Evaluating Greenhouse Gas Emissions Benefits of Emerging Green Technologies in Passenger Transportation in the Quebec Context

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ABSTRACT

The transport produces 43.5% of Quebec's greenhouse gas (GHG) emissions; more than half of these emissions come from passenger transportation. In Quebec, transport emissions have grown by 30% from 1990 to 2009.

Accordingly, this research evaluates the impact on GHG of alternative fuels and technologies in public transit and personal motor vehicles in the Quebec context using link-level GHG estimation methods. The transit technologies examined were analyzed using a lifecycle approach, mainly focusing on fuel production and vehicle operation phases, with the aid of GHGenius and MOVES. The demand for hybrid vehicles, its determinants as well as some potential market penetration scenarios were also investigated for Quebec City and the Island of Montreal. Different sources of data were combined to generate GHG inventories and estimate motor vehicle travel demand including: GPS, train and vehicle fleet fuel consumption rates, the Canadian Census, origin-destination surveys, and vehicle registration records.

The results demonstrate that the use of alternative technologies can lead to significant GHG reductions. Among the bus technologies, it was found that hybrid buses are the best option with savings of 43.3%, followed by compressed natural gas (20.5%) and biodiesel (12.5%). For commuter rail, electric technology can reduce emissions by 98%; however, hydrogen fuel cell trains may be competitive in terms of cost-benefit ratio. Although hybrid personal vehicles have the potential for great GHG reductions, the limited spatial distribution of purchasers indicates that this technology will have a more modest impact than what might be expected. From an optimistic perspective where the vehicle fleet is composed of 25% hybrid vehicles, the impact would only lead to a 10% decrease in GHGs.

RÉSUMÉ

Le secteur des transports contribue 43,5 % des émissions de gaz à effet de serre (GES) au Québec; plus que la moitié de ses émissions vient du transport de passager. Les émissions du secteur des transports a accrue par 30% entre 1990 et 2009.

En conséquence, cette recherche évalue l'impact des carburants et technologies alternatives en transport collectif et les véhicules personnels sur les GES dans le contexte québécois en utilisant les méthodes d'estimations de GES aux niveaux des liens. Les technologies des transports communs sont analysées en utilisant l'analyse de cycle de vie, particulièrement la production du carburant et l'opération du véhicule, avec l'aide de GHGenius et MOVES. Le marché pour les véhicules hybrides, ses déterminants et puis des scénarios potentiels de pénétration du marché sont examinés pour la ville de Québec et l'Ile de Montréal. Différents sources de données sont combinés pour générer l'inventaire de GES et estimer la demande de transport incluant le GPS, le taux de consommation des carburant, le Census, les enquêtes origine-destination et l'enregistrement de véhicules automobiles.

Les résultats démontrent que les technologies alternatives réduient effectivement les émissions de GES. Parmi les technologies d'autobus, les autobus hybrides sont les meilleurs choix avec des réductions de 43,3 %, suivi par le gaz à naturel compressé (20,5 %) et le biodiesel (12,5 %). Pour les trains de banlieue, les trains électriques peuvent diminuer les émissions par 98%; pourtant, les trains à hydrogène sont compétitifs selon le rapport cout-bénéfice. Bien que les véhicules hybrides ont la potentiel d'éviter beaucoup de GES, la distribution spatiale du marché des véhicules hybrides indiquent que cette technologie aura un impact modeste. Dans le cas optimiste, le remplacement de 25% du parc d'automobiles vont mener à une baisse de 10% des GES.

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CONTRIBUTIONS OF AUTHORS

Please note that some chapters have or will be presented at different conferences. These papers were written in collaboration with other authors.

The work on transit bus technologies was presented in part at the Conference on Advanced Systems for Public Transport (CASPT) in July 2012. The methodology on this study has been reworked to include a comparative analysis between methods as well as the investigation of an additional alternative technology. Moreover, the emissions were re-evaluated and new results were obtained. The other authors were primarily responsible for editorial work.

The study on commuter rail technologies was presented at the Transportation Research Board (TRB) 91st Annual Meeting. The other authors were also mainly responsible for editing the paper.

The chapter on hybrid-electric vehicles will be presented at the TRB 92nd Annual Meeting in January 2013.

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1 Introduction

1.1 CONTEXT

In Quebec in 2009, greenhouse gas (GHG) emissions totalled 81.8 Mt of CO_2-equivalent, representing 11.9% of Canada's total GHG emissions. The transportation sector contributed 43.5% of these emissions with road transportation being the largest emitter (MDDEP, 2011). The large transportation emissions are intuitive given the fact that the main source of electricity is hydro-power in Quebec. Rail transport is the only mode that utilizes electricity as an energy source which explains the low contribution from this category. For example, the metro system in Montreal operates completely on electricity. It is also worth noting that transport emissions contribute 35.5% of Ontario's GHG inventory. Transport emissions are generated by passengers and freight transportation. **Figure 1-1** illustrates the breakdown of the transportation emissions in Quebec as reported by Natural Resources Canada (2012a)[1]. The majority of road and air transport emissions come from passenger travel whereas rail and marine transportation come mostly from the movement of goods.

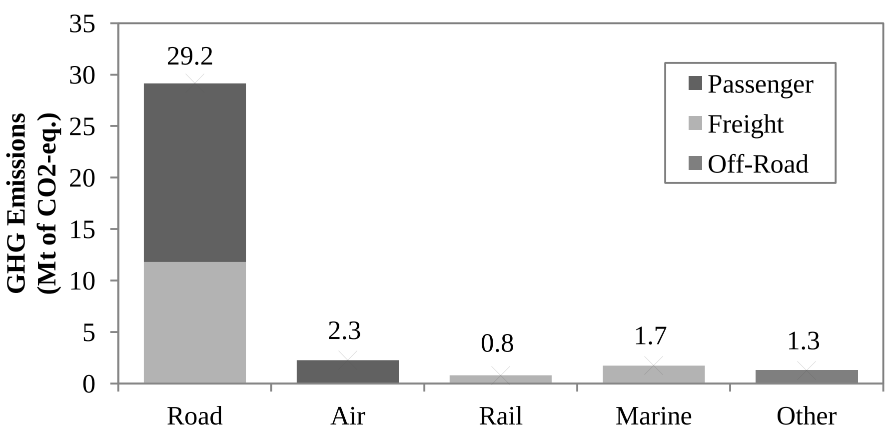

Figure 1-1 Transport emissions in Quebec 2009
Source: NRCan, 2012a

Total transport emissions in Quebec have grown by 29.6% from 1990 to 2009 (MDDEP, 2011). Road transportation is largely responsible for the increase in transport emissions. This increase can be associated to the rising number of road vehicles including cars, motorcycles, light trucks and heavy vehicles – being this phenomenon also associated to the growth of the population and number of households. However, total emissions by automobiles decreased by 0.6 Mt of CO_2-

[1] Transport emissions reported by Ministère du développement durable, de l'environnement et des parcs and Environment Canada are slightly different. The former combine emissions between passenger and freight transportation and the exact breakdown between the two is not specified. For this reason, emissions estimated by Environment Canada are presented in Figure 1.

equivalent from 1990 to 2009 due to the car fleet renewal (MDDEP, 2011). Older car models were replaced with cleaner and more fuel efficient vehicles. For instance, in the Montreal region, the average fuel consumption rate in 2003 was 9.6 L/100 km compared to 9.3 L/100km in 2008 for the same region.

Table 1-1 GHG Emissions by Province in 2009

Province	GHG Emissions (Mt)	Transport (Mt)	Passenger Transport (Mt)	Population
Newfoundland and Labrador	9.5 (1.4%)	4.1 (2.3%)	2.2 (2.3%)	508,900 (1.5%)
Prince Edward Island	1.9 (0.3%)	0.7 (0.4%)	0.4 (0.5%)	141,200 (0.4%)
Nova Scotia	21.0 (3.0%)	4.9 (2.8%)	2.7 (2.8%)	940,300 (2.8%)
New Brunswick	18.4 (2.7%)	4.3 (2.4%)	2.1 (2.2%)	750,000 (2.2%)
Quebec	**81.8 (11.9%)**	**35.6 (19.7%)**	**19.6 (20.5%)**	**7,826,900 (23.2%)**
Ontario	165.0 (23.9%)	58.6 (32.9%)	37.1 (38.9%)	13,072,700 (38.8%)
Manitoba	20.3 (2.9%)	5.7 (3.2%)	3.2 (3.3%)	1,219,200 (3.6%)
Saskatchewan	73.1 (10.6%)	8.9 (5.0%)	3.8 (4.0%)	1,029,300 (3.1%)
Alberta	234.0 (33.9%)	29.9 (16.8%)	11.5 (12.1%)	3,671,700 (10.9%)
British Columbia & Territories	65.7 (9.5%)	25.8 (14.5%)	12.7 (13.3%)	4,569,400 (13.5%)
Canada	**690.0 (100%)**	**178.5 (100%)**	**95.5 (100%)**	**33,729,700 (100%)**

Source: NRCan, 2012a; MDDEP, 2011

In comparison, the transportation sector makes up 25.8% of Canada's GHG inventory (NRCan, 2012a). Passenger transport makes up more than half of the 25.8%. Road vehicles emit 83% of passenger transport emissions which is a little lower than the 89% observed in Quebec (NRCan, 2012a). Quebec and Ontario produce the largest passenger transport emissions owing to their large populations. On a per capita basis, the passenger transport of Quebec is the lowest in Canada: 2.5 tonnes/person compared to the national average of 2.8 tonnes/person in 2009. The GHG emissions by province are presented in **Table 1-1**.

1.2 STRATEGIES TO REDUCE GHGS

In the last years, governments and public agencies at different levels (city, regional and provincial) have been looking for strategies to reduce fuel energy consumption and cut GHGs in the transportation sector. Different strategies that can be found in the literature include: the reduction of car usage (distances traveled), the improvement of transit accessibility (e.g., increase of frequencies in existing routes or new services in areas without transit) and strategies linked to land use (densification and diversification of land uses). With respect to land use, the idea is to encourage people to be less automobile-dependent, promote active transportation and reduce their carbon footprint.

Other important strategies are linked to the replacement of traditional, or the introduction of, new technologies for personal motor vehicles and public transit (e.g. electric, hybrid, biodiesel). Technological changes are identified in the transportation literature as some of the most effective methods to reduce GHGs. Research on alternative fuels and technologies have intensified recently for several reasons, including global warming and the energy crisis. Global warming and climate change is a growing concern which is caused by the increase in CO_2 emitted from anthropogenic sources especially motor vehicles. Changes in weather patterns can have detrimental effects on biological and ecological systems. The Kyoto Protocol was adopted in 2005 as a means to reduce GHG emissions across the globe and fight against climate change. In 2011, Canada pulled out of the protocol citing financial strains on the economy. The country also experienced an increase in emissions in 2009, when the goal was to reduce it by 5% from 1990 levels between 2008 and 2012 (Environment Canada, 2011). The energy crisis, which saw a dramatic increase in oil prices, during the 2000s, has also led to a renewed interest in alternative fuels in order to reduce dependency on petroleum. Due to the increasing demand and the limited supply of oil, the price of a barrel of crude oil skyrocketed which peaked at $147 in July 2008 (Trading Charts, 2012). Alternative technologies would mitigate the impact of the energy crisis and reduce GHG emissions.

Several actions and strategies have been announced by governments in the last few years. The most recent example is the announcement made of the 2013-2020 Climate Change Action Plan (CCAP 2020), at the beginning of June 2012 by the Quebec government. This plan is accompanied by a set of strategies for adapting to climate change. This includes an ambitious target of a 20% emissions reduction by 2020 based on 1990 levels. The new plan aims to reduce emissions by 11.7 million tonnes between 2012 and 2020. This will bring emissions down from 83.9 million tonnes in 1990 to 67.1 million tonnes in 2020. A reduction of 2.5% from 1990 levels has already been achieved in 2009. Strategies to limit transportation emissions focus on promoting active transportation and exploiting alternative technologies. Among the main strategies in passenger transportation announced by this plan include improving accessibility to public transit and alternatives to single-occupant commuting by increasing service and creating new infrastructure such as bike paths, high occupancy vehicle lanes and park and ride lots; and renewing the vehicle fleet by replacing them with more fuel-efficient vehicles and launching an inspection and maintenance programs for older vehicles. Other strategic plans in transportation are investing in intermodal passenger and freight transportation; improving efficiency of rail, marine and air transport; and reducing carbon footprint of road freight transportation (MDDEP, 2012).

Quebec has the potential to dramatically reduce GHG emissions in the transportation sector due to one important energy source. One of the main resources in Quebec is hydro-power, which makes electricity a natural source of energy for transportation. Hydro-Quebec is the main supplier of electricity in Quebec. It has a long standing history in Quebec's economic development, and is continuously involved in numerous large-scale hydroelectric projects. It is also the world's largest hydroelectricity producer with 60 hydroelectric generating stations and a total capacity of 36,700 megawatts (Hydro-Québec, 2011a). Over 90% of electricity in Quebec is generated from hydro-power. Hydroelectricity is not as important in the rest of Canada or in the United States as shown in **Figure 1-2**. Only 59% and 9% of electricity comes from hydro-power in Canada and the US, respectively. Coal and natural gas (NG) are the two main energy sources in the US.

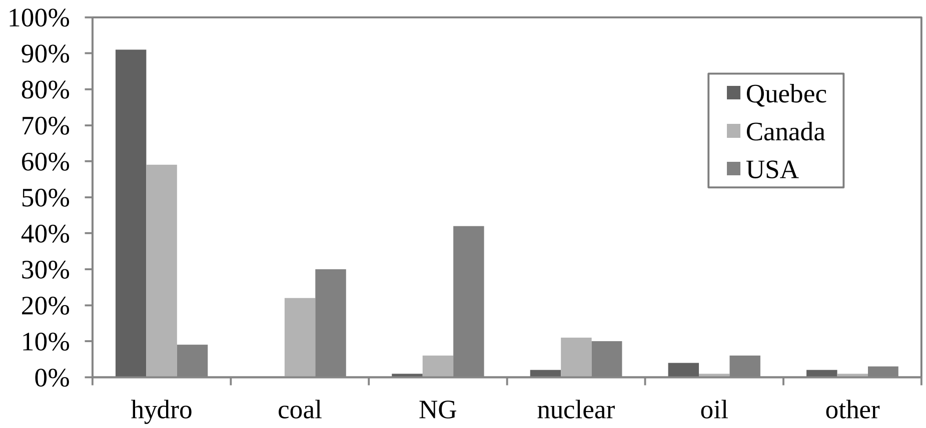

Figure 1-2 Electricity sources in Quebec, Canada and US
Source: Hydro-Québec, 2011a

Accordingly, the Quebec government, Hydro-Québec and transportation agencies have turned to electricity as the key solution in reducing GHG emissions. For personal travel, there are two pilot projects to introduce and market electric vehicles. One pilot project is the introduction of the electric Nissan Leaf into Communauto's car-sharing service. Another experiment is the installation of 120 electric charging stations in the Greater Montreal and Quebec areas, known as the Electric Circuit, to increase the driving range of electric vehicles. They are in partnership with Metro, Rôtisserie St-Hubert, RONA and Agence métropolitaine de transport (AMT); charging stations are located in the parking lots of these participating organizations. It costs only $2.50 per charge regardless of the recharging time. A 240-volt charging station would take 3-4 hours for a plug-in hybrid or 6-8 hours for an electric vehicle to fully recharge the batteries (Hydro-Québec, 2012a). Furthermore, there are large-scale plans to electrify public transit. It was recently announced that the government would invest $30 million to develop the "greenest" electric transit bus (Novabus, 2012). This is in accordance with the Société de transport de Montreal (STM) which has stated that it plans on converting the entire bus fleet to electric buses by 2025. The

AMT is also conducting feasibility studies on a complete electrification of the commuter rail network.

1.3 ALTERNATIVE TECHNOLOGIES IN PASSENGER TRANSPORTATION

This section provides a short description of the most common traditional and alternative passenger transportation technologies. These technologies include diesel, compressed natural gas, biodiesel and diesel-electric hybrid for transit buses; diesel, electric and hydrogen fuel cell for commuter rail; and gasoline, electric and gasoline-electric hybrid for passenger cars.

1.3.1 Transit Buses

a) Diesel

Traditional transit buses run on diesel fuel. There are new legislations set by the Canadian government requiring the use of cleaner diesel fuel by limiting the sulphur levels to 15 ppm to reduce pollution. This is known as ultra low sulphur diesel (ULSD).

b) Compressed natural gas (CNG)

CNG is mainly composed of methane which is a greenhouse gas. It is a cleaner alternative to diesel due to lower CO_2 emissions produced. It comes from natural gas that is extracted from underground gas fields or oil wells, treated at a processing plant and then delivered to fueling stations where it is compressed to be ready to be pumped and stored in on-board vehicle tanks. The issue with CNG buses is the on-board storage tanks. They require additional space and suffer from increased risk of explosion.

c) Biodiesel

Biodiesel is distinguished from traditional diesel by its feedstock. Whereas diesel is a petroleum product, biodiesel comes from a variety of animal- and plant-based feedstock. It is used in standard diesel engines with minor or no modifications. Buses can run on pure biofuels; however, it is known to cause wear on the engine and pure diesel freezes in cold temperatures. It is usually used as additives to diesel fuel to reduce pollutant emissions. Biodiesel blends are indicated by BXX where XX is the percentage of the biofuel in the mixture (How Stuff Works, 2012). Biodiesel is typically made up of a blend of 20% biofuel and 80% petroleum diesel. There are a variety of biofuels available such as soybean, animal fat, jatropha, rapeseed, etc.

d) Diesel-electric hybrid

Hybrid bus technology combines a diesel engine with an electric motor. They work together to improve fuel efficiency and reduce emissions. From a stopped position, the electric motor provides the power to accelerate. The hybrid vehicle only uses the electric motor for speeds up to 15 mph (24 km/h). At cruising speeds, only the diesel engine operates which also powers the generator to produce electricity and stores it in a battery for later use. For heavy acceleration, the engine and electric motor operate simultaneously. The battery also recharges through regenerative braking. At a complete stop, the battery turns on while the other two components turn off to keep the auxiliary systems functioning. This technology is most useful in urban driving conditions which are characterized by frequent stops (Voelcker, 2012).

1.3.2 Commuter Trains

a) Diesel

The standard technology for commuter rail in North America is diesel locomotive hauled coach trains. Diesel locomotives consist of a diesel engine, prime mover, traction motors (which use electricity), fuel tank and operator controls to push or pull passenger cars and coach cabs along railways. This configuration does not require additional infrastructure for power supply, although naturally, refueling stations are still needed. This popularity of this traditional approach to commuter rail services is mainly due to low capital costs, low risk, quick delivery and its flexibility to rail operators. Despite these advantages, the performance of diesel trains in terms of power, acceleration and speed, is low compared to electrified trains. Due to the combustion of fossil fuels during rail operation, diesel-powered trains are the most polluting compared to electric trains using renewable or non-renewable electricity production and hydrogen fuel cell powered trains (LTK Engineering Services, 2010).

Another diesel rail technology is the diesel multiple units (DMU) which are self-propelled and powered by one or more diesel engines. DMUs can have a variety of transmission types such as mechanical, electrical and hydraulic. Its performance is better than diesel locomotives due to faster acceleration and good adhesion on steep grades but inferior to electric multiple units (EMU). These are a practical and cost-efficient alternative for short trains consisting of a maximum of 4-6 units (LTK Engineering Services, 2010).

b) Electric

There are two types of electric-powered trains: electric locomotive and EMUs. Locomotives use a push-pull configuration while EMUs are self-propelled electric vehicles. Electric commuter trains are rare in North America; however, they are quite common in Europe. Unlike diesel locomotives, electric locomotives do not carry prime movers on-board. Both electric technologies obtain energy from an off-car electrified traction power supply and distribution systems such as overhead catenary wires or a third-rail system in which electrical infrastructure is placed on the ground alongside existing railway tracks (LTK Engineering Services, 2010). Electrified trains offer many benefits including lighter weight, higher speed, higher system capacity, faster acceleration and faster travel times (LTK Engineering Services, 2010). Electric locomotives can use renewable energy sources which results in zero tailpipe emissions. Indirect emissions from electric propulsion are a function of the fuel source from which electricity is generated. EMUs are expensive and the high costs are only justified by high ridership levels and high frequency service (LTK Engineering Services, 2010). **Figure 1-3** demonstrates the diesel and electric commuter rail technologies used in Montreal.

Figure 1-3 Diesel-electric train (left) and EMUs (right) in Montreal
Source: LTK Engineering Services, 2010

c) Hydrogen fuel cell

This train technology is not well-established and feasibilities studies are currently being conducted in Japan, Denmark and Canada. Hydrogen fuel cell technology converts stored hydrogen into electricity. It is a clean process as it only emits water vapor. The most popular method of hydrogen production is steam methane reforming (SMR). Steam reacts with methane at high temperatures to produce carbon monoxide and hydrogen. Hydrogen can also be produced from renewable resources such as wind or solar energies. One clear advantage of hydrogen locomotives over electric trains is that they are compatible with existing railways and additional infrastructure for power supply is not necessary which would lower infrastructure costs. The main drawbacks of hydrogen fuel cells are the space needed to store hydrogen tanks on-board as well as the risk of explosion upon collision. The components that make up a hydrogen fuel cell vehicle are the hydrogen gas tanks, the fuel cell system, cooling system, electric engine and automatic transmission.

1.3.3 Automobile

a) Gasoline

Standard automobiles use a combustion engine fuelled with gasoline. This fuel generates the most pollution since it is the least fuel-efficient of available technologies; however, it is the preferred choice due to its performance in terms of speed and acceleration and long range. It is also the cheaper option as the market for emerging green technologies has not been established.

b) Electric

At the turn of the 20th century, electric automobiles were introduced. Their success was short-lived when internal combustion engines became more prominent. Electric vehicles were reintroduced in the 1990s but several factors prevented them from reaching commercial success, including low consumer demand. Electric vehicles are powered by electric motors that obtain electricity from batteries. The battery is recharged by plugging-in to charging stations. The use of electric vehicles results in zero exhaust emissions, and they are nearly silent. The drawbacks are the shorter distances that can be travelled before the battery needs recharging and lower speeds. A fully recharged battery can take several hours to charge.

c) Gasoline-electric hybrid

Hybrid cars combine gasoline engines and electric motors. They function similarly to hybrid buses except that they use a gasoline engine instead of a diesel engine. They were first introduced in the late 1990s and have gained popularity in the 2000s. Hybrid passenger cars offer the best of gasoline and electric technologies by reducing pollution yet increasing mileage, making it easier to refuel/recharge and maintaining high speeds on highways.

1.4 METHODS AND TECHNIQUES TO EVALUATE TECHNOLOGICAL IMPACTS

In order to evaluate technologies with respect to sustainable outcomes, lifecycle assessment (LCA) should be conducted. There are several tools available to estimate the carbon footprint of transportation fuels and technologies. It is evident that lifecycle emissions vary for different technologies. A literature review on LCA and software tools to evaluate the impact of technology on emissions is presented in this section.

1.4.1 LCA

LCA summarizes pollutant and GHG emissions for all life stages from cradle-to-grave. The upstream stage, prior to the operation phase, is associated with vehicle manufacturing, infrastructure construction and fuel production. The downstream stage is related to the disposal of the vehicle and/or recycling of all materials used. In the past, the vehicle operation stage has been the focus of environmental impact assessments due to the lack of data associated with the other life stages and it is also assumed to contribute the largest amount of emissions. Recent studies have shown that a significant portion of emissions is attributed to stages other than vehicle operation. Lifecycle energy and GHG emissions are around 70% larger than vehicle operation while pollutant emissions are up to four times as large (Chester et al., 2010). An LCA is a more suitable tool towards making sustainable choices since it looks at the complete carbon footprint of a system (Yan and Crookes, 2009).

Lifecycle stages are divided into two categories:

- Well-to-Tank (WtT); and
- Tank-to-Wheel (TtW).

The WtT consists of resource extraction, material processing, manufacturing, transport and fuel production whereas the TtW is the fuel consumption or operational stage. The full lifecycle is also known as Well-to-Wheel. Depending on the fuel, the WtT phase could include different processes. For diesel, the lifecycle involves petroleum recovery, crude transportation, storage and refining, and production transportation, storage and distribution (Ally and Pryor, 2007; Karman, 2006). The lifecycle of CNG goes through production and processing before the product is transported, stored and distributed (Ally and Pryor, 2007; Karman, 2006).

The proportion of emissions attributed to each lifecycle stage varies for different transportation modes. Vehicle operation for most transportation modes is responsible for the largest portion of lifecycle GHGs (Castella et al., 2009; Chester and Horvath, 2010; von Rozycki et al., 2003). For passenger cars, it accounts from 67% to 74% of the total life cycle emissions (Schafer et al., 2006), whereas the production, distribution and disposal of personal motor vehicles contribute less than 10% to the life cycle energy and GHG emissions (Schafer et al., 2006). In contrast, direct emissions only accounted for 23% of the carbon footprint of a bus rapid transit system (Cui et al., 2010). For bus transit fuelled by diesel and CNG, operational emissions also dominate life cycle emissions; however, fuel production is the most polluting stage for hydrogen-fuelled buses (Ally and Pryor, 2007). Tailpipe emissions make up 79.9% and 85.7% of the life cycle emissions for diesel buses and CNG buses, respectively (Karman, 2006). In the railway industry, the situation is different. Total life cycle GHG emissions are 2.1 and 1.4 times higher than just operational emissions for heavy rail transit (HRT) and high-speed rail (HSR), respectively (Horvath and Chester, 2008). A sizeable amount of emissions are associated with infrastructure construction and electricity production: both these upstream emissions account for about 20% for heavy rail and 10% for high speed rail (Chester and Horvath, 2010). Moreover, vehicle manufacturing accounts for only 6% for HRT and less than 1% for HSR (Horvath and Chester, 2008).

Differences in defining system boundaries can explain the discrepancies between emissions reported in the studies (Yan and Crookes, 2009). Some studies do not consider road and infrastructure construction as they do not vary for different fuels (Beer et al., 2002). Similarly, few studies have considered downstream stages since the emissions are similar for alternative technologies and fuels (Beer et al., 2002; Castella et al., 2009), and the evaluation of waste management and material reuse is quite complicated (Chester and Horvath, 2009).

1.4.2 LCA Tools

There are various tools available for LCA. The study by Karman (2006) compared the results of three lifecycle models: CSIRO study (Beer et al., 2000), GHGenius ($(S\&T)^2$ Consultants Inc, 2005), and Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) (Wang, 1999). While the CSIRO study presents a more favourable picture for CNG than for diesel from a lifecycle perspective, both GHGenius and GREET predict higher lifecycle emissions for CNG (Karman, 2006). Results vary due, among other things, to the fact that they use different emissions databases and parameters. Although MOBILE 6 is currently obsolete, numerous studies have based their results on the emission factors generated by this software before it was replaced with Motor Vehicle Emission Simulator (MOVES) which are both widely used in the US. Macroscopic models such as COPERT 4 and MOBILE 6 are useful for estimating emissions on a regional level and are typically based on driving cycle average emission factors (Coelho et al., 2009). MOVES is based on second-by-second data from dynamometers as well as real-world measurements (Coelho et al., 2009). MOVES differs from MOBILE 6 in that it can also be used to evaluate the local effects of transportation projects (US EPA, 2010). The emission factors are intended to estimate emissions during the operational phase only. Both LCA tools and emission factor generators require input parameters; these tools use extensive inventories. In the case that data is missing, assumptions on technology level, climate and geographical conditions, electricity sources and transport are made (Yan and Crookes, 2009). In order to have accurate results, it is necessary to obtain as much data as possible.

LCA can also be conducted without the means of software tools. The alternative technique is to use emission factors from reliable sources. A different factor is applied for each lifecycle phase and for each technology. Emission factors are very sensitive to vehicle characteristics and driving conditions (Chester et al., 2010; Frey et al., 2007; Pandian et al., 2009; Rabl, 2002). They can vary depending on the vehicle type, age, weight, engine parameters, pollution control technology, road classification, passenger load, road grade, average speed, number of stops, fuel type, etc. For example, one study tested the fuel consumption and emissions rates for a range of cruising speeds, acceleration and road grade and found that the optimal speed for fuel economy is between 50-70 km/h (Wang et al., 2008). Frequent stopping and idling time also contribute to higher emissions. This is particularly true for urban transit buses which spend a significant amount of time idling due to the frequent stops for passengers to board and alight (Frey et al., 2007; Jayaratne et al., 2010; Pandian et al., 2009). Moreover, passenger load has an effect on emissions due to the increased weight; the effect of passenger load on fuel consumption is noticeable for speeds higher than 10 km/h (Frey et al., 2007).

1.5 INTERNATIONAL LITERATURE

Empirical evidence of the impact on GHG of alternative technologies for public transit and personal vehicles is summarized in this section.

In the current context, the positive impact of new transportation technologies in terms of energy savings, and reduction of GHG and pollutant emissions have attracted a lot of attention. This includes the impact of the introduction of new motor vehicle technology such as electric and hybrid personal vehicles, and the use of biodiesel, electric or hybrid buses in public transit. Some studies evaluate different motor vehicle technologies in North America and Europe (Schafer et al., 2006; Wee et al., 2005; Zamel and Li, 2006). Other studies investigate the impact of bus technologies in Australia, China, Portugal and the United States (Ally and Pryor, 2007; Frey et al., 2007; Karman, 2006). Still other studies describe how LCA has been used to assess the technological impacts on GHGs (Akerman, 2011; Castella et al., 2009; Chester and Horvath, 2009; Chester and Horvath, 2010; Haseli et al., 2008; Horvath and Chester, 2008; Lenzen, 1999; Marin et al., 2010a, 2010b; Schafer et al., 2006; Vincent and Jerram, 2006; von Rozycki et al., 2003; Wee et al., 2005; Zamel and Li, 2006). This literature review on the alternative technologies in different transportation modes is divided in three main areas: transit bus technologies, commuter train technologies and passenger car technologies. Research issues are also discussed in this section.

1.5.1 Transit Bus Technologies

Research on bus technologies typically analyzes diesel fuel, CNG and biofuels. One study comparing the lifecycle emissions of transit bus technologies in Beijing, China, reveals that a small reduction can be achieved by switching from diesel to CNG which emit 2,801 g/mile and 2,732 g/mile, respectively (Karman, 2006). A second study in China examines ethanol and diesel blends of biofuels. Depending on the feedstock, bioethanols can cause more harm to the environment (Yan and Crookes, 2009). In contrast, biodiesel derived from rapeseed or soybean can offer substantial GHG savings of about 60 g/MJ from conventional diesel (Yan and Crookes, 2009). Another study investigates diesel, CNG and hydrogen fuel cell technologies for transit buses in Perth, Australia. The findings indicate the lifecycle emissions of alternative fuels exceed that of diesel due to the lower fuel efficiency of CNG and the fuel production of hydrogen. Although improvement in the fuel economy and the use of clean energy sources for hydrogen systems could lead to potential reductions of 50% (Ally and Pryor, 2007).

1.5.2 Commuter Train Technologies

Studies on commuter trains look at electric and hydrogen technologies from various production methods and energy sources. Horvath and Chester (2008) compare an electric high speed rail and a diesel heavy rail in California, USA. It was found that the total GHGs are 4.3 times higher and the operation emissions are 2.3 times higher for the standard diesel technology. Haseli et al. (2008) and Marin et al. (2010a,b) explored various configurations of hydrogen fuel cell and internal combustion engine systems for GO Transit in Ontario, Canada. They find that greater reductions are expected for fuel cell systems than combustion engine systems, and by utilizing renewable energy sources such as solar and wind. The most favourable which combines wind energy and a copper-chloride plant has emissions of 1.21 kg/km which is just 9% of the current diesel technology. The copper-chlorine process is a thermochemical cycle which decomposes water into hydrogen and oxygen, and requires a high heat requirement. The heat requirement is achieved by burning hydrogen which is produced from renewable energy sources. The process is a closed loop cycle which means that the chemicals are recycled and GHGs are not emitted into the atmosphere. Train electrification from coal and natural gas were also evaluated. The use of coal-powered electricity was found to produce more emissions than the reference case while using electricity produced from natural gas was found to lead to 19% reduction or 2.54 kg/km.

1.5.3 Passenger Car Technologies

Relating to passenger cars, fuel cell, battery electric and hybrid technology are mainly studied in the literature. A study of the vehicle fleet in Portugal evaluates the GHG emissions of various combinations of fuels and propulsion systems, including fuel cell hybrid, fuel cell plug-in hybrid, battery electric, biofuels in internal combustion engines and biofuels in plug-in hybrid vehicles. An electric vehicle emits 120.7 g/km while a hydrogen fuel cell plug-in hybrid from centralized natural gas reforming generates 106.2 g/km (Baptista et al., 2010). These are reductions of 39-46% from the 198.2 g/km emitted from a conventional gasoline automobile (Baptista et al., 2010). In real-world simulated driving conditions, fuel consumption of hybrid vehicles are lower by 40-60% than standard gasoline vehicles in urban conditions (Fontaras et al., 2008) which implies great GHG savings. A similar lifecycle study exploring numerous alternative technologies in passenger cars supports the minimal emissions from purely electric vehicles (less than 10,000 kg over a lifetime; however, the high costs and low mileage are major drawbacks (Lave et al., 2000). Important decreases of 40-50% are also evaluated for hybrid and fuel cell technology; although, the benefits may not be justified by their higher costs (Lave et al., 2000).

1.5.4 Research Issues

There are numerous studies comparing the environmental impact of alternative technologies, some using a LCA while many concentrate on emissions from operation. Despite this growing literature, there are several shortcomings in the literature and this thesis aims to fill these gaps.

Many studies consider only a few technologies for one transportation mode (Frey et al., 2007; Karman, 2006; Meegahawatte et al., 2010; Rabl, 2002). In order to fill this gap in the literature, this thesis explored the several popular alternative technologies in bus transit, commuter trains and passenger cars for one study area. These include CNG, biodiesel, electric, hydrogen and hybrid technology. Research on electric technology from hydro-power is also scarce due to the ‘dirty’ electricity source mix in other cities and countries. Lifecycle emissions of hydroelectricity are estimated to be very high in these study areas since it includes the construction of hydroelectric dams (Vincent and Jerram, 2006).

Moreover, there are few studies done in the Canadian context (Haseli et al., 2008; Marin et al., 2010a,b), particularly in Quebec where hydroelectricity is an important resource and hydroelectric generating stations already exist. In this province, the environmental benefits of electric technology are not overshadowed by indirect emissions (i.e. electricity generation) which make Quebec more suitable to utilize electricity in transportation. The availability of clean energy sources should be an indication of great potential reductions in GHG emissions.

The methodology applied in most regional (macro) studies utilizes general emission factors and/or fuel consumption rates (Ally and Pryor, 2007; Haseli et al., 2008; Lave et al., 2000). Emissions are highly dependent on the vehicle and local driving conditions which can lead to over or under-estimation of environmental benefits. For this reason, link-level GHG estimation methods are better suited to assess the impact of transportation technologies. In this thesis, transit technologies were analyzed at the corridor-level. For the bus transit study, topography, vehicle age, meteorology and speed profile are incorporated in the analysis. For the commuter train study, actual fuel consumption and electricity consumption levels of the train network are used. With passenger cars, the average fuel consumption of the vehicle fleet at the neighbourhood-level and simulated trip distances were quantified.

Factors such as government incentives and travel needs are commonly considered in the market demand of hybrid vehicles; however, socio-demographics are rarely investigated (Diamond, 2009; Kurani et al., 1994, 1996; Lieven et al., 2011; Ozaki and Sevastyanova, 2011). The socio-demographic attributes that were tested in this study are age, gender, education, income, children and car ownership. Also, a spatial analysis of hybrid vehicle market has not been reported. The location of hybrid vehicle households can give insight on the nature of the market for hybrid vehicles.

1.6 OBJECTIVES

The general objective of the research in this thesis is to evaluate the impact on GHGs of the introduction of alternative green technologies in public transit and personal motor vehicles in the Quebec context. These include alternative technologies for commuter trains and bus transit as well as hybrid motor vehicles for personal travel.

The particular objectives are to:

- Evaluate transit technologies adopting a lifecycle approach, particularly emissions from fuel production and vehicle operation; and
- Investigate the demand of hybrid vehicles in Montreal and Quebec City, its determinants, and some potential market penetration scenarios.

1.7 METHODOLOGY

The impact on GHG emissions was evaluated for various alternative technologies in public transit and passenger cars. For bus transit, the following technologies were investigated: diesel, biodiesel, CNG, diesel-electric hybrid. The commuter rail technologies that were analyzed are diesel, electric and hydrogen fuel cell. For personal vehicles, hybrid passenger cars were compared to standard gasoline vehicles.

Lifecycle emissions include the following stages: fuel production, vehicle manufacturing, infrastructure construction, operation and disposal/recycling of materials. The procedure for estimating lifecycle emissions is data intensive; for this reason, it can be quite challenging to carry out a complete LCA. The analysis in this thesis is primarily limited to the emissions from fuel production in the upstream phase and the operation phase. For transit buses, the emissions from vehicle manufacturing, which is part of the upstream phase, were also examined. Emissions from the operation phase are generated by the direct fuel consumption of the vehicle. The downstream phase of a lifecycle, disposal and/or recycling, is excluded from the analysis for the three passenger transportation modes because these emissions are assumed to be similar between technologies (Beer et al., 2002).

GHG emissions were measured as the equivalent mass of carbon dioxide (CO_2-equivalent). The total emissions include three important GHGs: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). To obtain the mass in CO_2-equivalent, the mass of each GHG is multiplied by its corresponding global warming potential (GWP). CO_2 is the most abundant of the three but it does not necessarily have the strongest effect on global warming. GWP measures the relative amount of heat trapped by the GHG in the atmosphere over a time period which is dependent on the level of infrared radiation absorption and atmospheric lifetime. The GWP of CO_2 is set to 1, such that the GWP of other GHGs is a factor of CO_2. According to the Intergovernmental Panel on Climate Change (IPCC, 2012), the 100-year GWP of CH_4 and N_20 are 21 and 310, respectively. These values were applied consistently in this research including GHGenius, MOVES and all emission factors.

The estimation of GHGs was carried out either using the mentioned software tools or using **Equation 1-1**:

$$GHG = EF \times FCR \times VKT \qquad [\mathbf{1\text{-}1}]$$

Here, EF is the emission factor, FCR is the fuel consumption rate and VKT is the vehicle-kilometres travelled of a link – where link is the roadway section between two main intersections, or an entire rail line for the commuter train. The calculation seems quite simple; however, the difficulty lies in acquiring data at corridor or city-level on each of the terms on the right-hand side of the equation. Input data relating to the specific corridor is also required in the software tools. Different sources of data and techniques are used for each case study. The methodology for the evaluation of GHGs at the link-level in each chapter is elaborated in this section.

The first term, EF, is the amount of GHG emitted per unit of fuel consumed; they differ by technology, by transportation mode and by lifecycle phase. Besides hydrogen technology, the emission factors were taken from the Urban Transportation Emissions Calculator (UTEC) tool developed by Transport Canada. The emission factors for the production of hydrogen gas were obtained by a study by Dincer (2007).

1.7.1 Bus Technology Case Study

A lifecycle analysis was conducted on a bus serving a busy urban corridor in Montreal. The upstream emissions that were considered are fuel production and vehicle manufacturing which was estimated using GHGenius v3.19a. This LCA tool contains an extensive national and regional database of Canada. The operation emissions were estimated using two methods: 1) MOVES 2010 using second-by-second speed profile; and 2) fuel consumption vs. speed curves using average link speeds. MOVES require local geographic and driving conditions of the specific corridor that includes fuel formulation, meteorology, topography and speed. The trend curves were used as a secondary method to estimate operation emissions due to the limitation of MOVES which does not analyze hybrid technology. Using these curves and Equation 1, the GHGs of each link are evaluated.

1.7.2 Commuter Rail Technology Case Study

The emissions from fuel production and operation were taken into account to calculate emissions of the Montreal commuter rail network. For electric and hydrogen technology, the operation phase is assumed to have zero emissions. The GHG analysis in this chapter does not involve any software; hence, Equation 1 was used. Actual recorded fuel/electricity consumption and vehicle-kilometres travelled of each rail corridor were provided by AMT. For the electrification scenario, the electricity consumption rate of the one electrified line was applied throughout the network. For the hydrogen scenario, the energy consumption rate of hydrogen was determined by relating the energy consumption of diesel fuel, the system efficiencies and the power output. The vehicle-kilometres travelled were assumed to remain constant for each technology scenario.

1.7.3 Car Technology Case Study

The analysis for passenger cars is limited to the operation phase. In this study, emissions were estimated at the city-level by aggregating the emissions of pure car trips done in Montreal and Quebec City. The fuel consumption rate is an average of the vehicle fleet at the zonal-level. Conversely, the trip distances were found by using a shortest path interface in GIS which considers congestion. Congested link-level travel times by time of day were provided by the Ministère des Transports du Québec (MTQ). The impact on GHG of different market penetration rates of hybrid vehicles was also evaluated. In these scenarios, the only term that changes in the equation is the fuel consumption rate which would reflect the proportion of hybrid vehicles in the new vehicle fleet.

1.8 ORGANIZATION OF THE DOCUMENT

This thesis is formed of five chapters. Chapter 2 provides the case study on transit buses serving the Côte-des-Neiges corridor. The analysis on the commuter rail network in Montreal is presented in Chapter 3. The impact of hybrid vehicle adoption in the metropolitan areas of Montreal and Quebec City is investigated in Chapter 4. The final chapter summarizes the results and includes final remarks.

2 Assessing the Impact of Bus Technologies on GHGs in a Major Montreal Corridor

2.1 INTRODUCTION

In the current context of climate change, public transit is seen as one of the most viable alternatives to the private car, in particular in urban areas or corridors with high population densities (Haseli et al. 2008). Despite the important benefits of public transit, it has been recognized that traditional transit buses of petroleum-based diesel are still associated with high fuel consumption rates and high production of GHG emissions per litre or kilometre with respect to new technologies. Obviously, this issue becomes very important when fleet size increases. This is the case of the Montreal local bus transit system (operated by the Société de transport de Montréal – STM) that operates a fleet of 1,696 buses with the majority running on diesel (STM, 2011a). Fleet operations generate about 147,000 tonnes of emissions in 2009 which represents about 0.2% of Quebec's GHG inventory (STM, 2011b). Furthermore, transit buses are responsible for 78.7% of total GHGs in public transit and 2.1% of the passenger transportation emissions generated in Quebec (NRCan, 2012a).

As part of the sustainable strategies, many local transit agencies in North America (including Montreal) are looking for strategies to reduce fossil fuel consumption and GHGs. Popular actions include the introduction of exclusive bus lanes; reduction of travel times by implementing smart cards, installing priority traffic signals and bus rapid transit (BRT) systems; fleet modernization (newer articulated buses) and the increase of ridership through subsidies and service frequencies[2]. For a literature review on strategies to reduce energy consumption and GHGs on bus transit systems, one can refer to Gallivan et al. (2011), Hensher and Golob (2008), Ou et al. (2010) and Yang et al. (2009) Another important transit strategy is the fleet replacement by greener emerging technologies such as compressed natural gas (CNG), biodiesel and diesel-electric hybrid transit buses. With respect to this last strategy, many studies have been documented in the international literature. For instance, some studies such as Beer et al. (2002), Ryan and Caulfield (2010) and Yan and Crookes (2009), evaluated the use of biodiesel as an alternative to regular diesel. Others studies, such as Ally and Pryor (2007), Clark et al. (2006), Karman (2006), and Rabl (2002) evaluated CNG and hybrid technologies, and highlighted their benefits in particular the GHG reductions during operations.

