Impact of Real-World Powertrain and Commute Patterns on Plug-in Hybrid Electric Vehicle Return-on-Investment

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1.0 Introduction

Plug-in Hybrid Electric Vehicles (PHEVs), which are partially powered by grid electricity instead of fossil fuel, have been identified as possible solutions to issues such as energy independence, climate change, and rising oil prices [1]. The United States is already importing 57% of its petroleum needs and is increasingly concerned about its dependence on imported petroleum [2]. In addition, the United States Energy Information Administration expects oil prices to increase over 60% in real terms between now and 2035, suggesting gas prices are likely to continue to rise [3]. Furthermore, Canada and the United States have both pledged at the Copenhagen Accords to reduce their 2020 GHG emissions by 17% compared to the 2005 base year [4]. Studies have shown that a large proportion of GHG emissions in both countries is attributable to transportation [5, 6].

Studies have shown that 60% of daily trips made in the United States are 50km or less [1]. In Canada, the estimated average straight-line commute distance is 7.6 km, which is approximately 10 km "Manhattan" distance [7]. Widespread PHEV adoption could mean a large portion of petroleum currently used to power these trips can be replaced with grid electricity. Combined with broader clean energy strategies, such as the Ontario Green Energy Act and recent US clean energy policies [8,9], PHEV adoption can help both countries reduce fossil fuel dependence and hit emissions reduction targets.

However, the impact PHEVs can have on the aforementioned issues is dependent on the level of consumer adoption. A consumer's decision to purchase a PHEV depends not only on the potential fuel savings but also if this reduction in operating cost is enough to justify the initial investment. Thus, a series of "tank-to-wheel" sensitivity analyses of different power-train configurations and driving cycles were undertaken to assess how the two factors jointly affect PHEV performance, and thus the attractiveness of PHEVs to consumers. The results of these analyses were then used as input to a Return-on-Investment analysis that helped determine potential PHEV demand.

2.0 PHEV Background

A PHEV combines the internal combustion engine of a conventional vehicle with an electric motor and battery pack, allowing a significant portion of trips to be powered by grid electricity alone. The majority of PHEVs couple the engine and electric motors in a split/parallel architecture, whereby the vehicle can be powered by only the electric motors, only the internal combustion engine, or by both simultaneously [10]. Vehicles featuring this type of architecture include the Toyota Prius PHEV [11]. PHEVs may also be designed in a series configuration, whereby the vehicle is driven by the electric motor only. Once the batteries are depleted, a small internal combustion engine powers a generator that in turn powers the electric motor.

There are four operating modes of that govern the usage of the electric motor and/or engine [10]:

- *Charge-Depleting Mode,* where the electric motor is on and powering the vehicle, hence depleting the charge in the battery. The engine may also provide power depending on vehicle demand.
- *Charge-Sustaining Mode,* where the vehicle is operated such that the state-of-charge in the battery pack is kept within a range of a specified "target SOC". In this mode, the engine provides the net energy needed for propulsion.
- *EV-only Mode,* where only the electric motor is on and thus no liquid fuel is consumed.
- *Engine-only Mode,* where only the engine is on and liquid fuel provides the propulsive energy of the vehicle.

The set of the operating modes and conditions in which they are employed comprise a PHEV's energy management or control strategy. For a PHEV in a split/parallel configuration, the vehicle typically starts in a charge depleting mode until a threshold state-of-charge is reached, at which point the vehicle enters a charge sustaining mode of operation.

3.0 Literature Review

In an extensive "well-to-wheels" study, the Electric Power Research Institute (EPRI) examined greenhouse gas emissions from both the electricity generation to charge the PHEV batteries and vehicle's consumption of liquid fuels [12]. They conclude that any meaningful level of PHEV adoption will result in a substantial decrease in GHG emissions by 2050. Even in their "worst-case" scenario, they estimate an annual GHG reduction 163 million tonnes compared to the 2006 base year [12].

Likewise, Samaras and Constantine report that PHEVs can reduce "use-phase" GHG emissions by up to 48% compared to conventional vehicles [1]. They caution, however that the overall impact of PHEV adoption may actually *increase* lifetime GHG emissions under a carbon-intensive electricity generation mix [1].

