based on the decisions makers' view of their importance of each criteria. The second group of methods utilize entropy derived weights to determine the importance of each criteria within each pillar of sustainability. The first group of methods are: (1) Rank Sum, (2) Rank Reciprocal, (3) Assigned Weights. The second group of methods are: (4) Simple Additive Weighting Method with Entropic Weights (SAW) and (5) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The last two approaches are the second group of methods and were utilized in Maimoun et al. (2016).

The SAW Method is used in conjunction with the first four methods to obtain the Sustainability Indicator (SI) or the comparison index for each pillar. This method utilizes the rank, r_{ij} and weights obtained using the specified method. The following equation is used to compute the SI:

$$SI_p = \sum_{j=1}^{k} W_j \times r_{ij}$$

Where *k* is the number of criteria that are assessed for pillar *p* and W_j is the assigned weight to criteria *j*. Once each of the three SI's are computed, the overall sustainability indicator can be computed with again using the SAW Method or by assigning weights to each pillar.

Method 1 and 2: Rank Sum and Rank Reciprocal

The rank sum and reciprocal methods have a similar procedure but use a different weighting formula. Each sustainability pillar's criteria were ranked in an order of most to least important in its effect on the fuel choice. This ranking is subjective and will depend on the decision-makers' perspective and priorities associated with transitioning to an alternative fuel. The following formulas provide weights that can be used to determine SIs. These two approaches were utilized when examining the economic and environmental pillar.

The rank sum approach:

$$W_j = \frac{(n - r_j + 1)}{\sum_k (n - r_k + 1)}$$

The rank reciprocal approach:

$$W_j = \frac{\frac{1}{r_j}}{\sum_k \frac{1}{r_k}}$$

Method 3: Assigned Weights

The weights for the environmental pillar were assigned based on reasoning and the importance of each indicators criteria. These assigned weights were applied to the environmental pillar at the sustainable index level and at the running and total emissions level. This application will be explained in greater detail in the following section.

Method 4: Entropic Weight and SAW

The entropic weight is computed based on the dispersion of the performance of each alternative. The entropic weight (W_j) of criterion j is computed using the following equations as presented in Madani et al. (2014).

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$

where:

$$d_j = E_j - 1$$

and

$$E_j = -\frac{1}{ln(m)} \sum_{i=1}^{m} P_{ij} \cdot ln(P_{ij})$$

and

$$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}$$

E_j above is the "*entropy of normalized performances under a given criterion*," (Maimoun et al., 2016) and m is the number of alternatives. Once the entropic weight is determined it is then utilized with the SAW Method.

Method 5: TOPSIS

The TOPSIS Method, which was developed by Hwang and Yoon (1981), selects the alternative that has the least performance distance from the ideal solution. The relative distance, CL_i^+ provides the decision maker a gauge of the alternative's performance with respect to the other alternatives and the "ideal performance". The lower the relative distance, the better the alternative. The procedure and the following formulae are outlined in detail in Madani et al. (2014). The first step is to normalize the performance to obtain a normalized utility N_{ij} as follows:

$$N_{ij}=\frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}$$

Next, a weighted normalized performance (V_{ij}) for each alternative *i* with respect to criteria *j* is obtained as follows:

$$V_{ij}=N_{ij}\cdot W_{ij}$$

The best (V_j^+) and worst (V_j^-) weighted normalized performance for each criterion are then identified and used to compute distance from the best and worst scenario d_i^+ and d_i^-, respectively, as follows:

$$d_i^+=\sqrt{\sum_{j=1}^{n}\left(V_{ij}-V_j^+\right)^2} \qquad and \qquad d_i^-=\sqrt{\sum_{j=1}^{n}\left(V_{ij}-V_j^-\right)^2}$$

Finally, the calculated distances are then used to compute the relative distance as follows:

$$CL_i^+=\frac{d_i^+}{d_i^+ + d_i^-}$$

3.6.5 Application of Ranking and Data Used for Analysis

The ranking methods and the various weights previously discussed will be used at multiple levels of the analysis. Figure 3-12 provides a visual breakdown of the overall analysis and the different weighting and ranking methods used. This section will discuss each pillar in detail and then discuss the different combinations used to combine the three pillars.

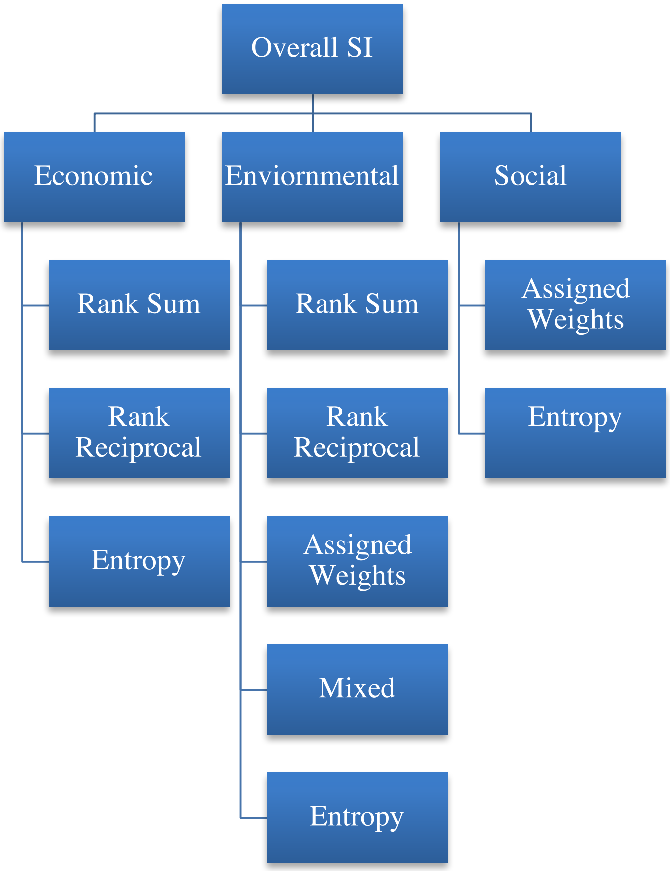


Figure 3-12: Weighting and Rank Approaches used for Each Sustainable Pillar

Economic

The economic criteria were ranked in three different orders and are presented in Table 3-13. This assortment of rankings reflects the variable preferences of different decision-makers. For example, Rank 2 reflects a scenario where the fuel price is the most important factor in a decision to transition to an AF. Economic Rank 1 prioritizes the vehicle costs and Rank 2 prioritizes fuel price. Rank 3 slightly differs from Rank 2 as it sets fuel price stability as the least important criterion. These three ranking orders are then evaluated using the Rank Sum and Rank Reciprocal Approaches. Entropy weights are also determined for the economic category and are used with the SAW method and as starting weights for TOPSIS.

Table 3-13: Economic Rankings

Criterion	Best Option	Rank 1	Rank 2	Rank 3
Vehicle Cost	Diesel	1	2	2
Fuel Price	CNG	2	1	1
Fuel Price Stability	CNG	4	3	4
Fueling Station Availability	Diesel	3	4	3

Environmental

Since there is no clear best or worst fueling alternative for the tailpipe emissions criterion, the relative ranks, r_{ij} must be obtained using a different approach to rank and weigh the pollutant impact. In Maimoun et al. (2016) entropy-derived weights were used at every level of the MCDA. This approach will be used and compared with other ranking and weights as will be discussed later in this section. The relative ranks, r_{ij} of the remaining environmental criteria are quite simple as there is a clear best and worst scenario for each criterion.

The GREET lifecycle GHG emissions favoured diesel-powered HDCVs, while the GHGenius results favoured a CNG-powered HDCVs. However, literature has reported lower levels of GHGs for CNG. For instance, the Natural Gas Use in Transportation Roundtable (2010) reports a 21% reduction in CNG relative to diesel in lifecycle GHG emissions. This trend was also found in Shahraeeni et al. (2015) and Rose et al. (2013). The difference between the two model outputs may be a result of different study areas and fuel characteristics (i.e., America vs. Canada). Due to this discrepancy, the GHGenius results will be used for further analysis since they are more in line with the findings from the literature and pertain to a Canadian tool that relies on Canadian data.

Running and Total Emissions Weight

A selected list of key pollutants from MOVES will be analyzed for running and start-related emissions. First, the relative rank for each pollutant and alternative is estimated, this rank will be then multiplied by the resulting weight obtained from the following procedure:

1. The pollutants examined were classified into three groups: GHG, Key Pollutants and Air Toxics; these groups are summarized in Table 3-14.
2. Both the GHG and Air Toxics group utilizes the pollutants' highest (i.e., maximum) reported emission in any fueling scenario (ie. All Diesel, All CNG).

3. The maximum value is then used as to determine the pollutants' weight and will be referred to as "*Pollutant Max Emission*". The GHG group includes pollutants that contribute to global warming.

The Pollutant Max Emissions were converted to their carbon dioxide equivalent emissions by using their respective global warming potential (GWP) using the following equation:

$$CO_2eq=[Pollutant\ Max\ Emission]\times GWP$$

The CO_2eq values allows for the pollutants to be compared at an environmental impact level. The weight of each GHG pollutant was then obtained using the following equation:

$$GHG\ Weights=\frac{CO_2eq}{\sum_1^3 CO_2eq\ for\ All\ Examined\ GHGs}$$

The group of Key Pollutants' emissions are measured by the Government of Canada and reported annually in the Air Pollutant Emission Inventory (APEI) (Environment and Climate Change Canada, 2017). The inventory for these pollutants is presented at a sector and overall total annually. The Transportation and Mobile Equipment sector is classified by transportation mode, vehicle and fuel type. The emissions associated with heavy-duty diesel vehicles are obtained for 2015 and the impact on the Ontario-wide total is calculated using the Emission Impact (%) equation presented below and the results are in Table 3-14. A sizeable portion, approximately 18% of total Ontario NO_x emissions are emitted from heavy-duty diesel vehicles. Therefore, a reduction in heavy-duty diesel vehicles will reduce overall Ontario-wide emissions of NO_x. The percentages obtained are then used to create weights for the SI.

$$Emission\ Impact\ (\%)=\frac{Pollutant\ Emissions\ (Heavy\text{-}Duty\ Diesel\ Vehicles)}{Grand\ Total\ Pollutant\ Emissions\ from\ APEI}$$

$$Key\ Pollutant\ Weights=\frac{Emission\ Impact\ for\ Pollutant\ i}{\sum_1^7\ Emission\ Impacts\ for\ All\ Key\ Pollutants}$$

The Air Toxics group includes the remainder of the pollutants examined, the analysis weight is obtained based on the Pollutants Max Emission as shown below:

$$Key\ Pollutant\ Weights=\frac{Pollutant\ Max\ Emission}{\sum_1^5 Pollutant\ Max\ Emissions\ for\ All\ Air\ Toxics}$$

The weights presented in Table 3-14 slightly change for the Total Emissions analysis for the GHG group and the Air Toxics group as the maximum emission values will vary when starts emissions are also assessed. The weights presented in Table 3-14 slightly change for the Total Emissions analysis for the GHG group and the Air Toxics group as the maximum emission values will vary when starts emissions are also assessed.

Table 3-14: Running Emissions Weights

Group	Pollutant	Approach Used	Associated Value	Weight
GHG	Carbon Dioxide	GWP: Convert Pollutant Max Emission to CO_2eq, use fractions	1	0.8497
	Methane		25	0.1442
	Nitrous Oxide		298	0.0061
Key Pollutants	Ammonia	Government of Canada APEI (2015): Emission Impact of Heavy-Duty Diesel Trucks on Total Inventory (%)	0.2258%	0.0108
	Carbon Monoxide		1.129%	0.0538
	Oxides of Nitrogen		17.58%	0.8376
	Particulate Matter (PM2.5)		0.7198%	0.0343
	Particulate Matter (PM10)		0.1888%	0.0090
	Sulfur Dioxide (SO_2) (SOx)		0.0197%	0.0009
	Volatile Organic Carbons		1.124%	0.0535
Air Toxics	Acetaldeyhde	MOVES Running Emissions: Air Toxic Fractions based on Max Emissions (kg)	9.3161	0.0053
	Acrolein		0.7806	0.0004
	Formaldehyde		80.4079	0.0461
	Total Gaseous Hydrocarbons		1654	0.9481

After determining the base weights of every pollutant in each group, four methods are used to determine the weight used for SI computation as shown in Figure 3-13. The employed ranking methods utilize the same procedure from the economic section, where pollutants are ranked in order of impact significance using their base weights. The total weights are determined using the rank sum and rank reciprocal approach. The third approach involves directly using the weights presented in Table 3-14. The groups GHG, Key Pollutants and Air Toxins are applied weights, W_g, of 0.5, 0.3 and 0.2, respectively to ensure the total score for the tailpipe emissions category falls at or below 1. The Emission Criterion SI equation summarizing the overall procedure was obtained using the following equation:

$$Emission\ Criterion\ SI = \sum_{j=1}^{k} W_b \times W_g \times r_{ij}$$

The fourth method is determining the weights using the entropy method and does not utilize the pollutant groups

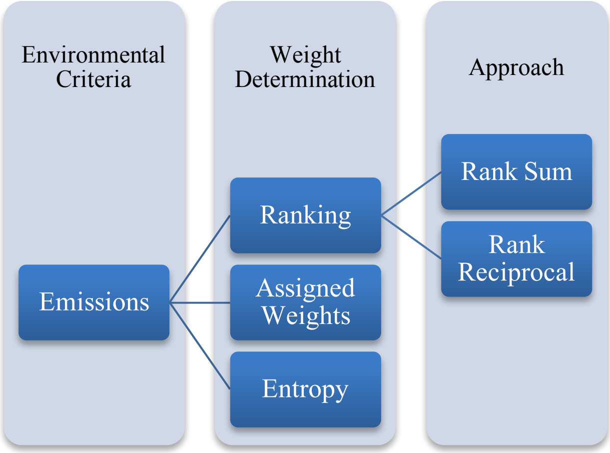


Figure 3-13: Emissions Ranking Approaches

Overall Environmental SI

Once ranking within each criterion is established, the criteria are then ranked in order of importance. Tailpipe running emission were considered the most important factor, followed by total energy consumption, life cycle emissions, and water footprint. Six approaches were used to estimate weights for the environmental criteria, these approaches are outlined in Table 3-15. In addition to these varying weights, there was three resultant indicators from the emissions criterion which was examined to include solely running and total emissions and during both study months. The environmental SIs are determined using the different approaches and as such will be compared to see if there are any major differences between the examined weighting approaches and seasons.

Table 3-15: Environmental Rankings Used

Method	**Weight Approach**			**Additional Description**
	RS	**RR**	**AW**	
1	✓			
2		✓		
3	✓		✓	Running Emissions were assigned a weight of 0.5 and the remaining criteria were ranked accordingly.
4		✓	✓	
5			✓	Environmental criteria were assigned weights.
6			✓	Running Emissions were assigned a weight of 0.5 and the remaining criteria were assigned equal weights
Weight Approach: RS=Rank Sum, RR=Rank Reciprocal, AW=Assigned Weights				

Social SI

The assigned weights used for the social pillar are based on the previously discussed costs associated with pollutant exposure. The cost estimates of average damages per tonne reported by Holland et al. (2005) are presented in Table 3-16. Value of a life year (VOLY) and value of a statistical life (VSL) are two approaches used by Holland et al. (2005) to estimate the value of mortality. The fraction of total cost per tonne is the impact each pollutant has on the overall emission costs. Either the VOLY or VSL approach is suitable for analysis since the two approaches have a very strong correlation and values which concludes that either fraction should provide similar results. As Figure 3-14 shows particulate matter is a major contributor to the total costs of exposure. The reported fractions in Figure 3-14 are applied to the ranks associated with the pollutants' emissions to determine the social indicator. The entropy-based weights are computed using the five pollutants rank (r_{ij}).

Table 3-16: Social Costs of Emissions

Average Damages per tonne of emissions for the EU25 (excluding Cyprus)				
	Cost per tonne of Emissions		*Fraction of Total Cost*	
PM mortality	*VOLY-mean*	*VSL-mean*	*VOLY-mean*	*VSL-mean*
O3 mortality	*VOLY-mean*	*VOLY-mean*	*VOLY-mean*	*VOLY-mean*
NH_3	€ 21,000	€ 31,000	0.2251	0.2266
NO_x	€ 8,200	€ 12,000	0.0879	0.0877
$PM_{2.5}$	€ 51,000	€ 75,000	0.5466	0.5482
SO2	€ 11,000	€ 16,000	0.1179	0.1170
VOCs	€ 2,100	€ 2,800	0.0225	0.0205
Total	€ 93,300	€ 136,800	Correlation	0.9999

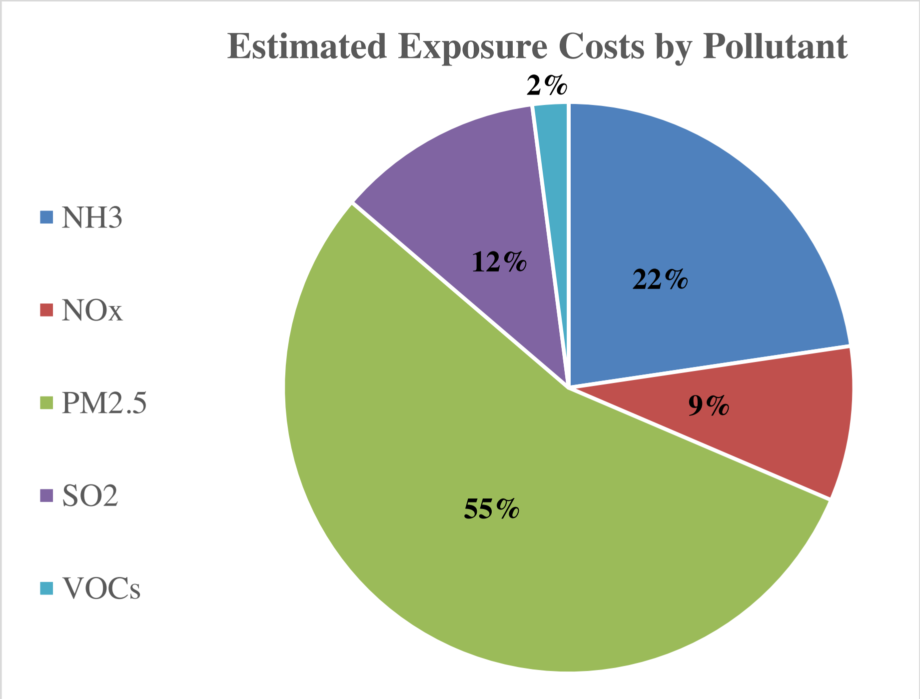


Figure 3-14: Social Costs of Emissions

Overall SI

The SIs for each pillar will be using assigned weights for the first three approaches (i.e., Rank Sum, Rank Reciprocal and Assigned weights), the entropy-based weights and the TOPSIS method. This analysis will be conducted for January and August and with and without Starts Emissions. Some of the analysis will not include the social criteria as the criterion assessed is similar to the environmental pillar. The overall results will be compared to see if there are any significant differences between the ranking methods used at the criterion and sustainability pillar level.

4. RESULTS AND DISCUSSION

4.1 LAM Results

4.1.1 Estimated CNG Demand

The estimated truck count model and associated statistics for the GTHA are presented in Table 4-1. The model explains 80 percent of the variability in the data. The number of trucks in each zone is dependent on the number of jobs that belong to the following industries: Construction (23), Manufacturing (31-33), Wholesale trade (41) and Transportation and warehousing (48-49). The GTHA count model is used to predict the HDCV counts in the GTHA in 2011.

Table 4-1: HDCV Count Model derived from GTHA Polk Data

Parameters	Coefficients	Standard Error	t-Statistic	P-value
Jobs 23, 31-33,41 and 48-49	0.0803	0.0011	73.3870	0
R^2	0.8026			
Adjusted R^2	0.8018			

The correlations between the estimated total HDCV counts and trips at the zonal level are presented in Table 4-2. The count model underestimates the total truck count in the GTHA. It is logical that total trips estimated in the GTHA are greater than the estimated HDCV counts as each vehicle has the potential to make several trips. All HDCV trip and count models have a high correlation with the GTHA Polk Count. The GTHA-derived count model has the highest correlation as it was derived from the GTHA Polk count, whilst the QRFM model has the lowest correlation as it was derived with data from outside of the study area.

Table 4-2: Correlations between Zonal Truck Counts and Trips

	Roorda et al. (2010) (24-hrs)	***QRFM***	***GTHA Truck Model***	***Polk Count***
Roorda et al. (2010) (24-hrs)	1			
QRFM	0.9640	1		
GTHA Truck Model	0.9921	0.9711	1	
Polk Count	0.8829	0.8697	0.8920	1
Total Count	**237,288**	**211,781**	**56,620**	**58,815**

The QRFM has been shown to overestimate overall freight trips as previously demonstrated by Holguín-Veras et al. (2013). This overestimation may be due to the freight activity differences between the GTHA and Phoenix, Arizona, the area the QRFM was derived from. Additionally, the zones used in the QRFM model may be smaller or larger than census tracts; which could give rise to the modifiable aerial unit problem (MAUP). MAUP occurs when a model that was estimated in one area using a specific set of zones for its derivation is used in a different geographical area with varying zone sizes or dissimilar aggregation schemes, producing inconsistent results when the analysis is applied.

In the existing study, the 12.5-hour HDCV trips from Roorda et al. (2010) sum up to a total of 156,420. When these values were scaled up using the CVS Fraction, the total estimated trip count surpassed the QRFM. This result emphasizes the size of commercial vehicle movement in the GHTA. The QRFM and Roorda et al. (2010) Model estimate approximately 3.6 to 4 daily trips per truck per day in the GTHA region. The results verify that in the absence of count data, truck trip and count models could be used as an alternative. However, based on the results, models that are developed with local data typically perform better.

The number of registered HDCVs per census tract in the GTHA was found to be 58,815 and distributed amongst 999 of the 1,326 census tracts comprising the study area. The zonal count of heavy-duty trucks per zone ranges from 1 and 5,966. The analysis of the GPS trip data suggests that the fraction of trips per census tract that traveled a 500 km distance from their point of origin ranged from 0 to 1 with a zonal average of 0.7145. A ratio of zero generally meant that all trips exceed a 500-km travel distance, which in the current study reflects a fleet that currently cannot transition towards CNG. Trucks in census tracts with a 0 fraction have no potential to adopt CNG trucks. Using the trip distance fraction, a total of 905 census tracts were found to have the potential to convert a portion of their fleets to CNG. A total of 815 of these tracts have less than 100 potential CNG trucks and the maximum number of potential CNG trucks in one CT is 3,234. The zonal distribution of potential CNG trucks is provided in Figure 4-1.

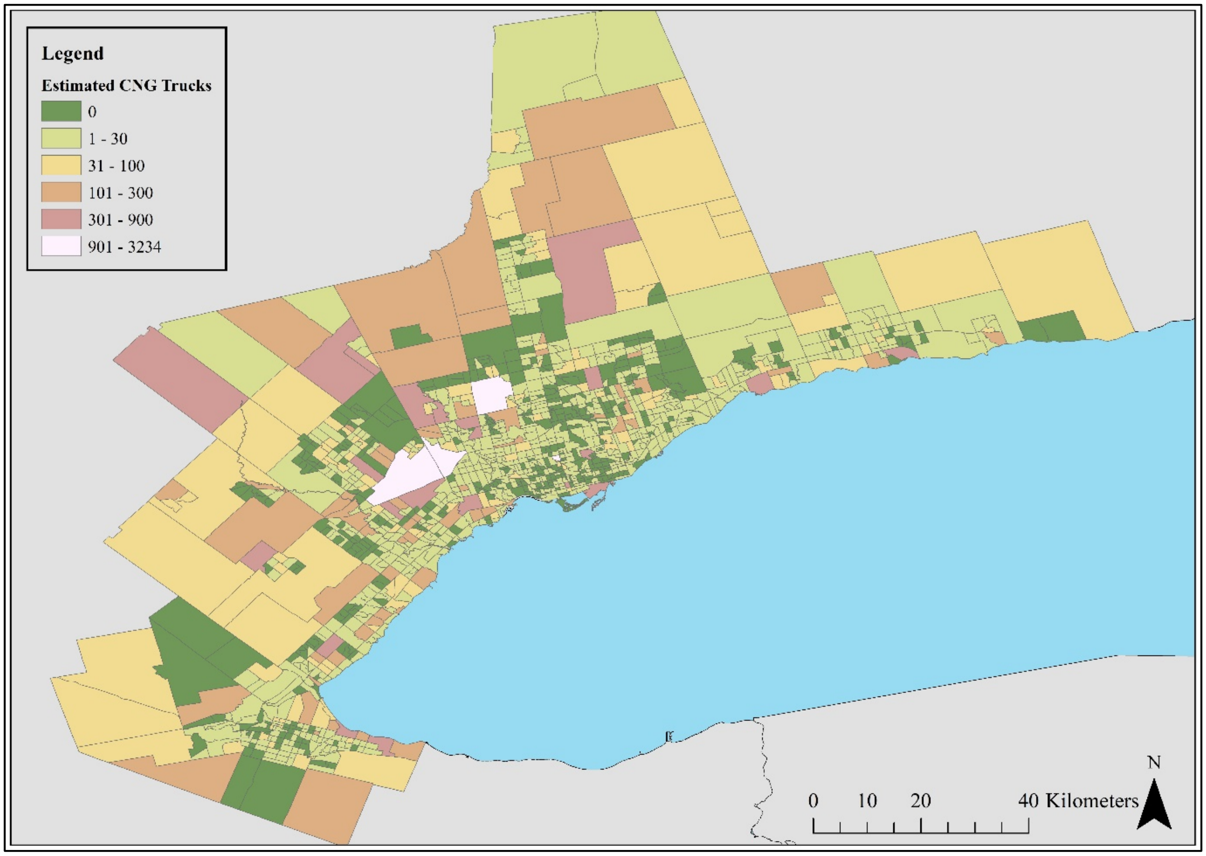


Figure 4-1: Estimated CNG Trucks per Census Tract

4.1.2 Suitability of Potential CNG Hubs

The suitability scores were obtained from the ArcGIS raster calculator using the procedure discussed in Section 3.3.2. These scores were then scaled to values ranging from 1 to 10, where a higher value reflects a more suitable classification. The suitability map shown in Figure 4-2 was produced in ArcGIS 10.2. Suitable sites are characterized by darker shades of blue. Sites with a suitability index of 8 or greater were selected as potential areas to establish CNG hubs, whilst the proximity to the existing natural gas pipeline was further used to select the exact sites as presented in Figure 4-3. Based on the suitability map, fifteen sites were selected. Many of these sites are in the southwestern region of the study area.

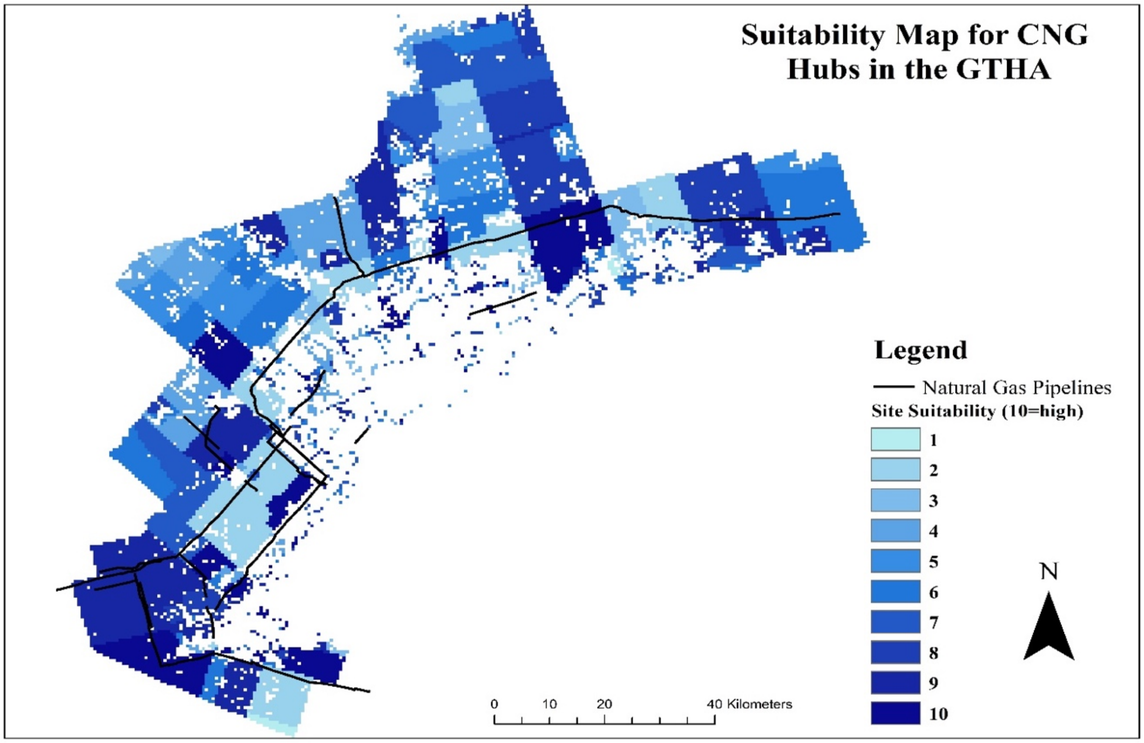


Figure 4-2: Site Suitability for a CNG Hub in the GTHA

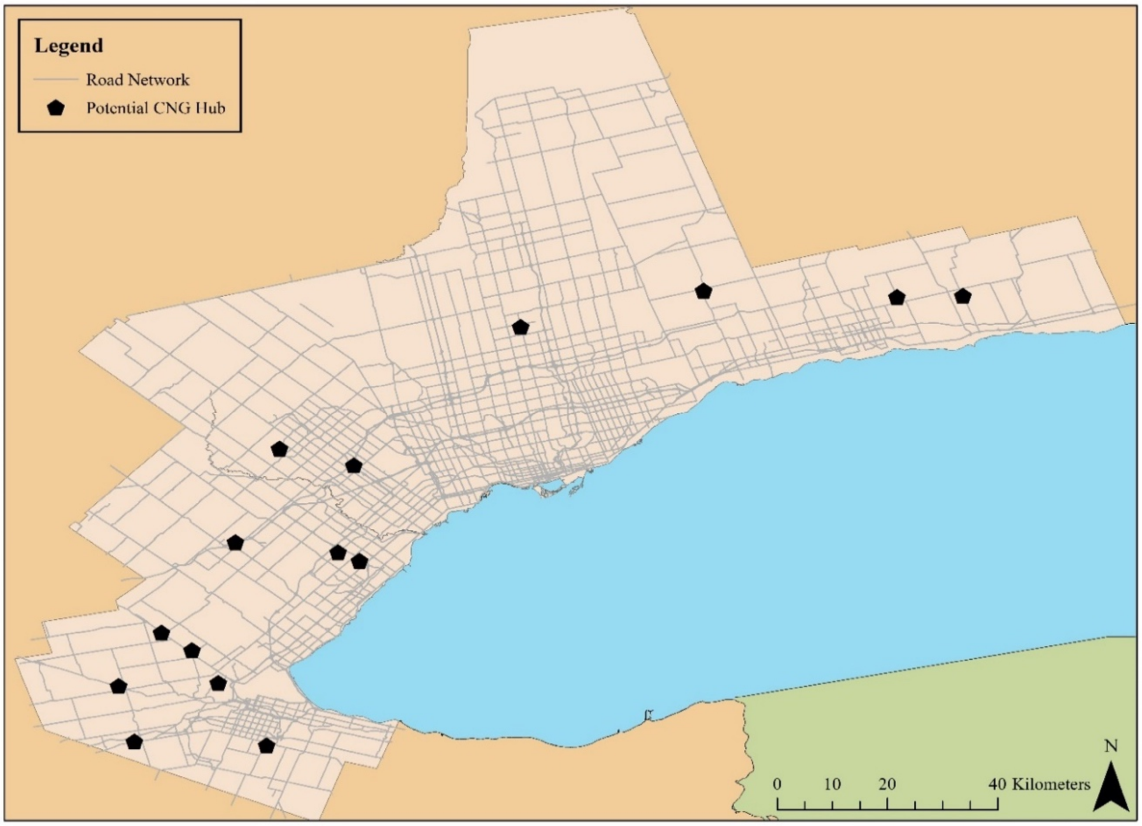


Figure 4-3: Potential Hubs in the GTHA

4.1.3 *Estimated Coverage*

Figure 4-4 visually presents the estimated coverage produced by the potential fifteen facilities. The service areas are only determined for the GTHA; however, there is potential to expand outside of the GTHA if sites are established in the Western region of the study area. The fifteen sites cover approximately 83% of the estimated demand and services the zone with the highest demand. More specifically, a total of 3,234 trucks could be serviced within a 20-minute driving time. The map indicates that two areas (R_1 and R_2) are not serviced. R_1 is the downtown Toronto while R_2 is the Northern region of the study area. Both regions are not near natural gas pipelines and do not meet the site selection criteria. In addition to not meeting the site requirements, downtown Toronto is likely to have higher volumes of traffic in the evenings which can cause substantial delays in the NG virtual pipeline network.

