Cold-Weather Modifications of Plug-in Hybrid Electric Vehicles for Manitoba Operation

C. Gregor, *Associate Member, IEEE*, and R.V. Parsons

***Abstract*--A series of cold-weather modifications that were made to ten plug-in hybrid electric vehicles (PHEV) as part of the Manitoba PHEV Demonstration are presented. These changes, which were all ultimately electrical in nature, involved improving the 12-volt battery system, and addressing cabin warmth. The ten vehicles were operated and monitored for a three-year period ending in August 2011. The modifications significantly improved operation of the vehicles during winter months, ensuring the success of the project.**

***Index Terms*-- electric vehicles; batteries**

I. Nomenclature

PHEV - plug-in hybrid electric vehicle (generic term).
PHV - plug-in hybrid vehicle (Toyota-specific term).
PCM - Hymotion Plug-in Conversion Module.

II. Introduction

In 2008, a ten-vehicle demonstration of plug-in hybrid electric vehicles (PHEV) was initiated in Manitoba. This project has represented one of the largest demonstrations of its kind within Canada over an extended period of time, with vehicle monitoring for a three-year period, ending in August 2011. Two public-domain reports have already been released describing the results of the project over each of the first two sequential years of monitoring. [1, 2]

Given that factory-built PHEV technology was not yet readily available at the start, the project involved ten Toyota Priuses, model years 2004-2009, converted to operate as PHEV using Hymotion Plug-in Conversion Modules (PCMs) from A123Systems Inc. The ten converted Priuses were all operated in the fleets of public-sector agencies in the vicinity of Winnipeg: the Vehicle and Equipment Management Agency (VEMA) of the Province of Manitoba (4 vehicles); Manitoba Hydro (2 vehicles); Manitoba Public Insurance (2 vehicles); City of Winnipeg (1 vehicle); and Red River College (1 vehicle).

Red River College played an integral role in this project. Most of the PHEV-conversions were done by qualified, automotive instructional-staff from the College. Indeed, through this project, Red River College became an authorized vehicle conversion centre for A123Systems Inc. Staff from the applied-research group were also involved, firstly in the collection and monitoring of logged vehicle data, and secondly in the ongoing development of cold weather modifications for the vehicles.

Manitoba has a unique and potentially challenging climate. There are relatively extreme swings in temperature from summer to winter, and, in particular, cold weather conditions during the winter. During the winter, it is not uncommon to have extended periods below -30ºC. Indeed, the northern City of Thompson in Manitoba is a well-established cold-weather testing centre for several major vehicle manufacturers.

Manitoba winter conditions can be problematic for many conventional vehicles. The novel nature of PHEV made cold-weather operation a specific concern. This paper describes two key sets of modifications made to the vehicles, both ultimately electrical in nature, to adapt the PHEV for winter operations. These involved firstly upgrading of the 12-volt battery system on-board the vehicles, and secondly addressing cabin warmth.

III. Upgrading of 12-Volt Battery System

In order to address cold-weather problems associated with the 12-volt battery system of the Prius, two separate modifications were undertaken, as illustrated in the schematic in Figure 1. These involved, firstly, the installation of a more robust 12-volt battery, and secondly, the implementation of a trickle charger system that would automatically recharge the 12-volt battery when the main PHEV battery was plugged into the grid. The 12-volt battery related modifications and results are presented in the following sections.

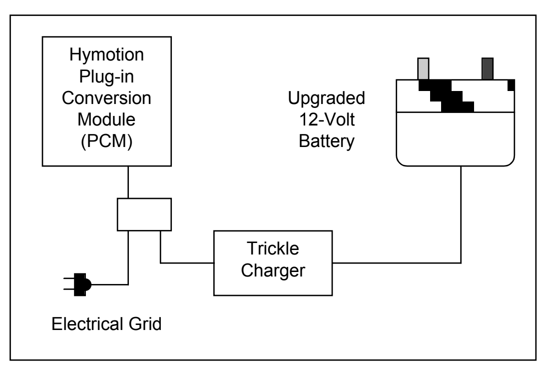

Fig. 1. Schematic of 12-Volt Battery Upgrades for PHEV.

Financial support for the Manitoba PHEV Demonstration was provided by the Government of Manitoba.

