# Plug-in Hybrid Electric Vehicle Demonstration

October 2010


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

## Manitoba PHEV Demonstration

## Report of Second Year Operations

## 2009/2010

### 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 second of three annual reports, covering the period from September 2009 to August 2010.

### Contents:



## Introduction

### Hybrids and PHEVs

"Hybrid vehicles" are defined most 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.

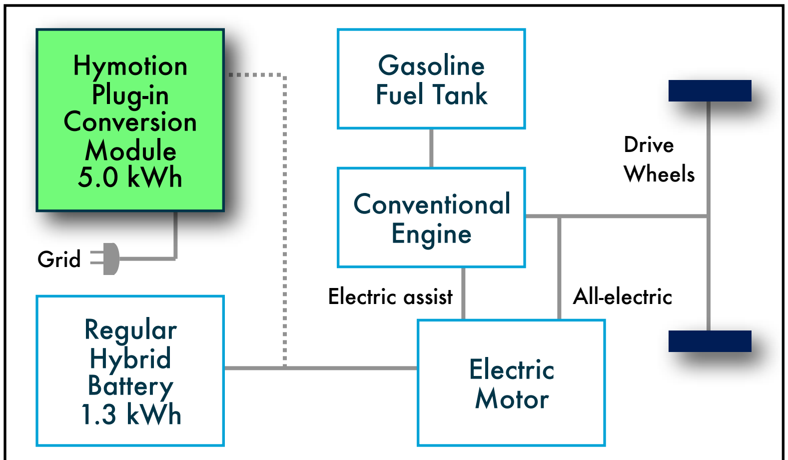
Hybrid electric operation can be implemented in various complex formats. Vehicles can be simply classified as either parallel hybrids, with a direct connection between the conventional engine and the drive wheels, with the electric motor only assisting; or series hybrids, with the conventional engine used solely to generate electricity, 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), like the Chevrolet Volt and Toyota Prius PHV, are anticipated to be available shortly, PHEV technology so far has 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 involves ten Toyota Priuses in Manitoba converted to operate as PHEVs, using Hymotion Plug-in Conversion Modules (PCMs) from A123Systems Inc. Coordination and financial administration is 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 a fully authorized vehicle conversion centre for A123Systems.

Otto-Link data-loggers, manufactured by Manitoba-based Persentech, are installed in each car to monitor characteristics of vehicle use. Installation and testing of IPLC-PHEV meters was also begun in 2010 to interactively monitor electricity consumption at the vehicle while plugged into the grid. This technology is manufactured by Manitoba-based Vantera Inc., and adapted from Vantera's existing Intelligent Parking Lot Controller (IPLC), already in common use in Manitoba and elsewhere.

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

Five different 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 are operating within public-sector fleets in the vicinity of Winnipeg. By agreement with the owners, vehicles are 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.

## Project Objectives

The demonstration has 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.

## Project Timeframe

The first vehicle was converted in late August 2008; the remaining nine vehicles were converted in mid-April 2009. Performance monitoring continues for a period of three years from the first conversion. This report covers the the period from September 2009 to August 2010. A subsequent report will cover the last year.

## Technical Details

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


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

# Demonstration Results

## Major Activities

Six major activities were completed for the demonstration by the end of August 2010, and are summarized in the following points:

1. On-going monitoring using Otto-Link units. Monitoring of the vehicles continued over the second year, in particular to evaluate average trips per day and average travel distance per day. These results are discussed in the next section on Vehicle Use (later on this page).
2. On-going monitoring of fuel consumption. Monitoring of gasoline consumption for all vehicles continued over the second year. This is described later under the section on Fuel Economy, on page 7.
3. Initiation of on-going preventative maintenance activities. Preventative maintenance activities, in particular oil changes, were initiated on selected vehicles at Red River College, with work undertaken by students under supervision. Selected oil analyses were also undertaken to better understand the impacts of PHEV operation on vehicle maintenance.
4. Further cold-weather upgrades. As described later under the section on Temperature Impacts, on page 11, improvements were investigated and implemented to address cabin warming.
5. Cold-weather performance testing. Tests were undertaken during the winter of 2009-2010 using two of the vehicles to better determine the impact of lower temperatures on PHEV fuel consumption performance. This is also described later under the section on Temperature Impacts, on page 11.
6. IPLC-PHEV meter initial implementation and testing. During the Fall of 2009 the first prototype IPLC-PHEV meter was installed on Unit #1982. The purpose of this technology for the demonstration has been to interactively monitor electricity consumption at the vehicle, and, as such, to be able to move between charging locations with the vehicle, rather than being fixed to a single recharging site. Although this specific device was used to gather selected data, its primary role was for testing to identify and permit addressing any operational issues. By the Summer of 2010, the first of the second generation IPLC-PHEV meters was more permanently installed on Unit #1981, as illustrated in the photograph on page 5, and on-going logging of electricity use began on this vehicle. Although only used as a monitor, the IPLC-PHEV meter also has smart-grid capabilities for future application to "intelligent-charging" of PHEV.

## 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 are 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 second 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 second year seven were involved primarily in irregular daily operation, 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 tabulation 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 second 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 poorly correlated (see First Year Report). Nevertheless, based on second year data, two of the vehicles did show strong correlations between these two parameters. These were Unit #1984 ($r^2$ = 0.81) and Unit #1987 ($r^2$ = 0.84). These results made sense given their uses for regular work operation, and 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 7. There are several important observations regarding these travel data:

- Data were missed for one unit.
- 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.
- All units showed significantly lower mean trips per day and shorter mean daily travel distance than for average vehicles as found by researchers at the University of Winnipeg (data on page 5).