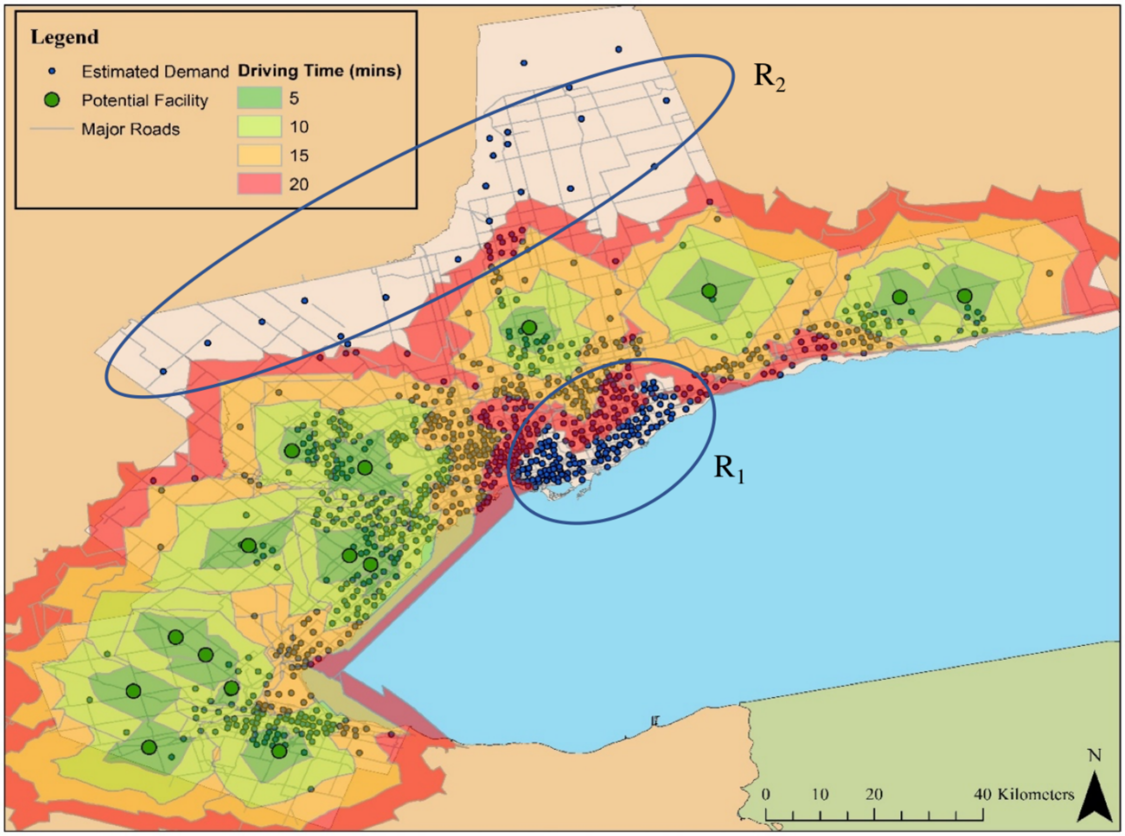


Figure 4-4: Estimated Service Areas for all 15 Sites

Table 4-3 and Figure 4-5 present the statistics and distribution associated with the serviced and unserved estimated demand. From Table 4-3, the total number of estimated trucks and trucks per census tract of the served demand is much greater than the unserved demand. Eight of the ten census tracts with the highest estimated demand range from 444 to 3,234 CNG trucks, of these demand points, eight tracts are reached within a 20-minute driving time. Figure 4-5 further emphasizes the coverage obtained by the proposed fifteen facilities in the GTHA.

Table 4-3: Statistics of Serviced and Unserved Estimated CNG Demand

		Serviced Estimated Demand	***Unserved Estimated Demand***
Demand Points		754	151
Estimated CNG Trucks at Demand	*Minimum*	1	1
	Maximum	3,234	1,572
	Sum	34,284	5,163
	Mean	45	34

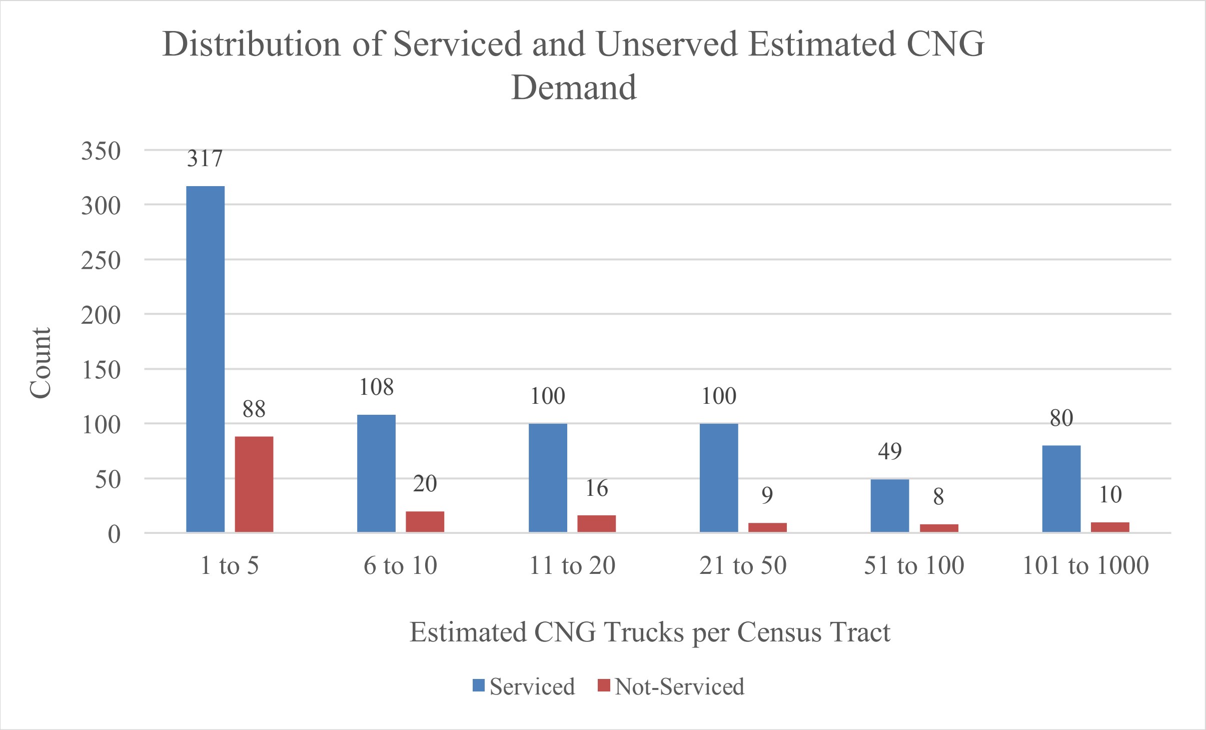


Figure 4-5: Coverage Distribution of Zonal CNG Counts

4.1.4 Proposed Facilities

The selection of the optimal number of facilities that are most suitable was determined using the ArcGIS Network Analyst Extension for 252 scenarios. These scenarios reflect different combinations of problem-type, maximum number of facilities to establish, driving time cut-off (from supply to demand) and the CNG volume at hubs. Some of the results will be presented in this section while the remaining outputs are provided in Appendix F. Each facility was assigned a number from 1 to 15 for identification as shown in Figure 4-6.

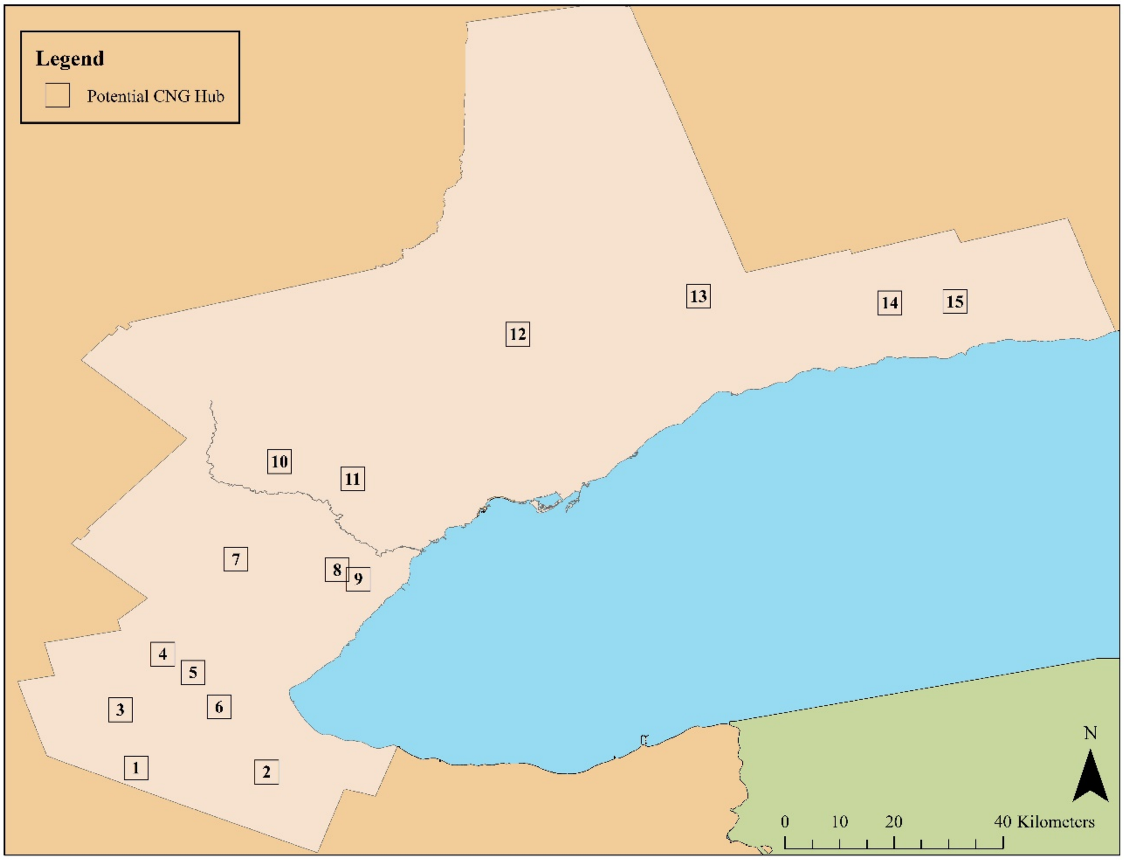


Figure 4-6: Facility Key

Model 1: P-Median

The p-median analysis shows that the number of refueling trucks at the facility does not have a significant impact on average travel time results. Figure 4-7 presents the consistency of average travel time across varying capacity levels of the facilities (i.e. hubs). Additionally, there is little variation with respect to which facilities are selected as ideal when the number of refueling trucks (supply) at the CNG Hub was varied. There is minor variation in the selected facility distribution and this is only observed when a CNG Hub houses thirty trucks. This is likely a result of the analysis depending on the road network characteristics and travel times.

Table 4-4 presents a summary of the frequency of selection for each facility with varying supply. Based on the results, facilities number 11 and 12 have the highest frequency selection and as such can be chosen as the top two sites for servicing the GTHA. Based on these results, a p-median problem may be more suitable when there are more exact values for the demand at each site and more detailed information pertaining the maximum capacity of the storage facility and refueling trucks.

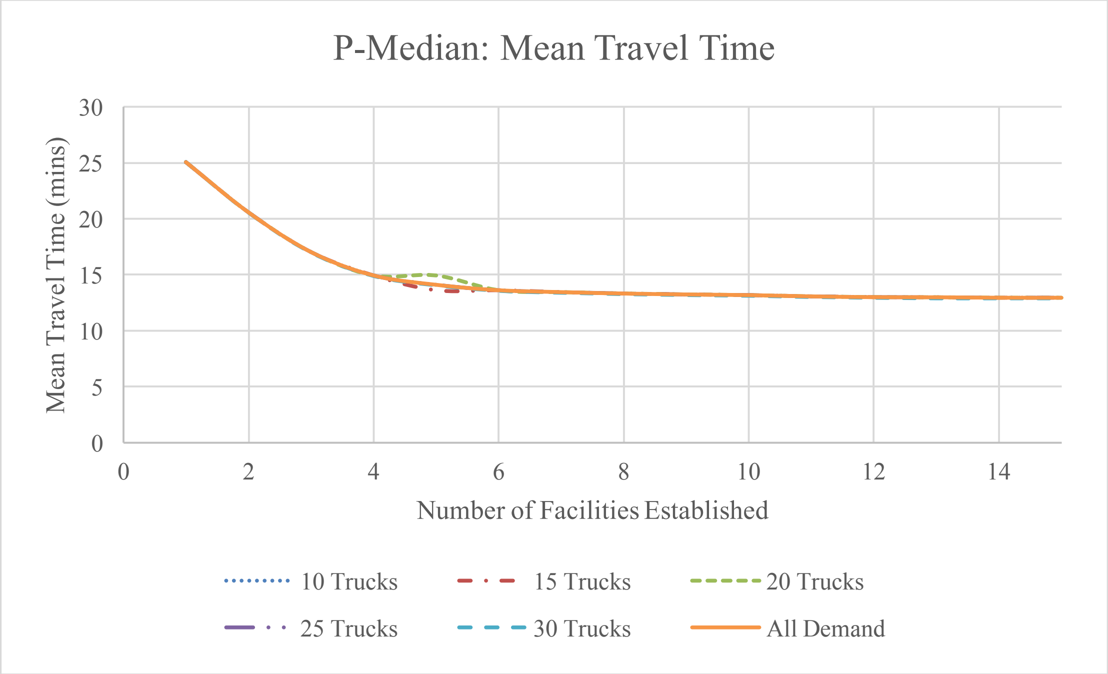


Figure 4-7: P-Median Approach- Mean Travel Time

Table 4-4: P-Median – Facility Selection

P-Median	**Frequency of Facility Selection**														
Trucks	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
10	5	13	6	1	5	2	9	4	11	7	15	14	10	12	6
15	5	13	6	1	5	2	9	4	11	7	15	14	10	12	6
20	5	13	6	1	5	2	9	4	11	7	15	14	10	12	6
25	5	13	6	1	5	2	9	4	11	7	15	14	10	12	6
30	5	13	5	1	6	2	9	4	11	7	15	14	10	12	6
658	5	13	6	1	5	2	9	4	11	7	15	14	10	12	6
Total	**30**	**78**	**35**	**6**	**31**	**12**	**54**	**24**	**66**	**42**	**90**	**84**	**60**	**72**	**36**

Model 2: Maximize Attendance

The locational selection of facilities under Model 2 varied more than the previous p-median results, however like Model 1 facilities number 4 and 11 were consistently the least and most chosen facilities, respectively. Each travel time cut-off value was assessed with varying number of facilities to establish (i.e. 1, 2,…, 15 facilities). The results in Table 4-5 indicate that Facility 4 was not selected for a cut-off time of 10 minutes as a fourteen-facility solution was better than a fifteen-facility solution. This likely occurs due to Facility 4's proximity to Facility 5 and 6.

Table 4-5: Maximize Attendance – Facility Selection

Max Attendance	**Frequency of Facility Selection**														
Cut-off Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
10 min	7	13	8	0	7	4	12	2	14	3	15	11	8	5	10
15 min	5	12	7	1	5	2	11	4	14	6	15	13	8	10	7
20 min	5	13	6	1	5	2	10	4	12	7	15	14	9	11	6
25 min	5	13	5	1	6	2	9	4	12	7	15	14	10	11	6
30 min	5	13	6	1	5	2	10	4	11	7	15	14	9	12	6
Total	**27**	**64**	**32**	**4**	**28**	**12**	**52**	**18**	**63**	**30**	**75**	**66**	**44**	**49**	**35**

As expected, a greater number of CNG hubs and longer travel times service more demand as shown in Figure 4-8. The plotted curves in the figure present the estimated coverage with the variation of the number of facilities established for each travel time cut-off value. For a travel time cut-off of thirty minutes the coverage plateaus at four facilities. Minimal additional coverage is obtained when more than four facilities are established. However, for a travel time cut-off of ten minutes there is no defined plateau as there is still an increase in coverage with the establishment of an additional facility.

Figure 4-9 presents the mean travel time against the number of established facilities for each of the travel time cut-offs. There is no significant average travel-time (from supply to demand) advantage of establishing more than six facilities. Establishing six or less in all travel time constraints usually only provides a difference of one to two minutes when establishing one to six facilities. However, this is doubled for a 30-minute travel time cut-off. The observed trend is likely due to the selection of different facilities in the 30-minute scenario, which is exhibited in Table 4-5. Based on both the travel time and demand coverage results of maximize attendance, it is evident that no more than six facilities should be established for any travel time constraint.

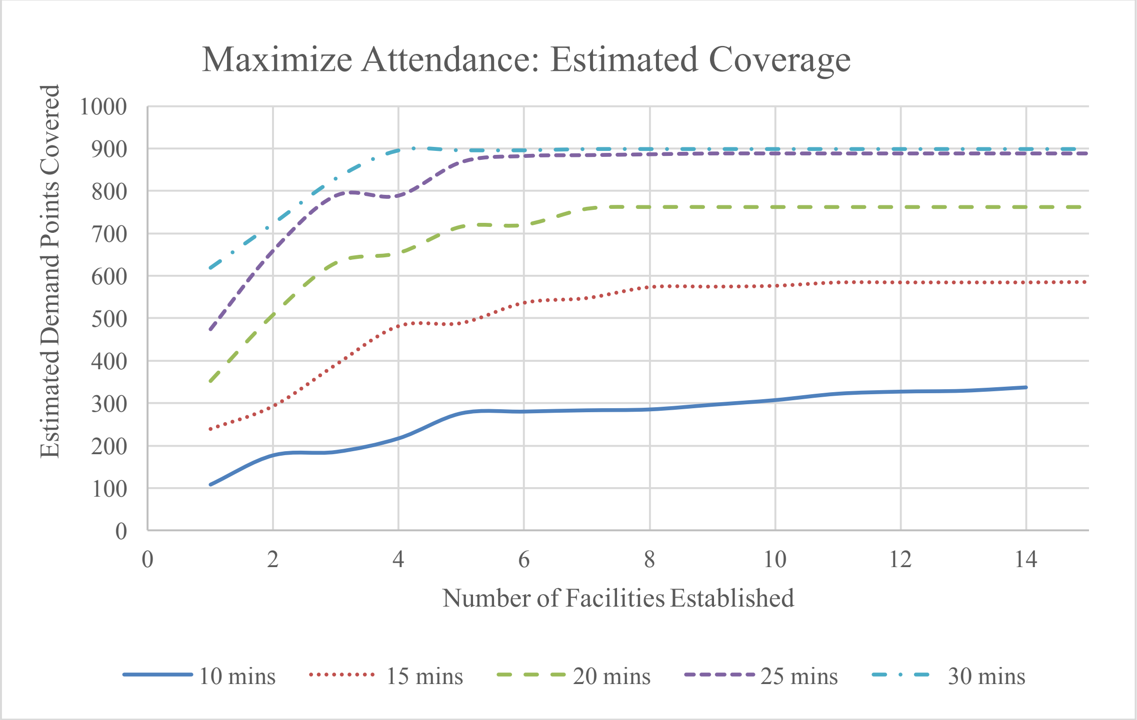


Figure 4-8: Maximize Attendance – Estimated Coverage

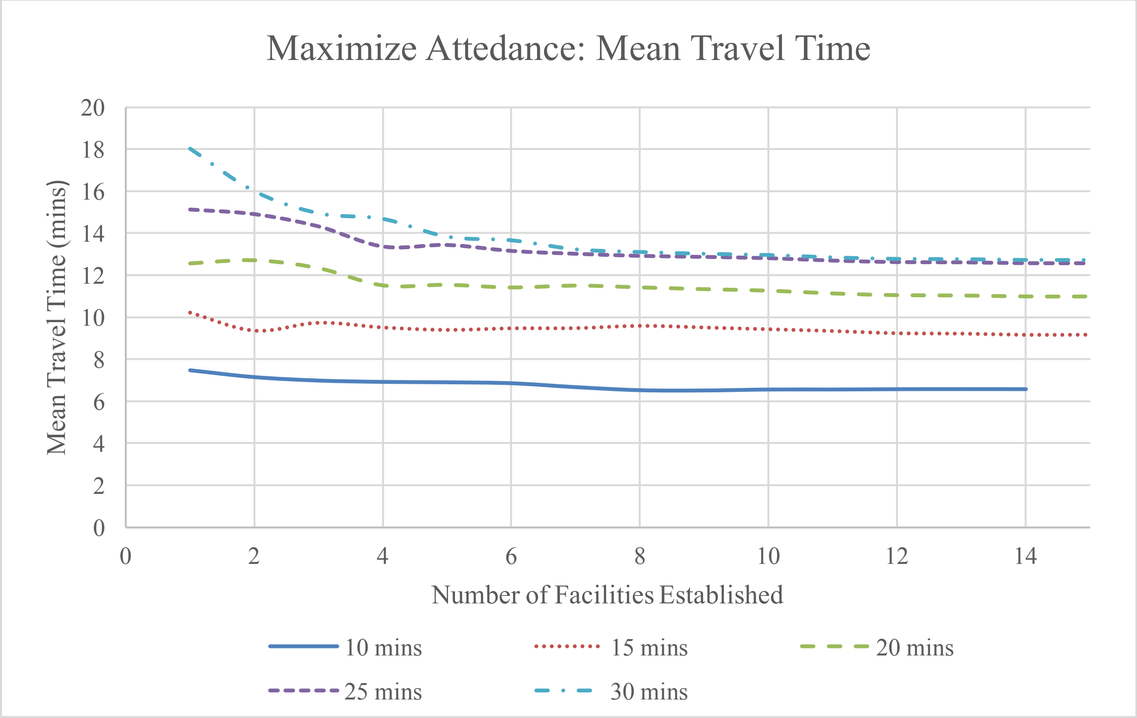


Figure 4-9: Maximize Attendance – Mean Travel Time

Model 3: Maximize Coverage

The maximize coverage location-allocation results are provided in Table 4-6. These results exhibit some spatial variation with respect to both the p-median and maximize attendance results, most notably with facility 11. Both p-Median and maximize attendance select this facility in every single scenario, whilst in three scenarios a different facility, facility 8 or 9 was selected in lieu of facility 11 (when the travel time cut-off was 25 and 30 minutes). Facility 4 continues to be the least chosen facility. Figures 4-10 and 4-11 visually present the estimated coverage and mean travel times to serve the estimated demand points, respectively. These results are similar to the maximize attendance results and again do not recommend the establishment of more than six facilities.

Table 4-6: Maximize Coverage – Facility Selection Frequency

Max Coverage	**Frequency of Facility Selection**														
Cut-off Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
10 min	7	13	8	0	7	4	12	2	14	3	15	11	8	5	10
15 min	7	13	4	4	7	1	8	3	12	6	15	14	10	11	5
20 min	6	13	5	2	6	2	8	5	9	7	15	14	11	12	5
25 min	6	12	4	1	8	2	8	6	7	11	13	14	10	13	5
30 min	5	13	6	1	5	2	9	4	11	7	14	13	12	12	6
Total	**31**	**64**	**27**	**8**	**33**	**11**	**45**	**20**	**53**	**34**	**72**	**66**	**51**	**53**	**31**

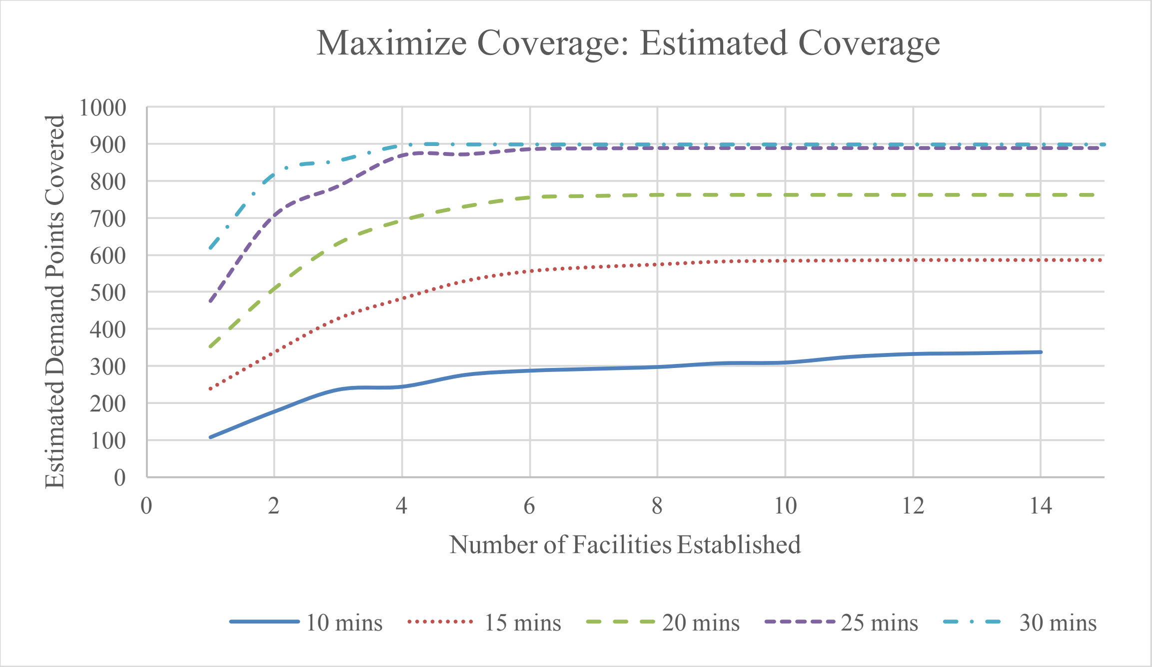


Figure 4-10: Maximize Coverage - Estimated Coverage

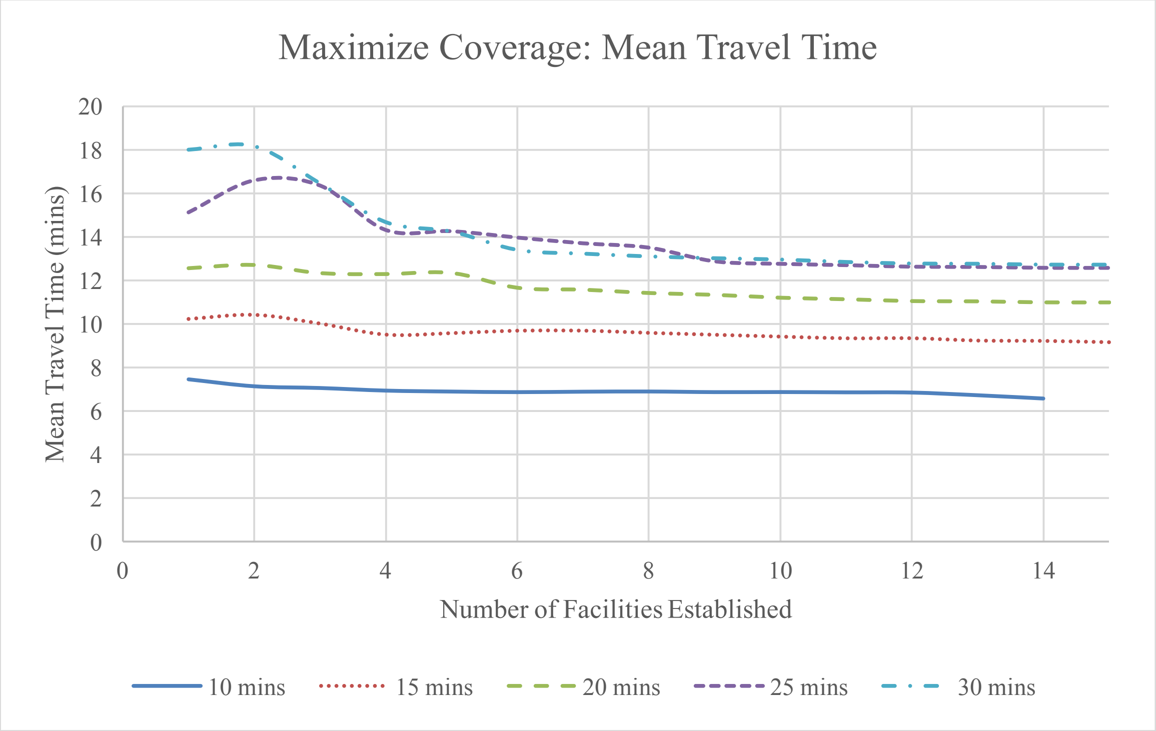


Figure 4-11: Maximize Coverage - Mean Travel Time

Model 2 and 3 Comparison

The correlation between the coverage results of the maximization of coverage and attendance is 0.9971. This exemplifies a strong relationship between the two solution sets. Table 4-7 provides the additional demand that Model 3 provides over the results from Model 2. In all but one scenario the demand points covered by the maximum coverage problem are greater than or equal to the maximize attendance results. One can conclude that the maximize coverage scenario provides better results than maximize attendance for this analysis.

Table 4-7: Difference between Maximize Coverage and Attendance

Difference between Maximize Coverage and Attendance Demand					
Number of Facilities	**Travel Time Constraint**				
	10 mins	**15 mins**	**20 mins**	**25 mins**	**30 mins**
1	0	0	0	0	0
2	0	44	0	46	95
3	51	37	0	-4	25
4	27	0	39	79	0
5	0	41	15	3	3
6	7	19	35	3	3
7	9	19	1	3	0
8	12	0	0	2	0
9	11	7	0	0	0
10	2	7	0	0	0
11	2	0	0	0	0
12	5	1	0	0	0
13	5	1	0	0	0
14	0	1	0	0	0
15	0	0	0	0	0

Model 4: Minimize Facilities

As previously exhibited, an increase in allotted refueling trailer travel-time translates into a greater value of demand points served. Table 4-8 details the minimal number of facilities to be established and estimated demand covered based on the cut-off travel time assigned. All demand points are covered within a 45-minute drive time. The minimum number of facilities required is achieved with a cut-off travel time of 50 minutes, with two facilities serving the entirety of the estimated GTHA demand. Spatially, the results of the selected facilities are slightly different than the other three models as facility 13 is selected as often as facility 11. The location of these two facilities is seen as strategic, providing optimal coverage for the GTHA. Establishing two facilities would produce a maximum travel time of 49 minutes and an average travel time of 21 minutes. These results suggest that six facilities may not necessarily be required which is ideal for the initial conversion to CNG as less hubs will reduce costs.

Table 4-8: Minimize Facilities – Established Facilities

Travel Time Cut-off (mins)	**Number of Facilities**	**Estimated Demand Covered**	**Selected Facility**														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
5	13	89	•	•			•	•	•	•	•	•	•	•	•	•	•
10	14	337	•	•	•		•	•	•	•	•	•	•	•	•	•	•
15	12	586	•	•		•	•		•		•	•	•	•	•	•	•
20	8	762		•	•				•		•		•	•	•	•	
25	8	888		•			•		•			•	•	•	•	•	
30	5	898		•									•	•	•	•	
35	5	900		•									•	•	•	•	
40	4	902		•									•	•		•	
45	3	905								•				•	•		
50	2	905											•		•		
55	2	905											•		•		
60	2	905											•		•		
Total			**3**	**8**	**2**	**1**	**4**	**2**	**5**	**3**	**4**	**4**	**11**	**9**	**11**	**8**	**3**

Overall Comparison

Comparing the overall selections from the four models, the consistent top three facilities are 11, 12 and 2. The selected facility frequency is presented in Table 4-9. The values in the table present the number of times each facility was selected in all the scenarios examined under each model. Facility 11 was the most frequently selected facility, it chosen as a hub 98% of the time. In addition to Facility 11, Facilities 2, 12 and 13 were selected as the top three choices in the four models. However, Facility 13 is only selected frequently in the minimize facilities approach.