[2] The successful increase in transit ridership suggests potential emissions savings that would have been generated from car commuting. The STM's 2020 Strategic Plan envisions a 5% modal transfer from car to public transit and a target of 540 million trips by transit (STM, 2011b). This goal is expected to have GHG savings of 780,000 tonnes in 2020 which is equivalent to the emissions of 156,000 cars (STM, 2011b).

Looking for fuel economies and GHG reduction, the Montreal local transit agency (STM) has also conducted two pilot projects to investigate the benefits of biodiesel and diesel-electric hybrid technology on buses. They experimented with three types of biofuel: animal fat, used cooking oil and vegetable oil, in blends of 5% and 20%. It was found that CO_2 emissions from direct consumption of biodiesel are equivalent to using conventional diesel (CRFA et al., 2003); similar fuel consumption rates should lead to equivalent emissions if the tested fuel is composed of 80% of the reference fuel. For the hybrid bus study, the technology was tested in Environment Canada laboratories in ideal conditions, on outdoor tracks in controlled settings, and on the field in real operation. The findings indicate that hybrid buses improve fuel economy by 30% and substantially reduce emissions in urban environments where stop-and-go driving behaviour is exhibited (STM, 2009). These studies solely investigate emissions during operation. Moreover, these local studies have not explored other technological alternatives such as CNG. Note that fuel consumption and then GHGs can vary according to different factors such as weather, topography (slope), operating speeds, unit age, passenger load, etc. It is not clear how these factors were taken into account.

Despite the importance of these local and international studies, very few studies have looked at the impact of various bus transit technologies for a particular corridor incorporating a lifecycle analysis (LCA) with local characteristics. LCA would take into account emissions from fuel production and vehicle manufacturing which could affect the selection of the most sustainable technology. The availability of LCA tools for transit buses makes it possible to carry out such analyses. Transit service operates most days and so it is expected that the majority of emissions are produced during operation. The issue is that LCA tools use general emission factors; however, emissions are highly dependent on local conditions such as speed and grade. For the estimation of operation emissions, it is useful to investigate at the micro-scale level (i.e. link-level) to obtain the most accurate results for the largest portion of lifecycle emissions.

Accordingly, the main objectives of this chapter are to:

1) Evaluate the impact of alternative bus transit technologies on GHGs using a lifecycle analysis; and

2) Compare the operation emissions estimated using second-by-second speeds and MOVES with emissions estimated using link-level average speeds.

Using an important bus transit corridor in Montreal as an application environment, the objectives are achieved by estimating upstream emissions (fuel and vehicle cycles) and operation emissions for one diesel bus serving Route 165 during peak periods. Then, as a second step, lifecycle emissions to three alternative technologies are compared: CNG, biodiesel and diesel-electric hybrid transit buses.

This introduction will be followed by a literature review on the lifecycle analysis of alternative fuels for bus transit. Section 3 will describe the methodology and the data needs. The fourth section is the presentation and the discussion of the results. The chapter ends with a summary of the study and its findings.

2.2 LITERATURE REVIEW

Lifecycle analysis considers emissions directly from fuel consumption, as well as the pre- and post-consumption phases. The pre-consumption or upstream phase includes fuel production and bus manufacturing while post-consumption or downstream stage is the disposal/recycling of materials.

In recent years, many studies have evaluated the environmental impact of bus emissions from fuel consumption. Despite the fact that LCA would be a more useful tool for decision-making towards sustainability (Yan and Crookes, 2009), it has been rarely applied in previous studies due to the lack of available data for processes occurring during the non-operational phases. Moreover, it is also argued that emissions during operation are the highest (Chester et al., 2010). In recent years, research concerned with estimating emissions throughout a full lifecycle is much more common. This is because stages before the operation of a vehicle can contribute significantly to the total emissions. Lifecycle energy and GHG emissions are around 70% larger than vehicle operation while pollutant emissions are up to four times as large (Chester et al., 2010). The evaluation of operational emissions for vehicles ignores the lifecycle components of the vehicles, infrastructure, and fuels which are necessary requirements for any transit mode (Chester et al., 2010). Several studies focus on GHG emissions (Ally and Pryor, 2007; Beer et al., 2002; Cui et al., 2010; Karman, 2006; Yan and Crookes, 2009), while others analyzed both GHG and pollutant emissions (Chester et al., 2010; Frey et al., 2007; Rabl, 2002).

The lifecycle studies on alternative bus technologies are described in this section. These studies investigate the following alternative fuels: CNG, liquefied natural gas (LNG), bioethanol, biodiesel, electric, diesel-electric hybrid, hydrogen and liquefied petroleum gas (LPG) (Ally and Pryor, 2007; Beer et al., 2002; Clark et al., 2006; Frey et al., 2007; Hao et al., 2010; Jayaratne et al., 2010; Karman, 2006; Rabl, 2002; Ryan and Caulfield, 2010; Yan and Crookes, 2009). For bus systems, alternative fuels are compared to standard diesel technology which, in most cases, has been shown to have the highest lifecycle GHG emissions compared to alternative fuels (Yan and Crookes, 2009).

Numerous LCA studies for bus technologies compare the emissions of diesel and natural gas (Ally and Pryor, 2007; Beer et al, 2002; Karman, 2006; Rabl, 2002; Yan and Crookes, 2009). The studies generally demonstrate that natural gas buses have higher lifecycle emissions or provide modest reductions. The lifecycle GHGs of Australian CNG transit buses are about 25% higher than standard diesel buses due to the lower fuel efficiency and emissions of methane (Ally and Pryor, 2007). Another study conducted in Australia indicates an 8.2% decrease to 1.54 kg/km for CNG while modest reductions are observed for LNG which generates 1.67 kg/km (Beer et al., 2002). The results reported by Karman (2006) are 2.80 kg/mile for diesel and 2.73 kg/mile for CNG buses in China. The small GHG benefits of CNG are also confirmed by Yan and Crookes (2009) who found that CNG transit buses emit 80 g/MJ. A study in Paris, France, reveals an increase in emissions from 1.69 kg/km for diesel buses to 2.03 kg/km for natural gas buses (Rabl, 2002). During acceleration, CNG is more favourable than diesel buses since the emission rate is lower by 15-20% (Jayaratne et al., 2010). Further reductions are possible by using bio-CNG; a study in Ireland showed a decrease of 63% from regular CNG buses (Ryan and Caulfield, 2010).

There is a huge interest in biofuels such as bioethanol and biodiesel. A typical lifecycle of a biofuel includes biomass cultivation, biofuel conversion and transportation to refuelling station (Yan and Crookes, 2009). The lifecycle GHG emissions of bioethanol are largely dependent on the feedstock. Bioethanol from wheat and corn show 6-21% higher GHG emissions than conventional diesel which emits 89 g/MJ, while ethanol derived from cassava and sugarcane demonstrate decreases of 16-44% (Yan and Crookes, 2009). Biodiesel produced from rapeseed and soybean offer substantially lower lifecycle GHGs: 25 g/MJ and 30 g/MJ, respectively (Yan and Crookes, 2009). Although a significant amount of GHGs are emitted in the upstream phase, the combustion of non-fossil carbon more than compensates for it (Beer et al., 2002). One study illustrates that biofuels have the lowest lifecycle GHG emissions: 0.82 kg/km for bioethanol from wood and 1.39 kg/km for biodiesel blend of 20% canola oil compared to 1.67 kg/km for diesel fuel (Beer et al., 2002).

The primary advantage of fully-electric buses over buses equipped with internal combustion engines is the absence of exhaust emissions. These vehicles are required to be plugged into the electric grid in order to recharge the battery which can take several hours. Consequently, a transitional technology, diesel-electric hybrid, has been developed until purely electric buses can be operated successfully. LCA studies on electric or hybrid buses are rare; thus, the impact on GHG is unfamiliar. The results of one study suggest that hybrid electric buses are extremely fuel efficient in congested and non-congested traffic in Mexico City compared to diesel and CNG buses (Clark et al, 2006). A report by the STM on hybrid buses reveals a 30% reduction in fuel consumption (STM, 2009). Since fuel consumption is directly related to GHG emissions, a proportional reduction is expected.

Hydrogen technology also emits zero emissions during operation which means that the lifecycle emissions are dominated by the fuel production phase. Hydrogen bus systems in Australia are slightly more GHG-polluting than diesel buses on a lifecycle basis due to the fuel production processes including extraction, transportation and compression (Ally and Pryor, 2007). The Portuguese study by Frey et al. (2007) supports this finding; hydrogen from SMR generates 12.5 g of CO_2/g of H_2-equivalent which is an 11.6% increase from the emissions of diesel. These emissions can be potentially reduced by 50% if improvements in fuel efficiency are realized (Ally and Pryor, 2007).

LPG is an example of an alternative fuel derived from fossil fuels; hence, there are still substantial amounts of GHGs associated with the combustion of this fuel. A LCA study in China showed that the emissions are slightly lower, about 77 g/MJ for LPG compared to 89 g/MJ for diesel (Yan and Crookes, 2009). The contradictory results of a second study in China indicate that the GHG emissions of gas-to-liquids fuels are higher than diesel by 12.6% (Hao et al., 2010). Another LCA study, in Australia, produced similar results to Yan and Crookes (2009); the GHG emissions of LPG are 70 g/MJ which is 12.5% lower than diesel (Beer et al., 2002).

Literature on the use of second-by-second vs. link-level average speeds for evaluating GHGs of transit buses is completely missing. The few studies that compare these two methods are applicable to automobiles and trucks (Bai et al., 2009; Frey et al., 2006). One study compares MOVES which uses second-by-second speeds with EMFAC which uses average travelling speeds (Bai et al., 2009). Both emissions models contain a database on vehicle activities and emission rates. Another study compares average emissions from MOBILE6, the predecessor of MOVES, and real-world estimates from a portable emissions monitoring system (PEMS) (Frey et al., 2006). Evidently, the results show that the use of second-by-second speeds will provide more accurate estimations since the acceleration events are not ignored (Bai et al., 2009; Frey et al., 2006). The differences in emissions between these methods are more significant when the number and duration of acceleration events change (Frey et al., 2006).

Despite the important body of literature, most lifecycle studies on bus technologies analyze emissions at the regional scale which assume consistent data specific to road, vehicle and driving characteristics (Ally and Pryor, 2007; Beer et al., 2002; Frey et al., 2007; Hao et al., 2010; Karman, 2006; Rabl, 2002; Yan and Crookes, 2009). Additionally, few studies in the Canadian context have been reported. This is important because the fuel formulation, weather and speed profile, among other factors, have an influential effect on emissions and these characteristics are different in other countries and corridors. Another shortcoming in the literature is the comparison of GHG estimation using second-by second speeds from real-world recordings and using average link speeds. Furthermore, the investigation of hybrid electric buses using a lifecycle approach is uncommon in the literature.

This research seeks to address the current weaknesses identified above in the literature on LCA for alternative methods for power buses. As such, it aims to compare lifecycle GHG emissions of four of the most popular technologies for bus transit: conventional diesel, biodiesel, CNG and hybrid, for a bus serving the Côte-des-Neiges corridor in Montreal. This corridor was chosen because of its importance. This is one of the top five busiest bus routes travels along this corridor. Moreover, it is situated in an urban setting, near Mount-Royal which enables us to examine the effect of topography.

2.3 METHODLOGY

The methodology proposed here consists of the following steps:

- Selection of the study corridor
- Definition of technological options
- Data collection and preparation
- Estimation of the upstream and operation GHGs
- Comparative analysis of operation emissions
- Evaluation of lifecycle emissions

2.3.1 Study Corridor

The bus corridor used as the case study is the Côte-des-Neiges (CDN) road which is served by multiple bus routes. It is located in the Côte-des-Neiges-Notre-Dame-de-Grâce borough in the centre of Montreal Island (**Figure 2-4**). It is bordered in the north by Jean-Talon Street and in the south by Sherbrooke Street. A section of the corridor runs along the edge of Mount Royal, Montreal's most famous natural landmark. This corridor is characterized by numerous restaurants, retail shops and two hospitals (**Figure 2-5**). It is located in an urban setting with a varying road grade and it is home to one of the busiest bus routes. These characteristics make it ideal to examine the effect of frequent stopping, congestion and topography.

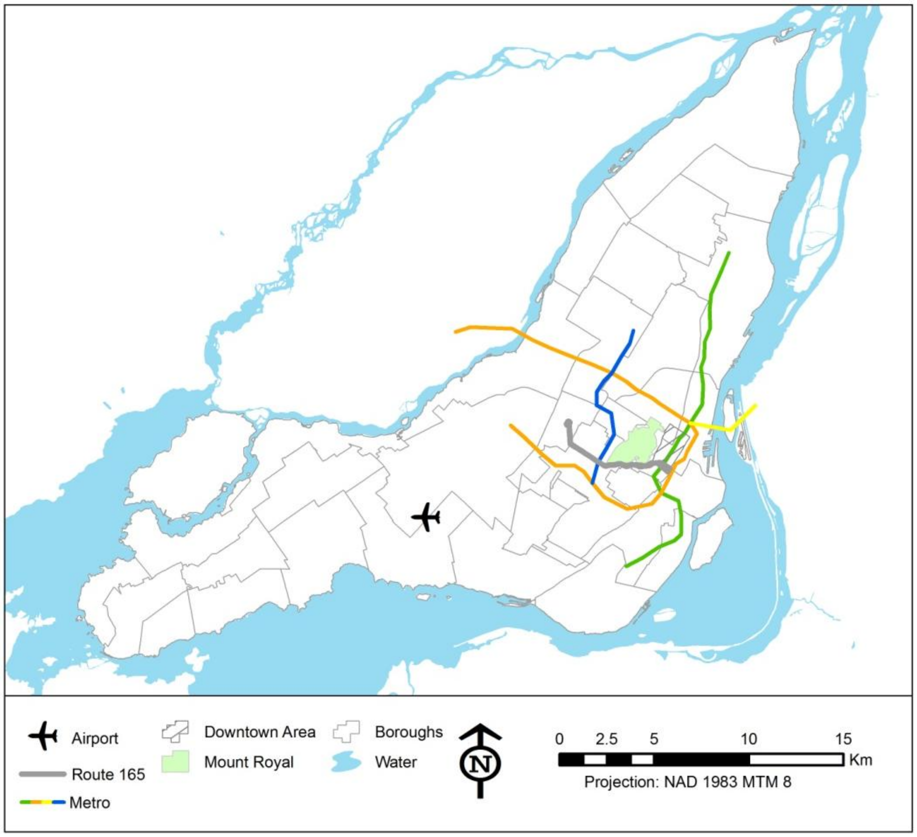

Figure 2-4 CDN study corridor

Figure 2-5 Route 165 bus travelling on CDN corridor

The case study focuses on Route 165/435 bus serving the CDN corridor in Montreal, Quebec. Route 165 has the fourth highest average weekday ridership with 29,879 passengers (STM, 2011a). In the northbound direction, Route 165 begins at the Guy-Concordia metro station and ends at the Mont-Royal commuter train station. In the southbound direction, it follows almost the same path except that it terminates at a different exit of the Guy-Concordia station. The path between these two exit stations is called deadheading and is omitted from the analysis. This route also passes by the Côte-des-Neiges metro station situated on the Blue line. Route 435 is an Express bus that operates during peak periods only. It serves two important corridors, one of them being the CDN corridor. It runs concurrently with Route 165 in order to provide additional service for commuters. Henceforth, the case study will be referred to as "Route 165".

2.3.2 Technological Options

The analysis investigates the most common alternative fuels which are then compared to the conventional diesel fuel used in transit buses. The alternative technologies under analysis are CNG, biodiesel and diesel-electric hybrid. Natural gas is an abundant resource which explains why CNG buses are already in operation in many countries worldwide. Although CNG is primarily composed of methane, it has been widely accepted as an alternative fuel since it produces lower GHG emissions than diesel. Biodiesel is a mix of diesel and a renewable resource such as vegetable oil and animal fat. Due to this composition, biodiesel is said to be a cleaner fuel on a lifecycle basis. This study examines biodiesel with a typical blend of 20% canola oil ("Canadian oil") and 80% petroleum diesel. Hybrid and CNG buses are in competition as they both provide significant GHG savings; however, hybrid buses can be twice as expensive (NREL, 2000). Hybrid bus technologies incorporate an electric motor and a diesel engine which work together depending on the speed and acceleration. Diesel fuel is traditionally used in transit buses; however, it is the most polluting. The reference technology is a cleaner diesel with 15 ppm of sulphur. Although there are other fuel options, some are in its experimental stages or not yet commercially available. This study focuses on green technologies that are more widely used in transit buses so that estimated GHG benefits can be attainable in the short-term.

2.3.3 Data Collection and Preparation

The study corridor was divided into links that are defined by the Route 165 bus stops situated at intersections. There are 30 links each in the northbound and southbound directions. Data needs on each link (i.e. length, speed and grade) as well as weather conditions, fuel composition and bus age distribution are defined as follows:

Length: Using GIS (ArcMap) the lengths of each link were estimated. The total length is 6,599 metres in the northbound direction and 6,734 metres in the southbound direction which gives a route length of 13.33 km. The average link length is 222 metres, with a minimum length of 71 metres and maximum length of 462 metres.

Speed: The second-by-second speed of the bus traveling along the corridor was recorded using a portable global positioning system (GPS) in October and November 2011 for one cycle (northbound and southbound) during the morning (6-9 AM) and afternoon (3:30-6:30 PM) peak periods. These months also correspond to the weather data collected. The GPS also collects altitude, latitude and longitude coordinates. These coordinates were plotted in GIS and a spatial join was carried out to associate each second to the travelled link. Then the average speed of each link was calculated. The altitude data was not considered since this was not very precise. **Figure 2-6** illustrates the speed profile in the northbound direction during the morning peak period.

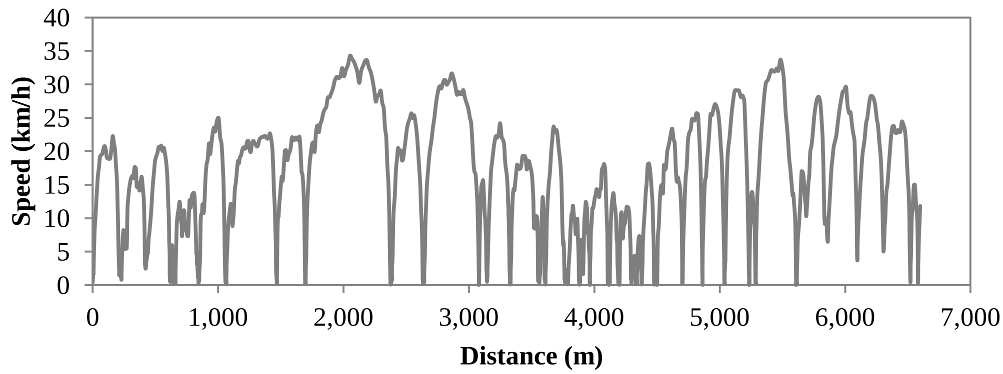

Figure 2-6 Speed profile: AM period and northbound direction

Grade: Since the altitude data recorded by the GPS unit was inaccurate, an online tool called GPS Visualizer was used. It uses a Digital Elevation Model (DEM) which provides "smoother" data than GPS and generally contains fewer erroneous measurements (Schneider, 2012). A file containing the latitude and longitude data is uploaded and the tool returns the elevation of each point. **Figure 2-7** shows the elevation profile along the CDN corridor. The link grade is the relative difference between the first and last elevation of a link as shown in **Equation 2-1**. In the northbound direction, the link grade ranges from -7.9% to +13.5%.

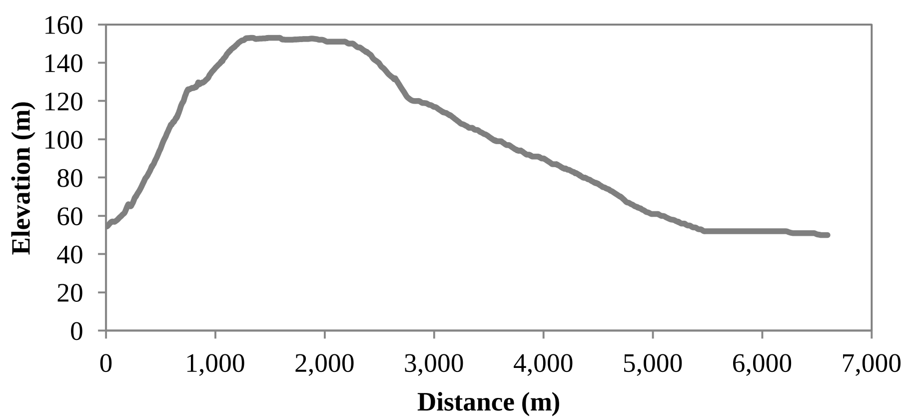

Figure 2-7 Elevation profile along corridor in northbound direction

$$Grade = \frac{Elevation_{last} - Elevation_{first}}{Elevation_{first}} \times 100\% \qquad [\textbf{2-1}]$$

Weather: MOVES require meteorology data including barometric pressure in inches of mercury (inHg), relative humidity as a percentage (%) and temperature in degree Fahrenheit (℉). This was acquired through Environment Canada using the National Climate Data and Information Archive (Environment Canada, 2012). The measurements at the McTavish weather station were selected as it is the closest to the study corridor. The hourly averages for the morning peak period in November and for the afternoon peak period in October were extracted – the same time period as when the GPS data was collected (**Table 2-2**). A unit conversion was necessary to change the original data which uses the metric system into the appropriate units.

Table 2-2 Hourly Average Meteorology Data

Month	Hour	Barometric Pressure (in Hg)	Relative Humidity (%)	Temperature (℉)
November	6:00 AM	29.75	75.53	40.12
	7:00 AM	29.76	75.23	40.11
	8:00 AM	29.77	75.13	40.76
October	3:00 PM	29.69	59.97	55.34
	4:00 PM	29.69	61.87	54.81
	5:00 PM	29.70	65.13	53.68

Age distribution: Data concerning the age and type of Route 165 buses were supplied by the STM. Route 165 buses are composed of 80% standard low-floor and 20% articulated buses, which were introduced in 2009. The oldest bus models were manufactured in 1991. Although the age of buses ranges from 1 to 21 years old, the articulated buses are in service 80% of the time. For this reason, it was decided to investigate the emissions of a bus for model year 2010 since the majority of articulated buses were manufactured in that year. A 2010 model year means that the bus is one year old because the emissions estimation is analyzed in 2011. Note that MOVES does not differentiate between a standard and an articulated bus; therefore, emissions will be underestimated since articulated buses are longer and carry more passengers.

Fuel composition: Conventional diesel fuel and three alternative technologies (biodiesel, CNG and diesel-electric hybrid) were analyzed. The current bus fleet runs on ultra low sulphur diesel with sulphur levels of 15 ppm (Rahumathulla, 2010). A biodiesel blend of 20% canola oil (B20) was chosen. Its properties take values of 20% of biofuel and 80% of conventional diesel. For example, the sulphur level of B20 would be 12 ppm, when the biofuel is sulphur-free. The fuel density is 0.85 and 0.88 g/cm^3 for diesel and for 100% biodiesel, respectively (US EPA, 2002). The heating value (energy content) is 129,500 Btu/gal for diesel and 118,296 Btu/gal for B20 (US EPA, 2002). The units are converted to grams per gallon for density and MJ/kg for energy content. These properties were re-evaluated for B20 using the appropriate proportions. The MOVES default values of diesel, B20 and CNG, were used for these properties: petroleum fraction, fossil fraction, carbon content, oxidation fraction and humidity correction factor. In addition, the default value of the energy content and fuel density for CNG were used. All other fuel formulation properties required by MOVES were set to zero including Reid vapour pressure (RVP), ethanol (ETOH) volume, methyl tertiary butyl ether (MTBE) volume, ethyl tertiary butyl ether (ETBE) volume, tertiary amyl methyl ether (TAME) volume, aromatic content, olefin content, benzene content, e200, e300, cetane index, PAH content. **Table 2-3** lists the fuel properties for the different technologies excluding hybrid since MOVES does not simulate this technology.

Table 2-3 Fuel Formulation of Diesel, B20 and CNG

Properties	Diesel	B20	CNG
Petroleum fraction	1	0.81	0
Fossil fraction	1	0.81	1
Carbon content (%)	0.02	0.0199	0.0161
Oxidation fraction	1	1	1
Humidity correction coefficient	0.0026	0.0026	0
Energy content (MJ/kg)	42.474	41.446	45
Fuel density (g/gal)	3,220	3,242	0

2.3.4 Estimation of Upstream and Operation GHG Emissions

The GHG emissions are estimated for the upstream and operation stages for one bus. The upstream stage includes emissions from fuel production and vehicle manufacturing which are estimated using GHGenius. Emissions from the operation phase are evaluated using second-by-second speed and average link speeds. In the former case, the analysis is done with the aid of MOVES. In the latter case, emissions are calculated using fuel consumption vs. speed technology curves. The four technologies that were investigated are conventional diesel, B20, CNG and hybrid buses.

a) Estimation of upstream emissions using GHGenius

This lifecycle tool was developed for Natural Resources Canada (NRCan) by Levelton Engineering Ltd. It is based on the Lifecycle Emissions Model (LEM) by Delucchi ((S&T)^2 Consultants Inc, 2005). Most lifecycle models use US data which may not be transferable to other countries. GHGenius is useful for the evaluation of lifecycle emissions of various conventional and alternative transportation fuels used by light and heavy-duty vehicles. It is capable of regional analysis in Canada which would produce provincial-specific results. The model also contains data for the US, Mexico and India. In comparison, the GREET Model by Argonne National Laboratory only uses data applicable to the US (Wang, 1999). The key differences between GHGenius and GREET are the system boundaries, the fuel pathways and the default values in the model ((S&T)^2 Consultants Inc, 2005).

GHGenius runs as a macro in Excel which contains extensive detailed data regarding vehicle fuel economy, electricity production, fuel composition, carbon sequestration, crude oil slates, fertilizer use, etc. The default values for the province of Quebec were applied with minor changes in the fuel specification such as the volume of canola oil in biodiesel (20%) and sulphur level in diesel (15 ppm). The analysis was set to the year 2011.

The model assumes a fuel consumption rate of 28.5 L/100 km for a typical Canadian diesel-fuelled bus in 2011. Lifetime vehicle kilometres travelled (VKT) is based on 1998 NRCan values for a gasoline heavy-duty vehicle with a 1% annual growth rate. GHGenius assumes that the lifetime VKT of diesel vehicles is about 20% longer than gasoline vehicles, while CNG vehicles have the same lifetime distances travelled as gasoline vehicles. Therefore, the lifetime VKT is 1.27 million km for diesel and biodiesel buses, and 1.06 million km for CNG buses. The lower lifetime VKT is justified by the higher maintenance needs of CNG buses.

The output results are expressed in grams of CO_2-equivalent per kilometre by lifecycle stage for various fuels and technologies. Only the four technologies of interest were investigated. Although GHGenius can estimate emissions during operation, these macro-analysis results were ignored in favour of corridor-specific emissions generated by MOVES. One step in the operation phase that is retained, 'C in end-use fuel from CO_2 in air', will be added to the overall emissions. This credit only applies to B20 caused by the absorption of CO_2 by the canola plant.

b) Estimation of second-by-second operating emissions using MOVES

The microsimulation tool was developed by the US Environmental Protection Agency (EPA). It is a software tool that estimates operation emissions of various transportation fuels and technologies at the micro-scale level (i.e. link level). Operation emissions include running exhaust, idling and starts. For this reason, it requires detailed input data relating to road geometry, vehicle driving cycle, fuel formulation, vehicle age and meteorology.

MOVES can run using second-by-second speed or average link speeds. The application of average speeds provides the least accurate results particularly for a bus which stops frequently; therefore, second-by-second speeds were used (US EPA, 2010). This method captures acceleration, deceleration and idling events. Emissions from starts are ignored as they are considered negligible compared to running exhaust and idling at stops. MOVES transform the input link drive schedule into an operating mode distribution which is the fraction of time spent in each operation mode (US EPA, 2010). For this part, hybrid buses could not be investigated which is one of the limitations of the software.

The simulations were run for a 'transit bus' on an 'urban unrestricted access' road type. MOVES was set to model emissions during weekdays in the year 2011; the month of October for afternoon peak hours and November for morning peak hours. The 'on-road vehicle equipment' was identified as 'compressed natural gas' for CNG, and 'diesel fuel' for both conventional diesel and B20. This assumes that biodiesel fuel would be used in a standard diesel bus. The following pollutants and processes were selected for running exhaust emissions: total gaseous hydrocarbons, total energy consumption, methane, nitrous oxide, atmospheric CO_2 and CO_2-equivalent. Even though CO_2-equivalent is the only pollutant of interest, MOVES requires the other pollutants and processes to be selected. Another assumption by MOVES is the mix of transit buses: 93% diesel, 6% CNG and 1% gasoline for model year 2011. This can be adjusted to reflect a fleet that is entirely of one fuel type in the 'alternative vehicle fuels & technologies' strategy input file. The simulation was repeated for each hour of the peak periods (i.e. hour beginning at 6 AM, 7AM, 8 AM, 3 PM, 4 PM, 5 PM) and for the three fuels; a total of 18 runs.

The output results are expressed as a rate (g/bus-km) or as an inventory (g) which can be viewed in MySQL query browser. The average emissions of the morning and afternoon peak hours are calculated, and then the GHG inventory was summed up in each direction for each peak period.

c) Estimation of link-level operating emissions using 'fuel consumption vs. speed' curves
Since MOVES does not evaluate emissions for hybrid buses (US EPA, 2010), fuel consumption curves from a recent local study were utilized to estimate emissions for hybrid buses, and the other technologies for comparison. These curves demonstrate the relationship between fuel consumption rates and average speed and were calibrated using a field study with instrumented buses (STM, 2009). Fuel consumption rates vary by speed; vehicles are less fuel efficient at low speeds. The fuel consumption curves for different technologies are shown in **Figure 2-8**. It can be seen that for speeds up to 50 km/h, the curves follow an exponential decay.

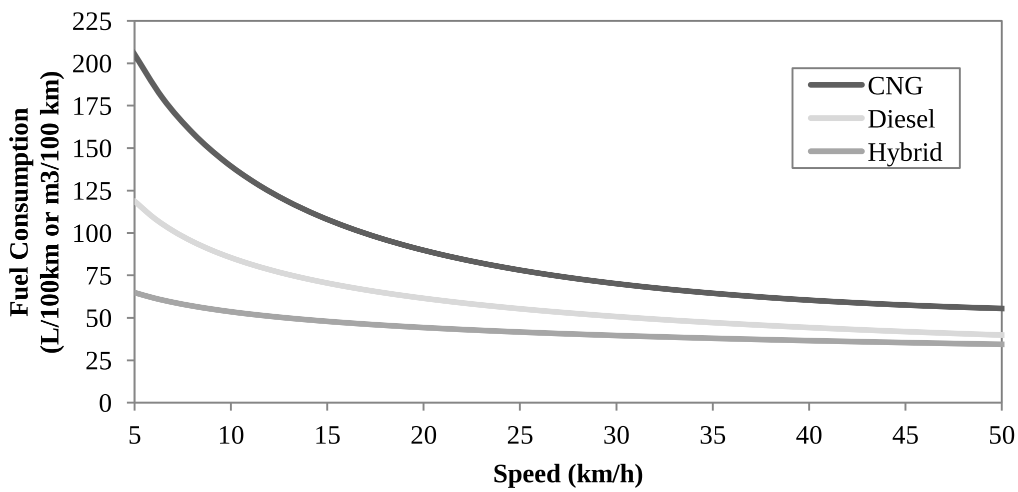

Figure 2-8 Fuel consumption curves of hybrid, diesel and CNG buses
(These are based on average speed including idling, Clark et al., 2009; STM, 2009)

These curves were determined by fitting a trend line to collected fuel consumption recordings. The diesel and hybrid curves were created by STM (2009) while the CNG curve was generated by Transit Cooperative Research Program (TCRP) (Clark et al., 2009).

The STM study was conducted under experiment real-time conditions with passengers and buses were instrumented for a year. Both the standard diesel bus and diesel-electric bus were of the same model make and year: Nova low-floor series (LFS), 2008, for comparable results. The STM buses used biodiesel with a 5% blend of animal fat and vegetable oil, and 95% petroleum diesel. The low blend of biofuel should not have a substantial effect on the results. The buses were put into service on routes in the downtown area, less dense areas and that passes by Mount Royal to test the effect of speed, frequent stops and topography. It is very likely that one of these routes is the same one chosen for this study. An advance data acquisition system supplied by ISAAC Instruments Inc. collected over 30 parameters relating to bus operation conditions such as fuel consumption, average speed, average acceleration, number of stops and idling time. The average speed is determined from one stop-and-go cycle which includes the acceleration, cruising, deceleration and idling time between two starts. The most important finding is that the acceleration rate has a strong effect on fuel consumption but at a much lower influence on hybrid buses. In fact, the highest reduction in fuel consumption is observed in hybrid buses at rapid acceleration rates. The environmental benefits of hybrid vehicles are optimized in urban settings which are characterized by numerous stops.

Fuel economy is the inverse of fuel consumption. It is a measure of the distance travelled for a volume of fuel. In order to obtain the fuel consumption curve for CNG, fuel economy was transformed to fuel consumption and converted to metric units. In the TCRP report, the fuel economy model was produced using data from a chassis dynamometer collected by the Department of Energy (DOE) and National Renewable Energy Laboratory (NREL) program, and then adjusted to fit limited field data. Due to the low number of test sites, fuel economy could not be recorded for a wide range of operating speeds. The in-field testing was conducted on routes belonging to the Washington Metropolitan Area Transit Authority (WMATA) and New York City Transit (NYCT) using 2005/2006 and 2002 model CNG buses, respectively. The CNG buses tested were equipped with the lean-burn engine instead of the new stoichiometric technology; no adjustments were made to reflect the minor improvement in fuel economy for the emerging technology. The average speed was considered to be similar to the route speed which excludes extended idling and deadheading. This is the same specification as the STM study. The effect of slopes was omitted from the model. Potential improvements in CNG technology make it difficult to predict its fuel economy.

Equations 2-2 to 2-4, as documented in the STM (2009) and TCRP (Clark et al., 2009) reports, were used to determine the fuel consumption/economy for every link based on the average speed, where FCR is the fuel consumption rate in litres/100 km, S is the average speed (km/h, or miles/h for CNG) and FE is the fuel economy in miles/diesel gallon equivalent. It was assumed that the fuel consumption rate of biodiesel behaves identical to conventional diesel (CRFA et al., 2003).

$$FCR_{(bio)diesel} = 255.331 \times S^{-0.4753} \qquad [\mathbf{2\text{-}2}]$$

$$FCR_{hybrid} = 101.031 \times S^{-0.2761} \qquad [\mathbf{2\text{-}3}]$$

$$FE_{CNG} = -0.0025 \times S^2 + 0.1944 \times S + 0.5524 \qquad [\mathbf{2\text{-}4}]$$

The GHG estimation of each link from average speeds uses a simple formula (**Equation 2-5**):

$$GHG_{link} = EF \times FCR \times VKT \qquad [\mathbf{2\text{-}5}]$$

Where,

EF – emission factor in grams/litre or grams/cubic metres

VKT – link length per 100 km

FCR is previously defined above.

Emission factors for transit buses in **Table 2-4** are supplied by Transport Canada (2012a). The GHGs of each link are totalled by direction and by peak period. Adjustment factors for passenger loads and temperature are not used.

Table 2-4 GHG Emission Factors

Technology	Emission Factor
Diesel (g/L)	2,691
B20 (g/L)	2,168
CNG (g/m^3)	1,711
Hybrid (g/L)	2,342

The lifecycle emissions are the sum of the upstream, and operation emissions produced for one cycle during both peak hours. The emissions credit for plant absorption is also added. For diesel, B20 and CNG, the operation emissions from MOVES are used. For hybrid technology, operation emissions calculated from fuel consumption curves are applied. Emissions generated by GHGenius are normalized by lifetime kilometres travelled; thus, it is multiplied by twice the route length (one for each peak period) to obtain the total upstream emissions.

2.4 RESULTS AND DISCUSSION

The results of the upstream, operation and lifecycle emissions are discussed in this section. Moreover, the costs of alternative bus transit technologies are briefly examined.

2.4.1 Upstream Emissions

The GHG emissions from the upstream phases are summarized in **Table 2-5** by technology. In increasing order of emissions, the fuel technologies are ranked: 1) CNG, 2) hybrid, 3) B20, and 4) diesel. Conventional diesel has the highest emissions due to the fuel production and feedstock recovery processes. The emissions for B20 are slightly lower than that of diesel. This is expected as B20 is still composed of 80% petroleum diesel. The vehicle cycle emissions are the same for diesel and B20. A 35% decrease in upstream emissions is found in hybrid buses. This reduction is mostly found in the fuel cycle. The manufacturing of hybrid vehicles is the most intensive considering it requires a diesel engine and an electric motor. CNG has the lowest upstream emissions, a reduction of 44% from diesel buses. The fuel cycle processes of CNG are not as demanding as diesel; however, the on-board CNG storage tanks require more material.

Table 2-5 Upstream Emissions

Process (g/km)	Diesel	B20	CNG	Hybrid
Fuel dispensing	0.4	0.4	4.4	0.2
Fuel storage and distribution	7.7	10.4	27.9	4.5
Fuel production	165.3	157.5	29.0	97.3
Feedstock transport	16.2	16.6	0	9.5
Feedstock recovery	147.3	143.8	38.2	86.6
Land-use changes, cultivation	3.5	26.4	0	2
Fertilizer manufacture	0	35.4	0	0
Gas leaks and flares	28.2	23.0	62.1	16.6
CO_2, H_2S removed from NG	0	0	19.6	0
Emissions displaced by co-products	-3.9	-99.5	0	-2.3
Total fuel cycle	**364.7**	**314.0**	**181.2**	**214.4**
Vehicle assembly and transport	5.0	5.0	6.3	7.3
Materials in vehicles	28.8	28.8	35.4	37.8
Total vehicle cycle	**33.8**	**33.8**	**41.7**	**45.1**
Total upstream	**398.5**	**347.8**	**222.9**	**259.5**

It is important to mention that due to the cultivation of canola and the absorption of CO_2 by this plant, GHGenius applies a credit of 252.7 g/km for B20. This occurs at the end of the operation phase; therefore, this amount will be deducted from the overall lifecycle emissions.

2.4.2 Operation Emissions

GHGs emitted during operation were estimated using second-by-second speeds in MOVES and averages speeds using fuel consumption curves. Recall that MOVES is not capable of analyzing emissions of hybrid buses; therefore, to make a fair comparison between hybrid buses and the other alternative technologies, link-level average emissions were evaluated. The operation emissions are the total for one bus travelling on one complete cycle (northbound and southbound) of Route 165 for morning and afternoon peak periods.

a) Second-by-second speed

The second-by-second estimates are presented in **Table 2-6**.The hourly emissions (not shown) were constant throughout their corresponding peak period; thus, it was not necessary to calculate the average emissions of the morning and afternoon peak periods. There were minor differences in temperature and relative humidity which explains the constant emissions. The operation emissions of CNG is lowest compared to diesel and B20 buses (from 23,624 grams to 28,002 grams), this represents a difference of over 4 kg of CO_2 per cycle in each peak period. Once again, the emissions of diesel and B20 buses are similar with diesel buses being slightly more polluting – with GHG rates of 2.11 and 2.10 kg/km, respectively. Moreover, note that these estimates are higher than those reported in previous studies for diesel and biodiesel, but the results are within the range for CNG (Beer et al., 2002; Karman, 2006; Rabl, 2002). For instance, the studies show that diesel has GHG emission rates that range between 1.67 and 1.74 kg/km, and CNG emits 1.54 to 2.03 kg/km (Beer et al., 2002; Karman, 2006; Rabl, 2002).

For both peak periods, the emissions of a bus travelling in the northbound direction are always lower than when it is going in the southbound direction by 10-15%. Even though the southbound route is a little longer, the emissions are still higher per kilometre. The southbound direction is towards the downtown area; therefore, ridership is most likely to be higher in that direction. A higher passenger load implies longer idling times at bus stops and more frequent stops which increase emissions. Similar emission level patterns are exhibited in the morning and afternoon peak periods for all three technologies. In the morning, commuters primarily travel southbound towards downtown for work or school. In the afternoon, some commuters return home while others make leisure trips to downtown.

Table 2-6 Operation Emissions from MOVES (for one cycle)

Direction	Emission Inventory (g)			Emission Rates (kg/km)		
	Diesel	B20	CNG	Diesel	B20	CNG
AM Peak						
Northbound	13,085	13,020	11,190	1.98	1.97	1.70
Southbound	15,058	14,982	12,434	2.24	2.22	1.85
Total	28,143	28,002	23,624	2.11	2.10	1.77
PM Peak						
Northbound	13,217	13,151	11,079	2.00	1.99	1.68
Southbound	14,881	14,806	12,529	2.21	2.20	1.86
Total	28,098	27,957	23,608	2.11	2.10	1.77

B20 = biodiesel; CNG = compressed natural gas

b) Average speed

Results for link-level estimates are reported in **Table 2-7**. Although the use of average link speeds rather than a second-by-second drive cycle was expected to produce less precise results, the link-level estimates are very consistent for diesel. For instance, referring to **Tables 2-6 and 2-7,** one observes rates of 1.98 kg/km and 1.92 kg/km, respectively, for diesel in the northbound direction during the morning period.

The emissions for all technologies, including hybrid buses in the northbound direction are lower than in the southbound direction – this is consistent with the second-by-second estimates reported previously. This pattern matches the results from using second-by-second speed for the other technologies. The most noticeable result is the large reduction, approximately 50%, in emissions for hybrid buses compared to diesel buses. A hybrid bus serving Route 165 would produce 15 kg of CO_2-equivalent for a complete cycle in each of the peak periods. B20 and traditional diesel are assumed to have the same fuel consumption rate but different emission factors. A 20% decrease in GHG emissions from diesel to B20 makes sense since there is a 20% difference in their emission factors. CNG consumes more fuel per distance which counteracts the lower emission rate of CNG compared to diesel.

The operation results are more or less the same in the morning and afternoon peak periods. It is noticeable that the emission rates are consistent in both directions during the afternoon peak. This is probably due to using average speeds which neglects acceleration and deceleration events.