## 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 | Primarily Commute |
| #1990 | Pool Vehicle | Irregular Use |

IPLC-PHEV Meter installed in Unit #1981

## 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 | 3.3 trips per day | 3.0 trips per day | 3.2 trips per day | 255 days |
| #1982 | 3.9 trips per day | 4.0 trips per day | 2.7 trips per day | 149 days |
| #1983 | 3.7 trips per day | 4.0 trips per day | 2.5 trips per day | 71 days |
| #1984 | 3.3 trips per day | 1.0 trips per day | 4.8 trips per day | 69 days |
| #1985 | 2.5 trips per day | 2.0 trips per day | 2.4 trips per day | 240 days |
| #1986 | Log data not available | | | |
| #1987 | 0.5 trips per day | 0.0 trips per day | 1.4 trips per day | 68 days |
| #1988 | 1.6 trips per day | 0.0 trips per day | 2.1 trips per day | 192 days |
| #1989 | 3.5 trips per day | 3.0 trips per day | 2.5 trips per day | 150 days |
| #1990 | 3.4 trips per day | 3.0 trips per day | 3.5 trips per day | 111 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 10% to 85% of their mean value. The vehicles could be divided into three categories:

- Units #1982 and #1983 showed the highest mean and median values, and continued from the first year to show results most similar to the study group of vehicles evaluated by the University of Winnipeg.
- Units #1981, #1989 and #1990 all had lower mean and median values, but were all similar to one another.
- All other units show results that are distinctly different.

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 none of the vehicles were similar statistically to the vehicle performance as determined for the larger study group by the University of Winnipeg. Again, the mean values were all lower, ranging from about 15% to 80% of their mean value. Median values were also all lower, with zero values in some cases. The latter is not an error but results from these 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.

- Mean daily travel distances for all units were significantly lower than the average overall travel distance for a Manitoba vehicle of 43 km per day (see side-bar on page 8), with vehicles ranging from 11% to 69% of this value.
- Consistent with the low mean daily travel distances, the total annual travel distances for each of the ten vehicles, as recorded during the second year of operation and summarized later in the Table on page 10, were much lower than the Manitoba average value of 16,000 km, in this case ranging from 32% to 87%. The average annual travel distance for the ten vehicles during the second year was about 9,200 km.
- The median trips per day and median daily travel distance values were zero in some cases.

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

In addition to comparing vehicle-use data for the ten PHEV to regular vehicles in Manitoba, the data for for each unit in the second year were compared to respective data for the first 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 the eight PHEV having data for both years using calculated t- and F-statistics respectively, with results summarized as follows:

- Only three units showed changes in mean trips per day that were statistically significant: Unit #1981, which increased, Unit #1984, which increased, and Unit #1988, which declined.
- Only Unit #1984 showed a statistically significant change in the standard deviation of trips per day, in this case increasing.
- Only three units showed changes in mean daily travel distance that were statistically significant: Unit #1982, Unit #1983, and Unit #1988, which all declined.
- All of the units showed significant changes in the standard deviation of daily travel distance, increasing for three and declining for five.

The most important implications of these results were for Unit #1984, which is the only one used purely for regular work operations. This unit showed the highest fuel consumption during the first year and, as discussed later, also showed the highest fuel consumption during the second year.

Unit #1984 had the second highest annual travel during the second year, with implications described later, but, also, the nature of this unit's use changed from the first year to the second. During the first year it was used entirely on a predetermined route circuit. During the second year this changed to a less defined route activity, but one also involving significantly more stop-and-go operation, with the vehicle turned off at each stop. The annualized travel by Unit #1984 was about the same for the two periods, but with a significant increase in the number of times the vehicle was stopped and restarted, roughly 40% to 50%. Given that this unit was not used on weekends, with zero trips on two of seven days per week, this was also evidenced by the significant increase in the standard deviation of trips per day. Theoretically, the change in use of this vehicle should have led to improved performance and fuel economy, but did not, as discussed later. The results for this unit, however, continued to provide valuable insights into PHEV operation.

The decline in both mean trips per day and mean daily travel distance for Unit #1988 simply reflected that this unit, primarily a pool-vehicle, was driven less. A lack of use was also noted for two other units used as pool-vehicles (i.e., #1986 and #1987). In all three cases annual travel for the second year was in the range of 5,000 km to 5,500 km, substantially lower than any of the other vehicles.

## Fuel Economy

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

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

For gasoline 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 no longer used officially anywhere, 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

# Measured Daily Travel Distance Data for Test Vehicles

| Identifier | Mean | Median | Standard Deviation | Data Points |
|---|---|---|---|---|
| #1981 | 29.6 km per day | 13.0 km per day | 53.2 km per day | 255 days |
| #1982 | 22.3 km per day | 19.7 km per day | 30.8 km per day | 149 days |
| #1983 | 19.2 km per day | 14.2 km per day | 24.1 km per day | 71 days |
| #1984 | 24.7 km per day | 0.2 km per day | 42.5 km per day | 69 days |
| #1985 | 24.9 km per day | 18.6 km per day | 66.7 km per day | 240 days |
| #1986 | Log data not available | | | |
| #1987 | 4.7 km per day | 0.0 km per day | 14.8 km per day | 68 days |
| #1988 | 11.1 km per day | 0.0 km per day | 18.0 km per day | 192 days |
| #1989 | 27.2 km per day | 23.5 km per day | 33.6 km per day | 150 days |
| #1990 | 18.7 km per day | 13.0 km per day | 25.1 km per day | 111 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

permit conversion to desired units (see side-bar Table on page 12).

The prototype IPLC-PHEV units for on-going monitoring of electrical energy consumption were only partially implemented during the second year. Estimates of electricity consumption were prepared (as described later under the section on Electricity Use, on page 17), but it was not possible to fully correlate both energy consumptions together.

The calculated overall fuel economy achieved for each of the ten PHEVs during the second year is provided in the Table on page 12. This involved operation from September 1, 2009 to August 31, 2010. It is important to note that the values for Unit #1981 and Unit #1982 excluded deliberate non-PHEV operations as part of a special test during January 2010 to evaluate the impact of cold weather on PHEV performance (as described later under the section on Temperature Impacts, on page 11).

Overall, fuel economy values ranged from 4.3 to 6.8 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 second year was calculated to be 5.5 Litres per 100 km, translating to approximately 43 MPG. Five vehicles had fuel economy better than this value and five vehicles were worse.

During the first year the aggregate fuel consumption had been calculated to be 4.8 Litres per 100 km. As such, average fuel consumption increased by about 15% during the second year. Fuel economy improved for three of the vehicles during the second year, but was worse for seven of the vehicles.