Furthermore, after investigating the performance of different PHEVs in real-world driving conditions, the Argonne National Laboratory concluded that liquid fuel consumption decreased linearly with available electrical energy [13] consistent with findings by Shiau [14] and Hauffe [15]. This suggests consumer behaviour – i.e., willingness to "plug in" – plays an important role in real-world PHEV performance.

However, one concern about the studies conducted by Shiau and Hauffe is that the standard EPA urban driving cycle was merely repeated until the desired charge distance was achieved [14,15]. In most cases, long trips are expected to be a mix of both highway and city driving, not exclusively urban as repeating the UDDS would suggest.

In addition, recent product announcements by Toyota, Chevrolet, Ford and Volvo indicate that first generation PHEVs will have all-electric ranges of 13-31 miles [11, 16, 17, 18] – much shorter than the 40- and 60-mile AERs assumed in recent literature.

4.0 Methodology

The main focus of this study is to determine the potential fuel savings through PHEV adoption. Studies show that consumers are willing to pay $2-$5 for every $1 of annual fuel savings, but only 80 cents for every $1 in annual savings in maintenance costs [19]. Thus, it is assumed that fuel savings will be the main driver towards fuel efficiency adoption.

While the Society of Automotive Engineers recommends the SAE J1711 method for calculation fuel consumption of HEVs and PHEVs, Silva et al have identified several key shortcomings of applying the method for other standard driving cycle and instead propose a more generic methodology [20]. This study adapts the methodology proposed by Silva for use with US and Canadian driving cycles:

- Repeat the driving cycle for Charge-depleting (CD) mode of operation only until the battery state-of-charge (SOC) reaches the charge sustaining level for charge-sustaining (CS) mode
- Repeat the driving cycle for CS mode operation only until final SOC is within 5% of target SOC
- Calculate the combined fuel consumption assuming equal probability of CS and CD modes of operation.

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Vehicles are specified in a manner that best reflects "representative" choices available to the consumer and based on what is reported to the automotive press. Powertrain configurations are then validated using the 0-60mph acceleration and EPA Combined Driving Cycle tests. The resulting acceleration times and fuel economy figures are then compared those reported in the automotive press. The process is repeated until the values converge.

The powertrain configurations developed are summarized in Tables 1 and 2. Consideration was given to create a representative set of

PHEVs available for sale in the near future – the chosen configurations have all been announced in the automotive press.

Table 1 Conventional vehicle configurations, based on data reported in automotive press [21]

Vehicle	**HEV**	**Compact**	**Midsized**	**SUV**
Chassis	Toyota Prius	Honda Civic	Toyota Camry	Ford Escape
Drag Area (m^2)	0.585	0.654	0.696	1.076
Engine Power (kW)	57	104	124	127
Gearbox	Planetary	5 speed auto	6 speed auto	6 speed auto
Battery Pack	1.3 kWh	N/A	N/A	N/A
Vehicle Mass (kg)	1449	1221	1480	1511

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Table 2 Vehicle configurations for PHEV vehicle types, based on data reported in automotive press [11], [17]

Vehicle	**Prius**	**Volt**	**Camry**	**Escape**
Chassis	Toyota Prius	Volt PHEV	Toyota Camry	Ford Escape
Drag Area (m^2)	0.585	0.630	0.672	0.696
Engine Power (kW)	73.00	55.00	110.00	114.00
Motor Power (kW)	60.00	111.00	105.00	70.00
Gearbox	Planetary	Planetary	Planetary	Planetary
Battery Pack	5.2 kWh	16 kWh	10 kWh	10 kWh
Vehicle Mass (kg)	1511	1780	1720	1816

This study utilized standard UDDS, HWFET and EPA Combined Cycles. These are cycles used by the Environmental Protection Agency to simulate urban, highway and combined urban/highway driving in fuel economy tests [22].

