Plug-in Hybrid Electric Vehicle Demonstration

October 2011

One of ten Toyota Priuses converted to PHEV for testing in Manitoba

Manitoba PHEV Demonstration

Report of Third Year Operations 2010/2011

Overview

This report documents the continued experience and outcomes with ten Toyota Priuses converted to Plug-in Hybrid Electric Vehicles (PHEVs) within Manitoba. This is the third and final of three annual reports on the demonstration, and covers the period from September 2010 to August 2011.

Contents:

Introduction

Hybrids and PHEVs

"Hybrid vehicles" are defined broadly as incorporating more than one source of power. Usually this means gasoline-electric hybrids. A conventional hybrid electric vehicle (HEV) incorporates an internal combustion engine with batteries for energy storage and at least one electric drive motor.

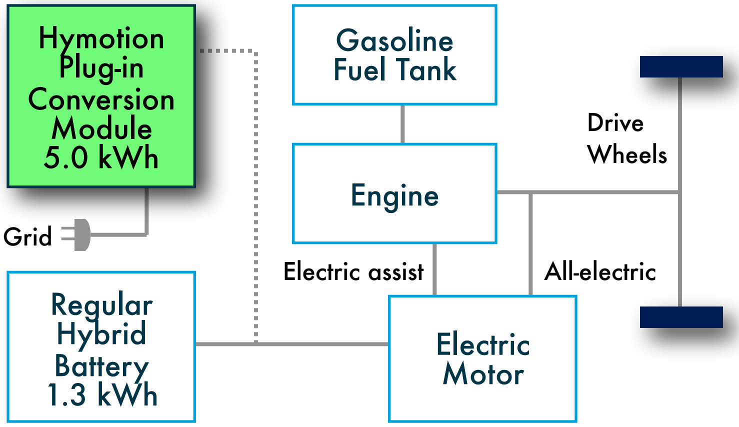
Hybrid electric operation can be implemented in various formats. Vehicles can be simply classified as either parallel hybrids, with a direct connection between the conventional engine and the drive wheels, with the electric motor only assisting; or series hybrids, with the conventional engine used solely to generate electricity, and having no direct connection to the drive wheels. The Toyota Prius can permit all-electric operation under certain conditions, and as such is considered as a mixed series-parallel system.

Although factory-built plug-in hybrid electric vehicles (PHEVs), such as the Chevrolet Volt and Toyota Prius PHV, are becoming commercially available, PHEV technology to date primarily involved the modification of conventional HEVs by the installation of additional "energy" batteries. A PHEV plugs into the electrical grid to charge its added batteries, and during operation uses energy from these batteries to help move the vehicle, whether all-electric or electric-assist.

What distinguishes the PHEV from the HEV is its ability to use grid-based electricity, with associated fuel cost and emissions reductions, but without the constraints and risks associated with being electric-only. With PHEV technology people drive normally, whether for work or pleasure, but do not consume as much fossil fuel.

Prepared by the **Centre for Emerging Renewable Energy Inc.**, in cooperation with

Red River College
OF APPLIED ARTS, SCIENCE AND TECHNOLOGY



Simplified PHEV Configuration

Manitoba Demonstration

This demonstration involved ten Toyota Priuses in Manitoba converted to operate as PHEVs, using Hymotion Plug-in Conversion Modules (PCMs) from A123Systems Inc. Coordination and financial administration has been provided by the non-profit Centre for Emerging Renewable Energy Inc. Conversions were performed by automotive instructional staff at Red River College. Red River College is now a fully-authorized vehicle conversion centre for A123Systems.

Otto data-loggers (photograph on page 8), as manufactured by Manitoba-based Persentech, were installed in each car to monitor characteristics of vehicle use. Selected interactive monitoring of electricity consumption of vehicles, while plugged into the grid, was done using an upgraded version of the IPLC-PHEV meter, the PM2 (photograph on page 5). This technology is manufactured by Manitoba-based Vantera Inc., and adapted from their Intelligent Parking Lot Controller (IPLC), already in common use in Manitoba and elsewhere.

Five separate public-sector agencies provided Toyota Priuses for conversion to PHEVs, as follows:

- Province of Manitoba, Vehicle and Equipment Management Agency (VEMA) (4);
- Manitoba Hydro (2);
- Manitoba Public Insurance (2);
- City of Winnipeg Fleet Management Agency (1); and
- Red River College (RRC) (1), with this unit leased through VEMA.

All these vehicles were operated within public-sector fleets in the vicinity of Winnipeg, Manitoba. By agreement with the owners, vehicles were not specifically identified in this report. Unique identifier numbers for each of the vehicles and their relevant operating characteristics are summarized in tables on page 4 and page 5 respectively.

(See Partner Profiles later in this document for more information about participating organizations)

Project Objectives

The demonstration had multiple objectives, outlined as follows:

- Gain experience with PHEV technology under real-world conditions within Manitoba;
- Understand the benefits and limitations of the technology;
- Develop skills working with the technology;
- Understand and address cold-weather issues that are of importance in Manitoba;
- Understand the potential market for further PHEV conversions versus factory-built vehicles; and
- Develop new business opportunities, as appropriate.

Project Timeframe

The first vehicle was converted in late August 2008; the remaining nine vehicles were converted in mid-April 2009. Monitoring of vehicle performance continued for a period of three years from first conversion. This report covers the final period from September 2010 to August 2011. This is the last annual report for the project.

Technical Details

Each converted Toyota Prius incorporated a Plug-in Conversion Module (PCM) from A123Systems, with capacity to store 5 kWh of energy from the electrical grid. A123Systems develops and manufactures advanced lithium-ion batteries and battery systems for the transportation, electric grid services, and portable power markets. (For more information visit the site www.a123systems.com).

The PCM was installed in the spare-tire wheel well in the rear cabin area of the Toyota Prius (see photograph on page 3), supplementing the existing 1.3 kWh nickel metal hydride battery which is part of the original equipment hybrid system and was left in the car as part of the conversion process. The PCM made additional electricity available for use by the Prius, permitting extended electrical operation beyond what would be normally possible.

A123Systems' Hymotion Plug-in Conversion Module installed in the rear compartment of Toyota Prius, behind nickel metal hydride stock hybrid battery

Demonstration Results

Major Activities

Seven major activities were conducted during the last year of the demonstration, and are summarized in the following points:

1. On-going monitoring using Otto data-logging units. Monitoring of the vehicles continued over the third year, in particular to evaluate average trips per day and average travel distance per day. These results are discussed in the following section on Vehicle Use.

2. On-going monitoring of liquid fuel (gasoline) consumption. Monitoring of liquid fuel consumption for all vehicles continued over the third year. This is described in the section on Fuel Economy, on page 7. Liquid fuel and electricity consumption data were also used to estimate greenhouse gas (GHG) emissions in order to understand potential reductions that might be possible with the technology. This is described in the section on GHG Reductions, on page 15.

3. On-going preventative maintenance monitoring. Selected oil analyses were continued in order to better understand the impacts of PHEV operation on vehicle maintenance. This is described in the section on Maintenance Impacts, on page 17.

4. Continued cold-weather performance monitoring. The monitoring of cold-weather operation continued through the third winter of the project, in particular to assess the adequacy of earlier vehicle modifications. This is described in the section on Temperature Impacts, on page 15.

5. Monitoring of electricity consumption. Monitoring of electricity consumption continued on selected vehicles (Unit #1981 and Unit #1982) using the upgraded PM2 device (see photograph o page 5). This is described in the section on Electricity Use, on page 19.

6. Selective performance data comparisons with commercial vehicles. During the third year of the demonstration a similar commercial (i.e., factory-built) vehicle was also under testing in Manitoba. This was the 2010 Toyota Prius Plug-in Hybrid Vehicle (PHV). Having other vehicles available permitted comparison of selected performance data. In this case only externally monitored data were considered, including liquid fuel (gasoline) consumption and/or electricity consumption (at the wall). This is described in the section on Additional Activities, on page 19. More information is provided in the side-bar on page 16.

