Impacts of Driving Patterns on Well-to-Wheel Performance of Plug-in Hybrid Electric Vehicles

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science

Civil Engineering
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Abstract

The well-to-wheel (WTW) environmental performance of plug-in hybrid electric vehicles (PHEVs) is sensitive to driving patterns, which vary within and across regions. This thesis develops and applies a novel approach for estimating specific regional driving patterns. The approach employs a macroscopic traffic assignment model linked with a vehicle motion model to construct driving cycles, which is done for a wide range of driving patterns. For each driving cycle, the tank-to-wheel energy use of two PHEVs and comparable non-plug-in alternatives is estimated. These estimates are then employed within a WTW analysis to investigate implications of driving patterns on the energy use and greenhouse gas emission of PHEVs, and the WTW performance of PHEVs relative to non-plug-in alternatives for various electricity generation scenarios. The results of the WTW analysis demonstrate that driving patterns and the electricity generation supply interact to substantially impact the WTW performance of PHEVs.
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Glossary of Terms

Autonomie: Vehicle performance simulation software.

Driving conditions: Driving characteristics such as average speed and fluctuations in speed that are associated with road type and level of congestion.

Driving cycle: A second-by-second speed profile meant to represent particular driving conditions.

Driving patterns: In this research, includes both driving conditions and driving distance between recharging of plug-in hybrid electric vehicles (PHEVs).

CALMOB6 vehicle motion model: a model that estimates the second-by-second fluctuations in speed associated congestion for each link in a traffic assignment model.

Certification driving cycle: A driving cycle used in federal fuel consumption and emissions testing programs.

Charge depleting (CD) mode: The initial operating mode of a PHEV in which grid-electricity is used to power the vehicle.

   All-electric CD mode (CDE): A CD mode control strategy of a PHEV in which the internal combustion engine (ICE) is only used in CD mode if the power demand exceeds the rated power of the battery or motor.

   Blended CD mode (CDB): A CD mode control strategy of a PHEV in which the ICE is used as a power source during CD mode even if the power demand can be supplied by the battery and motor alone.

Charge sustaining (CS) mode: The second operating mode of a PHEV that begins once the battery is depleted to a target state of charge. CS mode driving is similar to (non-plug-in) hybrid electric vehicle operation.

Coefficient of variation of speed: The standard deviation of speed normalized by the average speed.
Emme 3: Macroscopic traffic assignment software.

Function unit: A unit that describes the main function of the system studied in a well-to-wheel (WTW) analysis, typically one vehicle kilometer traveled. All data in a WTW analysis is normalized according to the functional unit.

Greenhouse gas (GHG): A gas that contributes to climate change through the greenhouse effect.

GREET: The Greenhouse gases, Regulated Emissions, and Energy use in Transportation model developed by Argonne National Laboratory.

Highway Fuel Economy Driving Schedule (HWFET): The highway certification driving cycle used by the United States Environmental Protection Agency.

Hybrid electric vehicle (HEV): A vehicle that includes an electric motor and high capacity battery in addition to an ICE. The battery and motor allow for improved fuel efficiency relative to similar internal combustion engine vehicles.

Internal combustion engine vehicle (ICEV): A conventional vehicle that combusts a liquid fuel in an ICE to provide power to the wheels.

Link: A representation of a road segment in a traffic assignment model.

Plug-in hybrid electric vehicle (PHEV): A HEV that includes a higher capacity battery that can be charged from the grid, thereby allowing the vehicle to displace liquid fuel with grid-electricity as a transportation fuel.

Series PHEV: A PHEV with a series drivetrain configuration. In a series drivetrain configuration, only the electric motor provides power to the wheels. When the ICE is operating, it is used to drive a generator that powers the electric motor rather than to directly drive the wheels.

Split PHEV: A PHEV with a split drivetrain configuration. In a split drivetrain configuration, the ICE has the ability to both drive a generator that powers the electric motor, as in a series PHEV, and to directly drive the wheels.
Real world driving cycles: Driving cycles obtained by tracking the second-by-second speeds of vehicles in real world operating conditions using GPS data loggers.

Regenerative braking: A hybrid vehicle technology that allows for some of the energy otherwise lost as waste heat during braking to be recaptured by the vehicle.

State of charge: The current energy capacity of a battery as a fraction of the battery’s total energy capacity. In a PHEV, the state of charge of the battery determines the PHEV’s operating mode.

System boundary: A description of the range of activities included in a life cycle assessment.

Tank-to-wheel (TTW): The use phase of the transportation fuel/vehicle life cycle.

Traffic assignment model: A model of the selection of routes between origins and destinations in transportation networks.

  Macroscopic traffic assignment model: A traffic assignment model that estimates average speeds on each link but does not estimate traffic flow on a second-by-second basis.

  Microscopic traffic assignment model: A traffic assignment model in which traffic flow is estimated by representing the movements of each vehicle in a network on a second-by-second basis.

Transportation Tomorrow Survey: A 24 hour trip-diary survey conducted in the Greater Toronto Area.

Travel demand model: A model used to estimate travel demand on a transportation network.

Urban Dynamometer Driving Schedule (UDDS): The city certification driving cycle used by the United States Environmental Protection Agency.

US06: The most aggressive certification driving cycle used by the United States Environmental Protection Agency. Also referred to as the Supplemental Federal Test Procedure.
Well-to-tank (WTT): The transportation fuel life cycle, from resource extraction up to and including fuel delivery to the vehicle. For PHEVs, fuel delivery includes both pumping liquid fuel into the fuel tank and charging the battery with grid-electricity.

Well-to-wheel (WTW): The entire transportation fuel/vehicle life cycle, including both WTT and TTW stages.
Chapter 1
Introduction

1.1 Research Motivation

Light-duty vehicles are the dominant mode of personal transportation in developed countries (about 74% and 85% of passenger kilometers traveled in Canada and the USA, respectively, occur in the light-duty vehicle fleet), and are a rapidly growing transportation mode in the developing world (NRCAn, 2010; TRB, 2011; Sager et al., 2011). Further, the global light-duty vehicle fleet is almost entirely comprised of internal combustion engine vehicles (ICEVs) and depends on petroleum for an estimated 95% of its energy needs (Ribeiro et al., 2007). Because of the size of the global light-duty vehicle fleet and due to its dependence on petroleum, it is responsible for an estimated 12% of total energy use, 27% of petroleum energy use, and 10% of energy-related greenhouse gas (GHG) emissions (Ribeiro et al., 2007; IEA, 2010). In Canada, the national impacts of the light-duty vehicle fleet are greater, at an estimated 15% of total energy use, 40% of petroleum energy use, and 17% of energy-related GHG emissions (NRCAn, 2010). In the USA, the national impacts of the light-duty vehicle fleet are even greater, at an estimated 17% of total energy use, 47% of petroleum energy use, and 21% of energy-related GHG emissions (TRB, 2011; Davis et al., 2010; EIA, 2011).

Some of the negative environmental impacts of the light-duty vehicle fleet can potentially be reduced through the adoption of plug-in hybrid electric vehicles (PHEVs), which include an electric motor and a high capacity battery that can be charged from the grid in addition to an internal combustion engine (ICE). The electric motor and battery of PHEVs enable them to displace petroleum with grid-electricity as a transportation fuel and to employ fuel efficiency technologies found in (non-plug-in) hybrid electric vehicles (HEVs) (Bradley and Frank, 2009). For example, both PHEVs and HEVs employ regenerative braking, which involves recapturing of some of the energy otherwise lost as waste heat during braking. However, these fuel efficiency technologies of PHEVs are more effective during some driving conditions than during others. Further, the extent to which grid-electricity displaces petroleum in PHEVs depends on the driving distance between recharging (referred to as “driving distance”). This characteristic of
PHEVs occurs because PHEVs initially use grid-electricity stored in the battery to power the vehicle [known as charge depleting (CD) mode] and then operate similarly to HEVs [known as charge sustaining (CS) mode] once the battery is depleted to a target state of charge. The distance over which a PHEV operates in CD mode is known as its CD range. This operating mode characteristic of PHEVs is illustrated in Figure 1.1, and additional details of PHEV characteristics and design options are provided in Chapter 2, Section 2.2.3. Since PHEVs use both grid-electricity and petroleum as fuels, their energy use and GHG emissions on a well-to-wheel (WTW) basis (i.e., including all fuel life cycle activities from resource extraction, processing, distribution, to use, and all transportation stages) also depend on the life cycle of the electricity generation supply involved in charging and on the petroleum life cycle (Kromer and Heywood, 2007).

![Figure 1.1. Example of the change in state of charge of a PHEV battery with driving distance. In this example, the initial state of charge is 90%, the target state of charge (at which the PHEV begins operating in CS mode) is 30%, and the CD range is about 22 km.](image)
1.2 Literature Review

1.2.1 Driving Patterns

As explained in Section 1.1, the WTW energy use and GHG emissions of PHEVs depend on both driving conditions and driving distance, which together are referred to as “driving patterns” in this thesis. Both driving conditions and driving distance are described in detail below.

1.2.1.1 Driving Conditions

Driving conditions such as average speed and fluctuations in speed associated with road type and level of congestion affect the tank-to-wheel (TTW), or use phase, energy use of PHEVs and other vehicle technologies. In hybrid vehicles (including both PHEVs and HEVs), TTW energy use tends to be lower during city driving conditions (i.e., low speed and congested) than during highway driving conditions (i.e., high speed and uncongested), because low speeds and high fluctuations in speed associated with congestion allow for a larger fraction of the energy used by the vehicle to be recaptured through regenerative braking. In ICEVs, TTW energy use tends to be lower during highway driving conditions, however, because high speeds and low congestion result in higher ICE efficiency and fewer idling losses (Kromer and Heywood, 2007).

The impacts of driving conditions on the TTW energy use of vehicles are usually determined by evaluating vehicles on driving cycles, which are second-by-second speed profiles meant to represent particular driving conditions. These analyses are often completed using certification driving cycles, or those used for federal fuel consumption and emissions testing programs. An example of a certification driving cycle is the Urban Dynamometer Driving Schedule (UDDS) (Figure 1.2), which the United States Environmental Protection Agency uses to estimate fuel consumption and emissions during city driving conditions (EPA, 2011). Further, studies that evaluate impacts of driving conditions on the TTW energy use of vehicles often use vehicle performance simulation software such as Autonomie, rather than actual vehicles (Autonomie, 2011).
Since driving conditions affect the TTW energy use of vehicles, driving conditions are important to consider in a WTW energy use and GHG emissions analysis because TTW energy use determines the magnitude of energy use and GHG emissions from each WTW stage. Further, driving conditions affect different vehicle technologies in unique ways, as described above. Despite the impact of driving conditions on the WTW environmental performance of PHEVs, WTW studies of PHEVs have generally not considered the sensitivity of their results to different driving cycle assumptions. Some studies that have examined the WTW performance of PHEVs and compared their performance to that of a HEV and an ICEV used a single certification driving cycle to determine the TTW energy use of each vehicle and PHEV operating mode (Shiau et al., 2010; Shiau et al., 2009), while other studies used weighted average results from multiple certification driving cycles to similarly produce a single TTW energy use result for each vehicle and PHEV operating mode (Duvall and Knipping, 2007; Gaines et al., 2007; Elgowainy et al., 2009; Samaras and Meisterling, 2008). Other studies have specifically examined implications of driving conditions on the energy use of PHEVs by drawing comparisons across driving cycles, but those studies only considered TTW energy use and did not examine WTW performance (Gonder et al., 2009; Kwon et al., 2008; Passier et al., 2007; Santini and Vyas, 2008; Vyas et al., 2007). Further, all of the aforementioned studies employed certification driving cycles, which

**Figure 1.2.** UDDS driving cycle used by the United States Environmental Protection Agency to estimate fuel consumption and emissions during city driving conditions (EPA, 2011).
tend to underestimate the aggressiveness of real world driving (Gonder et al., 2009; Kwon et al., 2008).