In addition, simulated Toronto driving cycles created by Raykin were also used. These cycles are based on survey data from the 2006 Transportation Tomorrow Survey (the household travel survey for Toronto) [23]. Reported trips were assigned using the EMME 3 transportation modelling software [23], from which a representative set of commutes were chosen based on travel distance and desired commute characteristics (urban-urban commute for example) [23]. The driving cycles were then constructed for each commute using the CALMOB6 Vehicle Motion Model [23]. These cycles were chosen to provide insight on how "localized" factors such as commute patterns affect PHEV performance.

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Three representative cycles were chosen for this study: an "urban" commute designed to simulate very aggressive stop-and-go traffic patterns, a "highway" commute that simulates a long-distance commute on mostly uncongested highways and a "suburban" commute representative of a suburban-CBD commute. The driving cycles are summarized in Table 3.

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As can be seen, the Canadian driving cycles have much more aggressive acceleration profiles. The average acceleration of the Canadian cycles varies between 1.44 m/s^2 and 1.69 m/s^2, compared to between 0.22 and 0.55 m/s^2 for the EPA driving cycles. It is expected that fuel efficiency figures would be lower for the Canadian driving cycles due to the higher demands placed on the powertrain.

Table 3 Characteristics of US EPA Driving Cycles Used in Study (speed figures in km/h and acceleration figures are in m/s^2)

	US Drive Cycles			Canadian Drive Cycles		
	UDDS	**HFWET**	**Combined**	**Urban**	**Highway**	**Mixed**
Length (km)	11.99	16.50	28.47	20.12	63.50	32.97
Max Speed	91.25	96.40	96.40	50.63	132.01	111.24
Average Speed	31.05	77.70	48.02	29.09	85.23	46.28
Standard Deviation	23.65	16.25	30.73	17.01	31.71	21.82
Average Acceleration	0.51	0.19	0.39	1.63	1.44	1.69
Standard Deviation	0.52	0.22	0.48	0.74	0.74	0.76

5.0 Results

As exhibited in Figure 1Figure 1, the UDDS driving cycle gives the best overall fuel efficiency, while the Raykin's Highway Cycle gives the worst. This is consistent with the fact that hybrid vehicles have better fuel efficiency in "city" driving cycles because the lower speeds allow for better utilization of the PHEV's all-electric mode. The frequent stop-and-go nature of city-based driving cycles allows for recharging of the batteries through regenerative braking, which effectively increases the battery's range.

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The Volt and Prius generally exhibit the best fuel efficiency performance. The Prius' superior fuel efficiency can be attributed to its lower vehicular mass and small engine. Since overall fuel consumption weighs both charge-depleting and charge-sustaining modes of operation equally, it is expected that a smaller vehicle like the Prius would have better fuel efficiency as it would consume less fuel in charge-sustaining mode.

The Volt's fuel efficiency is better attributed to the fact that its small engine is used to charge the batteries in charge-sustaining mode. This effectively "decouples" the engine operation from the power demands of the vehicle, allowing the engine to always operate at its "optimal" condition, thereby minimizing fuel consumption.

As expected, the fuel consumption of all vehicles is higher for the Raykin's driving cycles as they are longer and place higher demands on the powertrain.

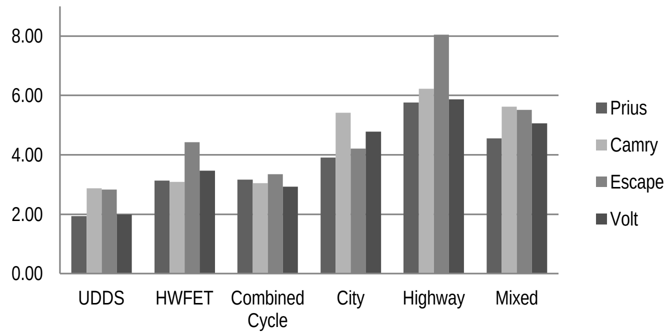

Figure 1 Overall fuel consumption figures (L/100km) for PHEV powertrains studied on US EPA and Canadian driving cycles

As illustrated by Figures 2 and 3, fuel consumption in the CS mode of operation is roughly double that in charge-depleting mode. This is consistent with the fact that vehicles are powered primarily by the engine in CS mode. The gap is even more pronounced for the Canadian cycles and demonstrates the importance of the starting battery charge on PHEV performance.