For all ten units, the second year total annual fuel consumption was plotted as a function of total annual travel distance, as presented in the Figure on page 12. The resulting correlation, also presented, was very strong ($r^2 > 0.92$), particularly for the seven vehicles used for irregular daily work operations. This correlation can be interpreted as meaning that on average a PHEV travelled about 2,000 km all-electrically (i.e., with no gasoline used), then travelled the remaining annual distance solely on gasoline, with a fuel economy of about 7 Litres per 100 km (i.e., from the slope). For the average annual travel distance of 9,200 km, this translated to about 22% being all-electric with resulting aggregate fuel consumption still being 5.5 Litres per 100 km.

Three vehicles showed strong deviation from the correlation on page 12, and they are specifically identified in the Figure. These were the two commuter vehicles (Unit #1982 and Unit #1989), which had noticeably better fuel economy than the overall correlation, and the one regular work operation vehicle (Unit #1984), which consumed noticeably more fuel than predicted by the overall correlation.

Given there was data for only two commuter vehicles, it was not possible to generate a proper separate correlation for these units. The behaviour of the units, however, was reasonably approximated by shifting the correlation line in the Figure to the right, as also illustrated on page 12. The resulting interpretation is that these two units on average travelled approximately 3,500 km all-electrically (i.e., with no gasoline used), then travelled the remaining annual distance solely on gasoline, with the same fuel economy as the other units, of about 7 Litres per 100 km. Based on the average annual travel distance of 9,200 km, this translated for the commuter vehicles to about 38% being all-electric, significantly higher than the average, and with resulting aggregate fuel consumption of 4.4 Litres per 100 km, roughly the average for the two commuter units.

The results for Unit #1984, with the highest fuel consumption of all vehicles, were not positive, but were nevertheless important, given that changes in performance could be reasonably explained. As noted earlier, this vehicle's use changed to a more irregular route, involving more stop-and-go, and, importantly, significantly more restarting of the vehicle. An operating-algorithm characteristic of the Toyota Prius Model Years 2004-2009 is that on start-up, the engine turns-on for a period, partly for engine warming and partly for catalytic converter operation. This appears counter-productive when the intent is to operate electrically, and it is known that Toyota has made modifications in new models to shorten the period. Given this existing algorithm, operating the vehicle over roughly the same overall travel distance, but with significantly more restarts, would lead inherently to increased fuel consumption.

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 two years since the beginning of the project. As illustrated, fuel consumption showed a recurring cyclic pattern, obviously linked to changes in seasonal temperatures, with fuel consumption rising during

# Measured Fuel Economy for Test Vehicles

| Identifier | Travel Distance | Fuel Consumed | Fuel Economy |
|---|---|---|---|
| #1981 | 13,860 km * | 817 Litres * | 5.9 Litre / 100 km |
| #1982 | 9,039 km * | 387 Litres * | 4.3 Liter / 100 km |
| #1983 | 11,317 km | 647 Litres | 5.7 Litre / 100 km |
| #1984 | 13,616 km | 923 Litres | 6.8 Litre / 100 km |
| #1985 | 10,253 km | 623 Litres | 6.1 Litre / 100 km |
| #1986 | 5,100 km | 237 Litres | 4.6 Litre / 100 km |
| #1987 | 5,552 km | 282 Litres | 5.1 Litre / 100 km |
| #1988 | 5,412 km | 260 Litres | 4.8 Litre / 100 km |
| #1989 | 9,566 km | 433 Litres | 4.5 Litre / 100 km |
| #1990 | 8,164 km | 488 Litres | 6.0 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 |

colder months and dropping during warmer months. It is also important to note that for this unit the incremental fuel economy recently achieved the desired A123Systems expectations (i.e. 2.4 Litres per 100 km or better), this during a warmer period. Also important to note is that the best calculated incremental fuel economy so far, about 1.9 Litres per 100 km achieved for Unit #1981 during the first year, has not been surpassed.

The fuel economy results showed commuting to be clearly the best application for the PHEV. As such, a priority for the final year of the demonstration is to shift several other vehicles to a commuter role, in order to verify the advantage.

For comparison purposes, assuming operation of a PHEV as a primarily commuting vehicle, with total travel of 16,000 km, translates to total fuel consumption of approximately 635 Litres of gasoline, 60 Litres of ethanol, and 1,100 kWh of electricity. This compares 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. These values are based on the following assumptions:

- Commuter PHEV travels approximately 38% all-electrically, or about 6,100 km, with electricity requirement of about 18.4 kWh per 100 km (described later under Electricity Use, on page 17).
- Commuter PHEV travels remaining distance, roughly 9,900 km, using gasoline at 7 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 included, with 8.5% of vehicle liquid fuel considered as ethanol.

Using rough consumer prices of $1.00 per Litre for liquid fuel and 7¢ per kWh for electricity, the annual fuel-related operating cost for the PHEV would be about $770. This compares to about $990 for a conventional Prius, and about $2,400 for an average Manitoba vehicle. Currently, given the capital cost of the conversion, in the range of $10,000 to $15,000, no realistic payback could be achieved for the PHEV. At the same time, the fuel economy achieved by the commuter PHEVs, being around 4.4 Litres per 100 km, is among the very best fuel economy achieved by any vehicle of any type under actual Manitoba conditions. The cost premium to achieve this high performance level is not high, and further, the capital cost for PHEV continue to decline as performance and production levels continue to increase.