1.2.1.2 Driving Distance

Driving distance affects the WTW energy use and GHG emissions of PHEVs by determining the fraction of vehicle kilometers traveled (VKT) that occurs in each operating mode. Once a PHEV is driven beyond its CD range, its average petroleum energy use increases asymptotically with driving distance towards its CS mode petroleum energy use (Shiau et al., 2010; Shiau et al., 2009; Moawad et al., 2009). To account for the impact of driving distance on the WTW environmental performance of PHEVs, various methods have been developed in the literature. Several WTW studies of PHEVs have presented data for boundary (i.e., extreme) driving distance scenarios, which are 100% CD mode driving (i.e., assuming that the PHEV is always driven a distance that is shorter than or equal to its CD range before recharging) and 100% CS mode driving (i.e., assuming that the PHEV is never recharged) (Gaines et al., 2007; Elgowainy et al., 2009; Silva et al., 2009). While these scenarios demonstrate the range of possible WTW results associated with variation in driving distance, PHEVs used in real world operating conditions may frequently be driven distances that fall between these extremes. Researchers have examined implications of these intermediate driving distances on the WTW performance of PHEVs by evaluating a continuous range of driving distances using data from a single driving cycle (Shiau et al., 2010; Shiau et al., 2009).

An alternative approach to account for impacts of driving distance on the environmental performance of PHEVs involves estimating the average fraction of VKT that occurs in CD mode at the fleet level, which is known as the utility factor (SAE, 2011). The utility factor method employs daily driving distance data and assumes that all individuals recharge their PHEVs once per day, overnight. The utility factor for a given CD range is determined by estimating the fraction of all VKT of vehicles that are driven less than or up to the CD range each day, as well as the VKT up to the CD range of vehicles whose daily driving distance exceeds the CD range. The utility factor for CD range D, UF(D), is calculated by (1.1) (Gonder and Simpson, 2006):

$$UF(D) = \frac{\left(\sum_{i=0}^{D} P_i \times i\right) + \left(\sum_{i=D+1}^{\infty} P_i \times D\right)}{\left(\sum_{i=0}^{\infty} P_i \times i\right)}$$ (1.1)
Where \( i \) is the driving distance in increments of one km, and \( P_i \) is the probability that a vehicle in the fleet is driven \( i \) kilometers per day.

An example utility factor curve for the Greater Toronto Area light-duty vehicle fleet in Ontario, Canada is constructed using the 2006 Transportation Tomorrow Survey and is shown in Figure 1.3 (DMG, 2008).\(^1\) Based on this utility factor curve, the utility factor of a PHEV with an estimated CD range of 22 km in the Greater Toronto Area is 0.5, suggesting that such a PHEV would operate in CD mode for half of all VKT, on average, that occur in the region’s light-duty vehicle fleet. Similar utility factor curves have been developed for the USA’s light-duty vehicle fleet using data from the National Household Travel Survey. Those utility factor curves have been used in various TTW and WTW studies of PHEVs (Kromer and Heywood, 2007; Duvall and Knipping, 2007; Gonder et al., 2009; EPRI, 2002; Samaras and Meisterling, 2008).\(^2\)

![Figure 1.3. Example utility factor curve for the Greater Toronto Area light-duty vehicle fleet. Daily driving distance determined assuming straight line distances between zone centroids.](image)

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\(^1\) The utility factor curve shown in Figure 1.3 differs from the one by Canizares et al. (2010), who also use the 2006 Transportation Tomorrow Survey for data, because they appear to have analyzed individual trips rather than daily driving tours.

\(^2\) Samaras and Meisterling (2008) do not use a complete utility factor curve in their analysis because they do not account for VKT up to the CD range of vehicles whose daily driving exceeds the CD range.
While the utility factor method has its benefits, it also has limitations. In particular, it assumes an equal likelihood of PHEV adoption across all drivers in the fleet, regardless of individual driving patterns. Further, a single utility factor curve is generally used irrespective of the driving cycle on which the CD range is estimated, while different driving cycles (and the real world driving conditions that they are meant to represent) may correspond to substantially different utility factor curves. As well, the utility factor method is used to produce a fleet average estimate of the fraction of VKT in each PHEV mode rather than to evaluate implications of driving distance on this fraction.

1.2.2 Regional Driving Patterns

Driving patterns exhibit significant variation within and across regions, and therefore the WTW energy use and GHG emissions of PHEVs ideally should be investigated at a regional level for specific local driving patterns. This variation occurs due to regional differences in road topography, traffic conditions, and other local characteristics (Hung et al., 2007; Lin and Niemeier, 2003). Further, these regional differences in driving patterns are not captured by certification driving cycles, which are meant to represent national fleet-average driving. However, regional driving patterns can be examined by using real world driving cycles, which are obtained by tracking the second-by-second speeds of vehicles in real world operating conditions using GPS data loggers. For instance, real world driving cycles from Kansas City and St. Louis have been used to analyze the TTW energy use and WTW performance of PHEVs (Moawad et al., 2009; Markel, 2006; Parks et al, 2007; Sioshansi and Denholm, 2009). Real world driving cycles can also be used to construct average regional driving cycles (Hung et al., 2007; Liaw and Dubarry, 2007; Shahidinejad et al., 2010). These average regional driving cycles are generally constructed using data from a real world driving cycle dataset such that certain statistics of the constructed driving cycle match with those of the entire dataset. While real world driving cycles can be used to evaluate regional driving patterns, the characteristics of these driving cycles depend on individual driving behaviors, which significantly affect the TTW energy use of PHEVs (Markel, 2006). The contribution of driving behaviors to TTW energy use of PHEVs necessitates a large sample size of participants when collecting real world driving cycles, thereby resulting in extensive data and resource requirements.
1.2.2.1 Travel Demand Modeling

An alternative approach for estimating regional driving patterns involves the use of travel demand models. Travel demand models employ regional travel demand data to estimate trips that are assigned to a road network model. Traffic assignment models that estimate average traffic speed for each link (i.e., road segment), known as macroscopic traffic assignment models, have been used to produce fuel consumption and emissions inventories for entire metropolitan areas (Hatzopoulou, 2008). Using this approach, fuel consumption and emissions are estimated as a function of average link speed, but not as a function of the congestion related fluctuations in speed. Since fluctuations in speed have significant and generally opposite effects on the TTW energy use of hybrid vehicles (both PHEVs and HEVs) and ICEVs, this average speed approach cannot be used to comprehensively evaluate driving pattern implications on the WTW performance of vehicles and to compare the WTW performance of different vehicle technologies. However, by using a macroscopic traffic assignment model linked with a vehicle motion model, it is possible to estimate and forecast driving cycles that account for congestion related fluctuations in speed for entire metropolitan areas (Meyer and Miller, 2001; Busawon and Checkel, 2006). This methodology and related details are described further in Chapter 2.

1.2.3 Well-to-Wheel Analyses of PHEVs

As described above, WTW analyses of PHEVs have generally not comprehensively examined implications of driving patterns; they have generally instead focused on implications of the electricity generation supply (Duvall and Knipping, 2007; Gaines et al., 2007; Elgowainy et al., 2009; Samaras and Meisterling, 2008; Parks et al., 2007; Peterson et al., 2011; Sioshansi and Denholm, 2009). Implications of the electricity generation supply on the WTW energy use and GHG emissions of PHEVs are described in Chapter 3.

1.3 Research Objectives

Based on the literature described above, the primary objectives of this thesis are listed below:

1. To demonstrate a travel demand modeling approach to estimate specific regional driving patterns that can be used to evaluate the TTW energy use of PHEVs.
2. To evaluate the impacts of selected specific regional driving patterns in the Greater Toronto Area on the TTW energy use of PHEVs and reduction in TTW petroleum energy use relative to an ICEV.

3. To evaluate the impacts of these driving patterns on the WTW energy use and GHG emissions of PHEVs.

4. To examine interactions between driving patterns and the electricity generation supply in affecting the WTW energy use and GHG emissions of PHEVs.

5. To evaluate implications of these interactions on the WTW energy use and GHG emissions of a PHEV relative to those of a HEV and an ICEV.

1.4 Thesis Organization

This thesis contains four chapters and two appendices. Chapter 2 demonstrates a travel demand modeling approach for estimating specific regional driving patterns that is used to evaluate the TTW energy use of PHEVs. Chapter 3 employs the TTW energy use data obtained in Chapter 2 to analyze implications of driving patterns on the WTW energy use and GHG emissions of PHEVs. Chapter 4 summarizes the key findings and contributions of this thesis and discusses possible future research directions. The appendices include additional relevant data.

Chapters 2 and 3 are based on previously submitted journal and conference papers, respectively:


1.5 References


Chapter 2
Estimating Impacts of Regional Driving Patterns on the Tank-To-Wheel Energy Use of Plug-in Hybrid Electric Vehicles

2.1 Introduction

The global light-duty vehicle fleet, which is primarily comprised of internal combustion engine vehicles (ICEVs), uses petroleum for an estimated 95% of its energy needs and is responsible for an estimated 27% of global petroleum energy use (Ribeiro et al., 2007; IEA, 2010). This high level of petroleum energy use, which mainly occurs during the tank-to-wheel (TTW) stage, has been linked to various negative environmental, energy, and economic impacts, leading policymakers to seek options that can reduce the light-duty vehicle fleet’s dependence on petroleum. As described in Chapter 1, one such option is the plug-in hybrid electric vehicle (PHEV), which stores grid-electricity in a high capacity battery and uses this electricity to power a motor, thereby displacing petroleum otherwise used in the PHEV’s internal combustion engine (ICE). PHEVs also reduce petroleum energy use relative to ICEVs through technologies that exist in (non-plug-in) hybrid electric vehicles (HEVs). For example, both PHEVs and HEVs employ regenerative braking, which involves recapturing some of the energy otherwise lost as waste heat during braking (Bradley and Frank, 2009).

PHEVs can reduce TTW petroleum energy use relative to ICEVs, but the magnitude of these reductions depends on driving patterns. In this thesis, the term “driving patterns” includes both driving distance between recharging (referred to as “driving distance”) and driving conditions (e.g., average speed and fluctuations in speed associated with road type and level of congestion). Driving distance affects average TTW petroleum energy use of PHEVs because PHEVs only displace petroleum with grid-electricity over a limited distance in charge depleting (CD) mode, and then operate similarly to HEVs in charge sustaining (CS) mode until their batteries are recharged. Driving conditions impact the fuel efficiency of PHEVs in each mode, largely by determining the fraction of energy used by the vehicle that is recaptured through regenerative braking (Kromer and Heywood, 2007). Further, driving patterns exhibit significant variation across regions (i.e., “inter-regional variability”) due to regional differences in road topography,
traffic conditions, and other local characteristics (Hung et al., 2007; Lin and Niemeier, 2003). Driving patterns also exhibit significant variation within regions (i.e., “intra-regional variability”). For these reasons, TTW petroleum energy use and related environmental impacts of PHEVs ideally should be evaluated at a regional level for specific driving patterns.

One approach for estimating specific regional driving patterns involves the use of travel demand models. Travel demand models employ regional travel demand data to estimate trips that are assigned to a road network model. In microscopic traffic simulation, traffic flow is estimated by representing the movements of each vehicle in a network on a second-by-second basis. Since microscopic traffic simulation models estimate second-by-second vehicle speeds, they can be used directly to construct driving cycles (Hung et al., 2007). However, the detailed data and extensive computation required by these models generally limit their applications to small networks. For example, Int Panis et al. (2006) used a microscopic traffic simulation model combined with an emissions model to estimate the impacts of a traffic management policy on vehicle emissions in a 2 by 2 km network. In contrast, macroscopic traffic assignment models require less data than microscopic models and can potentially be used to estimate and forecast driving patterns for entire metropolitan areas. However, while microscopic models estimate second-by-second speeds for each vehicle, macroscopic traffic assignment models only estimate average traffic speed for each link in a network (Meyer and Miller, 2001). As a result, macroscopic traffic assignment models do not estimate fluctuations in speed associated with different congestion conditions and cannot be used directly to construct driving cycles. To address this limitation of macroscopic models, the CALMOB6 vehicle motion model was developed to estimate second-by-second fluctuations in speed associated with congestion for each link, while adhering to the link’s average speed and length as estimated by the macroscopic traffic assignment model (Busawon and Checkel, 2006).

Macroscopic traffic assignment models integrated with the CALMOB6 vehicle motion model (referred to as the “CALMOB6-based approach”) can be used to estimate specific regional driving patterns within entire metropolitan areas and to forecast changes in those driving patterns over time. Estimating specific regional driving patterns is important for evaluating PHEVs because their performance is highly sensitive to driving patterns (Kromer and Heywood, 2007), which exhibit significant inter- and intra-regional variability. However, the CALMOB6-based approach has to date only been used to evaluate ICEVs (Achtymichuk, 2010).
The objectives of this chapter are; 1) to modify and demonstrate the CALMOB6-based approach for estimating specific regional driving patterns, and 2) to evaluate the impacts of these driving patterns on TTW total and petroleum energy use of PHEVs and reduction in petroleum energy use (referred to as “petroleum savings”) relative to an ICEV. I demonstrate this approach using two different PHEV designs and driving patterns estimated for eight selected commutes within the Greater Toronto Area.