7. Survey of consumer attitudes on electric vehicles. During the third year of the demonstration the University of Manitoba Transport Institute undertook a survey of consumer attitudes to electric vehicles, both all-electrics and PHEVs. This activity is reported separately from this report, and is described in the section on Additional Activities, on page 20.

Vehicle Use Characteristics

Although fuel economy improvement is the key desired outcome of the project (described next under Fuel Economy), it is well recognized that fuel-use depends not just on the vehicle technology employed, but also significantly on the nature of vehicle-use characteristics (e.g. driver habits and duty cycle), as well as weather conditions (discussed later under Temperature Impacts).

In the Table on page 5, the ten vehicles were categorized, based on their vehicle-use characteristics:

- Nature of the driver, particularly whether this involved primarily
  (a) single driver, or
  (b) multiple drivers; and

- Nature of the operating cycle of the vehicle, particularly whether (a) primarily regular commute, (b) regular work route, (c) irregular daily operation, or (d) combination of commute and irregular daily operation.

For all individual vehicles, the nature of use during the third year remained essentially within the same assigned categories as during the first year. There were some alterations in operations that did impact on performance, as described later. Of the ten vehicles, during the third year seven were involved primarily in irregular daily operation (with some commuting), two were used primarily for commuting (Unit #1982 and Unit #1989), and one was used in a regular daily work-related operation (Unit #1984).

Prior to the start of the PHEV demonstration, a separate on-going project was already underway by researchers at the University of Winnipeg. This involved the same Otto Driving Companion data-loggers, but assessing a much larger sample of regular vehicles, i.e., 79 vehicles operated by volunteers over a one year period. Summary statistics from their work are presented in the side-bar on page 5 for relevant parameters.

The Otto data-loggers can in general permit the comparison of diverse parameters. Based on discussions with the researchers at the University of Winnipeg, two key parameters were selected for presentation and further analysis as part of the demonstration reports:

- Trips per day; and
- Daily travel distance.

A summary of the PHEV data for the third year of operations is presented in the Tables on page 6 and page 8, described as follows:

- Table on page 6 summarizes data on the trips per day for each vehicle including mean, median, standard deviation, and number of data points (i.e. number of days).
- Table on page 8 summarizes data on the daily travel distance for each vehicle including mean, median, standard deviation and number of data points.

Data on linear correlations of daily travel distance as a function of trips per day are not presented for all units, given that the two parameters were previously shown in most cases to be very poorly correlated (see First Year Report). Based on third year data, two of the vehicles did show some reasonable level of correlation between these two parameters. These were Unit #1984 (r^2 = 0.68) and Unit #1986 (r^2 = 0.71). These results made sense given their uses for regular work operation, and as a short-distance pool vehicle, respectively. All other vehicles continued to show very poor correlations.

Further explanation of the vehicle-use data collected is provided on page 6. There are several important observations regarding these travel data:

Summary of Toyota Priuses Converted in Demonstration

Identifier	Year	Odometer	Identifier	Year	Odometer
#1981	2008	11,509 km	#1986	2009	131 km
#1982	2008	6,542 km	#1987	2009	35 km
#1983	2008	2,497 km	#1988	2008	9,649 km
#1984	2004	134,599 km	#1989	2007	42,496 km
#1985	2008	14,203 km	#1990	2004 †	27,005 km

Notes: Identifier numbers are unique to this project; odometer readings are at time of conversion; † rebuilt unit

Transport-related Characteristics of Vehicles

Identifier	Nature of Driver	Nature of Operating Cycle
#1981	Split Regular Driver and Pool Vehicle	Some Commute, Mostly Irregular Use
#1982	Primarily Single Regular Driver	Primarily Commute
#1983	Single Regular Driver with some Pool	Commute and Irregular Daily Use
#1984	Primarily Single Regular Driver	Regular Daily Work Operation
#1985	Primarily Single Regular Driver	Commute and Irregular Daily Use
#1986	Pool Vehicle	Irregular Use
#1987	Pool Vehicle	Irregular Use
#1988	Rotating Single Regular Driver	Commute and Irregular Daily Use
#1989	Rotating Single Regular Driver	Commute and Irregular Daily Use
#1990	Pool Vehicle	Irregular Use

IPLC-PHEV PM2 Meter installed in Unit #1982

University of Winnipeg

Summary of relevant vehicle statistics

Trips per day:

Mean:	4.5 trips per day
Median:	4.0 trips per day
Standard Deviation:	3.1 trips per day

Daily travel distance:

Mean:	35.8 km per day
Median:	26.0 km per day
Standard Deviation:	42.4 km per day

Blair, D., and R. Smith. University of Winnipeg. Unpublished results from analysis of Otto Driving Companion data. For more information visit the site: http://auto21.uwinnipeg.ca

Measured Trips per Day Data for Test Vehicles

Identifier	Mean	Median	Standard Deviation	Data Points
#1981	4.1 trips per day	4.0 trips per day	2.8 trips per day	70 days
#1982	2.8 trips per day	2.0 trips per day	2.3 trips per day	254 days
#1983	Log data not available			
#1984	1.2 trips per day	0.0 trips per day	2.1 trips per day	150 days
#1985	2.9 trips per day	3.0 trips per day	2.5 trips per day	71 days
#1986	1.5 trips per day	0.0 trips per day	2.1 trips per day	170 days
#1987	Log data not available			
#1988	3.3 trips per day	3.0 trips per day	3.3 trips per day	81 days
#1989	3.7 trips per day	3.5 trips per day	2.1 trips per day	78 days
#1990	4.0 trips per day	4.0 trips per day	3.1 trips per day	94 days

What do the data on vehicle-use characteristics mean?

Data on "trips per day":

In the Table on page 6, summary statistical data are presented for each vehicle, including mean, median and standard deviation. For all vehicles the mean trips per day were lower than for the University of Winnipeg data, ranging from about 26% to 91% of their mean value. The vehicles could be divided into three categories:

- Units #1981 and #1990 had the highest mean and median values, and during the last year showed results most similar to the study group of vehicles evaluated by the University of Winnipeg.
- Units #1984 and #1986 had lowest mean and median values, but were similar to one another.
- All other units show results that were relatively distinct.

Data on "daily travel distance":

In the Table on page 8, summary statistical data are presented for each vehicle, including mean, median and standard deviation. In this case during the last year, vehicle performance showed a split, with three vehicles having longer travel distances, and the others all lower than the study group by the University of Winnipeg. Median values were zero in some cases. The latter was not an error but resulted from vehicles being idle on weekends and additional days.

Overall, the vehicle use characteristics of the PHEVs were quite different from the larger group studied by the University of Winnipeg. This primarily reflects their fleet-based operation.

- Data were missed for two units, in both cases due to memory limitations of the data logger.
- The number of data points (i.e. days) for each unit are included in the tables and are less than expected. This was due to limitations in the storage capacity of the data loggers.
- When compared to the expected average vehicle values found by researchers at the University of Winnipeg (data on page 5), all units showed significantly lower mean trips per day and generally shorter mean daily travel distances (noting three were longer).
- Mean daily travel distances for two of the vehicles (Unit #1985 and Unit #1990) were higher than the average overall travel distance for a Manitoba vehicle of 43 km per day (see side-bar on page 8), with all other vehicles being lower.
- Total annual travel distances, provided later in the table on page 10, were larger for two vehicles than the Manitoba average value of 16,000 km (i.e., Units #1988 and #1990).
- The average annual travel distance for the ten vehicles was about 9,400 km during the third year.
- The median trips per day and median daily travel distance values were zero in some cases.

These observations all reflected the fleet-based nature of use, as compared to typical vehicles. Only selected unit were used on weekends. As such, most units recorded a relatively high number of non-use days, particularly pool vehicles. These might be unused for more extended periods.