## 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.

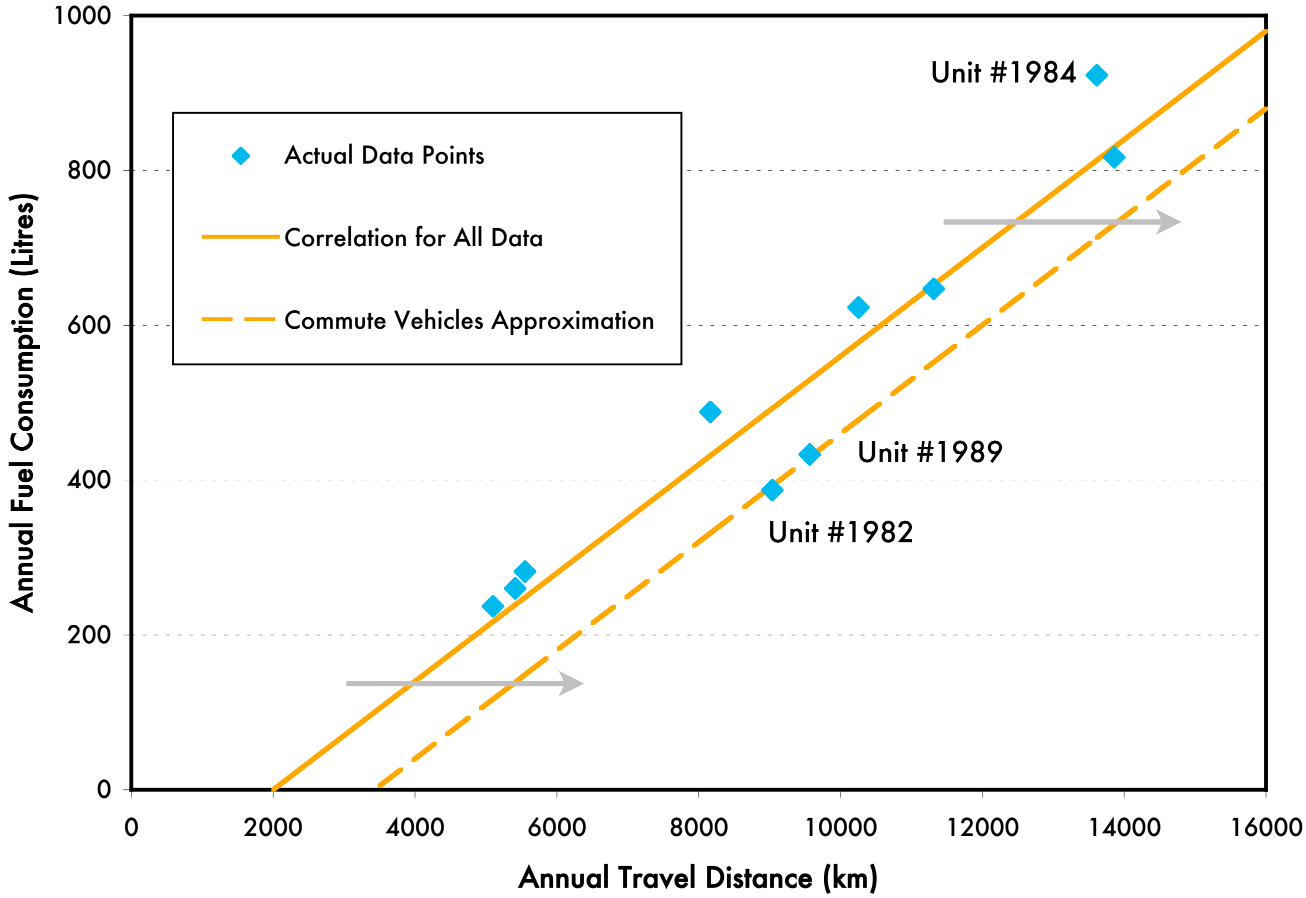
Major assumptions used in these estimates are also summarized on page 13.

The results 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 produces a dramatic reduction. Even compared to the conventional Prius, the PHEV achieves a net reduction of just over about one tonne. The reduction is 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 reduces the apparent reduction.