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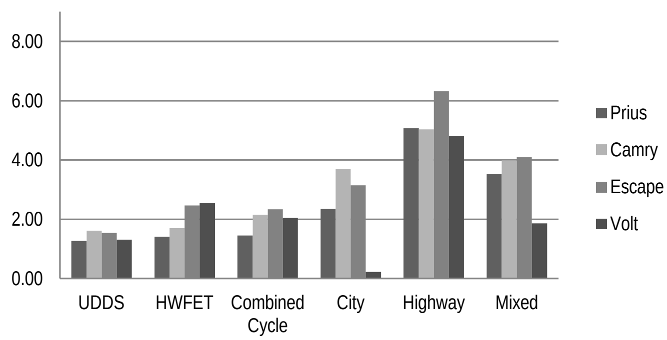

Figure 2 CD-mode fuel consumption figures (L/100km) for PHEV powertrains studied on US EPA and Canadian driving cycles

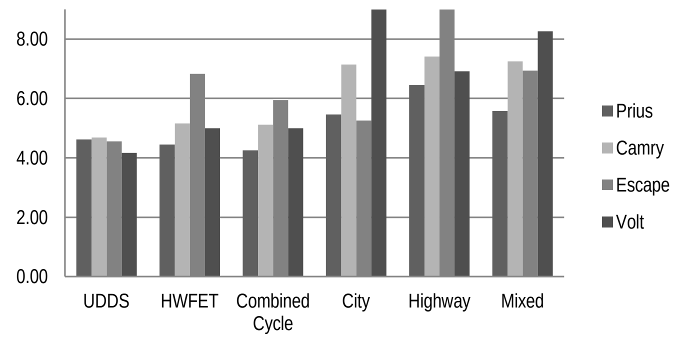

Figure 3 CS-mode fuel consumption figures (L/100km) for PHEV powertrains studied on US EPA and Canadian driving cycles

6.0 ROI Analysis

In order to gauge potential consumer interest in PHEVs, the simulation results were used as input for a preliminary return-on-investment analysis for the PHEV configurations considered.

The price premium of a PHEV is considered an "investment" that yields annual fuel savings. The ratio of annual fuel savings to the initial price premium – defined as the additional cost of a PHEV compared to a functionally-equivalent conventional vehicle – would be a consumer's ROI. For example if a consumer's annual fuel savings as a percentage of the initial price premium were 2% but could get 3% from a by investing in a bond or GIC, then the added initial cost of a PHEV would not be a wise investment. On the other hand, if another consumer has a ROI of 10%, then purchasing a PHEV would be a good financial decision.

For the purposes of this study, government incentive programs were not considered as PHEVs must be economically competitive with conventional vehicles in their own right without government subsidies.

The initial price for the conventional vehicles, HEVs and the Volt were taken to be the Manufacture Suggested Retail Price (MSRP) for

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Comment [M6]: We have to be sure to compare apples to oranges here. To my understanding, financing rate is the annual interest rate that you pay on the amount borrowed. It includes paying interest, but does not include paying off the principal. That is my understanding, though I have never taken out a car loan, so maybe I am making a mistake here.

You are comparing this to annual fuel cost savings as a percentage of investment premium. So say you take a loan out on the premium, you pay interest of 3.9% but you also have to pay back the principal. So your annual payments are much greater than 3.9% of your loan.

So maybe to ensure apples to apples comparison, we say "For example if a consumer's annual fuel savings as a percentage of the initial price premium were 2.5% but the annual loan payments on that premium amounted to 5% of the loan, a PHEV would not be worth the added cost."

Also, 5% is probably an unrealistic number (amounts to a loan amortization of well over 20 years). Can you check what is more typical for a car loan, so we have reasonable numbers in the example?

base trim and automatic transmission as published in the automotive press [16, 24]. The MSRP for other PHEVs were estimated by taking adding $7000 to the price of the corresponding HEV models, the upper end of what Silva estimated the PHEV premium to be [24]. The "ROI" for each PHEV are calculated against CVs and HEVs with "functional equivalence" – which in this case would be the compact, midsized and SUV vehicle classes. The estimated costs for the vehicles studied are summarized above in Table 4.