The number of facilities to establish will then depend on what is more desirable: reducing variable costs or fixed costs. Variable costs in this context are the costs related to the transportation of fuel while fixed costs are the costs associated with establishing and operating the CNG Hub itself. Establishing more facilities will increase fixed costs, but it has the potential to reduce variable costs if there is a significant reduction in travel time. In practice these variable cost savings will depend on which trucking firms will convert to CNG fuel. Therefore, end-user feedback would be an advantageous input to decide the number and location of facilities to establish.

The results from all the tested scenarios suggest minimal variation in the average service time when the number of proposed facilities dropped from fifteen to six. Therefore, it is not economical to establish more than six facilities to service the GTHA area. However, establishing six facilities may be too costly for a new NGV market. From the minimize facility results, two facilities provide total GTHA coverage with a 21-minute average travel time. This result is likely most pragmatic for the initial stages of the introduction of the CNG virtual pipeline. Spatially, one of these facilities should be Facility 11, while the other could be either 12, 2, 9 or 13.

Table 4-9: Summary of Selected Facility Frequency

Facilities	**P-Median**	**Maximize Attendance**	**Maximize Coverage**	**Minimize Facilities**	**Total**	**Percentage Chosen**
Top 3 Facilities	11	11	11	11		
	12	12	12	13		
	2	2	2	12		
1	30	27	31	3	91	36%
2	78	64	64	8	214	85%
3	35	32	27	2	96	38%
4	6	4	8	1	19	8%
5	31	28	33	4	96	38%
6	12	12	11	2	37	15%
7	54	52	45	5	156	62%
8	24	18	20	3	65	26%
9	66	63	53	4	186	74%
10	42	30	34	4	110	44%
11	90	75	72	11	248	98%
12	84	66	66	9	225	89%
13	60	44	51	11	166	66%
14	72	49	53	8	182	72%
15	36	35	31	3	105	42%
Scenarios	**90**	**75**	**75**	**12**	**252**	

4.1.5 Validations

The existing trucking firms in the Yellow Pages were used to verify that the locations of the suggested facilities will in fact provide sufficient GTHA truck yard coverage and will aid in facility selection. Figure 4-12 presents the location of potential CNG hubs and the existing firms in the GTHA. Clearly Facility 13, which was favoured in the minimize facilities problem type does not provide any significant immediate coverage as opposed to facility 2, 9, 11 and 12. Additionally, Facility 13 does not seem to have trucking firms in its proximity. However, this site was identified as a potential location since existing trucking firms were not factored into the suitability analysis but it meets the siting criteria. Also, Facility 13 is in an area that is primarily surrounded by the open area land use category. Most firms (74.5%) are located in the following land use categories (in descending order of contribution): resource and industrial, residential, governmental and institutional and commercial. From Figure 4-12, Facility 11 is in a trucking firm-dense area. Therefore, the sole coverage of Facility 11 was evaluated. Then, the coverage of facility 11 and one other facility (2, 9, 12 and 13) was assessed. These results are presented in Table 4-10 and coverage maps are provided in Appendix G.

Based on the table, if the desired travel time cut is 10, 20 or 30 minutes or less, facility 9, 12 and 2 in addition to facility 11, respectively will provide the most coverage. Spatially each hub has its advantages when combined with Facility 11. Facility 2 covers a good portion of the Toronto CMA and all firms in the Hamilton CMA. Visually Facility 2 appears to provide definite potential to expand outside of the GTHA. Confirming this with the existing trucking firms, with a 30-minute driving window facility 2 extends its coverage outside of the GTHA to approximately nineteen trucking firms. Facility 9 provides sufficient coverage of the Hamilton CMA and some additional coverage of the Toronto CMA. Establishing Facility 11 and 12 provide for almost complete coverage of the Toronto CMA. Whilst Facility 13 provides some Oshawa coverage with a twenty-minute service time, however this facility does not provide the highest coverage in any time cut-off scenario, therefore it is not the optimal solution with respect to coverage. Based on both spatial and coverage results, either Facility 2 and 12 in addition to Facility 11 are the ideal candidates for establishing a CNG Hub. The selection between the two facilities will depend on whether servicing the entire Toronto CMA and any additional Oshawa demand (Facility 12) or serving the Hamilton CMA and/or outside the GTHA region (Facility 2).

Table 4-10: Locational Validation Results

Coverage (%)	1 Facility	2 Facilities (11 and…)				
Time (mins)	11	2	9	12	13	Best Option
5	19%	19%	23%	20%	19%	9
10	43%	47%	51%	45%	43%	9
15	55%	61%	64%	65%	55%	12
20	71%	80%	76%	82%	75%	12
25	80%	89%	86%	88%	86%	2
30	88%	95%	94%	91%	92%	2

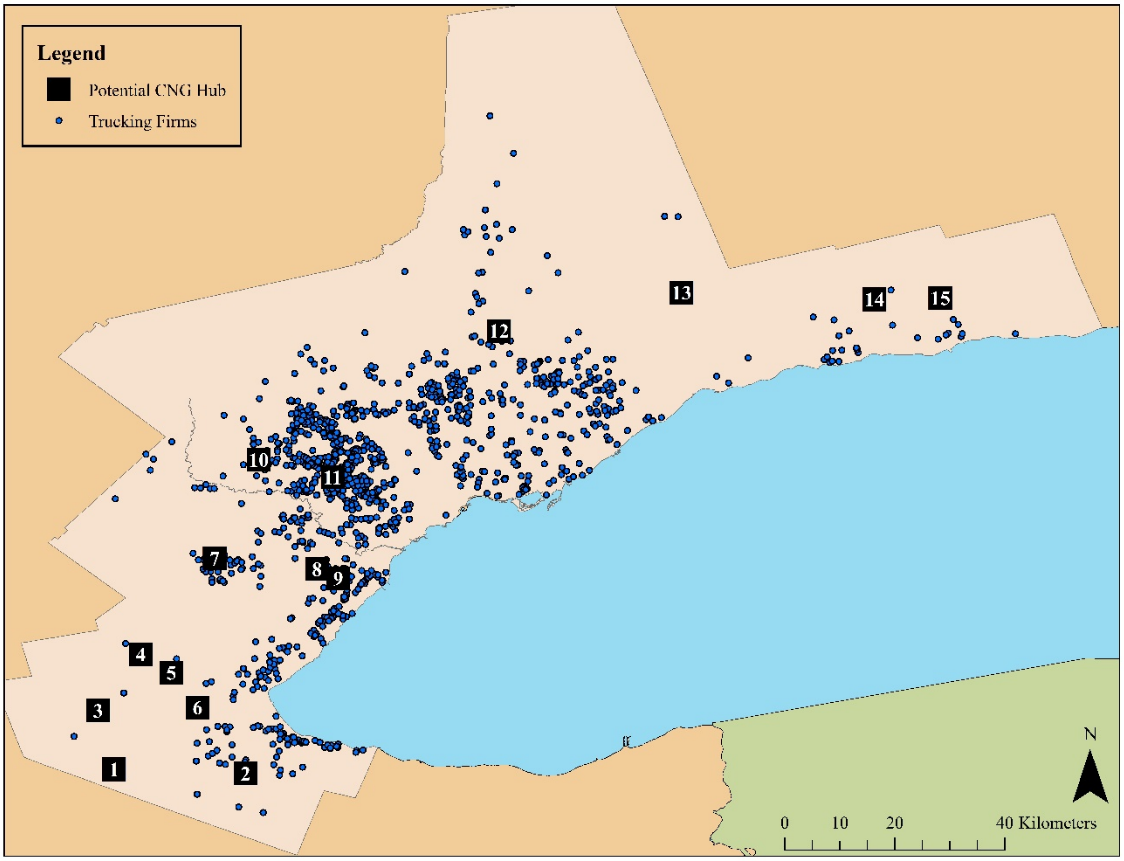


Figure 4-12: Potential CNG Hubs and Yellow Pages Trucking Firms

4.2 Transportation Modelling Results

4.2.1 Passenger Trip Generation

Passenger trips were first estimated using the Maoh et al. (2009) model and the census division totals were compared with the 2011 TTS results. Table 4-11 presents a summary of this comparison. The generated trips for the 24-hour totals and the other peak periods follow the same trend with respect to zonal distribution as all correlations between the predicted trip totals and the observed TTS data are at least 0.99. The best overall percent difference results are for the 24-hour total trips with a mean percent difference of 4% and a maximum of 10%. The Calgary model underestimates the overall trip attractions whilst overestimating daily trip productions. This shows that on a census division level, the Maoh et al. (2009) model derived in Calgary provides good estimates of the daily TTS passenger trips. In contrast, the morning peak period has the greatest discrepancies per census division for trip attractions and productions. The average percent difference between observed and estimated trips is 53% with a minimum and maximum of 34% and 66% respectively. The AM Peak zonal percent differences for both productions and attractions are higher than the average of the PM and Off Peaks. The full aggregate period totals and zonal percent differences are presented in Appendix H. The validation factors obtained are presented in Table 4-12. These factors were used to scale the zonal trip productions and attractions in order to adjust the Calgary model to the GTHA. The updated hourly trip generation and attraction models per census tract for each GTHA census division is presented in Appendix I.

Table 4-11: Initial Passenger TG Results compared with TTS Data

		Percent Difference			Correlation	
Period	**Time Frame**	**Mean**	**Minimum**	**Maximum**	**O_i**	**D_j**
AM	6 am to 9 am	53%	34%	66%	0.9964	0.9998
PM	3 pm to 6 pm	28%	12%	41%	0.9997	0.9958
All	24 hours	4%	0%	9%	0.9995	0.9994
Off	18 hours	25%	11%	40%	0.9977	0.9974

Table 4-12: Validation Factors for GTHA Passenger Trip Generation

Census Division	**All Modes: 6 to 9 am**		**All Modes: 3 to 6 pm**		**All Modes: Rest 18 hours**	
	O_i	**D_j**	**O_i**	**D_j**	**O_i**	**D_j**
Halton	1.6698	1.6961	1.2675	1.3222	0.8069	0.8555
Hamilton	1.4083	1.6113	1.1929	1.1244	0.7754	0.8228
York	1.7602	1.8161	1.3568	1.3942	0.7180	0.7605
Durham	1.7219	1.8086	1.3207	1.3902	0.8438	0.8951
Peel	1.7183	1.8933	1.4225	1.3537	0.6694	0.7050
Toronto	1.5700	1.9957	1.5212	1.2185	0.7216	0.7644

4.2.2 Commercial Trip Generation

The generated HDCV trips were discussed in section 4.1.1, and the LDCV and MDCV trips were further obtained to estimate a comprehensive traffic flow. The total 24-hour daily trips by made LDCVs, MDCVs and HDCVs are 844,043, 388,209, and 237,294, respectively. For 12 pm the values are 58,033, 26,694 and 16,359 for LDCV, MDCV and HDCV, respectively. Appendix J presents maps of the trip generation counts per census tract at 12 pm. The distributions are quite similar for all commercial vehicles and there are four census tracts that continuously have the highest trip counts. Unlike passenger trips, commercial trip counts on a zonal basis are not readily available, therefore the commercial trips in this study area can only be validated once these trips are assigned onto the road network.

4.2.3 Trip Distribution

Trip distribution for both passenger and commercial trips produced origin-destination matrices that are balanced with respect to both trip productions and attractions using the fratar method. Correlations between the marginal totals and their respective estimated trip attractions and productions were obtained for each hour and vehicle type to validate the fratar outputs. All correlations were 1 verifying that the overall zonal totals were accounted for in the analysis. Additionally, the maximum absolute difference between the marginal totals and the estimated trip totals at a zonal level were obtained. The maximum difference between the marginal totals and the estimated trip totals was 1.30 which further validates that the OD matrices are an accurate representation of the predicted trips. The differences at an hourly level per mode are provided in Appendix J.

4.2.4 Traffic Assignment

The assigned trips were converted back to their vehicle equivalents prior to comparing the results with the MITL study and the CVS counts. Since passenger and light-duty commercial vehicles were assigned together the results must be separated for validation. The fraction of passenger vehicles per hour was obtained from the total passenger and LDCVs matrices. These fractions were then applied to the assigned flow to approximate the PV flow and LDCV flow separately.

The correlation between both the estimated hourly VKT in this study and the MITL study are all above 0.88 showing a similar hourly trend, as shown in Table 4-13. However, the estimates in this study are much higher for every mode except MDCVs. This discrepancy may be due to the generalization of this study's passenger trips, as recent studies have estimated passenger trip generation based on trip purpose. The cause of the underestimation of MDCVs is unknown and can potentially be due to road assignment differences between the two studies as link length plays a factor in VKT estimates.

Table 4-13: VKT Comparison with MITL Study 2014

TA Vehicle Type	Correlation	Estimated VKT	MITL VKT	Difference
PV	0.9741	224,245,271	132,425,186	91,820,085
LDCV	0.9349	18,081,477	15,564,505	2,516,972
PV and LDCV	0.9787	201,093,989	147,989,691	53,104,298
MDCV	0.9367	4,363,001	5,892,671	(1,529,670)
HDCV	0.8869	4,606,463	3,249,379	1,357,084

The traffic counts were also compared to the 2006 Commercial Vehicle Survey. The statistics of the hourly correlations are presented in Table 4-14 and Appendix J lists all hourly results. The pattern of the weekday passenger CVS traffic counts correlates strongly with the passenger and LDCV traffic assignments as all hourly correlations were above 0.7. Based on the correlations, the PVs and LDCVs present the same distribution of vehicle assignment. Which was expected as these two vehicle types were assigned together. The CVS truck counts correlates best with the assigned HDCVs and the worst with the assigned MDCV flow.

Table 4-14: Traffic Assignment comparison with CVS 2006

CVS 2006	***Weekday Passenger***		***Weekday Truck***		
TA **Overall**	*PV*	*PV & LDCV*	*MDCV*	*HDCV*	*MDCV & HDCV*
Mean	0.9240	0.9240	0.7365	0.8027	0.7839
Minimum	0.7008	0.7008	0.6228	0.7254	0.7004
Maximum	0.9721	0.9721	0.8079	0.8816	0.8603

Both the difference and absolute difference between the assigned traffic and the traffic counts were assessed every hour at each station. In comparison to the fifteen CVS observation stations, 67% of the hourly traffic counts were similar in magnitude to the assigned PV and LDCV traffic. The assigned passenger and LDCV traffic fared better with respect to magnitude. This is likely due to the inclusion of some light-duty trucks in the passenger traffic count. However, 29% of hourly comparisons between the counts and assigned PV and LDCV flow results were found to be generally higher than the counts. This result shows a potential overestimation in the traffic assignment or can be due to the potential inclusion of only some LDCVs in the CVS traffic count.

The hourly truck counts were compared in magnitude with: (1) HDCV flow, (2) MDCV and HDCV flow and (3) all CV flow. All hourly HDCV flows were lower than traffic counts. 8% of the daily MDCV and HDCV flow were found to be higher than the trucks counts. Lastly, 50% of all commercial vehicle flow was found to be generally higher than the CVS counts, whereas 33% was found to be approximately equal in variation. These results show that the truck classification used by CVS may include more than Class 7 and 8 vehicles.

The absolute difference was summed for each hour, providing the overall magnitude difference for the counts and predictions. The largest absolute difference total for the passenger traffic counts were found at 6:00 am and during the PM Peak Period (3 to 6 pm). The inconsistency in the PM peak period may be due to the nature of the estimation procedure used for the passenger trips. As aforementioned in Section 3.4.1, the passenger trip generation parameters were updated using the inverse AM OD matrix from the 2011 TTS Survey. The examined difference between the evening trip counts suggests that there is a notable number of unaccounted trips occurring in the evening such as social or shopping trips. The assigned total MDCV and HDCV flow compares best with the truck counts magnitude. Which further emphasizes the inclusion of some MDCVs in the CVS Truck count. The lower HDCV flows in our study is likely a result of the inclusion of other commercial vehicles in the count. At the hourly level, the largest absolute difference was found at 11 am, this hour had the highest fraction of CV traffic so this result is expected. The variation associated in magnitude and overall traffic distribution between the estimated and observed traffic flow can also be attributed due to the study year variation. Five years can potentially change the overall traffic trends. The hourly absolute differences and their totals and the assigned trend for each vehicle type is detailed in Appendix J

Maps presenting the 12 pm traffic assignments are also found in Appendix J. From the PV and LDCV flow map, the majority of the traffic was found to be centralized in Toronto with higher densities in Downtown Toronto. Additionally, the Hamilton CMA exhibits higher traffic flow in Downtown Hamilton. The MDCV traffic assignment is visually spatially similar to the HDCV traffic assignment but the MDCV flow exhibits more movement in both the Hamilton and Toronto Downtown areas. This assignment makes sense as MDCVs are more likely to be in the downtown area at 12 pm as opposed to HDCVs. Figure 4-13 presents the HDCV flow at 12 pm in the GTHA overlaid on a kernel density map of the existing trucking firms in the GTHA (see section 3.3.1.5). Darker shades of blue represent a greater density of trucking firms. The HDCV flow in the GTHA is greater in areas with higher densities of trucking firms. This further validates the spatial distribution of the traffic assignment since higher proportions of traffic were assigned on road links closer in vicinity to areas with higher densities of trucking firms. It is important to note that these trucking firms were not the source used to estimate HDCV trip generation, however they are likely to correlate as the Statistics Canada employment counts should reflect the employees at these firms. Based on these validation results, it is safe to assume that the traffic assignment results can be used for further analysis.

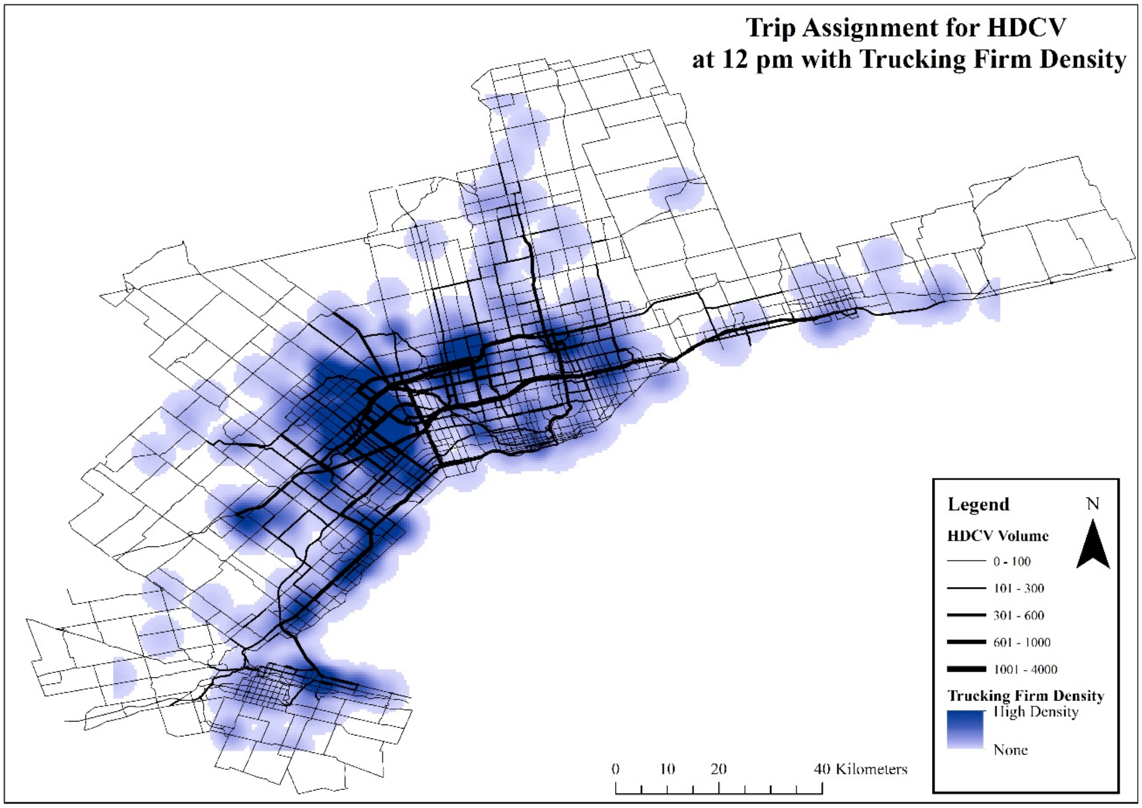


Figure 4-13: HDCV Traffic Assignment with Yellow Pages Firm Density

4.3 MOVES Emission Results

The emission rates obtained from MOVES2014a and the traffic results estimated in this study were used to produce an inventory of both running and start emissions. Emission rates were generated for 60 pollutants, but only 25 pollutants were further assessed in addition to energy consumption. This section first presents the running emissions and starts emissions of the varied fueling scenarios. Then, these emissions will be combined and presented as total emissions and the contribution of both processes will be evaluated. Finally, in the last portion of this section, the fuel advantage by pollutant results are compared to literature. Additional results to those discussed in this section are presented in Appendix K.

4.3.1 Running Emissions

As previously mentioned, the running emissions are the emissions released during operation when the engine is fully warmed up. The specified MOVES run produced running emission rates for three processes (running exhaust, crankcase running exhaust and refueling spillage loss). The emissions from each process were combined and summed for each pollutant under each fueling scenario. The running emission results do not completely lean towards one fuel. Of the twenty-five pollutants examined, four pollutants (tirewear and brakewear particulate matter (PM_{10} and $PM_{2.5}$)) released the same volume of emissions in both seasons. Of the remaining twenty-one pollutants, in the winter, the use of CNG fuel lowered the emissions of eleven pollutants, while diesel outperformed CNG with respect to ten pollutants. In the summer, CNG use lowered the emissions of ten pollutants whereas diesel was a better alternative with respect to the other eleven pollutants. Overall, all pollutants except nitrogen dioxide exhibited the same emission trend in both seasons; NO_2 emissions were lower in the winter and higher in the summer with an all-CNG fleet.

The pollutants were grouped based on their environmental impact or their physical characteristics and their results are evaluated in detail.

Greenhouse Gases

The major GHGs examined include: CO_2, methane, and nitrous oxide. MOVES computes the CO_2eq of GHGs. Upon examination of the three pollutants, it is evident that CNG reduces CO_2 emissions in both January and August. Figure 4-14 presents the CO_2 emissions in tonnes, there is no major drop in CO_2 emissions between the two one-fuel scenarios. There is an average percent change decrease of 6% from an all-diesel to an all-CNG scenario. It is interesting to note that there are more CO_2 emissions in the summer than winter. On the other hand, an all-CNG fleet produces about 463 and 20 times more methane and nitrous oxide emissions, respectively than an all-diesel fleet. Overall, diesel emits lower levels of CO_2 equivalent emissions as shown in Figure 4-15. The percent difference between the two sole-fuel scenarios is lower in the summer (6%) as opposed to the winter (10%). The CO_2eq emissions are about 1.1 times higher in the all-CNG scenario. The difference between the two cases is not as wide as CH_4 and N_2O, however CO_2eq emissions are reported in tonnes, which are a thousand times larger than kilograms therefore any reduction, even though minimal will make a substantial difference.

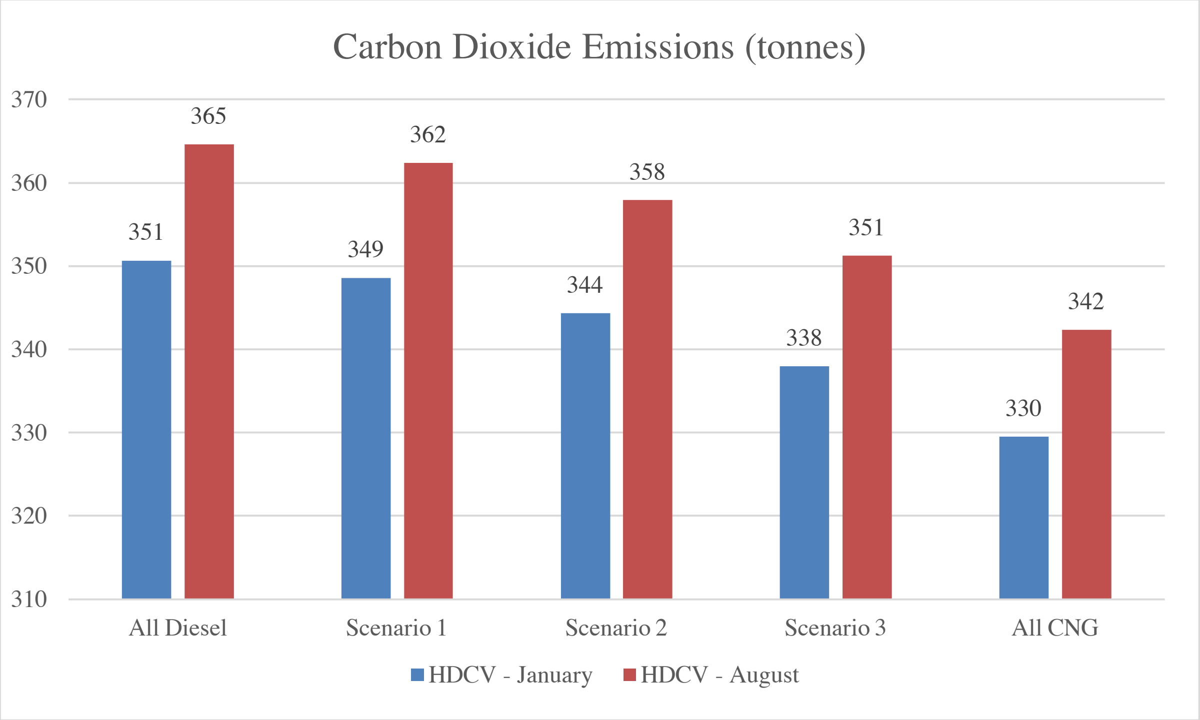


Figure 4-14: Running CO_2 Emissions at 12 pm from HDCVs

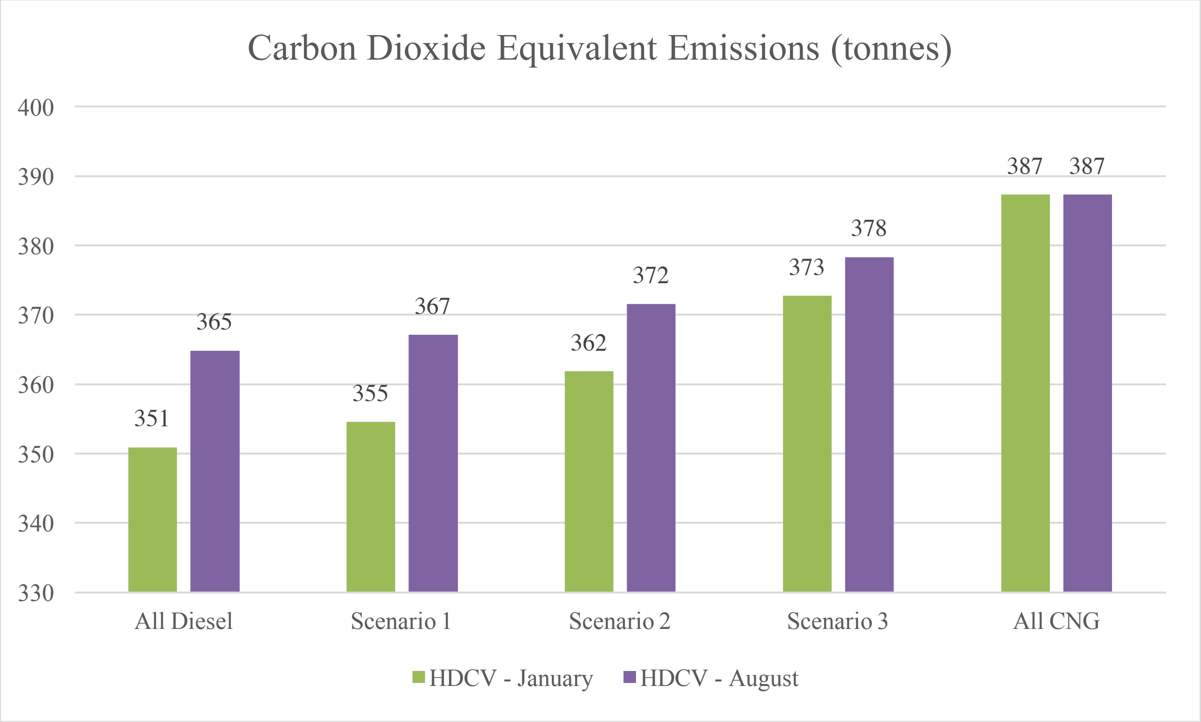


Figure 4-15: Running CO_2eq Emissions at 12 pm from HDCVs

The Oxides of Nitrogen

Oxides of Nitrogen (NO_x) are a family of seven compounds that are composed of nitrogen and oxygen. When airborne, these compounds cause adverse effects on human health and the environment. Some of these compounds include nitrous oxide (N_2O), nitric or nitrogen oxide (NO), and nitrogen dioxide (NO_2). The analysis provides results for these three compounds. Nitrous oxide results were previously discussed in the GHG section. N_2O emissions are greater in an all-CNG scenario (8.83 kg) as opposed to an all-diesel scenario (0.43 kg) and are consistent during both seasons. Figures 4-16 and 4-17 present the NO_x emissions in January and August, respectively. Overall, the NO_x emissions are lower in an all-CNG scenario in both months. Nitrogen oxide is the greatest component of NO_x emissions and exhibit the same seasonal trend. NO_2 emissions from an all-CNG fleet are found to be lower in January but are higher in August. The percent difference between the two one-fuel categories is lower in the winter at 4.4% and 9.3% in the summer. This variation is important to consider when transitioning to an AF, as the benefits should be present year-round. However, the overall trend of the NO_x group in both seasons present CNG as clean fuel alternative.

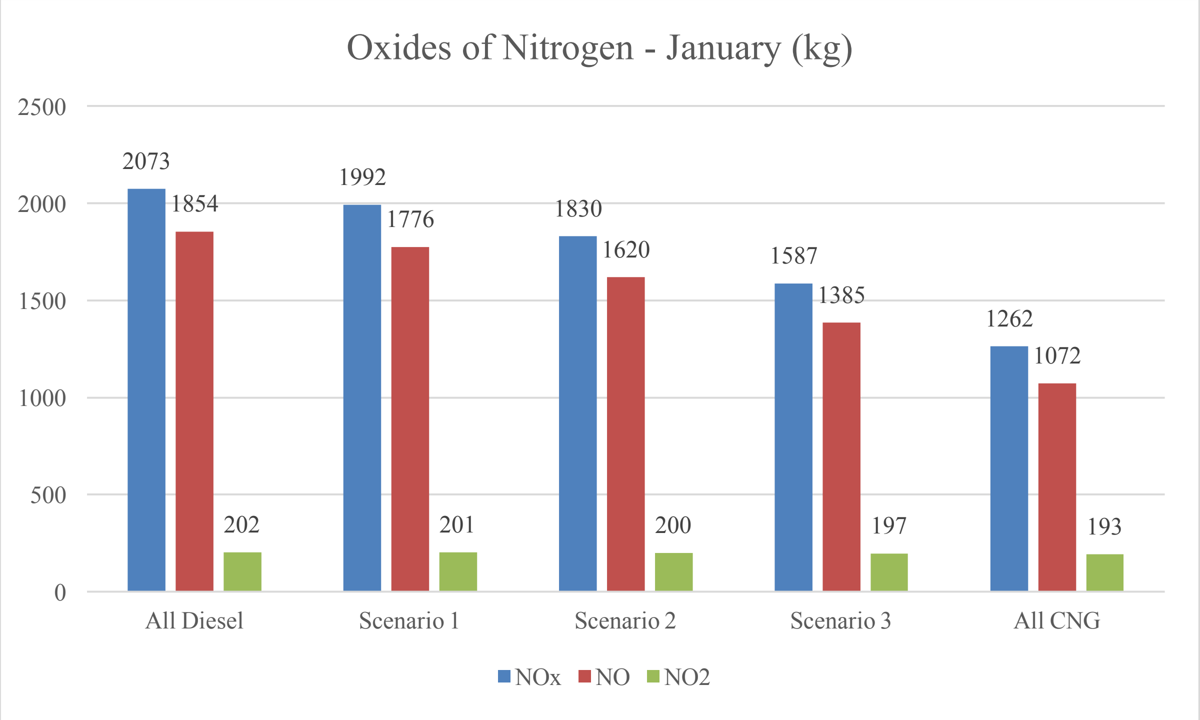


Figure 4-16: Oxides of Nitrogen in January at 12 pm

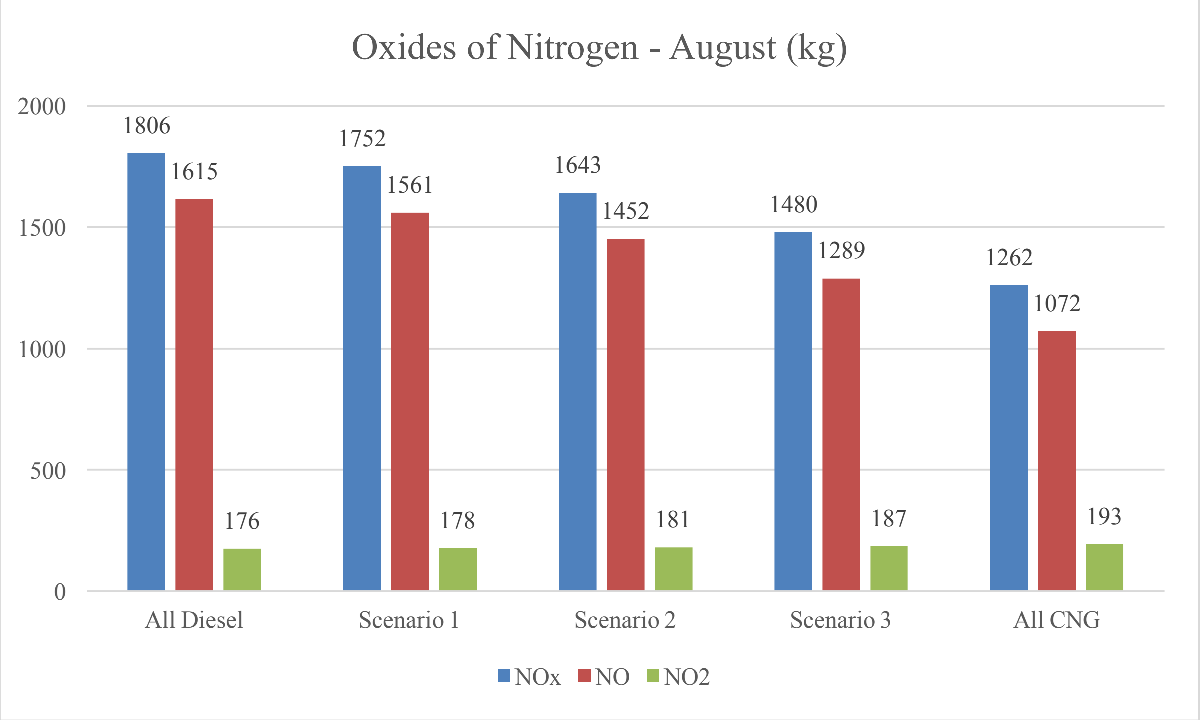


Figure 4-17: Oxides of Nitrogen in August at 12 pm

Particulate Matter

Studies in literature push for the conversion of diesel HDCVs towards NGVs as the latter have been found to reduce PM emissions. The two sizes of PM: PM_{10} and $PM_{2.5}$ and their constituents both exhibited this trend. The PM emissions at 12 pm for both months are presented in Table 4-15. Both PM_{10} and $PM_{2.5}$ exhibited a similar trend with respect to their reduction. A CNG fleet will emit approximately 78.7% lower PM emissions than a diesel fleet in the GTHA.