In addition to comparing vehicle-use data for the ten PHEVs to regular vehicles in Manitoba, the data for for each unit in the third year were compared to respective data for the second year in order to determine any important potential changes in use. For both the parameters, trips per day and daily travel distance, the mean value and the standard deviation value were compared for seven PHEVs having data for both years, with results summarized as follows:

- Four units showed changes in mean trips per day that were statistically significant: Unit #1981, which increased; Unit # 1982, which decreased; Unit #1984, which decreased; and Unit #1988, which increased.
- Two units showed statistically significant changes in the standard deviation of trips per day, decreasing for Unit #1984 and increasing for Unit #1988.
- Four units showed changes in mean daily travel distance that were statistically significant: Unit #1982 and Unit #1984, which decreased; and Unit #1988 and Unit #1990, which increased.
- All seven units showed significant changes in the standard deviation of daily travel distance decreasing for five and increasing for two.

Fuel Economy

As described in the first two reports, the primary units for reporting of fuel (energy) economy in this demonstration are as follows:

- Litres per 100 kilometre for liquid fuel consumption; and
- Kilowatt-hours (kWh) per 100 kilometre for electrical energy consumption as a separate value.

For liquid fuel consumption, reference periodically is made to "miles per U.S. gallon" (MPG), given this is an official unit in the U.S. and thus important for reference purposes. Units of "miles per Imperial gallon" (MPIG) are not employed directly, given this unit is not officially used in North America, and also can cause significant confusion with MPG values from the U.S. when not properly identified. A table of equivalent values for gasoline fuel economy is provided to permit conversion to desired units (see side-bar Table on page 10).

The upgraded PM2 units from Vantera for on-going monitoring of electrical energy consumption were used selectively during the third year. Estimates of electricity consumption were prepared (as described later under the section on Electricity Use, on page 19), but it was not possible to correlate the two forms of energy consumptions.

The calculated overall fuel economy achieved for each of the ten PHEVs during the third year is provided in the Table on page 10. This involved operation from September 1, 2010 to August 31, 2011.

Overall, during the third year fuel economy values ranged from 4.0 to 9.5 Litres per 100 km. This reflected differences in not only the extent of electricity use, but also the nature of driving operations and temperature conditions. Overall aggregate fuel consumption for all vehicles during the third year was calculated to be 6.2 Litres per 100 km, essentially the same as a conventional Prius. Six vehicles had fuel economy better than this value and four vehicles were worse.

Given aggregate fuel consumption of 4.8 Litres per 100 km during the first year, 5.5 Litres per 100 km during the second year,

Measured Daily Travel Distance Data for Test Vehicles

Identifier	Mean	Median	Standard Deviation	Data Points
#1981	38.8 km per day	29.5 km per day	44.5 km per day	70 days
#1982	13.6 km per day	10.6 km per day	12.5 km per day	254 days
#1983	Log data not available			
#1984	4.0 km per day	0.0 km per day	8.1 km per day	150 days
#1985	54.2 km per day	17.9 km per day	145.1 km per day	71 days
#1986	11.3 km per day	0.0 km per day	20.4 km per day	170 days
#1987	Log data not available			
#1988	31.5 km per day	22.0 km per day	38.4 km per day	81 days
#1989	26.7 km per day	22.2 km per day	18.9 km per day	78 days
#1990	60.3 km per day	35.4 km per day	74.4 km per day	94 days

Otto Driving Companion logger mounted on vehicle dash-board

Average Travel Distance

Statistics Canada regularly publishes the "Canadian Vehicle Survey" (Catalogue no. 53-223-XIE) with recent summary annual data for Manitoba as follows:

Year	Number Vehicles†	Travel Distance (km/year)	Average (km/year)
2000	583721	9334200000	15,991
2001	592212	9669300000	16,327
2002	601943	8691100000	14,438
2003	605115	11044200000	18,251
2004	616015	8840500000	14,351
2005	623383	9314400000	14,942
2006	631517	10256500000	16,241
2007	643582	11845400000	18,405
2008	659493	9705000000	14,716

† Vehicles less than 4.5 tonne mass

Mean annual travel 15,872 ± 1,601 km/year
Aggregate average travel 15,962 km/year
Resulting daily travel is about 43 km per day

and 6.2 Litres per 100 km during the third year, some type of consistent worsening trend could be implied, potentially linked to aging of vehicles or lack of novelty. Further analysis, however, suggested that, aside from temperature conditions, the nature of vehicle operation was likely most important.

Over the full three years, the ten vehicles travelled in aggregate 233,000 km, consuming 13,100 Litres of fuel. This translated to overall average fuel consumption of 5.6 Litres per 100 km, which is roughly 10% better overall compared to the conventional Prius at about 6.2 Litres per 100 km under Manitoba conditions. As such, the performance improvement was incremental rather than dramatic.

Consistent increases in fuel consumption were observed for five of the vehicles over the three years. These were for Unit #1981, Unit #1983, Unit #1985, Unit #1988, and Unit #1989. These changes appeared to reflect key specific differences in how vehicles were used, rather than any changes in the applications of the vehicles, as described in the last section.

Two vehicles, on the other hand, had very consistent performance. Unit #1982 averaged 4.6 Litres per 100 km ± 7%. This unit was deliberately operated to emulate a typical commuter, and was one of the top performing units overall. Fuel economy was more than 25% better than a Prius, and more than 17% better than Unit #1990 described below. Unit #1982 was consistently stored outside, even during winter.

Unit #1990 was operated as a pool vehicle primarily within the vicinity of Winnipeg, and averaged 5.6 Litres per 100 km ± 7%. This vehicle matched the aggregate overall fuel consumption for the demonstration, and, as such, could be deemed to represent a typical fleet vehicle.

Unit #1985 and Unit #1986 showed consistently good fuel economy, comparable with Unit #1982. But, like Unit #1990, these were both pool vehicles. Importantly these two units were uniquely stored inside for the entire period when not in use. As such, the ways in which the vehicles were used and their heating requirements appeared to be important.

In the Figure on the top of page 12, annual fuel consumption is plotted as a function of annual travel distance for all vehicles. The top line represents expected performance of a conventional Prius, (i.e., slope of 6.2 Litres per 100 km, and passing through the origin). Of the thirty data points (10 vehicles each for 3 years), only four data points were above this line, three of which were during the last year. As such, for more than 87% of occurrences with all vehicles, the PHEVs outperformed the expected fuel consumption for a conventional Prius. Given the relatively low fuel volumes involved, a few units having higher annual fuel consumption significantly impacted the overall results.

The second line from the top on page 12 is the linear regression for all thirty data points. The resulting correlation was very strong (i.e., $r^2 = 0.93$). The slope in this case corresponded to 6.5 Litres per 100 km, but intersected the x-axis, with the implication that this distance, corresponding to approximately 1,000 km, represented the average all-electric travel, not using any liquid fuel. In this case, given the slightly higher fuel consumption, the average PHEV converged with fuel consumption for a conventional Prius when the annual travel distance reached 21,000 km.

The interpretation is that in a given year, each vehicle travelled 1,000 km all-electric on average, followed by remaining travel using liquid fuel at a rate slightly above that expected for a conventional Prius. Given overall average annual travel per vehicle of about 7,800 km, each vehicle traveled 13% all-electric on average.

Using an electricity value of approximately 18.2 kWh per 100 km under primarily electric mode (described later under Electricity Use, on page 19) meant that on average about 2.8 kWh of electricity was required to displace a Litre of liquid fuel for the PHEVs. This value was within the expected range of between 2 to 4 kWh per Litre.