2.2 Methods

I select commutes in the Greater Toronto Area using a macroscopic traffic assignment model, develop driving cycles for those commutes using the CALMOB6 vehicle motion model, and analyze PHEV performance for those driving cycles using vehicle performance simulation software. These methods are described in the following sections.

2.2.1 Traffic Assignment

I conduct traffic assignments for the Greater Toronto Area using Emme 3, a user-equilibrium traffic assignment tool (INRO, 2011). The traffic assignments are performed using travel demand data from the 2006 Transportation Tomorrow Survey, a 24 hour trip diary survey conducted on 5% of households in the Greater Toronto Area with a total of approximately 150,000 surveyed households and 402,000 persons (DMG, 2008). The 2006 Transportation Tomorrow Survey contains the most recent available Transportation Tomorrow Survey data.

The Transportation Tomorrow Survey database can be queried according to trip characteristics such as start time, mode, and purpose. I find that during the AM peak hour (7:00-7:59 AM) 61% of auto trips start at home and end at work, while during the PM peak hour (5:00-5:59 PM) 44% of auto trips start at work and end at home. Due to the large fraction of commute trips that occur

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3 For PHEVs operating in CD mode, TTW total energy use refers to both petroleum and electricity use. For PHEVs operating in CS mode, HEVs, and ICEVs, TTW total and petroleum energy use are equivalent. Additional details on this subject are provided in Section 2.2.3.

4 User-equilibrium traffic assignment models assign routes such that none of the trip-makers can change their routes to improve their travel times for the given congestion conditions.
during peak hours, I demonstrate the CALMOB6-based approach for these commute trips. In this thesis, I define a commute as an auto tour comprised of a trip from home to work during the AM peak hour (“AM trip”) with a corresponding return trip during the PM peak hour (“PM trip”).

I analyze commutes with an estimated round trip travel time of 40 minutes +/- one minute. Commute travel times are estimated by performing traffic assignments for the AM and PM peak hours using the corresponding Transportation Tomorrow Survey travel demand matrices and summing the travel times accordingly. I keep commute duration constant in order to force a trend in which commute distance is correlated with speed. This method results in a wide range of driving patterns being captured in the commute selection process: within the 40 minute commute criterion, driving distances and conditions vary substantially (20 to 68 km, congested city to uncongested highway). Eight of these commutes are then chosen based on distance and commute orientation: the shortest and longest commutes within the City of Toronto, from the suburbs to the City of Toronto (peak direction), from the City of Toronto to the suburbs (reverse direction), and within the suburbs.\(^5\) I use these distance and commute orientation criteria to ensure final selection of commutes that represent a range of driving patterns.

The eight commutes analyzed in this study are shown in Figure 2.1. Commute routes and characteristics are determined using the “Shortest Paths – Isochrones” worksheet in Emme 3, which displays one of the shortest travel time paths for a given trip. Using trip characteristics obtained from this worksheet, the commutes are assigned to one of three categories: city (C), suburban (SU), or highway (HWY). City commutes are assumed to occur entirely on arterial, collector, and local roads, and describe the three shortest commutes (C1-C3) in this study. Suburban commutes are assumed to contain some highway driving in congested conditions and describe the three commutes of intermediate distance (SU1-SU3). Highway commutes are assumed to be comprised primarily of uncongested highway driving and describe the two longest commutes (HWY1 and HWY2). Within each commute category, the number corresponds to

\(^5\) Regional boundaries are identified using the Transportation Tomorrow Survey 2001 Greater Toronto Area zone system (DMG, 2008).
distance (e.g., HWY1 is shorter than HWY2). The commutes are described as follows (quantitative characteristics of the commutes are in Section 2.3.2);

- **C1**: Short peak direction commute entirely within the City of Toronto boundary. Home location is in the inner urban area of Toronto\(^6\) and work location is in the central business district.

- **C2**: Short inner suburb peak direction commute. Home location is in an inner suburb and work location is in the inner urban area of Toronto.

- **C3**: Short outer suburb peak direction commute near Pearson International Airport, where high employment and airport traffic result in heavily congested roads during peak hours. Home and work locations are both in the outer suburbs of Toronto near the airport.

- **SU1**: Short inner suburb reverse direction commute that includes driving on Highway 401 (the major east-west highway in the Greater Toronto Area) during the PM trip (not shown in Figure 2.1). Home location is in the inner urban area of Toronto and work location is in an inner suburb.

- **SU2**: Long reverse direction commute entirely within the City of Toronto boundary that includes driving on Highway 401 and the Don Valley Parkway (the only north-south highway providing direct access to the Toronto central business district). Home location is in the Toronto central business district and work location is in the inner urban area of Toronto.

- **SU3**: Long inner suburb peak direction commute that occurs almost entirely on Highway 427 (the busiest north-south highway in the Greater Toronto Area) (MTO, 2007). Home location is in an inner suburb and work location is in the inner urban area of Toronto.

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\(^6\) Defined as the area within the City of Toronto boundary that is south of Highway 401 but excluding the central business district.
• **HWY1**: Long inner suburb reverse direction commute that occurs almost entirely on Highway 401. Home location is in the inner urban area of Toronto and work location is in an outer suburb.

• **HWY2**: Long outer suburb reverse direction commute that occurs almost entirely on Highway 401. Home and work locations are in the outer suburbs of Toronto.

Among these eight commutes, I capture a wide range of common driving patterns that occur in the Greater Toronto Area during commuting hours.

![Figure 2.1](image_url)  
**Figure 2.1.** Routes for the AM trips of the eight commutes analyzed in this study. Dashed lines are commutes; C = City; SU = Suburban; HWY = Highway; Solid black line indicates the City of Toronto boundary; Dark thick grey lines are highways, dark thin grey lines are arterial roads, and light grey lines are collector and local roads.

### 2.2.2 Constructing Driving Cycles

Driving cycles are constructed for the AM and PM trips of each commute using the CALMOB6 vehicle motion model (Busawon and Checkel, 2006). The vehicle motion model uses link parameters from Emme 3 or other traffic assignment software to produce second-by-second speed traces that approximate fluctuations in speed associated with congestion for each link,
constrained by the link length and average speed. In Emme 3, congestion is determined for each link with volume delay functions, in which average link speed is estimated as a function of auto volume: as auto volume increases, the average speed decreases relative to the free flow speed (Jastrzebski, 2000). Free flow speeds in the Emme Greater Toronto Area network range from 40 to 110 km/h and equal the posted speed limit for most links. For certain links in the network that are located in the central business district, the free flow speed is assumed to be lower than the posted speed limit. For most links that represent high speed road types, the free flow speed is assumed to be the posted speed limit plus 10 km/h (DMG, 2004).

The CALMOB6 vehicle motion model has been calibrated based on estimated TTW energy use by adjusting its acceleration/deceleration assumptions (Achtymichuk, 2010). Under most conditions, the model employs acceleration/deceleration rates of $2.5 \text{ m/s}^2$ up to 50 km/h and $1.67 \text{ m/s}^2$ above 50 km/h. For “congestion” links (see below), the vehicle motion model reduces these rates by 50%. The vehicle motion model also assumes that speed traces start and end at the free flow speed of the corresponding link. I use a version of the CALMOB6 vehicle motion model that produces five types of speed traces based on level of congestion:

- **Free Flow**: there is no delay on the link associated with congestion and the vehicle motion model produces a constant speed trace at the free flow speed of the link.

- **Reduced Cruise**: there is some delay on the link and the vehicle motion model produces a constant speed trace at a reduced cruise speed.

- **Partial Stop**: the delay on the link is sufficient to produce a speed trace with a partial stop (i.e., a deceleration to a reduced driving speed followed immediately by an acceleration back to the starting speed).

- **Complete Stop**: there is enough delay on the link to produce a speed trace with a complete stop and up to 30 seconds of idling.

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7 Several speed trace names have been modified to better correspond to how the vehicle motion model is used in this study.
- **Congestion:** delay on the link exceeds the amount of time required for a complete stop and 30 seconds of idling and the vehicle motion model produces a speed trace with multiple stops. The acceleration/deceleration rates are also reduced by 50% and the assumed starting/ending speeds on the link are decreased.

These speed traces are an abstract representation of actual driving behaviors. Since the vehicle motion model has been calibrated, however, they provide reasonable estimates of TTW energy use for different speed and congestion conditions.

For each AM and PM trip, speed traces are produced for each link and concatenated in sequence to create a driving cycle. Transitions are inserted between speed traces at a rate of 2.5 m/s^2 if the free flow speeds of the corresponding links do not match. This high rate reduces the impact of the transitions on driving cycle distance. All driving cycles include an initial 30 second idling period (Busawon and Checkel, 2006), and ramping up to and down from the free flow speeds of the first and last links, respectively, at the appropriate acceleration rates.

Figure 2.2 compares the driving cycles for the AM trips of commutes C1 and HWY2 and identifies the five speed trace types produced by the vehicle motion model. Commute C1 is highly congested and is primarily comprised of “congestion” and “complete stop” speed traces, whereas commute HWY2 is relatively uncongested and mainly consists of “reduced cruise”, “partial stop”, and “free flow” speed traces.
Figure 2.2. Driving cycles for the AM trips of commute A) C1 and B) HWY2.

Table 2.1 summarizes the driving cycle statistics for each commute. Average and maximum acceleration and deceleration rates are not included as they are found to be similar across all commutes. Since travel duration is constant across the commutes, commute distance is correlated with driving cycle speed. Further, commute distance is inversely related to the coefficient of variation of speed (i.e., fluctuation in speed associated with congestion), time percentage of the driving cycle spent idling, and the number of stops in the driving cycle. These opposing trends result in a range of driving patterns – from short distance and highly congested city driving to long distance and uncongested highway driving – with which to demonstrate the CALMOB6-based approach for evaluating PHEVs. For reference, Table 2.1 also includes statistics for three United States Environmental Protection Agency certification driving cycles:
the UDDS, the highway certification driving cycle (known as “HWFET”), and the US06 certification driving cycle (EPA, 2011).

### Table 2.1. Summary of driving cycle statistics for each commute. Driving cycles for AM and PM trips are concatenated to estimate statistics for the entire commute.

<table>
<thead>
<tr>
<th>Commute</th>
<th>Distance (km)</th>
<th>Average Speed (km/h)</th>
<th>Max Speed (km/h) (^a)</th>
<th>Coefficient of Variation of Speed (%) (^b)</th>
<th>Percent of Cycle Idling (%)</th>
<th>Number of Stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>20</td>
<td>29</td>
<td>51</td>
<td>58</td>
<td>12.5</td>
<td>29</td>
</tr>
<tr>
<td>C2</td>
<td>27</td>
<td>37</td>
<td>62</td>
<td>53</td>
<td>15.1</td>
<td>35</td>
</tr>
<tr>
<td>C3</td>
<td>29</td>
<td>40</td>
<td>72</td>
<td>51</td>
<td>11.1</td>
<td>31</td>
</tr>
<tr>
<td>SU1</td>
<td>33</td>
<td>46</td>
<td>112</td>
<td>47</td>
<td>9.8</td>
<td>21</td>
</tr>
<tr>
<td>SU2</td>
<td>42</td>
<td>59</td>
<td>124</td>
<td>46</td>
<td>6.0</td>
<td>12</td>
</tr>
<tr>
<td>SU3</td>
<td>53</td>
<td>73</td>
<td>128</td>
<td>45</td>
<td>6.3</td>
<td>12</td>
</tr>
<tr>
<td>HWY1</td>
<td>64</td>
<td>85</td>
<td>132</td>
<td>37</td>
<td>3.2</td>
<td>3</td>
</tr>
<tr>
<td>HWY2</td>
<td>68</td>
<td>94</td>
<td>133</td>
<td>31</td>
<td>2.4</td>
<td>2</td>
</tr>
<tr>
<td>UDDS (^c)</td>
<td>12</td>
<td>32</td>
<td>91</td>
<td>75</td>
<td>18.9</td>
<td>17</td>
</tr>
<tr>
<td>HWFET (^d)</td>
<td>17</td>
<td>78</td>
<td>96</td>
<td>21</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>US06 (^e)</td>
<td>13</td>
<td>77</td>
<td>129</td>
<td>51</td>
<td>7.5</td>
<td>5</td>
</tr>
</tbody>
</table>

\(^a\) For some commutes, the maximum speed exceeds the highest free flow speed in the Greater Toronto Area network (110 km/h) because certain speed traces start and end at a speed that is greater than the free flow speed.