Curtis Gregor is Research Technologist with Applied Research & Commercialization, Red River College, 2055 Notre Dame Avenue, Winnipeg, MB, Canada, R3H 0J9 (e-mail: cgregor@rrc.mb.ca).
Robert V. Parsons is Secretary/Treasurer of the non-profit organization acting as project administrator for the demonstration, the Centre for Emerging Renewable Energy (CERE), c/o Suite 1200, 155 Carlton, Winnipeg, MB, Canada R3C 3H8 (e-mail: robert.parsons@gov.mb.ca).

A. Overview of Prius and PHEV Conversion Batteries

The Toyota Prius was used as the base vehicle in this project for conversion to PHEV. It incorporates two separate batteries, a small 12-volt lead acid battery, primarily used for start-up and accessories, and a larger 1.3 kWh nickel metal hydride battery. [3] The latter hybrid or "traction" battery is part of the original equipment hybrid system, operating at a voltage level of over 200 V and providing motive power for the vehicle. This unit was left in the car as part of the conversion process.

For conversion to PHEV, a Hymotion PCM from A123Systems, involving lithium ion technology, was installed in each vehicle. Each PCM has the capacity to store 5 kWh of electrical energy from the grid. The PCM makes additional electricity available for use by the Prius, permitting extended electrical operation beyond what would be normally possible.

B. Prius 12-volt Battery

The Toyota Prius, model years 2004-2009, has been shipped with a standard 28 Ah rated, 12-volt battery. The main function of this battery has been to engage a relay, which in turn powers-on the main hybrid battery. In addition to this main function, the 12-volt battery also provides power to vehicle accessories, including displays and audio systems. Importantly, as part of the PHEV conversion, the 12-volt battery system was initially left unaltered.

Due to both space constraints and the limited functions required of the 12-volt battery, Toyota has opted to use a much smaller unit than is typical for conventional non-hybrid vehicles. But in order to be able to initiate the vehicle's start-up sequence, the 12-volt battery must maintain a voltage level of approximately 10.6 V at minimum. If the voltage drops below the critical threshold level, the relay will not engage, and the vehicle becomes incapable of starting. While it is inconvenient in any location to be stranded in a vehicle that will not start, in Manitoba's winter conditions, this becomes a safety concern as well. Further, in cold-weather, lead acid battery capacity is reduced, further compromising the 12-volt unit.

Anecdotally, the 12-volt battery of the Toyota Prius was known to be a weak-point. For example, it has become standard practice to replace the 12-volt battery in Priuses commonly used as taxis in the Winnipeg area. At the same time, while the operation and performance of the Toyota Prius has been well documented and investigated, including the main hybrid battery, virtually nothing has been reported on the 12-volt battery system of the Prius in academic literature, in particular 12-volt battery problems.

C. 12-volt Battery Problems

One of the ten Priuses was converted to PHEV earlier than the others, during Fall 2008, by personnel from A123Systems. This was done in part as a means to pre-test vehicle winter performance. Staff from Red River College was involved as observers, with the remaining nine conversions being undertaken later, in April of 2009, by Red River College staff.

Operation of the first PHEV during the winter of 2008-2009 exposed serious problems with the 12-volt battery system on-board the vehicle. A complete failure of the first PHEV occurred during one particularly cold period in December 2008, keeping the vehicle out of operation for more than one-week. It was further identified that the 12-volt battery problems had been worsened by the installation of a data logger on the CAN-bus of the vehicle that exerted a constant power draw on the 12-volt system. As such, it was clear that the existing 12-volt battery on its own was incapable of maintaining the necessary threshold voltage to permit start-up of the vehicle, and preventing a vehicle failure. Upgrades to the first vehicle's 12-volt system were undertaken in December 2008, and these changes were duplicated for the other vehicles in April 2009.

D. Selection of Appropriate Replacement 12-Volt Battery

The selection of an appropriate, more robust replacement 12-volt battery for the PHEV was based on three main technical criteria, outlined in Table I. These were intended to reflect the desired outcome whereby the 12-volt battery would maintain a minimum threshold voltage for start-up under Manitoba conditions.

TABLE I
CRITERIA FOR SELECTION OF REPLACEMENT 12-VOLT BATTERY

Criterion	Description
Dimensions	Battery needed to fit within available space, with contact terminals in the same locations.
Capacity	Battery needed to have sufficient amp-hour capacity.
Performance in the Cold	Battery needed to be able to perform well under expected cold-weather conditions.