Table 2-7 Operation Emissions from Fuel Consumption Curves (for one cycle)

Direction	Emission Inventory (g)				Emission Rates (kg/km)			
	Diesel	B20	CNG	Hybrid	Diesel	B20	CNG	Hybrid
AM Peak								
Northbound	12,690	10,222	12,497	7,392	1.92	1.55	1.89	1.12
Southbound	14,380	11,583	14,505	7,989	2.14	1.72	2.15	1.19
Total	27,070	21,805	27,002	15,381	2.03	1.64	2.03	1.15
PM Peak								
Northbound	13,728	11,058	13,755	7,725	2.08	1.68	2.08	1.17
Southbound	14,079	11,340	14,215	7,875	2.09	1.68	2.11	1.17
Total	27,807	22,398	27,970	15,600	2.09	1.68	2.10	1.17

c) Comparative analysis of operation emissions

Both methods produce very similar emission levels for diesel; 55-56 kg for one cycle in both peak periods. B20 estimates are underestimated while CNG emissions are overestimated with the link-level method with respect to second-by-second estimates. The average speed method underestimates B20 emissions by 21% and overestimates CNG emissions by 16% with respect to the results from MOVES. This can be due to the fact that there have been some improvements in CNG technology since the publication of the TCRP report (Clark et al., 2009). There are also uncertainties associated with the fuel economy of this relatively new technology which explains the vast difference in operation emissions from the two methods. In contrast, the fuel consumption behaviour of traditional diesel buses is well-established which leads to more comparable results.

The average operation emission rates for diesel, B20 and CNG, range from 1.6-2.1 kg/km using the trend curves, and 1.8-2.1 kg/km using MOVES. A hybrid bus travelling on the CDN corridor emits less than 1.2 kg/km. These estimates are still higher than those reported in the literature for diesel but are closer in values for biodiesel and CNG (Beer et al., 2002; Karman, 2006; Rabl, 2002). Emission rates for hybrid buses were not found. Since B20 was underestimated using average link speeds, the average emission rates are closer to the 1.39 kg/km estimated by Beer et al. (2002). Since the emissions pattern is similar in both methods (i.e. higher emissions in the southbound direction, and similar emissions between morning and afternoon peak), either method is valid in the estimation of operating GHGs. This suggests that the use of link-level speeds can still be valid when there is a lack of data relating to technologies for estimating second-by-second emissions, in particular for regular diesel. An average link speed which includes idling is sufficient for GHG estimation. Whether second-by-second or average speeds are used, the same qualitative result is found: B20, CNG and hybrid technology offer greater benefits than diesel during operation.

2.4.3 Lifecycle Emissions and Cost-Ratio

The summary of the lifecycle emissions are presented in **Table 2-8**. These are the sum of the upstream and operation (including the carbon absorption credit) emissions during peak periods, for one complete cycle of Route 165. The greatest environmental benefits can be found by converting the current diesel fleet to hybrid buses (-43.3%), followed by CNG buses (-20.5%) and in last place are B20 buses (-12.5%). This means that the use of biofuels does not offer substantial GHG savings. If the emissions absorbed by the canola plant are omitted, B20 would have minimal reductions of only 2.4%. It is not surprising that hybrid buses offer the largest benefits in urban driving conditions, which is the perfect setting to demonstrate its fuel efficiency. The lowest upstream emissions are attributed to CNG where as the lowest operation emissions are associated with diesel-electric hybrid buses.

Table 2-8 Lifecycle Emissions (for one cycle in both peak periods)

Emissions	Diesel	B20	CNG	Hybrid
Upstream (kg)	10.63	9.27	5.94	6.92
Operation (kg)	56.24	55.96	47.23	30.98
Carbon absorption (kg)	0.00	-6.73	0.00	0.00
Lifecycle (kg)	66.87	58.50	53.18	37.90
Lifecycle rates (kg/km)	2.51	2.19	1.99	1.42

The lifecycle emission rates are 1.42-2.51 kg/km for the alternative fuels tested for a bus travelling the CDN corridor. These rates are much higher for diesel and B20 while the rate for CNG is within the upper range of the estimates found in the literature. For diesel, the emission factors reported are 1.67-1.74 kg/km, and for CNG, they range from 1.54 to 2.03 kg/km (Beer et al., 2002; Karman, 2006; Rabl, 2002). An emission rate of 1.39 kg/km was documented in the literature (Beer et al., 2002). The primary reason for this is the inclusion of local geographic and driving conditions which affects the fuel consumption and GHG emissions. In this study, second-by-second speed recordings were used which takes into account all acceleration and deceleration events. Typical driving profile of a transit bus is characterized by these stop-and-go events which creates additional emissions. If average fuel consumption rates were to be used, these events would be neglected and the emissions would be underestimated.

Note also that from **Figure 2-9**, operation emissions make up the largest portion of lifecycle emissions (82-89%), which is reasonable as buses operate almost all day. This suggests that although lifecycle analyses are useful to compare the GHG impact between new transportation developments, such as metro extensions or implementation of a BRT system, and existing transportation systems; it is not necessary to conduct LCA for the conversion of transit buses to alternative technologies since the results would lead to the same conclusions without the estimation of upstream emissions.

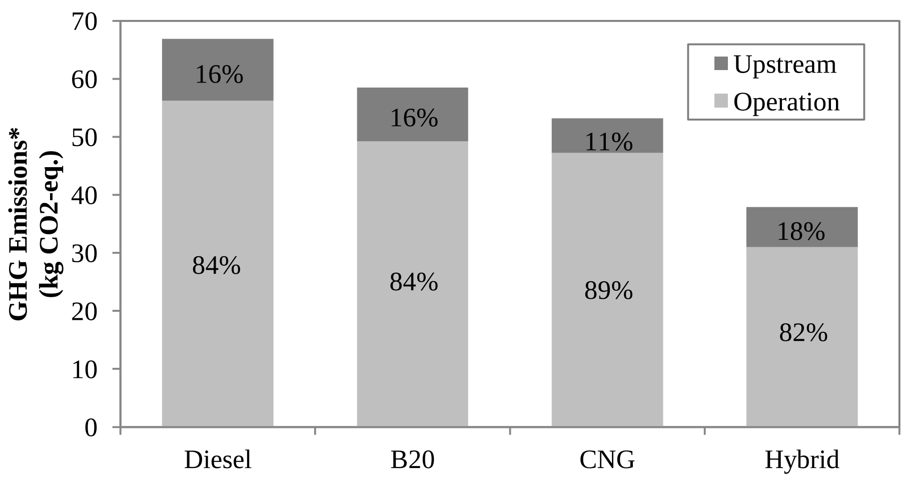

Figure 2-9 Portions of lifecycle stages
(GHG emissions is for one complete cycle of Route 165 in both peak periods)

In terms of lifecycle environmental benefits, hybrid buses are more advantageous than CNG buses. However, a cost-analysis is imperative in order for governments and agencies to make an informed decision. This brief section shifts the focus from GHG impact to cost-analysis. A quick comparison of costs between CNG and hybrid technology indicates that hybrid buses are more expensive than CNG buses. The Quebec government recently purchased 509 diesel-electric buses for $471 million; the ones that Montreal is acquiring are estimated to be about $657,500 per bus (Riga, 2012). Hybrid buses cost around $150,000-200,000 more than standard diesel buses (Riga, 2012) where as CNG buses would cost in additional $25,000-50,000 (NREL, 2000). With the current prices of diesel fuel at 118.3 cents/litre (NRCan, 2012b) and CNG at $1.57/GJ (NRCan, 2012c), both the fixed and operating costs reveal that CNG is the lower-cost option. Suppose the average speed is 18 km/h; using the link-level method, the fuel consumption rate is 45.5 L/100 km for hybrid and 96.0 m^3/100 km for CNG. Also, the heating value of CNG is 38.1 MJ/m^3 (Transport Canada, 2012a). From this information, the following operation costs are obtained: $53.81/100 km and $5.74/100 km for hybrid and CNG buses, respectively. The cost-ratios (=cost/GHG savings) are also calculated to verify the cost-effectiveness of alternative technologies. The GHG savings are the reduction in GHG emissions by converting from diesel to the alternative technology for a bus completing one cycle of Route 165 in both peak periods. Regarding the fixed cost, the cost-ratios are $603,200/kg for hybrid buses and $1 million/kg for CNG buses. Using operation costs, the ratios for hybrid and CNG are $0.49/kg and $0.11/kg, respectively. It is interesting that in terms of operation costs, it is much more cost-effective to operate CNG buses. Nonetheless, given the lower GHG savings of CNG and the relatively similar purchase costs, it is more economical to adopt hybrid buses.

2.5 CONCLUSION

This study investigates the lifecycle GHG emissions of alternative technologies including conventional diesel, biodiesel, CNG and diesel-electric hybrid. Also, the sensitivity of the results with respect to the method used is explored – second-by-second emissions are computed and compared with link-level emissions. Upstream emissions were estimated using GHGenius, while the operation emissions were evaluated with two methods: second-by-second drive cycle emissions using MOVES, and link-level emissions using fuel consumption curves and average link speeds. For this research, a major bus transit corridor (Route 165 travelling on the CDN corridor) in Montreal is used as an application environment. For diesel, B20 and CNG, the results from MOVES were reported. Given the fact that MOVES does not evaluate hybrid technologies, the results using the fuel consumption curves were used for hybrid buses.

Among other things, the main findings indicate that second-by-second vs. link-level emissions produce consistent estimates for diesel emissions. However, the link-level method underestimates B20 emissions by 21% and overestimates CNG emissions by 16% with respect to the results from MOVES. This means that although the link-level method can still provide approximate estimates, the second-by-second method is preferred. In some circumstances, the link-by-level method still can be justified. In particular, when there is a lack of second-by-second speed data, or when one needs to evaluate emissions for an entered network or region. Moreover, software like MOVES does not include hybrid technologies.

With respect to emission generation, the results indicate that CNG has the lowest upstream emissions due to the limited processes in the fuel production of natural gas, and hybrid technology produces the lowest operation emissions. Emissions and fuel consumption is directly related to acceleration events; thus, the use of an electric motor for stop-and-go driving conditions leads to significant GHG reductions. Overall, hybrid technology is the best option taking into account lifecycle emissions. The bus technologies are ranked in increasing order of lifecycle GHG emissions generated: 1) hybrid, 2) CNG, 3) biodiesel, and 4) diesel. GHG savings range from 8.4-29.0 kg of CO_2-equivalent (12.5-43.3%) during the peak periods from converting the current diesel technology to the alternative fuels tested.

As hypothesized, operation emissions make up the largest portion, at least 80%, of lifecycle emissions. Accordingly, the evaluation of these emissions should be carried out with accuracy. The results are likely to be different for a different corridor and a different drive cycle since emissions vary with speed and topography among other factors; although, the methodology is still valid for other corridors. Since the acceleration and deceleration events are taken into account, the estimated emissions will likely be higher and more accurate than if an average corridor speed was used. This also implies that practices to reduce the carbon footprint of transit buses should focus on the operation stage. A typical driving profile of an urban bus cannot be changed as it's in their nature to stop frequently. In order to reduce GHG emissions, the emission rate or fuel consumption needs to decrease. The most effective means to achieve this is by implementing alternative technologies particularly diesel-electric hybrid propulsion systems. Furthermore, the cost-ratios reveal that hybrid buses are more cost-effective than CNG buses. Although the fixed and operation costs are much lower for CNG bus systems, it costs less to achieve GHG reductions in hybrid technology than CNG buses.

3 Analysis of GHG Emissions for City Passenger Trains: Is Electricity an obvious option for Montreal commuter trains?

3.1 INTRODUCTION

Rail transit has gained popularity in recent years, providing accessibility and mobility to populations outside the core of metropolitan areas; however, they require large investments for the construction of infrastructure including railways, electrical feeder systems, stations and maintenance yards. In some cases, it also involves acquiring land to build new rail infrastructure operating on grade-separated right-of-ways, away from vehicular traffic. Despite these drawbacks, rail systems have the capability of moving mass numbers of commuters: 1,500 compared to 200 persons per hour per foot width of road for cars assuming single occupancy (Smith, 2003; TRB, 2000). For an occupancy rate of 1.6 passengers/car and 66 passengers/train, a car consumes 2.7 times more energy, emits 3.1 times more GHGs and emits 8.5 times more pollutants than a diesel heavy rail train per passenger-miles travelled (PMT) (Chester and Horvath, 2008).

The main reluctance for rail development is the high cost of infrastructure and equipment which is about 16 times more expensive than roads per unit length (Smith, 2003). Such investments are only justified economically and socially if there is sufficient passenger demand. As a result, variations of the conventional heavy rail transit (HRT) have been developed such as the light rail transit (LRT) and high speed rail (HSR) in order to reduce costs and travel time. Although, the application of HSR is only appropriate for trips between metropolitan cities (Alvarez, 2010). Other benefits include increased accessibility and mobility, reduced congestion and lower air pollution (Rutzen et al., 2010). The implementation of new technologies such as electric and fuel cell systems has made rail transit even more attractive from an environmental perspective by further decreasing GHG and pollutant emissions (Dincer, 2007; Marin et al., 2010a,b). Hydrogen fuel cell is an emerging technology for commuter rail and has not yet been proven; however, studies have found that it can substantially decrease GHG emissions in transportation. When hydrogen in a fuel cell is used to generate electricity or combusted with air, the only by-products are water, heat and low-levels of NO_x, depending on the source of hydrogen and its impurity (Dincer, 2007).

There are several feasibility studies being conducted on hydrogen trains. For example, the world's first hydrogen fuel cell hybrid train was developed by the East Japan Railway Company (JR East) in 2006. Also, Vemb-Lemvig-Thyborøn Jernbane (VLTJ) is in the process of launching Europe's first hydrogen powered train in Denmark. Lastly, Bombardier and the Ontario Ministry of Transport are currently studying the feasibility of a hydrogen-powered passenger train.

Some previous work has looked at the impact of new technologies in commuter rail systems in Canada (Marin et al., 2010a,b; Haseli et al., 2008). One study analyzed multiple hydrogen production techniques from renewable and non-renewable sources for internal combustion engines and fuel cell systems, and compares them to diesel and electric trains (Haseli et al., 2008). However, few studies have looked at lifecycle analysis, including train manufacturing and infrastructure construction components, coupled with lifecycle costs in order to make sustainable decisions. Also, there are few studies that analyze a combination of both new technologies and ridership management policies to reduce GHG emissions. Due to the dominance of coal-based electricity generation plants, no studies to our knowledge compare technologies with electricity produced from renewable energy which is common in Europe and in Quebec. With the advent of hydrogen technology, it is worth investigating its viability for commuter rail in Montreal, Quebec, given its renewable electricity production.

Accordingly, the objectives of this chapter are to:

1) Evaluate GHG emissions of the commuter rail in the region of Montreal for four technology scenarios (base case, complete electrification, hydrogen fuel cell from SMR and from wind energy) and a ridership scenario; and

2) Estimate operation and capital costs of the alternative technologies as well as determine the cost-benefit ratio of the technology scenarios.

The paper is divided into six sections. The following section presents a literature review on previous studies investigating the emissions impacts of alternative commuter train technologies. The third section introduces the commuter rail system in Montreal and explains the data sources used. The methodology for GHG estimation and the cost-benefit analysis is found in section 4. Section 5 discusses the results. Conclusions are provided in the last section.

3.2 LITERATURE REVIEW

This literature focuses on two aspects: analysis of GHG lifecycle for rail systems and studies looking at the impact of alternative rail technologies.

3.2.1 Lifecycle GHG Emissions of Rail Systems

For the planned California high-speed rail (CAHSR), an electric system, the largest portion of emissions is associated with the operation phase. For the existing San Francisco Bay Area heavy rail commuter line (Caltrain) running on diesel, the emissions are evenly split between the operation phase and the other lifecycle components. In this case, the lifecycle emissions of heavy rail are 4 times the electric HSR: 160 g CO_2-eq./PMT vs. 37 g CO_2-eq./PMT (Horvath and Chester, 2008).

In a more recent study the effect of using HSR in mitigating climate change in Sweden is studied. The author found that 550,000 tonnes of GHG per annum by 2025/2030 would be reduced which comes from a shift of freight from truck to rail, and air and road passenger travel to high-speed rail (Akerman, 2011). Overall, HSR consumes less energy and is less polluting than conventional trains due to the features associated with a high-speed train: travelling longer distances with fewer stops, and therefore, a more uniform speed profile; electric traction; higher power supply voltages, lower passenger loads, etc. (Alvarez, 2010). Also, the energy consumption from auxiliary services is negatively correlated with speed although higher speeds are positively correlated with fuel consumption per unit distance (Alvarez, 2010).

The results of an American study comparing diesel buses, bus rapid transit and LRT system show that the LRT was the most environmentally-damaging due to the production of electricity from fossil fuels (Vincent and Jerram, 2006).

3.2.2 GHG Emissions of Alternative Rail Technologies

The electrification of trains requires large capital investments for the additional infrastructure; however, it is one of the most efficient transportation systems as it transfers more than 85% of the electricity input to the wheels (Marin et al., 2010a,b). Also, the use of renewable resources such as hydro-power, solar energy, wind and geothermal energy for electricity production would eliminate the combustion of fossil fuels. This would greatly affect the overall emissions since these energy sources are assumed to have zero emissions from direct use (Meegahawatte et al., 2010; Smith, 2003; TRB, 2000). The lifecycle CO_2 emissions for diesel-electric hybrid and electric freight trains are 45 g/tonne-km and 44 g/tonne-km, respectively (Wee et al., 2005).

Fuel cell technology has the potential to reduce GHG emissions generated from internal combustion engines. In general, hydrogen fuel cell vehicles have lower emissions than hydrogen internal combustion engine vehicles. There are a variety of production methods for hydrogen. A few examples are steam methane reforming (SMR), a thermochemical cycle using thermal energy and electrolysis using wind or solar energy. Depending on the method of hydrogen production, the emissions can vary greatly. The most popular method, SMR via electrolysis, emits 5.5 kilogram of CO_2 for every kilogram of hydrogen produced (Meegahawatte et al., 2010). The best method for hydrogen production from an environmental point of view is a combination of renewable energy with the copper-chlorine cycle (Haseli et al., 2008). This is a thermochemical cycle which decomposes water into hydrogen and oxygen, and requires a high heat requirement. The heat requirement is achieved by burning hydrogen which is produced from renewable energy sources. The process is a closed loop cycle which means that the chemicals are recycled and GHGs are not emitted into the atmosphere. The CO_2 emissions of a hydrogen-fuelled passenger train are about 9% of a diesel train, or an electric train that uses coal to produce electricity (Haseli et al., 2008).

Although it has been established that the use of hydrogen would lead to fuel and energy reductions, it cannot be confirmed that they would compensate for the high costs and difficulties with storage (Hillmansen, 2003; Steinberg and Scott, 1984). The storage of hydrogen gas requires large amounts of space; therefore, the most likely solution is to carry compressed hydrogen in storage tanks. This is a problem due the reactivity of hydrogen and the risk of explosion. This requires the storage tanks to withstand accidental impacts but still remain lightweight which is costly (Hillmansen, 2003).

An in-between potential solution (between diesel and fuel cell trains) could be to implement hybrid fuel cell technologies until the costs of fuel cell locomotive decrease. This would allow for a more economical transition to a completely fuel cell locomotive (Steinberg and Scott, 1984). Additionally, some European countries such as Sweden, Norway, Switzerland, and Austria, already obtain a large proportion of energy from clean sources, in particular, hydroelectricity. Under these conditions, it is unlikely that fuel cell technology will be adopted for existing electric rail networks. Nevertheless, hydrogen remains competitive with electricity due to the lower infrastructure costs since additional electrical infrastructure is not required. According to the Strategic Rail Authority, a rail trip in the U.K. generates, on average, 56 g of CO_2 per passenger-kilometre for a hydrogen-fuelled train compared with 146 g of CO_2 per passenger-kilometre for a private vehicle with 1.3 passengers (Hillmansen, 2003].

Despite the importance of previous work in the literature, few studies have addressed the impact of new technologies in commuting train systems in North America, and, in particular, in Canada. One of the few studies is the GO Transit in Ontario, Canada (Haseli et al., 2008; Marin et al., 2010a,b). These recent studies have recognized the benefits of hydrogen fuel cell trains including GHG savings and flexibility on existing railways since there is no need for additional infrastructure. A case study in Quebec would demonstrate greater GHG reductions by using renewable electricity supply which is in contrast to the predominance of coal-powered electricity plants in North America. It would be important to verify the viability of hydrogen commuter trains in Montreal, Quebec, given its clean electricity production from hydropower.

From this literature, the emissions from vehicle manufacturing of rail transit are not as important as the fuel and infrastructure lifecycles (Horvath and Chester, 2008). In a complementary study by the same authors, the vehicle manufacturing phase for a passenger car is about 8% (Chester and Horvath, 2008). It is expected that this proportion would be even smaller for trains if they operate all day compared to a car which runs a fraction of that time. Although emissions from additional electrical infrastructure are not negligible, it is minimal with respect to the total emissions over time. One study confirms the small contribution of emissions from vehicle manufacturing and infrastructure construction to lifecycle emissions (Horvath and Chester, 2008). Furthermore, the rail infrastructure already exists and the alternative scenarios do not entail developing a new rail network from scratch. In the absence of lifecycle studies of rail infrastructure, calculation for emissions from infrastructure construction is omitted. For these reasons, the GHG analysis will be limited to emissions from vehicle operation and fuel production.

Market analysis is also beyond the scope of the paper. It is unknown how electrification of an existing rail network would affect the capacity or the demand of existing dams and reservoirs or even the composition of electricity. Therefore, it is assumed that the current set of electricity generating stations in Quebec is able to sustain a full electrification of Montreal's commuter rail.

Given the importance of hydroelectricity in Quebec, it would not be valuable to consider other electric sub-configurations. It is highly unlikely that the predominance of hydropower in Quebec's electricity composition will change in the foreseeable future. The paper will analyze, among others, these two extreme cases: current scenario of diesel technology (with one existing electrified line) and complete electrification. Partial electrification scenarios can be roughly estimated by taking proportions from the two extreme values. These cases can be investigated further in the future.

3.3 DATA DESCRIPTION

This section provides a short portrait of the current Montreal rail network as well as the different sources of data used in the estimation of GHGs and ridership for the alternative scenarios.

3.3.1 Montreal Commuter Rail Network

The commuter rail network in Montreal, operated by the Agence métropolitaine de transport (AMT), is a heavy rail system that presently spans 204.4 km (AMT, 2011). The current network comprises of 51 stations and five lines: Vaudreuil-Hudson, Deux-Montagnes, Candiac, Mont-Saint-Hilaire and Blainville-Saint-Jérôme, which serve the Greater Montreal area (**Figure 3-10**). It has an average weekday ridership of 71,900 passengers (AMT, 2011). The train fleet is composed of 39 diesel locomotives and 58 EMUs (AMT, 2010). Diesel trains travel on all lines except for Deux-Montagnes, the only electrified line with a length of 29.9 km (AMT, 2011). Deux-Montagnes has been running electric trains since its beginning, in 1906, due to the poor ventilation in the Mont-Royal tunnel.

Construction is underway to extend the network on the east side of Montreal; the sixth line will be called the Mascouche line. Dual-mode locomotives have already been purchased for the Mascouche line. This line also passes through the Mont-Royal tunnel; therefore, partial electrification is necessary. A feasibility study on the electrification of the AMT commuter rail is in progress.

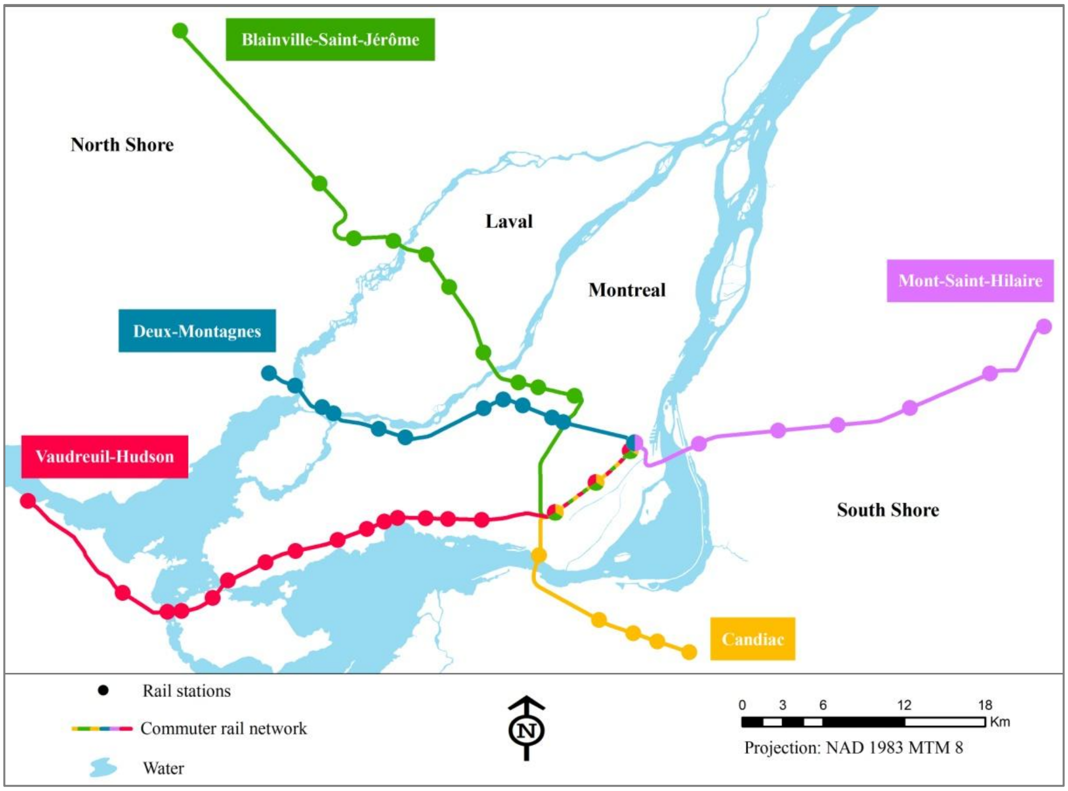

Figure 3-10 Commuter rail network in Montreal

3.3.2 Fuel Consumption and Kilometres Travelled

The annual diesel fuel and electricity consumption of the commuter rail network (**Figure 3-11**), as well as the total passenger-kilometres travelled (PKT), vehicle-kilometres travelled (VKT) and train-kilometres traveled for each rail line for 2005 to 2008 were supplied by AMT. In 2008, the commuter rail network consumed 7.364 million litres of diesel and 21.662 million kilowatt-hours of electricity (77.982 million MJ). The diesel fuel consumption can be estimated for each of the four rail corridor based on the proportion of VKT. In this case, it is assumed that the trains serving each rail line have the same consumption rate – fleet characteristics were not available. All the electricity is consumed on the Deux-Montagnes corridor. Although VKT has increased over the years, the diesel and electricity consumptions have decreased due to the regular renewal of the fleet to newer and more efficient rolling stock (AMT, 2011). **Table 3-9** shows the total PKT, VKT, train-km and fuel/electricity consumption of each rail line in 2008. These figures are used extensively to estimate GHGs, operation costs and capital costs.

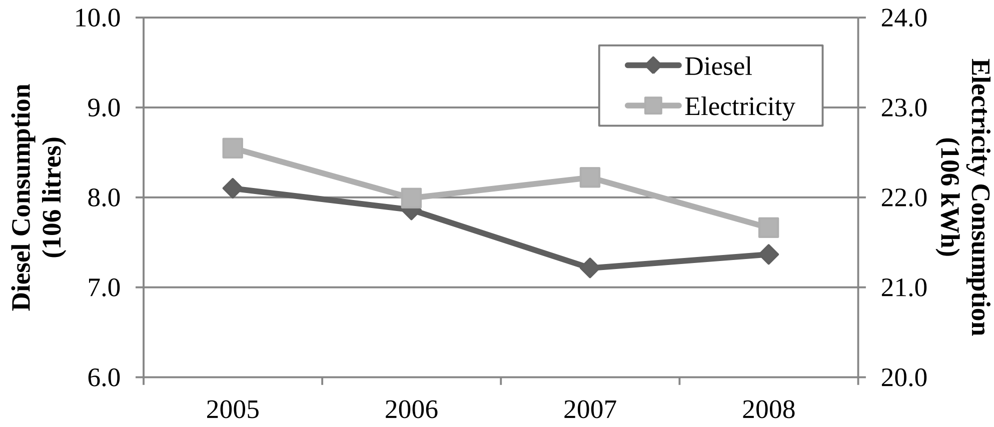

Figure 3-11 Annual diesel fuel and electricity consumption of AMT network

Table 3-9 Annual Km Travelled and Fuel Consumption by Rail Corridor

Corridor	Passenger-km ($x10^3$)	Vehicle-km ($x10^3$)	Train-km	Fuel Consumption (L or MJ)
Deux-Montagnes[1]	145,082	3,778	405,021	77,982,023
Dorion-Rigaud	81,524	1,619	293,716	2,591,942
Blainville-Saint-Jérôme	55,865	2,075	220,125	3,320,547
Mont-Saint-Hilaire	34,828	701	74,938	1,121,240
Delson-Candiac	10,927	206	51,589	330,271

[1] This is the electric line; the other lines run on diesel.

3.4 METHODOLOGY

The methodology consists of three steps:

- Estimation of GHGs for alternative technologies;
- Computing of operation and capital costs of each technology; and
- Comparison of alternatives using a cost-benefit ratio.

These three steps are detailed as follows.

3.4.1 GHG Estimation

The GHG emissions are evaluated for alternative technology and ridership scenarios. For the technology scenarios, the purpose is to determine potential GHG reductions from converting to an alternative fuel. The ridership scenario is based on the emissions estimated from the technology scenarios, and passenger occupancy. These results would show how the emissions change by ridership and whether a change in technology or ridership is more effective at reducing emissions.

Four technology scenarios are analyzed: 1) base case; 2) complete electrification; 3) hydrogen fuel cell by SMR, 4) hydrogen fuel cell using wind energy. The total GHG emissions include emissions generated from fuel production and operation. Recall that the emissions from vehicle manufacturing and infrastructure construction are omitted since it is assumed to be minimal with respect to lifecycle emissions. The GHG calculation for alternative technologies is carried out using emission factors for different rail technologies (**Table 3-10**). The emission factor for diesel heavy rail is a general emission rate that does not take into account the specific diesel technology being used. There are zero exhaust emissions for electricity and hydrogen fuel cell. For electric generation in Quebec, the emission factor is minimal which includes all activities that occur at the generation plant (Environment Canada, 2007; Transportation Canada, 2012).

Two hydrogen production methods are explored: one using wind energy and another using SMR. The main difference is that one method uses a renewable resource which would be interesting to compare to electricity from hydro-power, another renewable resource. The fuel cycle of hydrogen from wind energy involves electricity generation from wind turbines, electrolysis at fueling stations to produce hydrogen and hydrogen compression (Dincer, 2007). The hydrogen production using SMR is more intensive as it requires the extraction of natural gas. The processes include transportation of natural gas through pipelines, reforming to produce hydrogen, hydrogen compression and delivery to fuelling stations (Dincer, 2007).

Table 3-10 GHG Emission Factors for Fuel Production and Operation

Technology	Fuel Production	Operation
Diesel (g/L)	724	3,007
Electric – hydro (g/MJ)	2.5	0
Hydrogen – wind (g/MJ)	20.55	0
Hydrogen – SMR (g/MJ)	84.8	0

Source: Dincer, 2007; Transport Canada, 2012a

a) Base case

The base case refers to the diesel-powered trains operating on four rail lines and the electric-powered trains running on one rail line on the current network excluding future extensions. Since the fuel and electricity consumption are known, a simple formula is used to calculate the GHG emissions (**Equation 3-1**), where C is the fuel or electricity consumption and EF is the emission factor. Emissions are estimated for both fuel production and operation phases.

$$\mathrm{GHG} = \mathrm{EF} \times \mathrm{C} \qquad [\mathbf{3\text{-}1}]$$

b) Complete electrification

The electrification scenario assumes that the rail network would consume electric energy at the same rate as on the Deux-Montagnes line which is 20.63 MJ/VKT. An additional term, VKT, is added to calculate GHG as shown in **Equation 3-2**, where CR is the consumption rate (MJ/VKT). The emissions are only evaluated for electricity production since no emissions are produced during operation.

$$\mathrm{GHG} = \mathrm{EF} \times \mathrm{CR} \times \mathrm{VKT} \quad [\mathbf{3\text{-}2}]$$

c) Hydrogen fuel cell

GHG estimation for hydrogen fuel cell cases also uses the above equation; however, the hydrogen energy consumption rate is unknown. In order to determine this, two assumptions are made: 1) the power output for all technologies is the same; and 2) the efficiency of a hydrogen system is 50%. The relationship between efficiency (%), power output (MJ/train-km) and energy consumption (MJ/train-km) is shown in **Equation 3-3**. Two other characteristics are needed, the heating value of diesel, 38.65 MJ/L, and the efficiency of diesel engines which is 24% (Transport Canada, 2012a; AEA Technology Rail, 2005). This procedure is quite simple and involves converting the diesel fuel consumption to energy consumption by diesel to energy consumption by hydrogen. The steps are outlined below.

$$\text{efficiency} = \frac{\text{power output}}{\text{energy}} \qquad [\mathbf{3\text{-}3}]$$

Determination of hydrogen consumption rate:

• Find the diesel fuel consumption rate in L/VKT (total VKT is for the diesel lines): (7,364,000 L) / (4,601,123 VKT) =1.60 L/VKT

• Convert to energy consumption rate of diesel using the heating value of diesel: (1.60 L/VKT) $\times$ (38.65 MJ/L) = 61.86 MJ/VKT

• Find the power output using the efficiency of diesel engines: (61.86 MJ/VKT) $\times$ 0.24 = 14.85 MJ/VKT

• Find the energy consumption rate for hydrogen using hypothesized efficiency of hydrogen system: (14.85 MJ/VKT) / 0.5 = 29.69 MJ/VKT

Finally, the hydrogen energy consumption rate is 29.69 MJ/VKT. This is the rate used for both hydrogen production methods. All other information is available to estimate GHG emissions.

d) Ridership scenario

In the ridership scenario, the total annual GHG emissions are normalized by PKT for each technology investigated. In other words, the GHG emissions per VKT are divided by the number of passengers per train-vehicle. In 2008, each train-vehicle had an average of 39.2 passengers which is an occupancy rate of only 18%. One EMU from the Deux-Montagnes line has a capacity of 214 passengers: 88 seated and 126 standing (Bombardier Inc., 2000). A range of ridership is analyzed, from low occupancy (10% or 21.4 passengers) to high occupancy (100% or 214 passengers). It is assumed that ridership would not change with different technologies.

It should be noted that although the emissions per PKT is lower for higher ridership levels, the total emissions remain the same for a given technology. The emissions savings comes from a mode shift from personal motor vehicles to public transit. This is beyond the scope of this thesis and therefore, it is not quantified.

3.4.2 Operation and Capital Costs

The costs of alternative commuter rail technologies are evaluated in this section. The total cost is defined as the initial investment and the first year of operation. This includes fuel/electricity, rolling stock, infrastructure and maintenance costs.

a) Operation costs

Operation costs is the cost incurred from direct use of a given fuel or technology. **Table 3-11** lists the direct costs per unit of fuel/electricity for diesel, hydroelectricity and hydrogen use. The price of diesel fuel including taxes in Montreal is $1.071/L which is much higher than the national average of $1.008/L (NRCan, 2011). The differences are mainly due to higher fuel taxes in Montreal than the rest of Canada. The low cost of hydroelectricity refers to the average price for large-power customers in Montreal (Hydro-Québec, 2011b). Regardless of the method of hydrogen production, the cost of hydrogen gas is approximately $35/GJ (Haseli et al., 2008). The annual operation cost is calculated by multiplying the unit costs with the corresponding total consumption of fuel/electricity.

Table 3-11 Unit Technology Costs

Technology	Cost
Diesel	$1.071/L
Hydroelectricity	$0.048/kWh
Hydrogen	$35/GJ

Source: NRCan, 2011; Hydro-Québec, 2011b; Haseli et al., 2008

b) Capital costs

The capital costs are estimated for the electric and hydrogen technologies for the current fleet size and rail network. Recall that the AMT commuter rail operates 39 locomotives and 174.5 km of track need to be electrified. Capital costs include the purchase of rolling stock, construction of infrastructure, and their maintenance. Two important feasibility reports were assessed to estimate the costs of a complete electrification scenario and a hydrogen fuel cell scenario. Since the GO Transit, serving the Greater Toronto and Hamilton Area (GTHA) in Ontario, is most similar to the AMT commuter rail, the electrification costs are based on figures estimated in the GO Transit Electrification Study (Delcan/Arup, 2010). The two Canadian commuter rail networks are similar in terms of coverage area, ridership level and technology (GO Transit, 2011). For the costs of hydrogen fuel cell technology, the Rail Safety and Standards Board (RSSB) Feasibility Report on hydrogen trains was used as a reference guide (AEA Technology Rail, 2005).

Rolling stock: It was estimated that the acquisition of 107 electric locomotives and 12 EMUs would cost $736 million in the GO Transit feasibility study. The cost of EMUs is about 40% higher than an electric locomotive. For that reason, the cost of one electric locomotive is $5.945 million. A locomotive is considered to be a set of 10 passenger coaches and the locomotive (Delcan/Arup, 2010). According to RSSB, a fuel cell locomotive would cost about £9-10 million (AEA Technology Rail, 2005). This translates to an average of $14.65 million for each hydrogen locomotive (XE, 2011a).

Infrastructure and maintenance: Electrical infrastructure includes a catenary system, power supply system, maintenance and layover facilities, overhead structures, infrastructure rework, sitework and special conditions and professional services. A reported $3.019 billion is the cost to completely electrify the 508.9 km of the GO Transit network. The infrastructure capital costs were estimated prior to any detailed design work; therefore, a 35% contingency is included to capture potential additional costs. In other words, the electrification scenario costs $5.932 million/km. In comparison, a study for the VLTJ (H2 Logic, 2006) proposes a more modest figure at €0.4-0.9 million/km which converts to $0.88 million/km (XE, 2011a).

The advantage of hydrogen technology is that it is very flexible, such that it can operate on existing railways with little or no modification. In this case, there are no costs associated with the infrastructure needed for hydrogen fuel cell systems. There are, however, maintenance costs that need to be considered. Due to the lack of information, it has been assumed that the maintenance costs of hydrogen fuel cell trains are equivalent to diesel trains (AEA Technology Rail, 2005). Although fuel cells are more reliable than internal combustion engines, the additional maintenance resources required would balance out these savings (AEA Technology Rail, 2005). The maintenance costs are $0.43 million/km which is taken from the GO Transit feasibility report (Delcan/Arup, 2010). Note that it is less expensive to maintain electric locomotives than diesel locomotives (Delcan/Arup, 2010). There are also costs associated with labour to operate and maintain the commuter train; however, these are not quantified as they would be the same for both technologies.

The capital costs are tabulated for easy reading in **Table 3-12**.

Table 3-12 Capital Costs by Technology

Technology	Rolling Stock ($ million/locomotive)	Infrastructure and Maintenance ($ million/km)
Electric	5.945	5.932
Hydrogen	14.650	0.435

Source: AEA Technology Rail, 2005; Delcan/Arup, 2010

3.4.3 Cost-Benefit Ratio

The European Union Emissions Trading System (EU ETS) was launched in 2005 with the goal of reducing industrial GHG emissions. It is based on the cap-and-trade principle in which industries have a limit on GHG emissions and receive allowances within this limit. Fines are imposed if the allowances, which are worth 1,000 tonnes of CO_2-equivalent, do not cover all its emissions. These allowances are sold or bought as needed from other industries at the market price (European Commission, 2011).

The price of CO_2 is determined by many factors such as energy prices and climate (Ballater et al., 2007). From 25 theoretical models of the carbon market, the price varies from 1-74 USD per ton of CO_2-equivalent (Springer, 2003). The forecasted market price of a CO_2 allowance for the summer of 2011 is € 15.75 (Reuters, 2011). In Canadian dollars, the market price of 1000 tonnes of CO_2-equivalent is $21.48 (XE, 2011b). Using the market price of carbon dioxide and the annual tonnes of GHG emissions for each technology, the cost of CO_2-equivalent emissions are calculated.

Alternatively, the market price of CO_2 can also be used to determine the monetary benefit of GHG reductions. The market price is simply multiplied by the GHG savings for each technology scenarios to obtain the benefits in dollars. With the costs and benefits in monetary terms, a cost-benefit ratio is computed to determine the best technology for implementation. A value over one indicates that the costs outweigh the benefits and a value under one means that the benefits compensate for the costs. The smallest cost-benefit ratio will establish which technology is the most cost-efficient.

3.5 RESULTS AND DISCUSSION

3.5.1 Alternative Technology Scenarios

The annual GHG emissions for the base case, electric and hydrogen scenarios are estimated using the information and procedures defined in the previous two sections. The CO_2-equivalent emissions for each alternative are provided in **Figure 3-12**. The conversion of the current fleet to all electric trains would reduce GHG emissions by 98.4% which is more than 27,000 tonnes/year. In contrast, the emissions savings from the switching to hydrogen fuel cell technologies are not as outstanding but still significant. An annual decrease of about 6,600 tonnes and 22,600 tonnes is expected for hydrogen produced by SMR and from wind energy, respectively. Even though hydrogen from wind energy is a cleaner technology than diesel-fuelled trains, annual GHG emissions are still 12 times that of electric trains. Using renewable energy sources provide the greatest reduction in GHG emissions as demonstrated by trains powered by hydroelectricity and by hydrogen produced from wind energy. If the electricity generation was coal-based or natural gas-based, the emissions would be much higher for the electrification case. In addition, hydrogen fuel cell trains would probably be the cleanest technology.

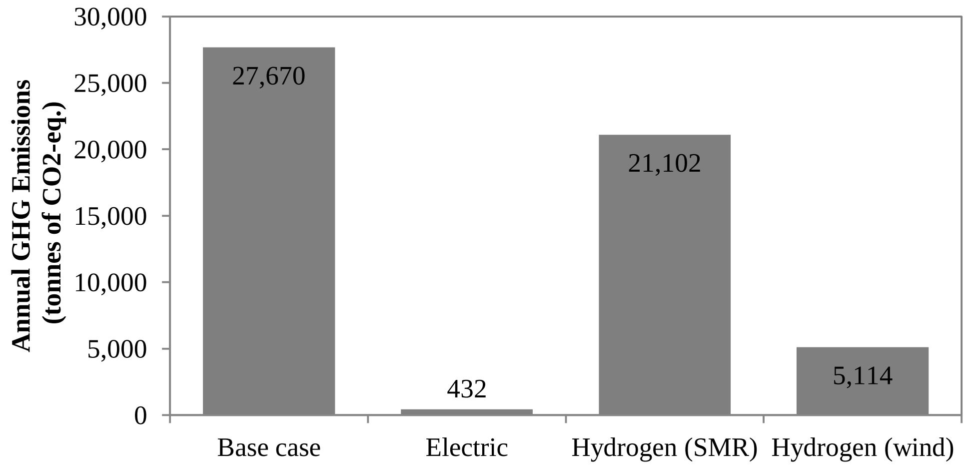

Figure 3-12 Annual GHG emissions of alternative technologies

Since the GO Transit feasibility report was referred to extensively to estimate costs, it would be interesting to see how the commuter rail in Toronto measure up to the one in Montreal in terms of GHG emissions. The total train-km travelled of GO Transit is unknown; therefore, GHG emissions are reported on a per train-km basis. For the GO Transit, the fuel consumption rate was assumed to be 5 L/train-km which is lower than the one for Montreal with 11.5 L/train-km (Marin et al., 2010a,b; Haseli et al., 2008). The emission factor for diesel shown in **Table 3-10** is used.