\(^b\) The coefficient of variation of speed is the standard deviation of speed normalized by the average speed, and therefore is used as a general measure of the level of congestion for each driving cycle.

\(^c\) Urban Dynamometer Driving Schedule (EPA, 2011).

\(^d\) Highway Fuel Economy Driving Schedule (EPA, 2011).

\(^e\) Also referred to as the Supplemental Federal Test Procedure (EPA, 2011).

### 2.2.3 Vehicle Selection and Simulation

Driving cycles are imported into Autonomie, a vehicle performance simulation tool developed by Argonne National Laboratory (Autonomie, 2011). Autonomie includes default vehicle models for various technologies including ICEVs, HEVs, PHEVs, as well as fully electric and fuel cell vehicles. I simulate two PHEV designs as well as a HEV and an ICEV.

PHEVs can vary in terms of drivetrain configuration, control strategy, battery capacity and other design characteristics. In this study, as in research conducted at Argonne National Laboratory (Moawad et al., 2009), I simulate PHEVs with series and split drivetrain configurations. In a series drivetrain configuration, only the electric motor provides power to the wheels. When the ICE is operating, it is used to drive a generator that powers the electric motor rather than to
directly drive the wheels. In a split drivetrain configuration, the ICE has the ability to both drive a generator that powers the electric motor, as in a series PHEV, and to directly drive the wheels. Also in line with Moawad et al. (2009), I assume that the series PHEV has an all-electric CD mode (CDE) control strategy and the split PHEV has a blended CD mode (CDB) control strategy. In a CDE control strategy, the battery is discharged to meet power demands during CD mode, and the ICE is only used in CD mode if power demands exceed the rated power of the battery or motor. While the series PHEV operates all-electrically in CD mode for certain driving cycles (e.g., the UDDS), the ICE is used intermittently on more aggressive driving cycles. This is consistent with observations in previous research (Kwon et al., 2008; Markel, 2006). In a CDB control strategy, the ICE is sometimes used as a power source during CD mode even if the power demands can be supplied by the battery and motor alone. CDB control strategies can vary in terms of design parameters such as the power threshold for ICE operation. In this study, the split PHEV has a CDB control strategy that is designed to keep the ICE operating near its most efficient point whenever it is on, which can result in the ICE charging the battery during CD mode. I choose to evaluate these two control strategies because they represent extremes in terms of CD mode operation: for a given battery capacity, a CDE control strategy results in little to no petroleum energy use during CD mode but also a very short CD range, while a CDB control strategy for best ICE efficiency results in much higher petroleum energy use during CD mode but a much longer CD range. The shorter CD range of the series PHEV with the CDE control strategy than of the split PHEV with the CDB control strategy is demonstrated in Figure 2.3.
Figure 2.3. Difference in CD range between the series PHEV with CDE control strategy and the split PHEV with CDB control strategy. The CD range of both PHEVs is estimated using the same driving cycle. The exact CD range of each PHEV varies according to the driving cycle.

All vehicles modeled are based on default midsize models included in the Autonomie software. To reasonably compare the vehicles, all vehicles are assumed to use conventional gasoline as a liquid fuel and are controlled for body and tire specifications. All vehicles are also controlled to meet the following acceleration requirement: 0-100 kilometers per hour in 10.5-11 seconds (alternatively, 0-60 miles per hour in 9.5-10 seconds). The default series and split PHEV models are the “Series Engine Midsize FixedGear PHEV 2wd Default” and “Split Midsize SingleMode PHEV 2wd Default”, respectively. I modify these models to each have 8 kWh of battery capacity and to be consistent in terms of number of battery cells and state of charge swing (i.e., percentage of battery capacity that is depleted during CD mode). For both PHEVs, several components are scaled iteratively such that the PHEVs are able to meet the acceleration criteria while being consistent in terms of mass. Similar mass for series and split PHEVs with comparable performance characteristics is a reasonable assumption due to a trade-off between component sizes and number of components in series and split PHEVs, respectively (e.g., a series PHEV requires a larger motor but a split PHEV requires a planetary gear set). The default HEV and ICEV models are the “Split Midsize SingleMode HEV 2wd Default” and “Conv Midsize Auto 2wd Default”, respectively, and are not modified in this study.
Selected characteristics of each vehicle are shown in Table 2.2. The specific vehicle designs that I analyze do not exist in the marketplace but are intended to represent a range of reasonable configurations and attributes for near-term vehicles. The series PHEV generally resembles the 2011 Chevrolet Volt in terms of its drivetrain configuration and control strategy, although the Chevrolet Volt has double the battery capacity (16 kWh), a slightly more powerful motor (112 kW) and lower mass (1715 kg), and differs in other aspects (Chevrolet, 2011). Due to these differences, a 2011 Chevrolet Volt would be expected to have a substantially higher CD range and somewhat lower TTW petroleum energy use during CD mode for the commutes analyzed in this study. To examine the implications of a higher battery capacity, I conduct a scenario analysis, modeling a series PHEV with a 16 kWh battery capacity.\(^8\) The split PHEV and HEV resemble the Toyota Prius in terms of drivetrain configuration and CS mode control strategy.

<table>
<thead>
<tr>
<th></th>
<th>PHEV (Series)</th>
<th>PHEV (Split)</th>
<th>HEV</th>
<th>ICEV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ICE Power (kW)</strong></td>
<td>55</td>
<td>90</td>
<td>90</td>
<td>115</td>
</tr>
<tr>
<td><strong>Motor Power (kW)</strong></td>
<td>100</td>
<td>63</td>
<td>63</td>
<td>-</td>
</tr>
<tr>
<td><strong>Generator Power (kW)</strong></td>
<td>55</td>
<td>51</td>
<td>51</td>
<td>-</td>
</tr>
<tr>
<td><strong>Battery Capacity (kWh)</strong></td>
<td>8</td>
<td>8</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td><strong>Battery State of Charge Swing (%)</strong></td>
<td>60</td>
<td>60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Frontal Area (m(^2))</strong></td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td><strong>Drag Coefficient</strong></td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Wheel Radius (m)</strong></td>
<td>0.317</td>
<td>0.317</td>
<td>0.317</td>
<td>0.317</td>
</tr>
<tr>
<td><strong>Vehicle Mass (kg)</strong></td>
<td>1781</td>
<td>1776</td>
<td>1680</td>
<td>1580</td>
</tr>
<tr>
<td><strong>0-100 km/h time (s)</strong></td>
<td>10.9</td>
<td>10.5</td>
<td>10.6</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Simulations are conducted for the AM and PM trips of each commute. For both PHEVs, it is assumed that the battery is recharged overnight and therefore the AM trip begins with a fully charged battery. Unless otherwise stated, it is also assumed that the PHEVs are not recharged at the workplace. Therefore, the ending battery state of charge of the AM trip is used as the beginning state of charge of the PM trip. If workplace recharging is assumed then the PM trip is

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\(^8\) Another reason for the scenario analysis is that CDE control strategies are generally considered to be a better design option for PHEVs with large battery capacities because battery cost ($/kWh) decreases as capacity increases for a given battery power requirement (Vyas et al., 2007).
simulated with a fully charged battery, which is similar to the “work charging” scenario from Peterson et al. (2011). The results of each commute trip are then weighted by distance to obtain average TTW energy use estimates for the entire commute.

Additional simulations are conducted to evaluate differences in impacts of driving conditions on TTW energy use across the commutes and to compare the commute driving cycles with the UDDS, HWFET, and US06 certification driving cycles. To estimate the impacts of driving conditions in isolation of the impacts of driving distance, PHEV simulations are conducted entirely in CD and CS modes for each commute and certification driving cycle. This step is necessary because the driving cycles vary in distance and distance largely determines the fraction of vehicle kilometers traveled (VKT) in each mode. For the CD mode simulations, I examine TTW total energy use (both petroleum and electricity use) to determine the full energy implications of different driving conditions. Electricity use is measured based on the difference in battery state of charge between the start and end of each driving cycle. This method is meant to only account for grid-derived electricity use, but more electricity is actually used than is indicated by this method because the battery is recharged throughout the driving cycle by the ICE and through regenerative braking. However, recharging by the ICE is taken into account in the petroleum energy use, and accounting for recharging through regenerative braking overestimates the grid-derived electricity use. Electricity use is reported as L/100 km gasoline equivalent (GE) based on an assumed gasoline energy content of 8.9 kWh per liter. This value is used by the United States Environmental Protection Agency to estimate TTW gasoline equivalent electricity use of PHEVs and fully electric vehicles (Fleming, 2009). For the PHEVs in CD mode, therefore, TTW total energy use (L/100 km GE) refers to both petroleum and electricity use; for the PHEVs in CS mode, the HEV, and the ICEV, TTW total energy use consists only of petroleum energy use. It should be noted that from a TTW perspective, an electric drivetrain is substantially more efficient than an ICE drivetrain (Creutzig et al., 2009). Thus, since less energy is wasted in an electric drivetrain, 1 L/100 km GE electrical energy use corresponds to higher energy demand by the vehicle than 1 L/100 km gasoline energy use. If a commute driving cycle exceeds the CD range of the PHEV, sections of the driving cycle are
simulated individually to ensure that the entire commute is simulated in CD mode. The CD mode petroleum and electricity use are then weighted by distance to obtain average values for the entire commute. Once the battery in a PHEV is depleted to a target state of charge, the PHEV switches to CS mode. Therefore, CS mode petroleum energy use is estimated by setting the initial battery state of charge parameter to this target state of charge prior to simulating the PHEV.

2.3 Results

General trends across commutes as well as comparisons between the commute driving cycles and certification driving cycles suggest that the CALMOB6-based approach provides intuitive estimates of driving pattern impacts on TTW energy use of PHEVs. The TTW petroleum energy use of the PHEVs is lowest on the city commutes and highest on the highway commutes, whereas the opposite is true for the ICEV; these opposite trends result in the largest petroleum savings for the PHEVs relative to the ICEV for the city commutes and the smallest savings for the highway commutes. These results are described below. All results in this chapter are for the TTW stage.

2.3.1 Driving Pattern Impacts on TTW Energy Use of PHEVs

Differences in driving conditions across the eight commutes result in substantial variation in TTW total energy use (includes both petroleum and electricity use as defined in Section 2.2.3) for both PHEVs in each mode (Figure 2.4). In general, total energy use of the PHEVs is lowest for the city commutes and highest for the highway commutes, increasing as both commute speed increases and congestion decreases. In the series PHEV, total energy use is 52% higher in CD mode and 30% higher in CS mode on commute HWY2 than on commute C1. Similarly in the split PHEV, total energy use is 64% higher in CD mode and 31% higher in CS mode on commute HWY2 than on commute C1.

9 This step is not necessary for the certification driving cycles because none exceed the CD range of either PHEV.

10 Commute SU3 is an exception to this trend due to the reasons described in Section 2.3.2.
Figure 2.4. Comparison of CD and CS mode TTW total energy use across commutes for the A) series PHEV, and B) split PHEV.

A similar trend is observed for CD mode TTW petroleum energy use of the PHEVs. The CD mode petroleum energy use generally increases as both commute speed increases and congestion decreases. An exception occurs for the series PHEV on the highway commutes, but for those commutes the series PHEV exhibits the highest electricity use. While electricity use does not directly contribute to petroleum energy use, higher electricity use results in a shorter CD range and therefore more VKT in CS mode for a given driving distance. Petroleum energy use of the
PHEVs also varies substantially within each commute category, following the same general trend observed across categories. For example, the series PHEV in CD mode uses 73% more petroleum on commute C3 than on commute C1. Similarly, the split PHEV in CD mode uses 46% more petroleum on commute C3 than on commute C1.