At the same time, in the Figure on page 12 seven of the data points showed significantly better performance (i.e., lowest on plot), and deviated significantly from the overall correlation. These data points were for five different vehicles, Unit #1982 over the entire three year period and four other units on occasion. The third line from the top on page 12 is the linear regression for these data points. The resulting correlation was again very strong (i.e., $r^2 = 0.99$). The slope in this case corresponded to 6.1 Litres per 100 km, with x-axis intercept of approximately 2,100 km

These data points were collectively termed "commuters" given similarities to Unit #1982. These cases corresponded to much further all-electric travel, followed by liquid fuel consumption at a rate

Measured Fuel Economy for Test Vehicles during Third Year

Identifier	Travel Distance	Fuel Consumed	Fuel Economy
#1981	9,191 km	588 Litres	6.4 Litre / 100 km
#1982	6,688 km	320 Litres	4.8 Liter / 100 km
#1983	6,484 km	617 Litres	9.5 Litre / 100 km
#1984	983 km	53 Litres	5.4 Litre / 100 km
#1985	13,410 km	927 Litres	6.9 Litre / 100 km
#1986	6,145 km	248 Litres	4.0 Litre / 100 km
#1987	4,477 km	202 Litres	4.5 Litre / 100 km
#1988	16,838 km	1,203 Litres	7.1 Litre / 100 km
#1989	9,897 km	552 Litres	5.6 Litre / 100 km
#1990	19,352 km	1,086 Litres	5.6 Litre / 100 km

Benchmark Fuel Economy Values

Conventional Toyota Prius:
As part of the first report of the demonstration, fuel use data was aggregated from twenty conventional Toyota Priuses operated by VEMA, Manitoba Hydro and the City of Winnipeg Fleet Management Agency. This value corresponded to approximately 6.2 Litres per 100 km for fleet-based operations. Although significantly higher than Transport Canada's reported fuel consumption for the Prius, this value is reasonable, reflecting actual performance under Manitoba conditions.

Average Manitoba Vehicle:
The report *Beyond Kyoto*, released by the Government of Manitoba, included data that the average fuel consumption for a vehicle in Manitoba has been about 15 Litres per 100 km. Also, Manitoba currently has an ethanol mandate of 8.5% pool blend average, applied to all gasoline fuel.

A123Systems Desired Performance Level:
The desired performance of the converted PHEV is 100 MPG, which corresponds to a fuel consumption of 2.4 Litres per 100 km.

Unit Conversions

L/100 km	MPG	MPIG
2	118	142
3	79	95
4	59	71
5	47	57
6	39	47
8	29	35
10	24	28
15	16	19

almost the same as a regular Prius. For an average annual travel of about 9,600 km for these seven cases, this meant roughly 22% all-electric. For a few units, the estimated proportion of all-electric travel exceeded 30% in some years.

"Commuter" operation appeared to correspond to several conditions: highly regular daily travel, in the range of about 20 to 30 km per day; intermittent, rather than steady use, with ample idle time; lower emphasis on highway travel; and continuous operation when in use, with vehicle not turned on and off repeatedly. Unit #1982 was consistently operated in this manner, but other units appeared to approximate the same pattern on occasions.

The circumstances associated with high fuel-consuming units were also important, some of which could be readily explained. During the first and second years Unit #1984 showed high fuel consumption. This was identified in the first year as due to steady operational use (i.e., ran all day) and in the second year to repeated on/off operation. In the third year this unit was used much less, but importantly its fuel consumption reduced back into line with other fleet-based units.

Unit #1988 showed particularly high fuel consumption in the third year, which could be explained, especially in comparison to Unit #1990. Both vehicles had comparable travel distances. While Unit #1990 was used primarily within the boundaries of the city, Unit #1988 involved partial but regular use on highways, at increased speeds. In this context, its elevated fuel consumption makes sense, given that even for a conventional Prius fuel-use is higher for highway-based than city-based travel. As such, although it is likely the fuel economy for Unit #1988 was better than other vehicles on the highway, in absolute terms the PHEVs operated most effectively under city driving conditions.

The impacts of seasonal operation were also important. A time-track of calculated "fill-to-fill" fuel economy values for Unit #1982 is presented in the second Figure on page 12, covering the full three years since the beginning of the project. As illustrated, fuel consumption showed a recurring cyclic pattern, obviously linked to changes in seasonal temperatures. Fuel consumption rose during colder months and dropped during warmer months.

Winter fuel consumption for Unit #1982 reached the highest level during the third winter. This was also the coldest winter of the three experienced. This may have been an important factor in the performance of all ten of the PHEVs during the final year.

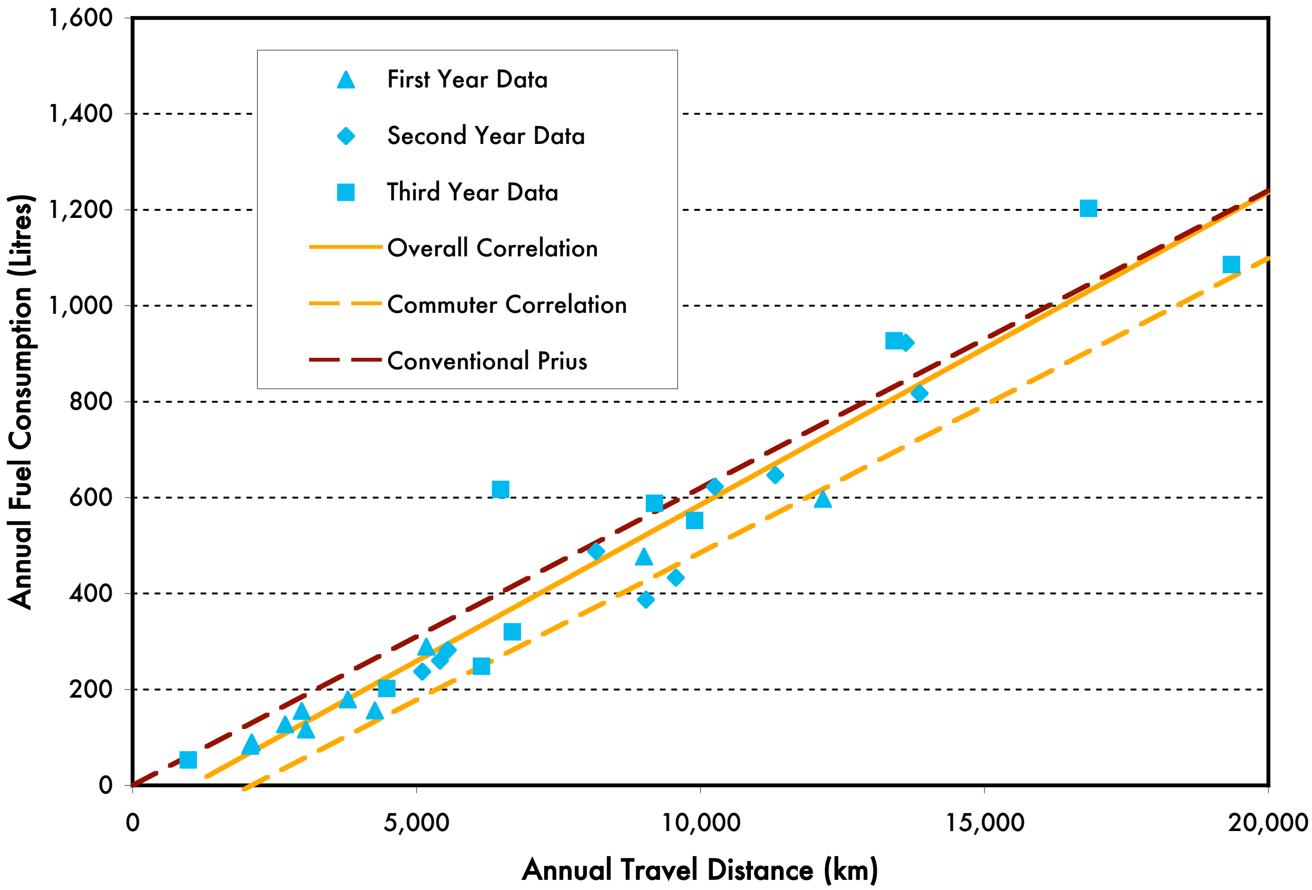
It is also important to note for Unit #1982 that incremental fuel economy did periodically approach or achieve the desired expectations as outlined by A123Systems (i.e. 2.4 Litres per 100 km or better). This, however, only occurred during the warmest months.