From **Figure 3-13**, it is noticeable that the GO Transit is cleaner than the AMT commuter rail: 26.5 kg/train-km vs. 18.7 kg/train-km, even though their fleet is entirely composed of diesel-powered trains. This discrepancy can be explained by the large difference between the fuel consumption of the commuter rail systems which is again 11.5 L/train-km for the AMT trains. In 2011, GO Transit completed a four-year plan to replace the old F-59 with the new MP40 locomotives, which meets the US Environmental Protection Agency Tier 2 Emission Standards (LTK Engineering Services, 2010).

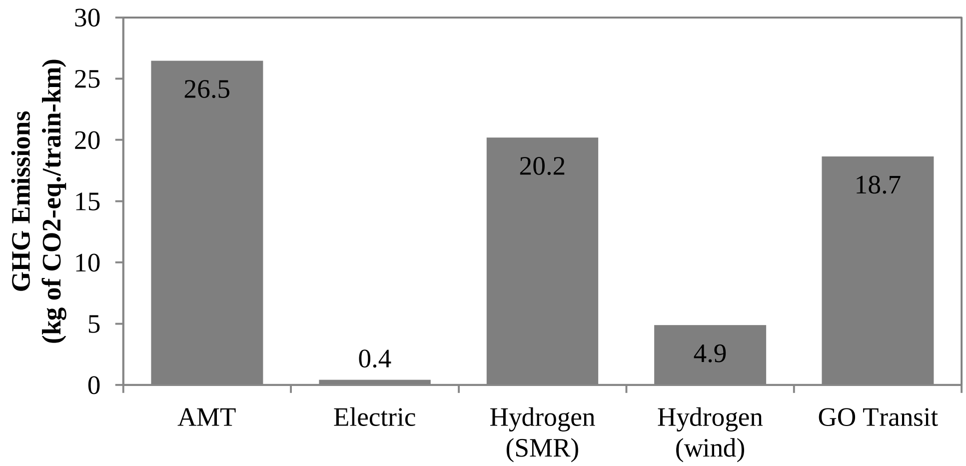

Figure 3-13 Comparison of GHG emissions between AMT and GO Transit

3.5.2 Ridership Scenario

The results of the GHG emissions for low to high ridership levels are explained in this section. **Figure 3-14** should be interpreted as such: each bar represents a technology scenario and the numbers on the bars indicate the number of passengers per train-vehicle. Starting at the top is the low passenger level; as one moves down the bar, the ridership level increases up to a maximum of 214 passengers. The dotted lines outline the emissions for six important ridership levels: low occupancy for hydrogen technology from SMR, current occupancy for base case, low occupancy for hydrogen technology from wind energy, high occupancy for base case, high occupancy for hydrogen (SMR), and high occupancy for hydrogen (wind). For each dotted line, the equivalent passenger levels for each technology are shown. For example, at 84.3 g/PKT (red line), the passenger level is 39.2 for the base case scenario and 29.9 for hydrogen from SMR scenario. The emissions at the low occupancy for hydrogen from wind energy scenario is 28.5 g/PKT (green line) which corresponds to 115.8 passengers for the base case and 88.3 passengers for hydrogen from SMR case. In order to reduce emissions from the red to the green line, the ridership would have to triple for the current commuter rail network. This is unlikely to happen particularly in the off-peak periods since most trains are already at full capacity during peak hours; therefore, a more reasonable solution to reduce GHG emissions per capita is by switching to a cleaner technology.

Additionally, it appears that given the low emissions from electric trains, the emissions from the current network will always be higher than a full electrification of the network even at full passenger occupancy for the reference case. Similarly, all technologies have GHG emissions higher than that of electrification for all ridership levels.

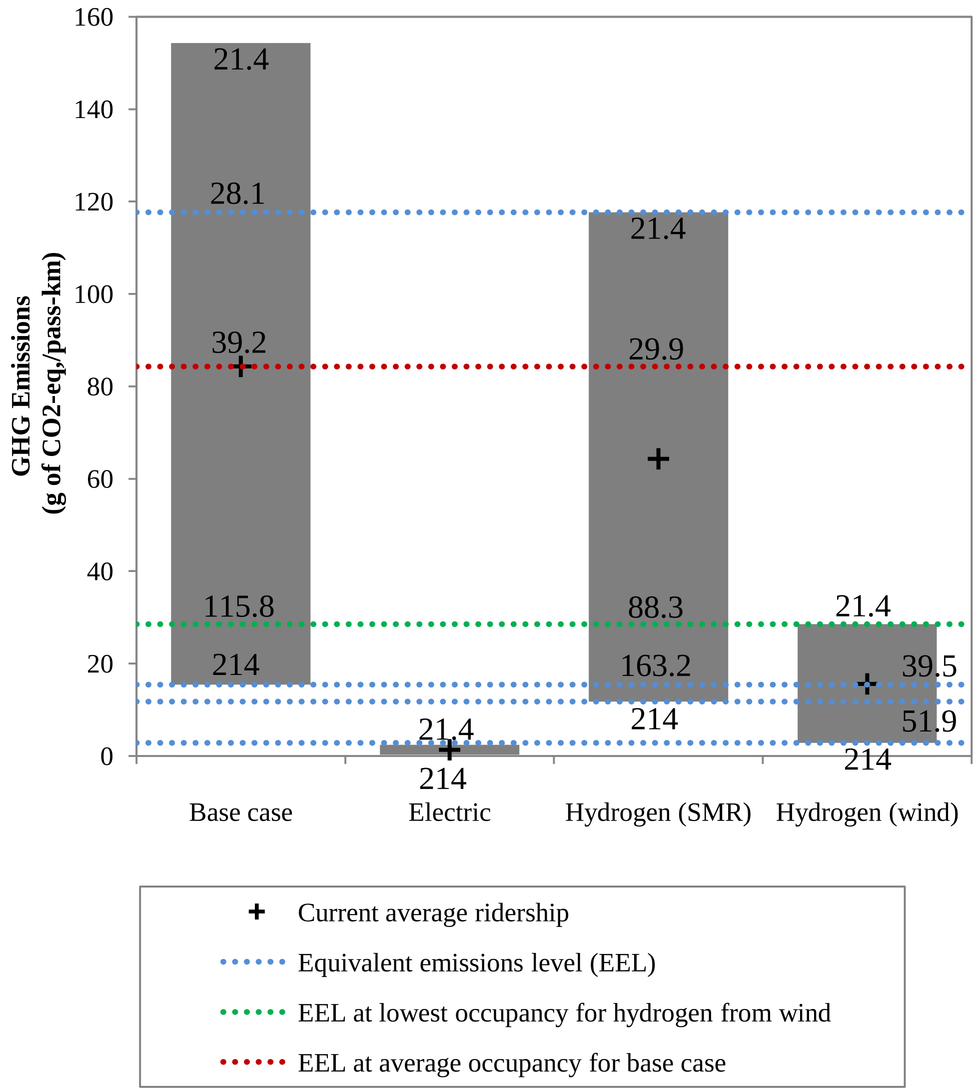

Figure 3-14 GHG emissions for ridership scenario

3.5.3 Operation and Capital Costs

The operation costs per train-km of the three technologies are shown in **Figure 3-15**. It is most economical to operate electric trains, less than $3/train-km, which are 3 times and 5 times cheaper than operating hydrogen fuel cell trains and diesel trains, respectively. The cost to operate the base case scenario is the sum of the costs for electric and diesel trains which is $14.88/train-km.

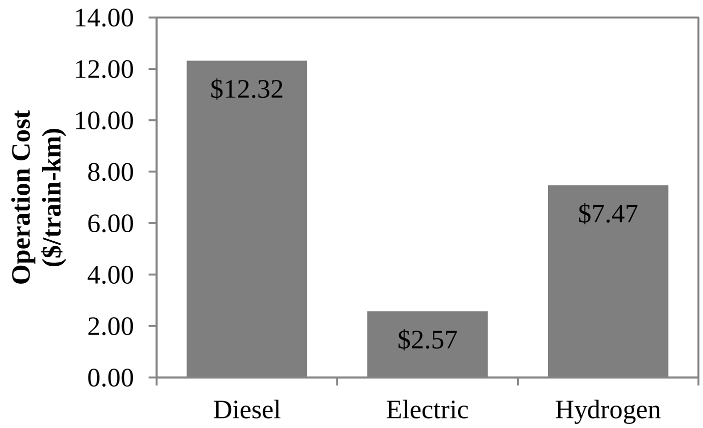

Figure 3-15 Operation costs by technology

Due to the low cost of electricity in Quebec at 4.8 ¢/kWh, it would not be suitable to apply these operating costs to other cities where electricity can cost 2-3 times as much as in Quebec. For example, the cost of electricity for large-power consumers is 9.75 ¢/kWh in Toronto, Ontario, and 12.64 ¢/kWh in New York, New York (Hydro-Quebec, 2011b). In addition, unless the electricity costs were to be raised to at least 13.96 ¢/kWh, the operating costs of electricity would still be the cheapest option. It is implausible that the cost of electricity in Montreal would surpass the cost in New York City.

A 30-year lifetime for commuter rail is assumed for both technologies (Chester and Horvath, 2008). The discount rate of 10% is suggested for federal government projects by Transport Canada (2012b). The annual operation costs, initial capital costs and net present values (NPV) of the electric and hydrogen technologies are displayed in **Table 3-13**. The majority of costs are due the purchase of new rolling stock and electrical infrastructure. The capital costs of the hydrogen scenario only include rolling stock and its maintenance. Although a hydrogen locomotive is 2.5 times more expensive than an electric locomotive, this is more than offset by savings from infrastructure construction. A complete electrification of the commuter rail network in Montreal has a hefty price tag of $1.3 billion. These estimates are comparable to the proposed cost of $1.2-1.5 billion by the Quebec government in a feasibility report that has been requested but not yet available (Bisson, 2011). The $721 million cost for the hydrogen fuel cell scenario seem modest compared to the electrification case. In terms of NPV costs, hydrogen trains would be the best scenario for implementation.

Table 3-13 Cost of Electric and Hydrogen Technologies

Technology	Operation Cost ($ millions)	Capital Cost ($ millions)	NPV Cost ($ millions)
Electric	2.7	1,267.0	1,292.3
Hydrogen	7.8	647.3	720.9

3.5.4 Cost-Benefit Ratio

The benefits are the GHG savings in monetary terms from switching to the alternative technology; they are \$585 for electric scenario, \$141 for hydrogen from SMR, and \$485 for hydrogen from wind energy. The cost-benefit ratios were calculated from these minimal benefits and the total costs for the electric and hydrogen scenarios. The costs and benefits of electrification are both substantial; however, the costs far outweigh the GHG benefits in monetary terms such that the cost-benefit ratio is 2.17×10^6. In fact, the cost-benefit ratios of the alternative scenarios are all over one, in the seven figure range, due to the high costs and small benefits (**Figure 3-16**). Hydrogen fuel cell from SMR has the highest cost-benefit ratio, 4.64×10^6, owing to the small GHG reductions. The lowest cost-benefit ratio, 1.35×10^6, is linked to hydrogen fuel cell from wind energy. This scenario has high potential GHG savings at a relatively low cost. As a result, hydrogen from wind technology is the most cost-effective option compared to the other two scenarios.

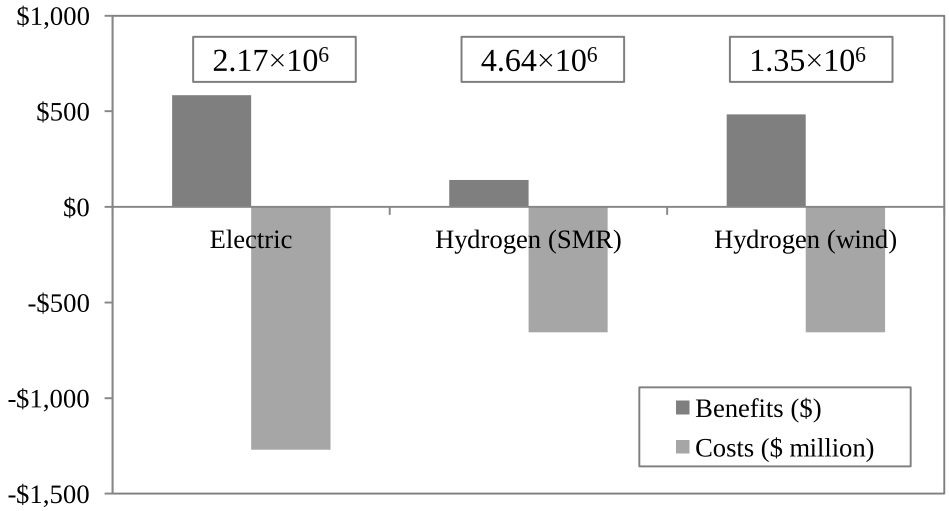

Figure 3-16 Cost-benefit ratios of electric and hydrogen scenarios

3.6 CONCLUSION

This chapter examined the GHG emissions for alternative technology and ridership scenarios for the commuter rail in Montreal. These technology scenarios were considered: base case, complete electrification, hydrogen fuel cell using SMR and hydrogen fuel cell using wind energy. The operation and capital costs for the electrification and hydrogen technologies were also evaluated. The costs and benefits were put into monetary terms to obtain the cost-benefit ratio and determine the most cost-efficient scenario.

A full electrification of the commuter rail network would lead to the greatest GHG reduction which is more than 27, 000 tonnes/year. This is a decrease of 98.4% from the current scenario. The hydrogen technologies had more modest GHG savings: 6,600 tonnes for hydrogen from SMR and

22,600 tonnes for hydrogen from wind energy. It is also noteworthy to mention that even if policies to encourage rail transit use are successful, the GHG emissions per capita of the reference case would still be higher than the electrification case for all ridership levels.

The electrification case is also associated with the lowest operating cost at $2.57/train-km. This is primarily due to Quebec's unique electricity source which is almost exclusively of hydro-power. Despite these benefits, electric infrastructure including overhead catenary and power substations are very expensive. In view of that, hydrogen-powered trains can be competitive with electric-powered trains. The implementation of hydrogen fuel cell commuter rail does not require the construction of infrastructure for power supply and distribution. Hence, the capital costs would mostly take into account the rolling stock. Hydrogen locomotives are twice as expensive as electric locomotives; however, the total cost is significantly lower than the electrification case. The costs are $1.3 billion for complete electrification compared with $721 million for a hydrogen fuel cell system.

The cost-benefit ratios indicate that hydrogen technology from wind power is the most cost-efficient scenario. This scenario demonstrates high GHG reductions at a relatively low cost. There are, however, several issues with hydrogen fuel cell technology for commuter rail. This is a new technology and further testing is required to prove its feasibility. There are also issues with storage, risk of explosion and commercial availability of hydrogen gas that need to be resolved. Feasibility studies of hydrogen trains are in progress in Japan, Denmark and Canada. Until hydrogen technology has been thoroughly tested, the implementation of this promising commuter rail technology would be premature and risky.

There were several limitations in this study. One major assumption is that the emissions from vehicle manufacturing and infrastructure construction are negligible; therefore, a LCA was not conducted. It would be ideal to quantify these emissions to further support the benefits of electric or hydrogen technology. The estimation of GHG emissions relies on linear coefficients and assumes constant parameters across time, loads and geometry. The availability of real fuel consumption rates dependent on speed, among other factors, would make it possible to investigate the fuel efficiency of alternative technologies in commuter rail service. Furthermore, fuel and electricity consumption are based on single values of system efficiency. It would be more robust to carry out a sensitivity analysis on a range of system efficiencies, specifically for the hydrogen fuel cell system, a hypothetical technology. From the results of the cost-benefit analysis, it was found that the electric scenario leads to great GHG reductions but at a very high cost. It would be worthwhile to examine hybrid commuter trains to verify how costs would differ compared to the high price tag of the full electrification case; perhaps, hybrid technology would be a more cost-effective option for implementation. This has also been left as future research. Only one element was examined for the benefits in the cost-benefit analysis, which explains the minimal benefits compared to the operation and capital costs. For future work, other aspects such as saved travel time and reliability should be considered to narrow the gap between costs and benefits.

4 Spatial Analysis of the Demand of Hybrid-Electric Vehicles and its Potential Impact on GHGs in Montreal and Quebec City

4.1 INTRODUCTION

Passenger cars contribute 56% of GHG emissions generated from passenger transportation and 31% of total GHGs in the transportation sector (NRCan, 2012a). These rates have remained steady in the last decade as vehicle ownership has increased while kilometres-travelled have declined (NRCan, 2010). As well, improvements in car technology such as increased fuel efficiency and exhaust emission control have also led to slight decreases in GHG emissions per vehicle since 1990. Technology change is considered by many to be the most promising solution to reduce GHG emissions without modifying travel behaviour (Axsen et al. 2009; Deakin, 2011).

Electric and hybrid-electric vehicles, that are becoming more and more popular, are particularly promising technologies to reduce vehicular GHGs. There are four types of electric vehicles, two of which are hybrid configurations: battery electric vehicles (BEV), extended-range electric vehicles (EREV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). BEVs are all-electric that get their power by plugging into an electricity grid. EREVs circumvent the low mileage of BEVs by using the internal combustion engine that powers the electric generator which recharges the battery (TVA, 2012). The internal combustion engine is only used to charge the battery while the electric motor powers EREVs (TVA, 2012). On the other hand, the electric motor supplements the internal combustion engine in HEVs; they work in combination depending on the speed and acceleration (Québec Government, 2012; TVA, 2012). The battery in HEVs is recharged through regenerative braking and the gasoline engine. In addition to these two methods of recharging, PHEVs are equipped with a large and powerful battery pack that is recharged with a plug connecting to the electric grid (TVA, 2012). This allows for hybrid vehicles to drive longer distances using only electric power (Québec Government, 2012).

Hybrid vehicles[3] became commercially available in 1997. At first, hybrid vehicles were disadvantaged with respect to traditional vehicles due to its worse performance and low fuel costs. Now, people are turning increasingly to more fuel-efficient technologies to reduce costs even if they come with a cost premium of $3,000-$6,350 (CTV News, 2011). Hybrid vehicles made up only 0.2% of the vehicle fleet in the province of Quebec in 2008 (according to the records of the provincial automobile insurer (SAAQ) vehicle inventory). At the same time, the hybrid fleet has been increasing dramatically. For instance in 2003, there were 339 hybrid vehicles in Quebec,

[3] Henceforth, the term 'hybrid vehicles' refers to HEVs only.

whereas by 2008 there were 7,085. This increase is likely partly due to government incentives in the form of rebates (CTV News, 2011). Currently, the provincial government offers rebates of up to $8,000 for first time purchases (Québec Government, 2012).

As a result, there is a growing literature investigating issues associated with new car technologies, such as: the impact of government policies, consumer purchase motivations, lifecycle cost analysis, market penetration, etc. Among them, an important topic is HEV demand analysis and its determinants (e.g. Axsen et al., 2009; de Haan et al., 2007; Diamond, 2009; and Gallagher and Muehlegger, 2011). In these analyses, various conceptual frameworks and methodologies have been used such as attitudinal surveys, risk perception studies, non-market economic valuation surveys, etc. Despite a surprisingly large literature, few studies have looked at the spatial distribution of the demand of hybrid vehicles and its link to residential neighbourhood characteristics such as socio-demographics, built environment and travel demand. Due to their higher costs, it is not difficult to believe that the HEV market is expected to be concentrated in high-income neighbourhoods. Given the effect of the built environment on so many other aspects of travel behaviour, it is relevant to ask if it can be expected to also affect HEV market penetration. In this research, it was hypothesized that dense neighbourhoods, where average households travel less by car, are positively linked with the penetration HEV rates. Another question is: what is the expected impact of HEVs on the GHG inventory at the city or regional level? Many studies have looked at the LCA of hybrid vehicles for different car usage profiles; however, few studies have explored the potential impacts of HEVs in terms of GHG emissions at the macro level (Helms et al., 2010; Nicolay et al., 2000; Samaras and Meisterling, 2008).

Accordingly, the objectives of this chapter are to:

1) Explore the link between socio-demographics, travel patterns and market penetration of hybrid vehicles; and

2) Evaluate the potential reduction in GHG emissions from HEVs using different market penetration scenarios.

The chapter continues with a literature review on the market for hybrid vehicle ownership. The third section describes in detail the methodology that was applied, followed by the data description and results sections. The sixth section concludes with a summary of the results and its implications.

4.2 LITERATURE REVIEW

This literature review concentrates on research related to hybrid vehicle ownership that attempts to understand and identify reasons behind hybrid vehicle purchases, as well as to develop policies to encourage their purchase (Ozaki and Sevastyanova, 2011). Once a market has been established, studies predict long-term market penetration rates under various scenarios.

4.2.1 Consumer Purchase Motivations of Hybrid Vehicles

There are several factors that have been found to influence the purchase of electric or hybrid vehicles. The most important factors found in the literature include fuel costs, vehicle price, travel needs, environmental concern and technological interest (Golob et al., 1993; Lieven et al., 2011; Ozaki and Sevastyanova, 2011).

The price of electric and hybrid vehicles is much higher than gasoline vehicles; therefore, people who purchase hybrid vehicles need to be able to afford it. Research has shown that hybrid vehicle owners tend to belong in the highest income brackets (Diamond, 2009). Although, it has been noted that this may change in the future as the increase in hybrid vehicle ownership is in response to rising gas prices and government incentives (Diamond, 2009; Gallagher and Muehlegger, 2011; Ozaki and Sevastyanova, 2011). Tax rebates offered by governments reduce the initial cost of purchasing a vehicle thus making prices more competitive to traditional cars. Also, owning a clean vehicle would reduce fuel costs due to its fuel efficiency. In some cases, hybrid vehicle drivers have the opportunity to drive in carpool lanes and avoid congestion (Ozaki and Sevastyanova, 2011); although, it has been found that this did not have a significant impact on hybrid vehicle sales (Gallagher and Muehlegger, 2011).

Many potential consumers have been reluctant to purchase electric vehicles because of concerns related to their travel needs. In the past, the limited driving range and lack of public charging stations has been a major drawback to electric vehicles (Kurani et al., 1994, 1996; Lieven et al., 2011). At the same time, a reflexive survey conducted to capture the demand for hybrid vehicles found that limited driving range was not a big issue for multi-car households (Kurani et al., 1996). The results also show that there is no statistically significant relationship between vehicle choices and households commute trip distances (Kurani et al., 1996). In fact, most households overestimated travel distances and falsely believed that an electric vehicle would not be able meet their driving range (Golob and Gould, 1998; Kurani et al., 1994). The study also recommends embracing the unique attributes of electric vehicles that are preferred by some consumers, such as home recharging and reduced-range (Kurani et al., 1994). In contrast, another study found a significant link between hybrid vehicle ownership and vehicle miles travelled; a 10% increase in vehicle-miles travelled per capita led to an 8-15% increase in the portion of hybrid vehicles by state (Diamond, 2009).

Another important factor in vehicle choice can be the environment. Some consumers are concerned with environmental degradation, and are motivated to reduce carbon emissions and its impact on the environment. Furthermore, environmentally-friendly consumers tend to be clustered in the same neighbourhood and residents may feel compelled to conform to the community's values and norms (Ozaki and Sevastyanova, 2011). These neighbourhoods may also be characterized by their low car usage. In spite of this, concerns for the environment do not necessarily translate into willingness to pay thousands of dollars more for clean vehicles (Kurani et al., 1996).

Besides high income and environmental consciousness, interest in technological innovations characterizes ‘early adopters’ of hybrid technology (Gallagher and Muehlegger, 2011; Ozaki and Sevastyanova, 2011). It seems that the current market for hybrid vehicles is made up mostly of “early adopters.” Evidently, market penetration of hybrid vehicles is still in the early stages and is far from being saturated.

In this growing literature, few studies examine the spatial distribution of the HEVs and its association to neighbourhood socio-demographics and built environment factors (Diamond, 2009; Ozaki and Sevastyanova, 2011). One study collect information on some of these factors which asked for age group, gender, household composition, household income, postal code (i.e. geographic location) and car ownership history (Ozaki and Sevastyanova, 2011). The majority of the respondents of this study were retired males aged 50 and over (Ozaki and Sevastyanova, 2011). Other important socio-demographic factors that could have some influence on the market for hybrid vehicles include population density, education level, fuel consumption rate, number of children, as well as analyzing data for different cities and multiple years. These factors have not been investigated before, and this research seeks to address this weakness.

4.2.2 Policies and Research Methods

The identification of the market for hybrid vehicles leads to several policy implications. It has been shown in several studies that government incentives are effective in increasing hybrid vehicle sales (de Haan et al., 2007; Diamond, 2009; Gallagher and Muehlegger, 2011; Ozaki and Sevastyanova, 2011). The quantity and the type of subsidies such as tax credits or tax waivers have varying effects (Gallagher and Muehlegger, 2011). Tax rebates seem to favour high-income households that are more likely to buy a hybrid vehicle in the first place (Diamond, 2009). Accordingly, it has been argued that subsidies should also be offered to families with children and low-income households (Ozaki and Sevastyanova, 2011). Environmental benefits do not appear to be a top priority for hybrid vehicle purchases: something that could indicate that environmental awareness is lacking (Ozaki and Sevastyanova, 2011). As such, it is argued that advertising campaigns educating the public on environmental and personal benefits of hybrid vehicle technology are needed (Ozaki and Sevastyanova, 2011). Evidence also shows that increasing gasoline prices encourage the purchase of more fuel-efficient vehicles (Diamond, 2009).

The primary methods used in the literature are stated preference surveys combined with exploratory data analysis (de Haan et al., 2007; Kurani et al., 1994, 1996; Lieven et al., 2011). The problem with this method is the discrepancy between what they say they would do and what they would actually do. Also, it is difficult to properly identify and measure the market of new technology since potential consumers are unfamiliar with it (Golob and Gould, 1998); it may not be sufficient to predict demand based on current preferences to similar products (Kurani et al., 1996). The questionnaires mostly inquire about the type and use of the vehicle, and their reasons for purchase. Some other studies use analysis of variance (ANOVA) or regression analysis (Diamond, 2009; Gallagher and Muehlegger, 2011; Ozaki and Sevastyanova, 2011).

4.2.3 Market Penetration Rates

The success of hybrid vehicle adoption can be determined by its market penetration rate. Several studies attempt to forecast the market penetration rates of hybrid (Axsen et al., 2009; Balducci, 2008) and fuel cell vehicles (Hollinshead et al., 2005). Other studies examine the effect on energy supply (Hadley and Tsvetkova, 2009), energy consumption and emissions for different market penetration scenarios (Baptista et al., 2010). New technology market penetration rates tend to follow an S-curve over time with two distinct phases (Hollinshead et al., 2005). The initial period experiences a slow growth whereby the technology is unfamiliar and people are unsure about its reliability. The slow growth is due to the high costs associated with the new technology whereby there is a lack of investment and resources to refine the emerging technology (Balducci, 2008). At this stage, market penetration ranges from 0% to 10% and typically lasts 14-19 years (Balducci, 2008; Hollinshead et al., 2005). The next phase is a steep slope in which everyone wants to try out the new popular technology termed the "neighbour effect" (Axsen et al., 2009). This period is associated with cost reductions and improved system efficiencies (Balducci, 2008; Hollinshead et al., 2005). The curve eventually levels off reaching a saturation point. There are factors that influence this saturation point. Barriers to the plug-in hybrid vehicle market include price, vehicle dependability, battery, vehicle design, manufacturing process, supply chain management, engineering capabilities, raw material limitations, and capacity of charging stations (Balducci, 2008; Baptista et al., 2010; Hollinshead et al, 2005). Based on different scenarios, market penetration can be as little as 2% to a maximum of 73% (Axsen et al., 2009; Balducci, 2008; Hollinshead et al., 2005). It usually takes about 12 years for the market penetration to increase from 10% to 90% (Balducci, 2008; Hollinshead et al. 2005).

Despite this large literature, there is a gap on the spatial analysis of the hybrid market. More specifically, few studies have explored the link between the HEV penetration rates and the link to neighborhood characteristics and travel patterns. Also, no studies were found that performed a market analysis and investigated the impact on GHG emissions at the city or regional level.

4.3 METHODOLOGICAL FRAMEWORK

To respond to the objectives of this study, the following steps are necessary:

• Identification of neighbourhood factors associated to HEV market

• Estimation of the GHG inventory for the base scenario

• Definition of the market penetration rates for the estimation of the GHGs for different scenarios.

This is expected to help identify the impact of HEV in terms of GHGs at the city-level under different scenarios.

4.3.1 Hybrid Market Spatial Analysis and Neighbourhood-Level Determinants

In this study, a hybrid market analysis is carried out at the neighbourhood level represented by the postal code areas. For each FSA, the car ownership characteristics are known. In particular, the total number of vehicles of each type is known including the number of hybrid vehicles in a particular year. The socio-demographics characteristics and travel distances are also known. Accordingly, an aggregate model representing the market penetration rate (MPR) is formulated as follows (**Equation 4-1**):

$$MPR_i = {}^{\lambda_i}/_{N_i} = f(I_i, H_i, P_i, D_i, \varepsilon_i) \qquad [\mathbf{4\text{-}1}]$$

Where,

MPR_i – penetration rate in area i

λ_i – Number of hybrid vehicles in a given area i

N_i – Total number of vehicles in a given area i

I_i – Income

H_i –Household structure (number of children, average family size, etc.)

Pi – Neighbourhood characteristics (population density, education, etc.)

D_i – Travel distances

ε_i – Unobserved factors

Once more, the hypothesis is that central neighbourhoods with high income and high residential density have a much higher penetration rate of hybrid vehicles than a suburban area with low residential density in which travel distances are much longer. Similarly, areas with low car usage are expected to prefer hybrid vehicles than those areas where car usage is relatively higher.

In order to establish this relationship, a Negative Binomial (NB) regression was applied. This regression was chosen because the number of hybrid vehicles in a given area is a count variable skewed to the right. Moreover, this model accommodates for unobserved factors (heterogeneities). The NB regression equation is presented in **Equation 4-2**, where β's are the model parameters, x's are the independent variables such as income (I_i) and household structure (H_i) as defined in **Equation 4-1**:

$$Y_i \sim \text{Poisson}(\lambda_i)$$
$$\lambda_i \times 100 = N_i \cdot exp(\beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k) \cdot exp(\varepsilon) \quad [\mathbf{4\text{-}2}]$$

This means that $100\lambda_i/N_i = exp(\beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k)$ and this model is estimated using a maximum likelihood method implemented in STATA (Statacorp, 2009). The left-hand term is multiplied by 100 to obtain proportions of hybrid vehicles as a percentage. The best-fit model is selected by minimizing the Akaike information criterion (AIC) and including significant variables at the 5% level. To find the best equation (combination of variables), the Akaike information criterion (AIC) is used which penalizes the model with more variables. The calculation of AIC is given by *AIC = 2k – 2ln(LL)*, where k is the number of parameters and LL is the log-likelihood of the model. Moreover, of the correlated variables, an attempt is made to select only one to remain in the model to reduce multi-collinearity.

To measure the impact of each variable on MPR_i, the elasticities are estimated. In this case, the elasticity measures the change in hybrid vehicle ownership for every 1% change in the independent variable. The elasticity at the means is calculated with the parameters estimated in the regression analysis and the sample means of the independent variables. This is demonstrated in **Equations 4-3 and 4-4** for continuous and discrete variables, respectively,

$$E_{i,continous} = \beta_i \times \frac{\overline{x_i}}{\bar{\mu}} \quad [\mathbf{4\text{-}3}]$$

$$E_{i,discrete} = \frac{\exp(\beta_i) - 1}{\exp(\beta_i)} \quad [\mathbf{4\text{-}4}]$$

Here, *E* is the elasticity, $\overline{x}$ is the mean of the independent variable and $\bar{\mu}$ is the mean of the penetration rate estimated with the model (i.e. $\mu_i = exp(\beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k)$).

4.3.2 GHG Estimation

Recall that one of the main objectives of this chapter is to evaluate the impact of hybrid vehicle technology at the regional level. For this purpose, the GHG inventory at the trip level is first estimated for the households, located within the study areas defined in this research that participated in the O-D surveys of 2008 for the Montreal region and 2006 for the Quebec City region. More details about the different data sources are provided later.

The GHG emissions generated from car trips were calculated for the Montreal and Quebec City regions using **Equation 4-5**, a methodology developed by Zahabi et al. (2012):

$$GHG_{trip} = \sum_{i=1}^{n}(L_i \times SPF_i) \times FCR \times EF \qquad [\textbf{4-5}]$$

Here, L is the link length, SPF is the speed correction factor, FCR is the fuel consumption rate (L/100km) and EF is the emission factor (kg/L). This multi-step process required the use of several softwares including MapInfo, STATA, Matlab, ArcMap and Excel. The steps are outlined below:

• From the OD Survey, extract the pure car trips where the trip maker is the driver of the vehicle.

• Determine the origin and destination centroids of the TAZs for all trips.

• Associate each trip ID with their OD centroids.

• Using congested link travel times (provided by the provincial ministry of transportation), and the shortest path tool in MapInfo, list the lengths and speeds of all links travelled in each trip using the congested times.

• Find the speed correction factor associated with the speed link, multiply it with the length of each link, and then find the sum of this product for each trip.

• Determine the FSA where the trip maker's residence is located and obtain the corresponding average fuel consumption rate (FCR). Finally, using a CO_2-equivalent emission factor of 2.364 kg/L of gasoline (Transport Canada, 2012a), determine the GHGs according to **Equation 4-5**.

Once the GHG emissions for each trip were found, these were expanded to reflect the total population in the study areas and summed up to find the GHG emissions generated from an entire FSA - for those associated to car trips involving only motor vehicle. This process was carried out for Montreal in 2008 and Quebec City in 2006 (Zahabi et al., 2012). Note also that transit trips or trips involving more than two motorized modes (including kiss-and-ride and park-and-ride trips) were not included.

4.3.3 Market Penetration Rates for GHG Scenarios

The final step is the formulation of market penetration scenarios which is based on a literature review, historical data on penetration rates in the two study areas and the variables identified in the regression analysis. For this purpose, different scenarios are formulated including the base scenario that is defined as the GHG inventory using OD survey data. The trend in hybrid vehicles appears to be an exponential growth between 2003 and 2008. At this stage, the penetration rate of a new technology is expected to be very steep. At some point, it is known that the market will become saturated and the number of hybrid vehicles will remain constant. The goal of this section is not to determine when this will occur but rather what reductions in GHG emissions can be expected for different market penetration rates.

Although, some studies predict high adoption rates, plausible rates between 0% and 25% are applied. Additionally, the Quebec government policies have established programs that aim to have a vehicle fleet composed of 25% electric vehicles by 2020 (Québec Government, 2012).

Since the proportion of hybrid vehicles across FSAs varies significantly, it is unrealistic to assume that all FSAs would have the same market penetration rates. Therefore, once the GHGs are estimated for each city for the base scenario, the FSAs are classified according to 3 types: FSAs with high, medium and low proportions of hybrid vehicles. Using the Jenks natural breaks classification method[4] (ESRI, 2012) on the Quebec City data, a proportion that is less than 0.07% is considered "low" where as a proportion greater than 0.27% is considered "high" (**Table 4-14**). All values in between the "low" and "high" proportions are put into the "medium" category. The same classification was adopted by Montreal FSAs to maintain consistency. If natural breaks produced from the Montreal data was used for Quebec City, all of these FSAs would be defined as low proportions. Furthermore, 0.1% was the average proportions of hybrid vehicles in Montreal in 2003 when they were first introduced, and 0.28% was the 2008 average proportions in Montreal. Afterwards, three scenarios were established: optimistic, medium and conservative as shown in **Table 4-15**.

Table 4-14 Classification of Proportions

Level	Proportions (%)	Count of FSAs in Montreal	Count of FSAs in Quebec City
Low	<0.07	3	35
Medium	0.07-0.27	54	11
High	>0.27	45	3

Table 4-15 Market Penetration Scenarios

Proportions	Optimistic	Medium	Conservative
High	25%	25%	20%
Medium	25%	15%	10%
Low	25%	5%	0%

The optimistic scenario assumes that all types of FSAs will reach saturation at the same time with a penetration rate of 25%. The conservative scenario will have lower penetration rates in which FSAs with low proportions will not exhibit any growth in the future. The medium scenario takes

[4] The Jenks natural breaks separate the data into classes such that the each class groups data with similar values and the differences between classes are maximized (ESRI, 2012).

on market penetration rates in-between the optimistic and conservative values. The rates decrease with decreasing proportions of hybrid vehicles.

In order to calculate the change in GHG emissions, it is necessary to determine the new average fuel consumption rate corresponding to each FSA. Due to differences in vehicle fleets in Montreal and Quebec City, the study areas are analyzed separately to determine the hybrid consumption rate. From the SAAQ data, it was found that the weighted average fuel consumption rate of the hybrid vehicle fleet in 2008 is 5.775 and 5.448 litres of gasoline for every 100 kilometres, for Montreal and Quebec City, respectively.

The new fuel consumption rate is the average between the current fuel consumption rate ($FCR_{current}$) and the hybrid fuel consumption rate weighted by the MPR of hybrid vehicles as formulated in **Equation 4-6**. Current fuel consumption corresponds to the year 2008 for both study areas. Note that it is assumed that the profile of the fuel consumption rate by speed behaves similarly between regular gasoline and hybrid vehicles. If fuel consumption curves were to be drawn, the only difference between the two curves is that the one for hybrid vehicles is rescaled to a smaller consumption rate.

$$FCR_{new} = FCR_{current} \times (1 - MPR) + FCR_{hybrid} \times MPR \qquad [\textbf{4-6}]$$

The GHG calculations are carried out using the equation mentioned earlier. The change in GHG emissions is estimated with **Equation 4-7**.

$$Change\ in\ GHG\ (\%) = \frac{GHG_{new} - GHG_{current}}{GHG_{current}} \times 100\% \qquad [\textbf{4-7}]$$

This procedure entails a few assumptions including 1) the hybrid vehicle fleet composition remains the same in the future in both study areas; 2) the current fuel consumption rate (which includes HEVs) does not change significantly if hybrid vehicles were excluded due to the very low proportions; 3) the same routes are traversed such that the length and speed of links do not change; 4) the emission factor of automobiles does not improve in the future; and 5) the fuel consumption of gasoline and hybrid vehicles does not change over time.

4.4 DATA DESCRIPTION

The unit of analysis in this research is the forward sortation area (FSA). FSAs are identified by the first three digits of a Canadian postal code. The two cities that were studied are Montreal and Quebec City. The analysis is limited to urban areas where the proportion of hybrid vehicles is highest. The Montreal region is defined as the Island of Montreal. It is comprised of 102 FSAs (first letter is ‘H’). In Quebec City, the census metropolitan area (CMA) was narrowed down to 49 FSAs (first letter is ‘G’). The Montreal and Quebec City study areas are shown in **Figures 4-17 and 4-18**. The study examines hybrid vehicle ownership in these geographic regions over multiple years: 2003 and 2008 in Montreal, and 2006 in Quebec City.

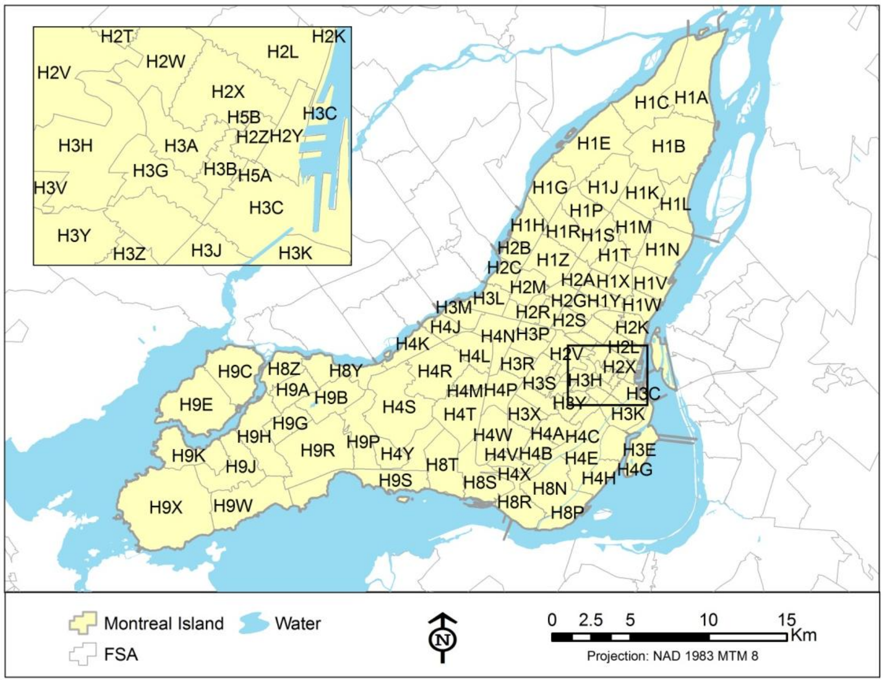

Figure 4-17 Montreal study area

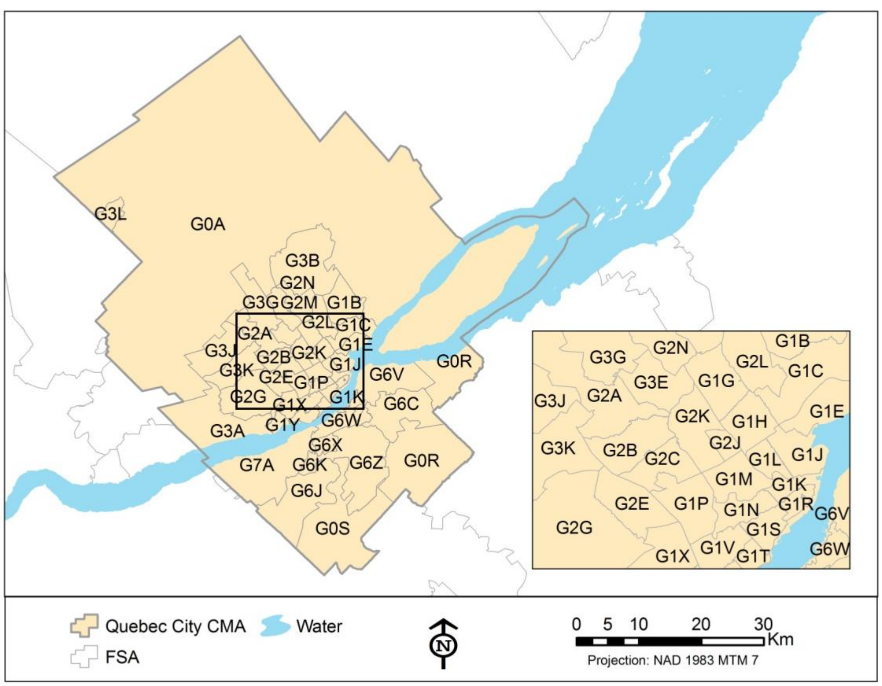

Figure 4-18 Quebec City study area

4.4.1 Data Sources

The three main sources of data are: the Canadian Census, Origin-Destination (OD) Surveys and the Société de l'assurance automobile du Québec (SAAQ – Quebec's provincial automobile insurance corporation). The SAAQ data used was first processed by the Centre for Data and Analysis in Transportation (CDAT). Socio-demographic information was taken from the Canadian Census and was available at the census tract-level. Due to different boundaries of census tracts and FSAs, some assumptions enabling comparison needed to be made. Namely, that the population is evenly distributed in the census tract such that the population in one FSA can be taken as the sum of the portion of the census tract populations covered within this FSA. This proportion is equivalent to the proportion of the census tract area in the FSA out of the total census tract area. Other socio-demographic attributes were treated in a similar fashion.