Table 4-15: Particulate Matter Emissions at 12 pm (kg)

Scenario	PM_{10}	$PM_{2.5}$	% Change from All Diesel		Organic Carbon	Elemental Carbon	Sulfate Particulate
			PM_{10}	$PM_{2.5}$			
All Diesel	106.01	97.53	0%	0%	11.37	55.35	2.64
10% CNG	97.71	89.81	-8%	-8%	10.93	50.01	2.39
30% CNG	81.10	74.37	-23%	-24%	10.04	39.33	1.88
60% CNG	56.19	51.21	-47%	-47%	8.71	23.30	1.13
All CNG	22.98	20.33	-78%	-79%	6.93	1.94	0.12

The PM constituents, elemental carbon and sulfate particulate experience a more significant percent change 96.5% and 95.4%, respectively than organic carbon with a 39%

decrease in emissions. PM emissions from tirewear and brakewear processes were found to be the same for every scenario, therefore the two are not of interest for this study but are presented in Appendix K.

Key Pollutants

The Ministry of Environment and Climate Change Canada reports emissions for six key air pollutants: ammonia, fine PM, NO_x, volatile organic compounds, carbon monoxide, and sulphur oxides. These pollutants contribute to air pollution problems such as smog and acid rain in Canada. Of these pollutants, PM, sulfur dioxide and oxides of nitrogen exhibit a decrease in emissions when a NGV is utilized. The other three pollutants in this category demonstrate an increase, the most notable is CO. 2.5 times more CO emissions are released with the use of CNG. This increase may be associated with the engine technology since incomplete combustion during vehicle operation will increase the production of CO emissions. This potentially can be combatted with improvements in technology as Grigoratos et al. (2016) report a reduction of CO emissions for a prototype heavy-duty engine. Half of the key pollutants suggest CNG is better alternative, while the other half do not support this transition. Examining the magnitudes of these emissions in Table 4-16 it is evident that the two major pollutants of interest, NO_x and fine PM demonstrate a modest and substantial decrease in emissions, respectively. However, the decrease occurs at a cost of an increase in three other key pollutants. The increased magnitude of CO is also troubling as it is roughly a tonne of additional emissions just for one hour, this impact annually will be substantial.

Table 4-16: Emissions of Key Pollutants (kg)

Scenario	**CO**	**Ammonia**	**VOCs**	**Sulfur Dioxide**		**$PM_{2.5}$**	**NO_x**	
				January	**August**		**January**	**August**
All Diesel	516	5.13	132	2.99	3.11	98	2073	1806
Scenario 1	593	5.47	137	2.86	2.98	90	1992	1752
Scenario 2	748	6.15	145	2.61	2.72	74	1830	1643
Scenario 3	980	7.18	158	2.24	2.33	51	1587	1480
All CNG	1290	8.55	175	1.74	1.80	20	1262	1262
% Difference[1]	86%	50%	28%	-53%	-53%	-131%	-49%	-35%

[1] The percent difference between the All CNG and All Diesel case (reference)

Air Toxics

The air toxins examined in this study include: total gaseous hydrocarbons, formaldehyde, acetylaldehyde, acrolein and non-methane hydrocarbons. The emission from air toxins (except for acrolein) increase with the introduction of CNG fuel. From this category of pollutants it is clear that diesel is a better alternative. The all-CNG scenario acrolein demonstrates an 81% decrease as opposed to an all-diesel scenario. However, these emissions are the lowest in magnitude for this group. Therefore, this category demonstrates more drawbacks associated with natural gas HDCVs. Table 4-17 presents air emissions of air toxins at 12 pm.

Table 4-17: Emissions of Air Toxics at 12 pm (kg)

Scenario	THC	NMHC	Formaldehyde	Acetyladehyde	Acrolein
All Diesel	124	119	10	4.27	0.78
Scenario 1	277	118	17	4.77	0.74
Scenario 2	583	118	31	5.78	0.65
Scenario 3	1042	116	52	7.30	0.51
All CNG	1654	114	80	9.32	0.33

Energy Consumption

The energy consumption associated with running emissions is found to be approximately 18% higher in an all-CNG scenario than its diesel counterpart. The energy consumption for all scenarios was found to be slightly greater, on average 4%, in summer months as opposed to winter months.

From these results, it is essential to further quantify the trade-offs associated with decreasing pollutants like carbon dioxide, PM and NO_x and in turn increasing emissions like methane, VOCs and ammonia. A fuel transition may have unexpected repercussions if there is a considerable raise in non-target emissions.

4.3.2 Start Emissions

Of the 25 pollutants examined, only seventeen pollutants were emitted from the Starts processes in winter and thirteen pollutants in summer. In winter, fourteen of these pollutants have lower emissions using NGVs, whilst eleven pollutants have lower emissions in the summer. Five pollutants fared better with the use of CNG fuel instead of diesel from its starts emissions as opposed to running emissions. These pollutants include:

THCs, CO, formaldehyde, acetaldehyde, and VOCs. One important factor to consider is that these emissions are not based on the number of starts in the GTHA and the rates per vehicle are generated by MOVES for modeled vehicle type. The *ratepervehicle* table was used to determine the emissions associated with starts. The processes that contribute to start emissions include: start exhaust, crankcase start exhaust and refueling spillage loss. The refueling spillage loss was only observed for three pollutants for diesel fuels and only found to be significant in the all-diesel fleet. The three pollutants that have measurable emissions for refueling losses are THC, NMHCs, and VOCs and all emit lower emissions when CNG is introduced to the fleet. Without the refueling loss emissions, this trend is still observed. Table 4-18 and 4-19 present the Start Emissions Inventory for January and August at 12 pm respectively.

Table 4-18: Winter Start Emissions for 12 pm (kg)

	Winter (January)				
Pollutant	**Base**	**10%**	**30%**	**60%**	**All CNG**
Total Gaseous Hydrocarbons	23.28	23.24	23.17	23.07	22.93
Carbon Monoxide (CO)	112.37	112.28	112.09	111.81	111.44
Methane	4.23	5.95	9.40	14.56	21.45
Nitrous Oxide	0.12	1.70	4.86	9.60	15.91
Formaldehyde	2.25	2.09	1.78	1.30	0.67
Acetaldehyde	0.91	0.83	0.68	0.45	0.14
Acrolein	0.16	0.14	0.11	0.06	0.00
Sulfur Dioxide	0.02	0.02	0.02	0.01	0.01
Non-Methane Hydrocarbons	19.05	17.28	13.75	8.45	1.39
Volatile Organic Compounds	21.94	19.94	15.92	9.89	1.85
Atmospheric CO_2	2,454.60	2,406.74	2,311.01	2,167.42	1,975.96
CO_2 Equivalent	2,596.46	3,392.26	4,984.14	7,371.68	10,555.16
Primary Exhaust PM10 - Total	0.26	0.26	0.26	0.25	0.24
Primary Exhaust PM2.5 - Total	0.24	0.24	0.23	0.23	0.21
Organic Carbon	0.09	0.10	0.10	0.09	0.08
Elemental Carbon	0.07	0.06	0.06	0.04	0.02
Sulfate Particulate	0.013	0.012	0.010	0.006	0.002
Total Energy Consumption (MJ)	33,156.07	33,187.64	33,250.79	33,345.50	33,471.78

Table 4-19: Summer Start Emissions for 12 pm (kg)

Pollutant	Summer (August)				
	Base	**10%**	**30%**	**60%**	**All CNG**
Total Gaseous Hydrocarbons	0.04	0.04	0.03	0.02	-
Carbon Monoxide (CO)	112.37	112.28	112.09	111.81	111.44
Nitrous Oxide	0.12	1.70	4.86	9.60	15.91
Sulfur Dioxide	0.01	0.01	0.01	0.01	0.01
Non-Methane Hydrocarbons	0.04	0.04	0.03	0.02	-
Volatile Organic Compounds	0.04	0.04	0.03	0.02	-
Atmospheric CO_2	1,456.59	1,428.19	1,371.38	1,286.17	1,172.55
CO_2 Equivalent	1,492.69	2,255.17	3,780.39	6,067.96	9,118.14
Primary Exhaust PM10 - Total	0.26	0.26	0.26	0.25	0.24
Primary Exhaust PM2.5 - Total	0.24	0.24	0.23	0.23	0.21
Organic Carbon	0.09	0.09	0.09	0.08	0.08
Elemental Carbon	0.07	0.06	0.06	0.04	0.02
Sulfate Particulate	0.013	0.012	0.010	0.006	0.002
Total Energy Consumption (MJ)	19,675.32	19,694.06	19,731.54	19,787.76	19,862.72

4.3.3 Total Emissions

This section combines both start and running emissions and discusses any major changes in the results. The combination of these two types of emissions leads to slightly lower performance by CNG HDCVs. Of the twenty-five pollutants studied, four again had consistent emissions in every fuel scenario. Of the remaining twenty-one pollutants, in the winter season CNG only provides an advantage for twelve of these pollutants and in the summer only ten of these pollutants, whilst diesel outperforms CNG with eleven pollutants in the summer. The winter results are consistent with the running emissions results, whilst the summer results present a fuel preference shift in one pollutant. This pollutant is the NMHCs, the start emissions in the winter provide approximately 15% of the total emissions for an all-diesel fleet – which is significant enough to make the NMHC emissions greater when using a diesel fleet. However, the lower levels of start-related NMHC emissions in the summer, could make diesel the better alternative. The remainder of the results are consistent with their fuel preference.

Table 4-20 presents the average, minimum and maximum percentage of running emissions from the total emissions. On average, the running emissions make up the majority of the total emissions, with one exception associated with CNG use and nitrous oxide – these values reflect the minimum percentages observed in Table 4-20 for all scenarios that include CNG. MOVES emission start rates for nitrous oxide from NGVs are approximately 130 times greater than diesel-powered HDCVs, which significantly impacts the overall emissions. This trend is observed during both seasons. For an all diesel fleet, methane has the lowest percentage of running emissions in the winter at a level of 56%, in the summer there are no methane starts emissions. For all scenarios except the all-CNG case, the average summer running percentages are greater than the winter. This change is likely because most of the summer start rates are generally higher than their winter counterparts. Appendix K presents the fraction of the running process' contribution to total emissions and energy consumption for each pollutant.

Table 4-20: Percentage of Running Emissions

Season	Statistic	All Diesel	Scenario 1	Scenario 2	Scenario 3	All CNG
Winter	Mean	89.37%	91.16%	92.29%	93.53%	95.00%
	Min	55.83%	42.83%	37.80%	36.31%	35.68%
	Max	99.87%	99.87%	99.86%	99.82%	99.40%
Summer	Mean	96.91%	94.51%	94.32%	94.34%	94.18%
	Min	78.20%	42.83%	37.80%	36.31%	35.68%
	Max	99.96%	99.99%	99.99%	100.00%	100.00%

4.3.4 Comparison to Literature

There is a vast collection of literature dedicated to observing the emissions differences between CNG and diesel-powered vehicles. Table 4-21 presents the "better scenario" as observed from the MOVES output and is compared to several studies. The examined studies vary with respect to their vehicle of interest and geographic location, including Canada, United States, Europe and India. Also, the results from these studies vary in their approach in quantifying the emissions – some studies use in-field results such as Vojtíšek-Lom et al. (2018), while others use GHGenius (Shahraeeni et al., 2015; Rose et al., 2013) or chassis dynamometer tests using multiple driving cycles (Kado et al., 2006; Ayala et al., 2002).

From Table 4-21 it is apparent that there are various factors that can affect vehicular emissions. The variation in emission trends are likely a result of the variety of vehicles studied and their respective study locations which can alter fuel formulation, vehicle performance standards (with respect to emissions), countermeasures and climate. With respect to PM emissions, Vojtíšek-Lom et al. (2018) reported that the addition of after-treatment equipment such as oxidation catalysts and particle filters on diesel engines release less PM than a CNG vehicle without after-treatment. When a three-way catalyst is added to a CNG engine its PM emissions become similar to the retrofitted diesel engine. Therefore, advancements in technology can also potentially skew the perceived benefit of either fuel. Therefore, it is essential to ensure both vehicles have similar after-treatment devices to control for these impacts.

There are some inconsistencies in literature with respect to carbon dioxide and carbon dioxide equivalent emissions. This is notably observed within Vojtíšek-Lom et al., (2018), as their study conducted laboratory tests using various drive cycle and on-road tests with different driving routes and varied factors like cold-start runs, road classes (urban, rural, highways) and peak hour. Examining the results from this study, the CO_2 and CO_2eq emissions do not consistently lean towards one fuel when comparing laboratory and on-road results. The majority of the laboratory results studied at different driving cycles do suggest CNG vehicles emit lower levels of CO_2 and CO_2eq emissions; however on-road studies contradict these results. In comparison to the current study at hand, the MOVES results do line up with Vojtíšek-Lom et al. (2018) with respect to CO_2eq emissions. While two studies (Rose et al., 2013 and Shahraeeni et al., 2015) suggest the CO_2eq emissions are lowered with the use of CNG. These results were obtained using GHGenius and in a Canadian context. The use of different GWP factors can potentially be the root cause of contradicting equivalent CO_2 results.

A vehicle retrofitted to use natural gas may not be as efficient as a factory-built NGV. This can explain some of the inconsistencies found with emission results like CO, as its release is mainly due to inefficiencies with the combustion process, which is more likely to be present in converted NGVs. Additionally, the age distribution used for the analysis (see Appendix E) has vehicles ranging from new to thirty years old. It is very unlikely that a diesel vehicle will be converted to CNG if it is very old, therefore the representation of NGVs is unrealistic. However, it is important to assess the emissions released at different stages of a vehicle's lifetime.

Table 4-21: Total Emissions Comparison to Literature

Pollutant	Better Scenario	Studies that Support Result	Studies that Contradict Results
Acetaldehyde	All Diesel	Kado et al., 2006	
Acrolein	All CNG		Kado et al., 2006
Ammonia	All Diesel	Vojtíšek-Lom et al., 2018	
Carbon Monoxide (CO)	All Diesel	Fontaras et al., 2012; Ayala et al., 2002; Texas Transportation Institute, 2009; Shahraeeni et al., 2015; Tong et al., 2017	Turrio-Baldassarri et al., 2006; Rose et al., 2013; Grigoratos et al., 2016
CO_2	All CNG	Ayala et al., 2002	Fontaras et al., 2012
CO_2 Equivalent	All Diesel	Cohen et al., 2003; Vojtíšek-Lom et al., 2018[1]	Rose et al., 2013; Shahraeeni et al. 2015
Formaldehyde	All Diesel	Kado et al., 2006	Turrio-Baldassarri et al., 2006
Methane	All Diesel	Vojtíšek-Lom et al., 2018	
Nitrogen Dioxide	All CNG (Winter), All Diesel (Summer)	Vojtíšek-Lom et al., 2018	
Nitrogen Oxide	All CNG	Vojtíšek-Lom et al., 2018	
Nitrous Oxide	All Diesel		Vojtíšek-Lom et al., 2018
Non-Methane Hydrocarbons	All CNG (Winter), All Diesel (Summer)		Kado et al., 2006
Oxides of Nitrogen	All CNG	Fontaras et al., 2012; Ayala et al., 2002; Cohen et al., 2003; Rose et al. 2013; Texas Transportation Institute, 2009; Grigoratos et al., 2016; Tong et al., 2017	Jayratne et al., 2009; Shahraeeni et al. 2015
Sulfur Dioxide	All CNG	Cohen et al., 2003; Tong et al., 2017 SO_x: Rose et al., 2013; Shahareeni et al. 2015;	
Total Gaseous Hydrocarbons	All Diesel	Fontaras et al., 2012; Texas Transportation Institute, 2009; Vojtíšek-Lom et al., 2018	Turrio-Baldassarri et al., 2006
Total PM_{10} and $PM_{2.5}$	All CNG	Fontaras et al., 2012; Turrio-Baldassarri et al., 2006; Rose et al., 2013	Shahareeni et al., 2015
Volatile Organic Compounds	All Diesel	Kado et al., 2006; Rose et al., 2013; Shahraeeni et al., 2015	Tong et al., 2017
Total Energy Consumption	All Diesel	Rose et al., 2013; Shahraeeni et al., 2015	

[1]On-Road Results, lab results suggest CNG is a better option	
Studied Vehicles	
LDV	Vojtíšek-Lom et al., 2018 (Station Wagons and Vans)
LDCV	Shahraeeni et al.,2015
WCV	Texas Transportation Institute, 2009; Fontaras et al., 2012; Rose et al., 2013
Transit Buses	Ayala et al., 2002; Cohen et al., 2003; Turrio-Baldassarri et al., 2006; Kado et al., 2006; Jayratne et al., 2009; Fontaras et al., 2012; Tong et al., 2017
HDCV	Grigoratos et al., 2016 (prototype engine)

These results further stress the need for field studies examining HDCVs with various after-treatment technologies to assess the emissions associated with real-time operation and traffic conditions and the additional weight associated with cargo. Additionally, it is not enough to assess how many pollutants CNG or diesel-powered vehicles emit lower levels of compared to the other fuel as the health effects and impacts and the emission quantity plays a role in how significant each pollutant is. Therefore, a MCDA must be conducted, as will be presented in the following section.

4.4 Multi-Criteria Decision Analysis

This section presents and discusses the multi-criteria decision analysis used to decide which fueling scenario is the best option. The first subsection (4.4.1) presents the life cycle assessment results obtained from GHGenius. The following three subsections present the calculated SIs for each sustainability pillar. The fifth subsection presents the SI results of each pillar using entropic weights and TOPSIS. The sixth section then combines the three pillars' SIs to obtain an overall sustainable index. The final section discusses the overall results and methods used.

4.4.1 Life Cycle Assessment: GHGenius Results

GHGenius was used to determine the life cycle emissions and energy use. The Ontario defaults were used for the analysis. Life cycle energy consumption was demonstrated to be lower with a diesel fleet. The "end-use" phase, which is considered to be the customers' utilization of the vehicle, has the highest energy consumption process. This result is also observed in MOVES, NGVs were found to consume more energy than a diesel-powered vehicle while running. Without this stage, CNG-powered vehicles utilize less energy during the life cycle. Figure 4-18 presents the breakdown of these emissions and their associated stages. CNG emits more emissions than diesel in the following three stages: the fuel distribution and storage phase, fuel dispensing and end-use. The fraction of energy used is greatest in the end-use stage, making up 79% and 86% of total life cycle energy use for diesel and CNG-powered vehicles, respectively. Overall, CNG require approximately 8% more energy diesel over the span of the entire life cycle. When this stage is removed from the analysis, diesel powered vehicles consume 39% more energy per vehicle km of travel than CNG trucks.

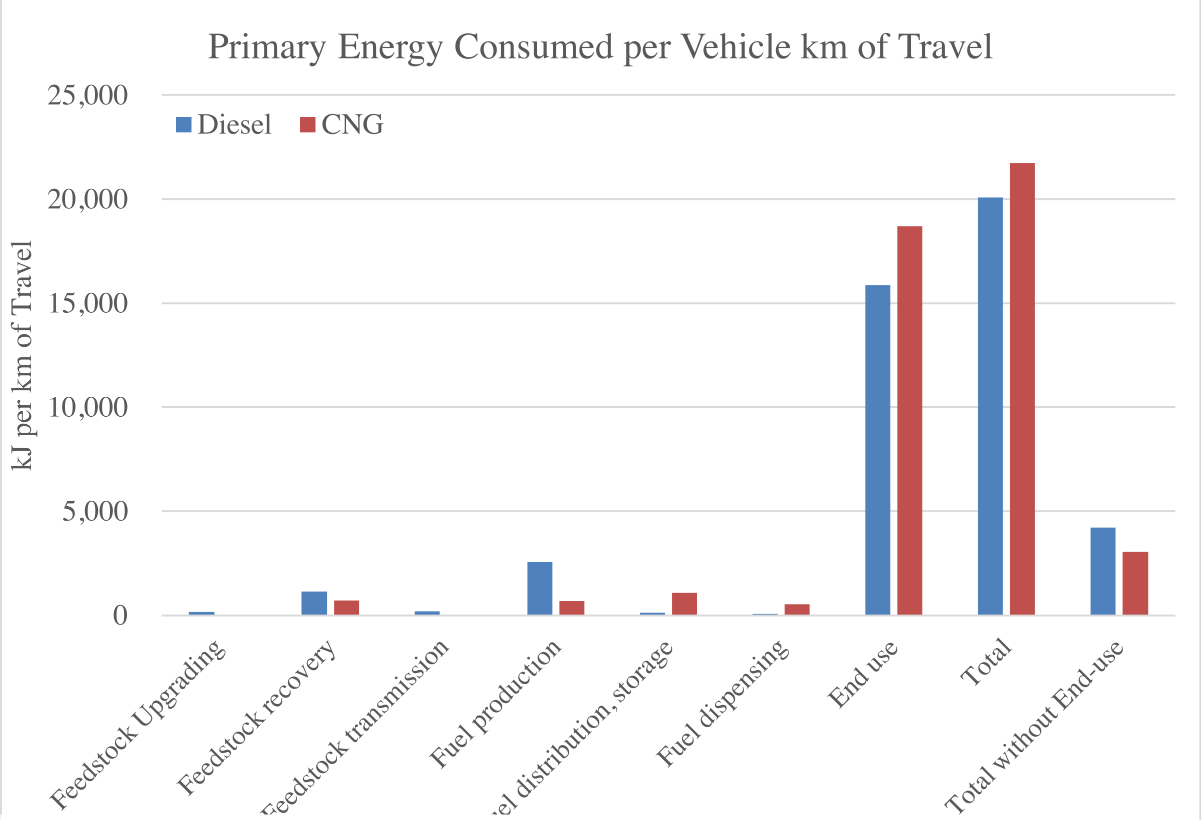


Figure 4-18: Life Cycle Energy Consumption (GHGenius Results)

Figure 4-19 illustrates the life cycle GHG emissions which are reported as CO_2-equivalent emissions. The feedstock production phase includes the GHG emissions emitted from: any land-use changes and cultivation required to produce the fuel, feedstock recovery and upgrading, gas leaks and flares and the removal of carbon dioxide and hydrogen sulfide from CNG. As with the energy consumption, the CO_2eq emissions are greatest during the vehicle operation stage, accounting for approximately 75% of the total life cycle emissions. The next major GHG emitting phases are the feedstock production stage for both fuels, and is then followed by the fuel production phase for diesel and fuel storage and distribution for CNG. Overall, CNG has lower life cycle CO_2eq emissions than diesel, and is only outperformed by diesel in the following stages: fuel storage and distribution, fuel dispensing, material production and vehicle assembly.

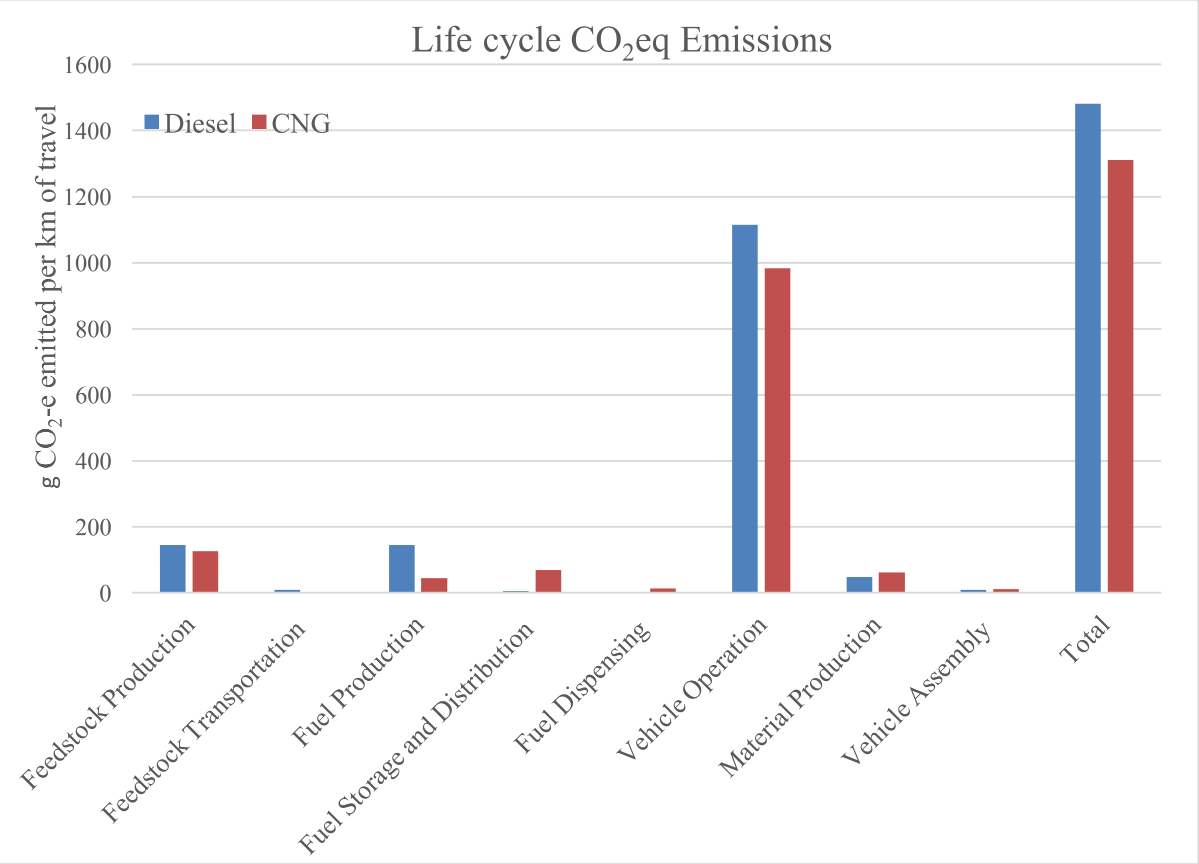


Figure 4-19: Life cycle CO_2eq Emissions (GHGenius)

MOVES CO_2eq emissions for the running and total processes are higher with the use of CNG, whilst GHGenius suggests the opposite for HDCVs. The total CNG CO_2eq emissions are on average 8% higher than the diesel equivalents in MOVES, while GHGenius results report that diesel emits 13% more CO_2eq emissions than CNG. These two simulation models were developed in different countries and their methods of analysis vary. This discrepancy may be due to the use of an American speed profile and fuel formulation in MOVES and potentially the use of the bus rates to scale up to a HDCV. This inconsistency can also be a result of the use of different GWPs used to obtain the carbon dioxide equivalent emissions. In comparison to literature, Rose et al. (2013) reported lower CO_2eq emissions during the vehicle operation phase of a waste collection vehicle operating with CNG as compared to diesel. From these results, one can conclude that the use of CNG in a Canadian context will likely reduce the CO_2-equivalent emissions.

4.4.2 Economic SI

Table 4-22 presents the obtained economic indicators. Rank 1 (vehicle acquisition or conversion cost is the key criteria) suggests diesel is the best option economically, whilst Rank 2 (fuel price is the key criteria) suggests CNG is the better choice. The rank sum and reciprocal approaches provide results that are similar in magnitude and trend for both Rank 1 and 2. Rank sum (RS) and reciprocal (RR) provide differing results with respect to Rank 3's approach – with RS suggesting both options are a good choice and RR suggesting CNG is better.

Table 4-22: Economic Sustainability Indicators

Ranking	**Rank**	**All Diesel**	**10% CNG**	**30% CNG**	**60% CNG**	**All CNG**	**Correlation**
Rank 1	*Sum*	0.60	0.58	0.54	0.48	0.40	1.0000
	Reciprocal	0.64	0.61	0.56	0.47	0.36	
Rank 2	*Sum*	0.40	0.42	0.46	0.52	0.60	1.0000
	Reciprocal	0.36	0.39	0.44	0.53	0.64	
Rank 3	*Sum*	0.50	0.50	0.50	0.50	0.50	-0.3693
	Reciprocal	0.40	0.42	0.46	0.52	0.60	

Note:
Rank 1: Vehicle acquisition or conversion cost is the key criteria
Rank 2: Fuel price is the key criteria
Rank 3: Fuel price is still the key criteria, fueling station availability is more important than fuel price stability (refer to Table 3-13)

4.4.3 Environmental SI

This section presents the environmental SIs obtained using Methods 1 (RS), 2 (RR) and 3 (Assigned Weights "AW"). The entropy and TOPSIS method (Methods 4 and 5) will be discussed in section 4.4.5. A differential will be calculated and discussed in this section. The differential Δ is computed as follows:

$$\Delta = |All\ Diesel\ SI - All\ CNG\ SI|$$

As discussed in Section 3.4, various weighting approaches were used for the emissions and environmental SI. The environmental SIs were obtained for the two types of emissions (running and total) during the two study months. The running and total emissions' SI results for RS and RR were consistent for both months and suggest diesel is a better option. The assigned weights (AW) ranking produced a similar trend for both seasons suggesting CNG as a better option. The results also present a slight CNG advantage in the summer. The differential Δ was largest for the assigned weights approach (0.38) and smallest for the rank reciprocal approach (0.05). The results suggest that all the pollutants emphasized in the assigned weights category favour CNG. In fact, this weighing approach focuses strongly on NO_x, CO_2 and Total Gaseous Hydrocarbons. Two of these pollutants release lower levels of emissions with the use of CNG fuel and their contribution to the overall ranking is 67%. This environmental advantage for CNG is likely the cause of the large score Δ for the assigned weights approach. The total emissions' SIs obtained from the assigned weights approach were slightly higher than the running emissions' SIs (winter average difference: 0.007 vs. summer average difference: 0.004). The Δ value between the two homogenous fuel mixtures is only marginally lower than the running emissions.