For comparison purposes, an economic analysis was undertaken with assumptions based experience for "commuter" operation, i.e., the best performing vehicles from the demonstration. This showed a model commuter PHEV to consume approximately 630 Litres of gasoline, 60 Litres of ethanol, and 900 kWh of electricity. This was compared to a conventional Prius over the same distance consuming about 910 Litres of gasoline and 80 Litres of ethanol; and an average Manitoba vehicle consuming about 2,200 Litres of gasoline and 200 Litres of ethanol. Assumptions are as follows:

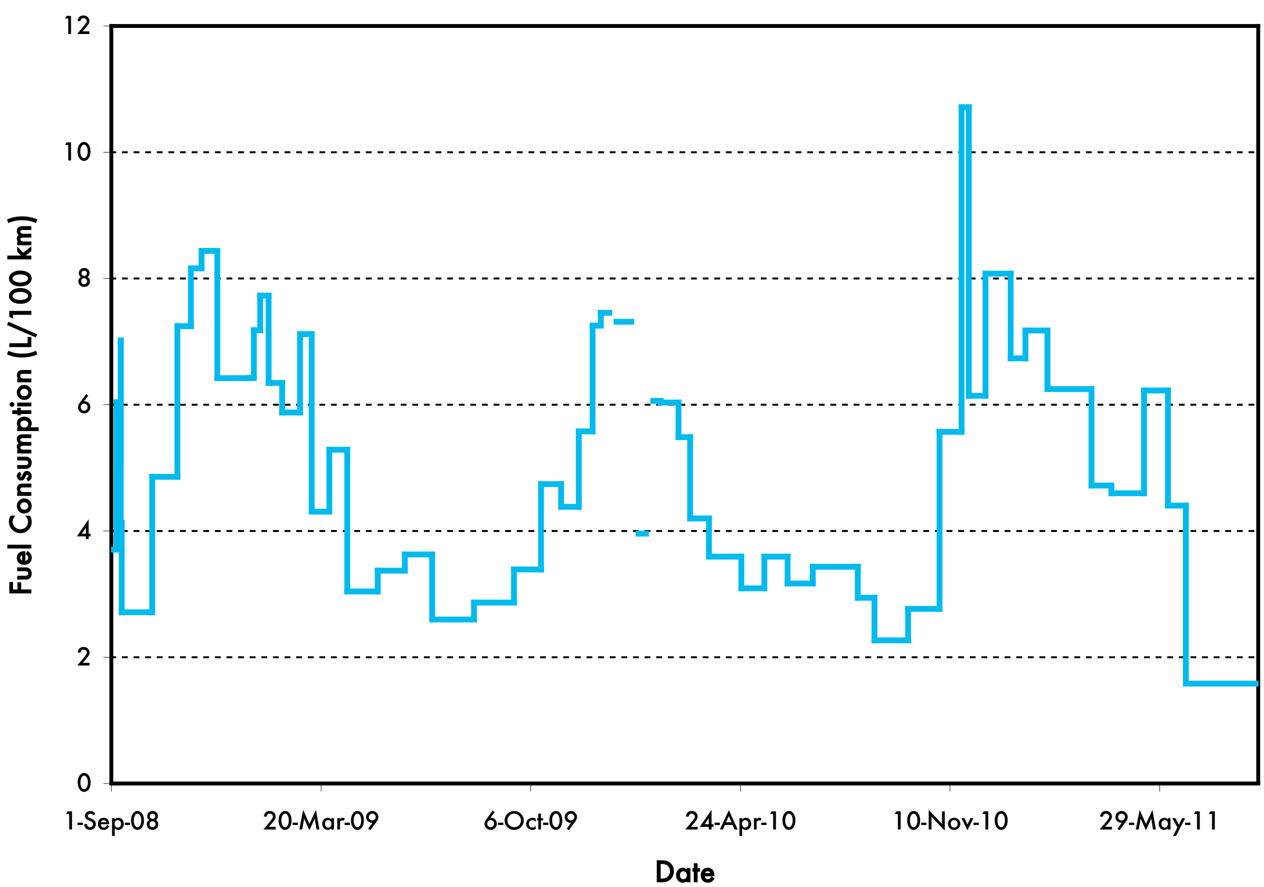
- Vehicle travel of 16,000 km annually in all cases.
- PHEV travel of approximately 30% all-electrically, or about 4,800 km, with electricity requirement of 18.2 kWh per 100 km (described later under Electricity Use, on page 19), consistent with commuter-use.
- Commuter PHEV traveling remaining distance with liquid fuel at a rate of 6.1 Litres per 100 km, as per earlier analysis.
- Conventional Prius overall fuel economy of 6.2 Litres per 100 km.
- Average Manitoba vehicle fuel economy of 15 Litres per 100 km.
- Manitoba ethanol fuel mandate, with 8.5% of vehicle liquid fuel considered as ethanol.
- Conventional vehicles requires 4 oil changes per year, while PHEV requires only 2 oil changes per year, with rough cost of $100 per oil change service.
- Cost of money of 6% for assumed life of eight years (based on previously estimated battery life).

The results of calculating the present value (PV) of operating savings for an eight year period are presented in the Figure at the top of page 14 for the PHEV compared to both an average Manitoba vehicle and a conventional Prius. The price per Litre of fuel is a key variable affecting the extent of savings. Using a reasonable range of fuel prices into the future (i.e., range of $1.10 to $1.60 per Litre average over eight years) suggested a PHEV likely would save $11,000 to

Analysis of Fuel Consumption with Distance for All PHEVs



Cyclic Interval Fuel Economy for Unit #1982 over Three Years



Greenhouse Gas (GHG) Emissions Comparison (Annual)

Vehicle	Annual Fuel Consumption	Well-to-Wheels Estimate	Tank-to-Wheels Estimate	NIR-Based Estimate
Commuter Plug-in Hybrid Electric Vehicle	Gasoline: 630 Litres Ethanol: 60 Litres Electricity: 900 kWh	2,330 kg 80 kg 20 kg	1,450 kg 0 kg 0 kg	1,450 kg 170 kg 20 kg
	Total Emissions	2,430 kg	1,450 kg	1,640 kg
Conventional Prius Hybrid Electric Vehicle	Gasoline: 910 Litres Ethanol: 80 Litres Electricity: n/a	3,370 kg 100 kg 0 kg	2,090 kg 0 kg 0 kg	2,090 kg 220 kg 0 kg
	Total Emissions	3,470 kg	2,090 kg	2,310 kg
Average Manitoba Vehicle	Gasoline: 2,200 Litres Ethanol: 200 Litres Electricity: n/a	8,140 kg 260 kg 0 kg	5,060 kg 0 kg 0 kg	5,060 kg 560 kg 0 kg
	Total Emissions	8,400 kg	5,060 kg	5,620 kg

How were the different emissions estimates calculated?

National Inventory Report (NIR) based estimate methodology:

In the NIR, prepared annually by Environment Canada, emissions are calculated according to the jurisdiction in which they occur, but are split between transportation and processing in major categories. For gasoline, only fuel combustion is included, with upstream processing excluded in Manitoba. The established emission factor for gasoline combustion is about 2.3 kg GHG per Litre. For ethanol, the NIR includes an emission factor of 1.5 kg GHG per Litre, ostensibly for combustion, but never fully explained and not directly corresponding to likely emissions from stoichiometric combustion. Upstream production of ethanol is aggregated with other industries, but corresponds to about 1.3 kg GHG per Litre. The renewable nature of ethanol is not considered. For electricity, Manitoba Hydro's emissions are effectively full-cycle, with a grid-mix average of about 0.02 kg GHG per kWh.