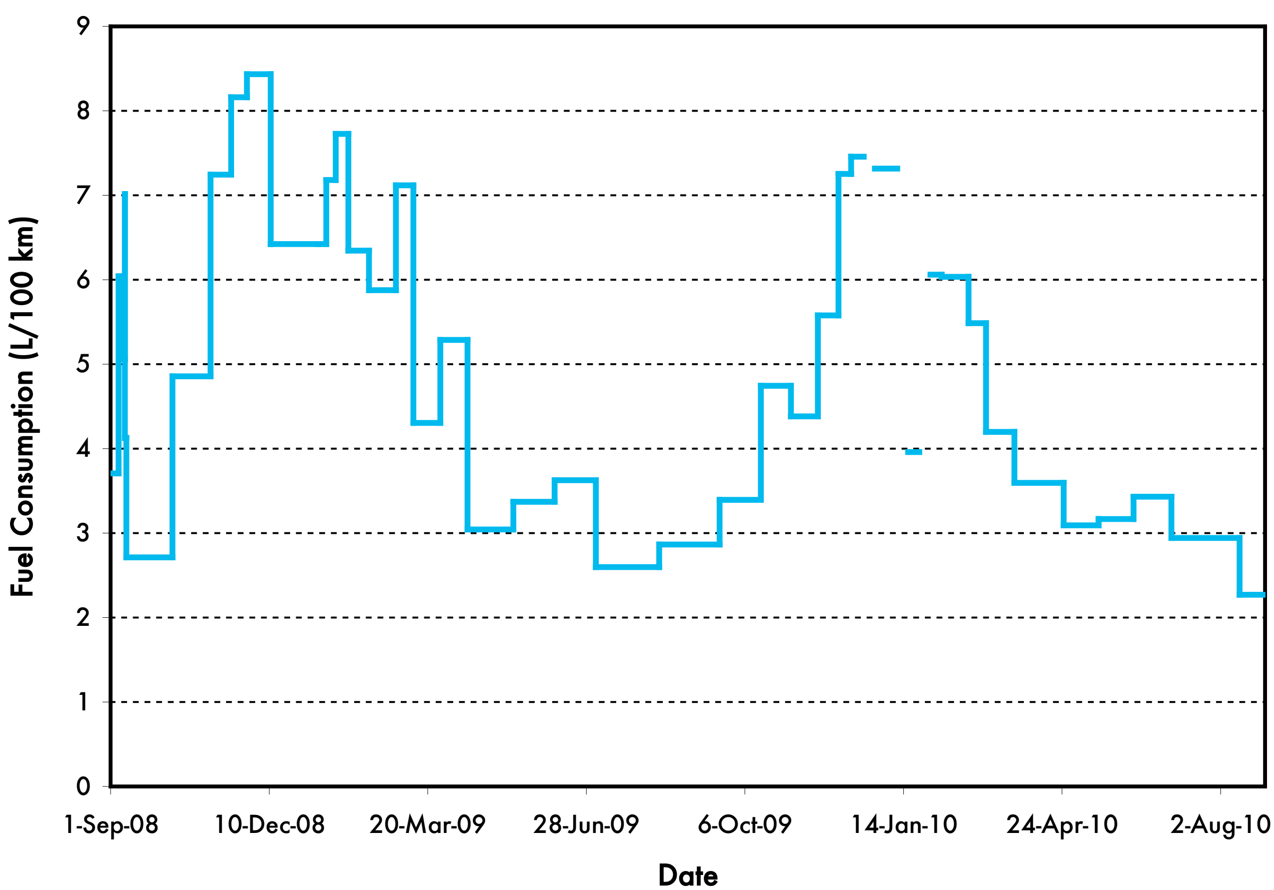
## Temperature Impacts

Manitoba's cold winter-weather presents a challenge to many new technologies, including PHEVs. During the first year of the demonstration, the most critical cold-weather problem identified was with regard to the 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 charge the 12-volt battery whenever the main L5V2 battery was being charged. This solution was implemented on all ten vehicles. During the second winter, no further significant difficulties were encountered on any vehicles. In one case, on Unit #1988, a 12-volt battery problem was encountered during the winter, with the battery drained, however, in this case it was determined that the vehicle had been inadvertently left on.

## Analysis of Fuel Consumption with Distance for All PHEV




## Cyclic Interval Fuel Economy for Unit #1982 over Two 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: 635 Litres<br>Ethanol: 60 Litres<br>Electricity: 1,100 kWh | 2,350 kg<br>80 kg<br>20 kg | 1,460 kg<br>0 kg<br>0 kg | 1,460 kg<br>170 kg<br>20 kg |
| | Total Emissions | 2,450 kg | 1,460 kg | 1,650 kg |
| Conventional Prius Hybrid Electric Vehicle | Gasoline: 910 Litres<br>Ethanol: 80 Litres<br>Electricity: n/a | 3,360 kg<br>110 kg<br>0 kg | 2,090 kg<br>0 kg<br>0 kg | 2,090 kg<br>240 kg<br>0 kg |
| | Total Emissions | 3,470 kg | 2,090 kg | 2,330 kg |
| Average Manitoba Vehicle | Gasoline: 2,200 Litres<br>Ethanol: 200 Litres<br>Electricity: n/a | 8,130 kg<br>270 kg<br>0 kg | 5,060 kg<br>0 kg<br>0 kg | 5,060 kg<br>570 kg<br>0 kg |
| | Total Emissions | 8,400 kg | 5,060 kg | 5,630 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 even 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.

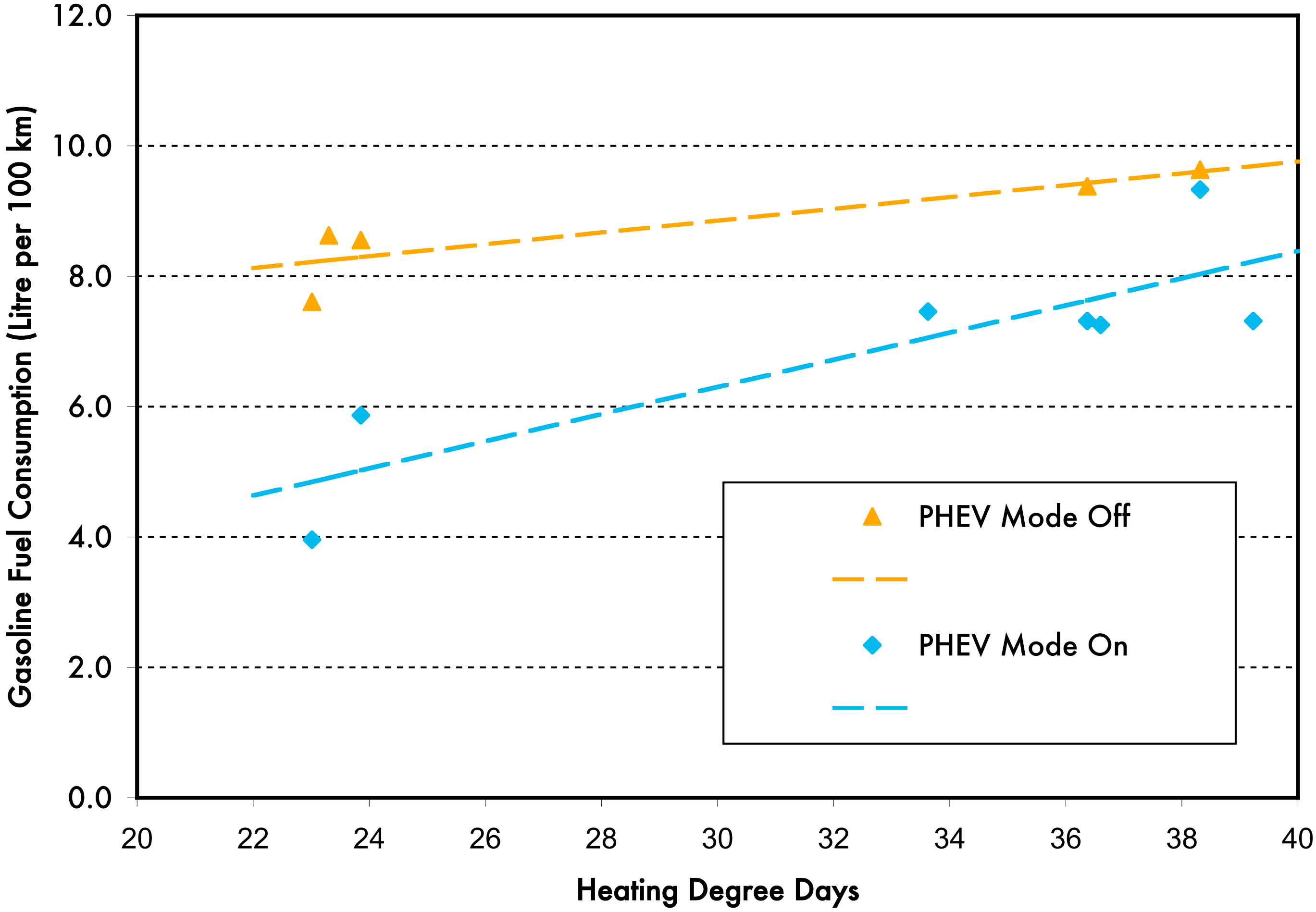
Tank-to-Wheels based estimate methodology:

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.