As part of its Prius Owner's Manual, Toyota does not actually provide a size specification for the 12-volt battery, i.e. Battery Council International (BCI) group number. [3] As part of technical training information, however, they do confirm that it involves absorbed glass mat technology, is sensitive to high voltages, and requires the current for any trickle charging system to be maintained at less than 3.5 A. [4]

Based on the criteria above, the Optima "Yellow-Top" D51 battery was selected for use in the PHEV. Although lead-acid based, this battery uses spiral cell technology that has deep cycle characteristics and a 38 Ah capacity. Detailed specifications are available from the manufacturer. [5]

E. Replacement Battery Implementation

The selected Optima D51 battery fit comfortably in the position of the stock Prius 12-volt battery. Two new 254 mm battery cables were also purchased for each battery. The stock Prius negative battery cable was too small to be reused on the new battery. Also, within the Prius, there is no positive cable attached to the terminal, only a battery clamp. The positive clamp was carefully removed and one new cable was then fixed to the attachment point using the original bolt. The negative battery cable was a straight swap in the original location.

F. Selection of Appropriate Trickle Charger

Given potential stress on the 12-volt battery system, particularly due to the data-logger, a trickle charger was also installed, as a redundant solution. The selection of an appropriate trickle charger for the PHEV was based on five technical criteria, outlined in Table II.

TABLE II
CRITERIA FOR SELECTION OF TRICKLE CHARGER

Criterion	Description
Size	Trickle charger needed to be compact and to fit in the available space in the rear cabin area of the Prius.
Adequate Temperature Limit	Trickle charger needed to able to operate at sufficiently low temperatures, as would be encountered in Manitoba.
Suitable Connectors	Trickle charger needed to be hard-wired to the 12-volt battery, not just "grip clamps."
Maximum Current	Trickle charger needed to have maximum charging current of no higher than 3.5 A.
Automatic Operation	Trickle charger needed to activate "automatically", without the general need for operator initiation.

Based on the criteria above, the CTEK 3300 3.3 A battery charger was selected for use in the PHEV. Detailed operating information and technical data are available from the manufacturer. [6]

G. Trickle Charger Implementation

The external plug-in connection for the A123Systems PHEV conversion is located on the rear bumper on the driver-side, but employing only a standard three-prong connector rather than a SAE J1772 based connector. Rather than linking the cord from this connection point directly to the Hymotion PCM, an intermediate junction box was installed in the rear lower compartment, permitting two output lines to be plugged-in: Hymotion PCM; and 12-volt trickle charger. The trickle charger itself, as illustrated in the photograph in Figure 2, was mounted on the top plate in the passenger-side corner of the rear luggage compartment, this in order to permit operator access if required.

Fig. 2. Positioning of trickle charger in rear luggage compartment of PHEV.

H. Performance of 12-Volt System Upgrades

Overall the upgrades were highly successful. All ten PHEV were driven through the winters of 2009-2010 and 2010-2011 as part of the project with the upgrades in place, resulting in generally problem-free operation. Short-term cold-weather failure incidents were still noted for three vehicles, but in all cases these could be readily explained. In two cases the vehicle had been left unplugged and/or was not driven for a long period of time. In the third case, the trickle charger had been deliberately disconnected for assessment purposes, and the vehicle had been left outside at -30ºC for several days. In all cases simply plugging-in the trickle charger for a few hours corrected the problem. For the PHEV, constant awareness of and attentiveness to the 12-volt system is required in cold weather, however, this is no different than for conventional vehicles.

IV. ADDRESSING CABIN WARMTH

In order to address cabin warmth in the PHEV, two separate modifications were undertaken. These involved, firstly, the installation of customized winter-covers for the fronts of the vehicles, and, secondly, the installation of electric in-car warmer units operated when the PHEV were parked and plugged-in. Cabin warmth-related modifications and results are presented in the following sections.

A. Cabin Warmth Problems with Prius and PHEV

In conventional gasoline-powered vehicles, cabin heating is provided from the engine coolant system, taking advantage of the ample waste-heat produced by internal combustion engines, which even today remain relatively inefficient. An unintended consequence of the increased efficiency of hybrids and PHEV is that decreased gasoline consumption also means there is much less waste-heat available for warming the cabin, and defrosting/defogging windows.