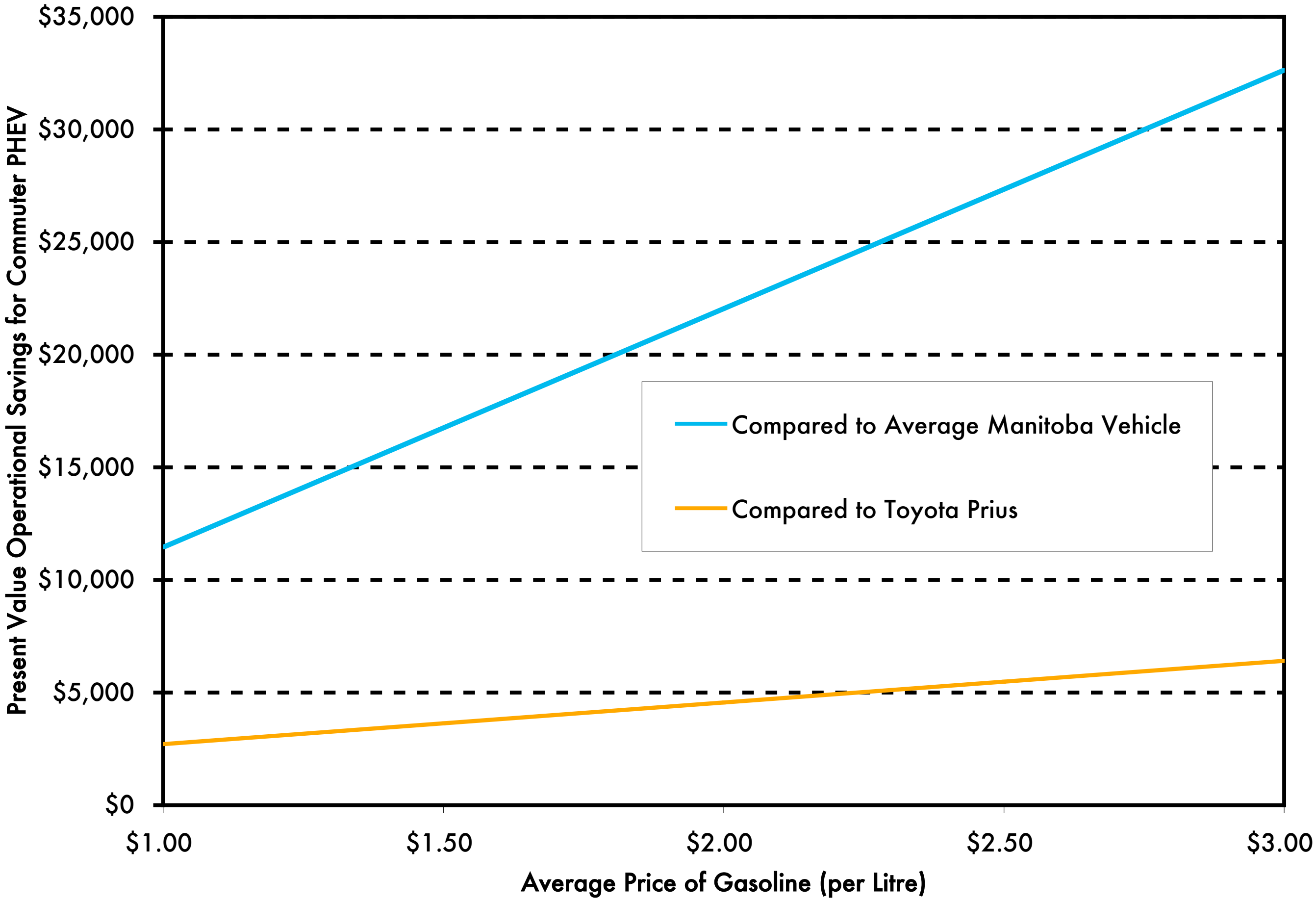
Tank-to-Wheels based estimate methodology:

On a tank-to-wheels basis, only emissions associated directly with fuel combustion at the vehicle are considered. In this case, the emission factor of 2.3 kg GHG per Litre applies to gasoline, but both ethanol and electricity are essentially zero, given that in neither case any appreciable net emissions are produced at the vehicle.

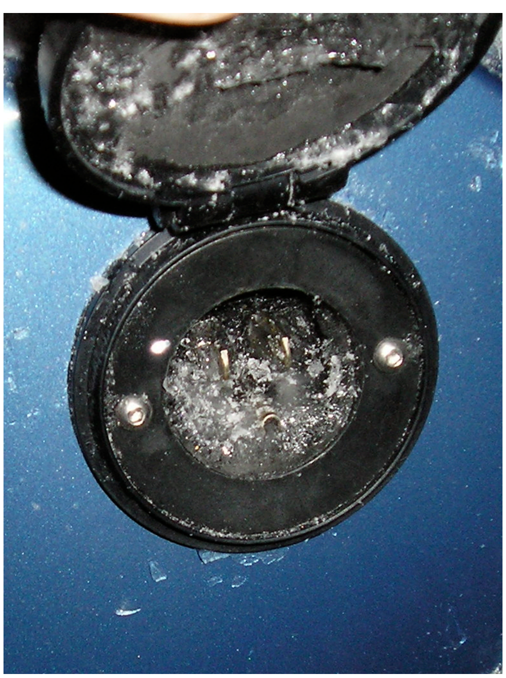
Well-to-Wheels based estimate methodology:

On a well-to-wheels basis, emissions associated with all steps in the production and use of the fuels are included. In this case, an emission factor of 3.7 kg GHG per Litre is reasonable for gasoline, 1.3 kg GHG per Litre is applicable to ethanol, recognizing its renewability, and 0.02 kg GHG per kWh for electricity as noted above. No emissions associated with so-called "indirect land use" are included, given both controversy and uncertainty.

Present Value PHEV Operational Savings over Eight Years



On-Going Operational Issues During Winter



Iced receptacle on Unit #1982 (left)

Start-up problems with Unit #1983 (right)

$16,000 (PV), as compared to an average Manitoba vehicle, and $1,200 to $2,100 (PV), as compared to a conventional Prius. If future gasoline prices were to increase to higher levels, the PHEV would become much more attractive economically, as illustrated.

The capital cost of the Prius conversion for this demonstration project, in the range of $10,000 to $15,000 per vehicle, could not provide a realistic payback compared to a conventional Prius. However, the focus of the demonstration was on understanding vehicle performance. Factory-built PHEVs were not available at the start of the project. The conversions in this case employed relatively early-stage technology, which was known to be relatively expensive in nature, especially compared to anticipated full-production vehicles.

At the same time, the fuel economy achieved by the PHEVs for "commuter" operation, being around 4.8 Litres per 100 km, was among the very best fuel economy achieved by any vehicle of any type under actual conditions within Manitoba. The cost premium to achieve this high performance level was not excessively high. The fuel consumption results obtained for the PHEVs, although incremental instead of dramatic, were highly positive.

The economic payback for new, commercial PHEVs will be different, likely to be better. Their economic viability will need to be evaluated. In general, the incremental capital costs for PHEVs and other electric vehicles are anticipated to continue to decline, as increased numbers of commercial models come into the market, and as performance and production levels continue to rise.

GHG Reductions

A summary of estimated greenhouse gas (GHG) emissions for the PHEV is presented in the Table on page 13, using three different bases:

- Well-to-wheels (WTW) emissions;
- Tank-to-wheels (TTW) emissions; and
- Methodology as employed in the National Inventory Report (NIR), as prepared by Environment Canada.

Major emissions-related assumptions are also summarized on page 13. The performance assumptions for the vehicles are as outlined in the previous section (page 11). Assumptions were updated from the second year report using additional data and experience from the third year of the demonstration.

The results continued to show that the accounting methodology used to compare GHG emissions has a very important impact on the extent of reductions achieved. On a WTW basis, which is arguably the most legitimate approach, the "commuter" PHEV produced a dramatic reduction. Even compared to the conventional Prius, the PHEV achieved a net reduction of over one tonne. The reduction was closer to six tonnes when compared to an average Manitoba vehicle. Considering emissions on only a TTW basis or according to the NIR methodology, significantly reduced the apparent reduction.