The six environmental SI ranking approaches listed in Table 4-23 were used to produce a total of thirty-six SIs following the scheme shown in Figure 4-20. All SIs suggest that CNG is a better alternative environmentally (see Appendix M). Table 4-23 presents some basic statistics for the calculated Δ values. The lowest average Δ is obtained when the emissions are assigned a weight of 50% and the remaining criteria are either assigned equal weights or weights obtained from the rank sum method. Equal weights provide the largest Δ when the emissions were ranked using the rank sum or rank reciprocal approach. Whilst emissions ranked using the assigned weight approach have the largest Δ between their two sole fuel categories when emissions are given a weight of 0.5 and the remaining of the environmental criteria were ranked using the rank reciprocal approach. There is no consistent minimum environmental ranking using the different emissions ranks.

Table 4-23: Environmental SI Statistics

Environmental SI Rank	Minimum	Maximum	Mean
Rank Sum	0.1360	0.3516	0.2860
Rank Reciprocal	0.1232	0.3819	0.3032
0.5% Tailpipe Emissions, Rest RS	0.0867	0.3562	0.2742
0.5% Tailpipe Emissions, Rest RR	0.1473	0.4168	0.3348
50% Tailpipe Emissions, Equal Rest	0.0867	0.3562	0.2742
Equal Weights	0.2100	0.3448	0.3038

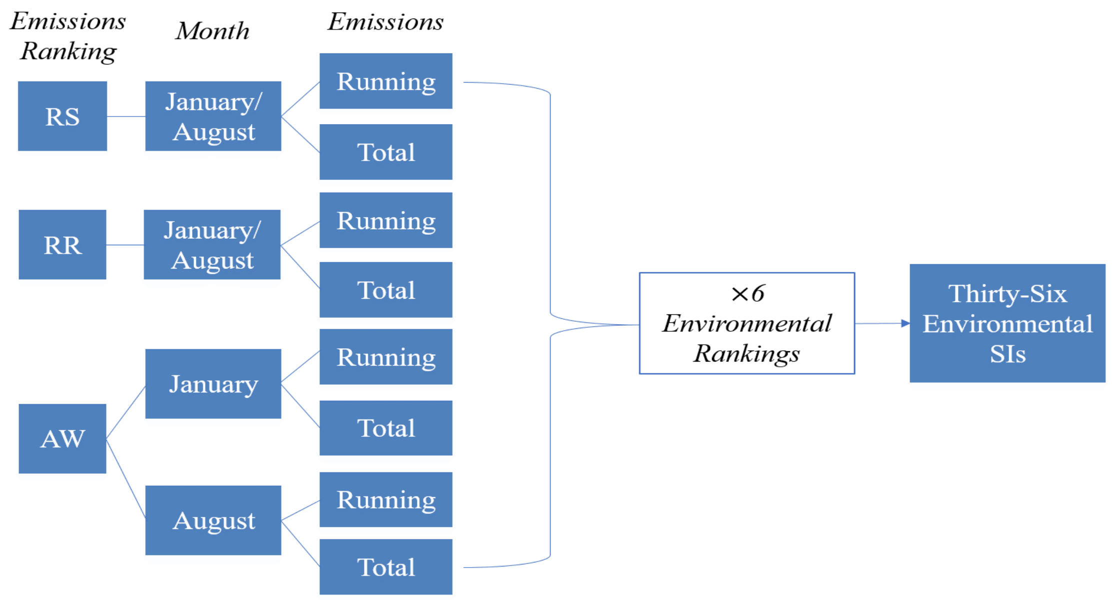


Figure 4-20: Environmental SIs Breakdown

4.4.4 Social SI

The social pillar assessed the human and crops exposure cost to emissions from five pollutants, as shown in Table 4-24. $PM_{2.5}$, SO_2 and NO_x emissions fare better with CNG use and make up 75% of the social costs associated with pollution (see Table 3-16). Based on the pollutants evaluated, the introduction of CNG to the HDCV fleet is shown to have social benefits. One downfall of the current social analysis is that it may be considering the emissions associated with these key pollutants twice (i.e. double-counting). Therefore, the overall SI will be considered with and without the social category to explore the variation in the two cases.

Table 4-24: Social Sustainability Indicator

		Ranks					**Sustainability Indicator**				
Pollutant	**Weight**	**All Diesel**	**10%**	**30%**	**60%**	**All CNG**	**All Diesel**	**10%**	**30%**	**60%**	**All CNG**
$PM_{2.5}$	0.5482	0	0.1	0.3	0.6	1	0.00	0.05	0.16	0.33	0.55
NH_3	0.2266	1	0.9	0.7	0.4	0	0.23	0.20	0.16	0.09	0.00
SO_2	0.1170	0	0.1	0.3	0.6	1	0.00	0.01	0.04	0.07	0.12
NO_x	0.0877	0	0.1	0.3	0.6	1	0.00	0.01	0.03	0.05	0.09
VOCs	0.0205	1	0.9	0.7	0.4	0	0.02	0.02	0.01	0.01	0.00
						SI	**0.25**	**0.30**	**0.40**	**0.55**	**0.75**

4.4.5 Entropic Weights and TOPSIS

The determination of entropy-based weights was quite straightforward for both the social and economic pillar. Both pillars favour CNG as the score increases with the addition of CNG to the fleet. These weights are then used as inputs for TOPSIS to determine which scenario is closest to the "ideal solution". Again, a lower relative distance (CL_i^+) translates to a better option. Table 4-25 presents both the entropic-derived scores and TOPSIS derived relative distances for the five scenarios. CNG appears to be the better fuel based on the social and economic pillar.

Table 4-25: Entropic-Derived Scores for the Economic and Social Pillar

Scenario	**Economic**		**Social**	
	Entropy	**CL_i^+**	**Entropy**	**CL_i^+**
All Diesel	0.3695	0.6890	0.2809	0.7307
10% CNG	0.3956	0.6829	0.3247	0.7222
30% CNG	0.4478	0.6207	0.4124	0.6417
60% CNG	0.5261	0.4353	0.5438	0.4252
All CNG	0.6305	0.3110	0.7191	0.2693

Environmental Category

The environmental category was again examined using the three emission ranking approaches (RS, RR and AW) for both emissions and seasons. In addition to entropic-derived weights, RS, RR and AW methods were used at the emissions criteria level as input for the environmental analysis using entropy-derived weights SAW and TOPSIS method (Methods 4 and 5). Table 4-26 presents the entropy-derived scores for emissions. These scores are the same for both running and total emissions as the pollutants examined in this analysis do not change their ranking values (r_{ij}) with the introduction of start emissions and are generally consistent for both seasons.

Table 4-26: Environmental Entropy Derived Scores

Entropy Scores	**Diesel**	**10%**	**30%**	**60%**	**CNG**
Emissions	0.4386	0.4509	0.4754	0.5123	0.5614

A total of eight categories are examined for the two tailpipe emission values (two seasons × four emission rankings). The environmental SIs are provided in Table 4-27. All results have a correlation of 1, and the two different emission results have a correlation of

1. All emissions ranking approaches and scenarios conclude that the introduction of CNG provides an environmental advantage. It is not surprising that all rank sum and reciprocal results have the same overall scores in every emission scenario and season. A variation between the running and total emissions is only found when the tailpipe emissions scores are obtained using the AW approach. The average Δ is 0.544 and there are only minor variations between the different approaches as the range is only 0.055. The only seasonal variation is found when the total emissions are examined and are ranked using the AW method.

Normalized emission SIs were used at the environmental level, this resulted in two SIs that both suggest CNG is a better environmental option. Method 3 and 4 (Assigned weights and entropy-derived weights) for emission ranking produced SIs with a Δ approximately 2.6 times greater than Method 1 and 2. This occurs because the RS and RR approaches for emissions suggest diesel is a better alternative than CNG.

Table 4-27: Environmental SIs obtained using Entropy-Derived Weights and SAW Procedure

Tailpipe Emissions	Season	Tailpipe Emissions Rank Approach	All Diesel	10% CNG	30% CNG	60% CNG	All CNG
Running	*Winter*	Rank Sum	0.2285	0.2828	0.3914	0.5543	0.7715
		Rank Reciprocal	0.2267	0.2814	0.3907	0.5547	0.7733
		Assigned Weights	0.2295	0.2836	0.3918	0.5541	0.7705
		Entropy	0.2273	0.2818	0.3909	0.5545	0.7727
	Summer	Rank Sum	0.2285	0.2828	0.3914	0.5543	0.7715
		Rank Reciprocal	0.2267	0.2814	0.3907	0.5547	0.7733
		Assigned Weights	0.2295	0.2836	0.3918	0.5541	0.7705
		Entropy	0.2273	0.2818	0.3909	0.5545	0.7727
Total	*Winter*	Rank Sum	0.2285	0.2828	0.3914	0.5543	0.7715
		Rank Reciprocal	0.2267	0.2814	0.3907	0.5547	0.7733
		Assigned Weights	0.2296	0.2837	0.3920	0.5543	0.7708
		Entropy	0.2273	0.2818	0.3909	0.5545	0.7727
	Summer	Rank Sum	0.2285	0.2828	0.3914	0.5543	0.7715
		Rank Reciprocal	0.2267	0.2814	0.3907	0.5547	0.7733
		Assigned Weights	0.2296	0.2837	0.3919	0.5542	0.7707
		Entropy	0.2273	0.2818	0.3909	0.5545	0.7727

TOPSIS was used to obtain the relative distance (CL_i^+) from the ideal solution for the environmental pillar. Again, the different emission ranking methods were used at the environmental level. The relative distance results are consistent for both seasons and the two examined emissions. All results suggest CNG to be the better option. Table 4-28 presents the relative distance values for the environmental pillar. It is interesting to note that the RS and RR emission ranking results are consistent with and without normalization and the normalized entropy values are the same as the raw values of the AW method. It is evident that differences between the relative distance values are insignificant and all suggest CNG is closer to the ideal solution.

Table 4-28: Environmental Relative Distance Values

Emission Scores	**Emissions Ranking Method**	**All Diesel**	**10% CNG**	**30% CNG**	**60% CNG**	**All CNG**
Raw Values	RS, RR and Entropy	0.7580	0.7475	0.6538	0.4196	0.2420
	AW	0.7581	0.7476	0.6539	0.4196	0.2419
Normalized	RS and RR	0.7580	0.7475	0.6538	0.4196	0.2420
	AW	0.7584	0.7479	0.6540	0.4195	0.2416
	Entropy	0.7581	0.7476	0.6539	0.4196	0.2419

4.4.6 Overall SI Results

The overall SIs are a combination of the SIs generated for two or three of the sustainability pillars. As previously discussed, the social pillar will not be included in some of the analysis. The results are broken down into three sections. The first set of results are the overall SIs obtained using different ranking and weight approaches. The second set of results were obtained using entropic weights in conjunction with the SAW method. Finally, the third set of results presents the relative distances obtained from the TOPSIS approach.

SAW for Ranking and Weights Approach

From Methods 1, 2 and 3 there are six economic scores, one social score and a total of thirty-six environmental scores for analysis. Therefore, a total of 216 potential overall SIs for each fueling scenario can be determined. The overall SIs will be estimated using six weighting approaches for each sustainable pillar (as presented in the second to fourth row of Table 4-29). The analysis was conducted at a seasonal level to determine if there were any discrepancies between the overall results with the consideration of both types of emissions. This creates "four groups" of results that are all assessed at the six weight approaches. The four groups are: Winter – Running Emissions, Summer – Running Emissions, Winter – Total Emissions and Summer – Total Emissions.

Most scenarios present CNG as the better alternative. 100% of scenarios suggest that CNG is a better option when all three pillars are included in the analysis, whilst 89% of the other economic-environmental scenarios suggest CNG is the better fueling option. The four groups of analyses provide the same total results that are presented in Table 4-29. Of the SIs that suggest diesel is a better alternative, the environmental emission were ranked using the RS or RR method.

Table 4-29: Overall SI Results

Sustainable Scenario		**1**	**2**	**3**	**4**	**5**	**6**	**Total**
Weights	***Economic***	0.33	0.40	0.33	0.50	0.40	0.30	
	Environmental	0.33	0.40	0.50	0.50	0.60	0.70	
	Social	0.33	0.20	0.17	0.00	0.00	0.00	
Economic Rank 1	*Rank Sum*	18	18	18	9	15	18	96
	Rank Reciprocal	18	18	18	6	9	16	85
Economic Rank 2	*Rank Sum*	18	18	18	18	18	18	108
	Rank Reciprocal	18	18	18	18	18	18	108
Economic Rank 3	*Rank Sum*	18	18	18	18	18	18	108
	Rank Reciprocal	18	18	18	18	18	18	108
	Total	108	108	108	87	96	106	**613**

Entropic Weights and SAW

Using entropic weights to determine the overall SI results for the two seasons and emissions all present the same final results: CNG is the preferred choice with an overall SI of 1, with 60% CNG holding the second highest score at 0.6, followed by 0.3 for 30% CNG and 0.1 for 10% CNG and a score of 0 for an all diesel fleet.

TOPSIS

Due to the nature of TOPSIS, entropic weights were estimated for each pillar prior to determining the relative distance values. This was done by normalizing the resultant entropy values and obtaining weights and then the relative distances for the examined pillars. Table 4-30 present the results and the best solution is an-all CNG scenario, followed by scenarios with decreasing quantities of CNG. It is clear that with and without the social pillar, the TOPSIS relative distances are consistent. This likely is a result of the normalization process used at each level of the analysis and the nature of the TOPSIS formulation.

Table 4-30: Overall Relative Distances

Pillars Assessed	**All Diesel**	**10% CNG**	**30% CNG**	**60% CNG**	**All CNG**
All Three Pillars	1.0000	0.9817	0.8083	0.3369	0.0000
Two Pillars (Economic & Environmental)	1.0000	0.9817	0.8083	0.3369	0.0000

5. CONCLUSION

5.1 Summary of Results

The overall objective of this project was to examine the feasibility of using an alternative fuel, CNG in heavy-duty commercial vehicles in the GTHA. Many studies have attributed the lack of sufficient refueling infrastructure as a deterrent of switching to an AF. This study suggests the implementation of an overnight virtual-pipeline with central CNG hubs for storage. For initial stages of CNG conversion, it is recommended to establish one CNG hub to store CNG and house refueling trucks, its location is presented in Figure 5-1. An additional site is recommended if there is significant CNG demand and its location is dependent on where in the GTHA fleets convert to CNG. These sites were selected based on their proximity to estimated CNG demand, access to existing natural gas pipelines and an effort to distance these sites from highly populated areas and water bodies. Once the demand for CNG increases, these sites can serve a dual purpose by introducing on-site refueling.

Once fuel access was established, the actual benefits must be quantified. This was done by modelling traffic in the GTHA to estimate traffic flow. These results were then used as input for MOVES to estimate the inventory of emissions. CNG-powered transit bus rates were used to scale the values to a CNG heavy-duty truck. From these results and literature, it was evident that CNG does decrease some pollutants with respect to diesel such as carbon dioxide, particulate matter and oxides of nitrogen, but it also increases some pollutants emitted such as methane and carbon monoxide.

At a lifecycle level the NGV energy consumption is greater than its diesel counterpart, but it emits lower GHG emissions. From multiple MCDAs and computations of sustainability indicators, CNG is favoured over diesel.

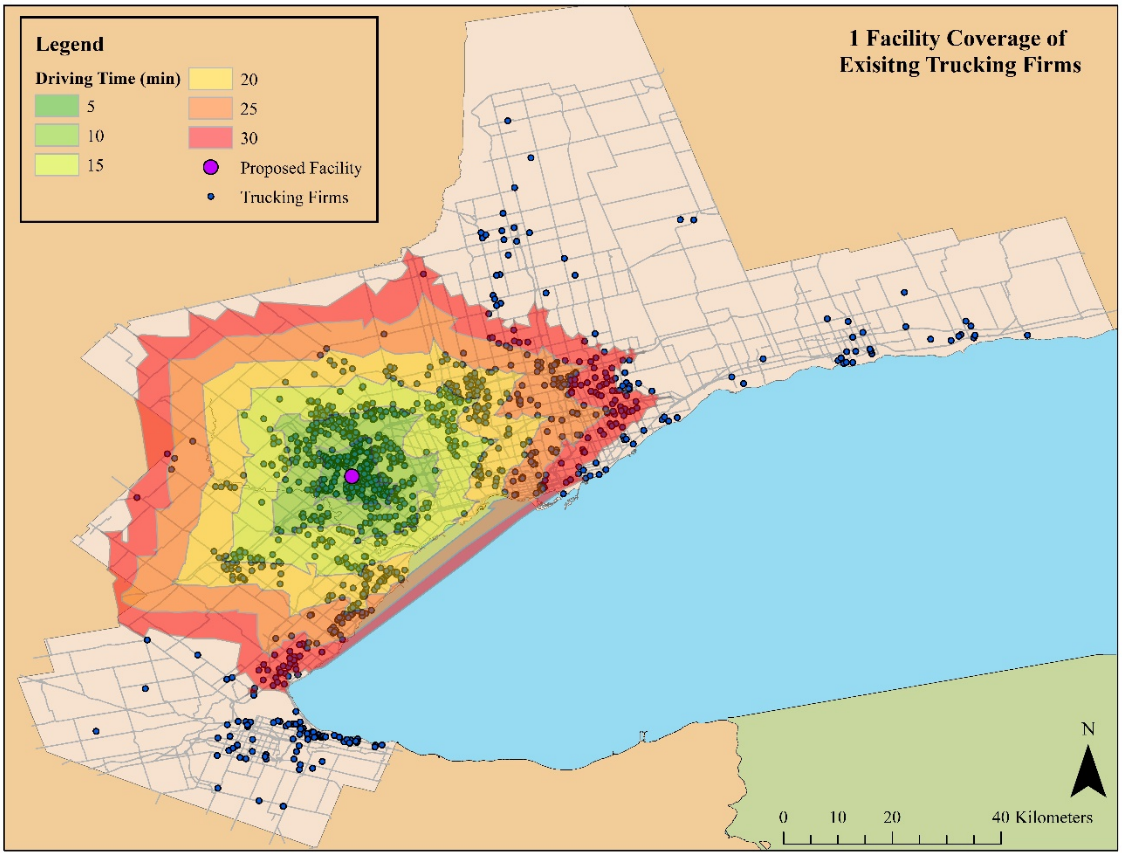


Figure 5-1: Proposed CNG Hub - Facility 11 Coverage

5.2 Contributions and Policy Implications

The contributions from this study include the following:

1) The procedure and locational analysis used for locating a CNG storage hub,
2) The application and analysis of this procedure in the GTHA,
3) Repurposes GPS Data to estimate the CNG conversion potential,
4) Passenger Trip Generation parameters for the GTHA,
5) Emission Inventory for HDCV for seasonal differences and
6) The comparison of different MCDA approaches.

The procedure proposed can be used a starting point for establishing CNG stations and can be modified to other AFs. The reuse of existing GPS data to estimate CNG potential is critical to determining which industries should be targeted for conversion. This research demonstrates the CNG refueling potential in GTHA will further encourage fleet operators to transition to NGVs and possible investments.

The policy implications arising from this study suggest that governmental financial support to help transition and the refueling infrastructure will perhaps provide a motivation for carriers to transition to CNG. As discussed in Flynn (2002) the NGV market may be unsustainable without constant financial support. This support can be in the form of governmental grants and reduced taxes on CNG to maintain the diesel-CNG differential. Again, a detailed cost-benefit analysis will provide more conclusive results.

5.3 Study Limitations and Direction for Future Developments

This section will discuss the limitations associated with some stages of the current research and suggestions for future work.

5.3.1 LAM

The overall location-allocation results can be improved with access to and the use of additional information. Detailed data reflecting land ownership in the GTHA will improve the accuracy of the locations for the proposed facilities. Considering existing zoning by-laws and any safety requirements for site selection can also ensure that the site can eventually become a NG refueling station. Information regarding local regulations and the actual capacity of CNG-carrying tractor-trailers will provide more accurate demand-allocation results. Costs of property acquisition or leasing will vary with location in the GTHA. Factoring these costs into the analysis will introduce an additional criterion to the suitability analysis. Targeting specific zones for CNG conversion (for example, Central GTHA) could enhance coverage and reduce travel time. Conducting a survey amongst GTHA fleet owners can help decision-makers gauge what areas will be more likely to demand CNG. These results can then be used to determine which zones to analyze.

5.3.2 Emissions Modelling

MOVES2014a does not model emissions for CNG HDCVs. Transferring ratios between transit buses and heavy-duty trucks is not an ideal approach to model emission results as the loaded weights associated with transit buses and HDCV vary. Additionally, the default speed profile was used for the analysis. This profile does not reflect HDCVs in a Canadian context or a GTHA-context. This can skew the magnitude of the inventory results but since it was consistently used for all scenarios it does not influence the MCDA results.

5.3.3 MCDA

A limitation of the current MCDA is not examining all potential criteria of interest. Additional social factors like safety and fuel diversity and economic factors such as operation and maintenance costs can also be included in this analysis. The objective of the mixed fuel scenarios was to compare the costs associated with each pollutants' emissions, however there was no readily available social Canadian costs. This would be an interesting set of analyses if the exposure cost per tonne of emissions was readily available. For future studies, it is also suggested to examine the costs and benefits of all sustainability pillars at a cost per weight of cargo transferred or per truckload. CNG HDCVs have a lower carrying capacity than their diesel counterparts due to the extra weight associated with fuel storage.

5.3.4 Additional Direction for Future Development

Prior to pushing for NGV, the technology of these vehicles requires assessment and should be at optimal operating conditions as "*NGV [only] has the potential to improve urban air quality when it has fuel injection with stoichiometric control*," (Flynn, 2002). However, Flynn further emphasized that once an alternative fuel is in operation, the primary focus should be providing reliable refueling and maintenance infrastructure and support. Therefore, improvements of vehicles and sufficient in-operation testing should be conducted before converting to NGVs. Further analysis of the CNG and diesel price differential and its estimated projection is an essential component in determining the economic benefit of the transition.

The next step would include conducting in-field tests of loaded HDCVs with portable emissions measurement systems (PEMS) to obtain in-operation emissions. Road tests provide the opportunity to study pollutants emitted under different driving cycles to verify whether emission trends are consistent in all driving conditions. If inconsistencies are present, one can then determine which fleet types would benefit more from the use of CNG as each industries' and fleets' freight tours vary and affect the driving cycle.

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A. APPENDICES

Appendix A: Detailed Truck Count and Trip Models

This appendix outlines the QRFM and Roorda et al. (2010) Freight Trip Models. Table A-1 presents the QRFM and Table A-2 presents the NAICS industry classification used for this model.

Table A-1: QRFM (Source: NCHRP Synthesis 384, 2008)

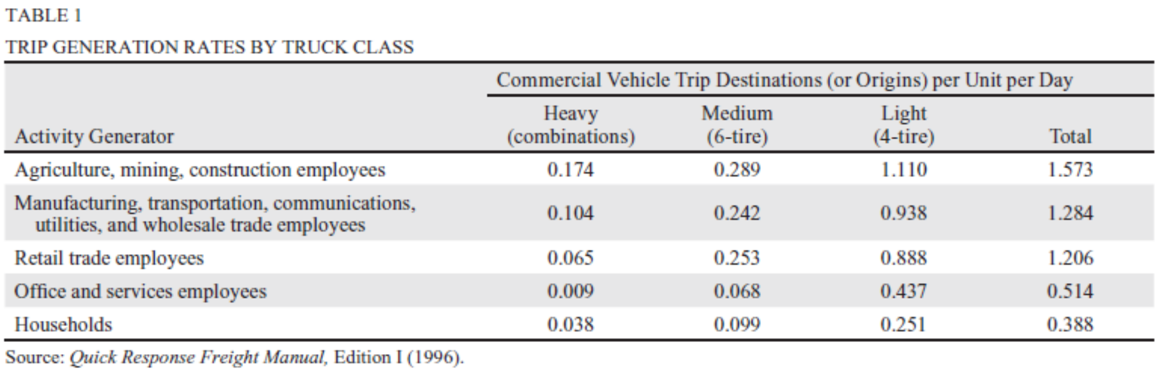


TABLE 1

TRIP GENERATION RATES BY TRUCK CLASS

	Commercial Vehicle Trip Destinations (or Origins) per Unit per Day			
Activity Generator	Heavy (combinations)	Medium (6-tire)	Light (4-tire)	Total
Agriculture, mining, construction employees	0.174	0.289	1.110	1.573
Manufacturing, transportation, communications, utilities, and wholesale trade employees	0.104	0.242	0.938	1.284
Retail trade employees	0.065	0.253	0.888	1.206
Office and services employees	0.009	0.068	0.437	0.514
Households	0.038	0.099	0.251	0.388

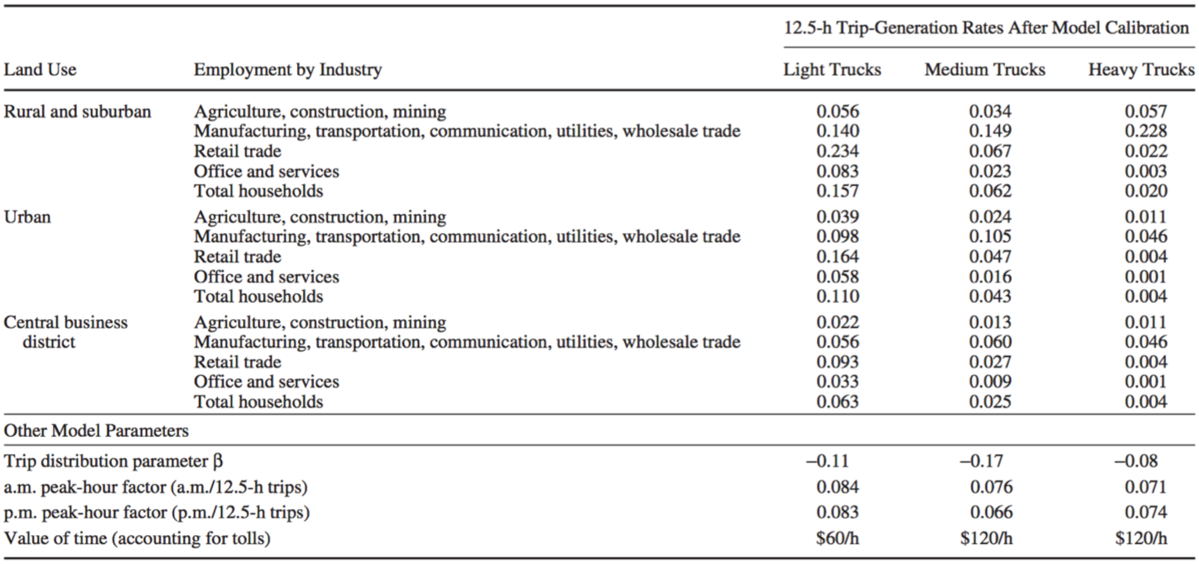
Source: *Quick Response Freight Manual,* Edition I (1996).

Table A-2: Industries used for the QRFM

Employment by Industry	NAICS Industry Sector
Agriculture, construction and mining	11 Agriculture, forestry, fishing and hunting
	21 Mining, quarrying, and oil and gas extraction
	23 Construction
Manufacturing, transportation, communication, utilities, wholesale trade	22 Utilities
	31-33 Manufacturing
	41 Wholesale trade
	48-49 Transportation and warehousing
Retail Trade	44-45 Retail trade
Office and Services	51 Information and cultural industries
	52 Finance and insurance
	53 Real estate and rental and leasing
	54 Professional, scientific and technical services
	55 Management of companies and enterprises
	56 Administrative and support, waste management and remediation services
	61 Educational services
	62 Health care and social assistance
	71 Arts, entertainment and recreation
	72 Accommodation and food services
	81 Other services (except public administration)
	91 Public administration

Table A-3 presents the Roorda et al. (2010) model and Figure A-1 presents the land use types were determined by the process discussed in the methods section, the above figure presents the distribution of the three land use types.

Table A-3: Roorda et al. (2010) Model



		12.5-h Trip-Generation Rates After Model Calibration		
Land Use	Employment by Industry	Light Trucks	Medium Trucks	Heavy Trucks
Rural and suburban	Agriculture, construction, mining	0.056	0.034	0.057
	Manufacturing, transportation, communication, utilities, wholesale trade	0.140	0.149	0.228
	Retail trade	0.234	0.067	0.022
	Office and services	0.083	0.023	0.003
	Total households	0.157	0.062	0.020
Urban	Agriculture, construction, mining	0.039	0.024	0.011
	Manufacturing, transportation, communication, utilities, wholesale trade	0.098	0.105	0.046
	Retail trade	0.164	0.047	0.004
	Office and services	0.058	0.016	0.001
	Total households	0.110	0.043	0.004
Central business district	Agriculture, construction, mining	0.022	0.013	0.011
	Manufacturing, transportation, communication, utilities, wholesale trade	0.056	0.060	0.046
	Retail trade	0.093	0.027	0.004
	Office and services	0.033	0.009	0.001
	Total households	0.063	0.025	0.004
Other Model Parameters				
Trip distribution parameter β		–0.11	–0.17	–0.08
a.m. peak-hour factor (a.m./12.5-h trips)		0.084	0.076	0.071
p.m. peak-hour factor (p.m./12.5-h trips)		0.083	0.066	0.074
Value of time (accounting for tolls)		\$60/h	\$120/h	\$120/h

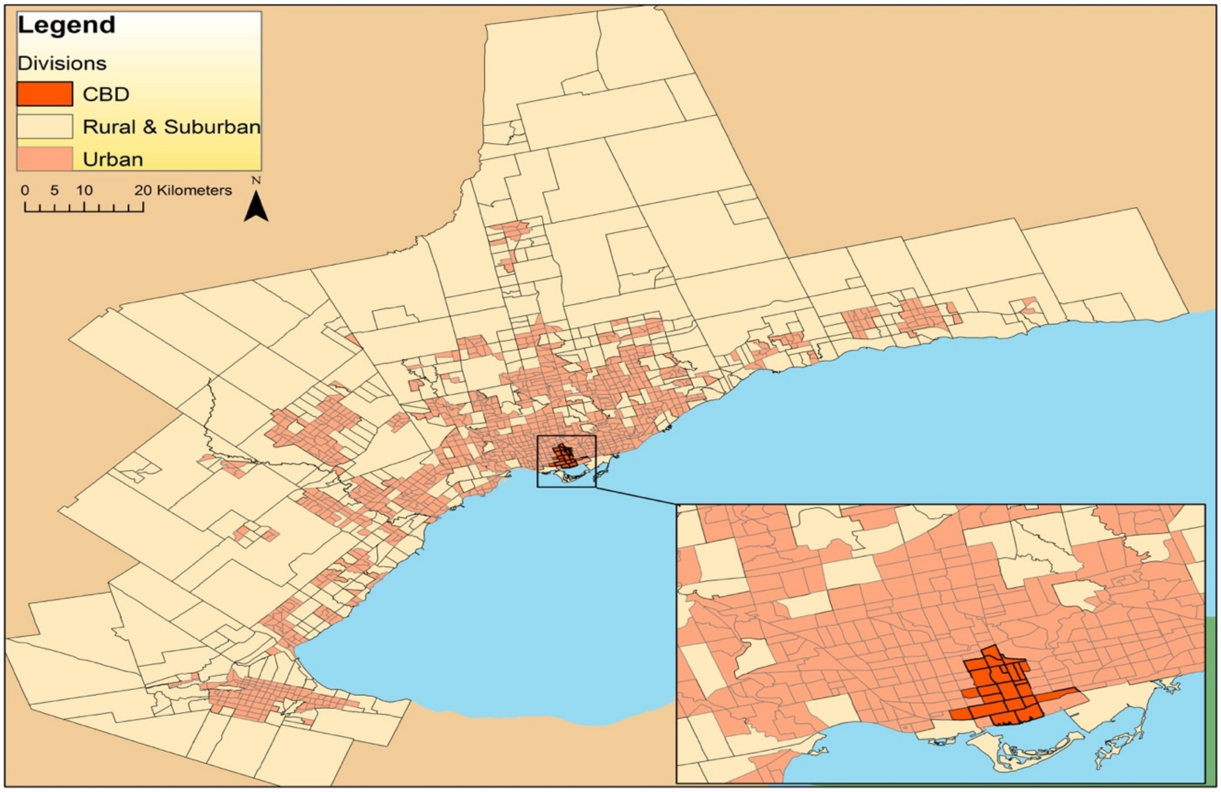


Figure A-1: Land use classifications used for the Roorda et al. (2010) Model

Appendix B: City of Calgary Passenger Trip Regression Models

This appendix provides the statistical results of the regression models obtained from Maoh et al. (2009) used to predict initial trip productions and attractions in the GTHA. The number of observations is 33 for each model.