Origin-destination surveys for Quebec and Montreal was used to find the average trip distances per household and to estimate GHGs. The OD surveys of Montreal and Quebec City are quite similar and are both characterized by large household samples (ca.5%) and are undertaken regularly (every 5-10 years) (Secrétariat de l'enquête Origine-Destination, 2008). The average daily trip distances include trips made during peak and off-peak periods on weekdays. Only car trips were analyzed, in other words, trips in which the only mode of travel was by motor vehicle. The process for estimating trip distances is similar to the procedure described for the estimation of GHGs. Using congested link travel times, provided by MTQ, the shortest paths by travel time are computed for each trip. The total trip distances and number of households were aggregated by FSA to find the average trip distances per household.

The annual vehicle fleet composition and the corresponding fuel consumption at the FSA-level are originally from the SAAQ and heavily processed by CDAT (Barla, 2008).

4.4.2 Trends and Spatial Analysis of Hybrid Vehicles

The number of hybrid vehicles increased exponentially between 2003 and 2008 in Quebec: in fact, it increased by almost 20, as illustrated in **Figure 4-19**. The trends in urbanized areas (i.e. island of Montreal and Quebec City CMA) exhibit slightly higher growth rate than in the rest of the province. The number of hybrid vehicles in the two cities considered makes up about 40% of the total in the province. This is expected since the study areas cover a population of 2.5 million out of 7.75 million people in the Quebec province.

Hybrid vehicles became commercially available in Quebec in 2003 with only two automobile manufacturers and 3 models: Honda Civic, Honda Insight and Toyota Prius. By 2008, Quebec consumers were choosing between 12 carmakers and 21 models. The distribution of hybrid vehicle manufacturers within the study areas is shown in **Figure 4-20**. In the introductory year, Toyota and Honda were equally popular. Since 2004, the Toyota brand became the most popular making up at least 50% of hybrid vehicles every year.

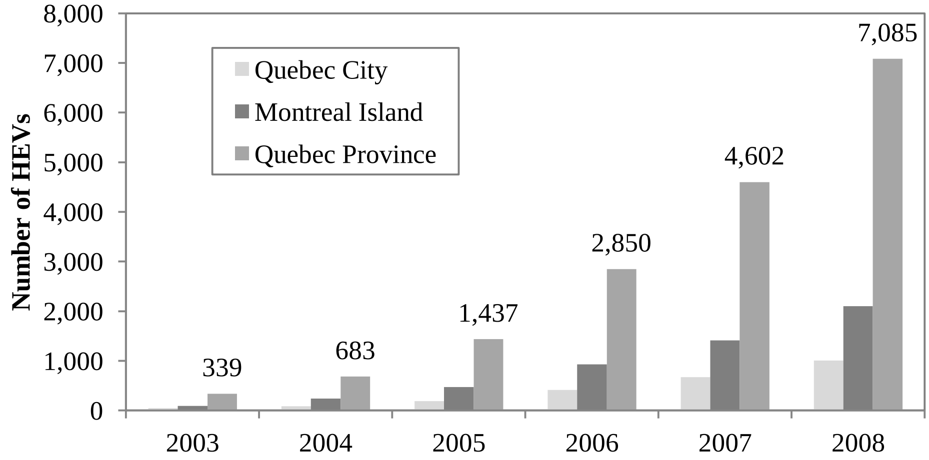

Figure 4-19 Trend in hybrid vehicles in Quebec City, Montreal and Quebec

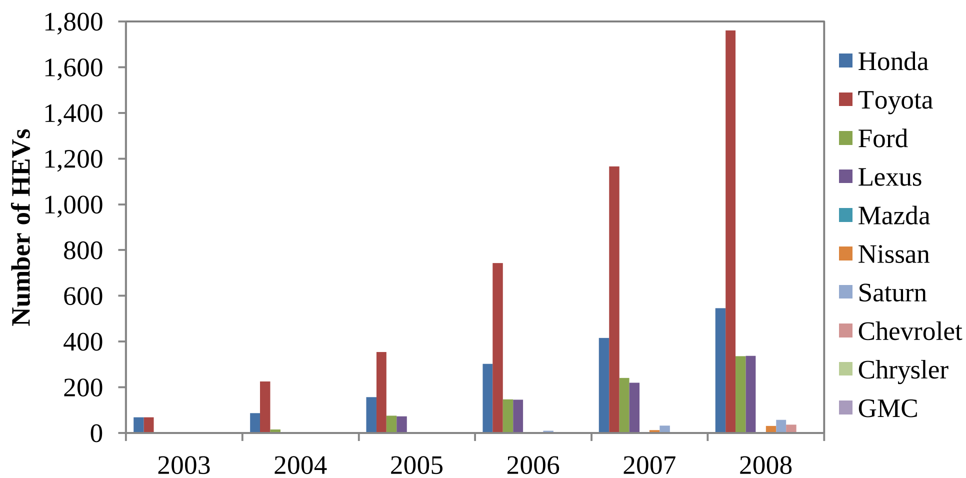

Figure 4-20 Trend in hybrid vehicle manufacturers in both study areas

The dependent variable use in this analysis is the percent of hybrid vehicles by FSA. The count of hybrid vehicles excludes those used for taxis in order to capture personal travel demand. In Montreal, zero hybrid vehicles were purchased for taxi driving in 2003. In 2008, there were 6 hybrid vehicles registered as taxis. In Quebec City in 2006, there were 6 hybrid taxi vehicles. The count of FSAs with zero hybrid vehicles are as follows: 51 in Montreal in 2003, 1 in Montreal in 2008 and 3 in Quebec City in 2006.

The proportion of hybrid vehicles was deemed more suitable to assess the relationship between socio-demographics and hybrid ownership. The use of absolute numbers would not be useful because some FSAs have inherently large vehicle fleets, which might also indicate a high number of hybrid vehicles. **Figures 4-21 to 4-23** depict where FSAs with high proportions are located.

Due to the recent introduction of hybrid technology in 2003, a clear pattern cannot be distinguished to locate households with hybrid cars. H4Y has the highest proportion; although, there are a small number of vehicles registered in this FSA.

In 2008, households with higher proportions of hybrid vehicles are located in the downtown core and in the West Island. These areas are associated with high household incomes that can afford the more expensive technology. The area near downtown, particularly the Plateau Mont-Royal borough, also exhibit high proportions. This is intuitive since this borough is known for being an environmentally conscious neighbourhood. Also, urban areas are generally associated with environmental consciousness. The same pattern can be discerned in Quebec City where the high proportion areas are situated in downtown, on the north shore of the Saint-Lawrence River.

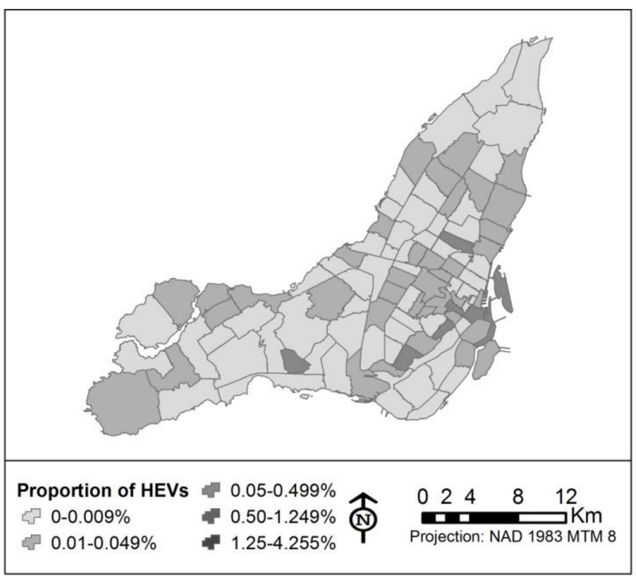

Figure 4-21 Proportion of hybrid vehicles in Montreal 2003

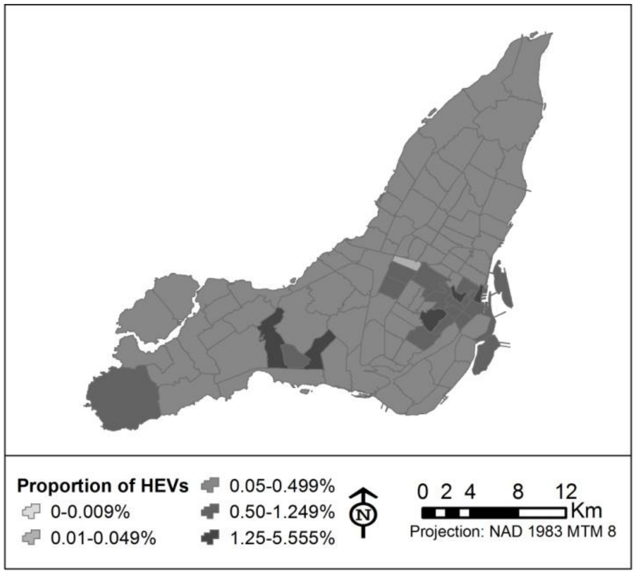

Figure 4-22 Proportion of hybrid vehicles in Montreal 2008

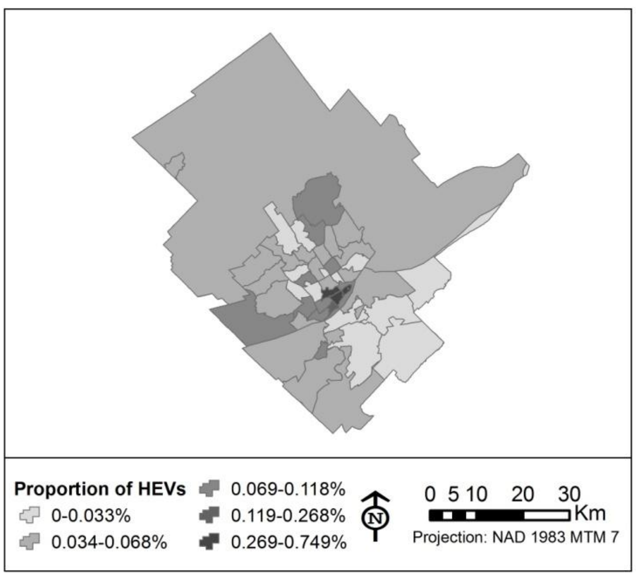

Figure 4-23 Proportion of hybrid vehicles in Quebec City 2006

4.4.3 Independent Variables and Correlations

FSA attributes that were considered and their respective units are described in **Table 4-16**. In summary, population, education level, gender, age, children, vehicle ownership, income, trip distances, fuel consumption rate were investigated. Two dummy variables were added one to explain the higher proportions of hybrid vehicles in Montreal (*mtl*), and another one for the growth of hybrid vehicle ownership over time (*add_year*). Even though the dataset for Quebec City corresponds to the year 2006, a dummy variable was not created to represent the different year. This is because it would have been the inverse of the *mtl* dummy variable and STATA would have omitted this variable in order to run the regression analysis. Note that FCR and *fuel_cons* are identical terms: the former is used for GHG calculations and the latter is used for the regression.

Table 4-16 Variables Tested in Model

Variable	Description
pop_dens	Population density in FSA (1,000 persons/km^2)
p_hs	Proportion of population with only a high school diploma in FSA
p_uni	Proportion of population with a post-secondary education in FSA
p_male	Proportion of population that are males in FSA
p_female	Proportion of population that are females in FSA
age	Average age of the population in FSA
kids_hh	Average number of children per household in FSA
ppl_hh	Average number of people per household in FSA
auto_hh	Average number of motor vehicles per household in FSA
inc_hh	Average annual household income in FSA ($10,000)
dist_hh	Average daily household driven distances in FSA (km)
fuel_cons	Average fuel consumption of vehicle fleet in FSA (L/100 km)
mtl	Dummy variable for Montreal (0 = no; 1 = yes)
add_year	Dummy variable for additional year (0 = no; 1 = yes)
all_veh	Total number of vehicles in FSA
HEV	Number of hybrid vehicles in FSA
p_HEV	Proportion of hybrid vehicles in FSA (%)

Inspection of the dataset indicates nine outliers that have populations of less than 15 people or have unusually low incomes. These FSAs were omitted from the final dataset. Subsequently, the final dataset combining Montreal and Quebec City for the three years has 244 observations (46 for Quebec City in 2006, 98 for Montreal in 2003 and 100 for Montreal in 2008). The summary statistics for each of the study areas are shown in **Table 4-17.**

a) Montreal

The Montreal sample indicates that the mean population density is 5,349 people per square kilometre with an average age of 39.3 years old and a household income of $67,000. In terms of education, it is surprising to see that 10% of the population lists high school diploma as their highest degree obtained and about 25% have a college/university degree. There are slightly more males than females in the sample data. On average, households have just one child and more than two people living there. They also own one vehicle and drive approximately 24.4 kilometres every weekday. The proportion of hybrid vehicles is quite low, averaging 0.19% in the Montreal study area; they range from 0% to as high as 2.23%.

b) Quebec City

The portrait of Quebec City is very different from Montreal in terms of population density, income and trip distances. The Quebec City region exhibits a much lower density than Montreal of about 1,460 people per square kilometre. Average household income is also two times smaller than the household incomes for Montreal Island. About the same percentage of people have only a high school degree while 13% earned a degree in post-secondary education. The gender distribution in Quebec City is identical to Montreal. Their household structure is also different; the average number of children per household is less than one with a family size of more than two people. Households in Quebec City own more cars on average and also travel 39.4 km by car every weekday. Given these vast differences, the proportions of hybrid vehicles are also smaller with a mean of 0.10%.

Table 4-17 Descriptive Statistics

	Montreal				Quebec City			
Variable	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
pop_dens	5.35	3.50	0.21	18.53	1.46	1.49	0.02	6.25
p_hs	0.10	0.03	0.04	0.16	0.12	0.03	0.04	0.16
p_uni	0.25	0.11	0.07	0.61	0.13	0.05	0.06	0.26
p_male	0.48	0.02	0.44	0.59	0.48	0.02	0.40	0.51
p_female	0.52	0.02	0.41	0.56	0.52	0.02	0.49	0.60
age	39.27	2.87	33	49	39.83	4.46	33	55
kids_hh	1.04	0.23	0.30	1.50	0.66	0.25	0.10	1.10
ppl_hh	2.25	0.38	1.30	3.20	2.32	0.39	1.20	2.90
inc_hh	6.66	2.94	3.29	25.07	3.51	0.69	2.30	6.13
auto_hh	1.03	0.39	0	2	1.42	0.42	0	2
dist_hh	24.40	15.92	0	77.92	39.36	18.61	0	78.80
fuel_cons	9.42	0.45	8.71	11.31	9.07	0.30	8.68	10.29
mtl	1	0	1	1	0	0	0	0
add_year	0.51	0.50	0	1	0	0	0	0
all_veh	7,552.97	3,600.95	115	20,689	10,951.63	10,709.36	13	53,356
HEV	11.05	15.37	0	89	8.83	14.42	0	89
p_HEV	0.19	0.30	0	2.23	0.10	0.16	0	0.75

To explore the linear association between hybrid penetration rates and the variables listed above, a correlation matrix was generated. From this, it is observed that the variables with the most explanatory power are population density, portion of population with a post-secondary education, average number of children per household, household size, household income, driven distances and dummy variable for hybrid vehicle growth trend. From the correlation matrix shown in **Table 4-18**, it can be observed that *p_uni* and *inc_hh*, *kids_hh* and *ppl_hh*, *dist_hh* and *ppl_hh*, and *dist_hh* and *pop_dens* are highly correlated to each other. As a result, it was a challenge to find the best fit model while reducing multicollinearity.

Table 4-18 Correlation Matrix

Variable	*p_HEV*	*pop_dens*	*p_uni*	*kids_hh*	*ppl_hh*	*inc_hh*	*dist_hh*	*add_year*
p_HEV	1							
pop_dens	-0.04	1						
p_uni	0.22	0.25	1					
kids_hh	-0.09	0.05	-0.05	1				
ppl_hh	0.00	-0.46	-0.31	**0.66**	1			
inc_hh	0.28	-0.15	**0.63**	0.33	0.23	1		
dist_hh	-0.29	**-0.58**	-0.25	0.30	**0.64**	0.14	1	
add_year	**0.54**	0.18	0.10	0.21	0.08	0.14	-0.40	1

4.5 RESULTS

The results of this study are presented in two parts. The first part is the interpretation of the relationship between neighbourhood factors and hybrid penetration rates. The second part demonstrates the impact of hybrid vehicles on GHG emissions under different scenarios.

4.5.1 Neighbourhood Factors

The models developed sought to establish a relationship between socio-demographics, travel behaviour and hybrid vehicle ownership. The three best models are presented in **Table 4-19**. It starts off with a basic model with only three variables. The subsequent models increase in complexity such that they fit the data better; however, the models tend to include variables that are less significant and that are correlated.

All three models include driven distances travelled and the dummy variable for growth trend. Other important variables are household income, population density, post-secondary education, number of children per household and household size. For all three models, the elasticity of *add_year*, which is a discrete variable, is the greatest. This is expected since the trend in hybrid vehicles is increasing at an exponential rate. Model 2 was chosen as the best-fit model because it balances the trade-offs between significant variables, multicollinearity and AIC. The models are discussed in detail below.

Table 4-19 Final Regression Models

	Model 1			Model 2			Model 3		
	β	P-value	E (%)	β	P-value	E (%)	β	P-value	E (%)
pop_dens				-0.14	0.01	-26.0			
p_uni				2.98	0.04	27.7			
kids_hh							-2.75	0.00	-107.2
ppl_hh							1.25	0.10	113.7
inc_hh	0.09	0.01	22.4				0.09	0.01	22.0
dist_hh	-0.02	0.11	-24.8	-0.03	0.06	-28.7	-0.01	0.48	-14.2
add_year	1.82	0.00	83.8	1.98	0.00	86.2	2.20	0.00	88.9
constant	-3.07	0.00		-2.61	0.00		-3.74	0.00	
ln (μ)		-281.89			-16.73			-19.64	
LL		-85.57			-83.10			-80.96	
AIC		179.13			178.19			175.92	

a) Model 1

The first model includes household income, driven distances travelled and the dummy variable for growth trend. All variables are significant and uncorrelated; nevertheless, it has the highest AIC compared to the other models. For *inc_hh*, a 1% change in household income would increase the proportion of hybrid vehicles by 22.4%. Likewise, an increase of 1% in the driven distances would lead to a decrease in the proportion of hybrid vehicles by 24.8%. In this case, hybrid vehicle ownership is more sensitive to travel behaviour than socio-demographics.

b) Model 2

Model 2 is composed of the following variables: population density, population with a post-secondary education, driven distances travelled and the dummy variable. The main difference between Models 1 and 2 is the population density since post-secondary education and income are equivalent terms. The AIC is lower in this model; however, there is multi-collinearity between *pop_dens* and *dist_hh*. The elasticities of population density, post-secondary education and distances travelled are between 25 and 30%. Recall that *pop_dens* is in thousands of people; hence, a 1% increase is equivalent to 100 people which result in a change of -26.0% in hybrid vehicles. It can be noticed that the elasticity of *dist_hh* is slightly higher in Model 2 than Model 1.

c) Model 3

Two additional variables were added in the third model. Besides number of children per household and household size, the variables are the same from Model 1. AIC is minimized in this model yet distance travelled is not significant anymore and multicollinearity exists. The elasticities for number of children per household and people per household are quite large: -107.2% and 113.7%, respectively. For household income, an elasticity value similar to the one in Model 1 is observed. With respect to driven distances, a difference of 40% in the elasticity is noticeable compared to the other models. This makes sense since this variable is not as statistically significant as it is in the previous models. Note that these elasticities should not be considered heavily as there is multicollinearity in this model.

d) Interpretation of parameter signs

Income and post-secondary education have a positive influence whereas number of children, population density and trip distances are negatively related to hybrid vehicle ownership. Higher income households are more likely to own hybrid vehicles since they can afford it. Similarly, people with a post-secondary education are perhaps more aware of global climate change and its effects and presumably are more environmentally conscious. Households with children consider space and performance more important aspects when purchasing a vehicle, while environmental impact is less important. It is interesting to see that population density has a negative effect on hybrid vehicle ownership. A dense area would imply a dense road network. On one hand, a well-connected road grid leads to people using active transportation. On the other hand, a hybrid vehicle would perform best in urban driving conditions. This is characterized as short trip distances and numerous stop-and-go events. The negative sign of trip distances reinforces the idea that people who carry out short trips are likely to own hybrid vehicles since they recognize the benefits of purchasing them with respect to their driving profile. This is in contrast to what was found in the literature which showed a positive relationship between hybrid vehicles and travel distances.

4.5.2 GHG Inventory

The total daily GHG amounts to 4,192 tonnes and 2,974 tonnes in Montreal and Quebec City, respectively. These estimates are for all FSAs in the study areas (i.e. island of Montreal and Quebec City CMA). The maps demonstrating the GHG levels across Montreal and Quebec are illustrated in **Figures 4-24 and 4-25**. The total emissions are greater in Montreal than in Quebec City since there are more car trips being made in Montreal. The FSAs with the highest levels of GHG are located farthest from the downtown core. These FSAs are also associated with the largest land area, population and vehicle fleet.

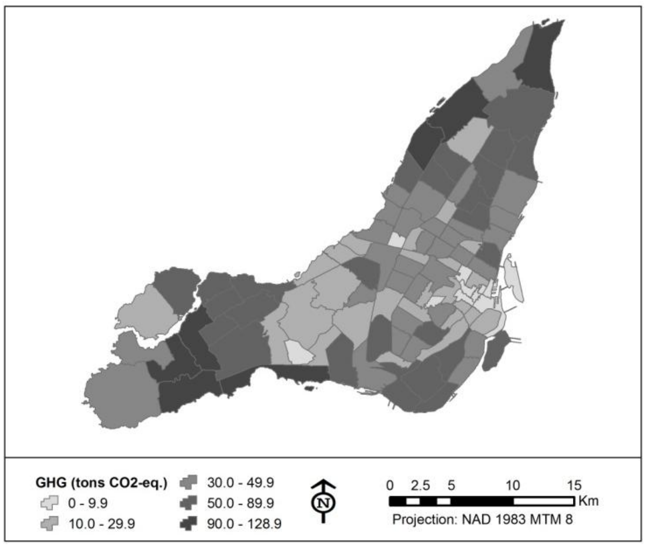

Figure 4-24 GHG inventory in Montreal 2008

Figure 4-25 GHG inventory in Quebec City 2006

4.5.3 Impact of Hybrid Vehicles on GHGs

The impact of hybrid vehicle technology on GHGs is summarized in **Figure 4-26** and **Table 4-20**. From these results, the following remarks can be made:

• For all three scenarios, Montreal would see much larger reductions than Quebec City due to the greater GHG inventory from car trips for Montreal and the larger number of FSAs with high proportions of hybrid vehicles compared to Quebec City.

• For Montreal, in the optimistic scenario, a 25% conversion of the vehicle fleet to hybrid vehicles would decrease emissions by 9.3% or 390.9 tonnes of CO_2-equivalent per day. Even though all but three FSAs are considered to have low proportions, the change in GHG emissions is -6.8% for the medium case and -4.9% for the conservative situation. The potential reduction in GHG for the optimistic scenario is almost twice as much as the conservative scenario. As expected, the greatest reductions are found in FSAs located in West Island and in the urban core where the total GHG emissions and proportions of hybrid vehicles are highest, respectively.

• For Quebec City, from an optimistic perspective, a Quebec City vehicle fleet composed of 25% hybrid vehicles would lead to a 10.0% reduction in GHG emissions which is close to 297.3 tonnes per day. This percentage is comparable to the result found for Montreal. In the medium scenario with market penetration rates between 5 and 25%, GHG emissions would decrease by 2.9%. A conservative approach, where the majority of FSAs do not experience any growth in hybrid vehicle ownership, still results in a 1.0% decrease in total GHG emissions. The environmental benefits of hybrid technology differ substantially between the optimistic and conservative scenarios; by a factor of 10. Due to the large number of low proportion FSAs, the results are more sensitive to changes in the market penetration rates. The same conclusion can be made for Quebec City: in general, the largest reductions in GHG are found in FSAs situated in the downtown core for the medium and conservative scenarios.

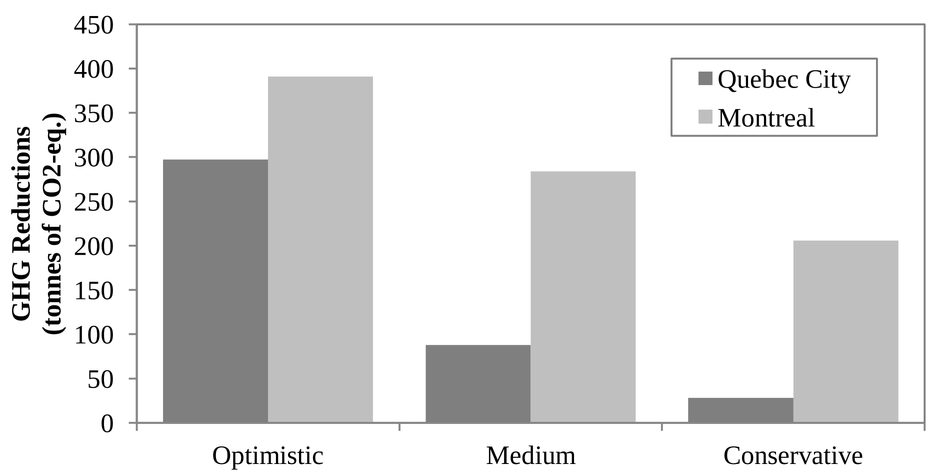

Figure 4-26 Daily GHG reductions by market penetration scenario

Table 4-20 Total Daily Change in GHG in Montreal and Quebec

City	Change/Reduction	Optimistic	Medium	Conservative
Montreal	Change in GHG (%)	-9.3	-6.8	-4.9
	GHG reduction (kg)	390,889	284,020	205,842
Quebec	Change in GHG (%)	-10.0	-2.9	-1.0
	GHG reduction (kg)	297,317	87,736	28,272

4.6 CONCLUSION

In this chapter, the link between socio-demographics, travel behaviour and hybrid vehicle ownership was explored in order to determine important factors that influence hybrid penetration rates. Also, the GHG emissions generated from car trips in Montreal and Quebec City were estimated for the base scenario. Lastly, the impact of hybrid vehicles on GHG emissions under different market penetration scenarios was evaluated.

Various neighbourhood characteristics were considered including income, education level, gender, household structure, car ownership and travel distances. From the best-fit regression model, it was determined that population density, post-secondary education and trip distances by car have the most significant influence on hybrid vehicle ownership – moreover, education is very correlated to economical household conditions. This implies that hybrid vehicle owners tend to be people with higher incomes and/or higher education, live in urban areas and make short trips. Urban areas, such as the downtown core, are generally associated with environmental consciousness, with very low emission rates per capita. This means that penetration rates will also depend on the economical situation with respect to HEV cost in these two cities. Also, in order to increase demand, policies should be implemented to increase the accessibility and appeal of hybrid vehicles to wider audience especially for lower income households such as rebates. Another important finding is the negative relationship between hybrid vehicles and trip distances which is unclear to findings in previous studies. The environmental benefits of HEVs are more evident for short commuting distances since vehicles drive at lower speeds and stop more frequently than highway driving conditions. This indicates that hybrid consumers understand hybrid technology and expect the benefits (i.e. fuel consumption savings) to be applicable to them by adopting HEVs.

The daily GHG inventory from car trips totalled to 4,192 tonnes in Montreal (2.26 kg per capita) and 2,974 tonnes in Quebec City (4.19 kg per capita). The emissions are much higher in Montreal due to the greater number of car trips carried out in the region. The reductions in GHG emissions vary between the different market penetration rates. From an optimistic perspective where the vehicle fleet is composed of 25% hybrid vehicles, GHGs would decrease by 10% in both cities: 390.9 tonnes/day in Montreal and 297.3 tonnes/day in Quebec City. This result is divergent from the figure estimated by the Quebec government which has stated that replacing the vehicle fleet with electric vehicles, 1 million passenger cars, would reduce emissions by 3.4 million tonnes annually (Hydro-Québec, 2012b). Using a conservative approach, GHG savings are between1-5%. The results are rather disappointing; even if the market for hybrid vehicles is successful, Quebec would not experience great environmental benefits in terms of GHGs.

The benefits of hybrid technology were much more pronounced in the bus transit case study while modest GHG savings are demonstrated in hybrid passenger cars. The results show that hybrid technology works best in stop-and-go conditions which is typical of public transportation while minimal benefits are observed for highway driving conditions. The average daily driven distances per household are 24.4 km and 39.4 km in the Montreal and Quebec City regions, respectively, which suggest that commuters are travelling on highways at constant speeds. In this case, it would not be advantageous to replace regular gasoline cars with hybrid vehicles. A better solution would be the adoption of purely electric vehicles; although, the limited driving range is still an issue for commuters with long travel distances. The availability of public charging infrastructure is one way to alleviate this concern which is a strategy that is currently being tested in Montreal by the Quebec government.

This study has several limitations such as the use of average fuel consumption rates of the vehicle fleet at the neighbourhood level, and the assumptions that the travel behaviour of commuters and the regular vehicle fleet will remain constant in the future. It would have been preferred to use a fuel consumption rate that is dependent on the speed; however, fuel consumption curves, such as the ones presented in Chapter 2, for hybrid passenger cars were unavailable. In addition, the assumptions stated denote that travel speeds stay the same and the fuel consumption rate of newer vehicles (regular and hybrid) does not improve over time.

5 Conclusion

5.1 SUMMARY

This thesis investigated the impact on GHG of alternative fuels and technologies in bus transit, commuter rail and passenger cars in the Quebec context. The results demonstrate that significant reductions can be found by adopting alternative technologies. The environmental benefits of alternative technologies in each of the case studies are summarized below.

Among the bus technologies, it was found that hybrid buses are the best option with savings of 43.3%, followed by CNG (20.5%) and biodiesel (12.5%). This translates to a reduction of 29.0 kg of CO_2-equivalent for hybrid technology, 13.7 kg of CO_2-equivalent for CNG and 8.4 kg of CO_2-equivalent for biodiesel buses for one cycle of the Route 165 during peak periods. The large emissions reductions of hybrid buses compared to biodiesel buses are in line with findings from the STM. A feasibility study on biodiesel buses estimated an annual GHG reduction of 22,000 tonnes for the entire STM bus fleet or 8.4 tonnes per bus (CRFA et al., 2003). STM also conducted a study on hybrid technology and found that the emissions of one bus could be reduced by 36 tonnes every year (STM, 2009). Hybrid articulated buses are currently being tested in Montreal.

For commuter rail, electric technology can reduce GHG emissions by 98.4% which is over 27,000 tonnes every year. The environmental benefits of hydrogen fuel cell are moderate: 6,600 tonnes for hydrogen from SMR and 22,600 tonnes for hydrogen from wind energy. Nevertheless, hydrogen trains may be competitive in terms of cost-benefit ratio. The cost for a complete electrification of the commuter rail in Montreal amounts to $1.3 billion compared to the $721 million for the implementation of the hydrogen technology. The cost-benefit ratio reveals that hydrogen fuel cell using wind energy is the more cost-efficient option; nevertheless, hydrogen trains are an emerging technology. There are still many issues that need to be resolved before full implementation such as risk of explosion of hydrogen tanks aboard buses and commercial availability of hydrogen gas.

Although hybrid vehicles have the potential for great GHG reductions, the spatial market distribution indicates that this technology will have a more modest impact than what is expected. From an optimistic perspective where 25% of the vehicle fleet is converted to hybrid vehicles, there would only be a 10% decrease in GHGs in both cities. This is a daily savings of 390.9 tonnes in Montreal and 297.3 tonnes in Quebec City. The Quebec government expects more promising benefits from electric vehicles. An annual reduction of 3.4 million tonnes is expected by replacing 1 million gasoline automobiles with electric vehicles which is 25% of the vehicle fleet in Quebec.

Other important findings are:

• This research supports the fact that GHG benefits of hybrid technology are optimized in an urban environment and/or stop-and-go driving conditions: the emissions reduction is much more pronounced in public transit than in personal motor vehicles. In addition, this was demonstrated in the bus transit case study in which there are smaller differences in the emissions rate in the northbound and southbound direction for a hybrid bus. The southbound direction is towards downtown which means that there is more congestion, more idling and therefore, more emissions. The emissions rate is 0.07 kg/km higher for hybrid technology and 0.2-0.3 kg/km higher for the other technologies in the southbound direction.

• The majority of emissions are generated during the operation phase for transit technologies; unless, of course, there are zero exhaust emissions which is the case for electric and hydrogen technologies. For bus transit, the upstream phases including fuel production and vehicle manufacturing make up 11-18% of lifecycle emissions. For commuter rail, the emissions generated from the production of diesel fuel contribute 24% of total emissions while the remaining is produced from the operation phase. The emissions of electric and hydrogen commuter rail are solely from the fuel/electricity production phase since there are not any GHGs emitted during the operation phase.

• The market for hybrid passenger cars is geared towards households with medium to high income, living in high dense neighbourhoods with high accessibility to transit and service (i.e. high land use mix). These neighbourhoods are also those in which car travel distances and emissions are the lowest.

This research also provides several methodological contributions to future studies on GHG analyses. Link-level GHG estimation methods were utilized to compare transportation technologies. Comparative analyses are carried out between methods (i.e. link-level vs. second-by-second estimates) and technologies (e.g. regular diesel vs. biodiesel, CNG and hybrid buses). In the bus case study, GHGs were estimated at the corridor-level by taking into account speed, topography, weather, vehicle age and fuel formulation. In addition, a comparative analysis of average link speed versus second-by-second speed profile to estimate bus transit emissions was carried out. Both methods produced similar results for diesel, a well-established technology. In contrast, the emissions were over or under-estimated for alternative technologies. In the train study, real recordings of fuel consumption and distances travelled of the commuter rail in Montreal was used to accurately evaluate emissions. For the car technologies study, a spatial analysis on hybrid vehicle market was conducted which considers socio-demographics and travel distances. The methodologies developed in this thesis can be applied to other corridors and cities.

5.2 LIMITATIONS

There are limitations in each of the case studies. In chapter 2, the software limitation of MOVES is that it cannot run analyses on hybrid-electric technology. Although the use of fuel consumption curves evaded this problem, estimates would be more consistent if the same methodology was used for all bus technologies. In chapter 3, a lifecycle analysis on alternative train technologies could not be carried out due to the lack of data. The results may have been different if emissions generated from vehicle manufacturing and infrastructure construction were included. In addition, hydrogen fuel cell is not a proven technology and it is uncertain whether a system efficiency of 50% is correct. In chapter 4, the regression analysis is based on vehicle records from 2003 to 2008 which is only 5 years since the introduction of hybrid vehicles in Quebec. More recent data, beyond 2008, would likely improve the models to identify socio-demographic patterns in hybrid vehicle ownership. Lastly, the fuel consumption rate applied is an average of the vehicle fleet. For more accurate GHG estimation, a fuel consumption rate dependent on the link speed should have been used. The assumption was that the fuel consumption curves of gasoline and hybrid cars are parallel but the hybrid curve is shifted downwards which may not be true.

5.3 FUTURE WORK

Due to some limitations, further analyses can be carried out to improve this research. First, a sensitivity analysis on the efficiency of hydrogen fuel cell systems would illustrate the range of impact on GHG emissions. Second, hybrid technology in commuter rail should be investigated specifically to assess the costs considering the grand price tag of a full electrification scenario. Third, fuel consumption-speed curves should be built using data collected in local real driving conditions for hybrid vehicles. This would allow for the estimation of GHGs of passengers cars at the link-level as oppose to a city-wide analysis. Fuel consumption curves can also be developed for commuter rail technologies. Correction factors for train load and geometry could also be determined.

5.4 IMPLICATIONS

Alternative technologies will certainly reduce GHG emissions in transportation; the impact varies from technology to technology. The use of alternative technology may offer great environmental benefits but there are key barriers to implementation. In public transit, the high cost may not be justified by the GHG reductions while a low market demand for clean technology in personal vehicles would make potential GHG savings unattainable. Governments and local transit agencies need to work together to create policies that promote alternative technologies in order to effectively reduce emissions

Quebec is one example that may actually be successful in meeting their objectives to lower GHG emissions in the transportation sector. In this province, where one of the most important resources is hydroelectricity, electric vehicles for transit or personal travel are the ideal candidate for maximum GHG savings. The Quebec government has recognized this and have proceeded with multiple strategic plans to utilize electricity in transportation including offering tax rebates for electric vehicles, building infrastructure for public charging stations and investing in research and development of electric technologies.