In addition to GHG emissions, an obvious benefit of the PHEVs was a reduction in smog pollutants. Although not directly evaluated, reductions would occur for nitrogen oxides, fine particulate material, and unburned hydrocarbons.

Temperature Impacts

Manitoba's cold winter-weather presents a challenge to many new technologies, including PHEVs. During the first year, the most critical cold-weather problem identified was performance of the factory-installed 12-volt battery on the Priuses. As described in the First Year Report, two solutions were developed by Red River College in conjunction with A123Systems to address this concern. These involved first, installing a more robust replacement 12-volt battery, and, second, installing a trickle charger to automatically recharge the 12-volt battery whenever the main PCM unit was being charged. This solution was implemented on all ten vehicles. During the second year, custom front covers were installed on eight of the vehicles and electric in-car warmers on six of the vehicles, both these measures to address cabin warmth.

These two sets of measures appeared to be successful into the third winter. No major difficulties were encountered, but ongoing challenges of winter operation still needed to be meet. Unit #1983 had start-up problems, but this was due to the vehicle having been left parked for an extended period, and was resolved using the on-board trickle charger. Unit #1982 experienced a more unique cold-weather problem. The vehicle's plug-point became completely filled with ice during an ice storm, as illustrated in the photograph on page 14. This required a heat-gun to resolve but was corrected, and again it was able to be plugged-in.

As described later under Additional Activities, a separate paper was prepared summarizing

Vehicles Compared for Fuel Consumption

Factory-built Toyota Prius PHV tested in Manitoba

Unit #1982 from Manitoba PHEV Demonstration

Toyota Plug-in Partnership Test Vehicle in Manitoba

In July 2010, the Province of Manitoba, together with Manitoba Hydro and the University of Manitoba announced a plug-in partnership with Toyota Canada. This involved the year-long testing in Manitoba of a 2010 model-year Toyota Prius Plug-in Hybrid Vehicle (PHV).

The news release describing this project is available at the following internet site: http://news.gov.mb.ca/news/index.html?archive=2010-07-01&item=9220

The unit was factory-built, rather than a conversion. It incorporated a 4 kWh capacity lithium battery as the main hybrid battery for the vehicle. The battery received electricity from the on-board generator system, including during regenerative breaking, and also could be recharged from the grid using a standard 110 volt receptacle.

The use of the vehicle was shared between participants on a monthly basis. The availability of this vehicle to the Department of Innovation, Energy and Mines permitted selected external monitoring for one-month periods during the summer, fall, winter, and spring. Only external data were involved, specifically electricity consumption as measured "at-the-wall" using the PM2 meter from Vantera Inc., and liquid fuel dispensed "at-the-pump". No on-board data-logging was involved.

Information on Idling and Associated Fuel-Use and Environmental Impacts

Environment Canada on idling-related GHG emissions:

http://oee.nrcan.gc.ca/transportation/idling/impact.cfm?attr=28

EPA on idling-related smog emissions: http://www.epa.gov/oms/consumer/f98014.pdf

Recent Quebec study on idling perceptions:

Belanger et al. 2009. Use of a remote car starter in relation to smog and climate change perceptions. International Journal of Environmental Research and Public Health. 6(2): 694–709.

the cold-weather upgrades undertaken for the vehicles and associated outcomes.

Additional positive feedback was obtained regarding the use of the electric in-car warmers. This measure made all the so-equipped vehicles much more pleasant for operators. Given the relatively cold nature of the third winter, it was found for Unit #1982 that the in-car warmer needed to be used full-time. The combined block-heater and in-car warmer load was measured using the PM2 meter and found to be about 1.1 kW. This represented about 26 kWh over a full day during winter, more than five times the energy recharge per day for motive operation. As discussed in the Second Year Report, the electrical load for the in-car warmer was not included for the purpose of fuel economy. In part this was because conventional vehicles also have a block-heater load that is substantially the same during the winter.

At face value, the use of electricity for vehicle warming might appear detrimental, but further review showed it to be positive. Electrical preheating meant that the PHEVs did not have to be idled using fuel, and could move immediately on start-up, offsetting gasoline.

During winter, some idling of conventional vehicles, including hybrids, in unavoidable. At the same time, excessive idling of conventional vehicles is a concern both in terms of excess fuel-use and emissions (refer to side bar on page 16). This concern has been increased given the market trend toward remote-starting of vehicles for preheating in the winter, and for pre-cooling using air conditioning (AC) in the summer. Yet little data are available regarding fuel consumption for deliberate idling.

Experience from the demonstration was used to calculate the cost and emissions associated with full-day electrical preheating of a PHEV in Manitoba during winter. The cost was only about $1.80, with the associated GHG emissions only about 0.5 kg, on a WTW basis.

Using a range of $1.10 to $1.60 per Litre as the average price for gasoline over the next eight years (see Fuel Economy), the cost of electricity for preheating would be roughly equivalent to using 1.1 to 1.6 Litres of liquid fuel for idling per day during winter. This is a reasonable range of fuel volume for idling a vehicle. As such, electrical preheating would appear to be no more costly, and likely cheaper.

Regarding emissions, the electricity used for preheating would cause roughly the same emissions as if 0.14 Litres of liquid fuel only were to be used for idling per day during the winter (see side-bar on page 13). Much more gasoline would be likely consumed for idling than this small amount. As such, a significant relative reduction in emissions likely would occur.

The electric in-car warmer was identified as a critical winter upgrade for the PHEVs as part of the demonstration. Confirming cost and emission reductions would require additional investigation.

At the same time, vehicle manufacturers have been investigating a variety of methods to ensure cabin warmth in commercially available EVs and PHEVs. Addressing winter operation remains a critical issue for all vehicles within Manitoba.

Maintenance Impacts

During the third year of operation, oil analyses were undertaken on samples from three different vehicles on various separate occasions (Unit #1981, Unite #1982 and Unit #1984), as well as several regular hybrids In most cases, standard oil-change intervals were observed, with 4,000 to 5,000 km on each sample. On one occasion, for Unit #1981, the interval was deliberately extended to 12,000 km to assess impacts. All oil analyses were undertaken by Blackstone Laboratories, based in Fort Wayne, Indiana.

Levels of wear metals in PHEV samples were found to be within normal ranges. The reported TBN (or total base number) values also were good, reflecting the amount of active additive remaining in the oil. Although observed values were obviously more diminished for the long-duration sample on Unit #1981, it too was within acceptable levels.

Given good oil condition, PHEVs may provide maintenance savings in addition to fuel savings. The extent is affected by variability between individual vehicles, and the intervals used for conventional hybrids and other vehicles, which have been changing as well. For initial economic analysis, it was assumed that a conventional vehicle traveling 16,000 km per year would need 4 oil changes (4,000 km interval), whereas a PHEV would need 2 oil changes (8,000 km interval).

The apparent abnormality of high fuel content in the oil continued to be observed. This, however, did not appear to be detrimental. Further investigation of potential maintenance savings is warranted.

Comparative Electricity Consumption - PHEV versus PHV

Vehicle	Air Conditioning On	Air Conditioning Off
Unit #1982 (Converted Prius PHEV)	19.1 ± 1.4 kWh / 100 km (n = 5)	16.0 ± 1.1 kWh / 100 km (n = 5)
Toyota Prius PHV (Factory-built Prius PHEV)	21.1 ± 3.1 kWh / 100 km (n = 5)	16.5 ± 0.6 kWh / 100 km (n = 5)
Average of two vehicles	20.1 ± 2.5 kWh / 100 km (n = 10)	16.3 ± 0.8 kWh / 100 km (n = 10)

Analysis of Variance (ANOVA) Results for Electricity Consumption

Factor	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Probability Value and Resulting Importance
Air Conditioning	1	73.79	73.79	22.58	$P < 0.001$ AC use is very significant statistically
Vehicle Type	1	7.75	7.75	2.37	$P > 0.100$ Vehicles are not statistically different
Interaction	1	2.79	2.79	0.85	$F < 1$ Interaction of main effects is not significant
Error	16	52.29	3.27	Critical $F_{1,16} = 4.49$ for 95% confidence	

What do these statistical analysis results mean?