Table A-4: AM Peak Passenger Trip Generation (Maoh et al., 2009)

AM Peak Trip Production (O_i) Model Estimates (Table 3.3)

Regression Statistics	
Multiple R	0.9680
R^2	0.9370
Adjusted R^2	0.9027
Standard Error	3090.99

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	4.40E+09	2.20E+09	230.4189	6.21E-19
Residual	31	2.96E+08	9554229		
Total	33	4.70E+09			
Coefficients					
	Value	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A
POP	0.289371	0.015588	18.56429	2.39E-18	0.25758
EMP	0.014047	0.022605	0.621399	0.53888	-0.03206

AM Peak Trip Attractions (D_j) Model Estimates (Table 3.4)

Regression Statistics	
Multiple R	0.9084
R^2	0.8252
Adjusted R^2	0.7873
Standard Error	5160.542

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3.90E+09	1.95E+09	73.1772	2.89E-12
Residual	31	8.26E+08	26631196		
Total	33	4.72E+09			
Coefficients					
	Values	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A
POP	0.134942	0.026024	5.185276	1.26E-05	0.081865
EMP	0.269245	0.037741	7.134109	5.12E-08	0.192273

Table A-5: PM Peak Passenger Trip Generation (Maoh et al., 2009)

PM Peak Trip Production (O_i) Model Estimates (Table 3.5)

Regression Statistics	
Multiple R	0.9150
R^2	0.8373
Adjusted R^2	0.7998
Standard Error	6313.069

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	6.36E+09	3.18E+09	79.75004	9.83E-13
Residual	31	1.24E+08	39854838		
Total	33	7.59E+09			
Coefficients					
	Value	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A
POP	0.20764	0.031836	6.522151	2.80E-07	0.14271
EMP	0.295264	0.046169	6.395254	4.01E-07	0.201102

PM Peak Trip Attractions (D_j) Model Estimates (Table 3.6)

Regression Statistics	
Multiple R	0.9478
R^2	0.8983
Adjusted R^2	0.8627
Standard Error	5032.362

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	6.93E+09	3.47E+09	136.838	8.33E-16
Residual	31	7.85E+08	25324667		
Total	33	7.72E+09			
Coefficients					
	Value	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A
POP	0.33723	0.025378	13.28848	2.43E-14	0.285472
EMP	0.085506	0.036803	2.323339	0.026892	0.010446

Table A-6: Off-Peak Passenger Trip Generation (Maoh et al., 2009)

Off Peak Trip Production (O_i) Model Estimates (Table 3.7)

Regression Statistics	
Multiple R	0.9347
R^2	0.8736
Adjusted R^2	0.8373
Standard Error	22320.65

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	1.07E+11	5.34E+10	107.1178	2.19E-14
Residual	31	1.54E+10	4.98E+08		
Total	33	1.22E+11			
Coefficients					
	Value	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A
POP	1.133041	0.112561	10.06606	2.74E-11	0.903472
EMP	0.74094	0.163237	4.539033	8.01E-05	0.408105

Off Peak Trip Attractions (D_j) Model Estimates (Table 3.8)

Regression Statistics	
Multiple R	0.9074
R^2	0.8234
Adjusted R^2	0.7855
Standard Error	25697.18

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	9.55E+10	4.77E+10	72.28823	3.37E-12
Residual	31	2.05E+10	6.60E+08		
Total	33	1.16E+11			
Coefficients					
	Value	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A
POP	1.061202	0.129588	8.189044	3.00E-09	0.796905
EMP	0.720359	0.187931	3.833107	0.00058	0.337072

Appendix C: 2006 Commercial Vehicle Survey GTHA Stations and Hourly Fractions

This appendix provides a summary of the hourly Commercial Vehicle Station observed passenger and commercial fractions in the GTHA study area. Table A-7 provides the fractions. Figure A-2 details the location of the stations which will be used for validating traffic assignments.

Table A-7: Hourly CVS Fractions

Peak	Hour	Passenger	Commercial
Off	0:00	0.0114	0.0212
	1:00	0.0061	0.0185
	2:00	0.0044	0.0171
	3:00	0.0040	0.0176
	4:00	0.0069	0.0227
	5:00	0.0236	0.0356
AM	6:00	0.0531	0.0465
	7:00	0.0701	0.0417
	8:00	0.0610	0.0457
Off	9:00	0.0517	0.0614
	10:00	0.0483	0.0679
	11:00	0.0477	0.0696
	12:00	0.0490	0.0688
	13:00	0.0514	0.0673
	14:00	0.0574	0.0630
PM	15:00	0.0650	0.0529
	16:00	0.0734	0.0434
	17:00	0.0756	0.0379
Off	18:00	0.0631	0.0397
	19:00	0.0490	0.0391
	20:00	0.0402	0.0358
	21:00	0.0358	0.0321
	22:00	0.0298	0.0293
	23:00	0.0221	0.0254

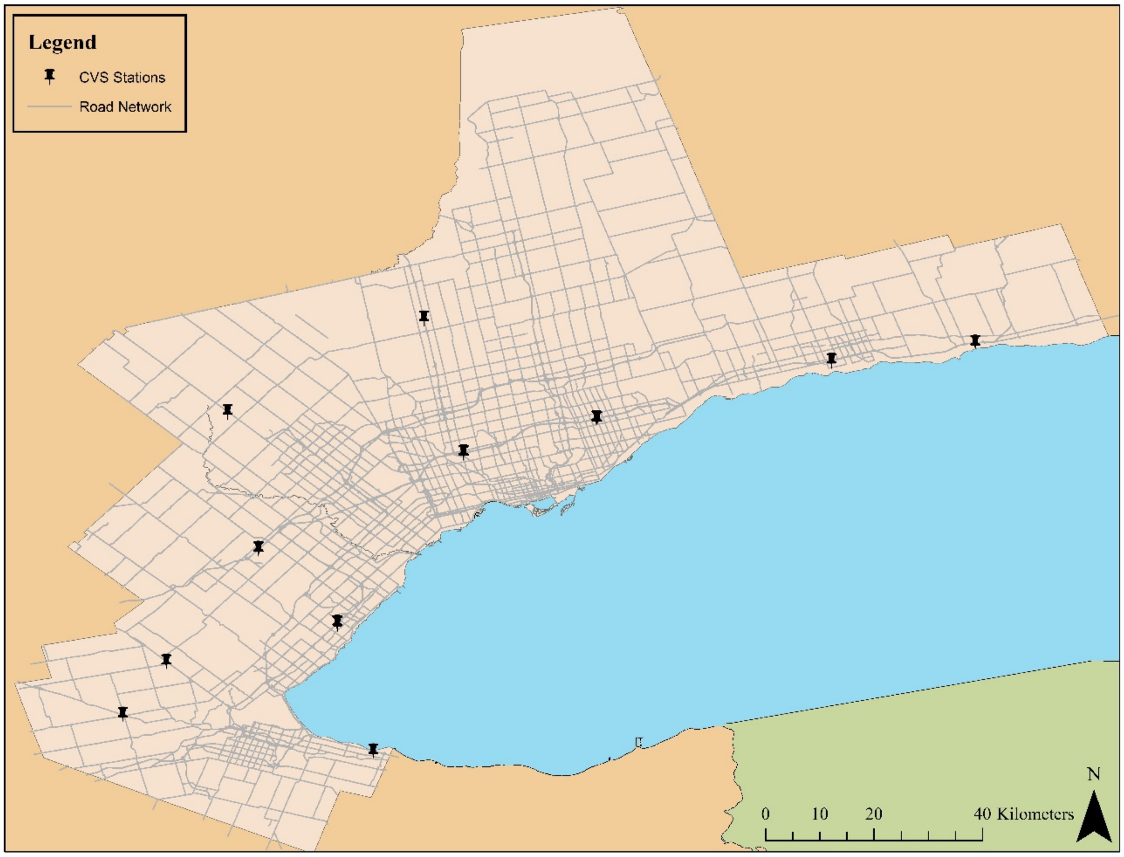


Figure A-2: CVS 2006 Stations

Appendix D: TTS 2011 Data and Transportation Modeling Summary

This appendix first summarizes the TTS Data used throughout this thesis. The GTHA study area is delineated using six census divisions (CDs). The CDs are the study zones used in the TTS study and provide trip total trip productions and attractions per zone. Table A-8 provides the total trip attractions and productions per zone.

Table A-8: TTS 2011 Data

Census Division	**All: 6 to 9**		**PM Peak: 3 to 6 pm**		**All: 24 hours**	
	O_i	**D_j**	**O_i**	**D_j**	**O_i**	**D_j**
Halton	247,300	210,200	210,200	247,300	1,041,000	1,041,700
Hamilton	215,700	196,700	196,700	215,700	980,000	980,700
York	536,500	462,400	462,400	536,500	2,066,600	2,066,700
Durham	290,900	227,500	227,500	290,900	1,180,100	1,180,100
Peel	658,700	625,000	625,000	658,700	2,553,100	2,546,400
Toronto	1,215,500	1,442,800	1,442,800	1,215,500	5,527,800	5,533,000
Total	**3,164,600**	**3,164,600**	**3,164,600**	**3,164,600**	**13,348,600**	**13,348,600**

Daily inter-zonal trip matrices for both all modal trips and automobile (passenger and driver) trips were obtained from the 2011 TTS Data and are presented in Table A-9. These trips were then used to obtain the following automobile fraction table used to scale the trips down.

Table A-9: GTHA Automobile Fraction

Destination **Origin**	***Toronto***	***Durham***	***York***	***Peel***	***Halton***	***Hamilton***
Toronto	0.6115	0.7864	0.8144	0.7847	0.6388	0.6674
Durham	0.7807	0.8814	0.9852	0.9653	0.9828	0.9189
York	0.8142	0.9847	0.8922	0.9778	0.9768	0.9235
Peel	0.7768	0.9494	0.9743	0.8536	0.9688	0.8905
Halton	0.6331	1.0000	0.9745	0.9716	0.8946	0.9588
Hamilton	0.6593	0.9131	0.9487	0.8893	0.9578	0.8163

This appendix also presents the traffic modelling approach utilized in this study as shown in Figure A-3.

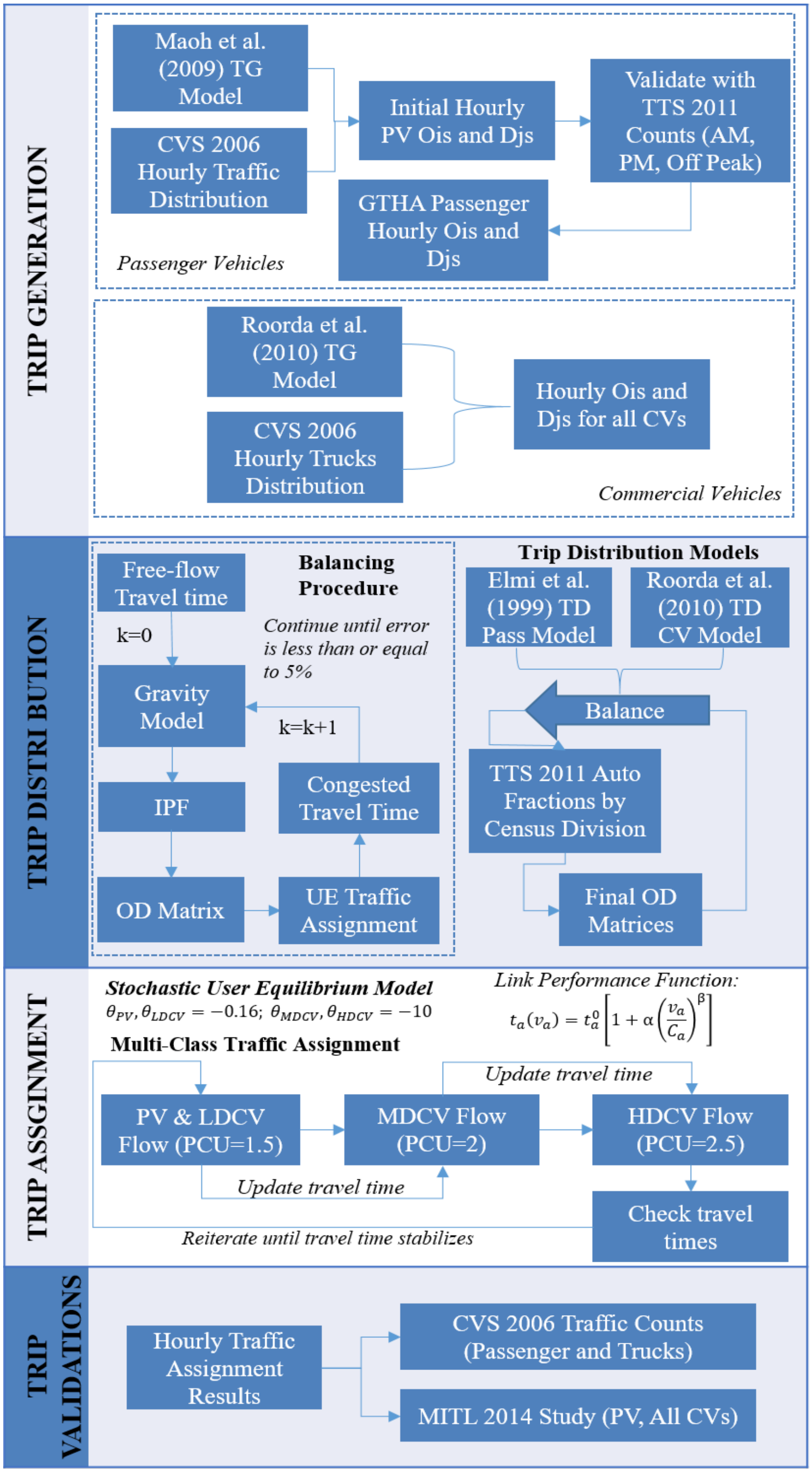


Figure A-3: Transportation Modeling Procedure

Appendix E: MOVES Input

This appendix summarizes the MOVES Inputs used in this study. As aforementioned, the Run Specification identifies the characteristics of a MOVES run. Tables A-10 and A-11 present the selections made for the current study. Table A-12 present some of the pollutants' environmental and health effects.

Table A-10: Run Specification for MOVES

RunSpec Tab	Selection Criteria	Option Selected/Input
Scale	Model	Onroad
	Domain/Scale	County
	Calculation Type	Emission Rates
Time Spans	Time Aggregation Level	Hour
	Years	2011
	Months	January, August
	Days	Weekdays
	Hours	Start and End: 12:00-12:59
Geographic Bounds	Region	Custom Domain
	County Id	1
	GPA Fraction	0
	Bar Pressure	29.29
	Vapor Adjust	0
	Spill Adjust	0
Vehicles/Equipment	On Road Vehicles	Transit Bus: CNG and Diesel Fuel Combination Short-haul truck: Diesel Fuel
Road Type	Available Road Types	Select All
Output - General Output	Mass Units	Grams
	Energy Units	Joules
	Distance Units	Kilometers
Output - Output Emissions	for All Vehicle/Equipment Categories	Fuel Type
	On and Off Road	Source Use Type (Vehicle Type)

Table A-11: Selected Pollutants and Processes

Pollutants and Processes		
Total Gaseous Hydrocarbons	Nitrous Oxide (N_2O)	Sulfur Dioxide (SO_2)
Non-Methane Hydrocarbons	Primary Exhaust $PM_{2.5}$ - Total	Total Energy Consumption
Volatile Organic Compounds	Primary Exhaust $PM_{2.5}$ - Species	Atmospheric CO_2
Methane (CH_4)	Primary $PM_{2.5}$ - Brakewear Particulate	CO_2 Equivalent
Carbon Monoxide (CO)	Primary $PM_{2.5}$ - Tirewear Particulate	Formaldehyde
Nitrogen Oxide (NO)	Primary Exhaust PM_{10} - Total	Acetaldehyde
Nitrogen Dioxide (NO_2)	Primary PM_{10} - Brakewear Particulate	Acrolein
Ammonia (NH_3)	Primary PM_{10} - Tirewear Particulate	Polycyclic Aromatic Hydrocarbons (PAH)
*Processes are selected based on checking the **Select Prerequisites** Box*		

Table A-12: Health and Environmental Effects of select Pollutants

Health Effects	**Pollutant**
Carcinogenic	THC, Diesel Exhaust
Decreased Immunity	NO_x
Aggravates existing respiratory illnesses	NO_x
Lung Disease; irritates eyes, throat and nose	NO_x
Exacerbates existing cardiovascular diseases	SO_2, PM, CO
Affects human and animal respiratory systems	SO_2
Irregular Heartbeats, non-fatal heart attacks	PM
Premature deaths from heart disease and lung cancer and in individuals with existing heart decrements	PM
Environmental Effects	**Pollutant**
Contributes to global warming	CO_2, CH_4, N_2O
Contributes to the formation of acid rain	NO_x, SO_2
Contributes to eutrophication and nitrification of lakes	NH_3, NO_x
Leads to the formation of ozone and/or PM, which produces smog	VOCs, NO_x
Contributes to Haze and reduces visibility	PM, SO_2
Damage Vegetation	PM, SO_2

Table A-13 presents the speed bins used in MOVES. Table A-14 summarizes the key inputs used for the County Data Manager. As aforementioned the Meteorology Inputs were obtained from the MITL 2014 Study which are based on the Ministry of Environment and Climate Change historical 30-year average (1980 to 2010) for the GTHA. The VKT is obtained from the traffic assignment which is then converted to VMT. This value is input as the daily VMT into MOVES and the hourly VMT fraction for 12 pm is assigned 1 to simplify the analysis. The fractions per road type were obtained also from the traffic assignment.

Figure A-4 depicts the HDCV age distribution from the 2012 GTHA Polk Data. A vehicle age ID of zero represents a new car whilst 1 represents a vehicle that is one year old and an age ID of 30 represents vehicles that are 30 years and older. 41.5% of the HDCVs are 5 years or younger, 72.2% of the vehicles are ten years old or newer and the bulk of the vehicles (96.7%) are younger than 20 years old making the HDCV fleet relatively young. The vehicle population in the GTHA is 58,815.

Table A-13: MOVES Speed Bins

Speed Bin	Average Bin Speed		Average Speed Bin Range		
	(mph)	(kph)	(mph)	Lower (kph)	Upper (kph)
1	2.5	4.02	speed < 2.5mph	0.00	4.02
2	5	8.05	2.5mph ≤ speed < 7.5mph	4.02	12.07
3	10	16.09	7.5mph ≤ speed < 12.5mph	12.07	20.12
4	15	24.14	12.5mph <= speed < 17.5mph	20.12	28.16
5	20	32.19	17.5mph <= speed <22.5mph	28.16	36.21
6	25	40.23	22.5mph <= speed < 27.5mph	36.21	44.26
7	30	48.28	27.5mph <= speed < 32.5mph	44.26	52.30
8	35	56.33	32.5mph <= speed < 37.5mph	52.30	60.35
9	40	64.37	37.5mph ≤ speed < 42.5mph	60.35	68.40
10	45	72.42	42.5mph ≤ speed < 47.5mph	68.40	76.44
11	50	80.47	47.5mph ≤ speed < 52.5mph	76.44	84.49
12	55	88.51	52.5mph ≤ speed < 57.5mph	84.49	92.54
13	60	96.56	57.5mph ≤ speed < 62.5mph	92.54	100.58
14	65	104.61	62.5mph ≤ speed < 67.5mph	100.58	108.63
15	70	112.65	67.5mph ≤ speed < 72.5mph	108.63	116.68
16	75	120.70	72.5mph ≤ speed	116.68	

Table A-14: Specific CDM Inputs

Meteorology Inputs	Average Temperature (F)	Relative Humidity
January	24.42	74.36
August	75.00	58.69

Traffic	VKT	VMT
12:00 PM	421,767	262,074

Road Type	VMT Fraction
Rural Restricted	0.0037
Rural Unrestricted	0.0898
Urban Restricted	0.5109
Urban Unrestricted	0.3957

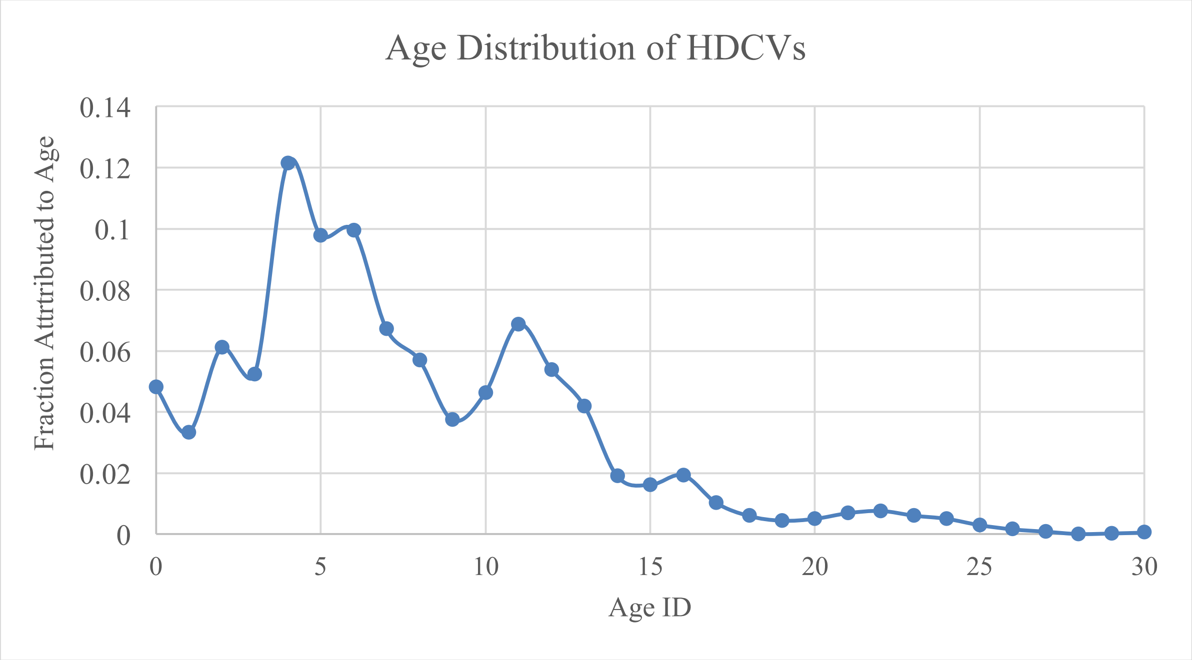


Figure A-4: HDCV Age Distribution

Appendix F: Detailed Locational Results

This appendix summarizes the statistical and locational results for selecting proposed facilities. The following map provides a key for the locational results.

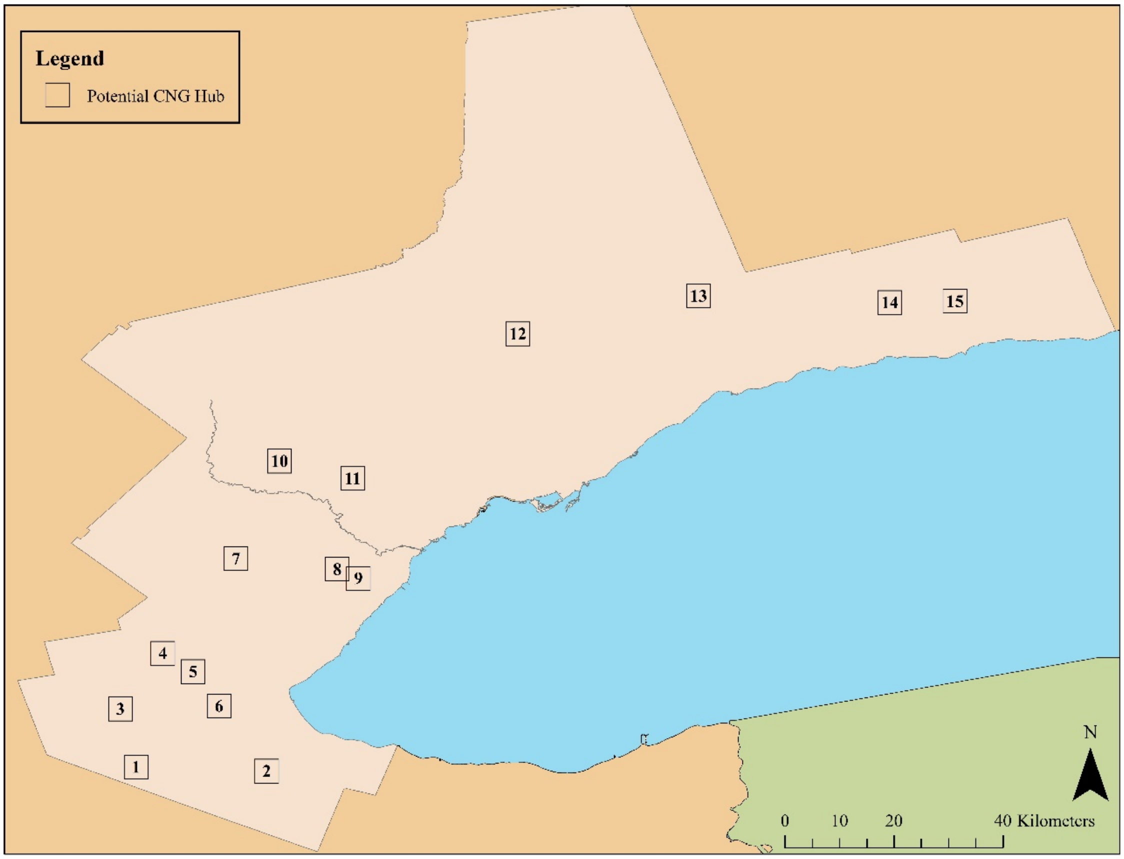


Figure A-5: Facility Key

P-Median

The following tables outline the locational distribution of facility selection based on the number of trucks. Where # is the number of facilities to be established.

Table A-15: P-median Selected Facilities – 10 Trucks

		Selected Facilities														
	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
10 Trucks	1											•				
	2											•	•			
	3		•									•	•			
	4		•									•	•		•	
	5		•							•		•	•		•	
	6		•							•		•	•	•	•	
	7		•					•		•		•	•	•	•	
	8		•	•				•		•		•	•	•	•	
	9		•	•				•		•	•	•	•	•	•	
	10		•	•				•		•	•	•	•	•	•	•
	11	•	•			•		•		•	•	•	•	•	•	•
	12	•	•			•		•	•	•	•	•	•	•	•	•
	13	•	•	•		•		•	•	•	•	•	•	•	•	•
	14	•	•	•		•	•	•	•	•	•	•	•	•	•	•
	15	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Table A-16: P-median Selected Facilities – 15 Trucks

		Selected Facilities														
	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Trucks	1											•				
	2											•	•			
	3		•									•	•			
	4		•									•	•		•	
	5		•							•		•	•		•	
	6		•							•		•	•	•	•	
	7		•					•		•		•	•	•	•	
	8		•	•				•		•		•	•	•	•	
	9		•	•				•		•	•	•	•	•	•	
	10		•	•				•		•	•	•	•	•	•	•
	11	•	•			•		•		•	•	•	•	•	•	•
	12	•	•			•		•	•	•	•	•	•	•	•	•
	13	•	•	•		•		•	•	•	•	•	•	•	•	•
	14	•	•	•		•	•	•	•	•	•	•	•	•	•	•
	15	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Table A-17: P-median Selected Facilities – 20 Trucks

20 Trucks		Selected Facilities														
	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	1											•				
	2											•	•			
	3		•									•	•			
	4		•									•	•		•	
	5		•							•		•	•		•	
	6		•							•		•	•	•	•	
	7		•					•		•		•	•	•	•	
	8		•	•				•		•		•	•	•	•	
	9		•	•				•		•	•	•	•	•	•	
	10		•	•				•		•	•	•	•	•	•	•
	11	•	•			•		•		•	•	•	•	•	•	•
	12	•	•			•		•	•	•	•	•	•	•	•	•
	13	•	•	•		•		•	•	•	•	•	•	•	•	•
	14	•	•	•		•	•	•	•	•	•	•	•	•	•	•
	15	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Table A-18: P-median Selected Facilities – 25 Trucks

25 Trucks		Selected Facilities														
	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	1											•				
	2											•	•			
	3		•									•	•			
	4		•									•	•		•	
	5		•							•		•	•		•	
	6		•							•		•	•	•	•	
	7		•					•		•		•	•	•	•	
	8		•	•				•		•		•	•	•	•	
	9		•	•				•		•	•	•	•	•	•	
	10		•	•				•		•	•	•	•	•	•	•
	11	•	•			•		•		•	•	•	•	•	•	•
	12	•	•			•		•	•	•	•	•	•	•	•	•
	13	•	•	•		•		•	•	•	•	•	•	•	•	•
	14	•	•	•		•	•	•	•	•	•	•	•	•	•	•
	15	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Table A-19: P-median Selected Facilities – 30 Trucks

		Selected Facilities														
	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
30 Trucks	1											•				
	2											•	•			
	3		•									•	•			
	4		•									•	•		•	
	5		•							•		•	•		•	
	6		•							•		•	•	•	•	
	7		•					•		•		•	•	•	•	
	8		•	•				•		•		•	•	•	•	
	9		•	•				•		•	•	•	•	•	•	
	10		•			•		•		•	•	•	•	•	•	•
	11	•	•			•		•		•	•	•	•	•	•	•
	12	•	•			•		•	•	•	•	•	•	•	•	•
	13	•	•	•		•		•	•	•	•	•	•	•	•	•
	14	•	•	•		•	•	•	•	•	•	•	•	•	•	•
	15	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Table A-20: Maximize Attendance Summary - Demand Points Serviced

Number of Facilities Established	**Travel Time Constraint**				
	10 mins	**15 mins**	**20 mins**	**25 mins**	**30 mins**
1	108	239	353	475	619
2	177	293	509	660	723
3	185	391	631	789	829
4	217	482	654	789	895
5	276	489	716	868	895
6	280	537	720	882	895
7	283	548	758	884	898
8	285	574	762	886	898
9	296	575	762	888	898
10	307	577	762	888	898
11	322	585	762	888	898
12	327	585	762	888	898
13	329	585	762	888	898
14	337	585	762	888	898
15		586	762	888	898

Table A-21: Maximize Attendance Summary - Mean Travel Time

Number of Facilities Established	Travel Time Constraint				
	10 mins	15 mins	20 mins	25 mins	30 mins
1	7.4578	10.2204	12.5588	15.1252	18.0104
2	7.1322	9.3494	12.7086	14.9061	15.9932
3	6.9683	9.7318	12.3319	14.3221	14.9456
4	6.9057	9.5028	11.5102	13.3627	14.6811
5	6.8851	9.3856	11.5403	13.4395	13.8353
6	6.8403	9.4643	11.4125	13.1558	13.6640
7	6.6552	9.4711	11.5047	13.0210	13.2361
8	6.5094	9.5839	11.4170	12.9200	13.1082
9	6.4971	9.5041	11.3333	12.8723	13.0258
10	6.5423	9.4191	11.2627	12.8117	12.9659
11	6.5439	9.3344	11.1291	12.6970	12.8525
12	6.5569	9.2249	11.0450	12.6249	12.7811
13	6.5617	9.2090	11.0328	12.6144	12.7708
14	6.5584	9.1482	10.9861	12.5743	12.7312
15		9.1554	10.9838	12.5724	12.7292

Table A-22: Maximize Coverage Summary - Demand Points Serviced

Number of Facilities Established	Travel Time Constraint				
	10 mins	15 mins	20 mins	25 mins	30 mins
1	108	239	353	475	619
2	177	337	509	706	818
3	236	428	631	785	854
4	244	482	693	868	895
5	276	530	731	871	898
6	287	556	755	885	898
7	292	567	759	887	898
8	297	574	762	888	898
9	307	582	762	888	898
10	309	584	762	888	898
11	324	585	762	888	898
12	332	586	762	888	898
13	334	586	762	888	898
14	337	586	762	888	898
15		586	762	888	898

Table A-23: Maximize Coverage - Mean Travel Time

Number of Facilities Established	Travel Time Constraint				
	10 mins	15 mins	20 mins	25 mins	30 mins
1	7.4578	10.2204	12.5588	15.1252	18.0104
2	7.1322	10.4107	12.7086	16.5991	18.1695
3	7.0514	10.0086	12.3319	16.3584	16.4608
4	6.9298	9.5028	12.2895	14.3116	14.6811
5	6.8851	9.5720	12.3395	14.2605	14.2498
6	6.8580	9.6838	11.6578	13.9647	13.4068
7	6.8792	9.6860	11.5699	13.7014	13.2361
8	6.8879	9.5839	11.4170	13.5026	13.1082
9	6.8586	9.4965	11.3333	12.8723	13.0258
10	6.8618	9.4126	11.1996	12.7576	12.9659
11	6.8486	9.3344	11.1291	12.6970	12.8525
12	6.8383	9.3393	11.0450	12.6249	12.7811
13	6.7128	9.2300	11.0328	12.6144	12.7708
14	6.5584	9.2162	10.9861	12.5743	12.7312
15		9.1554	10.9838	12.5724	12.7292

Table A-24: Minimize Facilities Method Results

Facility Data		Travel Time Statistics			
Travel Time Cut-off (mins)	Number of Facilities Required	Minimum	Maximum	Mean	Standard Deviation
5	13	0.40	4.99	3.64	1.17
10	14	0.40	9.99	6.56	2.19
15	12	0.62	14.98	9.34	3.47
20	8	0.62	19.92	11.42	4.40
25	8	0.62	24.64	13.50	5.44
30	5	0.62	29.91	14.25	5.63
35	5	0.62	32.01	14.28	5.67
40	4	0.62	37.48	14.82	6.12
45	3	0.62	44.86	18.34	7.00
50	2	1.34	48.93	21.03	9.59
55	2	1.34	48.93	21.03	9.59
60	2	1.34	48.93	21.03	9.59

Appendix G: Validations of Facility Selection

This appendix provides service area maps created to determine which potential sites will provide a significant coverage of the GTHAs existing trucking firms.