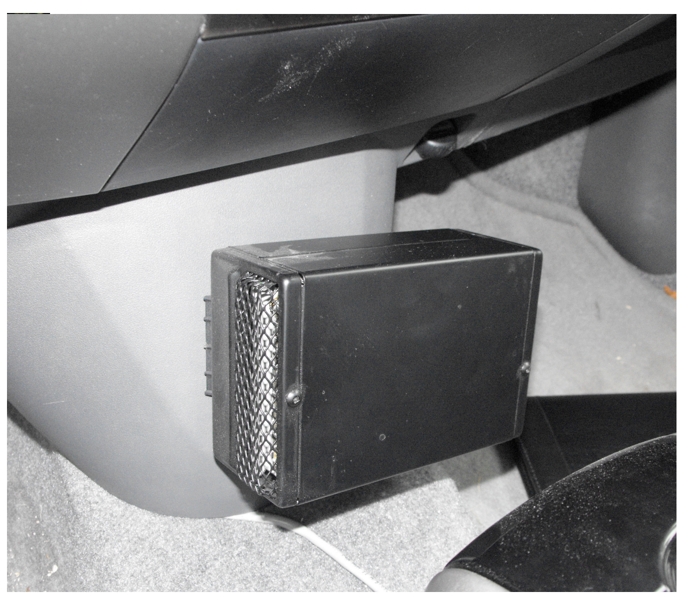
Well-to-Wheels based estimate methodology:

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.

# Test of PHEV Winter Performance - Units #1981 and #1982




What do these data mean?: During winter, the performance with the PHEV mode on was always better than regular hybrid (i.e., lower fuel use), but the benefit of PHEV operation was diminished as the temperature became colder.

Customized winter front cover (left) and electric in-car warmer (right) implemented to address cold-weather cabin heating concerns

During the second winter, the focus shifted to addressing cabin warmth in the PHEVs and better quantifying the impacts of cold weather on PHEV performance.

Cabin warmth: In gasoline-powered vehicles, cabin heating is provided by the engine coolant system, taking advantage of the ample waste-heat produced by internal combustion engines, which even today are relatively inefficient. With the increased efficiency of HEV operation combined with the use of grid electricity for motive operation, less gasoline is consumed by PHEV, but as a consequence there is also much less waste-heat available for warming the cabin.

During the winter of 2008-2009, Unit #1982, which was the first converted to PHEV, was specifically noted to be relatively cold, with the cabin only slowly warming up. In order to address this issue, combinations of two different approaches were implemented on vehicles during the late Fall of 2009.

The first involved implementation of customized winter covers on the fronts of eight of the ten vehicles. (See Photograph on page 14). Two of the cars were normally parked indoors and did not require this. The winter covers produced some incremental improvement, but drivers still noted the units to be cool.

The second measure involved the installation of on-board electric heaters (preheaters) in six of the eight vehicles with winter covers. (See Photograph o page 14). These were tied in with the block heater plug at the front of the vehicle and maintained separate from the main L5V2 battery and trickle charger connected at the rear of the vehicle.

The effect of the heaters for drivers was both substantial and positive. Preheating using these in-car warmers effectively addressed concerns for drivers regarding the vehicles being cold.

PHEV performance: As seen earlier in the plot of incremental fuel consumption over time for Unit #1982 on page 12, the fuel economy fluctuated in a cyclic manner over the year, with fuel consumption increasing during colder weather. In order to better quantify the effect of cold weather on PHEV performance, a test was conducted for a period of six weeks from late December 2009 through to early February 2010 using two of the vehicles (Unit #1981 and Unit #1982). Over this period, on alternating weeks, one of the vehicles was set to PHEV-on, with the other to PHEV-off. At the end of each week, the PHEV mode for the two cars was switched. Each of the two vehicles was refueled each Sunday, with fuel volume and odometer reading recorded. At the same time, the average temperature over each week was determined, as measured by average heating degree days (HDD) from meteorological data for Winnipeg.

The results for this test are presented in the Figure on page 14. As can be seen, these data showed fuel consumption to increase with colder temperature (i.e., higher HDD) for both PHEV-on and PHEV-off, as would be expected. Under all conditions, the fuel consumption for PHEV-on mode was always lower than for PHEV-off mode. But the slope was steeper for the PHEV-on mode, meaning that fuel consumption suffered more for the PHEV-on mode. Thus, although there was always a benefit for the PHEV in terms of lower fuel consumption, the extent of the benefit declined as the average temperature dropped.