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APPENDIX A

Data and Results for Chapter 2

Table A-1 Route 165 Fleet

Year	Standard bus		Articulated bus	
	Number	Percentage (%)	Number	Percentage (%)
1991	5	0.80		
1992	10	1.61		
1993	17	2.73		
1994	50	8.04		
1995	30	4.82		
1996	32	5.14		
1997	37	5.95		
1998	22	3.54		
2001	38	6.11		
2002	102	16.40		
2003	28	4.50		
2004	64	10.29		
2005	20	3.22		
2006	24	3.86		
2007	16	2.57		
2008	22	3.54		
2009	45	7.23	57	36.54
2010	57	9.16	80	51.28
2011	3	0.48	19	12.18
Total buses	622	100.00	156	100.00
Transactions	1,557,793	20.6	5,997,493	79.4

Table A-2 Diesel and Biodiesel Properties

Fuel	Density (g/cm^3)	Heating Value (btu/gal)	Density (g/gal)	Heating Value (MJ/kg)
Conventional diesel	0.85	129,500	3219.7	42.474
Biodiesel (B100)	0.88	118,296	3333.3	37.476
B20 blend (B20)	0.856	127,259	3242.4	41.446

Table A-3 Link Characteristics: AM

Link ID	Direction	Length (m)	Speed (km/h)	Grade (%)	Link ID	Direction	Length (m)	Speed (km/h)	Grade (%)
1	NB	219.5	13.820	-0.456	31	SB	70.7	3.806	0.000
2	NB	207.0	14.602	5.750	32	SB	207.5	2.610	-0.289
3	NB	174.4	10.212	13.536	33	SB	179.1	24.071	0.837
4	NB	251.6	8.809	8.188	34	SB	268.6	17.509	0.372
5	NB	204.8	12.689	9.230	35	SB	212.5	25.504	0.471
6	NB	352.2	22.054	4.089	36	SB	231.8	27.838	0.000
7	NB	211.0	19.141	2.891	37	SB	201.7	6.060	0.000
8	NB	128.7	31.735	-0.777	38	SB	436.6	18.738	0.916
9	NB	197.1	47.792	0.203	39	SB	191.3	6.313	2.091
10	NB	345.1	20.241	-0.406	40	SB	205.4	10.327	1.996
11	NB	129.1	28.143	-4.259	41	SB	129.0	6.048	3.024
12	NB	118.5	7.956	-6.160	42	SB	197.6	6.227	3.390
13	NB	461.8	25.113	-1.386	43	SB	242.0	7.490	3.140
14	NB	218.5	10.638	-7.872	44	SB	231.6	9.278	2.806
15	NB	249.9	11.667	-2.881	45	SB	146.4	5.976	1.640
16	NB	161.8	6.548	-4.203	46	SB	148.2	5.246	3.103
17	NB	202.1	7.236	-2.475	47	SB	239.8	8.317	2.835
18	NB	168.9	4.007	-2.427	48	SB	350.1	18.945	3.113
19	NB	249.1	6.138	-2.047	49	SB	346.4	14.245	3.493
20	NB	197.9	18.469	-3.840	50	SB	247.2	15.897	6.351
21	NB	155.4	15.894	-4.182	51	SB	196.3	34.959	3.057
22	NB	176.5	15.921	-3.060	52	SB	318.3	24.496	0.628
23	NB	257.1	9.993	-1.206	53	SB	156.2	15.914	0.000
24	NB	311.8	16.306	-1.764	54	SB	228.1	9.677	0.132
25	NB	110.9	23.402	-2.706	55	SB	361.3	33.360	-1.799
26	NB	136.0	25.953	0.000	56	SB	228.5	10.648	-4.857
27	NB	232.3	30.061	0.000	57	SB	207.0	18.529	-7.779
28	NB	212.1	29.438	0.000	58	SB	209.6	15.583	-10.593
29	NB	273.3	18.843	-0.366	59	SB	163.6	6.072	-12.957
30	NB	285.1	18.251	-0.351	60	SB	181.3	11.997	-7.006

Table A-4 Link Characteristics: PM

Link ID	Direction	Length (m)	Speed (km/h)	Grade (%)	Link ID	Direction	Length (m)	Speed (km/h)	Grade (%)
61	NB	219.5	17.675	-0.046	91	SB	70.7	3.806	0.000
62	NB	207.0	17.612	6.716	92	SB	207.5	6.215	-0.386
63	NB	174.4	8.798	13.479	93	SB	179.1	21.588	0.837
64	NB	251.6	11.504	7.512	94	SB	268.6	10.885	0.372
65	NB	204.8	13.578	12.355	95	SB	212.5	22.114	0.471
66	NB	352.2	18.069	2.470	96	SB	231.8	26.094	0.000
67	NB	211.0	18.976	3.460	97	SB	201.7	3.564	0.000
68	NB	128.7	30.318	-0.544	98	SB	436.6	12.098	0.916
69	NB	197.1	40.751	0.000	99	SB	191.3	7.620	2.039
70	NB	345.1	17.448	-0.290	100	SB	205.4	17.280	2.142
71	NB	129.1	34.361	-4.104	101	SB	129.0	4.138	2.869
72	NB	118.5	11.372	-5.991	102	SB	197.6	16.626	3.542
73	NB	461.8	15.398	-1.278	103	SB	242.0	6.938	3.058
74	NB	218.5	7.411	-8.513	104	SB	231.6	31.123	2.763
75	NB	249.9	10.294	-2.841	105	SB	146.4	5.549	1.435
76	NB	161.8	2.937	-4.203	106	SB	148.2	3.736	3.305
77	NB	202.1	9.751	-2.623	107	SB	239.8	5.620	2.794
78	NB	168.9	5.673	-2.012	108	SB	350.1	11.733	3.171
79	NB	249.1	16.948	-2.047	109	SB	346.4	8.852	3.724
80	NB	197.9	7.073	-3.739	110	SB	247.2	9.760	6.270
81	NB	155.4	8.411	-4.053	111	SB	196.3	42.856	2.853
82	NB	176.5	12.185	-3.060	112	SB	318.3	51.953	0.628
83	NB	257.1	8.013	-1.245	113	SB	156.2	27.009	0.000
84	NB	311.8	4.166	-1.796	114	SB	228.1	15.845	0.175
85	NB	110.9	11.233	-2.706	115	SB	361.3	34.936	-1.744
86	NB	136.0	18.376	0.000	116	SB	228.5	21.001	-8.490
87	NB	232.3	24.128	0.000	117	SB	207.0	20.642	-4.928
88	NB	212.1	19.176	0.000	118	SB	209.6	9.712	-10.355
89	NB	273.3	26.884	-0.366	119	SB	163.6	16.035	-12.224
90	NB	285.1	19.430	-0.351	120	SB	181.3	18.809	-7.558

Table A-5 Link Grade: AM

Link ID	First elevation (m)	Last elevation (m)	Grade (%)	Link ID	First elevation (m)	Last elevation (m)	Grade (%)
1	50.0	49.0	-0.456	31	49.0	49.0	0.000
2	54.5	66.4	5.750	32	49.0	48.4	-0.289
3	66.9	90.5	13.536	33	48.5	50.0	0.837
4	91.5	112.1	8.188	34	50.0	51.0	0.372
5	112.3	131.2	9.230	35	51.0	52.0	0.471
6	131.7	146.1	4.089	36	52.0	52.0	0.000
7	146.9	153.0	2.891	37	52.0	52.0	0.000
8	153.0	152.0	-0.777	38	52.0	56.0	0.916
9	152.0	152.4	0.203	39	56.0	60.0	2.091
10	152.4	151.0	-0.406	40	60.1	64.2	1.996
11	151.0	145.5	-4.259	41	64.6	68.5	3.024
12	145.3	138.0	-6.160	42	68.9	75.6	3.390
13	137.5	131.1	-1.386	43	75.7	83.3	3.140
14	130.6	113.4	-7.872	44	83.5	90.0	2.806
15	113.2	106.0	-2.881	45	90.0	92.4	1.640
16	105.7	98.9	-4.203	46	92.7	97.3	3.103
17	98.7	93.7	-2.475	47	97.4	104.2	2.835
18	93.6	89.5	-2.427	48	104.3	115.2	3.113
19	89.2	84.1	-2.047	49	115.5	127.6	3.493
20	84.1	76.5	-3.840	50	128.1	143.8	6.351
21	76.3	69.8	-4.182	51	144.0	150.0	3.057
22	69.6	64.2	-3.060	52	150.0	152.0	0.628
23	64.1	61.0	-1.206	53	152.0	152.0	0.000
24	60.7	55.2	-1.764	54	152.0	152.3	0.132
25	55.0	52.0	-2.706	55	152.1	145.6	-1.799
26	52.0	52.0	0.000	56	144.9	133.8	-4.857
27	52.0	52.0	0.000	57	132.4	116.3	-7.779
28	52.0	52.0	0.000	58	115.8	93.6	-10.593
29	52.0	51.0	-0.366	59	92.8	71.6	-12.957
30	51.0	50.0	-0.351	60	70.7	58.0	-7.006

Table A-6 Link Grade: PM

Link ID	First elevation (m)	Last elevation (m)	Grade (%)	Link ID	First elevation (m)	Last elevation (m)	Grade (%)
61	50.0	49.9	-0.046	91	49.0	49.0	0.000
62	52.1	66.0	6.716	92	49.0	48.2	-0.386
63	67.6	91.1	13.479	93	48.5	50.0	0.837
64	91.6	110.5	7.512	94	50.0	51.0	0.372
65	111.2	136.5	12.355	95	51.0	52.0	0.471
66	136.5	145.2	2.470	96	52.0	52.0	0.000
67	145.5	152.8	3.460	97	52.0	52.0	0.000
68	152.7	152.0	-0.544	98	52.0	56.0	0.916
69	152.0	152.0	0.000	99	56.1	60.0	2.039
70	152.0	151.0	-0.290	100	60.0	64.4	2.142
71	151.0	145.7	-4.104	101	64.7	68.4	2.869
72	145.5	138.4	-5.991	102	68.7	75.7	3.542
73	137.6	131.7	-1.278	103	76.0	83.4	3.058
74	131.4	112.8	-8.513	104	83.6	90.0	2.763
75	112.8	105.7	-2.841	105	90.0	92.1	1.435
76	105.5	98.7	-4.203	106	92.3	97.2	3.305
77	98.5	93.2	-2.623	107	97.3	104.0	2.794
78	93.0	89.6	-2.012	108	103.9	115.0	3.171
79	89.2	84.1	-2.047	109	115.3	128.2	3.724
80	84.0	76.6	-3.739	110	128.5	144.0	6.270
81	76.3	70.0	-4.053	111	144.4	150.0	2.853
82	69.6	64.2	-3.060	112	150.0	152.0	0.628
83	64.1	60.9	-1.245	113	152.0	152.0	0.000
84	60.6	55.0	-1.796	114	152.0	152.4	0.175
85	55.0	52.0	-2.706	115	152.2	145.9	-1.744
86	52.0	52.0	0.000	116	144.9	125.5	-8.490
87	52.0	52.0	0.000	117	124.5	114.3	-4.928
88	52.0	52.0	0.000	118	114.4	92.7	-10.355
89	52.0	51.0	-0.366	119	92.0	72.0	-12.224
90	51.0	50.0	-0.351	120	70.8	57.1	-7.558

Table A-7 Fuel Consumption Rate and Fuel Economy: AM-Northbound Links

Link ID	Fuel consumption rate			Fuel economy
	(Bio)Diesel (L/100km)	Hybrid (L/100km)	CNG (m^3/100km)	CNG (mpg)
1	73.287	48.929	113.765	2.037
2	71.394	48.191	109.829	2.110
3	84.619	53.191	137.532	1.685
4	90.777	55.406	150.352	1.542
5	76.320	50.095	120.108	1.930
6	58.687	43.005	84.378	2.747
7	62.775	44.720	92.312	2.511
8	49.365	38.894	67.898	3.414
9	40.636	34.736	56.249	4.121
10	61.129	44.035	89.080	2.602
11	52.266	40.205	72.719	3.187
12	95.283	56.987	159.598	1.452
13	55.174	41.490	77.854	2.977
14	82.991	52.594	134.117	1.728
15	79.430	51.271	126.638	1.830
16	104.519	60.134	178.018	1.302
17	99.675	58.499	168.457	1.376
18	132.005	68.869	227.037	1.021
19	107.785	61.218	184.326	1.257
20	63.850	45.164	94.448	2.454
21	68.573	47.075	104.010	2.228
22	68.518	47.053	103.896	2.231
23	85.495	53.510	139.365	1.663
24	67.745	46.744	102.315	2.265
25	57.056	42.306	81.311	2.851
26	54.318	41.115	76.314	3.037
27	50.654	39.480	69.997	3.311
28	51.160	39.709	70.842	3.272
29	63.245	44.915	93.244	2.486
30	64.212	45.312	95.170	2.435

Table A-8 Fuel Consumption Rate and Fuel Economy: AM-Southbound Links

Link ID	Fuel consumption rate			Fuel economy
	(Bio)Diesel (L/100km)	Hybrid (L/100km)	CNG (m^3/100km)	CNG (mpg)
31	135.279	69.856	232.222	0.998
32	161.826	77.518	269.160	0.861
33	56.297	41.978	79.905	2.901
34	65.491	45.834	97.738	2.371
35	54.770	41.313	77.126	3.005
36	52.538	40.327	73.187	3.167
37	108.438	61.434	185.574	1.249
38	63.414	44.984	93.578	2.477
39	106.355	60.745	181.579	1.276
40	84.172	53.027	136.595	1.697
41	108.540	61.467	185.769	1.248
42	107.047	60.975	182.913	1.267
43	98.056	57.945	165.211	1.403
44	88.568	54.619	145.775	1.590
45	109.161	61.671	186.950	1.240
46	116.132	63.929	199.888	1.160
47	93.294	56.293	155.535	1.490
48	63.082	44.847	92.920	2.494
49	72.239	48.521	111.583	2.077
50	68.568	47.073	103.999	2.229
51	47.147	37.869	64.464	3.596
52	55.830	41.776	79.049	2.932
53	68.533	47.059	103.926	2.230
54	86.812	53.987	142.116	1.631
55	48.208	38.361	66.076	3.508
56	82.954	52.580	134.041	1.729
57	63.752	45.123	94.251	2.459
58	69.222	47.333	105.341	2.200
59	108.337	61.401	185.382	1.250
60	78.383	50.877	124.438	1.863

Table A-9 Fuel Consumption Rate and Fuel Economy: PM-Northbound Links

Link ID	Fuel consumption rate			Fuel economy
	(Bio)Diesel (L/100km)	Hybrid (L/100km)	CNG (m^3/100km)	CNG (mpg)
61	65.198	45.715	97.147	2.386
62	65.308	45.760	97.369	2.380
63	90.833	55.426	150.469	1.540
64	79.960	51.469	127.752	1.814
65	73.905	49.168	115.055	2.015
66	64.518	45.437	95.782	2.420
67	63.033	44.827	92.823	2.497
68	50.449	39.388	69.660	3.327
69	43.834	36.299	59.863	3.872
70	65.600	45.878	97.958	2.366
71	47.535	38.049	65.046	3.563
72	80.400	51.634	128.677	1.801
73	69.614	47.489	106.149	2.184
74	98.550	58.115	166.205	1.395
75	84.299	53.074	136.860	1.694
76	153.010	75.037	257.873	0.899
77	86.499	53.874	141.464	1.638
78	111.900	62.566	192.103	1.207
79	66.512	46.248	99.804	2.322
80	100.757	58.867	170.613	1.359
81	92.793	56.118	154.508	1.500
82	77.807	50.660	123.228	1.881
83	94.958	56.874	158.936	1.458
84	129.577	68.130	223.098	1.039
85	80.873	51.810	129.671	1.787
86	64.004	45.227	94.755	2.446
87	56.233	41.951	79.788	2.905
88	62.721	44.698	92.205	2.514
89	53.415	40.717	74.716	3.102
90	62.330	44.536	91.433	2.535

Table A-10 Fuel Consumption Rate and Fuel Economy: PM-Southbound Links

Link ID	Fuel consumption rate			Fuel economy
	(Bio)Diesel (L/100km)	Hybrid (L/100km)	CNG (m^3/100km)	CNG (mpg)
91	135.279	69.856	232.222	0.998
92	107.151	61.009	183.111	1.266
93	59.287	43.259	85.522	2.710
94	82.090	52.262	132.227	1.753
95	58.612	42.973	84.236	2.752
96	54.178	41.053	76.065	3.047
97	139.569	71.134	238.802	0.971
98	78.072	50.760	123.785	1.872
99	97.256	57.670	163.599	1.417
100	65.902	46.001	98.567	2.352
101	129.996	68.257	223.783	1.036
102	67.121	46.494	101.042	2.294
103	101.686	59.182	172.455	1.344
104	49.824	39.103	68.638	3.377
105	113.082	62.949	194.300	1.193
106	136.469	70.212	234.071	0.990
107	112.400	62.728	193.033	1.201
108	79.216	51.191	126.189	1.837
109	90.570	55.333	149.925	1.546
110	86.462	53.861	141.385	1.639
111	42.797	35.798	58.585	3.956
112	39.055	33.945	54.890	4.223
113	53.298	40.665	74.510	3.111
114	68.674	47.115	104.215	2.224
115	47.161	37.875	64.486	3.594
116	60.068	43.590	87.022	2.664
117	60.563	43.798	87.980	2.635
118	86.662	53.933	141.804	1.635
119	68.286	46.961	103.421	2.241
120	63.299	44.937	93.350	2.483

Table A-11 Operation Emissions from FCR Curves: AM Links

Link ID	GHG emissions (grams of CO_2-eq.)				Link ID	GHG emissions (grams of CO_2-eq.)			
	Diesel	Hybrid	B20	CNG		Diesel	Hybrid	B20	CNG
1	432.8	251.5	348.6	427.2	31	257.3	115.6	207.3	280.9
2	397.6	233.6	320.3	388.9	32	903.6	376.7	727.8	955.6
3	397.0	217.2	319.8	410.3	33	271.4	176.1	218.6	244.9
4	614.6	326.5	495.1	647.2	34	473.4	288.4	381.4	449.3
5	420.6	240.2	338.8	420.8	35	313.2	205.6	252.3	280.4
6	556.2	354.7	448.0	508.4	36	327.7	218.9	263.9	290.2
7	356.4	221.0	287.1	333.2	37	588.5	290.2	474.0	640.4
8	170.9	117.2	137.7	149.5	38	745.1	460.0	600.1	699.1
9	215.6	160.4	173.7	189.7	39	547.4	272.1	441.0	594.3
10	567.7	355.9	457.3	526.0	40	465.3	255.1	374.8	480.1
11	181.6	121.6	146.3	160.7	41	376.7	185.7	303.4	409.9
12	303.9	158.2	244.8	323.6	42	569.3	282.2	458.5	618.5
13	685.6	448.7	552.3	615.1	43	638.6	328.4	514.4	684.1
14	487.9	269.1	393.0	501.4	44	552.0	296.3	444.6	577.7
15	534.1	300.0	430.2	541.4	45	429.9	211.4	346.3	468.1
16	455.0	227.9	366.5	492.8	46	463.3	222.0	373.2	507.0
17	542.0	276.8	436.6	582.4	47	602.1	316.2	485.0	638.2
18	600.1	272.5	483.4	656.3	48	594.3	367.7	478.7	556.6
19	722.7	357.2	582.1	785.8	49	673.4	393.7	542.4	661.4
20	340.0	209.3	273.9	319.8	50	456.1	272.5	367.4	439.9
21	286.8	171.4	231.0	276.6	51	249.0	174.1	200.6	216.5
22	325.4	194.5	262.1	313.7	52	478.2	311.4	385.2	430.5
23	591.6	322.2	476.5	613.1	53	288.1	172.2	232.1	277.8
24	568.5	341.4	457.9	545.9	54	532.8	288.3	429.1	554.5
25	170.2	109.8	137.1	154.2	55	468.7	324.6	377.5	408.5
26	198.8	130.9	160.1	177.6	56	510.1	281.4	410.9	524.1
27	316.7	214.8	255.1	278.2	57	355.1	218.7	286.0	333.8
28	292.1	197.3	235.2	257.1	58	390.4	232.3	314.4	377.7
29	465.1	287.5	374.7	436.0	59	477.0	235.3	384.2	519.0
30	492.6	302.5	396.8	464.2	60	382.3	216.0	308.0	385.9

Table A-12 Operation Emissions from FCR Curves: PM Links

Link ID	GHG emissions (grams of CO_2-eq.)				Link ID	GHG emissions (grams of CO_2-eq.)			
	Diesel	Hybrid	B20	CNG		Diesel	Hybrid	B20	CNG
61	385.0	235.0	310.1	364.8	91	257.3	115.6	207.3	280.9
62	363.7	221.8	293.0	344.8	92	598.3	296.5	481.9	650.1
63	426.2	226.3	343.3	448.9	93	285.8	181.5	230.2	262.1
64	541.4	303.3	436.1	550.0	94	593.4	328.8	478.0	607.8
65	407.2	235.8	328.0	403.1	95	335.2	213.9	270.0	306.3
66	611.4	374.8	492.5	577.1	96	337.9	222.8	272.2	301.6
67	357.8	221.5	288.2	335.1	97	757.5	336.0	610.1	824.0
68	174.7	118.7	140.7	153.4	98	917.3	519.0	738.9	924.7
69	232.5	167.6	187.3	201.9	99	500.6	258.3	403.2	535.4
70	609.2	370.8	490.7	578.4	100	364.3	221.3	293.4	346.4
71	165.2	115.1	133.0	143.7	101	451.2	206.2	363.4	493.8
72	256.4	143.3	206.5	260.9	102	356.9	215.2	287.5	341.6
73	865.1	513.6	696.8	838.7	103	662.3	335.4	533.4	714.1
74	579.4	297.4	466.7	621.3	104	310.5	212.1	250.1	272.0
75	566.8	310.6	456.6	585.1	105	445.4	215.8	358.7	486.5
76	666.2	284.3	536.6	713.8	106	544.4	243.8	438.5	593.7
77	470.3	254.9	378.9	489.1	107	725.4	352.3	584.3	792.1
78	508.7	247.6	409.8	555.3	108	746.3	419.7	601.2	755.9
79	445.9	269.9	359.2	425.5	109	844.3	448.9	680.1	888.6
80	536.6	272.8	432.2	577.7	110	575.2	311.8	463.3	598.0
81	388.1	204.3	312.6	410.9	111	226.0	164.6	182.1	196.7
82	369.5	209.4	297.6	372.1	112	334.5	253.1	269.5	298.9
83	657.0	342.5	529.3	699.2	113	224.1	148.8	180.5	199.2
84	1087.3	497.5	875.8	1190.3	114	421.4	251.6	339.5	406.6
85	241.3	134.5	194.3	246.0	115	458.5	320.5	369.3	398.6
86	234.2	144.0	188.7	220.5	116	369.4	233.3	297.5	340.2
87	351.5	228.2	283.2	317.1	117	337.3	212.3	271.7	311.5
88	358.0	222.1	288.4	334.7	118	488.7	264.7	393.7	508.5
89	392.8	260.6	316.4	349.4	119	300.7	179.9	242.2	289.5
90	478.2	297.3	385.2	446.0	120	308.8	190.8	248.7	289.5

Table A-13 Operation Emissions from MOVES: AM Links

Link ID	GHG emissions (grams of CO_2-eq.)			Link ID	GHG emissions (grams of CO_2-eq.)		
	Diesel	B20	CNG		Diesel	B20	CNG
1	459.2	456.9	369.1	31	513.7	511.1	318.7
2	590.1	587.1	510.1	32	1027.0	1021.8	756.3
3	766.7	762.9	787.3	33	347.1	345.3	325.3
4	1050.5	1045.3	981.4	34	416.6	414.5	333.0
5	670.2	666.9	708.6	35	345.4	343.7	315.5
6	707.3	703.7	680.6	36	341.4	339.7	313.3
7	380.4	378.5	346.2	37	482.4	480.0	385.8
8	235.3	234.1	246.4	38	773.0	769.1	645.6
9	280.8	279.3	213.6	39	547.7	544.9	456.6
10	332.5	330.9	253.6	40	519.0	516.4	449.9
11	181.0	180.1	165.9	41	354.1	352.3	297.9
12	176.6	175.7	122.2	42	612.4	609.3	458.5
13	557.8	555.0	460.6	43	728.0	724.3	621.0
14	316.4	314.8	224.9	44	750.1	746.4	611.5
15	384.4	382.5	272.5	45	523.1	520.5	393.3
16	356.2	354.5	281.7	46	501.2	498.7	368.8
17	478.9	476.5	339.3	47	850.5	846.3	740.4
18	519.3	516.7	397.6	48	737.3	733.6	695.2
19	703.1	699.6	493.5	49	782.1	778.2	710.5
20	263.4	262.1	218.4	50	712.6	709.1	682.2
21	248.6	247.4	219.4	51	455.7	453.4	432.9
22	296.6	295.1	252.1	52	311.3	309.8	233.5
23	585.8	582.8	507.7	53	300.8	299.3	264.0
24	453.1	450.8	348.9	54	488.9	486.4	415.0
25	162.1	161.3	138.9	55	289.4	288.0	248.3
26	203.9	202.9	167.2	56	404.9	402.9	318.8
27	375.3	373.4	325.0	57	161.5	160.7	112.0
28	355.3	353.5	323.1	58	269.6	268.3	189.5
29	485.8	483.3	420.6	59	306.1	304.5	202.6
30	508.8	506.3	413.7	60	204.7	203.6	138.8

Table A-14 Operation Emissions from MOVES: PM Links

Link ID	GHG emissions (grams of CO_2-eq)			Link ID	GHG emissions (grams of CO_2-eq)		
	Diesel	B20	CNG		Diesel	B20	CNG
61	477.8	475.4	433.7	91	513.7	511.1	318.7
62	510.6	508.1	484.0	92	572.6	569.7	500.9
63	852.0	847.7	819.0	93	299.1	297.6	262.0
64	972.2	967.4	867.4	94	589.1	586.1	416.2
65	828.2	824.1	899.1	95	314.2	312.6	271.9
66	620.3	617.2	503.6	96	325.8	324.2	281.6
67	476.0	473.6	456.4	97	774.6	770.7	640.3
68	180.1	179.2	157.6	98	899.7	895.2	757.6
69	235.2	234.0	197.3	99	516.2	513.6	453.3
70	382.5	380.6	283.9	100	518.2	515.6	520.4
71	146.3	145.5	133.3	101	494.7	492.2	399.8
72	134.4	133.7	90.2	102	477.9	475.5	451.7
73	676.5	673.1	548.8	103	680.4	677.0	540.0
74	365.4	363.6	240.1	104	407.4	405.4	399.4
75	361.7	359.9	270.5	105	455.0	452.7	358.3
76	550.6	547.9	401.5	106	621.7	618.6	464.8
77	337.5	335.8	248.0	107	860.1	855.8	720.0
78	397.4	395.4	281.0	108	890.0	885.6	853.0
79	387.0	385.1	328.2	109	953.2	948.4	836.1
80	399.8	397.7	289.5	110	829.8	825.6	813.2
81	296.3	294.9	205.8	111	501.8	499.3	444.7
82	277.9	276.5	219.8	112	321.7	320.1	233.1
83	554.0	551.2	410.5	113	157.3	156.5	112.5
84	875.5	871.1	670.8	114	425.5	423.3	377.0
85	223.5	222.4	174.3	115	464.4	462.0	400.3
86	170.7	169.8	117.2	116	198.4	197.4	136.8
87	325.3	323.6	288.7	117	178.9	178.0	120.2
88	393.8	391.8	363.4	118	274.0	272.6	192.3
89	444.8	442.6	415.6	119	152.3	151.5	100.3
90	363.4	361.6	279.4	120	213.3	212.2	152.7

APPENDIX B

Data and Results for Chapter 3

Table B-1 Total Network PKT, VKT, Train-km

	Entire Network	Network excluding Deux-Montagnes
PKT	328,226,220	183,144,322
VKT	8,380,766	4,601,123
Train-km	1,045,389	640,368

Table B-2 GHG Emissions for Operation and Fuel Production for Base Case

Base Case	Operation Emissions (tonnes of CO_2-eq.)	Fuel production Emissions (tonnes of CO_2-eq.)
Deux-Montagnes (electric)	0	194.96
Dorion-Rigaud (diesel)	7,793.97	1,876.57
Blainville-Saint-Jérôme (diesel)	9,984.89	2,404.08
Mont-Saint-Hilaire (diesel)	3,371.57	811.78
Delson-Candiac (diesel)	993.13	239.12
Total	22,143.55	5,331.54

Table B-3 GHG Emissions of Technology Scenarios by Rail Corridor (tonnes of CO_2-eq.)

Rail Corridor	Base case	Electric	Hydrogen (SMR)	Hydrogen (wind)
Deux-Montagnes	194.96	194.96	9,516.72	2,306.23
Dorion-Rigaud	9,670.54	83.53	4,077.67	988.16
Blainville-Saint-Jérôme	12,388.96	107.01	5,223.92	1,265.94
Mont-Saint-Hilaire	4,183.34	36.14	1,763.94	427.47
Delson-Candiac	1,232.24	10.64	519.59	125.91
Total	27,670.04	432.28	21,101.84	5,113.71
GHG reduction	-	27,237.76	6,568.202	22,556.33

Table B-4 GHG Emissions of Technology Scenarios per PKT, VKT and Train-km

GHG Emissions	Base case	Electric	Hydrogen (SMR)	Hydrogen (wind)
in g of CO_2-eq./PKT	84.30	1.32	64.29	15.58
in g of CO_2-eq./VKT	3301.61	51.58	2517.89	610.17
in kg of CO_2-eq./Train-km	26.47	0.41	20.19	4.89

Table B-5 GHG Emissions for Ridership Scenario (g of CO_2-eq./PKT)

Passenger Occupancy	Base case	Electric	Hydrogen (SMR)	Hydrogen (wind)
Low (21.4 pass./veh.)	154.28	2.41	117.66	28.51
High (214 pass./veh.)	15.43	0.24	11.77	2.85
Difference	138.85	2.17	105.89	25.66

Table B-6 Passenger Levels for Ridership Scenario

Dotted Line	Base case	Electric	Hydrogen (SMR)	Hydrogen (wind)	GHG (g/PKT)
Low occupancy (hydrogen-SMR)	28.1	-	21.4	-	117.66
Current occupancy (base case)	39.2	-	29.9	-	84.30
Low occupancy (hydrogen-wind)	115.8	-	88.3	21.4	28.51
High occupancy (base case)	214	-	163.2	39.5	15.43
High occupancy (hydrogen-SMR)	-	-	214	51.9	11.77
High occupancy (hydrogen-wind)	-	-	-	214	2.85
GHG (g/VKT)	3301.61	51.58	2517.89	610.17	

Table B-7 Cost Breakdown by Technology

Technology	Locomotive ($ million)	Infrastructure ($ million)	Operation Cost ($)
Electric	231.9	1,035.1	2,683,698
Hydrogen	571.4	75.9	7,805,862
Base case			8,926,604

Table B-8 Net Present Value of Total Costs

Year	Electrification		Hydrogen	
	Cost ($)	NPV ($)	Cost ($)	NPV ($)
0	1,267,000,000	1,267,000,000	647,300,000	647,300,000
1	2,683,698	2,439,725	7,805,862	7,096,238
2	2,683,698	2,217,932	7,805,862	6,451,126
3	2,683,698	2,016,302	7,805,862	5,864,660
4	2,683,698	1,833,002	7,805,862	5,331,509
5	2,683,698	1,666,365	7,805,862	4,846,826
6	2,683,698	1,514,878	7,805,862	4,406,206
7	2,683,698	1,377,161	7,805,862	4,005,641
8	2,683,698	1,251,965	7,805,862	3,641,492
9	2,683,698	1,138,150	7,805,862	3,310,447
10	2,683,698	1,034,682	7,805,862	3,009,498
11	2,683,698	940,620	7,805,862	2,735,907
12	2,683,698	855,109	7,805,862	2,487,188
13	2,683,698	777,372	7,805,862	2,261,080
14	2,683,698	706,702	7,805,862	2,055,527
15	2,683,698	642,456	7,805,862	1,868,661
16	2,683,698	584,051	7,805,862	1,698,783
17	2,683,698	530,955	7,805,862	1,544,348
18	2,683,698	482,687	7,805,862	1,403,953
19	2,683,698	438,806	7,805,862	1,276,321
20	2,683,698	398,915	7,805,862	1,160,292
21	2,683,698	362,650	7,805,862	1,054,811
22	2,683,698	329,681	7,805,862	958,919
23	2,683,698	299,710	7,805,862	871,744
24	2,683,698	272,464	7,805,862	792,495
25	2,683,698	247,695	7,805,862	720,450
26	2,683,698	225,177	7,805,862	654,954
27	2,683,698	204,706	7,805,862	595,413
28	2,683,698	186,097	7,805,862	541,285
29	2,683,698	169,179	7,805,862	492,077
30	2,683,698	153,799	7,805,862	447,343
Total		1,292,298,992		720,885,193

APPENDIX C

Data and Results from Chapter 4

Table C-1 Distribution of Hybrid Vehicles in Study Areas by Year

	Quebec Province	Montreal Island	Quebec City
2003	339	92	46
2004	683	238	88
2005	1437	471	188
2006	2850	931	417
2007	4602	1413	674
2008	7085	2104	1006

Table C-2 Distribution of Hybrid Vehicle Manufacturers by Year

Manufacturer	2003	2004	2005	2006	2007	2008	Total
Honda	69	86	156	302	415	546	1,574
Toyota	69	225	354	743	1,166	1,761	4,318
Ford	0	15	76	147	240	336	814
Lexus	0	0	73	146	219	337	775
Mazda	0	0	0	1	1	1	3
Nissan	0	0	0	0	13	30	43
Saturn	0	0	0	9	32	57	98
Chevrolet	0	0	0	0	1	36	37
Chrysler	0	0	0	0	0	2	2
GMC	0	0	0	0	0	4	4
Clean	0	0	0	0	0	0	0
Cadillac	0	0	0	0	0	0	0
Total	138	326	659	1,348	2,087	3,110	7,668

Table C-3 Proportion of Hybrid Vehicles in Quebec City 2006

FSA	*all_veh*	*HEV*	*Taxi HEV*	*p_HEV*	FSA	*all_veh*	*HEV*	*Taxi HEV*	*p_HEV*
G0A	53,356	28	0	0.052	G2E	12,759	2	0	0.016
G0R	48,482	16	0	0.033	G2G	6,278	3	0	0.048
G0S	40,761	16	0	0.039	G2J	2,281	0	0	0.000
G1A	13	0	0	0.000	G2K	5,620	3	0	0.053
G1B	8,471	4	0	0.047	G2L	7,172	4	0	0.056
G1C	19,999	9	0	0.045	G2M	2,532	3	0	0.118
G1E	12,148	1	0	0.008	G2N	4,072	0	0	0.000
G1G	12,432	7	0	0.056	G3A	10,415	10	0	0.096
G1H	15,231	16	1	0.098	G3B	4,377	4	0	0.091
G1J	8,369	4	0	0.048	G3E	7,409	3	0	0.040
G1K	7,235	7	0	0.097	G3G	5,698	1	0	0.018
G1L	8,803	2	0	0.023	G3H	4,613	1	0	0.022
G1M	9,851	6	0	0.061	G3J	4,960	2	0	0.040
G1N	4,805	36	0	0.749	G3K	7,852	4	0	0.051
G1P	9,143	2	0	0.022	G3L	6,177	4	0	0.065
G1R	5,751	32	1	0.539	G3M	3,039	2	0	0.066
G1S	12,328	89	0	0.722	G6C	4,161	1	0	0.024
G1T	3,718	10	0	0.269	G6J	6,117	4	0	0.065
G1V	8,355	9	0	0.108	G6K	4,334	5	0	0.115
G1W	10,445	9	0	0.086	G6V	20,204	14	0	0.069
G1X	13,507	14	2	0.089	G6W	13,026	4	0	0.031
G1Y	7,948	5	0	0.063	G6X	6,105	3	0	0.049
G2A	7,888	3	0	0.038	G6Z	10,910	1	0	0.009
G2B	11,622	2	0	0.017	G7A	11,970	8	0	0.067
G2C	4,862	4	0	0.082	Total	517,604	417	4	0.080

Table C-4 Proportion of Hybrid Vehicles in Montreal 2003

FSA	*all_veh*	*HEV*	*Taxi HEV*	*p_HEV*	FSA	*all_veh*	*HEV*	*Taxi HEV*	*p_HEV*
H1A	15,695	1	0	0.006	H3R	4,749	1	0	0.021
H1B	10,942	0	0	0.000	H3S	8,525	0	0	0.000
H1C	4,838	0	0	0.000	H3T	3,318	1	0	0.030
H1E	20,046	0	0	0.000	H3V	2,114	1	0	0.047
H1G	17,454	2	0	0.011	H3W	7,888	0	0	0.000
H1H	12,263	0	0	0.000	H3X	8,979	0	0	0.000
H1J	8,256	2	0	0.024	H3Y	4,832	0	0	0.000
H1K	13,039	0	0	0.000	H3Z	5,207	5	0	0.096
H1L	13,208	3	0	0.023	H4A	8,827	3	0	0.034
H1M	12,111	2	0	0.017	H4B	5,949	3	0	0.050
H1N	7,993	1	0	0.013	H4C	4,273	0	0	0.000
H1P	9,013	2	0	0.022	H4E	10,081	0	0	0.000
H1R	12,122	0	0	0.000	H4G	8,000	4	0	0.050
H1S	8,819	3	0	0.034	H4H	6,890	0	0	0.000
H1T	10,817	1	0	0.009	H4J	5,645	0	0	0.000
H1V	5,477	1	0	0.018	H4K	5,453	0	0	0.000
H1W	7,473	1	0	0.013	H4L	11,497	0	0	0.000
H1X	10,118	1	0	0.010	H4M	5,324	0	0	0.000
H1Y	8,522	8	0	0.094	H4N	9,788	0	0	0.000
H1Z	11,446	0	0	0.000	H4P	3,443	1	0	0.029
H2A	5,900	0	0	0.000	H4R	9,326	1	0	0.011
H2B	6,426	0	0	0.000	H4S	5,255	0	0	0.000
H2C	6,240	1	0	0.016	H4T	5,803	0	0	0.000
H2E	7,127	0	0	0.000	H4V	6,961	0	0	0.000
H2G	7,348	0	0	0.000	H4W	10,302	0	0	0.000
H2H	5,704	0	0	0.000	H4X	2,970	1	0	0.034
H2J	7,254	1	0	0.014	H4Y	3,740	8	0	0.214
H2K	9,498	0	0	0.000	H4Z	47	2	0	4.255
H2L	5,705	0	0	0.000	H5A	60	0	0	0.000
H2M	7,356	0	0	0.000	H5B	129	0	0	0.000
H2N	3,115	0	0	0.000	H8N	11,721	1	0	0.009
H2P	5,310	0	0	0.000	H8P	9,671	0	0	0.000
H2R	6,252	1	0	0.016	H8R	12,448	0	0	0.000
H2S	7,044	1	0	0.014	H8S	9,095	1	0	0.011
H2T	4,496	2	0	0.044	H8T	7,263	0	0	0.000
H2V	9,903	2	0	0.020	H8Y	8,318	2	0	0.024
H2W	2,773	0	0	0.000	H8Z	7,004	1	0	0.014
H2X	3,388	0	0	0.000	H9A	7,795	1	0	0.013
H2Y	4,695	1	0	0.021	H9B	10,097	1	0	0.010
H2Z	597	0	0	0.000	H9C	6,183	2	0	0.032
H3A	2,130	1	0	0.047	H9E	1,653	0	0	0.000
H3B	4,422	0	0	0.000	H9G	8,467	0	0	0.000
H3C	2,793	2	0	0.072	H9H	12,803	0	0	0.000
H3E	7,804	1	0	0.013	H9J	11,835	2	0	0.017
H3G	2,964	2	0	0.067	H9K	3,237	0	0	0.000
H3H	3,628	1	0	0.028	H9P	5,587	0	0	0.000
H3J	2,760	0	0	0.000	H9R	12,844	1	0	0.008
H3K	3,696	1	0	0.027	H9S	10,932	1	0	0.009
H3L	7,296	0	0	0.000	H9W	10,416	0	0	0.000
H3M	6,421	1	0	0.016	H9X	5,258	1	0	0.019
H3N	6,815	0	0	0.000	Total	739,516	92	0	0.012
H3P	5,002	1	0	0.020					

Table C-5 Proportion of Hybrid Vehicles in Montreal 2008

FSA	*all_veh*	*HEV*	*Taxi HEV*	*p_HEV*	FSA	*all_veh*	*HEV*	*Taxi HEV*	*p_HEV*
H1A	17,279	47	0	0.272	H3R	4,673	30	0	0.642
H1B	10,301	11	1	0.097	H3S	8,284	22	0	0.266
H1C	6,264	7	0	0.112	H3T	2,990	9	0	0.301
H1E	20,689	17	1	0.077	H3V	1,864	4	0	0.215
H1G	16,980	17	0	0.100	H3W	7,314	15	0	0.205
H1H	12,240	12	0	0.098	H3X	8,767	26	0	0.297
H1J	7,921	24	0	0.303	H3Y	4,786	64	0	1.337
H1K	13,089	26	1	0.191	H3Z	4,667	42	0	0.900
H1L	13,464	15	0	0.111	H4A	8,749	47	0	0.537
H1M	12,640	28	0	0.222	H4B	6,059	22	1	0.347
H1N	8,690	7	0	0.081	H4C	5,157	20	0	0.388
H1P	9,045	8	0	0.088	H4E	10,602	11	1	0.094
H1R	12,557	8	0	0.064	H4G	8,300	15	0	0.181
H1S	9,216	11	0	0.119	H4H	7,030	15	0	0.213
H1T	10,890	16	0	0.147	H4J	5,424	6	0	0.111
H1V	6,085	14	0	0.230	H4K	5,460	21	0	0.385
H1W	7,790	11	0	0.141	H4L	11,906	21	0	0.176
H1X	9,888	21	0	0.212	H4M	5,543	15	0	0.271
H1Y	8,948	18	0	0.201	H4N	9,798	20	0	0.204
H1Z	11,083	10	0	0.090	H4P	3,410	13	0	0.381
H2A	5,901	5	0	0.085	H4R	11,251	27	0	0.240
H2B	6,338	13	0	0.205	H4S	8,224	16	0	0.195
H2C	6,202	10	0	0.161	H4T	7,888	29	0	0.368
H2E	6,868	6	0	0.087	H4V	6,888	9	0	0.131
H2G	7,435	16	0	0.215	H4W	10,573	18	0	0.170
H2H	4,127	12	0	0.291	H4X	2,973	10	0	0.336
H2J	7,101	29	0	0.408	H4Y	6,961	87	0	1.250
H2K	9,685	30	0	0.310	H4Z	40	0	0	0.000
H2L	6,223	27	0	0.434	H5A	18	1	0	5.556
H2M	7,561	17	0	0.225	H5B	115	1	0	0.870
H2N	3,118	11	0	0.353	H8N	11,569	22	0	0.190
H2P	4,710	15	0	0.318	H8P	9,974	10	0	0.100
H2R	6,113	13	0	0.213	H8R	12,355	14	0	0.113
H2S	7,098	16	0	0.225	H8S	9,610	17	0	0.177
H2T	4,195	11	0	0.262	H8T	7,790	21	0	0.270
H2V	9,594	69	0	0.719	H8Y	8,552	11	0	0.129
H2W	2,590	11	0	0.425	H8Z	7,417	9	0	0.121
H2X	3,176	17	0	0.535	H9A	7,993	21	0	0.263
H2Y	4,656	62	0	1.332	H9B	10,561	18	1	0.161
H2Z	643	7	0	1.089	H9C	6,840	17	0	0.249
H3A	1,880	32	0	1.702	H9E	1,682	8	0	0.476
H3B	1,679	11	0	0.655	H9G	8,559	12	0	0.140
H3C	3,873	38	0	0.981	H9H	14,084	28	0	0.199
H3E	9,239	47	0	0.509	H9J	12,639	28	0	0.222
H3G	2,767	15	0	0.542	H9K	3,930	11	0	0.280
H3H	3,393	17	0	0.501	H9P	3,986	89	0	2.233
H3J	2,861	15	0	0.524	H9R	13,203	44	0	0.333
H3K	4,017	8	0	0.199	H9S	11,102	35	0	0.315
H3L	7,241	23	0	0.318	H9W	10,619	53	0	0.499
H3M	6,481	8	0	0.123	H9X	5,377	29	0	0.539
H3N	6,578	1	0	0.015	Total	756,863	2104	6	0.277
H3P	4,905	31	0	0.632					

Table C-6 Initial Regression Dataset

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
G0A	0.020	0.134	0.087	0.510	0.490	38	0.7	2.5	1.7	3.466	66.412	9.394	0	0
G0R	0.019	0.116	0.088	0.509	0.491	38	0.9	1.2	1.9	3.119	58.155	9.642	0	0
G0S	0.045	0.112	0.084	0.504	0.495	35	0.9	2.7	1.9	3.316	71.876	9.595	0	0
G1A	3.561	0.066	0.190	0.402	0.599	55	0.1	1.6	0.0	4.321	0.000	10.285	0	0
G1B	0.590	0.146	0.078	0.500	0.499	36	1.0	2.8	1.7	3.382	50.929	9.022	0	0
G1C	1.597	0.135	0.093	0.480	0.520	40	0.7	2.5	1.5	3.220	39.540	8.957	0	0
G1E	2.104	0.132	0.088	0.467	0.534	45	0.5	2.1	1.1	3.005	26.450	8.943	0	0
G1G	2.064	0.135	0.101	0.480	0.520	42	0.7	2.3	1.4	3.176	32.261	8.915	0	0
G1H	3.408	0.124	0.077	0.463	0.537	45	0.4	2.0	1.1	2.967	23.816	8.919	0	0
G1J	3.155	0.138	0.090	0.478	0.523	42	0.4	1.9	0.9	2.299	15.426	8.679	0	0
G1K	4.102	0.113	0.156	0.508	0.492	43	0.3	1.7	0.7	2.664	12.674	8.907	0	0
G1L	5.471	0.142	0.101	0.458	0.543	44	0.3	1.8	0.8	2.407	13.917	8.714	0	0
G1M	1.938	0.156	0.057	0.469	0.532	44	0.4	2.0	1.1	2.551	19.285	8.993	0	0
G1N	2.403	0.120	0.106	0.476	0.524	41	0.3	1.9	0.9	2.386	14.610	9.758	0	0
G1P	1.713	0.115	0.105	0.474	0.525	43	0.5	2.2	1.3	2.989	28.260	8.932	0	0
G1R	6.245	0.089	0.257	0.469	0.532	45	0.2	1.6	0.6	3.504	10.819	8.899	0	0
G1S	4.638	0.065	0.224	0.416	0.584	48	0.3	1.9	0.8	4.136	13.951	9.144	0	0
G1T	1.524	0.035	0.255	0.481	0.519	43	0.8	2.7	1.5	6.133	31.049	9.308	0	0
G1V	1.737	0.057	0.194	0.474	0.527	42	0.3	1.9	1.0	3.237	16.697	8.808	0	0
G1W	2.387	0.066	0.197	0.465	0.536	44	0.5	2.1	1.2	3.992	24.601	8.796	0	0
G1X	1.913	0.086	0.182	0.454	0.546	44	0.4	2.0	1.2	3.554	26.910	8.725	0	0
G1Y	1.967	0.068	0.248	0.486	0.515	39	0.8	2.6	1.6	4.927	47.036	8.885	0	0
G2A	0.583	0.132	0.095	0.493	0.507	40	0.7	2.5	1.6	3.407	41.746	9.051	0	0
G2B	1.453	0.140	0.078	0.482	0.518	39	0.7	2.4	1.4	3.059	33.749	8.842	0	0
G2C	1.054	0.131	0.138	0.485	0.514	36	0.7	2.3	1.6	3.731	40.034	9.140	0	0
G2E	1.532	0.127	0.109	0.489	0.511	39	0.8	2.5	1.6	3.516	39.164	9.085	0	0
G2G	0.274	0.122	0.141	0.491	0.509	38	0.9	2.6	1.6	3.822	44.616	9.047	0	0