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The annual distance driven was assumed to be 16,000 km – chosen based on the results of Statistics Canada's Canadian Vehicle Survey, which reported that the average annual distance driven in 2007 was 15,797 km [25].

Three driving behaviours assuming different splits in urban, combined and highway driving were tested. The first assumes predominantly urban driving, the second assumes an equal split between the different driving types and the last assumes predominantly highway driving. They are summarized in Table 5.

Table 4 Summary of vehicle costs used in the ROI analysis, based on [16, 20, 24]. Chevy Volt price premium is based on cost compared to Civic and Prius HEV.

Model	Price ($)	Price Premium ($) (CV/HEV)
Honda Civic	$ 18,580.00	-
Toyota Camry	$ 25,310.00	-
Ford Escape	$ 25,599.00	-
Prius	$ 27,800.00	-
Camry Hybrid	$ 30,900.00	-
Escape Hybrid	$ 38,399.00	-
Chevy Volt	$ 42,000.00	$16,690/$11,100
Prius PHEV	$ 34,800.00	$16,220/$7000
Camry PHEV	$ 37,900.00	$12,590/$7000
Escape PHEV	$ 45,399.00	$19800/$7000

Table 5 Summary of the driving scenarios used in the ROI analysis.

Driving Scenario	1 – Mostly Urban	2 – Urban/Highway Mix	3 – Mostly Highway

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This is for easy cross reference with your new labelling of Figure 4.

	%	km driven	%	km driven	%	km driven
Urban	60%	9,600	33%	5,280	10%	1,600
Combined	30%	4,800	33%	5,280	30%	4,800
Highway	10%	1,600	33%	5,280	60%	9,600

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Three cost assumptions were assumed for the ROI analyses. They were chosen to cover a range of possibilities in both fuel and electricity prices and are discussed below. In all cases, it is assumed the PHEVs are charged at night and thus at off-peak rates.

- *Case 1* – this business-as-usual case assumes fuel and electricity costs. Fuel is assumed to be $1.25 per litre and electricity the current Ontario off-peak cost of 5.1 cents per kWh [26]
- *Case 2* – this high fuel cost case assumes fuel cost to be $2.50 per litre, roughly double what it is currently
- *Case 3* – this high electricity cost case assumes off-peak electricity cost to be 10.2 cents/kWh, double the current rate

The three cost assumptions combined with the three driving assumptions combine to give a total of 9 test scenarios (summarized in Figures 4 and 5~~).~~). ~~The results are summarized below.~~

Table 6 **Summary of the driving scenario/cost scenario case combinations studied in the ROI analysis**

\ Cost Scenario Driving Scenario \	1	2	3
1	Case 1	Case 2	Case 3
2	Case 4	Case 5	Case 6
3	Case 7	Case 8	Case 9