During the winter of 2008-2009, the first unit converted to PHEV was found to be cold by drivers and passengers. The cabin warmed up only slowly. Even with the heater controls set to maximum level, it could still take 15-20 minutes to adequately heat-up the interior of the car. This also meant having the gasoline engine run almost continuously, significantly defeating the purpose of the PHEV to reduce gasoline consumption. In preparation for the second winter, options to address cabin warmth were investigated, and implemented in the late Fall of 2009/early Winter of 2010. One option that was investigated, but could not be implemented was to change the thermostat of the vehicle.

B. Custom Winter Covers

For eight of the ten PHEV, customized winter covers were fabricated and installed in order to cover the upper and lower grill openings on the front of the vehicle. The intent of a winter cover in general is to reduce air-flow and thus to permit the coolant system to operate at an increased temperature. The winter covers were found to be of some benefit, but not nearly as successful as the in-car warmers discussed next.

C. Electric In-Car Warmers

For six of the ten PHEV, an electric in-car warmer was installed in the cabin, in addition to the winter covers described earlier. One of these units is illustrated in the photograph in Figure 3.

Fig. 3. Electric in-car warmer mounted in PHEV.

The in-car warmers were purchased off the shelf from a local automobile parts supplier. Each unit was installed with two screws at the base of the lower dashboard area between the driver and passenger positions. The power wires were routed out through the firewall and around the engine to the front of the car. This wire was connected into a "T" plug along with the engine block heater, such that both were fed from a single connection.

The general intent was for the front connection to be plugged in at night along with the block heater, potentially using a timer to reduce the operating period to 2 to 4 hours prior to start-up. In some cases, i.e., for PHEV left outside at all times, the front connection, including the in-car warmer, was plugged-in at all times when the vehicle was not being operated.

The impact of the in-car warmers was immediate and significant. These units kept the vehicles substantially warmer, easing the burden on the engine system to provide heat. Several drivers and passengers who had used vehicles prior to and after installation of in-car warmers commented on the improvement achieved.

Importantly, the use of electric in-car warmers has broader implications and benefits than just for PHEV, as a means to reduce gasoline consumption and associated greenhouse gas (GHG) emissions. The last decade has seen increased use of remote-start systems for cars. These remote-starters can be useful and convenient for drivers to pre-heat (or pre-cool) vehicles prior to operation, but their use results in significant engine idling, wasted fuel and unnecessary emissions. The use of electrical pre-heating (or pre-cooling) systems instead can, in general, reduce fuel consumption in favour of electricity from the grid. Such a transition is of particular benefit in jurisdictions such as Manitoba, having a high-renewable content grid mix.

V. Multiple Vehicle Electrical Loads

The adaptations meant that the PHEV each had up to four separate, identifiable electrical loads: main Hymotion PCM; 12-volt battery trickle charger; block heater; and in-car warmer. The two battery loads were directed to a common connection point at the rear of the vehicle, while the two heating loads were directed to a common connection point at the front of the vehicle. This arrangement was fortuitous in that it led to important observations regarding the nature of the associated electrical loads for the PHEV.

During the winter, it became clear that roughly five times more electricity could be used for heating a vehicle than for charging its batteries for motive operation, i.e. up to 25 kWh per day for heating, while plugged-in, versus up to 5 kWh per day for batteries. Although heating requirements could be significantly the greater of the two, importantly, this load was no larger than what could be already experienced for a conventional vehicle with a block-heater. As such, PHEV heating would not represent, overall, a new electrical load.

The nature of loads and positioning of connections for the PHEV required two separate circuits during the winter. Electricity consumption was discretely monitored for vehicles, but only considering that to the main Hymotion PCM and the 12-volt trickle charger (i.e., at rear of vehicle). Although the trickle charger load was small, it too ultimately displaced gasoline consumption, and thus was legitimate to consider.

Although there were up to four separate electrical loads for each PHEV, the experience from the demonstration showed that these loads could be serviced from a single, Level 1 (i.e., 110 V, 15 A) charging point, as long as the loads could be intelligently sequenced. The Hymotion PCM desirably would be charged at initial plug-in, for roughly 4 to 6 hours, so that it would be subsequently available when needed. The heating loads on the other hand, would be most important for the hours prior to starting the vehicle, to ensure warmth when needed by the driver. The trickle charger was found to have a small and intermittent load that could be essentially "fit-in" where available.