Differences in TTW energy use between the two PHEVs result from their distinct control strategies and drivetrain configurations. In CD mode, petroleum energy use is much lower but electricity use is higher for the series PHEV than the split PHEV because the series PHEV has a CDE control strategy while the split PHEV has a CDB control strategy for best ICE efficiency. The former control strategy only employs the ICE in CD mode if the power demands of the driving cycle exceed the peak power output of either the battery or motor, while the latter control strategy frequently employs the ICE at high power in CD mode. Since the ICE is used less in CD mode in the series PHEV than in the split PHEV, total energy use in CD mode is also much lower in the series PHEV. However, the split PHEV has a longer CD range for each commute. In CS mode, petroleum energy use is slightly higher in the series PHEV than in the split PHEV because drivetrain efficiency losses are higher in a series drivetrain than in a split drivetrain when the ICE is used to power the wheels.

Driving conditions affect TTW energy use of the PHEVs largely by determining the fraction of energy used by the vehicles that is recaptured through regenerative braking. This fraction is highest on the city commutes and lowest on the highway commutes. For the split PHEV operating in CS mode, this fraction is about 14% on commute C1 but only 4% on commute HWY2.

Including the contribution of driving distance to the fraction of VKT in each mode produces estimates of average TTW petroleum energy use of the PHEVs for each commute (Figure 2.5).\textsuperscript{11} For the series PHEV, driving occurs entirely in CD mode for commutes C1-SU1, whereas the longer commutes exceed the CD range and the fraction of VKT in CD mode decreases with increasing commute distance. For the split PHEV, only the highway commutes exceed the CD range. For commutes that exceed the CD range, average petroleum energy use falls between the

\textsuperscript{11} Similar estimates for TTW total energy use (including electricity use) are provided in Table 3.1 and Table B.1.
CD and CS mode petroleum energy use. Since petroleum energy use is much higher in CS mode than in CD mode and CS mode driving only occurs on the longer commutes, the general trend in average petroleum energy use for both PHEVs is more pronounced than the trends observed in Figure 2.4. This is the case for the series PHEV despite low petroleum energy use in CD mode on the highway commutes (Figure 2.4) because only 36% and 32% of VKT on commutes HWY1 and HWY2, respectively, occur in CD mode. For the longer commutes that exceed the CD range of the series PHEV, the scenario analysis for double the battery capacity shows a reduction in petroleum energy use compared to the base series PHEV, but the general petroleum energy use trend does not change. As well, the trend in petroleum energy use of the HEV generally resembles the trend for both PHEVs. Since the HEV does not recharge from the grid, however, its petroleum energy use (as measured on a per kilometer basis) is only determined by driving conditions and not by driving distance.

![Figure 2.5](image)

**Figure 2.5.** Comparison of average TTW petroleum energy use across vehicles and commutes. e = commute exceeds the CD range of the PHEV.

While TTW petroleum energy use of the PHEVs and HEV is higher on the highway commutes than on the city commutes, the opposite is true for the ICEV. Petroleum energy use of the ICEV decreases as both commute speed increases and congestion decreases due to a corresponding
increase in ICE efficiency and decrease in idling losses, respectively (the ICE efficiency is 23% on commute C1 but 32% on commute HWY2).

Since the PHEVs and the ICEV exhibit opposite TTW petroleum energy use trends across the commutes, PHEV petroleum savings relative to the ICEV are highest on commute C1 (9 and 7.6 L/100km for the series and split PHEVs, respectively) and lowest on commute HWY2 (2.4 and 2.5 L/100km for the series and split PHEVs, respectively) (Figure 2.6). Although the petroleum savings relative to the ICEV are lowest on commute HWY2, they are still substantial whereas the HEV petroleum savings relative to the ICEV on the same commute are minimal (0.3 L/100km). In addition, workplace PHEV recharging can increase PHEV petroleum savings relative to the ICEV for commutes that exceed the CD range of the PHEV. For example, workplace recharging for the series PHEV on commute HWY2 nearly doubles the petroleum savings relative to the ICEV.

![Figure 2.6](image)

**Figure 2.6.** Petroleum savings relative to ICEV for all hybrid vehicles. 
* = petroleum savings relative to the ICEV assuming workplace recharging.
2.3.2 Comparison with Certification Driving Cycles

Simulations of the vehicles on the certification driving cycles reveal that TTW total energy use is lowest for the hybrid vehicles and ICEV on the UDDS and HWFET, respectively, and highest for all vehicles on the US06.

Figure 2.7 compares TTW total energy use between these United States Environmental Protection Agency certification driving cycles and the commute driving cycles for all vehicles. For the PHEVs in CD mode, total energy use falls between that on the UDDS and US06 on all commute driving cycles except SU3. Commute SU3 is primarily comprised of congested driving at highway speeds, resulting in a driving cycle with the highest standard deviation of speed and thus the highest power demands of all commute driving cycles. While total energy use is higher on the SU3 than on the US06, this does not necessarily suggest that the SU3 results are invalid, as the US06 may underestimate the power demands of real world driving (Kwon et al., 2008). For the PHEVs in CS mode and the HEV, the results are similar to those for the PHEVs in CD mode except that total energy use is marginally higher on several non-SU3 commute driving cycles than on the US06.

![Figure 2.7](image.png)

**Figure 2.7.** Comparison of TTW total energy use between commute driving cycles developed in this study and United States Environmental Protection Agency certification driving cycles. PHEV results are for CD mode only; Uncertainty bars on left hand side columns represent the range in total energy use for non-SU3 commute driving cycles.
The TTW total energy use of the ICEV is higher on all commute driving cycles than on the HWFET and is also higher on all city and suburban driving cycles than on the US06. The US06 is meant to represent aggressive high speed driving, while the city and suburban driving cycles represent peak hour commuting in highly congested conditions. Accordingly, the US06 has a higher average speed and fewer stops than any of the city or suburban driving cycles, and a lower proportion of time spent idling than all city and suburban driving cycles except SU2 and SU3 (Table 2.1). Higher average speed and less idling correspond to higher ICE efficiency and fewer idling losses, respectively, and therefore to lower overall total energy use of the ICEV (Kromer and Heywood, 2007).

2.4 Discussion

While certification driving cycles can be used to approximate the impacts of driving patterns on TTW energy use of PHEVs, they do not capture inter- or intra-regional differences in driving patterns and can only be used to produce point estimates of TTW total or petroleum energy use of PHEVs for a given driving distance and driving condition. Researchers have partially addressed this limitation by using regional real world driving cycles to construct average regional driving cycles for different driving categories (e.g., weekday, weekend; city, highway) (Hung et al., 2007; Shahidinejad et al., 2010). However, I demonstrate that driving cycles can vary substantially within such categories, and that this variation can have a large impact on TTW energy use of PHEVs. This variation is not captured by certification driving cycles or by the approaches described above that employ real world driving cycles, but is captured by the CALMOB6-based approach.

Differences in driving conditions across the commutes analyzed contribute substantially to the TTW energy use trends. Driving conditions impact petroleum energy use of all hybrid and conventional vehicles, but have opposite effects: increasing speed and decreasing congestion are directly related to petroleum energy use in PHEVs and HEVs and inversely related to petroleum energy use in ICEVs. With PHEVs, driving distance also impacts petroleum energy use by largely determining the fraction of VKT that occurs in each mode. While studies that have
evaluated impacts of driving distance on TTW energy use of PHEVs using certification driving cycles have made contributions to the field, they have been limited in that they have assumed a single driving condition (i.e., driving cycle) regardless of the driving distance. While methods are being developed to estimate driving distance distributions (i.e., utility factor curves) that correspond to specific driving conditions (i.e., driving cycles), these methods produce estimates of PHEV performance that are aggregated at the fleet level and also employ certification driving cycles (SAE, 2011). The relationship between driving distance and conditions in this chapter results from holding commute duration constant, but I nonetheless demonstrate that the CALMOB6-based approach can be used to estimate unique driving conditions for specific trips of varying distances.

A framework for analyzing PHEVs that involves the use of a macroscopic traffic assignment model and regional trip data allows an analyst to evaluate a range of scenarios. While only the Greater Toronto Area is considered in this study, other jurisdictions for which a regional travel demand model is available can similarly be examined taking into account their local characteristics. Within a region, scenarios can be developed to evaluate specific policies. I analyze a set of commuting scenarios with and without workplace recharging to demonstrate the CALMOB6-based approach. However, more comprehensive scenarios can be developed using detailed trip information contained in the Transportation Tomorrow Survey and in similar data sources for other regions. Further, since PHEVs are an emerging technology that will take years to achieve meaningful levels of market penetration, forecasting their future impacts is desirable (Samaras and Meisterling, 2008). With traffic assignment models, regional changes in congestion can be forecasted and the corresponding effects on the TTW energy use of PHEVs can be evaluated.

The results of this study indicate that the CALMOB6-based approach is expected to be useful for evaluating the TTW energy use of PHEVs. Both driving distance and driving conditions affect the energy use trends and are easily estimated for specific regional driving patterns using the CALMOB6-based approach. Further, driving cycles developed using the CALMOB6-based approach affect TTW energy use of the vehicles in expected ways and also reasonably compare to certification driving cycles in terms of TTW energy use estimates. Hence, the CALMOB6-based approach appears to reasonably estimate impacts of specific regional driving patterns on the TTW energy use of PHEVs.
Utilizing the CALMOB6 vehicle motion model to construct driving cycles is beneficial because the vehicle motion model can be linked directly with a macroscopic traffic assignment model and because the driving cycles appear to reasonably estimate TTW energy use of PHEVs, but has drawbacks since driving cycles developed by the vehicle motion model are an abstract representation of actual driving patterns. In particular, the vehicle motion model employs aggressive assumptions about the impacts of congestion on speed fluctuation that may not correspond to the fluctuations in speed that typically occur at similar levels of congestion in real world conditions. However, while the vehicle motion model may not represent actual driving behaviors in this regard, it has been calibrated to reflect results for TTW energy use obtained using a microscopic traffic simulation model (Achtymichuk, 2010). Nonetheless, future research may involve modifications to these assumptions such that the vehicle motion model more closely reflects actual driving behaviors.

The results of this analysis indicate that PHEVs can produce substantial petroleum savings relative to ICEVs over a range of driving patterns, including those for which HEV petroleum savings relative to ICEVs are diminished. The magnitude of those savings, however, depends on additional factors not considered in this study. Driving behaviors are assumed to be constant for all vehicles but may exhibit differences among drivers of hybrid and conventional vehicles (Moawad et al., 2009). Impacts of temperature are not considered but extreme temperatures can decrease PHEV petroleum savings relative to an ICEV due to reduced battery performance and negative impacts of climate control requirements (Rousseau, 2008; Kromer and Heywood, 2007; Barnitt et al., 2010). Driving distances that exceed those considered in this study would generally result in higher VKT in CS mode and diminished PHEV petroleum savings relative to an ICEV. Further, petroleum savings per kilometer do not correspond to petroleum savings per commute due to differences in VKT across commutes.

While reducing petroleum energy use is an important sustainability objective, policymakers and other stakeholders need to be aware of other environmental, economic, and social impacts of PHEVs and trade-offs associated with their use. Workplace recharging increases PHEV petroleum savings relative to an ICEV for commutes that exceed the CD range, but daytime charging can also contribute to peak electricity demand (Axsen and Kurani, 2010), and can result in the use of inefficient and highly polluting peaking power plants (Kromer and Heywood, 2007; Valentine et al., 2010). Of particular importance in analyzing PHEVs is an evaluation of their
well-to-wheel (WTW) environmental performance, taking into account the electricity generation supply used for charging and the gasoline fuel cycle. PHEVs charged by wind-based electricity result in very low greenhouse gas (GHG) emissions during their use, while those charged by coal-based electricity increase GHG emissions relative to HEVs (Gaines et al., 2007). In many regions of the USA, depending on the regional electricity generation mix, PHEVs may increase sulfur dioxide emissions relative to ICEVs (Peterson et al., 2011).

While only TTW energy use is examined in this chapter, the CALMOB6-based approach can be used to model the TTW stage in a study that evaluates the WTW environmental performance of PHEVs. Thus, the next chapter involves using the TTW energy use data obtained in this chapter to demonstrate how driving patterns affect the WTW energy use and GHG emissions of PHEVs.

2.5 Summary

- I applied an approach for estimating specific regional driving patterns that involves using a macroscopic traffic assignment model linked with a vehicle motion model.

- Using this approach, I estimated TTW energy use of PHEVs and comparable non-plug-in alternatives for a range of driving patterns by assuming a constant commute duration.