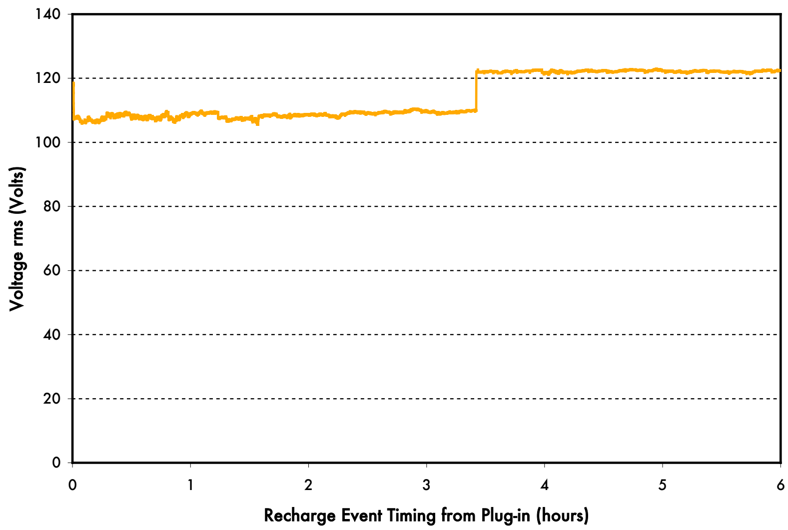
## Maintenance Impacts

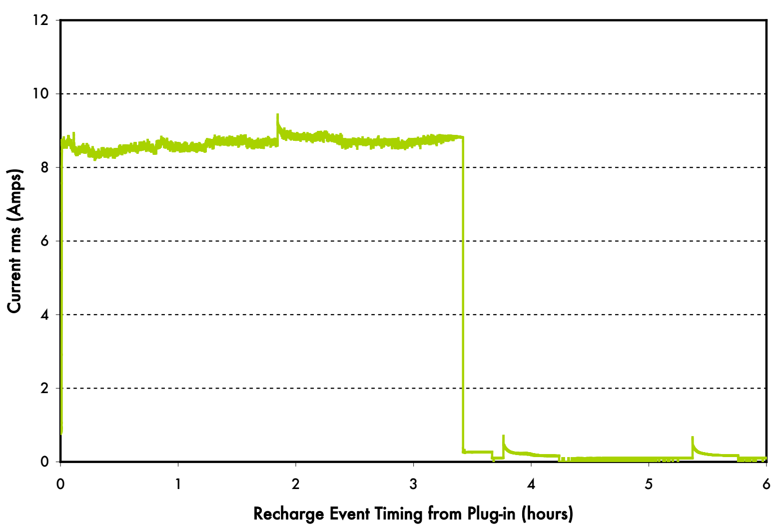
During the second year of the demonstration a problem was encountered with one of the L5V2 batteries that necessitated its replacement, this on Unit #1989. Based on cumulative time on all vehicles to that point, this translated to an aggregate Mean Time Between Failure ($1/\lambda$) of about 64,000 hours or about 8 years. The use of lithium ion batteries in vehicles on a commercial basis is still relatively new, such that it is difficult to judge the relative nature of this performance. However, it is important to note that General Motors recently announced a battery guarantee of 8 years or 160,000 km for the impending commercial release of the new Volt extended range electric vehicle, which is essentially consistent with the performance of the PHEV so far.

Oil analyses were undertaken on samples from two separate vehicles (Units #1981 and #1988). In both cases, standard oil-change intervals were observed, with approximately 5,000 km on each sample. Oil analyses were conducted by Blackstone Laboratories, based in Fort Wayne, Indiana.

All levels of wear metals in each sample were within normal ranges. In both cases, the reported TBN (or total base number) values also were good. This reading reflects the amount of active additive remaining in the oil, and suggested the oil change interval could be extended.

# Electrical Data Plots for Representative PHEV Recharging Event (Unit #1981, August 25, 2010)



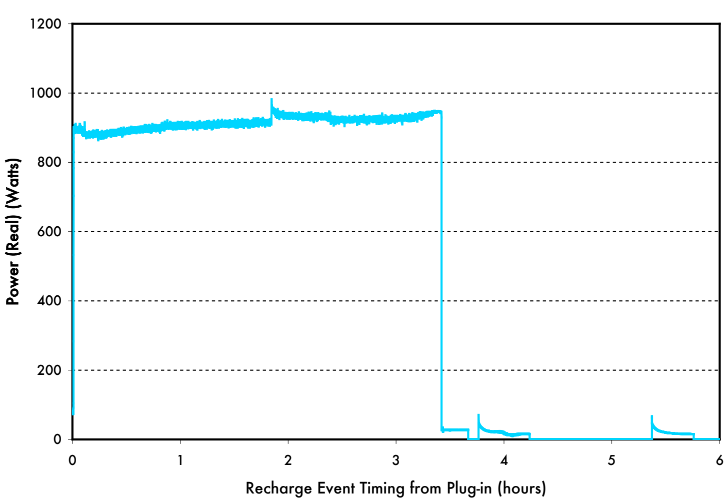



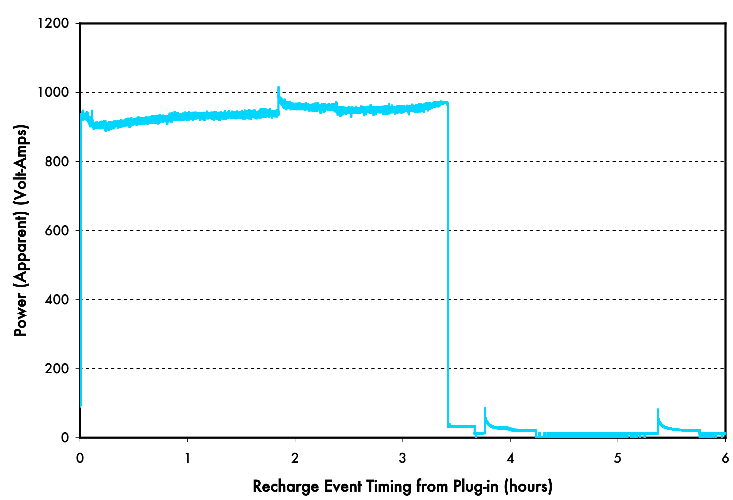

## Recharging Event Summary

Unit #1981 was recharged on August 25, 2010 at a residential location, but not the same location for which plots were illustrated in the first year PHEV report. The recharging event covered a full 12 hour period, but the charging of the main battery was completed within less than six hours. In this case, the PCM was not fully drained prior to plugging-in. The IPLC-PHEV recorded the following data that could be retrieved on a memory stick without any further downloading required:

- Time (seconds);
- Voltage rms (Volts);
- Current rms (Amps);
- Power (Real) (Watts); and
- Temperature (C), with temperature measured external to the meter.

The apparent power could be easily calculated by multiplying voltage times current. Over the entire period, the vehicle was charged with 3.17 kWh (summing power times time for all intervals), with apparent power being approximately 3.33 kVA. As such, the approximate power factor at this residential location was about 0.95. The input power monitored in this case included both the main battery and the 12-volt trickle charger.