It is also important to be able to identify and distinguish electricity used for motive battery charging versus vehicle heating. This was inherently accomplished for the PHEV due to the two separate connection points. The potential value of electricity for these different uses can be substantially different. Also, as noted for Manitoba, electricity used to support the vehicle-heating load is not necessarily incremental. Distinguishing electricity for batteries versus heating may be particularly important for new PHEV or all-electric vehicles, which only have a single electrical connection point.

VI. General Need for Cold-Weather Adaptation

The cold-weather improvements undertaken at Red River College for the PHEV turned out to be an important success factor for the Manitoba PHEV Demonstration. Without these modifications, vehicle failures and reduced performance would have resulted.

An important illustrative comparison of the importance of cold-weather modifications occurred with the demonstration in Manitoba of a factory-built 2010 Toyota Prius Plug-in Hybrid Vehicle (PHV), as part of Toyota's Plug-in Partnership program in North America. [7] The demonstration of this vehicle, involving Manitoba, Manitoba Hydro and the University of Manitoba began in July 2010. In general, during the Fall of 2010, it was found that the factory-built Prius out-performed the converted PHEV in terms of lower fuel consumption during the shoulder season. However, during the mid-winter of 2010-2011, the reverse situation seemed to occur. Although not always consistent, on many occasions the converted PHEV had lower fuel consumption than the factory-built PHV under the same temperature conditions. Importantly, no special modifications had been made to the factory-built PHV. Although not entirely clear, given other driving-related factors obviously being involved, the fact that cold-weather adaptations were made in one case but not the other appeared to contribute to the observed results. More detailed follow-up evaluation is warranted to confirm relative cold-weather impacts.

The Manitoba PHEV Demonstration showed the importance of evaluating and implementing cold-weather adaptations for individual types of vehicles, in order to ensure optimal operation. Recently, the creation of a new Electric Vehicle Technology and Education Centre (EV-TEC) was announced at Red River College. [8] One of the key functions of the new EV-TEC will be to understand cold-weather impacts and to investigate suitable adaptation of vehicles.

VII. References

[1] Manitoba PHEV Demonstration Report of Second Year Operations. Available: http://www.gov.mb.ca/stem/energy/transportation/index.html

[2] Manitoba PHEV Demonstration Report of First Year Operatons. Available: http://www.gov.mb.ca/stem/energy/transportation/index.html

[3] Toyota. Pruis: 2008 Owner's Manual, pp. 465,468.

[4] Toyota Technical Training, Toyota Hybrid System Course 071, High Voltage Battery, pp. 3-8-3-9. Available at site (with permission of manufacturer): http://www.autoshop101.com/forms/Hybrid03.pdf

[5] Optima Batteries. 2008. Product Specifications, Model D51. Available: http://www.optimabatteries.com/_media/documents/specs/D51_D51R.pdf

[6] CTEK Sweden. Battery Charger for Lead-Acid Batteries. Available: http://ecee.colorado.edu/~ecen4517/components/US3300_en.pdf

[7] Government of Manitoba. 2010. Manitoba to put Toyota's new Prius Plug-In Hybrid Electric Vehicle to the Test. Available: http://news.gov.mb.ca/news/index.html?archive=2010-07-01&item=9220

[8] Government of Manitoba. 2011. Selinger Government partners with Industry, Red River College to Develop Electric Vehicles. Available: http://news.gov.mb.ca/news/print,index.html?item=11342

VIII. Biographies

Curtis Gregor holds a diploma in Electronics Technology from Red River College, and is an Associate Member of IEEE. He is currently Research Technologist with the Applied Research & Commercialization group at Red River College. He undertook evaluation and implementation of cold-weather modifications for the Manitoba PHEV Demonstration. He is also involved with a variety of applied research projects in sustainable infrastructure.

Robert V. Parsons holds technical degrees in engineering from the University of Calgary, and a Master of Business Administration (MBA), with Distinction, from the Schulich School of Business, York University, Toronto. He currently acts as Advanced Energy Projects Manager with the Energy Division of Manitoba Innovation, Energy and Mines, and is the Secretary/Treasurer of the non-profit Centre for Emerging Renewable Energy Inc. (CERE). Parsons acted as the overall Project Manager for the Manitoba PHEV Demonstration.