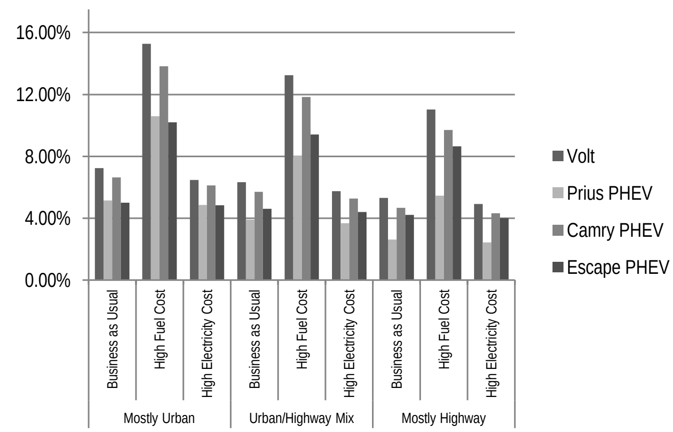

Figure 4 PHEV returns-on-investment as compared to conventional vehicles

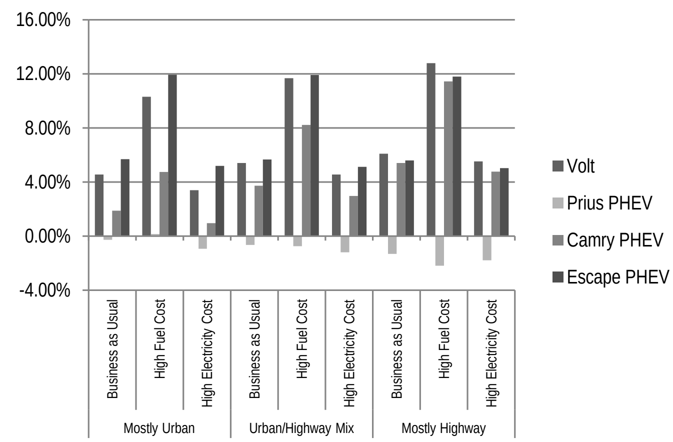

Figure 5 PHEV returns-on-investment as compared to conventional

Unsurprisingly, the ROI for all PHEVs is highest when fuel prices are the highest, maximizing the fuel savings versus a comparable CV or HEV. Fuel savings is by far the most important factor in determining PHEV ROI as even under predominantly urban driving and high electricity costs, electricity consumption is less than 30% of total operating costs. For most cases, it accounts for less than 10% of total operating costs.

Although in some cases the ROI is as high as 15%, a study by Potoglou and Kanaroglou showed that consumers were only willing to pay $2-$5 for every $1 of annual fuel savings [19], thus implying an expected ROI of 20-50%. For the implied ROI over HEVs to reach the 20% threshold, the price premium would have to drop by approximately 60% or the fuel price needs to be 4-8 times today's price. Also implicit in the analysis is that the price premium is recovered upon resale. If this is not the case, the ROI would be even lower! Thus, the gap between the offered ROI and that expected by consumers needs to be closed before PHEVs can see any widespread adoption.

Additionally, for the most part PHEVs offer minimal ROI compared to existing hybrids – in the case of the Prius PHEV, the ROI compared against the Prius HEV is actually *negative*. This is because the Prius HEV is already so fuel efficient that when one factors in the cost of electricity, the plug-in version costs *more* to operate. Other PHEV configurations offer positive ROIs as compared to their HEV counterparts, but they are much lower than what is implied by the results of Potoglou's survey. Thus, the only way PHEVs can close this gap between the current offered ROI and expected ROI is if fuel prices increase or if battery technology advances enough to reduce the price premium.

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7.0 Conclusion

Based on the analyses of real-world powertrain configurations and driving cycles derived from survey data, it has been determined that the performance of PHEVs is influenced mostly by battery size and starting charge of the battery. The performance of PHEVs drops dramatically once the vehicles transition from charge-depleting mode of operation, when they are reliant mostly on electric drive for propulsion, to charge-sustaining mode of operation, when they rely on the internal combustion engine for propulsion. Thus, longer driving cycles or distances between charges negatively impact PHEV performance by increasing the proportion of the trip the PHEV operates in charge-sustaining mode. All in all, the results of these analyses indicate that so long as the distance between charges is kept reasonably low, PHEVs can profoundly reduce fuel consumption for the average consumer.

Fuel savings notwithstanding, the subsequent ROI analysis indicates that at current prices, the returns-on-investment offered by PHEVs are much lower than what consumers have indicated they would expect in surveys. In fact, the incremental ROI going from an HEV to a PHEV is minimal in most cases. In order for PHEVs to be attractive to the majority of consumers, either the price premium needs to decrease or the fuel prices needs to substantially increase relative to the cost of electricity. Government policy can also play a role in increasing PHEV attractiveness. For example, a generous tax incentive will help close the price gap between PHEVs and conventional vehicle types, while a gas tax or oil price floor would increase the price of fuel to the levels necessary to encourage PHEV adoption en masse.

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References

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