- The results revealed substantial variation in TTW energy use of PHEVs across driving patterns.

- The TTW energy use results followed those expected given a constant commute duration assumption.

- TTW petroleum energy use of the PHEVs and HEV were lowest for the city driving patterns and generally highest for the highway driving patterns, whereas the opposite trend was observed for the ICEV.

- The constructed driving cycles produced a reasonable range of TTW energy use estimates relative to those produced using certification driving cycles.
2.6 References


Chapter 3
Implications of Driving Patterns on Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles

3.1 Introduction

As described in Chapter 1, the well-to-wheel (WTW) energy use and greenhouse gas (GHG) emissions of plug-in hybrid electric vehicles (PHEVs) depend on driving patterns. Driving distance determines the fraction of vehicle kilometers traveled (VKT) in charge sustaining (CS) and charge depleting (CD) mode. Researchers have examined implications of driving distance on tank-to-wheel (TTW) petroleum energy use of PHEVs, demonstrating that average TTW petroleum energy use increases with driving distance after the PHEV begins operating in CS mode (Shiau et al., 2010; Shiau et al., 2009; Moawad et al., 2009). Driving conditions such as driving speed and fluctuations in speed associated with congestion affect the fuel efficiency of PHEVs, as with any other vehicle technology. For hybrid vehicles [both PHEVs and hybrid electric vehicles (HEVs)] low speeds and high congestion tend to result in higher fuel efficiency than high speeds and low congestion, while the opposite is true for internal combustion engine vehicles (ICEVs) (Kromer and Heywood, 2007). Accordingly, fuel efficiency of PHEVs is generally higher during city than during highway driving conditions (Vyas et al., 2007; Santini and Vyas, 2008). In this chapter, the driving patterns from Chapter 2 are evaluated because they represent a range from most favorable to least favorable in terms of petroleum energy use of PHEVs and fuel efficiency of PHEVs relative to that of ICEVs. These driving patterns vary from short distance, low speed, and congested to long distance, high speed, and uncongested.

The WTW energy use and GHG emissions of PHEVs also depend on the electricity generation supply involved in charging. Many studies examining the WTW performance of PHEVs have focused on implications of the electricity generation supply while not comprehensively considering sensitivities to driving pattern assumptions (Parks et al., 2007; Peterson et al., 2011; Samaras and Meisterling, 2008; Sioshansi and Denholm, 2009; Duvall and Knipping, 2007; Gaines et al., 2007; Elgowainy et al., 2009). Duvall and Knipping (2007) showed that GHG emissions of a PHEV are lowest when charging from renewable electricity (e.g., hydroelectricity...
or wind) and highest when charging from coal-based electricity. Gaines et al. (2007) demonstrated that PHEVs reduce energy use (total, fossil, and petroleum) and GHG emissions relative to HEVs for most non-coal boiler electricity generation pathways when the liquid fuel is assumed to be gasoline produced from crude oil. Elgowainy et al. (2009) demonstrated that PHEVs reduce energy use and GHG emissions relative to ICEVs for a wide range of electricity generation pathways under the same liquid fuel assumption. However, Gaines et al. (2007) and Elgowainy et al. (2009) only considered one set of driving conditions in their analyses.

Substantial uncertainty exists in estimating the electricity generation supply involved in charging of PHEVs. The electricity generation supply varies by region, season, time of day, and with weather conditions (Kromer and Heywood, 2007; Parks et al., 2007). It also changes over time as old electricity generating facilities are decommissioned and new ones come on line (Samaras and Meisterling, 2008). For example, in Ontario, Canada, large changes to the electricity generation supply are proposed by 2020, including a plan to phase out coal by 2014 (Ontario, 2010). In the future, the marginal electricity generation supply involved in charging of PHEVs will also depend on the level of PHEV market penetration (Sioshansi and Denholm, 2009; Valentine et al., 2010). Due to this variability in the types of electricity generating facilities involving in charging of PHEVs, a range of electricity generation scenarios is considered in this chapter. These scenarios range from 100% hydroelectric to 100% coal-based electricity.

Studies evaluating the impacts of driving patterns on energy use of PHEVs have generally not considered WTW environmental performance, while studies that have analyzed the WTW environmental performance of PHEVs have generally focused on implications of the electricity generation supply. The objectives of this chapter are; 1) to evaluate the impacts of driving patterns on the WTW energy use and GHG emissions of PHEVs, 2) to examine interactions between driving patterns and the electricity generation supply in affecting these metrics, and 3) to evaluate implications of these interactions on the WTW energy use and GHG emissions of a PHEV relative to those of a HEV and an ICEV. The analysis is conducted using a range of driving patterns and electricity generation scenarios.
3.2 Methods

Well-to-wheel models are developed to investigate energy use and GHG emissions of a PHEV, HEV, and ICEV. For electricity used by the PHEV, four scenarios are considered:

1. **100% hydroelectric.**

2. **100% natural gas.** A natural gas combined cycle (NGCC) electricity generating facility is assumed using conventional natural gas.

3. **100% coal.** A pulverized coal boiler electricity generating facility is assumed. This technology constitutes the majority of existing coal facilities in the USA and Canada.

4. **Current Ontario average electricity generation mix (referred to as “Ontario mix”).** The Ontario mix is based on the Province’s 2010 electrical energy output by fuel type, which was 55% nuclear, 20% hydroelectric, 14% natural gas boiler, 8% coal, 2% wind, and 1% biomass (IESO, 2011; GHGenius, 2011).

The functional unit, which all metrics are normalized by, is one VKT. The metrics examined are total, fossil, and petroleum energy use, and GHG emissions. Total energy use is a measure of the energy efficiency of each option and includes the use of all energy types (non-renewable and renewable, fossil and non-fossil), but does not distinguish between the use of different types of energy. Fossil energy use is a measure of the use of fossil fuels only, including petroleum, natural gas, and coal. Fossil energy use is an important environmental metric but does not account for non-renewable, non-fossil energy use (e.g., uranium). Petroleum is the dominant transportation fuel feedstock of the current global light-duty vehicle fleet, but the petroleum energy use metric does not account for the use of other energy sources, which are important to consider when evaluating PHEVs. The GHG emissions (CO₂, CH₄, and N₂O) are reported in grams CO₂ equivalents (g CO₂-eq) based on 100-year global warming potentials (IPCC, 2006). While life cycle activities associated with vehicle energy use are included in this study, other stages of the vehicle life cycle (manufacture, end-of-life, etc.) are not considered.

3.2.1 Well-to-Tank (WTT) Methods

A WTT analysis is conducted for both petroleum and electricity used by the PHEV. For petroleum, gasoline is assumed (details are provided below). The WTT analysis of petroleum
includes activities related to feedstock recovery, processing, and all transportation stages. For electricity used by the PHEV, various electricity generation scenarios are considered, as described above. The WTT analysis of electricity includes activities related to feedstock recovery, processing, use in the electricity generating facility, transmission and distribution of electricity to the wall outlet, charging of the PHEV, and transportation stages. While the electricity generation scenarios include activities associated with the fuel life cycle, the scenarios do not include activities associated with facility construction, maintenance, decommissioning, or labor. Further, the Ontario electricity generation mix is a scenario and is not meant to represent the actual WTT performance of the Province’s electricity generation mix.

Well-to-tank data are obtained from GREET version 1.8d.1 (ANL, 2011). For gasoline, a 50/50 blend by volume of conventional and reformulated gasoline from crude oil (with a 9.4% share of oil sands products in the crude oil blend) is assumed. These are the default gasoline specifications assumed in GREET version 1.8d.1. Scenario analyses are conducted for 100% conventional and 100% reformulated gasoline produced from crude oil without oil sands products. Gasoline WTT energy use and GHG emissions data are obtained from the “Petroleum” worksheet, where “Crude for use in U.S. Refineries” is assumed for the feedstock. For electricity, WTT energy use and GHG emissions are obtained from the “Electric” worksheet. For hydroelectricity and wind electricity, GREET does not take into account efficiency losses associated with conversion of primary energy (i.e., flowing water, moving air) to electrical energy. In other words, for those renewable electricity options, it is assumed that one kWh of total energy is used per one kWh of electricity generated. This assumption is similar to that used by Creutzig et al. (2009). For nuclear electricity, a 35% electricity generation efficiency is assumed (GHGenius, 2011). For all electricity generation scenarios, the transmission and distribution efficiency is assumed to be 92%. This is the default assumption in GREET and GHGenius (ANL, 2011; GHGenius, 2011). Charging efficiency is assumed to be 90% (Kromer and Heywood, 2007).

3.2.2 Tank-to-Wheel Methods

Modeling of the TTW energy use was conducted as described in Chapter 2. Driving cycles were developed for routes of identical driving time but varying driving distance and orientation within the Greater Toronto Area, using a novel travel demand modeling approach. By keeping driving
time constant but varying driving distance, a trend across driving cycles was produced in which driving distance is directly related to driving speed and inversely related to measures of congestion [coefficient of variation of speed (i.e., congestion related fluctuation in speed), time percentage of driving cycle spent idling, and number of stops in the driving cycle]. These driving cycles represent a wide range of driving patterns, and are categorized as follows:

1. **City (C):** short distance, low speed, congested; no highway driving.

2. **Suburban (SU):** intermediate distance, speed, and congestion; some congested highway driving.

3. **Highway (HWY):** long distance, high speed, and uncongested; primarily uncongested highway driving.

Since driving cycles were used to represent driving patterns, the two terms are used interchangeably in this chapter. For quantitative characteristics of each driving cycle, refer to Table 2.1.

For each driving cycle (comprised of both the AM and PM trips as described in Chapter 2), Autonomie vehicle performance simulation software was used to estimate the TTW energy use of two PHEVs, a HEV, and an ICEV (Autonomie, 2011). Details of those methods are provided in Section 2.2.3. The TTW data for the series PHEV is used for the WTW analysis in this chapter.

The petroleum energy use data obtained from modeling of the TTW stage is used in place of the default fuel consumption data in GREET to determine the TTW energy use and GHG emissions from gasoline combustion.

### 3.3 Results and Discussion

#### 3.3.1 Driving Patterns

Driving patterns (i.e., driving distance and driving conditions) affect the WTW performance of PHEVs in two ways. First, driving distance determines the proportions of electricity and
gasoline involved in propelling the PHEV. Second, driving conditions affect TTW energy use per VKT. Since all WTW activities are normalized by one VKT (the functional unit), driving conditions determine the magnitude of energy use and GHG emissions from each WTW stage. This effect of driving conditions on WTW performance applies to all vehicle technologies.

Driving patterns affect TTW energy use of the different vehicle technologies in unique ways. Relevant TTW energy use results from Chapter 2 are shown in Table 3.1 and are summarized below.

- **PHEV**: Both driving distance and driving conditions contribute to a trend in which average petroleum energy use per kilometer is lowest for the city driving patterns and is highest for the highway driving patterns. In terms of driving distance, for the short distance city driving patterns all VKT occur in CD mode, while for the long distance highway driving patterns most VKT occurs in CS mode (for the same reason, average electrical energy use per kilometer is highest for the city driving patterns and lowest for the highway driving patterns). Some petroleum energy is still used during the city driving patterns because the ICE turns on if the power demands of the driving cycle exceed the rated power of the battery or electric motor. This finding is consistent with observations in previous research (Kwon et al., 2008; Markel, 2006). In terms of driving conditions, fuel efficiency of the PHEV is higher during the low speed and congested city driving patterns than during the high speed and uncongested highway driving patterns.

- **HEV**: Only driving conditions contribute to a trend in which petroleum energy use per kilometer is lower for the city driving patterns than for the highway driving patterns. As with the PHEV, fuel efficiency of the HEV is higher during the low speed and congested city driving patterns than during the high speed and uncongested highway driving patterns.

- **ICEV**: Opposite to the PHEV and HEV trends, driving conditions contribute to a trend in which petroleum energy use per kilometer is higher for the city driving patterns than for the highway driving patterns. Fuel efficiency of the ICEV is lower during the low speed and congested city driving patterns than during the high speed and uncongested highway driving patterns.
Table 3.1. TTW energy use estimates used in this chapter. PHEV estimates are based on the analysis of the series PHEV in Chapter 2. Similar data for the split PHEV is provided in Appendix A.