Given the good condition of the oil, an important follow-up test being undertaken for the last year of the demonstration is to extend the interval between oil changes on one of the vehicles. In this case, the interval will be extended as much as reasonable, if possible to about 12,000 km, and then the oil retested. Reduced engine running time for the PHEV translates to potentially longer oil and engine life, with reduced maintenance time and maintenance cost benefits.

One abnormality noted in both samples tested was a high level of fuel in the oil: one sample at 3.8%; and the other at 3.3%. The desired level for this parameter is <2.0%. As noted by Blackstone, this condition is not necessarily uncommon, and can be caused by idling or stop-and-go driving. This finding makes sense given the nature of the PHEV, but it was uncertain if this problem was general or specific to the vehicles tested. For all of the converted PHEV, the engine will run for a period of time at startup for engine warming and catalytic converter operation, as noted earlier. In general, a car engine will run fuel-rich when it is cold or first started, and then lean out as it warms up. An important follow-up for the last year of the demonstration is to analyze oil samples from a broader number of vehicles in order to evaluate the extent of this condition.

## Electricity Use

During the second year of the demonstration, work proceeded on the IPLC-PHEV meter. This unit, developed by Vantera Inc., is intended to be used to monitor ongoing electricity consumption and, importantly, to remain with the vehicle and not lose functionality or data when unplugged from the grid, or the vehicle moved to a different charging location, important issues for all types of electric vehicles.

Beginning in the fall of 2009, a prototype IPLC-PHEV meter was implemented briefly on Unit #1982. From experience gained with this meter, improvements were made, and a finalized model was implemented on Unit #1981, as illustrated in the Photograph on page 5.

Given that the IPLC-PHEV units were not yet available for all cars or for a sufficient length of time (i.e. to cover any full refueling interval), it was not possible to comprehensively correlate electricity consumption to gasoline consumption and any associated operating conditions.

Preliminary results were obtained for Unit #1981 while operating in a primarily electric mode over sequential travel intervals. Cumulative data showed electrical energy consumption in this case to be approximately 18.4 kWh per 100 km, or 5.4 km per kWh. This value could not yet be linked with an associated gasoline consumption value, but was reasonable. For example, recent data for the Chevrolet Volt suggest expected electricity consumption of approximately 16 kWh per 100 km.

In the earlier section on GHG Reductions, the value of 18.4 kWh per 100 km was used for the all-electric component of energy-use for the PHEV. If this amount of electricity is assumed to reduce liquid fuel consumption by 7 Litres per 100 km (i.e., slope value for all vehicles on page 12), the offset translates to about 2.6 kWh per Litre of liquid fuel, which is reasonable.

The IPLC-PHEV meter also permits the simple logging of charge profiles. Presented on page 16 are time traces for a representative recharging event for Unit #1981 on August 25, 2010. This event covered a full 12-hour period, but with the PCM having been only partly drained prior to charging. More than 40,000 data points were collected in this case, with logging at 1 second intervals. Four data plots are presented on page 16 for electricity "at the wall plug" going to the vehicle, although foreshortened in this case to only 6 hours, given that main battery charging was effectively completed during that period. Data plots include:

- Voltage (i.e. root mean squared or $V_{rms}$) in volts;
- Current (i.e. $I_{rms}$) in amps;
- Real Power in watts; and
- Apparent Power in volt-amps (calculated from $V_{rms} \times I_{rms}$).

Several important observations can be made from these plots. Firstly, the voltage to the vehicle in this case dropped during the main recharging from 120 volts to about 110 volts (unlike constant voltage in the first year report plot). Secondly, the current going to the vehicle rose up rapidly but without overshooting, and then leveling at about 8.6 amps during the main charging, consistent with the earlier results. Given a lower voltage in this case, the power level was lower, ranging from about 890 to 930 watts. Once the main charging cycle for the PCM was completed, the current did not drop to zero immediately. Further there were several recurrent blips in current, which may have been associated with the 12-volt trickle-charger. Thirdly, the shape of the power curve over the course of recharging cycle again was not quite the same as that observed by others, such as Manitoba Hydro for their beta-test vehicle.

One last important consideration for the PHEV is that electricity use involves more than just the batteries, including a variety of additional loads: trickle-charger; block heater; in-car warmer; computers and other ancillary loads associated with main batteries; etc. A key emerging question is which loads should be considered for the purposes of fuel economy determination? For this project, based on experience so far, only incremental electricity loads associated with motive operation have been included, specifically the main L5V2 battery plus auxiliaries, and the trickle charger, but not the block heater or in-car warmer, given that these devices could be employed on a conventional vehicle.

## Additional Activities

No major additional activities were undertaken in the second year.

### Contacts:

Robert Parsons, Secretary/Treasurer
Centre for Emerging Renewable Energy Inc.
(Non-profit project administrator)
Telephone: 204-945-6077
Email: robert.parsons@gov.mb.ca

Ray Hoemsen, P.Eng., Director of Applied Research & Commercialization, Red River College
Telephone: 204-632-2523
Email: rhoemsen@rrc.mb.ca

### Acknowledgements:

Funding for this project was provided by the Province of Manitoba.

## Next Steps

Over the final year of the project, several activities will be pursued:

- Completing implementation of the IPLC-PHEV units in vehicles, in conjunction with Vantera.
- Continuing to track data, and enhance the quality of data as much as possible.
- Shifting more vehicles, as possible, to a commuter role in order to confirm application advantage.
- Undertaking a survey of user and public attitudes toward PHEVs.
- Pursuing broader analysis of lubricating oil from vehicles.
- Developing conclusions from the demonstration and preparing recommendations for follow-up actions, based on the real-world experience gained.

## 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 providing 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) plays a significant role in the Government of Manitoba's resource conservation efforts by leading and participating in projects that promote renewable energy development, improve energy efficiency and manage resource use to ultimately reduce Manitoba's greenhouse gas emissions, and provided funding and staff-time support for the project (www.gov.mb.ca/stem/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 is providing additional support as the demonstration proceeds, and also made a vehicle (leased through VEMA) available for conversion (www.rrc.mb.ca).

Vantera Inc. is a Manitoba-based manufacturer of intelligent electrical-load management technologies, and is providing IPLC-PHEV units to be used for comprehensive electricity consumption monitoring for all 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).