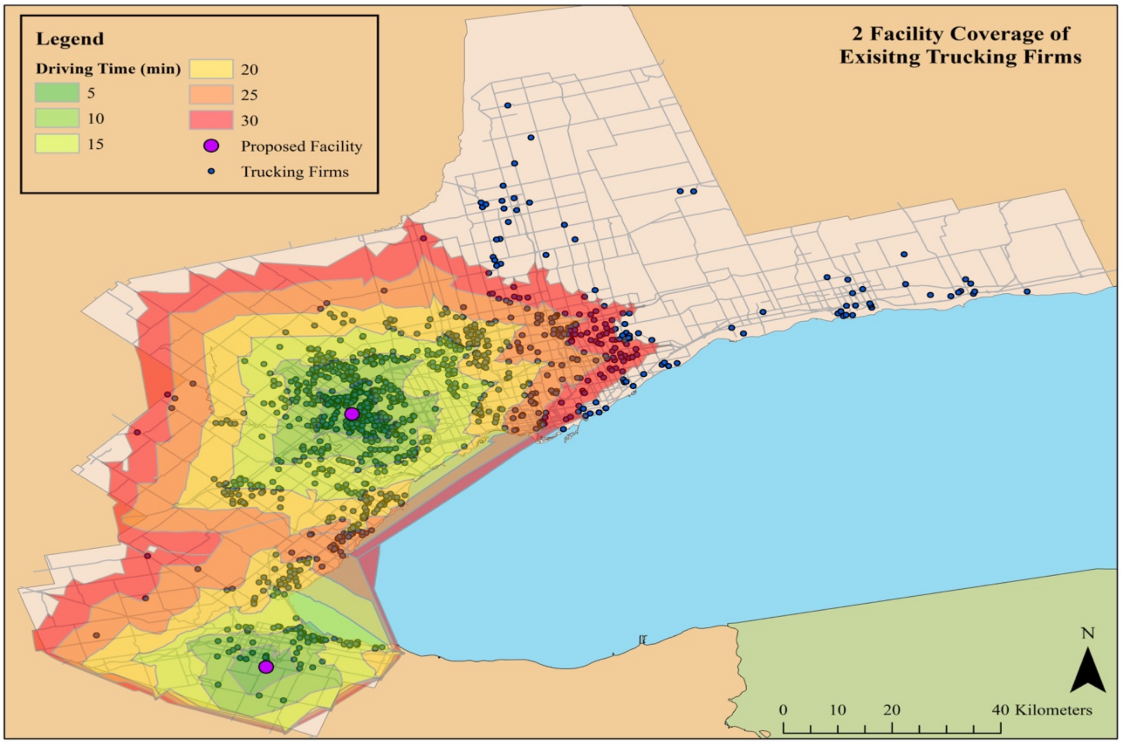


Figure A-6: Facilities 2 and 11 Coverage

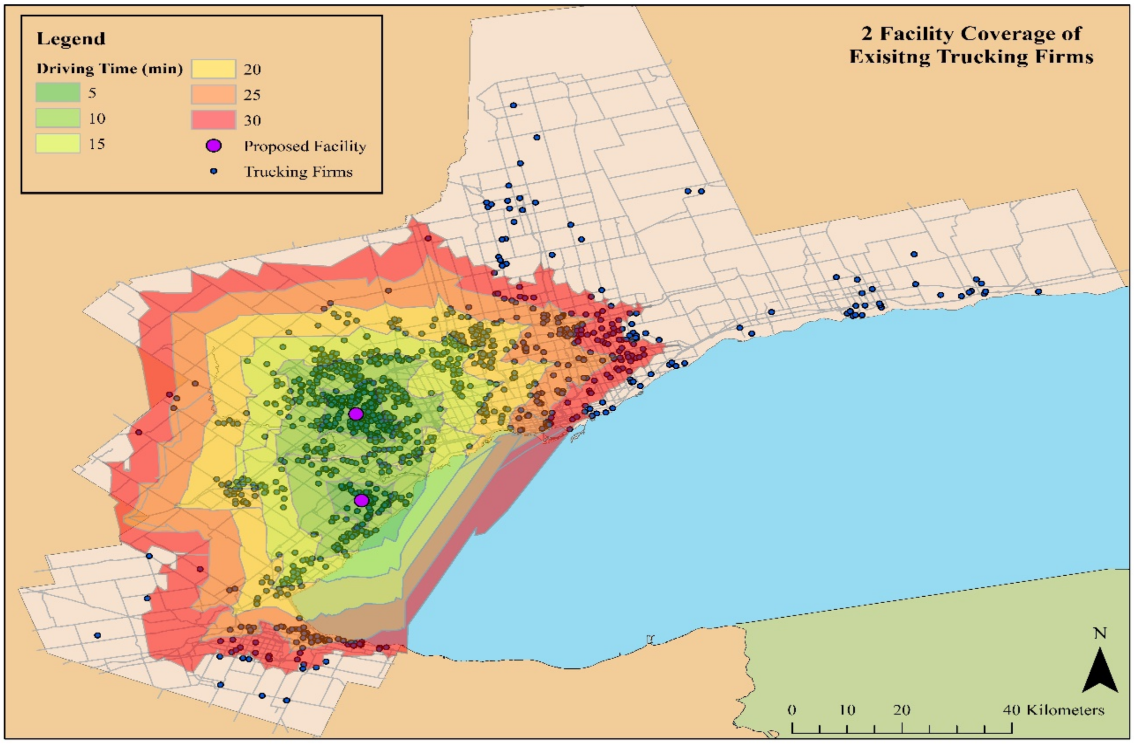


Figure A-7: Facilities 9 and 11 Coverage

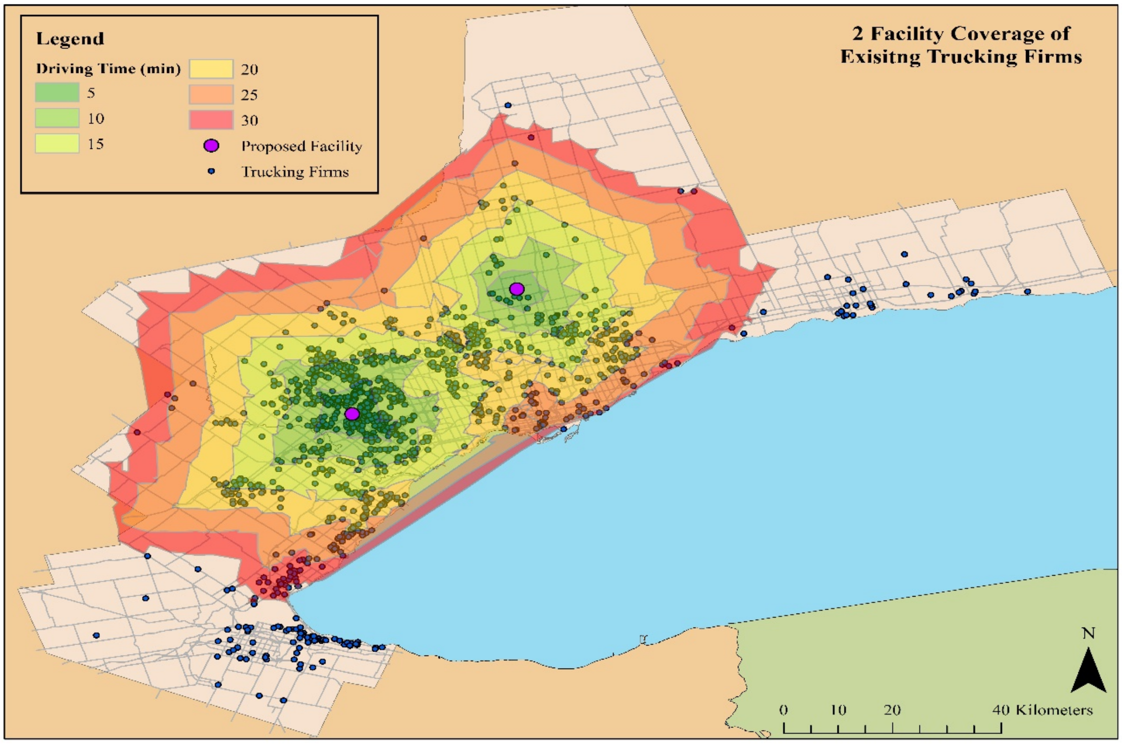


Figure A-8: Facilities 11 and 12 Coverage

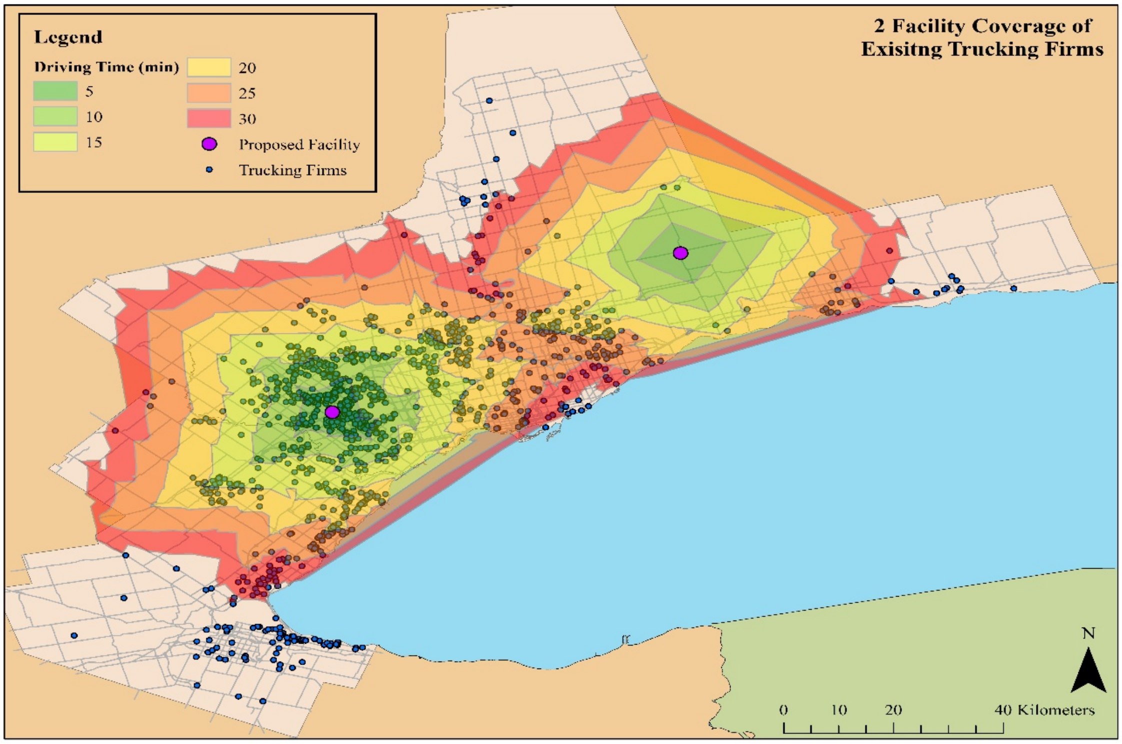


Figure A-9: Facilities 11 and 13 Coverage

Appendix H: Predicted Passenger Trips and TTS Data Used

This appendix provides the values of both the GTHA predicted trips and observed trips based on the 2011 TTS. The results are aggregated at a CD level and then broken down into different time periods: AM Peak, PM Peak, Off Peak and All 24 hours.

Table A-25: Predicted Trips in the GTHA

Predicted	All: 6 to 9 am		All: 3 to 6 pm		All: 24 hours		Rest 18 hours	
Census Division	**O_i**	**D_j**	**O_i**	**D_j**	**O_i**	**D_j**	**O_i**	**D_j**
Halton	148,103	123,935	165,840	187,038	1,037,118	993,810	723,175	682,837
Hamilton	153,167	122,079	164,895	191,830	1,050,053	1,004,579	731,992	690,671
York	304,797	254,611	340,814	384,808	2,132,743	2,043,565	1,487,133	1,404,145
Durham	168,937	125,785	172,251	209,248	1,125,404	1,074,250	784,216	739,217
Peel	383,353	330,103	439,368	486,583	2,718,909	2,607,857	1,896,189	1,791,170
Toronto	774,204	722,970	948,458	997,504	5,699,159	5,481,216	3,976,497	3,760,742
Totals	1,932,560	1,679,483	2,231,626	2,457,011	13,763,386	13,205,276	9,599,201	9,068,782

Table A-26: Observed Trips in the GTHA

2011 TTS	AM Peak		PM Peak		All: 24 hours		Rest 18 hours	
Census Division	**O_i**	**D_j**	**O_i**	**D_j**	**O_i**	**D_j**	**O_i**	**D_j**
Halton	247,300	210,200	210,200	247,300	1,041,000	1,041,700	583,500	584,200
Hamilton	215,700	196,700	196,700	215,700	980,000	980,700	567,600	568,300
York	536,500	462,400	462,400	536,500	2,066,600	2,066,700	1,067,700	1,067,800
Durham	290,900	227,500	227,500	290,900	1,180,100	1,180,100	661,700	661,700
Peel	658,700	625,000	625,000	658,700	2,553,100	2,546,400	1,269,400	1,262,700
Toronto	1,215,500	1,442,800	1,442,800	1,215,500	5,527,800	5,533,000	2,869,500	2,874,700
Totals	3,164,600	3,164,600	3,164,600	3,164,600	13,348,600	13,348,600	7,019,400	7,019,400

Table A-27: Percent Difference of Predicted and Observed Trips in the GTHA

Percent Difference	All: 6 to 9		All: 3 to 6		All: 24 hours		Rest 18 hours	
Census Division	**Oi**	**Dj**	**Oi**	**Dj**	**Oi**	**Dj**	**Oi**	**Dj**
Halton	50%	52%	24%	28%	0%	5%	21%	16%
Hamilton	34%	47%	18%	12%	7%	2%	25%	19%
York	55%	58%	30%	33%	3%	1%	33%	27%
Durham	53%	58%	28%	33%	5%	9%	17%	11%
Peel	53%	62%	35%	30%	6%	2%	40%	35%
Toronto	44%	66%	41%	20%	3%	1%	32%	27%

Appendix I: Estimated Passenger Trip Parameters

Table A-28: Calibrated Trip Generation Model Parameters (Productions O_i) for GTHA

	Halton		Hamilton		York		Durham		Peel		Toronto	
Hour	Pop	Emp	Pop	Emp	Pop	Emp	Pop	Emp	Pop	Emp	Pop	Emp
0:00	0.0174	0.0114	0.0167	0.0109	0.0155	0.0101	0.0182	0.0119	0.0144	0.0094	0.0155	0.0102
1:00	0.0092	0.0060	0.0089	0.0058	0.0082	0.0054	0.0096	0.0063	0.0076	0.0050	0.0082	0.0054
2:00	0.0066	0.0043	0.0064	0.0042	0.0059	0.0038	0.0069	0.0045	0.0055	0.0036	0.0059	0.0039
3:00	0.0061	0.0040	0.0059	0.0039	0.0055	0.0036	0.0064	0.0042	0.0051	0.0033	0.0055	0.0036
4:00	0.0104	0.0068	0.0100	0.0066	0.0093	0.0061	0.0109	0.0071	0.0087	0.0057	0.0093	0.0061
5:00	0.0358	0.0234	0.0344	0.0225	0.0319	0.0208	0.0375	0.0245	0.0297	0.0194	0.0320	0.0209
6:00	0.1392	0.0068	0.1174	0.0057	0.1467	0.0071	0.1435	0.0070	0.1432	0.0070	0.1309	0.0064
7:00	0.1839	0.0089	0.1551	0.0075	0.1939	0.0094	0.1897	0.0092	0.1892	0.0092	0.1729	0.0084
8:00	0.1601	0.0078	0.1350	0.0066	0.1688	0.0082	0.1651	0.0080	0.1648	0.0080	0.1505	0.0073
9:00	0.0785	0.0513	0.0755	0.0493	0.0699	0.0457	0.0821	0.0537	0.0651	0.0426	0.0702	0.0459
10:00	0.0733	0.0479	0.0705	0.0461	0.0652	0.0427	0.0767	0.0501	0.0608	0.0398	0.0656	0.0429
11:00	0.0725	0.0474	0.0696	0.0455	0.0645	0.0422	0.0758	0.0495	0.0601	0.0393	0.0648	0.0424
12:00	0.0745	0.0487	0.0716	0.0468	0.0663	0.0434	0.0779	0.0510	0.0618	0.0404	0.0666	0.0436
13:00	0.0781	0.0510	0.0750	0.0491	0.0695	0.0454	0.0816	0.0534	0.0648	0.0424	0.0698	0.0457
14:00	0.0872	0.0570	0.0838	0.0548	0.0776	0.0508	0.0912	0.0597	0.0724	0.0473	0.0780	0.0510
15:00	0.0799	0.1137	0.0752	0.1070	0.0856	0.1217	0.0833	0.1184	0.0897	0.1276	0.0959	0.1364
16:00	0.0903	0.1284	0.0850	0.1208	0.0966	0.1374	0.0941	0.1338	0.1013	0.1441	0.1084	0.1541
17:00	0.0930	0.1322	0.0875	0.1244	0.0995	0.1415	0.0969	0.1378	0.1043	0.1484	0.1116	0.1587
18:00	0.0958	0.0626	0.0921	0.0602	0.0852	0.0557	0.1002	0.0655	0.0795	0.0520	0.0857	0.0560
19:00	0.0745	0.0487	0.0716	0.0468	0.0663	0.0434	0.0779	0.0510	0.0618	0.0404	0.0666	0.0436
20:00	0.0610	0.0399	0.0586	0.0383	0.0543	0.0355	0.0638	0.0417	0.0506	0.0331	0.0546	0.0357
21:00	0.0544	0.0356	0.0523	0.0342	0.0484	0.0316	0.0569	0.0372	0.0451	0.0295	0.0486	0.0318
22:00	0.0453	0.0296	0.0435	0.0285	0.0403	0.0264	0.0474	0.0310	0.0376	0.0246	0.0405	0.0265
23:00	0.0335	0.0219	0.0322	0.0211	0.0298	0.0195	0.0350	0.0229	0.0278	0.0182	0.0300	0.0196

Table A-29: Calibrated Trip Generation Model Parameters (Attractions D_j) for GTHA

	Halton		Hamilton		York		Durham		Peel		Toronto	
Hour	Pop	Emp	Pop	Emp	Pop	Emp	Pop	Emp	Pop	Emp	Pop	Emp
0:00	0.0174	0.0114	0.0167	0.0109	0.0155	0.0101	0.0182	0.0119	0.0144	0.0094	0.0155	0.0102
1:00	0.0092	0.0060	0.0089	0.0058	0.0082	0.0054	0.0096	0.0063	0.0076	0.0050	0.0082	0.0054
2:00	0.0066	0.0043	0.0064	0.0042	0.0059	0.0038	0.0069	0.0045	0.0055	0.0036	0.0059	0.0039
3:00	0.0061	0.0040	0.0059	0.0039	0.0055	0.0036	0.0064	0.0042	0.0051	0.0033	0.0055	0.0036
4:00	0.0104	0.0068	0.0100	0.0066	0.0093	0.0061	0.0109	0.0071	0.0087	0.0057	0.0093	0.0061
5:00	0.0358	0.0234	0.0344	0.0225	0.0319	0.0208	0.0375	0.0245	0.0297	0.0194	0.0320	0.0209
6:00	0.1392	0.0068	0.1174	0.0057	0.1467	0.0071	0.1435	0.0070	0.1432	0.0070	0.1309	0.0064
7:00	0.1839	0.0089	0.1551	0.0075	0.1939	0.0094	0.1897	0.0092	0.1892	0.0092	0.1729	0.0084
8:00	0.1601	0.0078	0.1350	0.0066	0.1688	0.0082	0.1651	0.0080	0.1648	0.0080	0.1505	0.0073
9:00	0.0785	0.0513	0.0755	0.0493	0.0699	0.0457	0.0821	0.0537	0.0651	0.0426	0.0702	0.0459
10:00	0.0733	0.0479	0.0705	0.0461	0.0652	0.0427	0.0767	0.0501	0.0608	0.0398	0.0656	0.0429
11:00	0.0725	0.0474	0.0696	0.0455	0.0645	0.0422	0.0758	0.0495	0.0601	0.0393	0.0648	0.0424
12:00	0.0745	0.0487	0.0716	0.0468	0.0663	0.0434	0.0779	0.0510	0.0618	0.0404	0.0666	0.0436
13:00	0.0781	0.0510	0.0750	0.0491	0.0695	0.0454	0.0816	0.0534	0.0648	0.0424	0.0698	0.0457
14:00	0.0872	0.0570	0.0838	0.0548	0.0776	0.0508	0.0912	0.0597	0.0724	0.0473	0.0780	0.0510
15:00	0.0799	0.1137	0.0752	0.1070	0.0856	0.1217	0.0833	0.1184	0.0897	0.1276	0.0959	0.1364
16:00	0.0903	0.1284	0.0850	0.1208	0.0966	0.1374	0.0941	0.1338	0.1013	0.1441	0.1084	0.1541
17:00	0.0930	0.1322	0.0875	0.1244	0.0995	0.1415	0.0969	0.1378	0.1043	0.1484	0.1116	0.1587
18:00	0.0958	0.0626	0.0921	0.0602	0.0852	0.0557	0.1002	0.0655	0.0795	0.0520	0.0857	0.0560
19:00	0.0745	0.0487	0.0716	0.0468	0.0663	0.0434	0.0779	0.0510	0.0618	0.0404	0.0666	0.0436
20:00	0.0610	0.0399	0.0586	0.0383	0.0543	0.0355	0.0638	0.0417	0.0506	0.0331	0.0546	0.0357
21:00	0.0544	0.0356	0.0523	0.0342	0.0484	0.0316	0.0569	0.0372	0.0451	0.0295	0.0486	0.0318
22:00	0.0453	0.0296	0.0435	0.0285	0.0403	0.0264	0.0474	0.0310	0.0376	0.0246	0.0405	0.0265
23:00	0.0335	0.0219	0.0322	0.0211	0.0298	0.0195	0.0350	0.0229	0.0278	0.0182	0.0300	0.0196

Appendix J: Traffic Modeling Procedure and Results

The second portion of the appendix will present visually maps of the commercial vehicle trip generation whilst the third portion presents tables discussed in Section 5.2.3 and 5.2.4 regarding trip distribution and trip assignment results in the GTHA.

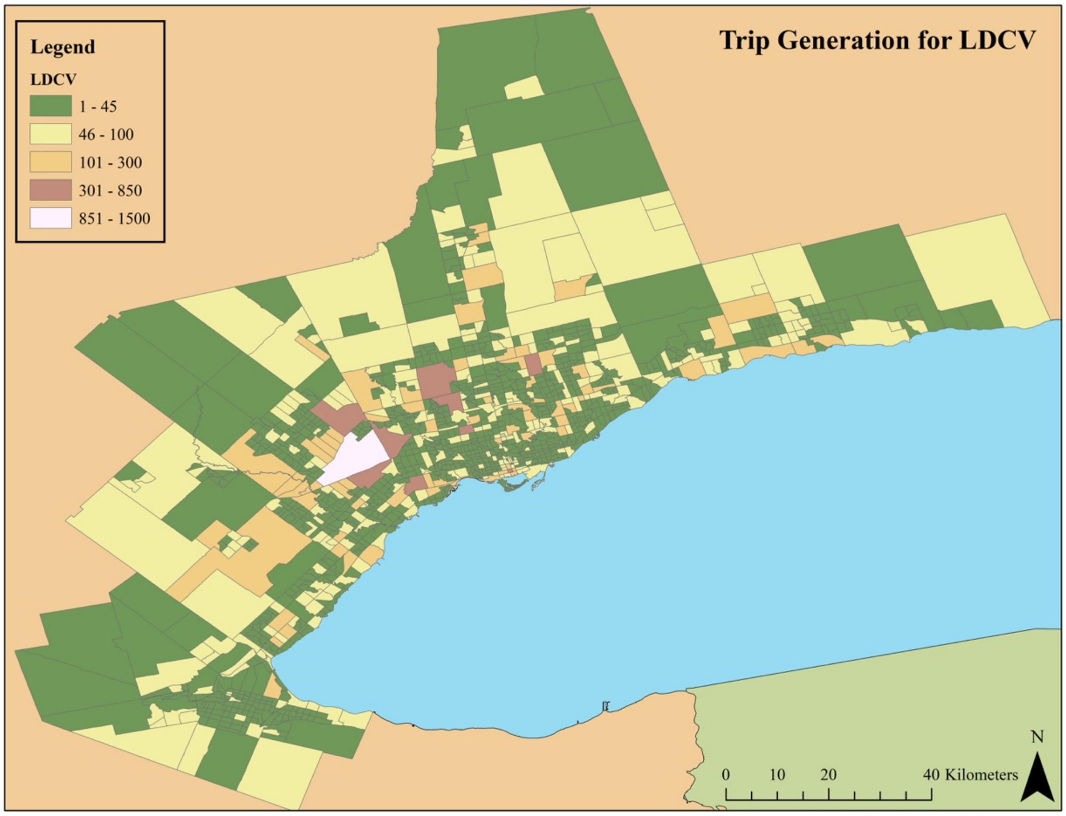


Figure A-10: Zonal Trip Generation for LDCVs

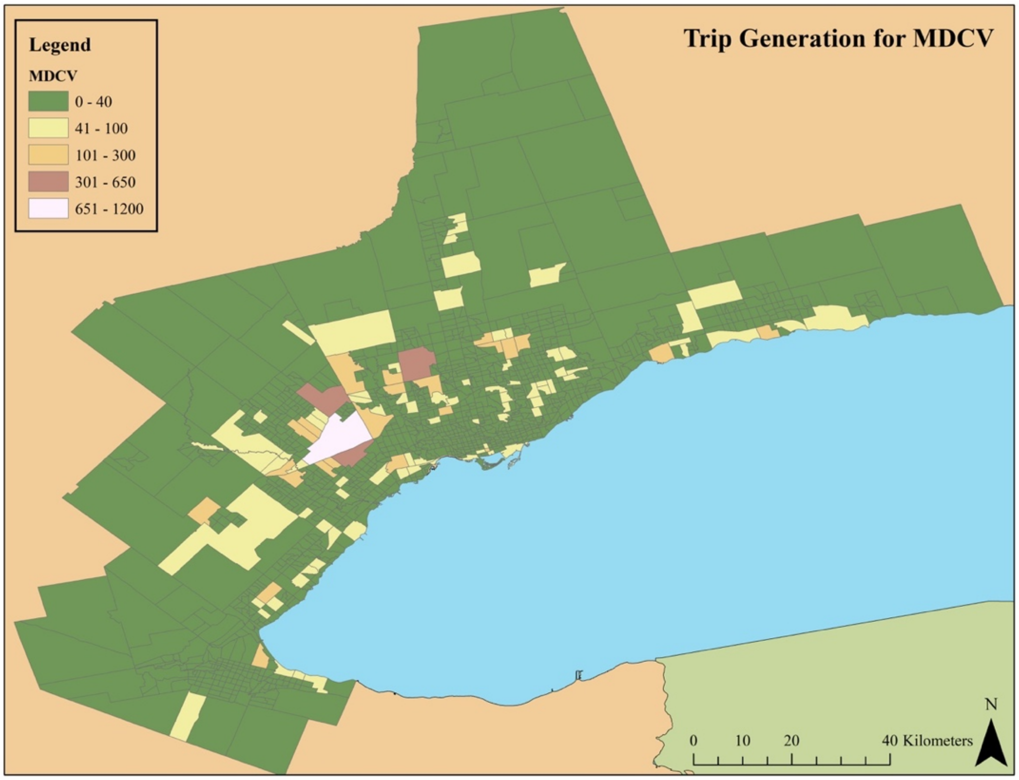


Figure A-11: Zonal Trip Generation for MDCVs

Figure A-12: Zonal Trip Generation for HDCVs

Table A-30: Trip Distribution Marginal Totals compared with O_i and D_j Values

Time	Max(Observed-Predicted)							
	O_i				D_j			
	PV	LDCV	MDCV	HDCV	PV	LDCV	MDCV	HDCV
0:00	0.1266	0.0348	0.0391	0.0277	0.0087	0.0156	0.0135	0.0186
1:00	0.0614	0.0307	0.0316	0.0244	0.0124	0.0146	0.0133	0.018
2:00	0.0464	0.0326	0.0362	0.0252	0.0126	0.0146	0.0128	0.0177
3:00	0.045	0.0324	0.033	0.0251	0.0106	0.0145	0.0127	0.0168
4:00	0.0746	0.0391	0.0407	0.0302	0.0101	0.0144	0.0135	0.0183
5:00	0.2478	0.0633	0.0633	0.078	0.0079	0.0123	0.0122	0.0192
6:00	0.8065	0.0976	0.0411	0.0654	0.0075	0.0134	0.0124	0.0169
7:00	1.0592	0.0842	0.0406	0.0616	0.0085	0.0138	0.0119	0.0157
8:00	0.9202	0.0934	0.0381	0.0678	0.0098	0.0142	0.0118	0.016
9:00	0.5519	0.1103	0.1169	0.091	0.0075	0.0106	0.0109	0.016
10:00	0.5201	0.1176	0.1201	0.1454	0.0073	0.0099	0.0104	0.0162
11:00	0.5071	0.125	0.1255	0.0992	0.0075	0.0158	0.0127	0.0164
12:00	0.5247	0.1188	0.1209	0.1498	0.0081	0.0111	0.0115	0.0167
13:00	0.5533	0.114	0.1211	0.1493	0.0081	0.0111	0.0113	0.0174
14:00	0.6088	0.1109	0.1127	0.1328	0.0084	0.0107	0.0121	0.0168
15:00	1.1172	0.0995	0.125	0.1145	0.0077	0.0133	0.0112	0.0149
16:00	1.2647	0.0817	0.101	0.0947	0.0075	0.014	0.0118	0.0189
17:00	1.3045	0.0663	0.0841	0.0841	0.009	0.0145	0.0123	0.0155
18:00	0.6757	0.0688	0.0718	0.0894	0.0073	0.0112	0.0123	0.0162
19:00	0.5298	0.0688	0.0742	0.0841	0.0077	0.0143	0.0112	0.0177
20:00	0.4237	0.0621	0.0675	0.0796	0.0083	0.014	0.0118	0.0171
21:00	0.379	0.0559	0.0555	0.0664	0.0074	0.0131	0.0115	0.0182
22:00	0.3151	0.0524	0.0525	0.0411	0.0077	0.0123	0.0129	0.019
23:00	0.2393	0.0439	0.0488	0.0313	0.0073	0.0129	0.0117	0.018
Minimum	0.045	0.0307	0.0316	0.0244	0.0073	0.0099	0.0104	0.0149
Maximum	1.3045	0.125	0.1255	0.1498	0.0126	0.0158	0.0135	0.0192
Mean	0.5376	0.0752	0.0734	0.0774	0.0085	0.0132	0.0121	0.0172

$$Max(Observed - Predicted) = Max\left|\sum_{i}^{1326} T_{ij} - O_i\right| \text{ or } Max\left|\sum_{j}^{1326} T_{ij} - D_j\right|$$

Table A-31: Traffic Assignment Results compared with CVS 2006 Traffic Counts

CVS	***Weekday Passenger***		***Weekday Truck***		
TA Hour	**PV**	**PV & LDCV**	**MDCV**	**HDCV**	**MDCV & HDCV**
0:00	0.9582	0.9582	0.8079	0.8328	0.8295
1:00	0.9614	0.9614	0.7230	0.7492	0.7449
2:00	0.9578	0.9578	0.7403	0.7694	0.7643
3:00	0.9581	0.9581	0.6979	0.7518	0.7079
4:00	0.8066	0.8066	0.6844	0.7386	0.7244
5:00	0.7008	0.7008	0.6842	0.7780	0.7502
6:00	0.8809	0.8809	0.7120	0.7982	0.7766
7:00	0.9579	0.9579	0.6980	0.7525	0.7412
8:00	0.9611	0.9611	0.6442	0.7254	0.7048
9:00	0.9089	0.9089	0.7268	0.8255	0.7903
10:00	0.9291	0.9291	0.7987	0.8756	0.8544
11:00	0.9547	0.9547	0.8043	0.8816	0.8603
12:00	0.9629	0.9629	0.8013	0.8780	0.8568
13:00	0.9589	0.9589	0.8021	0.8737	0.8543
14:00	0.9520	0.9520	0.8048	0.8548	0.8428
15:00	0.9071	0.9071	0.7463	0.8108	0.7961
16:00	0.8612	0.8612	0.6983	0.7835	0.7613
17:00	0.8662	0.8662	0.6228	0.7313	0.7004
18:00	0.9215	0.9215	0.6783	0.7688	0.7421
19:00	0.9534	0.9534	0.7502	0.8204	0.8012
20:00	0.9629	0.9629	0.7429	0.8037	0.7876
21:00	0.9581	0.9581	0.7620	0.8259	0.8089
22:00	0.9635	0.9635	0.7662	0.8155	0.8036
23:00	0.9721	0.9721	0.7781	0.8188	0.8099
Mean	0.9240	0.9240	0.7365	0.8027	0.7839
Minimum	0.7008	0.7008	0.6228	0.7254	0.7004
Maximum	0.9721	0.9721	0.8079	0.8816	0.8603

Table A-32: Absolute Difference between CVS Counts and Assigned Traffic

	Passenger Count		*Truck Count*		
Time	PV	PV & LDCV	HDCV	HDCV & MDCV	All CV
0:00	3090	4182	2021	1538	2002
1:00	1377	2979	1766	1344	1883
2:00	1025	2853	1631	1244	1645
3:00	1117	3255	1678	2905	4439
4:00	3377	5713	2165	1646	2227
5:00	13517	15836	3401	2678	3252
6:00	19566	20554	4797	3947	2750
7:00	14843	16744	4301	3539	2677
8:00	12483	14579	4714	3879	2892
9:00	17968	17839	6322	4910	3883
10:00	15430	14917	6475	4912	4629
11:00	12127	13264	6633	5032	4682
12:00	11042	13372	6556	4973	4630
13:00	11758	13928	6413	4865	4513
14:00	13815	15025	6012	4561	4387
15:00	19104	21058	5360	4325	2962
16:00	24794	26891	4398	3549	2493
17:00	25500	27324	3847	3165	2307
18:00	16762	18597	3791	2947	3124
19:00	12362	12259	3733	2834	3157
20:00	9438	9288	3414	2592	3174
21:00	9891	9150	3063	2327	2789
22:00	6724	7782	2799	2129	2705
23:00	4724	5485	2430	1846	2446
Totals	281,833	312,874	97,718	77,687	75,650
Min	1,025	2,853	1,631	1,244	1,645
Max	25,500	27,324	6,633	5,032	4,682
Mean	11,743	13,036	4,072	3,237	3,152

Table A-33 examines the magnitude comparison of the traffic counts observed and the estimated assigned traffic.