<table>
<thead>
<tr>
<th>Driving Cycle</th>
<th>PHEV</th>
<th>HEV</th>
<th>ICEV</th>
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<tr>
<td></td>
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<td>Gasoline (L/100 km)</td>
<td>Gasoline (L/100 km)</td>
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<td>135</td>
<td>1.1</td>
<td>6.1</td>
</tr>
<tr>
<td>C2</td>
<td>129</td>
<td>1.6</td>
<td>6.9</td>
</tr>
<tr>
<td>C3</td>
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<td>1.9</td>
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</tr>
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<tr>
<td>HWY2</td>
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</tr>
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</table>

Specific impacts of driving patterns on the WTW energy use and GHG emissions of PHEVs depend on the electricity generation supply involved in charging. These interactions between driving patterns and the electricity generation supply, as well as the implications for WTW energy use and GHG emissions of a PHEV relative to those of a HEV and an ICEV are described below for all metrics. Unless otherwise stated, all results below are on a WTW basis.

### 3.3.2 Well-to-Wheel Total Energy Use

Well-to-wheel total energy use for all driving patterns and PHEV charging scenarios is shown in Figure 3.1. Regardless of the charging scenario, total energy use of the PHEV is lowest for the city driving patterns (C1-C3) and is generally highest for the highway driving patterns (HWY1-HWY2). Regardless of the driving pattern, total energy use of the PHEV is lowest for the hydroelectric scenario and is highest for the coal scenario. For each charging scenario, total energy use of the PHEV is determined by that of the corresponding electricity pathway. Electric propulsion (i.e., electricity powered movement of the PHEV during CD mode) results in 66% lower total energy use for the hydroelectric scenario than for the coal scenario. Since the charging scenario determines total energy use during electric propulsion, the charging scenario also determines the extent to which driving distance affects total energy use of the PHEV. This is demonstrated by comparing, across charging scenarios, total energy use between driving pattern C1 (all VKT in CD mode) and HWY2 (lowest fraction of VKT in CD mode). For the
hydroelectric scenario, total energy use is 59% lower for C1 than for HWY2; for the coal scenario, total energy use is only 29% lower for C1 than for HWY2. Thus, driving distance can have a large impact on total energy use of PHEVs when charging from hydroelectricity due to the corresponding low energy use of CD mode driving, but has a much smaller impact when charging from coal-based electricity due to the relatively high energy use of CD mode driving.

![Figure 3.1. WTW total energy use of the vehicles across driving patterns and PHEV charging scenarios. Light portions of PHEV results represent total energy use associated with electric propulsion. Dark portions represent total energy use associated with gasoline propulsion.](image)

Well-to-wheel total energy use for the Ontario electricity generation mix and NGCC scenarios is slightly lower than that for the coal scenario. The Ontario electricity generation mix has a large nuclear fraction. These facilities (on a per kWh-generated basis) have higher electricity generating station efficiencies than coal boiler facilities. For the NGCC scenario, NGCC facilities have substantially higher efficiencies than coal boiler facilities but natural gas also has higher energy use associated with fuel production (fuel cycle) than coal.

Well-to-wheel total energy use of the PHEV relative to that of the HEV and ICEV depends on both driving patterns and the charging scenario. For the hydroelectric scenario, reductions in total energy use for the PHEV relative to the HEV and ICEV are highest for the city driving
patterns and lowest for the highway driving patterns. This is the case because, for the short distance city driving patterns, all VKT of the PHEV occur in CD mode, which results in very low total energy use when charging from hydroelectricity. Further, the city driving conditions (i.e., low speed and congested) result in a large difference in fuel efficiency between the PHEV and ICEV. For the long distance highway driving patterns, a small fraction of VKT occurs in CD mode and the highway driving conditions (i.e., high speed and uncongested) result in a small difference in fuel efficiency between the PHEV and ICEV. For the coal scenario, total energy use of the PHEV is essentially the same as that of the HEV for all driving patterns. PHEVs charging from coal-based electricity use less total energy than ICEVs for the city and suburban driving patterns, but this reduction occurs due to differences in fuel efficiency between those two vehicles and not due to electric propulsion. In summary, the electricity generation supply involved in charging of a PHEV clearly determines the reductions in total energy use that PHEVs can achieve relative to HEVs and ICEVs.

### 3.3.3 Well-to-Wheel Fossil Energy Use

Well-to-wheel fossil energy use for all driving patterns and PHEV charging scenarios is shown in Figure 3.2. With respect to the driving patterns, fossil energy use of the PHEV is lowest for the city driving patterns and is generally highest for the highway driving patterns. As expected, fossil energy use is lowest for the hydroelectric scenario and is highest for the coal scenario. For the hydroelectric scenario, electric propulsion does not involve any fossil energy use (assuming activities involved in facility construction, maintenance, decommissioning, and labor are excluded from the system boundary). Consequently, the PHEV charging from hydroelectricity and operating in CD mode only uses fossil energy when petroleum is used by the ICE. For the coal scenario, fossil and total energy use of electric propulsion are essentially equal because almost all energy used in that electricity pathway is fossil based. Thus, driving distance can potentially have a larger impact on fossil than total energy use of PHEVs because electric propulsion can involve electricity generation sources that do not use any fossil energy.
Well-to-wheel fossil energy use for the Ontario electricity generation mix and NGCC scenarios falls between that of the hydroelectric and coal scenarios. Fossil energy use for the Ontario electricity generation mix scenario is only slightly higher than that of the hydroelectric scenario because little fossil energy is used in the nuclear fuel cycle (and more generally in the Ontario electricity generation mix). For the NGCC scenario, fossil and total energy use are essentially equal because almost all of the energy used in the NGCC pathway is fossil based.

Well-to-wheel fossil energy use of the PHEV relative to that of the HEV and ICEV depends on both driving patterns and the charging scenario. The hydroelectric scenario results in substantial reductions in fossil energy use relative to the HEV and ICEV for all driving patterns. For the hydroelectric scenario, fossil energy use of the PHEV is 82% lower than that of the HEV and 89% lower than that of the ICEV for C1; fossil energy use of the PHEV is 27% lower than that of the HEV and 30% lower than that of the ICEV for HWY2. These reductions are greater than those for total energy use because fossil energy is not used in the hydroelectricity pathway. For the coal scenario, the trends in fossil energy use of the PHEV relative to the HEV and ICEV are equivalent to the trends in total energy use. Overall, charging PHEVs from low fossil electricity can result in substantial fossil energy use reductions relative to HEVs and ICEVs for short
distance driving patterns. Charging PHEVs from coal boiler facilities, however, does not result in reductions in fossil energy use relative to HEVs, and only results in reductions relative to ICEVs under certain driving conditions.

3.3.4 Well-to-Wheel Petroleum Energy Use

Unlike with WTW total and fossil energy use, WTW petroleum energy use of the PHEV is insensitive to the electricity generation scenario because of the extremely small amount of petroleum energy used in all examined electricity pathways. Petroleum energy use of all vehicles only depends on driving patterns. Petroleum energy use of the PHEV is 82% lower than that of the HEV and 89% lower than that of the ICEV for C1; petroleum energy use of the PHEV is 27% lower than that of the HEV and 30% lower than that of the ICEV for HWY2. PHEVs can achieve petroleum energy use reductions relative to both HEVs and ICEVs through CD mode driving, in which petroleum is displaced by electricity as a transportation fuel, and can achieve further reductions relative to ICEVs under driving conditions that result in fuel efficiency differences between PHEVs and ICEVs. These reductions are insensitive to the electricity generation supply, except when an oil-fired electricity generating facility is in the supply mix.

3.3.5 Well-to-Wheel GHG Emissions

Well-to-wheel GHG emissions for all driving patterns and PHEV charging scenarios are shown in Figure 3.3. As with total and fossil energy use, GHG emissions of the PHEV are lowest for the city driving patterns with hydroelectric charging and are generally highest for the highway driving patterns with coal charging. For the hydroelectric scenario, electric propulsion does not involve any GHG emissions (based on the assumed system boundary). For that scenario, GHG emissions trends across driving patterns correspond to those for fossil energy use because the hydroelectricity pathway does not involve GHG emissions or fossil energy use; both GHG emissions and fossil energy use are 81% lower for C1 than for HWY2. For the coal scenario, however, GHG emissions are only 16% lower for C1 than for HWY2 (compared to 28% for fossil energy use). More so than with energy use (total, fossil, or petroleum), the electricity generation supply determines the extent to which driving distance affects GHG emissions of PHEVs. Driving distance has a large impact on GHG emissions of PHEVs when charging from hydroelectricity due to the corresponding lack of GHG emissions associated with electric
propulsion, but has a marginal impact when charging from coal-based electricity due to the high GHG emissions intensity of that pathway.

![Figure 3.3. WTW GHG emissions of the vehicles across driving patterns and PHEV charging scenarios. Light portions of PHEV results represent GHG emissions associated with electric propulsion. Dark portions represent GHG emissions associated with gasoline propulsion.](image)

Well-to-wheel GHG emissions for the Ontario electricity generation mix and NGCC scenarios are generally closer to those for the hydroelectric scenario than the coal scenario. For the Ontario electricity generation mix scenario, the nuclear fuel cycle (and Ontario electricity generation mix in general) involves low fossil energy use, and therefore low GHG emissions. The NGCC scenario results in much lower GHG emissions than the coal scenario, beyond the difference in fossil energy use between those two scenarios, because natural gas also has a lower carbon content than coal (14 vs. 25 kg C/GJ).

Well-to-wheel GHG emissions of the PHEV relative to those of the HEV and ICEV depend on both driving patterns and the charging scenario. For the hydroelectric and Ontario electricity generation scenarios, reductions in GHG emissions of the PHEV relative to the HEV and ICEV resemble those for fossil energy use. For the NGCC scenario, reductions in GHG emissions of the PHEV relative to the HEV and ICEV are greater than those for fossil energy use due to the
low carbon content of natural gas. For the coal scenario, GHG emissions of the PHEV are greater than those of the HEV for all driving patterns, and are greater than those of the ICEV for the highway driving patterns. Charging PHEVs from low fossil electricity or NGCC can result in substantial GHG emissions reductions relative to HEVs and ICEVs for short distance driving patterns. Charging PHEVs from coal boiler facilities, however, does not result in GHG emissions reductions relative to HEVs, and only results in reductions relative to ICEVs under certain driving conditions. Further, for highway driving conditions, PHEVs charging from coal boiler facilities can potentially result in larger GHG emissions than ICEVs.

3.3.6 WTT versus TTW energy use and GHG emissions

For gasoline propulsion, the WTT stage is responsible for only a small proportion of WTW energy use and GHG emissions (17% of WTW total energy use, 16% of WTW fossil energy use, 8% of WTW petroleum energy use, and 19% of WTW GHG emissions). Scenario analyses for 100% conventional and 100% reformulated gasoline produced from crude oil without oil sands products do not affect these general trends or the overall WTW results.

For electric propulsion, the contributions of the WTT stage to WTW energy use and GHG emissions depend on the metric and electricity generation scenario. The WTT stage is responsible for all GHG emissions of the PHEV from electric propulsion, because electric propulsion does not involve any tailpipe emissions. In general, activities upstream of electricity generation represent small portions of WTW energy use and GHG emissions of the PHEV from electric propulsion.

3.4 Conclusions

This chapter demonstrates important interactions between driving patterns and the electricity generation supply that affect the WTW energy use and GHG emissions of PHEVs and have implications for informing environmentally beneficial usage and adoption patterns for these vehicles. Relative to previous studies, this chapter more comprehensively investigates the implications of driving patterns on the WTW energy use and GHG emissions of PHEVs, and is the first WTW analysis that employs TTW data obtained using driving cycles developed from a macroscopic traffic assignment model. Regardless of the electricity generation supply, short
distance, low speed, and congested driving results in lower WTW energy use and GHG emissions of PHEVs than long distance, high speed, and uncongested driving. Frequent charging (i.e., short distance driving) results in the lowest WTW energy use and GHG emissions of PHEVs in regions that have favorable electricity generation supplies (i.e., energy efficient, low in fossil energy use, and low in GHG emissions). Within regions, PHEVs can have lower energy use and GHG emissions if charging occurs when the marginal electricity generation supply is favorable (e.g., natural gas on the margin in a region otherwise dominated by coal). Irrespective of the electricity generation supply, PHEVs are likely to achieve larger reductions in WTW energy use and GHG emissions compared to ICEVs for city driving conditions (i.e., low speed and congested) than for highway driving conditions (i.e., high speed and uncongested). Under the least favorable electricity generation circumstances (e.g., 100% coal), PHEVs do not reduce WTW energy use and GHG emissions relative to HEVs or ICEVs due to CD mode driving, but reduce WTW energy use and GHG emissions relative to ICEVs under relatively favorable driving conditions.