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
G2J	0.981	0.139	0.157	0.458	0.541	44	0.4	2.0	1.3	4.135	24.025	8.948	0	0
G2K	0.625	0.131	0.141	0.485	0.515	41	0.5	2.2	1.6	4.128	34.884	9.103	0	0
G2L	0.715	0.133	0.132	0.480	0.521	38	0.7	2.4	1.5	3.856	41.684	8.821	0	0
G2M	0.326	0.136	0.109	0.485	0.514	39	0.7	2.4	1.6	3.406	44.305	8.927	0	0
G2N	0.299	0.132	0.104	0.492	0.509	39	0.7	2.5	1.6	3.464	45.681	9.187	0	0
G3A	0.206	0.077	0.181	0.502	0.499	36	1.1	2.9	1.8	4.762	64.839	9.168	0	0
G3B	0.084	0.089	0.182	0.512	0.488	35	0.9	2.8	2.0	4.399	78.800	9.336	0	0
G3E	1.328	0.135	0.076	0.495	0.505	34	0.9	2.7	1.7	3.420	48.361	8.944	0	0
G3G	0.252	0.149	0.059	0.510	0.490	35	0.9	2.7	1.8	2.997	59.052	9.094	0	0
~~G3H~~	~~0.038~~	~~0.147~~	~~0.080~~	~~0.518~~	~~0.483~~	~~38~~	~~0.7~~	~~2.5~~	~~1.6~~	~~3.599~~	~~60.866~~	~~9.199~~	~~0~~	~~0~~
G3J	0.206	0.135	0.083	0.504	0.497	34	0.8	2.6	1.6	3.248	51.926	9.007	0	0
G3K	0.532	0.141	0.087	0.498	0.502	34	0.9	2.7	1.7	3.355	56.190	8.961	0	0
~~G3L~~	~~0.000~~	~~0.147~~	~~0.077~~	~~0.518~~	~~0.482~~	~~37~~	~~0.7~~	~~2.5~~	~~1.0~~	~~3.604~~	~~74.710~~	~~9.915~~	~~0~~	~~0~~
~~G3M~~	~~0.000~~	~~0.000~~	~~0.000~~	~~0.000~~	~~0.000~~	~~0~~	~~0.0~~	~~0.0~~	~~1.4~~	~~0.000~~	~~49.704~~	~~9.005~~	~~0~~	~~0~~
G6C	0.109	0.125	0.076	0.499	0.501	36	0.8	2.6	2.0	3.324	59.435	9.436	0	0
G6J	0.110	0.116	0.099	0.508	0.493	34	1.0	2.8	1.8	3.458	65.020	9.099	0	0
G6K	1.014	0.114	0.125	0.497	0.503	35	1.0	2.7	1.8	3.710	56.869	8.958	0	0
G6V	0.653	0.121	0.094	0.468	0.532	43	0.6	2.3	1.4	3.147	35.828	9.041	0	0
G6W	0.735	0.121	0.108	0.478	0.522	40	0.6	2.2	1.5	3.408	37.244	8.993	0	0
G6X	1.044	0.119	0.118	0.475	0.525	39	0.6	2.3	1.5	3.161	42.645	8.787	0	0
G6Z	0.234	0.109	0.117	0.499	0.501	33	1.0	2.8	1.8	3.777	60.991	9.006	0	0
G7A	0.212	0.104	0.151	0.502	0.499	35	0.9	2.7	1.8	4.010	58.970	9.185	0	0
H1A	2.353	0.151	0.101	0.478	0.522	38	1.1	2.5	1.3	6.174	48.843	9.352	1	0
H1B	1.316	0.157	0.079	0.484	0.516	40	1.0	2.4	1.2	5.556	39.582	9.649	1	0
H1C	0.876	0.136	0.096	0.510	0.490	33	1.4	3.2	1.6	6.561	54.966	9.520	1	0
H1E	3.360	0.123	0.100	0.479	0.521	37	1.3	2.8	1.4	5.845	47.843	9.501	1	0
H1G	7.149	0.121	0.081	0.456	0.543	39	1.2	2.3	0.9	4.443	27.236	9.379	1	0

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
H1H	7.617	0.128	0.098	0.453	0.546	41	1.1	2.1	0.9	4.313	21.708	9.411	1	0
H1J	1.167	0.141	0.181	0.465	0.535	41	0.9	2.1	1.1	6.041	35.533	10.408	1	0
H1K	5.033	0.131	0.168	0.469	0.532	39	1.0	2.3	1.1	6.154	33.537	9.196	1	0
H1L	5.355	0.147	0.107	0.470	0.530	40	0.9	2.1	1.0	5.087	31.529	9.193	1	0
H1M	5.081	0.148	0.210	0.459	0.541	44	0.8	2.0	1.0	6.476	27.198	9.143	1	0
H1N	2.567	0.140	0.120	0.468	0.532	42	0.9	2.1	0.8	5.078	21.376	9.326	1	0
H1P	3.402	0.123	0.137	0.467	0.533	39	1.1	2.3	1.2	5.539	31.329	9.658	1	0
H1R	6.038	0.112	0.121	0.478	0.523	38	1.1	2.5	1.2	5.444	27.464	9.476	1	0
H1S	6.302	0.111	0.147	0.460	0.540	42	1.0	2.2	1.0	5.208	22.439	9.429	1	0
H1T	7.531	0.126	0.197	0.446	0.555	45	0.9	1.9	0.9	5.694	23.030	9.175	1	0
H1V	5.353	0.108	0.146	0.504	0.494	38	1.0	1.9	0.8	4.148	18.837	9.187	1	0
H1W	9.340	0.113	0.139	0.504	0.496	38	1.0	1.9	0.7	4.060	18.708	9.256	1	0
H1X	6.047	0.121	0.193	0.464	0.536	40	0.9	1.8	0.8	5.064	18.151	8.957	1	0
H1Y	10.167	0.104	0.213	0.467	0.533	39	0.9	1.8	0.8	5.002	18.292	8.978	1	0
H1Z	5.171	0.104	0.069	0.469	0.531	35	1.4	2.5	0.9	4.063	20.089	9.519	1	0
H2A	8.867	0.120	0.120	0.479	0.521	39	1.2	2.2	0.8	4.317	21.174	9.336	1	0
H2B	6.331	0.113	0.196	0.462	0.539	42	1.0	2.0	0.9	5.441	24.195	9.126	1	0
H2C	6.831	0.094	0.275	0.459	0.541	42	0.9	2.0	0.8	6.522	22.973	9.039	1	0
H2E	12.188	0.104	0.148	0.472	0.528	39	1.1	2.1	0.7	4.317	14.788	9.133	1	0
H2G	10.485	0.103	0.213	0.483	0.517	39	0.9	1.8	0.7	4.786	19.051	9.161	1	0
H2H	10.449	0.085	0.332	0.485	0.515	37	0.7	1.8	0.7	5.251	14.137	9.288	1	0
H2J	12.470	0.065	0.429	0.505	0.494	37	0.7	1.7	0.6	6.279	18.247	8.924	1	0
H2K	8.945	0.100	0.218	0.532	0.468	38	0.9	1.8	0.6	4.377	16.713	9.573	1	0
H2L	8.650	0.075	0.333	0.568	0.433	40	0.6	1.7	0.5	5.109	14.397	9.444	1	0
H2M	5.214	0.108	0.236	0.463	0.536	40	1.0	2.1	1.1	6.079	29.473	9.016	1	0
H2N	5.328	0.110	0.119	0.479	0.520	39	1.2	2.3	1.0	4.531	23.208	9.930	1	0
H2P	8.113	0.117	0.238	0.479	0.520	38	0.9	2.0	0.8	5.229	20.085	9.270	1	0

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
H2R	10.658	0.095	0.263	0.483	0.517	37	0.9	1.9	0.6	4.565	15.212	9.069	1	0
H2S	10.420	0.084	0.257	0.489	0.512	37	0.9	1.9	0.6	4.608	15.967	9.159	1	0
H2T	12.715	0.069	0.363	0.489	0.511	36	1.0	2.0	0.7	5.281	15.255	9.248	1	0
H2V	6.549	0.050	0.452	0.467	0.533	37	1.2	2.2	0.9	8.939	21.883	9.466	1	0
H2W	8.825	0.048	0.424	0.503	0.496	36	0.8	1.7	0.6	5.690	13.511	9.273	1	0
H2X	12.074	0.072	0.450	0.532	0.469	39	0.7	1.4	0.4	5.088	9.459	9.378	1	0
H2Y	3.154	0.061	0.607	0.571	0.428	43	0.3	1.4	0.9	12.996	16.542	10.593	1	0
~~H2Z~~	~~2.764~~	~~0.005~~	~~0.036~~	~~0.582~~	~~0.421~~	~~48~~	~~0.1~~	~~2.1~~	~~0.6~~	~~0.487~~	~~5.097~~	~~10.269~~	~~1~~	~~0~~
H3A	5.371	0.063	0.608	0.486	0.514	40	0.6	1.3	0.4	11.313	8.271	10.940	1	0
H3B	0.607	0.039	0.454	0.542	0.450	39	0.4	1.5	2.0	4.978	0.000	11.033	1	0
H3C	1.436	0.097	0.313	0.510	0.490	41	0.7	1.7	1.0	6.681	25.267	10.398	1	0
H3E	3.318	0.070	0.531	0.467	0.532	41	0.8	1.8	1.3	12.905	38.312	9.586	1	0
H3G	5.202	0.059	0.522	0.488	0.512	42	0.4	1.4	0.7	9.983	25.141	10.046	1	0
H3H	4.763	0.084	0.496	0.508	0.491	38	0.7	1.5	0.4	5.682	10.783	9.610	1	0
H3J	7.631	0.076	0.254	0.488	0.512	35	1.4	2.2	0.8	5.628	22.373	9.371	1	0
H3K	3.400	0.089	0.141	0.501	0.498	36	1.2	1.9	0.8	3.833	20.341	9.554	1	0
H3L	4.981	0.101	0.285	0.474	0.526	41	1.1	2.0	0.9	6.926	23.606	9.161	1	0
H3M	5.590	0.113	0.238	0.475	0.525	42	1.2	2.3	1.2	6.520	37.111	9.384	1	0
H3N	18.532	0.112	0.114	0.521	0.479	36	1.4	2.5	0.7	3.529	13.386	9.473	1	0
H3P	3.493	0.063	0.430	0.473	0.526	41	1.2	2.6	1.4	13.959	33.339	9.792	1	0
H3R	3.709	0.069	0.460	0.470	0.531	39	1.2	2.5	1.4	13.634	47.098	9.908	1	0
H3S	13.406	0.104	0.298	0.482	0.518	35	1.3	2.3	0.7	4.448	14.986	9.392	1	0
H3T	9.289	0.066	0.469	0.458	0.542	38	0.9	1.8	0.6	5.728	16.942	8.976	1	0
H3V	5.333	0.072	0.547	0.441	0.558	43	0.7	1.6	0.5	5.452	11.893	8.863	1	0
H3W	10.773	0.080	0.321	0.465	0.535	37	1.2	2.3	0.7	5.649	17.235	9.420	1	0
H3X	6.607	0.086	0.384	0.462	0.538	40	1.1	2.1	1.1	8.409	25.005	9.730	1	0
H3Y	3.902	0.048	0.546	0.476	0.525	39	1.2	2.5	1.5	21.842	32.858	10.614	1	0

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
H3Z	7.066	0.067	0.499	0.438	0.562	46	0.9	1.7	0.8	11.942	16.108	10.060	1	0
H4A	7.492	0.062	0.433	0.467	0.533	38	1.0	2.0	0.9	7.696	24.840	9.410	1	0
H4B	6.665	0.086	0.325	0.465	0.535	40	1.0	1.9	0.8	5.369	17.190	9.222	1	0
H4C	3.530	0.094	0.203	0.498	0.502	37	1.0	1.9	0.8	4.088	23.006	9.555	1	0
H4E	6.055	0.137	0.122	0.472	0.527	41	1.0	2.0	0.8	5.038	24.005	9.322	1	0
H4G	8.884	0.121	0.147	0.483	0.517	38	1.0	1.8	0.6	4.069	17.973	9.204	1	0
H4H	5.957	0.134	0.131	0.457	0.543	41	1.0	2.0	0.9	5.309	25.672	9.201	1	0
H4J	6.290	0.113	0.212	0.478	0.522	38	1.2	2.4	0.9	5.289	23.905	9.204	1	0
H4K	2.676	0.091	0.297	0.486	0.515	40	1.2	2.6	1.4	9.025	39.119	9.479	1	0
H4L	5.885	0.109	0.239	0.462	0.538	41	1.2	2.4	1.0	6.047	22.069	9.254	1	0
H4M	3.881	0.100	0.286	0.492	0.508	38	1.3	2.6	1.4	7.614	45.473	9.652	1	0
H4N	4.466	0.118	0.237	0.479	0.521	38	1.2	2.3	0.9	4.616	24.995	9.380	1	0
H4P	1.501	0.096	0.277	0.489	0.511	37	1.3	2.5	1.0	6.345	23.603	10.519	1	0
H4R	1.393	0.126	0.237	0.479	0.522	40	1.0	2.2	1.2	5.887	31.355	9.619	1	0
H4S	0.209	0.090	0.301	0.491	0.509	34	1.1	2.5	1.2	8.867	26.027	10.534	1	0
H4T	0.205	0.086	0.357	0.487	0.514	36	1.1	2.5	0.0	9.586	0.000	10.470	1	0
H4V	7.565	0.093	0.293	0.459	0.541	40	1.2	2.2	0.9	5.926	21.796	9.363	1	0
H4W	3.633	0.102	0.313	0.453	0.547	48	1.0	2.3	1.2	8.195	27.529	9.646	1	0
H4X	4.040	0.081	0.358	0.474	0.526	39	1.2	2.4	1.4	8.757	30.610	9.662	1	0
H4Y	0.220	0.137	0.156	0.495	0.506	38	1.1	2.5	0.0	6.462	0.000	10.660	1	0
~~H4Z~~	~~0.353~~	~~0.034~~	~~0.648~~	~~0.597~~	~~0.392~~	~~38~~	~~0.9~~	~~1.5~~	~~0.0~~	~~5.203~~	~~0.000~~	~~10.787~~	~~1~~	~~0~~
~~H5A~~	~~0.354~~	~~0.034~~	~~0.648~~	~~0.597~~	~~0.393~~	~~38~~	~~0.9~~	~~1.5~~	~~0.0~~	~~5.216~~	~~0.000~~	~~11.717~~	~~1~~	~~0~~
~~H5B~~	~~4.026~~	~~0.000~~	~~0.002~~	~~0.586~~	~~0.418~~	~~48~~	~~0.0~~	~~2.1~~	~~0.0~~	~~0.044~~	~~0.000~~	~~10.903~~	~~1~~	~~0~~
H8N	3.580	0.145	0.133	0.477	0.522	39	1.0	2.3	1.2	5.534	33.752	9.369	1	0
H8P	5.813	0.136	0.147	0.451	0.549	43	0.9	2.1	1.1	5.973	34.946	9.261	1	0
H8R	3.949	0.136	0.136	0.478	0.521	37	1.1	2.2	1.1	5.120	33.318	9.475	1	0
H8S	2.646	0.147	0.113	0.468	0.531	41	1.0	2.1	1.1	5.109	33.562	9.325	1	0

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
H8T	1.946	0.118	0.234	0.474	0.526	40	1.0	2.2	1.2	7.069	43.819	9.298	1	0
H8Y	2.838	0.099	0.207	0.484	0.516	36	1.3	2.7	1.3	6.611	45.482	9.274	1	0
H8Z	3.168	0.128	0.218	0.483	0.517	38	1.2	2.5	1.6	6.602	59.449	9.299	1	0
H9A	3.350	0.095	0.284	0.494	0.506	35	1.5	3.0	1.8	8.832	68.972	9.592	1	0
H9B	2.956	0.090	0.258	0.491	0.509	36	1.4	3.0	1.6	7.444	54.430	9.373	1	0
H9C	1.136	0.106	0.219	0.496	0.503	34	1.4	3.0	1.7	9.367	75.234	9.444	1	0
H9E	0.218	0.114	0.176	0.501	0.498	36	1.2	2.7	1.9	9.114	64.979	9.813	1	0
H9G	3.365	0.081	0.268	0.484	0.516	36	1.4	3.0	1.7	8.005	62.699	9.334	1	0
H9H	2.647	0.099	0.242	0.481	0.520	36	1.3	2.8	1.7	7.987	68.796	9.382	1	0
H9J	2.372	0.083	0.278	0.492	0.508	33	1.4	3.0	1.8	9.412	77.919	9.489	1	0
H9K	0.628	0.094	0.244	0.481	0.519	33	1.3	2.9	1.7	8.267	63.133	9.208	1	0
H9P	0.281	0.130	0.168	0.493	0.508	38	1.1	2.6	1.4	6.505	44.405	10.425	1	0
H9R	1.489	0.096	0.279	0.478	0.522	37	1.3	2.6	1.6	8.190	58.411	9.588	1	0
H9S	2.223	0.106	0.300	0.471	0.529	43	1.0	2.2	1.3	8.386	44.584	9.473	1	0
H9W	1.736	0.064	0.387	0.488	0.512	37	1.3	2.9	1.7	12.503	70.309	9.749	1	0
H9X	0.413	0.064	0.329	0.508	0.491	40	1.1	2.6	1.6	9.521	75.530	9.683	1	0
H1A	2.434	0.147	0.113	0.476	0.524	40	1.0	2.4	1.2	6.049	29.834	9.119	1	1
H1B	1.297	0.147	0.075	0.485	0.515	41	1.0	2.3	1.2	5.163	24.554	9.347	1	1
H1C	1.023	0.128	0.117	0.510	0.489	34	1.5	3.2	1.6	7.084	49.223	9.349	1	1
H1E	3.420	0.129	0.100	0.476	0.524	39	1.3	2.7	1.3	5.966	27.315	9.329	1	1
H1G	7.159	0.117	0.082	0.464	0.535	40	1.2	2.3	0.9	4.162	15.383	9.223	1	1
H1H	7.714	0.108	0.102	0.462	0.538	41	1.2	2.2	0.8	3.904	12.445	9.206	1	1
H1J	1.267	0.129	0.181	0.460	0.540	43	0.9	2.1	1.1	5.794	17.138	9.974	1	1
H1K	5.093	0.113	0.156	0.471	0.529	40	1.0	2.3	1.1	5.856	20.561	9.032	1	1
H1L	5.402	0.131	0.120	0.476	0.524	41	0.9	2.1	1.0	4.957	20.477	8.952	1	1
H1M	5.457	0.109	0.176	0.458	0.543	46	0.8	2.0	1.0	5.569	16.079	8.923	1	1
H1N	2.566	0.129	0.144	0.474	0.525	43	0.9	2.1	0.9	4.581	13.381	9.030	1	1

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
H1P	3.453	0.111	0.140	0.471	0.528	40	1.1	2.4	1.2	5.428	17.428	9.556	1	1
H1R	6.161	0.121	0.129	0.478	0.522	39	1.1	2.5	1.2	5.095	17.101	9.372	1	1
H1S	6.663	0.123	0.150	0.458	0.541	43	1.0	2.3	1.0	4.599	13.792	9.256	1	1
H1T	7.500	0.113	0.192	0.455	0.546	44	0.9	2.0	0.8	4.893	13.073	8.930	1	1
H1V	5.417	0.108	0.176	0.508	0.492	38	1.0	1.9	0.8	3.978	14.064	8.893	1	1
H1W	9.366	0.111	0.170	0.517	0.483	38	0.9	1.9	0.7	3.739	10.026	8.956	1	1
H1X	6.416	0.103	0.210	0.470	0.530	40	0.9	1.9	0.8	4.500	11.935	8.723	1	1
H1Y	10.565	0.100	0.245	0.470	0.530	39	0.9	1.9	0.8	4.663	13.360	8.709	1	1
H1Z	5.198	0.106	0.080	0.473	0.527	36	1.4	2.6	0.9	4.015	12.648	9.336	1	1
H2A	8.748	0.111	0.135	0.482	0.519	40	1.1	2.3	0.7	4.034	10.060	9.163	1	1
H2B	6.356	0.095	0.197	0.464	0.537	42	1.0	2.0	0.9	4.769	16.268	8.874	1	1
H2C	6.854	0.090	0.267	0.465	0.535	42	0.9	2.1	1.0	5.448	16.600	8.781	1	1
H2E	11.825	0.102	0.181	0.480	0.520	39	1.1	2.1	0.8	4.032	9.750	8.914	1	1
H2G	10.449	0.102	0.246	0.489	0.511	39	0.9	1.9	0.8	4.373	13.055	9.057	1	1
H2H	10.265	0.084	0.338	0.491	0.509	37	0.7	1.8	0.8	4.576	10.086	8.751	1	1
H2J	12.580	0.082	0.428	0.508	0.492	37	0.7	1.7	0.7	5.434	10.922	8.746	1	1
H2K	9.018	0.123	0.242	0.540	0.460	38	0.8	1.8	0.6	3.710	7.916	9.320	1	1
H2L	8.743	0.086	0.317	0.586	0.415	40	0.7	1.9	0.5	4.521	7.983	9.352	1	1
H2M	5.204	0.108	0.219	0.469	0.531	41	1.0	2.1	1.0	5.623	17.127	8.776	1	1
H2N	5.246	0.131	0.154	0.489	0.511	40	1.1	2.4	0.9	4.663	14.014	9.788	1	1
H2P	7.822	0.096	0.264	0.487	0.514	38	0.9	2.0	0.7	4.747	13.027	8.880	1	1
H2R	10.440	0.095	0.282	0.483	0.516	37	0.9	1.9	0.7	4.331	10.748	8.806	1	1
H2S	10.372	0.087	0.292	0.492	0.508	37	0.9	1.9	0.7	4.150	9.808	8.971	1	1
H2T	12.629	0.095	0.366	0.493	0.507	37	0.9	2.0	0.6	5.119	9.154	9.067	1	1
H2V	6.463	0.063	0.368	0.476	0.524	37	1.2	2.3	0.9	9.120	12.821	9.321	1	1
H2W	8.814	0.085	0.384	0.509	0.491	37	0.8	1.9	0.6	5.604	6.936	9.080	1	1
H2X	11.890	0.070	0.313	0.528	0.473	39	0.8	2.0	0.5	4.065	7.447	9.230	1	1

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
H2Y	4.475	0.080	0.499	0.554	0.448	42	0.5	1.8	1.0	11.474	15.868	10.197	1	1
H2Z	3.512	0.058	0.261	0.576	0.424	49	0.7	2.4	0.4	4.593	7.581	9.744	1	1
H3A	5.525	0.049	0.340	0.487	0.514	41	0.6	2.0	1.3	9.955	0.392	10.528	1	1
H3B	1.114	0.066	0.300	0.445	0.557	47	0.5	2.4	0.7	5.800	2.129	11.305	1	1
H3C	0.906	0.094	0.358	0.545	0.455	39	0.7	1.9	1.0	7.631	14.703	9.949	1	1
H3E	4.080	0.069	0.452	0.471	0.528	42	0.8	2.0	1.3	11.183	28.939	9.485	1	1
H3G	5.282	0.057	0.392	0.497	0.503	43	0.7	1.7	0.8	9.098	7.205	9.984	1	1
H3H	4.703	0.071	0.386	0.527	0.474	37	0.8	1.8	0.6	5.416	9.880	9.562	1	1
H3J	8.105	0.112	0.248	0.488	0.513	36	1.3	2.3	0.7	5.741	14.095	9.229	1	1
H3K	3.666	0.109	0.176	0.500	0.500	37	1.1	2.1	0.8	3.993	12.758	9.356	1	1
H3L	5.019	0.100	0.265	0.486	0.514	40	1.0	2.1	0.9	5.557	14.640	8.955	1	1
H3M	5.686	0.101	0.216	0.480	0.520	44	1.1	2.4	1.1	6.017	18.884	9.206	1	1
H3N	17.996	0.136	0.108	0.516	0.484	37	1.4	2.5	0.8	3.292	9.437	9.330	1	1
H3P	3.484	0.046	0.353	0.476	0.524	41	1.2	2.8	1.3	14.647	22.977	9.624	1	1
H3R	3.726	0.064	0.351	0.473	0.527	39	1.3	2.6	1.5	14.300	24.000	9.725	1	1
H3S	13.241	0.102	0.268	0.477	0.523	36	1.2	2.4	0.8	4.744	9.026	9.298	1	1
H3T	9.332	0.060	0.372	0.468	0.531	38	0.8	2.0	0.8	5.512	10.873	8.841	1	1
H3V	5.242	0.046	0.441	0.456	0.544	42	0.8	1.7	0.5	4.697	7.210	8.766	1	1
H3W	10.552	0.099	0.280	0.464	0.536	37	1.2	2.4	0.8	4.994	9.834	9.284	1	1
H3X	6.594	0.090	0.325	0.462	0.539	40	1.1	2.3	1.0	8.223	15.937	9.549	1	1
H3Y	3.923	0.037	0.418	0.478	0.522	40	1.2	2.6	1.2	25.070	15.132	10.486	1	1
H3Z	7.526	0.045	0.347	0.447	0.553	46	0.8	2.0	0.8	11.591	9.746	9.776	1	1
H4A	7.539	0.079	0.367	0.469	0.531	38	1.0	2.1	0.9	6.759	14.692	9.155	1	1
H4B	7.034	0.095	0.296	0.465	0.535	40	1.0	2.1	0.9	4.829	15.807	9.077	1	1
H4C	3.803	0.115	0.215	0.494	0.506	37	0.9	2.0	0.7	4.029	10.849	9.370	1	1
H4E	6.066	0.130	0.151	0.476	0.524	41	0.9	2.1	0.9	4.325	14.245	9.109	1	1
H4G	9.536	0.122	0.192	0.485	0.515	38	0.9	2.0	0.8	3.790	11.893	8.928	1	1

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
H4H	6.171	0.133	0.166	0.467	0.533	41	1.0	2.2	0.9	4.882	17.474	8.963	1	1
H4J	6.354	0.109	0.199	0.480	0.520	38	1.2	2.5	1.0	4.357	18.002	8.990	1	1
H4K	2.778	0.094	0.242	0.483	0.517	41	1.2	2.7	1.3	8.439	25.735	9.282	1	1
H4L	6.271	0.091	0.227	0.463	0.536	41	1.2	2.5	1.0	5.332	13.304	9.021	1	1
H4M	4.048	0.084	0.260	0.489	0.511	39	1.3	2.7	1.3	6.968	19.621	9.421	1	1
H4N	4.610	0.105	0.218	0.480	0.521	38	1.2	2.4	1.0	4.146	12.703	9.275	1	1
H4P	1.530	0.103	0.228	0.480	0.519	37	1.3	2.6	0.9	5.854	15.268	10.047	1	1
H4R	1.574	0.109	0.228	0.476	0.525	41	1.1	2.4	1.1	5.900	15.467	9.405	1	1
H4S	0.352	0.086	0.338	0.482	0.518	35	1.2	2.6	1.7	9.581	42.950	9.795	1	1
H4T	0.330	0.075	0.369	0.479	0.521	37	1.1	2.5	1.3	10.286	22.252	9.812	1	1
H4V	7.632	0.087	0.257	0.458	0.542	41	1.2	2.3	1.0	5.426	16.128	9.203	1	1
H4W	3.781	0.080	0.243	0.459	0.541	47	1.0	2.4	1.1	7.617	18.660	9.388	1	1
H4X	4.147	0.088	0.278	0.476	0.523	39	1.2	2.6	1.3	9.714	23.364	9.455	1	1
H4Y	0.233	0.137	0.182	0.493	0.506	39	1.2	2.6	0.0	6.575	0.000	9.544	1	1
~~H4Z~~	~~0.983~~	~~0.066~~	~~0.304~~	~~0.415~~	~~0.589~~	~~50~~	~~0.6~~	~~2.6~~	~~0.0~~	~~7.629~~	~~0.000~~	~~10.750~~	~~1~~	~~1~~
~~H5A~~	~~0.937~~	~~0.064~~	~~0.296~~	~~0.405~~	~~0.598~~	~~51~~	~~0.6~~	~~2.7~~	~~0.0~~	~~7.612~~	~~0.000~~	~~10.272~~	~~1~~	~~1~~
H5B	5.139	0.057	0.257	0.594	0.405	49	0.7	2.4	0.0	4.269	0.000	10.161	1	1
H8N	3.600	0.154	0.147	0.470	0.531	41	1.0	2.3	1.1	5.258	17.568	9.238	1	1
H8P	5.906	0.129	0.157	0.455	0.545	45	0.9	2.1	1.1	5.347	18.251	9.067	1	1
H8R	4.022	0.145	0.138	0.481	0.519	38	1.1	2.3	1.1	4.850	20.991	9.255	1	1
H8S	2.748	0.147	0.128	0.472	0.529	41	1.0	2.2	1.0	4.829	20.573	9.059	1	1
H8T	1.968	0.122	0.229	0.474	0.526	41	1.0	2.2	1.4	6.616	27.078	9.088	1	1
H8Y	2.853	0.118	0.210	0.483	0.517	38	1.3	2.8	1.4	7.077	27.414	9.091	1	1
H8Z	3.358	0.121	0.190	0.481	0.519	39	1.2	2.6	1.5	6.218	32.905	9.078	1	1
H9A	3.474	0.115	0.249	0.493	0.507	37	1.4	3.0	1.6	9.059	40.339	9.409	1	1
H9B	2.972	0.114	0.242	0.493	0.508	38	1.4	3.0	1.6	7.810	36.453	9.227	1	1
H9C	1.197	0.114	0.234	0.486	0.513	36	1.4	3.0	1.9	9.671	56.243	9.280	1	1

Table C-6 Initial Regression Dataset (continued)

FSA	*pop_dens*	*p_hs*	*p_uni*	*p_male*	*p_female*	*age*	*kids_hh*	*ppl_hh*	*auto_hh*	*inc_hh*	*dist_hh*	*fuel_cons*	*mtl*	*add_year*
H9E	0.208	0.141	0.184	0.496	0.505	39	1.1	2.6	1.8	10.472	42.182	9.710	1	1
H9G	3.332	0.119	0.211	0.484	0.517	39	1.3	2.9	1.8	7.718	42.398	9.146	1	1
H9H	2.756	0.124	0.213	0.479	0.521	38	1.3	2.7	1.6	8.306	39.262	9.249	1	1
H9J	2.417	0.103	0.246	0.489	0.511	36	1.4	3.0	2.0	9.788	56.074	9.254	1	1
H9K	0.855	0.119	0.239	0.487	0.512	34	1.4	3.0	1.8	9.013	46.754	9.163	1	1
H9P	0.285	0.139	0.182	0.493	0.506	39	1.2	2.6	1.5	6.418	32.491	9.536	1	1
H9R	1.547	0.107	0.244	0.476	0.524	40	1.2	2.6	1.5	7.833	32.749	9.284	1	1
H9S	2.267	0.110	0.245	0.470	0.530	43	1.0	2.3	1.4	8.233	29.084	9.220	1	1
H9W	1.726	0.082	0.327	0.489	0.511	39	1.3	2.9	1.8	13.451	48.438	9.527	1	1
H9X	0.431	0.079	0.290	0.501	0.499	40	1.1	2.7	1.7	11.416	43.371	9.481	1	1

Table C-7 Speed Correction Factor

Speed (km/h)	Speed correction factor	Speed (km/h)	Speed correction factor	Speed (km/h)	Speed correction factor
0	0	41	1.18	82	0.91
1	16.79	42	1.17	83	0.91
2	11.45	43	1.16	84	0.92
3	8.91	44	1.15	85	0.92
4	6.36	45	1.14	86	0.92
5	5.05	46	1.12	87	0.93
6	4.21	47	1.11	88	0.95
7	3.70	48	1.10	89	0.94
8	3.26	49	1.09	90	0.95
9	2.92	50	1.08	91	0.94
10	2.68	51	1.07	92	0.96
11	2.53	52	1.06	93	0.97
12	2.34	53	1.06	94	0.98
13	2.22	54	1.05	95	0.99
14	2.11	55	1.04	96	1
15	2.06	56	1.04	97	0.99
16	1.97	57	1.03	98	1.03
17	1.90	58	1.02	99	1.03
18	1.83	59	1.01	100	1.03
19	1.77	60	1	101	1.03
20	1.71	61	1	102	1.03
21	1.67	62	0.99	103	1.03
22	1.63	63	0.99	104	1.04
23	1.58	64	0.99	105	1.04
24	1.54	65	0.99	106	1.05
25	1.50	66	0.99	107	1.05
26	1.48	67	0.99	108	1.06
27	1.45	68	0.99	109	1.07
28	1.42	69	0.99	110	1.08
29	1.40	70	0.98	111	1.08
30	1.38	71	0.98	112	1.09
31	1.35	72	0.97	113	1.10
32	1.33	73	0.97	114	1.11
33	1.31	74	0.96	115	1.12
34	1.29	75	0.95	116	1.13
35	1.27	76	0.94	117	1.13
36	1.26	77	0.93	118	1.14
37	1.25	78	0.92	119	1.16
38	1.23	79	0.92	120	1.17
39	1.21	80	0.91		
40	1.20	81	0.92		

Table C-8 Fuel Consumption Rate of Hybrid Vehicles in Quebec City (2008)

FSA	FCR	Count of cars	FCR*Car	FSA	FCR	Count of cars	FCR*Car
G0A	5.388	52	280.2	G2E	5.750	16	92.0
G0R	5.576	45	250.9	G2G	5.381	16	86.1
G0S	5.443	30	163.3	G2J	0.000	0	0.0
G1A	0.000	0	0.0	G2K	5.807	14	81.3
G1B	5.800	8	46.4	G2L	5.150	6	30.9
G1C	5.406	16	86.5	G2M	4.250	4	17.0
G1E	5.882	11	64.7	G2N	4.900	2	9.8
G1G	5.594	18	100.7	G3A	5.338	34	181.5
G1H	5.400	34	183.6	G3B	5.678	9	51.1
G1J	5.425	4	21.7	G3E	5.650	8	45.2
G1K	5.086	21	106.8	G3G	4.900	2	9.8
G1L	4.567	9	41.1	G3H	5.267	6	31.6
G1M	5.575	12	66.9	G3J	6.400	3	19.2
G1N	4.420	55	243.1	G3K	5.033	6	30.2
G1P	5.540	10	55.4	G3L	7.200	3	21.6
G1R	5.583	83	463.4	G3M	4.800	1	4.8
G1S	5.541	184	1019.5	G6C	5.467	3	16.4
G1T	6.152	21	129.2	G6J	5.380	10	53.8
G1V	5.639	23	129.7	G6K	5.829	7	40.8
G1W	5.071	35	177.5	G6V	5.985	33	197.5
G1X	5.197	32	166.3	G6W	5.531	16	88.5
G1Y	5.255	31	162.9	G6X	6.600	5	33.0
G2A	5.436	14	76.1	G6Z	5.500	11	60.5
G2B	5.833	6	35.0	G7A	5.517	24	132.4
G2C	5.785	13	75.2	Total	5.263	1006	5481.1
Weighted Average FCR = 5.448 L/100km							

Table C-9 Fuel Consumption Rate of Hybrid Vehicles in Montreal (2008)

FSA	FCR	Count of cars	FCR*Car	FSA	FCR	Count of cars	FCR*Car
H1A	5.945	47	279.4	H3R	6.360	30	190.8
H1B	5.355	11	58.9	H3S	6.255	22	137.6
H1C	5.671	7	39.7	H3T	5.467	9	49.2
H1E	6.435	17	109.4	H3V	4.850	4	19.4
H1G	6.135	17	104.3	H3W	5.193	15	77.9
H1H	5.875	12	70.5	H3X	6.081	26	158.1
H1J	5.817	24	139.6	H3Y	6.739	64	431.3
H1K	5.050	26	131.3	H3Z	5.686	42	238.8
H1L	5.673	15	85.1	H4A	5.147	47	241.9
H1M	5.500	28	154.0	H4B	4.964	22	109.2
H1N	6.300	7	44.1	H4C	5.150	20	103.0
H1P	5.550	8	44.4	H4E	5.009	11	55.1
H1R	5.000	8	40.0	H4G	4.980	15	74.7
H1S	5.427	11	59.7	H4H	5.320	15	79.8
H1T	5.613	16	89.8	H4J	6.267	6	37.6
H1V	4.943	14	69.2	H4K	5.876	21	123.4
H1W	4.645	11	51.1	H4L	5.448	21	114.4
H1X	5.643	21	118.5	H4M	6.173	15	92.6
H1Y	5.028	18	90.5	H4N	6.145	20	122.9
H1Z	5.600	10	56.0	H4P	6.546	13	85.1
H2A	6.600	5	33.0	H4R	6.415	27	173.2
H2B	5.985	13	77.8	H4S	6.031	16	96.5
H2C	5.720	10	57.2	H4T	6.217	29	180.3
H2E	5.417	6	32.5	H4V	5.967	9	53.7
H2G	5.769	16	92.3	H4W	6.283	18	113.1
H2H	5.075	12	60.9	H4X	5.490	10	54.9
H2J	5.676	29	164.6	H4Y	5.298	87	460.9
H2K	6.143	30	184.3	H4Z	0.000	0	0.0
H2L	5.563	27	150.2	H5A	7.500	1	7.5
H2M	5.035	17	85.6	H5B	7.800	1	7.8
H2N	7.082	11	77.9	H8N	5.677	22	124.9
H2P	5.480	15	82.2	H8P	5.310	10	53.1
H2R	5.046	13	65.6	H8R	5.029	14	70.4
H2S	5.444	16	87.1	H8S	5.871	17	99.8
H2T	5.427	11	59.7	H8T	5.805	21	121.9
H2V	5.941	69	409.9	H8Y	5.582	11	61.4
H2W	5.545	11	61.0	H8Z	5.489	9	49.4
H2X	5.935	17	100.9	H9A	6.195	21	130.1
H2Y	6.239	62	386.8	H9B	5.422	18	97.6
H2Z	5.614	7	39.3	H9C	5.212	17	88.6
H3A	6.738	32	215.6	H9E	6.463	8	51.7
H3B	5.773	11	63.5	H9G	6.092	12	73.1
H3C	6.392	38	242.9	H9H	5.511	28	154.3
H3E	5.789	47	272.1	H9J	5.825	28	163.1
H3G	6.040	15	90.6	H9K	4.864	11	53.5
H3H	6.253	17	106.3	H9P	5.428	89	483.1
H3J	5.787	15	86.8	H9R	6.445	44	283.6
H3K	4.838	8	38.7	H9S	5.980	35	209.3
H3L	4.935	23	113.5	H9W	5.891	53	312.2
H3M	5.988	8	47.9	H9X	5.290	29	153.4
H3N	4.100	1	4.1	Total	5.677	2104	12151.5
H3P	6.452	31	200.0				

Weighted Average FCR = 5.775 L/100km

Table C-10 GHG Calculation for Optimistic Scenario: Quebec City

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change **(%)**
G0A	1,530.5	9.394	5.448	8.408	25	361,411.2	323,462.7	-10.5
G0R	261.4	9.642	5.448	8.594	25	63,656.4	56,734.5	-10.9
G0S	568.5	9.595	5.448	8.558	25	118,222.1	105,450.1	-10.8
G1A	0.0	10.285	5.448	9.076	25	0.0	0.0	0.0
G1B	326.4	9.022	5.448	8.128	25	67,462.8	60,782.7	-9.9
G1C	688.9	8.957	5.448	8.080	25	138,910.9	125,307.8	-9.8
G1E	380.9	8.943	5.448	8.069	25	70,775.0	63,861.0	-9.8
G1G	405.6	8.915	5.448	8.049	25	78,570.2	70,931.8	-9.7
G1H	415.0	8.919	5.448	8.051	25	78,892.0	71,217.2	-9.7
G1J	238.2	8.679	5.448	7.871	25	44,506.3	40,364.6	-9.3
G1K	182.5	8.907	5.448	8.042	25	31,212.0	28,182.2	-9.7
G1L	222.6	8.714	5.448	7.898	25	42,447.8	38,470.8	-9.4
G1M	212.5	8.993	5.448	8.106	25	45,213.2	40,758.3	-9.9
G1N	101.3	9.758	5.448	8.681	25	19,444.8	17,297.8	-11.0
G1P	245.7	8.932	5.448	8.061	25	48,844.3	44,082.1	-9.7
G1R	155.3	8.899	5.448	8.036	25	26,280.8	23,733.4	-9.7
G1S	265.1	9.144	5.448	8.220	25	49,538.0	44,532.4	-10.1
G1T	97.2	9.308	5.448	8.343	25	19,546.1	17,519.8	-10.4
G1V	237.4	8.808	5.448	7.968	25	39,859.0	36,058.5	-9.5
G1W	279.5	8.796	5.448	7.959	25	57,274.0	51,824.4	-9.5
G1X	388.8	8.725	5.448	7.906	25	79,470.8	72,009.8	-9.4
G1Y	300.4	8.885	5.448	8.026	25	59,525.7	53,769.3	-9.7
G2A	281.7	9.051	5.448	8.151	25	61,481.6	55,363.5	-10.0
G2B	340.0	8.842	5.448	7.993	25	72,266.1	65,332.4	-9.6
G2C	125.3	9.140	5.448	8.217	25	28,324.1	25,464.2	-10.1
G2E	421.1	9.085	5.448	8.176	25	83,396.6	75,051.3	-10.0
G2G	196.1	9.047	5.448	8.147	25	43,195.5	38,900.0	-9.9
G2J	43.8	8.948	5.448	8.073	25	9,639.1	8,696.7	-9.8
G2K	143.4	9.103	5.448	8.189	25	31,011.2	27,898.8	-10.0
G2L	220.7	8.821	5.448	7.978	25	48,693.0	44,038.8	-9.6
G2M	83.3	8.927	5.448	8.057	25	17,054.1	15,392.8	-9.7
G2N	145.0	9.187	5.448	8.252	25	30,669.3	27,549.2	-10.2
G3A	451.6	9.168	5.448	8.238	25	91,152.6	81,907.6	-10.1
G3B	203.6	9.336	5.448	8.364	25	42,233.2	37,836.8	-10.4
G3E	269.4	8.944	5.448	8.070	25	54,937.0	49,568.8	-9.8
G3G	234.9	9.094	5.448	8.183	25	51,298.8	46,157.4	-10.0
G3H	121.6	9.199	5.448	8.262	25	41,457.1	37,231.1	-10.2
G3J	203.7	9.007	5.448	8.118	25	42,396.6	38,208.7	-9.9
G3K	363.1	8.961	5.448	8.083	25	70,985.5	64,029.2	-9.8
G3L	2.3	9.915	5.448	8.799	25	703.9	624.6	-11.3
G3M	83.6	9.005	5.448	8.116	25	28,147.7	25,368.2	-9.9
G6C	145.7	9.436	5.448	8.439	25	36,548.1	32,686.8	-10.6
G6J	264.5	9.099	5.448	8.186	25	61,564.6	55,389.8	-10.0
G6K	169.0	8.958	5.448	8.080	25	37,533.4	33,857.3	-9.8
G6V	682.4	9.041	5.448	8.143	25	138,124.0	124,401.7	-9.9
G6W	409.7	8.993	5.448	8.107	25	86,523.3	77,998.1	-9.9
G6X	236.4	8.787	5.448	7.953	25	46,436.3	42,025.2	-9.5
G6Z	476.8	9.006	5.448	8.117	25	77,429.0	69,782.3	-9.9
G7A	507.8	9.185	5.448	8.251	25	99,935.3	89,770.7	-10.2
Total						2,974,200.2	2,676,883.0	