Table A-33: Traffic Assignment Results compared to CVS 2006 Counts

CVS	**Traffic Assignment**	**Generally Lower**	**Approximately Equal**	**Generally Higher**
Passenger	PVs	63%	38%	0%
	PVs & LDCVs	4%	67%	29%
Truck	HDCVs	100%	0%	0%
	MDCV & HDCV	92%	0%	8%
	ALL CV	17%	33%	50%
Generally Lower		6 or less stations were found to have higher counts of assigned traffic		
Approximately Equal		Only 7 or 8 stations reported higher or lower counts than assigned traffic		
Generally Higher		More than 8 stations were found to have higher magnitude in assigned traffic		

Figures A-13 and A-14 depict assigned PV and LDCV flow and MDCV flow, respectively.

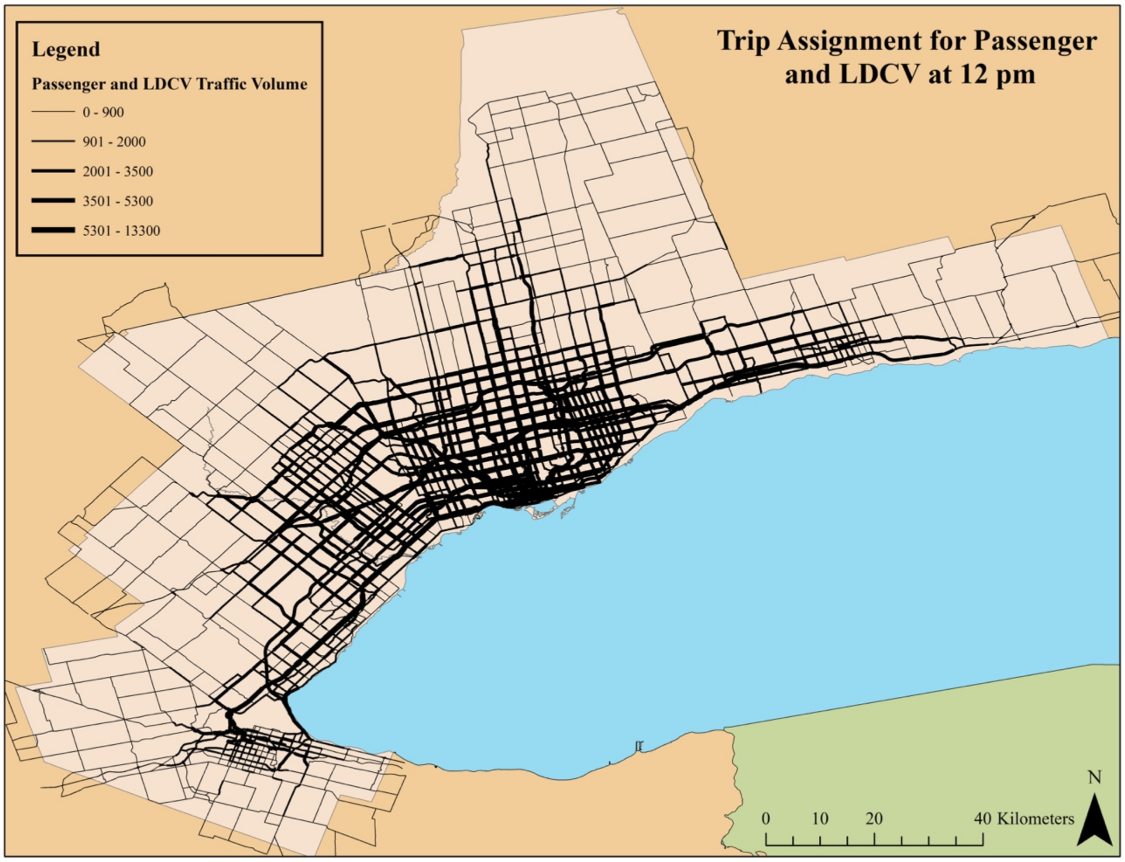


Figure A-13: PV and LDCV Flow at 12 pm

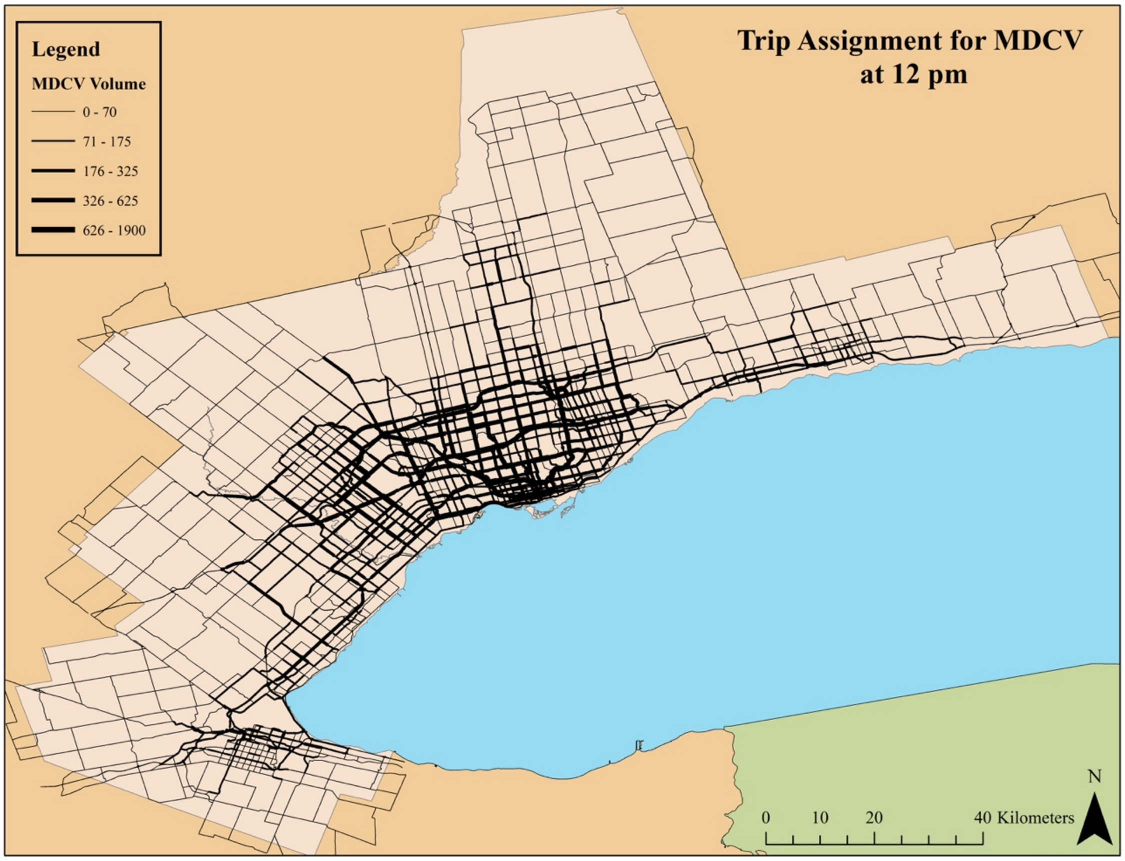


Figure A-14: MDCV Flow at 12 pm

Appendix K: Additional MOVES Results

This appendix provides the additional MOVES output results that were not presented in detail in Section 5.3. The following tables and figures are related to running emission results.

Table A-34: PM Tirewear and Brakewear Emissions (kg)

	Brakewear	Tirewear	Total
$PM_{2.5}$	4.92	1.37	6.30
PM_{10}	39.40	9.16	48.56

Table A-35: Oxides of Nitrogen Emissions (kg)

	NO_x		N_2O	NO		NO_2	
Scenario	**January**	**August**	**Both**	**January**	**August**	**January**	**August**
All Diesel	2073.31	1805.98	0.43	1854.42	1615.31	202.15	176.22
Scenario 1	1992.22	1751.62	1.27	1776.18	1560.98	201.42	177.94
Scenario 2	1830.06	1642.92	2.95	1619.70	1452.32	199.65	181.39
Scenario 3	1586.80	1479.87	5.47	1384.98	1289.34	197.00	186.57
All CNG	1262.47	1262.47	8.83	1072.02	1072.02	193.47	193.47

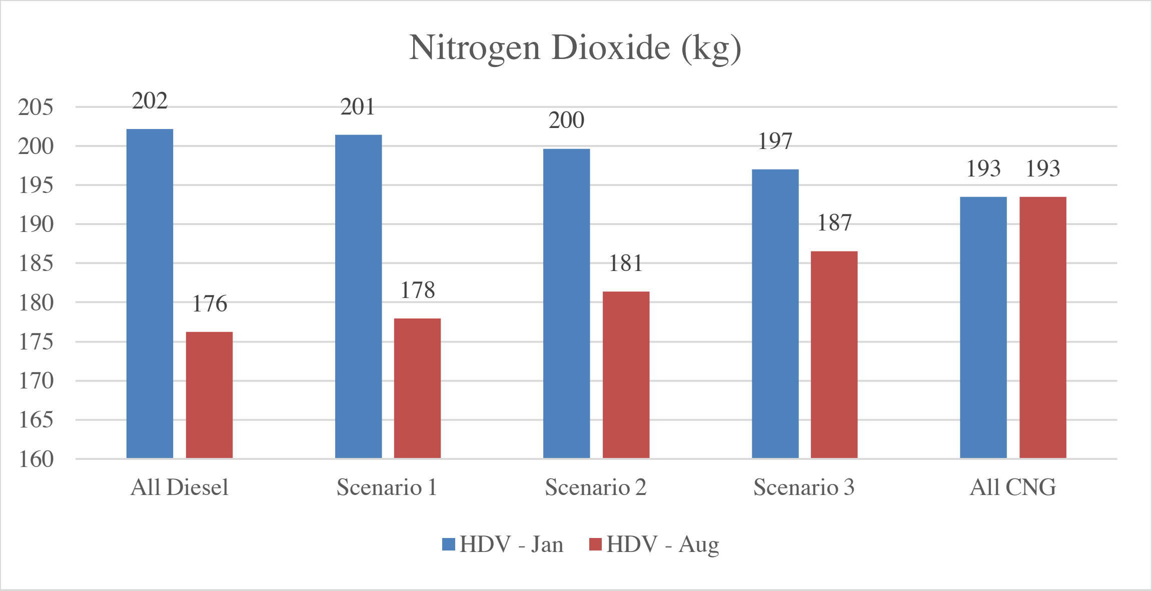


Figure A-15: Nitrogen Dioxide Emissions (kg)

Tables A-36 and A-37 present the percent contribution of running emissions to total emissions, followed by tables presenting the total estimated emissions and energy consumption for 12 pm.

Table A-36: Running Emissions Contribution- Summer

		Percent Running – Summer				
ID	**Pollutant Name**	**All Diesel**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**All CNG**
1	Total Gaseous Hydrocarbons	99.96%	99.99%	99.99%	100.00%	100.00%
2	Carbon Monoxide (CO)	82.10%	84.08%	86.97%	89.76%	92.05%
6	Nitrous Oxide	78.20%	42.83%	37.80%	36.31%	35.68%
31	Sulfur Dioxide	99.60%	99.60%	99.61%	99.63%	99.66%
79	Non-Methane Hydrocarbons	99.96%	99.96%	99.97%	99.98%	100.00%
87	Volatile Organic Compounds	99.96%	99.97%	99.98%	99.99%	100.00%
90	Atmospheric CO_2	99.60%	99.61%	99.62%	99.64%	99.66%
98	CO_2 Equivalent	99.59%	99.39%	98.99%	98.42%	97.70%
100	PM10 - Total	99.75%	99.73%	99.68%	99.55%	98.95%
110	PM2.5 - Total	99.75%	99.73%	99.69%	99.56%	98.95%
111	Organic Carbon	99.22%	99.20%	99.15%	99.05%	98.87%
112	Elemental Carbon	99.87%	99.87%	99.86%	99.82%	98.87%
115	Sulfate Particulate	99.50%	99.50%	99.48%	99.44%	98.51%
91	Total Energy Consumption	99.60%	99.61%	99.62%	99.64%	99.66%

Table A-37: Running Emissions Contribution - Winter

		Percent Running – Winter				
ID	**Pollutant Name**	**All Diesel**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**All CNG**
1	Total Gaseous Hydrocarbons	82.20%	91.85%	96.10%	97.82%	98.63%
2	Carbon Monoxide	82.10%	84.08%	86.97%	89.76%	92.05%
5	Methane	55.83%	97.69%	98.76%	99.03%	99.14%
6	Nitrous Oxide	78.20%	42.83%	37.80%	36.31%	35.68%
25	Formaldehyde	81.14%	88.90%	94.56%	97.56%	99.17%
26	Acetaldehyde	82.43%	85.14%	89.49%	94.20%	98.49%
27	Acrolein	83.17%	83.78%	85.30%	88.77%	99.26%
31	Sulfur Dioxide	99.30%	99.31%	99.32%	99.35%	99.40%
79	Non-Methane Hydrocarbons	84.28%	85.67%	88.50%	92.69%	98.80%
87	Volatile Organic Compounds	84.03%	85.90%	89.35%	93.87%	98.96%
90	Atmospheric CO_2	99.30%	99.31%	99.33%	99.36%	99.40%
98	CO_2 Equivalent	99.27%	99.05%	98.64%	98.06%	97.35%
100	PM10 - Total	99.75%	99.73%	99.68%	99.55%	98.95%
110	PM2.5 - Total	99.75%	99.73%	99.69%	99.56%	98.95%
111	Organic Carbon	99.22%	99.12%	99.06%	98.95%	98.87%
112	Elemental Carbon	99.87%	99.87%	99.86%	99.82%	98.87%
115	Sulfate Particulate	99.50%	99.50%	99.48%	99.44%	98.51%
91	Total Energy Consumption	99.30%	99.32%	99.34%	99.37%	99.40%

Table A-38: Total Emissions released at 12 pm (Winter)

Pollutant Id	Pollutant Name	TOTAL Emissions – Winter (kg)				
		All Diesel	Scenario 1	Scenario 2	Scenario 3	All CNG
1	Total Gaseous Hydrocarbons	130.75	285.34	594.51	1,058.27	1,676.62
2	Carbon Monoxide (CO)	627.92	705.31	860.10	1,092.27	1,401.84
3	Oxides of Nitrogen	2,073.31	1,992.22	1,830.06	1,586.80	1,262.47
5	Methane	9.58	258.20	755.43	1,501.28	2,495.75
6	Nitrous Oxide	0.56	2.97	7.81	15.07	24.74
25	Formaldehyde	11.94	18.86	32.68	53.42	81.08
26	Acetaldehyde	5.17	5.60	6.46	7.75	9.46
27	Acrolein	0.94	0.88	0.76	0.58	0.33
30	Ammonia	5.13	5.47	6.15	7.18	8.55
31	Sulfur Dioxide	3.01	2.88	2.63	2.25	1.75
32	Nitrogen Oxide	1,854.42	1,776.18	1,619.70	1,384.98	1,072.02
33	Nitrogen Dioxide	202.15	201.42	199.65	197.00	193.47
79	Non-Methane Hydrocarbons	121.17	120.62	119.51	115.65	115.65
87	Volatile Organic Compounds	137.42	141.41	149.38	161.35	177.30
90	Atmospheric CO_2	353,120.16	350,957.16	346,631.15	340,142.14	331,490.12
98	CO_2 Equivalent	353,524.21	357,959.54	366,830.49	380,136.64	397,878.27
100	Primary Exhaust PM10 - Total	106.28	97.97	81.36	56.44	23.22
106	Primary PM10 - Brakewear Particulate	39.40	39.40	39.40	39.40	39.40
107	Primary PM10 - Tirewear Particulate	9.16	9.16	9.16	9.16	9.16
110	Primary Exhaust PM2.5 - Total	97.77	90.05	74.61	51.44	20.54
111	Organic Carbon	11.46	11.02	10.13	8.80	7.01
112	Elemental Carbon	55.42	50.08	39.38	23.34	1.96
115	Sulfate Particulate	2.65	2.40	1.89	1.14	0.12
116	Primary PM2.5 - Brakewear Particulate	4.92	4.92	4.92	4.92	4.92
117	Primary PM2.5 - Tirewear Particulate	1.37	1.37	1.37	1.37	1.37
91	Total Energy Consumption (MJ)	4,769,853.53	4,854,398.77	5,023,489.24	5,277,124.94	5,615,305.88

Table A-39: Total Emissions released at 12 pm (Summer)

Pollutant ID	Pollutant Name	TOTAL Emissions - Summer				
		All Diesel	**Scenario 1**	**Scenario 2**	**Scenario 3**	**All CNG**
1	Total Gaseous Hydrocarbons	107.52	262.13	571.37	1,035.22	1,653.69
2	Carbon Monoxide (CO)	627.92	705.31	860.10	1,092.27	1,401.84
3	Oxides of Nitrogen	1,805.98	1,751.62	1,642.92	1,479.87	1,262.47
5	Methane	5.35	252.24	746.03	1,486.72	2,474.30
6	Nitrous Oxide	0.56	2.97	7.81	15.07	24.74
25	Formaldehyde	9.69	16.76	30.91	52.12	80.41
26	Acetaldehyde	4.27	4.77	5.78	7.30	9.32
27	Acrolein	0.78	0.74	0.65	0.51	0.33
30	Ammonia	5.13	5.47	6.15	7.18	8.55
31	Sulfur Dioxide	3.12	2.99	2.73	2.33	1.81
32	Nitrogen Oxide	1,615.31	1,560.98	1,452.32	1,289.34	1,072.02
33	Nitrogen Dioxide	176.22	177.94	181.39	186.57	193.47
79	Non-Methane Hydrocarbons	102.17	103.38	105.80	107.21	114.27
87	Volatile Organic Compounds	115.52	121.51	133.50	151.48	175.45
90	Atmospheric CO_2	366,040.93	363,785.17	359,273.64	352,506.34	343,483.28
98	CO_2 Equivalent	366,339.90	369,349.97	375,370.37	384,400.71	396,441.25
100	Primary Exhaust PM10 - Total	106.28	97.97	81.36	56.44	23.22
106	Primary PM10 - Brakewear Particulate	39.40	39.40	39.40	39.40	39.40
107	Primary PM10 - Tirewear Particulate	9.16	9.16	9.16	9.16	9.16
110	Primary Exhaust PM2.5 - Total	97.77	90.05	74.61	51.44	20.54
111	Organic Carbon	11.46	11.01	10.13	8.79	7.01
112	Elemental Carbon	55.42	50.08	39.38	23.34	1.96
115	Sulfate Particulate	2.65	2.40	1.89	1.14	0.12
116	Primary PM2.5 - Brakewear Particulate	4.92	4.92	4.92	4.92	4.92
117	Primary PM2.5 - Tirewear Particulate	1.37	1.37	1.37	1.37	1.37
91	Total Energy Consumption (MJ)	4,944,399.19	5,031,805.38	5,206,617.77	5,468,836.34	5,818,461.11

As mentioned in Section 4.3.2, there were two methods utilized to calculate the emissions inventory. The first one is to simply assign each link to a speed bin and sum the total VKT for each speed bin and multiply these results by the MOVES emission rates. The second method produces an inventory of pollutants by interpolating an emission rate based on the congested speed on the link. The two methods provided similar results. The correlations between the results for the five fuelling scenarios using the two inventory determination methods is strong (at least 0.99) in the case of all running emissions. With the exception of brakewear and tirewear pollutants as the results are approximately similar in every scenario. The maximum absolute difference between the interpolation and rates results are presented in the following table. Some of the values appear to be quite large, however the largest percent difference between the two values was found to be 1.30% which is quite small. Therefore, in the case of this analysis there is no significant difference between the two methods.

Table A-40: Comparison between the Interpolation and Speed Bin Rates Methods

Pollutant Id	Pollutant Name	Correlation	Max |Rates-Interpolation|	Units
1	Total Gaseous Hydrocarbons	1.0000	12.411	kg
2	Carbon Monoxide (CO)	1.0000	5.7249	kg
3	Oxides of Nitrogen	1.0000	12.955	kg
5	Methane	1.0000	19.275	kg
6	Nitrous Oxide	1.0000	72.335	g
25	Formaldehyde	1.0000	0.5144	kg
26	Acetaldehyde	1.0000	0.0754	kg
27	Acrolein	1.0000	2.0885	g
30	Ammonia	1.0000	7.2606	g
31	Sulfur Dioxide	1.0000	19.314	g
32	Nitrogen Oxide	1.0000	11.633	g
33	Nitrogen Dioxide	0.9999	1.1354	kg
79	Non-Methane Hydrocarbons	1.0000	0.8098	kg
87	Volatile Organic Compounds	1.0000	1.2027	kg
90	Atmospheric CO_2	1.0000	2.2659	tonnes
91	Total Energy Consumption	1.0000	30,608	MJ
98	CO_2 Equivalent	1.0000	2.2675	tonnes
100	Primary Exhaust PM10 - Total	0.9974	0.8212	kg
106	Primary PM10 - Brakewear Particulate	0.0957	0.5149	kg
107	Primary PM10 - Tirewear Particulate	0.5049	0.0072	kg
110	Primary Exhaust PM2.5 - Total	1.0000	0.7555	kg
111	Organic Carbon	1.0000	0.0961	kg
112	Elemental Carbon	1.0000	0.4004	kg
115	Sulfate Particulate	1.0000	20.653	g
116	Primary PM2.5 - Brakewear Particulate	-0.4494	0.0644	kg
117	Primary PM2.5 - Tirewear Particulate	-0.3434	0.0011	kg

Appendix L: GREET and GHGenius Procedure and Results

The GREET Fleet Footprint Calculator has some defaults for the average annual VMT, the average fuel economy and fuel production assumptions. The number of each type of vehicle for the on-road fleet is a total of 58,815 for this study and is broken down based on the different fueling scenarios as explained for the Starts Emissions. The daily VKT was obtained from the traffic assignment results and can be easily switched to VMT. However, to scale this value up to the annual VMT required by GREET, MOVES' Annual Average Weekday Vehicles Miles Traveled (AAADVMT) Converter was used and the value was determined to be 978,589,701 vehicle-miles for the fleet, and 16,643 miles for the vehicle. The fuel source was assumed to be North American and the average fuel economy for both diesel and CNG was assumed to be 6.295 mi/GGE and 5.00 mi/GGE respectively (where GGE is gasoline gallon equivalent).

Table A-41: GREET Fleet Results

Scenarios	**All Diesel**	**10%**	**30%**	**60%**	**All CNG**
GHG Emissions (short tons CO_2eq)	1,966,585	1,986,399	2,026,032	2,085,476	2,164,737
Petroleum Usage (barrels of oil)	3,514,100	3,165,139	2,467,100	1,420,159	24,199

The GHGenius model has many Canadian default values and is very detailed with respect to the fueling formulation. The Ontario defaults were selected for the analysis and heavy-duty trucks were selected as the vehicle of interest. The highway fraction was 0.5 which is similar to our research's results. The bulk of the GHGenius results are presented in the thesis.

Appendix M: Environmental SI Results

This appendix provides the full results of the analysis discussed in section 5.4.2. Table A-42 presents the emission rank results. Table A-43 summarizes the entropy-derived environmental scores obtained when the emission ranks were normalized. These values are consistent for both seasons. Table A-44 presents the overall environmental SIs obtained using six ranking approaches for the environmental criteria and the six tailpipe emission ranks presented in the previous table. Where Δ is the differential between the all-diesel scenario and the all-CNG fueling scenario.

Table A-42: Tailpipe Emission SIs

Ranking Approach	**Emission**	**Season**	**All Diesel**	**10% CNG**	**30% CNG**	**60% CNG**	**All CNG**	**Δ**
Rank Sum	Both	Both	0.5800	0.5640	0.5320	0.4840	0.4200	0.1600
Rank Reciprocal	Both	Both	0.5228	0.5183	0.5091	0.4954	0.4772	0.0457
Assigned Weights	Running	Winter	0.3130	0.3504	0.4252	0.5374	0.6870	0.3740
		Summer	0.3105	0.3484	0.4242	0.5379	0.6895	0.3790
	Total	Winter	0.3221	0.3589	0.4325	0.5428	0.6900	0.3679
		Summer	0.3160	0.3535	0.4286	0.5411	0.6912	0.3751

Table A-43: Entropy Derived Environmental SIs obtained after Emission Normalization

Tailpipe Emissions Rank	**Diesel**	**10% CNG**	**30% CNG**	**60% CNG**	**CNG**
Rank Sum and Rank Reciprocal	0.3695	0.3956	0.4478	0.5261	0.6305
Entropy and Assigned Weights	0.1634	0.2307	0.3654	0.5673	0.8366

Table A-44: Environmental SIs obtained using Methods 1, 2 and 3

Environ SI	Emissions Rank	Diesel	10%	30%	60%	CNG	Δ
Rank Sum	RS	0.4320	0.4456	0.4728	0.5136	0.5680	0.1360
	RR	0.4091	0.4273	0.4637	0.5182	0.5909	0.1817
	AW: Run (W)	0.3252	0.3602	0.4301	0.5350	0.6748	0.3496
	AW: Run (S)	0.3242	0.3594	0.4297	0.5352	0.6758	0.3516
	AW: Total (W)	0.3288	0.3636	0.4330	0.5371	0.6760	0.3471
	AW: Total (S)	0.3264	0.3614	0.4314	0.5364	0.6765	0.3501
Rank Reciprocal	RS	0.4384	0.4507	0.4754	0.5123	0.5616	0.1232
	RR	0.4110	0.4288	0.4644	0.5178	0.5890	0.1781
	AW: Run (W)	0.3102	0.3482	0.4241	0.5380	0.6898	0.3795
	AW: Run (S)	0.3090	0.3472	0.4236	0.5382	0.6910	0.3819
	AW: Total (W)	0.3146	0.3523	0.4276	0.5406	0.6912	0.3766
	AW: Total (S)	0.3117	0.3497	0.4257	0.5397	0.6918	0.3801
0.5% Tailpipe Emissions, Rest Rank Sum	RS	0.4567	0.4653	0.4827	0.5087	0.5433	0.0867
	RR	0.4281	0.4425	0.4712	0.5144	0.5719	0.1438
	AW: Run (W)	0.3232	0.3585	0.4293	0.5354	0.6768	0.3537
	AW: Run (S)	0.3219	0.3575	0.4288	0.5356	0.6781	0.3562
	AW: Total (W)	0.3277	0.3628	0.4329	0.5381	0.6783	0.3506
	AW: Total (S)	0.3247	0.3601	0.4309	0.5372	0.6789	0.3542
0.5% Tailpipe Emissions, Rest Rank Reciprocal	RS	0.4264	0.4411	0.4705	0.5147	0.5736	0.1473
	RR	0.3978	0.4182	0.4591	0.5204	0.6022	0.2044
	AW: Run (W)	0.2929	0.3343	0.4171	0.5414	0.7071	0.4143
	AW: Run (S)	0.2916	0.3333	0.4166	0.5417	0.7084	0.4168
	AW: Total (W)	0.2974	0.3385	0.4208	0.5441	0.7086	0.4112
	AW: Total (S)	0.2944	0.3359	0.4188	0.5433	0.7092	0.4148
0.5% Tailpipe Emissions, Rest Equal Weights	RS	0.4567	0.4653	0.4827	0.5087	0.5433	0.0867
	RR	0.4281	0.4425	0.4712	0.5144	0.5719	0.1438
	AW: Run (W)	0.3232	0.3585	0.4293	0.5354	0.6768	0.3537
	AW: Run (S)	0.3219	0.3575	0.4288	0.5356	0.6781	0.3562
	AW: Total (W)	0.3277	0.3628	0.4329	0.5381	0.6783	0.3506
	AW: Total (S)	0.3247	0.3601	0.4309	0.5372	0.6789	0.3542
Equal Weights	RS	0.3950	0.4160	0.4580	0.5210	0.6050	0.2100
	RR	0.3807	0.4046	0.4523	0.5239	0.6193	0.2386
	AW: Run (W)	0.3283	0.3626	0.4313	0.5343	0.6717	0.3435
	AW: Run (S)	0.3276	0.3621	0.4310	0.5345	0.6724	0.3448
	AW: Total (W)	0.3305	0.3647	0.4331	0.5357	0.6725	0.3420
	AW: Total (S)	0.3290	0.3634	0.4321	0.5353	0.6728	0.3438

Where:
Environ SI. Represents the overall environmental pillar ranking approach used.
RS=Rank Sum, RR=Rank Reciprocal and AW=Assigned Weights
W=Winter (January) and S=Summer (August)
Run=Running Emissions and Total= Total Emissions

VITA AUCTORIS

NAME: Amal Ghamrawi

PLACE OF BIRTH: Windsor, ON

YEAR OF BIRTH: 1993

EDUCATION: Vincent Massey Secondary School, Windsor, ON, 2011

University of Windsor, B.A.Sc., Windsor, ON, 2015

University of Windsor, M.A.Sc., Windsor, ON, Forthcoming