The following simplified calculations do not account for important considerations related to travel trends, electricity supply characteristics, and other aspects but are included for perspective. If 5% of the USA light-duty vehicle fleet drives in congested city conditions that resemble the C1 driving cycle in this thesis, then replacing ICEVs from that portion of the light-duty vehicle fleet with PHEVs charging from hydroelectricity would reduce GHG emissions by about 49 million metric tonnes/year, or about 4.5% of the GHG emissions from the Nation’s light-duty vehicle fleet (TRB, 2011; Davis et al., 2010; DOT, 2009). If those PHEVs charge from coal boiler facilities, however, then reductions in GHG emissions from the nation’s light-duty vehicle fleet would only be about 1.3%. Further, PHEVs charging from coal boiler facilities and used for uncongested highway driving that resembles the highway driving cycles (HWY1 and HWY2) would not reduce GHG emissions from the light-duty vehicle fleet. Thus, jurisdictions that are generally characterized as having a favorable electricity generation supply and frequent traffic congestion should be most willing to support PHEVs on the basis of their energy use and GHG emissions benefits. In contrast, extensive support for PHEVs on the basis of their environmental benefits should be limited in jurisdictions dominated by coal power and characterized by uncongested highway driving.
While it is important to analyze the WTW energy use and GHG emissions of PHEVs, displacing petroleum with electricity as a transportation fuel requires consideration of additional energy, environmental, and economic aspects. Charging PHEVs from hydroelectricity can only occur in regions that have significant hydroelectric resources. Other renewable electricity generation options may have similar resource restrictions. Charging PHEVs from natural gas involves the use of a non-renewable fossil energy resource. Charging PHEVs from coal has questionable environmental benefits, and coal dominates the marginal electricity supply for charging of PHEVs in many regions of the USA (Kromer and Heywood, 2007; Elgowainy et al., 2009). Other electricity generation scenarios not considered in this study would produce different results. In particular, oil-fired power in the electricity generation supply affects the WTW petroleum energy use of PHEVs. Other environmental aspects not evaluated in this study are also important to consider. PHEVs could transfer tailpipe air pollutant emissions from regions of high population density (i.e., cities) to electricity generating facility emissions in regions of lower population density (i.e., rural areas). On the other hand, production of PHEV batteries results in air pollutant emissions that do not occur during production of non-plug-in vehicles (Notter et al., 2010). Further, policies that reduce demand for light-duty vehicle travel are necessary in addition to technological transitions in the light-duty vehicle fleet to meet 2050 GHG emissions reductions goals and to achieve substantial transportation sector energy use reductions (TRB, 2011; Sager et al., 2011). Regarding economic aspects, since PHEVs displace petroleum with electricity their operating costs are generally lower than those of HEVs and ICEVs, but their capital costs are substantially higher due to the high costs of their batteries and other components (NAS, 2010).

3.5 Summary

- I examined impacts of driving patterns on the WTW energy use and GHG emissions of PHEVs and interactions between driving patterns and the electricity generation supply that affect this WTW performance.

- The WTW energy use and GHG emissions of PHEVs were found to be lower for the city than highway driving patterns, regardless of the electricity generation supply.
• However, the extent to which driving patterns affect the WTW performance of PHEVs depended on the electricity generation supply.

• When charging from hydroelectricity, large differences in WTW performance were observed across driving patterns; when charging from coal, these differences were relatively small.

• When charging from coal, PHEVs were not found to reduce WTW energy use or GHG emissions relative to non-plug-in alternatives due to short distance driving (i.e., electric propulsion), and only reduced WTW energy use and GHG emissions relative to ICEVs due to differences in vehicle fuel efficiency associated with driving conditions.
3.6 References


Chapter 4
Conclusions

4.1 Key Findings and Contributions

This thesis integrated travel demand modeling and life cycle assessment techniques. I demonstrated a novel application of a travel demand modeling approach to estimate regional driving patterns for evaluating the tank-to-wheel (TTW) energy use of plug-in hybrid electric vehicles (PHEVs), and used this approach to examine impacts of driving patterns on the well-to-wheel (WTW) energy use and greenhouse gas (GHG) emissions of those vehicles. This travel demand modeling approach was demonstrated for the Greater Toronto Area over a range of driving patterns. The approach incorporated information about trip distances, road types used, average speeds encountered, and congestion conditions to estimate TTW energy use of PHEVs. The TTW energy use estimates were then applied within a WTW analysis to demonstrate how driving patterns and the electricity generation supply interact to affect the WTW energy use and GHG emissions of PHEVs and how these interactions influence the WTW performance of PHEVs relative to that of similar hybrid electric vehicles (HEVs) and internal combustion engine vehicles (ICEVs).

Chapter 2 demonstrated the travel demand modeling approach for estimating TTW energy use of PHEVs. A macroscopic traffic assignment model linked with a vehicle motion model (i.e., the CALMOB6-based approach) was used to estimate driving cycles for selected commutes of constant duration within the Greater Toronto Area. These commutes represented a wide range of driving patterns from short distance, low speed, and congested (i.e., city) to long distance, high speed, and uncongested (i.e., highway). The estimated driving cycles were imported into vehicle performance simulation software to determine the impacts of the corresponding driving patterns on the TTW energy use of two PHEVs, a HEV, and an ICEV. The energy use trends followed those expected for a constant commute duration assumption: the city driving patterns resulted in the lowest TTW petroleum energy use of the PHEVs and HEV, while the highway driving patterns resulted in the lowest TTW petroleum energy use of the ICEV. These opposite trends resulted in the largest petroleum savings for the PHEV relative to the ICEV on the city driving
patterns and the smallest savings on the highway driving patterns. Further, the driving cycles developed by using the CALMOB6-based approach produced a reasonable range of TTW energy use estimates relative to those produced using certification driving cycles. Thus, the novel approach demonstrated in Chapter 2 can be used to estimate driving cycles for specific regional driving patterns in order to examine implications of those driving patterns on the TTW energy use of PHEVs and other vehicles. Further, the general methods used in Chapter 2 to evaluate a workplace charging scenario can also be used to conduct more comprehensive scenario analyses (as described below in Section 4.2).

Chapter 3 incorporated the TTW energy use data from Chapter 2 within a WTW analysis to evaluate implications of driving patterns on the WTW energy use and GHG emissions of PHEVs. Well-to-tank models were developed for petroleum as well as four different electricity generation scenarios: hydroelectric, natural gas (combined cycle), coal (boiler), and the Ontario average electricity generation mix. Regardless of the electricity generation supply, the city driving patterns resulted in lower WTW energy use and GHG emissions of a PHEV than the highway driving patterns. Driving a PHEV for short distances was found to result in substantial reductions in WTW energy use and GHG emissions relative to driving long distances under certain electricity generation scenarios (e.g., hydroelectricity and natural gas), but not under others (e.g., coal). Further, I found that a PHEV reduces WTW energy use and GHG emissions relative to a HEV and an ICEV due to short distance driving when charging from hydroelectricity, natural gas, or the Ontario average electricity generation mix but not when charging from coal. When charging from coal, a PHEV only reduces WTW energy use and GHG emissions relative to an ICEV under relatively favorable driving conditions (e.g., city) due to differences in fuel efficiency of the vehicles. These findings indicate that frequent charging (i.e. short distance driving) is most beneficial for WTW energy use and GHG emissions of PHEVs in regions that have favorable electricity generation supplies (i.e., energy efficient, low in fossil energy use, and low in GHG emissions). Within regions, PHEVs can have lower WTW energy use and GHG emissions if charging occurs when the marginal electricity generation supply is favorable (e.g., natural gas on the margin in a region otherwise dominated by coal). Thus, jurisdictions that are generally characterized as having favorable electricity generation supplies and frequent traffic congestion should be most willing to support PHEVs on the basis of their energy use and GHG emissions benefits. To my knowledge, Chapter 3 is the first WTW
analysis that employs TTW data obtained using driving cycles developed from a macroscopic traffic assignment model and that comprehensively investigates implications of driving patterns on the WTW energy use and GHG emissions of PHEVs.

4.2 Future Research

Based on the research conducted for this thesis, the following is a list of possible future research directions:

- Further evaluation and calibration of the CALMOB6 vehicle motion model. While the CALMOB6 vehicle motion model has been calibrated based on TTW energy use estimates obtained using a microscopic traffic assignment model, it nonetheless employs aggressive assumptions about the impacts of congestion on speed fluctuation that may not correspond to the fluctuations in speed that typically occur at similar levels of congestion in real world conditions. Further, the CALMOB6 vehicle motion model was calibrated for an ICEV but not for hybrid vehicles, which may respond differently to the assumptions of the model. Future research could therefore involve modifications to the assumptions of the vehicle motion model such that it more closely reflects actual driving behaviors.

- Application of the CALMOB6-based approach to other commutes and jurisdictions. While only the Greater Toronto Area was considered in this study, other jurisdictions for which a regional travel demand model is available can similarly be examined taking into account their local characteristics.

- More comprehensive scenario analyses. Using the (disaggregated) Transportation Tomorrow Survey and the Emme 3 Greater Toronto Area traffic assignment model, it would be possible to evaluate region-wide energy and environmental implications of different levels of PHEV market penetration and charging scenarios (e.g., home only, home and work, home/work/shopping). To estimate the marginal electricity sources assumed for charging at different levels of PHEV market penetration and at different times of day, economic dispatch models could be developed for the current Ontario
electricity supply as well for future scenarios (Peterson et al., 2011; Blumsack et al., 2008). However, a region-wide analysis would likely require simplifying assumptions of TTW energy use of PHEVs (i.e., not involving CALMOB6 and Autonomie for driving cycle estimation and analysis of each trip).

- Inclusion of additional environmental metrics and life cycle activities. Additional environmental metrics that may be significantly affected by driving patterns include air pollutant emissions as well as water consumption and withdrawal. Significant life cycle activities that have not been considered in this thesis include those related to battery and vehicle production and disposal. Battery production is particularly important to consider because batteries are the primary marginal component of PHEVs when compared to HEVs and ICEVs and their production results in substantial energy use and GHG emissions (Samaras and Meisterling, 2008; Notter et al., 2010).

- Examination of financial implications of driving patterns and technology choice, taking into account driving conditions (i.e., the driving cycle) as well as driving distance between recharging. Initial operating cost estimates for each vehicle and driving pattern examined in this thesis are provided in Appendix B.
4.3 References


### Appendices

Appendix A

### Additional Data

**Table A.1.** TTW energy use estimates for the split PHEV for each commute.

<table>
<thead>
<tr>
<th>Driving Cycle</th>
<th>PHEV</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Electricity</td>
<td>Gasoline</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Wh/km)</td>
<td>(L/100 km)</td>
</tr>
<tr>
<td>C1</td>
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</tr>
<tr>
<td>C2</td>
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</tr>
<tr>
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<td></td>
</tr>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>HWY2</td>
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<td></td>
</tr>
</tbody>
</table>
Appendix B

Operating Cost Estimates

Preliminary operating cost estimates are shown in Figure B.1 and are produced using the following electricity assumptions:

- Electricity costs (¢/kWh) (Toronto Hydro, 2011):
  - Off-peak charge: 5.9
  - On-peak charge: 10.7
  - Transmission charge: 1.216
  - Distribution charge: 1.271
  - Regulatory asset recovery rate rider: -0.232
  - Wholesale operations charge: 0.65
  - Debt retirement charge: 0.7

- Electricity adjustment factor (i.e., transmission and distribution efficiency): 0.92
- Electricity charging efficiency: 0.9
- Fixed electricity costs are not included.
- Potential PHEV-specific electricity costs and taxes (e.g., fuel taxes) are not considered.
- Insurance, depreciation, repair, and maintenance costs are also not considered.
Figure B.1. Operating cost estimates for the vehicles across driving patterns, assuming A) $1/L gasoline, and B) $2/L gasoline. In both cases, off-peak charging of the PHEVs is assumed and uncertainty bars represent the change in operating cost of the PHEVs if on-peak charging is assumed.

References

Toronto Hydro, 2011. Electricity Rates