In order to evaluate electricity consumption, experiments were undertaken in the form of a two-way analysis of variance (ANOVA). Two vehicles were compared, Unit #1982 from the PHEV demonstration, versus the factory-built Toyota Prius PHV; both units with air conditioning (AC) off versus AC on fully. Each vehicle was driven five times separately over the course of approximately two weeks from late-July to mid-August under relatively consistent temperature conditions. Electricity consumption was measured using the PM2 meter. The same driver operated both vehicles, which were driven around 20 km for each trip event. ANOVA is based on assessing F-statistics, which involve ratios of the differences between different test conditions relative to differences (i.e., random errors) within each set of conditions. In order to be deemed statistically significant, these ratios must be higher than "critical" values. The F-statistic for air conditioning was much larger, indicating that the use of air conditioning was significant. On the other hand, the difference between the two vehicles was not significant.

Electricity Use

During the third year of the demonstration, selective monitoring of electricity use was continued using the IPLC-PHEV PM2 device, as developed by Vantera Inc. (see photograph on page 5). Two vehicles were primarily monitored, Unit #1981 and Unit #1982.

Most importantly, during the summer of 2011 electricity used by Unit #1982 was closely monitored in parallel testing with the factory-built 2010 model year Toyota Prius PHV, as described earlier in the side bar on page 16.

Testing was conducted in the form of a two-way analysis of variance (ANOVA) experiment. Each of the two vehicles was driven as entirely electrical as possible, firstly with AC off and then with AC on fully. Five separate drives were undertaken for each combination of vehicle and AC setting. The same driver was involved for all, using a consistent route of around 20 km. All testing was done within a two-week period in late July to early August, involving relatively consistent temperature conditions.

The results are presented in the Tables on page 18, including statistical analysis details. It was found that there was no significant difference between electricity use for the two vehicles. At the same time, there was a significant increase in electricity use when AC was on, roughly 25% higher. With AC off, the vehicles averaged 16.3 kWh per 100 km, and with AC on they averaged 20.1 kWh per 100 km.

The average of these two values was 18.2 kWh per 100 km and corresponded to roughly 50% travel with AC on. This was very close to the value of 18.4 kWh per 100 km cited in the Second Year Report based on very preliminary testing.

In the earlier sections on Fuel Economy and GHG Reductions, the value of 18.2 kWh per 100 km was used for the all-electric component of energy-use for the PHEVs.

The PM2 meter was also used to monitor electricity-use during winter operation, although not as systematically. Electricity use was found to be lower during winter compared to the summer as described previously. Values tended to be in the range of about 10 to 13 kWh per 100 km. The observed behaviour of reduced electricity-use in the cold was very different from all-electric vehicles, for which electricity-use increases in the cold, this obviously due to increased heating requirements.

There were two significant uncertainties regarding reduced winter electricity-use that could not be clarified through the course of the demonstration. Firstly, there were not sufficient data points to directly correlate electricity-use with the ambient temperature. The exact nature of this relationship remains unknown. Secondly, the precise reason for reduced electricity consumption could not be confirmed, in particular whether this was due to reduced energy availability from the battery because of effects of lower temperatures on battery chemistry, or due to reduced energy demand by the vehicle, given that increased engine operation was required in the cold in any event for heating purposes.

Additional Activities

Several additional activities were completed during the final year of the demonstration.

Comparison of PHEV to PHV: The presence of a prototype factory-built Toyota Prius PHV over an entire year under the Toyota Plug-in Partnership program, coinciding with the final year of PHEV demonstration permitted direct comparisons between the two types of vehicles, specifically Unit #1982 from the demonstration (see page 16). As noted in the last section, the electricity used by the two vehicles was not statistically different. This allowed a more meaningful comparison of liquid fuel-use by the two vehicles. Over the course of the year different relative behaviour was observed, yielding important insights for both units.

During both the fall and spring shoulder seasons, fuel consumption was best for the Toyota PHV, roughly 20% to 30% lower than Unit #1982. This appeared to result from much better integration of the battery into the vehicle and its more seamless operation.

During the winter period, both vehicles had much higher fuel consumption. Although not entirely consistent, fuel consumption appeared somewhat higher overall for the Toyota PHV. The better performance of the converted PHEV appeared to result from the fact that specific cold weather upgrades had been undertaken. The Toyota PHV was the same vehicle as used in tests elsewhere in North America, without any changes. During the final summer, both vehicles showed much lower liquid fuel consumption, but again the converted PHEV appeared to be better. Given that electricity consumption did not differ, it made sense that the vehicle having larger battery capacity, in this case the converted PHEV, would operate more on electricity.

Survey of consumer attitudes on electric vehicles: The University of Manitoba Transport Institute undertook the survey, the results of which will be released separately.

Presentations and papers: During the third year of the demonstration three presentations/papers were completed:

R. Hoemsen and R. Parsons. 2010. *Manitoba PHEV Demonstration*. EV2010 Conference, Vancouver, BC. Electric Mobility Canada.

R. Parsons. 2011. *Manitoba PHEV Demonstration: Experience from a Three-Year Collaboration*. EV2011 Conference, Toronto, ON. Electric Mobility Canada.

C. Gregor and R. Parsons. 2011. *Cold-Weather Modifications to Plug-in Hybrid Electric Vehicles for Manitoba Operation*. IEEE Electric Power and Energy Conference, Winnipeg, MB. IEEE.

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Partner Profiles

A123Systems Inc. develops and manufactures advanced lithium-ion batteries and battery systems for the transportation, electric grid services, and portable power markets, and supplied Hymotion Plug-in Conversion Modules for the project (www.a123systems.com).

Centre for Emerging Renewable Energy Inc. is a Manitoba-based non-profit organization, and provided funding administration and project management for the demonstration.

City of Winnipeg Fleet Management Agency is an Agency of the City of Winnipeg that delivers fleet management services to City Departments, and provided one vehicle for conversion (www.winnipeg.ca/fleet/).

Manitoba Hydro is a Manitoba crown corporation and integrated electrical and natural gas utility, and provided two vehicles for conversion (www.hydro.mb.ca).

Manitoba Innovation, Energy and Mines (IEM), through its Energy Division, is responsible for energy and energy efficiency policy, facilitating renewable energy development, and business development for energy product manufacturing; and provided funding and staff-time support for the project (http://www.manitoba.ca/iem/energy/index.html).

Manitoba Public Insurance is a Manitoba crown corporation and public vehicle-insurance agency, and provided two vehicles for conversion (www.mpi.mb.ca).

Persentech Inc. is a Manitoba-based manufacturer of personal sensor devices and solutions for location-based services, and supplied Otto-Link data-logging equipment for the project (www.persentech.com).

Red River College is a Winnipeg-based post-secondary institution, specializing in technology and trades education, and applied research. The College is certified as a Hymotion conversion centre, and staff undertook conversion of vehicles to PHEV. The College provided support to the demonstration as it proceeded, and also made a vehicle (leased through VEMA) available for conversion (www.rrc.mb.ca).

University of Manitoba Transport Institute is based within the Department of Supply Chain Management as part of the I.H. Asper School of Business. The Institute's mission is to facilitate economic prosperity, environmental sustainability, and social advancement. It has been a Canadian leader in research on many complex transportation issues. The Institute undertook a survey on consumer attitudes to electric vehicles as part of the demonstration (http://umanitoba.ca/asper/ti/).

Vantera Inc. is a Manitoba-based manufacturer of intelligent electrical-load management technologies, and provided IPLC-PHEV PM2 units for comprehensive electricity consumption monitoring on selected vehicles (www.iplc.com).

Vehicle and Equipment Management Agency is a special operating agency (SOA) of the Government of Manitoba for fleet management services, and provided five vehicles (four in Government Departments plus one at RRC) for conversions (www.vema.gov.mb.ca).