Table C-11 GHG Calculation for Medium Scenario: Quebec City

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
G0A	1,530.5	9.394	5.448	9.197	5	361,411.2	353,821.5	-2.1	0.052	low
G0R	261.4	9.642	5.448	9.433	5	63,656.4	62,272.0	-2.2	0.033	low
G0S	568.5	9.595	5.448	9.387	5	118,222.1	115,667.7	-2.2	0.039	low
G1A	0.0	10.285	5.448	10.043	5	0.0	0.0	0.0	0.000	low
G1B	326.4	9.022	5.448	8.843	5	67,462.8	66,126.8	-2.0	0.047	low
G1C	688.9	8.957	5.448	8.781	5	138,910.9	136,190.3	-2.0	0.045	low
G1E	380.9	8.943	5.448	8.768	5	70,775.0	69,392.2	-2.0	0.008	low
G1G	405.6	8.915	5.448	8.742	5	78,570.2	77,042.5	-1.9	0.056	low
G1H	415.0	8.919	5.448	8.398	15	78,892.0	74,287.1	-5.8	0.105	medium
G1J	238.2	8.679	5.448	8.518	5	44,506.3	43,678.0	-1.9	0.048	low
G1K	182.5	8.907	5.448	8.388	15	31,212.0	29,394.1	-5.8	0.097	medium
G1L	222.6	8.714	5.448	8.551	5	42,447.8	41,652.4	-1.9	0.023	low
G1M	212.5	8.993	5.448	8.815	5	45,213.2	44,322.2	-2.0	0.061	low
G1N	101.3	9.758	5.448	8.681	25	19,444.8	17,297.8	-11.0	0.749	high
G1P	245.7	8.932	5.448	8.758	5	48,844.3	47,891.9	-1.9	0.022	low
G1R	155.3	8.899	5.448	8.036	25	26,280.8	23,733.4	-9.7	0.556	high
G1S	265.1	9.144	5.448	8.220	25	49,538.0	44,532.4	-10.1	0.722	high
G1T	97.2	9.308	5.448	8.729	15	19,546.1	18,330.3	-6.2	0.269	medium
G1V	237.4	8.808	5.448	8.304	15	39,859.0	37,578.7	-5.7	0.108	medium
G1W	279.5	8.796	5.448	8.294	15	57,274.0	54,004.3	-5.7	0.086	medium
G1X	388.8	8.725	5.448	8.233	15	79,470.8	74,994.2	-5.6	0.104	medium
G1Y	300.4	8.885	5.448	8.714	5	59,525.7	58,374.4	-1.9	0.063	low
G2A	281.7	9.051	5.448	8.871	5	61,481.6	60,258.0	-2.0	0.038	low
G2B	340.0	8.842	5.448	8.672	5	72,266.1	70,879.4	-1.9	0.017	low
G2C	125.3	9.140	5.448	8.586	15	28,324.1	26,608.2	-6.1	0.082	medium
G2E	421.1	9.085	5.448	8.903	5	83,396.6	81,727.5	-2.0	0.016	low
G2G	196.1	9.047	5.448	8.867	5	43,195.5	42,336.4	-2.0	0.048	low
G2J	43.8	8.948	5.448	8.773	5	9,639.1	9,450.6	-2.0	0.000	low
G2K	143.4	9.103	5.448	8.920	5	31,011.2	30,388.7	-2.0	0.053	low
G2L	220.7	8.821	5.448	8.652	5	48,693.0	47,762.1	-1.9	0.056	low

Table C-11 GHG Calculation for Medium Scenario: Quebec City (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
G2M	83.3	8.927	5.448	8.405	15	17,054.1	16,057.3	-5.8	0.118	med
G2N	145.0	9.187	5.448	9.000	5	30,669.3	30,045.2	-2.0	0.000	low
G3A	451.6	9.168	5.448	8.610	15	91,152.6	85,605.6	-6.1	0.096	med
G3B	203.6	9.336	5.448	8.753	15	42,233.2	39,595.4	-6.2	0.091	med
G3E	269.4	8.944	5.448	8.770	5	54,937.0	53,863.4	-2.0	0.040	low
G3G	234.9	9.094	5.448	8.912	5	51,298.8	50,270.6	-2.0	0.018	low
G3H	121.6	9.199	5.448	9.012	5	41,457.1	40,611.9	-2.0	0.022	low
G3J	203.7	9.007	5.448	8.829	5	42,396.6	41,559.0	-2.0	0.040	low
G3K	363.1	8.961	5.448	8.785	5	70,985.5	69,594.2	-2.0	0.051	low
G3L	2.3	9.915	5.448	9.692	5	703.9	688.0	-2.3	0.065	low
G3M	83.6	9.005	5.448	8.828	5	28,147.7	27,591.8	-2.0	0.066	low
G6C	145.7	9.436	5.448	9.237	5	36,548.1	35,775.8	-2.1	0.024	low
G6J	264.5	9.099	5.448	8.916	5	61,564.6	60,329.7	-2.0	0.065	low
G6K	169.0	8.958	5.448	8.431	15	37,533.4	35,327.8	-5.9	0.115	med
G6V	682.4	9.041	5.448	8.862	5	138,124.0	135,379.6	-2.0	0.069	low
G6W	409.7	8.993	5.448	8.815	5	86,523.3	84,818.2	-2.0	0.031	low
G6X	236.4	8.787	5.448	8.620	5	46,436.3	45,554.1	-1.9	0.049	low
G6Z	476.8	9.006	5.448	8.828	5	77,429.0	75,899.6	-2.0	0.009	low
G7A	507.8	9.185	5.448	8.999	5	99,935.3	97,902.4	-2.0	0.067	low
Total						2,974,200.2	2,886,464.5			

Table C-12 GHG Calculation for Conservative Scenario: Quebec City

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
G0A	1,530.5	9.394	5.448	9.394	0	361,411.2	361,411.2	0.0	0.052	low
G0R	261.4	9.642	5.448	9.642	0	63,656.4	63,656.4	0.0	0.033	low
G0S	568.5	9.595	5.448	9.595	0	118,222.1	118,222.1	0.0	0.039	low
G1A	0.0	10.285	5.448	10.285	0	0.0	0.0	0.0	0.000	low
G1B	326.4	9.022	5.448	9.022	0	67,462.8	67,462.8	0.0	0.047	low
G1C	688.9	8.957	5.448	8.957	0	138,910.9	138,910.9	0.0	0.045	low
G1E	380.9	8.943	5.448	8.943	0	70,775.0	70,775.0	0.0	0.008	low
G1G	405.6	8.915	5.448	8.915	0	78,570.2	78,570.2	0.0	0.056	low
G1H	415.0	8.919	5.448	8.572	10	78,892.0	75,822.1	-3.9	0.105	medium
G1J	238.2	8.679	5.448	8.679	0	44,506.3	44,506.3	0.0	0.048	low
G1K	182.5	8.907	5.448	8.561	10	31,212.0	30,000.1	-3.9	0.097	medium
G1L	222.6	8.714	5.448	8.714	0	42,447.8	42,447.8	0.0	0.023	low
G1M	212.5	8.993	5.448	8.993	0	45,213.2	45,213.2	0.0	0.061	low
G1N	101.3	9.758	5.448	8.896	20	19,444.8	17,727.2	-8.8	0.749	high
G1P	245.7	8.932	5.448	8.932	0	48,844.3	48,844.3	0.0	0.022	low
G1R	155.3	8.899	5.448	8.209	20	26,280.8	24,242.9	-7.8	0.556	high
G1S	265.1	9.144	5.448	8.405	20	49,538.0	45,533.5	-8.1	0.722	high
G1T	97.2	9.308	5.448	8.922	10	19,546.1	18,735.6	-4.1	0.269	medium
G1V	237.4	8.808	5.448	8.472	10	39,859.0	38,338.8	-3.8	0.108	medium
G1W	279.5	8.796	5.448	8.461	10	57,274.0	55,094.2	-3.8	0.086	medium
G1X	388.8	8.725	5.448	8.397	10	79,470.8	76,486.4	-3.8	0.104	medium
G1Y	300.4	8.885	5.448	8.885	0	59,525.7	59,525.7	0.0	0.063	low
G2A	281.7	9.051	5.448	9.051	0	61,481.6	61,481.6	0.0	0.038	low
G2B	340.0	8.842	5.448	8.842	0	72,266.1	72,266.1	0.0	0.017	low
G2C	125.3	9.140	5.448	8.771	10	28,324.1	27,180.1	-4.0	0.082	medium
G2E	421.1	9.085	5.448	9.085	0	83,396.6	83,396.6	0.0	0.016	low
G2G	196.1	9.047	5.448	9.047	0	43,195.5	43,195.5	0.0	0.048	low
G2J	43.8	8.948	5.448	8.948	0	9,639.1	9,639.1	0.0	0.000	low
G2K	143.4	9.103	5.448	9.103	0	31,011.2	31,011.2	0.0	0.053	low
G2L	220.7	8.821	5.448	8.821	0	48,693.0	48,693.0	0.0	0.056	low

Table C-12 GHG Calculation for Conservative Scenario: Quebec City (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
G2M	83.3	8.927	5.448	8.579	10	17,054.1	16,389.5	-3.9	0.118	medium
G2N	145.0	9.187	5.448	9.187	0	30,669.3	30,669.3	0.0	0.000	low
G3A	451.6	9.168	5.448	8.796	10	91,152.6	87,454.6	-4.1	0.096	medium
G3B	203.6	9.336	5.448	8.947	10	42,233.2	40,474.6	-4.2	0.091	medium
G3E	269.4	8.944	5.448	8.944	0	54,937.0	54,937.0	0.0	0.040	low
G3G	234.9	9.094	5.448	9.094	0	51,298.8	51,298.8	0.0	0.018	low
G3H	121.6	9.199	5.448	9.199	0	41,457.1	41,457.1	0.0	0.022	low
G3J	203.7	9.007	5.448	9.007	0	42,396.6	42,396.6	0.0	0.040	low
G3K	363.1	8.961	5.448	8.961	0	70,985.5	70,985.5	0.0	0.051	low
G3L	2.3	9.915	5.448	9.915	0	703.9	703.9	0.0	0.065	low
G3M	83.6	9.005	5.448	9.005	0	28,147.7	28,147.7	0.0	0.066	low
G6C	145.7	9.436	5.448	9.436	0	36,548.1	36,548.1	0.0	0.024	low
G6J	264.5	9.099	5.448	9.099	0	61,564.6	61,564.6	0.0	0.065	low
G6K	169.0	8.958	5.448	8.607	10	37,533.4	36,063.0	-3.9	0.115	medium
G6V	682.4	9.041	5.448	9.041	0	138,124.0	138,124.0	0.0	0.069	low
G6W	409.7	8.993	5.448	8.993	0	86,523.3	86,523.3	0.0	0.031	low
G6X	236.4	8.787	5.448	8.787	0	46,436.3	46,436.3	0.0	0.049	low
G6Z	476.8	9.006	5.448	9.006	0	77,429.0	77,429.0	0.0	0.009	low
G7A	507.8	9.185	5.448	9.185	0	99,935.3	99,935.3	0.0	0.067	low
Total						2,974,200.2	2,945,928.0			

Table C-13 GHG Calculation for Optimistic Scenario: Montreal

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)
H1A	207.5	9.119	5.775	8.283	25	98,358.8	89,342.3	-9.2
H1B	134.0	9.347	5.775	8.454	25	61,854.6	55,945.5	-9.6
H1C	72.3	9.349	5.775	8.455	25	43,017.1	38,906.6	-9.6
H1E	204.3	9.329	5.775	8.441	25	113,270.3	102,482.7	-9.5
H1G	191.8	9.223	5.775	8.361	25	98,031.4	88,869.8	-9.3
H1H	107.7	9.206	5.775	8.348	25	58,797.2	53,319.5	-9.3
H1J	39.9	9.974	5.775	8.925	25	23,204.1	20,762.1	-10.5
H1K	147.5	9.032	5.775	8.218	25	76,125.5	69,263.6	-9.0
H1L	131.4	8.952	5.775	8.158	25	67,816.0	61,799.6	-8.9
H1M	142.1	8.923	5.775	8.136	25	72,063.9	65,709.4	-8.8
H1N	67.6	9.030	5.775	8.216	25	34,451.5	31,347.4	-9.0
H1P	87.5	9.556	5.775	8.611	25	52,795.5	47,573.5	-9.9
H1R	113.8	9.372	5.775	8.473	25	64,940.6	58,710.0	-9.6
H1S	80.2	9.256	5.775	8.386	25	44,636.7	40,440.2	-9.4
H1T	118.9	8.930	5.775	8.142	25	58,950.2	53,743.8	-8.8
H1V	58.2	8.893	5.775	8.113	25	31,381.2	28,631.0	-8.8
H1W	75.5	8.956	5.775	8.161	25	39,914.6	36,370.7	-8.9
H1X	108.8	8.723	5.775	7.986	25	53,514.7	48,994.3	-8.4
H1Y	75.2	8.709	5.775	7.976	25	37,404.4	34,254.4	-8.4
H1Z	80.7	9.336	5.775	8.446	25	42,763.9	38,686.4	-9.5
H2A	43.7	9.163	5.775	8.316	25	23,024.1	20,895.9	-9.2
H2B	68.4	8.874	5.775	8.100	25	35,392.5	32,302.8	-8.7
H2C	73.7	8.781	5.775	8.030	25	38,552.9	35,253.8	-8.6
H2E	68.5	8.914	5.775	8.129	25	37,556.0	34,250.3	-8.8
H2G	79.4	9.057	5.775	8.237	25	40,380.3	36,722.4	-9.1
H2H	33.7	8.751	5.775	8.007	25	17,674.0	16,171.6	-8.5
H2J	71.5	8.746	5.775	8.004	25	37,690.7	34,490.0	-8.5
H2K	91.5	9.320	5.775	8.434	25	52,990.4	47,952.1	-9.5
H2L	60.7	9.352	5.775	8.458	25	34,722.7	31,402.8	-9.6
H2M	75.3	8.776	5.775	8.026	25	38,007.2	34,758.2	-8.5
H2N	14.6	9.788	5.775	8.785	25	9,163.1	8,223.9	-10.2
H2P	46.9	8.880	5.775	8.104	25	26,116.5	23,834.0	-8.7
H2R	57.7	8.806	5.775	8.049	25	31,104.8	28,428.5	-8.6
H2S	64.2	8.971	5.775	8.172	25	34,364.4	31,304.1	-8.9
H2T	39.4	9.067	5.775	8.244	25	22,027.8	20,028.7	-9.1
H2V	74.5	9.321	5.775	8.435	25	36,296.6	32,844.8	-9.5
H2W	15.2	9.080	5.775	8.254	25	8,550.3	7,772.4	-9.1
H2X	35.6	9.230	5.775	8.366	25	19,261.0	17,458.8	-9.4
H2Y	9.1	10.197	5.775	9.092	25	5,565.9	4,962.5	-10.8
H2Z	2.3	9.744	5.775	8.752	25	1,173.9	1,054.4	-10.2
H3A	0.2	10.528	5.775	9.340	25	81.9	72.7	-11.3
H3B	0.6	11.305	5.775	9.922	25	312.7	274.5	-12.2
H3C	17.5	9.949	5.775	8.906	25	8,601.1	7,699.1	-10.5
H3E	125.0	9.485	5.775	8.558	25	66,935.3	60,390.7	-9.8
H3G	15.5	9.984	5.775	8.932	25	8,709.6	7,791.8	-10.5
H3H	31.9	9.562	5.775	8.616	25	19,432.7	17,508.8	-9.9
H3J	25.4	9.229	5.775	8.365	25	14,133.6	12,811.5	-9.4
H3K	37.9	9.356	5.775	8.461	25	21,915.4	19,818.8	-9.6
H3L	71.6	8.955	5.775	8.160	25	37,060.8	33,771.3	-8.9
H3M	51.9	9.206	5.775	8.348	25	27,204.4	24,669.9	-9.3
H3N	35.8	9.330	5.775	8.442	25	20,747.4	18,771.2	-9.5
H3P	72.1	9.624	5.775	8.662	25	31,206.1	28,086.1	-10.0

Table C-13 GHG Calculation for Optimistic Scenario: Montreal (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)
H3R	68.8	9.725	5.775	8.738	25	36,195.1	32,520.1	-10.2
H3S	64.9	9.298	5.775	8.418	25	38,790.3	35,116.2	-9.5
H3T	41.2	8.841	5.775	8.075	25	23,389.3	21,361.6	-8.7
H3V	5.7	8.766	5.775	8.018	25	3,232.9	2,957.1	-8.5
H3W	41.7	9.284	5.775	8.407	25	25,585.8	23,168.3	-9.4
H3X	69.5	9.549	5.775	8.606	25	39,520.4	35,615.7	-9.9
H3Y	47.0	10.486	5.775	9.309	25	30,055.6	26,680.0	-11.2
H3Z	23.6	9.776	5.775	8.776	25	16,831.9	15,109.9	-10.2
H4A	103.9	9.155	5.775	8.310	25	51,762.7	46,986.0	-9.2
H4B	65.5	9.077	5.775	8.251	25	33,359.8	30,326.6	-9.1
H4C	37.5	9.370	5.775	8.472	25	20,886.1	18,882.9	-9.6
H4E	112.5	9.109	5.775	8.276	25	59,236.9	53,817.1	-9.1
H4G	73.6	8.928	5.775	8.140	25	39,608.3	36,112.1	-8.8
H4H	87.2	8.963	5.775	8.166	25	43,374.8	39,518.8	-8.9
H4J	50.5	8.990	5.775	8.186	25	26,373.2	24,015.8	-8.9
H4K	38.7	9.282	5.775	8.406	25	20,060.1	18,165.3	-9.4
H4L	103.5	9.021	5.775	8.209	25	54,968.2	50,024.3	-9.0
H4M	61.0	9.421	5.775	8.509	25	31,757.4	28,685.4	-9.7
H4N	73.3	9.275	5.775	8.400	25	40,069.6	36,289.8	-9.4
H4P	23.8	10.047	5.775	8.979	25	13,360.3	11,940.3	-10.6
H4R	31.3	9.405	5.775	8.498	25	17,502.7	15,814.0	-9.6
H4S	29.4	9.795	5.775	8.790	25	15,921.6	14,288.1	-10.3
H4T	30.4	9.812	5.775	8.803	25	17,574.5	15,767.0	-10.3
H4V	64.3	9.203	5.775	8.346	25	32,573.2	29,540.1	-9.3
H4W	98.2	9.388	5.775	8.485	25	58,687.8	53,041.9	-9.6
H4X	58.0	9.455	5.775	8.535	25	20,766.5	18,746.1	-9.7
H4Y	0.0	9.544	5.775	8.602	25	0.0	0.0	0.0
H4Z	0.0	10.750	5.775	9.506	25	0.0	0.0	0.0
H5A	0.0	10.272	5.775	9.148	25	0.0	0.0	0.0
H5B	0.0	10.161	5.775	9.065	25	0.0	0.0	0.0
H8N	140.3	9.238	5.775	8.372	25	77,087.9	69,864.8	-9.4
H8P	105.4	9.067	5.775	8.244	25	53,437.7	48,587.8	-9.1
H8R	131.1	9.255	5.775	8.385	25	73,062.8	66,195.8	-9.4
H8S	87.2	9.059	5.775	8.238	25	42,552.2	38,696.0	-9.1
H8T	109.7	9.088	5.775	8.260	25	54,201.5	49,262.1	-9.1
H8Y	123.9	9.091	5.775	8.262	25	68,900.3	62,618.7	-9.1
H8Z	153.9	9.078	5.775	8.253	25	77,778.0	70,703.5	-9.1
H9A	105.7	9.409	5.775	8.500	25	63,734.7	57,581.9	-9.7
H9B	105.0	9.227	5.775	8.364	25	63,234.3	57,320.7	-9.4
H9C	125.8	9.280	5.775	8.404	25	63,107.4	57,149.1	-9.4
H9E	28.2	9.710	5.775	8.726	25	14,182.3	12,745.6	-10.1
H9G	103.9	9.146	5.775	8.303	25	63,550.2	57,695.3	-9.2
H9H	229.7	9.249	5.775	8.380	25	127,306.7	115,354.5	-9.4
H9J	227.9	9.254	5.775	8.384	25	107,128.4	97,061.0	-9.4
H9K	89.4	9.163	5.775	8.316	25	49,342.2	44,781.5	-9.2
H9P	61.8	9.536	5.775	8.596	25	27,269.2	24,580.9	-9.9
H9R	150.6	9.284	5.775	8.407	25	87,006.1	78,785.5	-9.4
H9S	238.4	9.220	5.775	8.359	25	128,852.3	116,817.4	-9.3
H9W	198.8	9.527	5.775	8.589	25	123,065.0	110,950.2	-9.8
H9X	113.6	9.481	5.775	8.555	25	36,546.4	32,975.4	-9.8
Total						4,192,038.9	3,801,149.5	-9.3

Table C-14 GHG Calculation for Medium Scenario: Montreal

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
H1A	207.5	9.119	5.775	8.283	25	98,358.8	89,342.3	-9.2	0.272	high
H1B	134.0	9.347	5.775	8.812	15	61,854.6	58,309.2	-5.7	0.107	medium
H1C	72.3	9.349	5.775	8.813	15	43,017.1	40,550.8	-5.7	0.112	medium
H1E	204.3	9.329	5.775	8.796	15	113,270.3	106,797.8	-5.7	0.082	medium
H1G	191.8	9.223	5.775	8.706	15	98,031.4	92,534.4	-5.6	0.100	medium
H1H	107.7	9.206	5.775	8.691	15	58,797.2	55,510.6	-5.6	0.098	medium
H1J	39.9	9.974	5.775	8.925	25	23,204.1	20,762.1	-10.5	0.303	high
H1K	147.5	9.032	5.775	8.543	15	76,125.5	72,008.4	-5.4	0.199	medium
H1L	131.4	8.952	5.775	8.476	15	67,816.0	64,206.1	-5.3	0.111	medium
H1M	142.1	8.923	5.775	8.450	15	72,063.9	68,251.2	-5.3	0.222	medium
H1N	67.6	9.030	5.775	8.542	15	34,451.5	32,589.0	-5.4	0.081	medium
H1P	87.5	9.556	5.775	8.989	15	52,795.5	49,662.3	-5.9	0.088	medium
H1R	113.8	9.372	5.775	9.192	5	64,940.6	63,694.4	-1.9	0.064	low
H1S	80.2	9.256	5.775	8.734	15	44,636.7	42,118.8	-5.6	0.119	medium
H1T	118.9	8.930	5.775	8.457	15	58,950.2	55,826.4	-5.3	0.147	medium
H1V	58.2	8.893	5.775	8.425	15	31,381.2	29,731.1	-5.3	0.230	medium
H1W	75.5	8.956	5.775	8.479	15	39,914.6	37,788.3	-5.3	0.141	medium
H1X	108.8	8.723	5.775	8.281	15	53,514.7	50,802.5	-5.1	0.212	medium
H1Y	75.2	8.709	5.775	8.269	15	37,404.4	35,514.4	-5.1	0.201	medium
H1Z	80.7	9.336	5.775	8.802	15	42,763.9	40,317.4	-5.7	0.090	medium
H2A	43.7	9.163	5.775	8.655	15	23,024.1	21,747.2	-5.5	0.085	medium
H2B	68.4	8.874	5.775	8.410	15	35,392.5	33,538.7	-5.2	0.205	medium
H2C	73.7	8.781	5.775	8.330	15	38,552.9	36,573.4	-5.1	0.161	medium
H2E	68.5	8.914	5.775	8.443	15	37,556.0	35,572.6	-5.3	0.087	medium
H2G	79.4	9.057	5.775	8.565	15	40,380.3	38,185.6	-5.4	0.215	medium
H2H	33.7	8.751	5.775	8.007	25	17,674.0	16,171.6	-8.5	0.291	high
H2J	71.5	8.746	5.775	8.004	25	37,690.7	34,490.0	-8.5	0.408	high
H2K	91.5	9.320	5.775	8.434	25	52,990.4	47,952.1	-9.5	0.310	high
H2L	60.7	9.352	5.775	8.458	25	34,722.7	31,402.8	-9.6	0.434	high
H2M	75.3	8.776	5.775	8.326	15	38,007.2	36,057.8	-5.1	0.225	medium

Table C-14 GHG Calculation for Medium Scenario: Montreal (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
H2N	14.6	9.788	5.775	8.785	25	9,163.1	8,223.9	-10.2	0.353	high
H2P	46.9	8.880	5.775	8.104	25	26,116.5	23,834.0	-8.7	0.318	high
H2R	57.7	8.806	5.775	8.352	15	31,104.8	29,499.0	-5.2	0.213	medium
H2S	64.2	8.971	5.775	8.492	15	34,364.4	32,528.2	-5.3	0.225	medium
H2T	39.4	9.067	5.775	8.573	15	22,027.8	20,828.3	-5.4	0.262	medium
H2V	74.5	9.321	5.775	8.435	25	36,296.6	32,844.8	-9.5	0.719	high
H2W	15.2	9.080	5.775	8.254	25	8,550.3	7,772.4	-9.1	0.425	high
H2X	35.6	9.230	5.775	8.366	25	19,261.0	17,458.8	-9.4	0.535	high
H2Y	9.1	10.197	5.775	9.092	25	5,565.9	4,962.5	-10.8	1.332	high
H2Z	2.3	9.744	5.775	8.752	25	1,173.9	1,054.4	-10.2	1.089	high
H3A	0.2	10.528	5.775	9.340	25	81.9	72.7	-11.3	1.702	high
H3B	0.6	11.305	5.775	9.922	25	312.7	274.5	-12.2	0.655	high
H3C	17.5	9.949	5.775	8.906	25	8,601.1	7,699.1	-10.5	0.981	high
H3E	125.0	9.485	5.775	8.558	25	66,935.3	60,390.7	-9.8	0.509	high
H3G	15.5	9.984	5.775	8.932	25	8,709.6	7,791.8	-10.5	0.542	high
H3H	31.9	9.562	5.775	8.616	25	19,432.7	17,508.8	-9.9	0.501	high
H3J	25.4	9.229	5.775	8.365	25	14,133.6	12,811.5	-9.4	0.524	high
H3K	37.9	9.356	5.775	8.819	15	21,915.4	20,657.4	-5.7	0.199	medium
H3L	71.6	8.955	5.775	8.160	25	37,060.8	33,771.3	-8.9	0.318	high
H3M	51.9	9.206	5.775	8.692	15	27,204.4	25,683.7	-5.6	0.123	medium
H3N	35.8	9.330	5.775	9.153	5	20,747.4	20,352.2	-1.9	0.015	low
H3P	72.1	9.624	5.775	8.662	25	31,206.1	28,086.1	-10.0	0.632	high
H3R	68.8	9.725	5.775	8.738	25	36,195.1	32,520.1	-10.2	0.642	high
H3S	64.9	9.298	5.775	8.770	15	38,790.3	36,585.9	-5.7	0.266	medium
H3T	41.2	8.841	5.775	8.075	25	23,389.3	21,361.6	-8.7	0.301	high
H3V	5.7	8.766	5.775	8.317	15	3,232.9	3,067.4	-5.1	0.215	medium
H3W	41.7	9.284	5.775	8.758	15	25,585.8	24,135.3	-5.7	0.205	medium
H3X	69.5	9.549	5.775	8.606	25	39,520.4	35,615.7	-9.9	0.297	high
H3Y	47.0	10.486	5.775	9.309	25	30,055.6	26,680.0	-11.2	1.337	high
H3Z	23.6	9.776	5.775	8.776	25	16,831.9	15,109.9	-10.2	0.900	high

Table |C-14 GHG Calculation for Medium Scenario: Montreal (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
H4A	103.9	9.155	5.775	8.310	25	51,762.7	46,986.0	-9.2	0.537	high
H4B	65.5	9.077	5.775	8.251	25	33,359.8	30,326.6	-9.1	0.363	high
H4C	37.5	9.370	5.775	8.472	25	20,886.1	18,882.9	-9.6	0.388	high
H4E	112.5	9.109	5.775	8.609	15	59,236.9	55,985.0	-5.5	0.104	medium
H4G	73.6	8.928	5.775	8.455	15	39,608.3	37,510.6	-5.3	0.181	medium
H4H	87.2	8.963	5.775	8.484	15	43,374.8	41,061.2	-5.3	0.213	medium
H4J	50.5	8.990	5.775	8.507	15	26,373.2	24,958.8	-5.4	0.111	medium
H4K	38.7	9.282	5.775	8.406	25	20,060.1	18,165.3	-9.4	0.385	high
H4L	103.5	9.021	5.775	8.534	15	54,968.2	52,001.9	-5.4	0.176	medium
H4M	61.0	9.421	5.775	8.509	25	31,757.4	28,685.4	-9.7	0.271	high
H4N	73.3	9.275	5.775	8.750	15	40,069.6	37,801.7	-5.7	0.204	medium
H4P	23.8	10.047	5.775	8.979	25	13,360.3	11,940.3	-10.6	0.381	high
H4R	31.3	9.405	5.775	8.860	15	17,502.7	16,489.5	-5.8	0.240	medium
H4S	29.4	9.795	5.775	9.192	15	15,921.6	14,941.5	-6.2	0.195	medium
H4T	30.4	9.812	5.775	8.803	25	17,574.5	15,767.0	-10.3	0.368	high
H4V	64.3	9.203	5.775	8.689	15	32,573.2	30,753.4	-5.6	0.131	medium
H4W	98.2	9.388	5.775	8.846	15	58,687.8	55,300.2	-5.8	0.170	medium
H4X	58.0	9.455	5.775	8.535	25	20,766.5	18,746.1	-9.7	0.336	high
H4Y	0.0	9.544	5.775	8.602	25	0.0	0.0	0.0	1.250	high
H4Z	0.0	10.750	5.775	10.501	5	0.0	0.0	0.0	0.000	low
H5A	0.0	10.272	5.775	9.148	25	0.0	0.0	0.0	5.556	high
H5B	0.0	10.161	5.775	9.065	25	0.0	0.0	0.0	0.870	high
H8N	140.3	9.238	5.775	8.718	15	77,087.9	72,754.1	-5.6	0.190	medium
H8P	105.4	9.067	5.775	8.573	15	53,437.7	50,527.8	-5.4	0.100	medium
H8R	131.1	9.255	5.775	8.733	15	73,062.8	68,942.6	-5.6	0.113	medium
H8S	87.2	9.059	5.775	8.567	15	42,552.2	40,238.5	-5.4	0.177	medium
H8T	109.7	9.088	5.775	8.591	15	54,201.5	51,237.9	-5.5	0.270	medium
H8Y	123.9	9.091	5.775	8.593	15	68,900.3	65,131.4	-5.5	0.129	medium
H8Z	153.9	9.078	5.775	8.583	15	77,778.0	73,533.3	-5.5	0.121	medium
H9A	105.7	9.409	5.775	8.864	15	63,734.7	60,043.0	-5.8	0.263	medium

Table C-14 GHG Calculation for Medium Scenario: Montreal (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
H9B	105.0	9.227	5.775	8.709	15	63,234.3	59,686.1	-5.6	0.170	medium
H9C	125.8	9.280	5.775	8.754	15	63,107.4	59,532.4	-5.7	0.249	medium
H9E	28.2	9.710	5.775	8.726	25	14,182.3	12,745.6	-10.1	0.476	high
H9G	103.9	9.146	5.775	8.640	15	63,550.2	60,037.3	-5.5	0.140	medium
H9H	229.7	9.249	5.775	8.728	15	127,306.7	120,135.3	-5.6	0.199	medium
H9J	227.9	9.254	5.775	8.732	15	107,128.4	101,088.0	-5.6	0.222	medium
H9K	89.4	9.163	5.775	8.316	25	49,342.2	44,781.5	-9.2	0.280	high
H9P	61.8	9.536	5.775	8.596	25	27,269.2	24,580.9	-9.9	2.233	high
H9R	150.6	9.284	5.775	8.407	25	87,006.1	78,785.5	-9.4	0.333	high
H9S	238.4	9.220	5.775	8.359	25	128,852.3	116,817.4	-9.3	0.315	high
H9W	198.8	9.527	5.775	8.589	25	123,065.0	110,950.2	-9.8	0.499	high
H9X	113.6	9.481	5.775	8.555	25	36,546.4	32,975.4	-9.8	0.539	high
Total						4,192,038.9	3,908,018.7			

Table C-15 GHG Calculation for Conservative Scenario: Montreal

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
H1A	207.5	9.119	5.775	8.451	20	98,358.8	91,145.6	-7.3	0.272	high
H1B	134.0	9.347	5.775	8.990	10	61,854.6	59,491.0	-3.8	0.107	medium
H1C	72.3	9.349	5.775	8.991	10	43,017.1	41,372.9	-3.8	0.112	medium
H1E	204.3	9.329	5.775	8.974	10	113,270.3	108,955.3	-3.8	0.082	medium
H1G	191.8	9.223	5.775	8.879	10	98,031.4	94,366.7	-3.7	0.100	medium
H1H	107.7	9.206	5.775	8.863	10	58,797.2	56,606.1	-3.7	0.098	medium
H1J	39.9	9.974	5.775	9.134	20	23,204.1	21,250.5	-8.4	0.303	high
H1K	147.5	9.032	5.775	8.706	10	76,125.5	73,380.8	-3.6	0.199	medium
H1L	131.4	8.952	5.775	8.635	10	67,816.0	65,409.4	-3.5	0.111	medium
H1M	142.1	8.923	5.775	8.608	10	72,063.9	69,522.1	-3.5	0.222	medium
H1N	67.6	9.030	5.775	8.704	10	34,451.5	33,209.8	-3.6	0.081	medium
H1P	87.5	9.556	5.775	9.178	10	52,795.5	50,706.7	-4.0	0.088	medium
H1R	113.8	9.372	5.775	9.372	0	64,940.6	64,940.6	0.0	0.064	low
H1S	80.2	9.256	5.775	8.908	10	44,636.7	42,958.1	-3.8	0.119	medium
H1T	118.9	8.930	5.775	8.615	10	58,950.2	56,867.6	-3.5	0.147	medium
H1V	58.2	8.893	5.775	8.581	10	31,381.2	30,281.1	-3.5	0.230	medium
H1W	75.5	8.956	5.775	8.638	10	39,914.6	38,497.0	-3.6	0.141	medium
H1X	108.8	8.723	5.775	8.428	10	53,514.7	51,706.6	-3.4	0.212	medium
H1Y	75.2	8.709	5.775	8.416	10	37,404.4	36,144.4	-3.4	0.201	medium
H1Z	80.7	9.336	5.775	8.980	10	42,763.9	41,132.9	-3.8	0.090	medium
H2A	43.7	9.163	5.775	8.825	10	23,024.1	22,172.8	-3.7	0.085	medium
H2B	68.4	8.874	5.775	8.564	10	35,392.5	34,156.6	-3.5	0.205	medium
H2C	73.7	8.781	5.775	8.481	10	38,552.9	37,233.2	-3.4	0.161	medium
H2E	68.5	8.914	5.775	8.600	10	37,556.0	36,233.7	-3.5	0.087	medium
H2G	79.4	9.057	5.775	8.729	10	40,380.3	38,917.1	-3.6	0.215	medium
H2H	33.7	8.751	5.775	8.156	20	17,674.0	16,472.1	-6.8	0.291	high
H2J	71.5	8.746	5.775	8.152	20	37,690.7	35,130.2	-6.8	0.408	high
H2K	91.5	9.320	5.775	8.611	20	52,990.4	48,959.8	-7.6	0.310	high
H2L	60.7	9.352	5.775	8.637	20	34,722.7	32,066.8	-7.6	0.434	high
H2M	75.3	8.776	5.775	8.476	10	38,007.2	36,707.6	-3.4	0.225	medium

Table C-15 GHG Calculation for Conservative Scenario: Montreal (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
H2N	14.6	9.788	5.775	8.986	20	9,163.1	8,411.8	-8.2	0.353	high
H2P	46.9	8.880	5.775	8.259	20	26,116.5	24,290.5	-7.0	0.318	high
H2R	57.7	8.806	5.775	8.503	10	31,104.8	30,034.3	-3.4	0.213	medium
H2S	64.2	8.971	5.775	8.652	10	34,364.4	33,140.2	-3.6	0.225	medium
H2T	39.4	9.067	5.775	8.738	10	22,027.8	21,228.2	-3.6	0.262	medium
H2V	74.5	9.321	5.775	8.612	20	36,296.6	33,535.2	-7.6	0.719	high
H2W	15.2	9.080	5.775	8.419	20	8,550.3	7,928.0	-7.3	0.425	high
H2X	35.6	9.230	5.775	8.539	20	19,261.0	17,819.2	-7.5	0.535	high
H2Y	9.1	10.197	5.775	9.313	20	5,565.9	5,083.2	-8.7	1.332	high
H2Z	2.3	9.744	5.775	8.950	20	1,173.9	1,078.3	-8.1	1.089	high
H3A	0.2	10.528	5.775	9.577	20	81.9	74.5	-9.0	1.702	high
H3B	0.6	11.305	5.775	10.199	20	312.7	282.1	-9.8	0.655	high
H3C	17.5	9.949	5.775	9.114	20	8,601.1	7,879.5	-8.4	0.981	high
H3E	125.0	9.485	5.775	8.743	20	66,935.3	61,699.6	-7.8	0.509	high
H3G	15.5	9.984	5.775	9.142	20	8,709.6	7,975.4	-8.4	0.542	high
H3H	31.9	9.562	5.775	8.805	20	19,432.7	17,893.5	-7.9	0.501	high
H3J	25.4	9.229	5.775	8.538	20	14,133.6	13,075.9	-7.5	0.524	high
H3K	37.9	9.356	5.775	8.998	10	21,915.4	21,076.7	-3.8	0.199	medium
H3L	71.6	8.955	5.775	8.319	20	37,060.8	34,429.2	-7.1	0.318	high
H3M	51.9	9.206	5.775	8.863	10	27,204.4	26,190.6	-3.7	0.123	medium
H3N	35.8	9.330	5.775	9.330	0	20,747.4	20,747.4	0.0	0.015	low
H3P	72.1	9.624	5.775	8.855	20	31,206.1	28,710.1	-8.0	0.632	high
H3R	68.8	9.725	5.775	8.935	20	36,195.1	33,255.1	-8.1	0.642	high
H3S	64.9	9.298	5.775	8.946	10	38,790.3	37,320.7	-3.8	0.266	medium
H3T	41.2	8.841	5.775	8.228	20	23,389.3	21,767.2	-6.9	0.301	high
H3V	5.7	8.766	5.775	8.467	10	3,232.9	3,122.6	-3.4	0.215	medium
H3W	41.7	9.284	5.775	8.934	10	25,585.8	24,618.8	-3.8	0.205	medium
H3X	69.5	9.549	5.775	8.795	20	39,520.4	36,396.7	-7.9	0.297	high
H3Y	47.0	10.486	5.775	9.544	20	30,055.6	27,355.1	-9.0	1.337	high
H3Z	23.6	9.776	5.775	8.976	20	16,831.9	15,454.3	-8.2	0.900	high

Table C-15 GHG Calculation for Conservative Scenario: Montreal (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
H4A	103.9	9.155	5.775	8.479	20	51,762.7	47,941.4	-7.4	0.537	high
H4B	65.5	9.077	5.775	8.416	20	33,359.8	30,933.3	-7.3	0.363	high
H4C	37.5	9.370	5.775	8.651	20	20,886.1	19,283.5	-7.7	0.388	high
H4E	112.5	9.109	5.775	8.776	10	59,236.9	57,069.0	-3.7	0.104	medium
H4G	73.6	8.928	5.775	8.612	10	39,608.3	38,209.8	-3.5	0.181	medium
H4H	87.2	8.963	5.775	8.644	10	43,374.8	41,832.4	-3.6	0.213	medium
H4J	50.5	8.990	5.775	8.668	10	26,373.2	25,430.2	-3.6	0.111	medium
H4K	38.7	9.282	5.775	8.581	20	20,060.1	18,544.3	-7.6	0.385	high
H4L	103.5	9.021	5.775	8.696	10	54,968.2	52,990.7	-3.6	0.176	medium
H4M	61.0	9.421	5.775	8.691	20	31,757.4	29,299.8	-7.7	0.271	high
H4N	73.3	9.275	5.775	8.925	10	40,069.6	38,557.7	-3.8	0.204	medium
H4P	23.8	10.047	5.775	9.192	20	13,360.3	12,224.3	-8.5	0.381	high
H4R	31.3	9.405	5.775	9.042	10	17,502.7	16,827.2	-3.9	0.240	medium
H4S	29.4	9.795	5.775	9.393	10	15,921.6	15,268.2	-4.1	0.195	medium
H4T	30.4	9.812	5.775	9.005	20	17,574.5	16,128.5	-8.2	0.368	high
H4V	64.3	9.203	5.775	8.861	10	32,573.2	31,360.0	-3.7	0.131	medium
H4W	98.2	9.388	5.775	9.027	10	58,687.8	56,429.4	-3.8	0.170	medium
H4X	58.0	9.455	5.775	8.719	20	20,766.5	19,150.2	-7.8	0.336	high
H4Y	0.0	9.544	5.775	8.790	20	0.0	0.0	0.0	1.250	high
H4Z	0.0	10.750	5.775	10.750	0	0.0	0.0	0.0	0.000	low
H5A	0.0	10.272	5.775	9.373	20	0.0	0.0	0.0	5.556	high
H5B	0.0	10.161	5.775	9.284	20	0.0	0.0	0.0	0.870	high
H8N	140.3	9.238	5.775	8.891	10	77,087.9	74,198.7	-3.7	0.190	medium
H8P	105.4	9.067	5.775	8.738	10	53,437.7	51,497.8	-3.6	0.100	medium
H8R	131.1	9.255	5.775	8.907	10	73,062.8	70,316.0	-3.8	0.113	medium
H8S	87.2	9.059	5.775	8.731	10	42,552.2	41,009.7	-3.6	0.177	medium
H8T	109.7	9.088	5.775	8.757	10	54,201.5	52,225.8	-3.6	0.270	medium
H8Y	123.9	9.091	5.775	8.759	10	68,900.3	66,387.7	-3.6	0.129	medium
H8Z	153.9	9.078	5.775	8.748	10	77,778.0	74,948.2	-3.6	0.121	medium
H9A	105.7	9.409	5.775	9.045	10	63,734.7	61,273.6	-3.9	0.263	medium

Table C-15 GHG Calculation for Conservative Scenario: Montreal (continued)

FSA	Σ(L×SPF)	Current FCR	Hybrid FCR	New FCR	MPR (%)	Current GHG	New GHG	GHG Change (%)	*p_HEV*	Level
H9B	105.0	9.227	5.775	8.882	10	63,234.3	60,868.8	-3.7	0.170	medium
H9C	125.8	9.280	5.775	8.930	10	63,107.4	60,724.1	-3.8	0.249	medium
H9E	28.2	9.710	5.775	8.923	20	14,182.3	13,032.9	-8.1	0.476	high
H9G	103.9	9.146	5.775	8.809	10	63,550.2	61,208.3	-3.7	0.140	medium
H9H	229.7	9.249	5.775	8.901	10	127,306.7	122,525.8	-3.8	0.199	medium
H9J	227.9	9.254	5.775	8.906	10	107,128.4	103,101.4	-3.8	0.222	medium
H9K	89.4	9.163	5.775	8.486	20	49,342.2	45,693.7	-7.4	0.280	high
H9P	61.8	9.536	5.775	8.784	20	27,269.2	25,118.6	-7.9	2.233	high
H9R	150.6	9.284	5.775	8.583	20	87,006.1	80,429.6	-7.6	0.333	high
H9S	238.4	9.220	5.775	8.531	20	128,852.3	119,224.4	-7.5	0.315	high
H9W	198.8	9.527	5.775	8.777	20	123,065.0	113,373.1	-7.9	0.499	high
H9X	113.6	9.481	5.775	8.740	20	36,546.4	33,689.6	-7.8	0.539	high
Total						4,192,038.9	3,986,196.6			