ECOLOGIC VEHICLES • RENEWABLE ENERGIES
MONACO
March 26-29 2009

Plug-In Hybrid Electric Vehicle (PHEV) Québec Test Program: A Major Real-World Test Study on Financial, Technological and Social Aspects of PHEVs.

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Abstract: *Plug-In Hybrid Electric Vehicles (PHEVs) are a promising alternative to conventional gas-powered vehicles. Nonetheless, their viability and potential to penetrate the automobile market is still unproven. This paper describes the PHEV-Québec test program, a recently launched major study on PHEVs, which will conduct real-world tests to examine their market potential, simultaneously accounting for technical, financial, human-behavior, and environmental factors. We will do this by evaluating a fleet of PHEVs driven by their owners in Quebec City. Moreover, using Quebec Université Laval's own electrical grid, we will account for vehicle-to-grid interactions. After the presentation of the project's main focus, some experimental results are discussed, including a comparison of the performance of a PHEV and a similar HEV.*

Keywords: Plug-In Hybrid Electric Vehicle (PHEV); Hybrid Electric Vehicle (HEV); Real-world field tests; Vehicle-to-grid infrastructure; PHEV fuel economy.

1. Introduction

The environment and energy security threat posed by the world's dependence on petroleum for transportation is well established. Current transportation research focuses, among other areas, on finding low-emission, practical, affordable, and sustainable alternatives to gasoline-powered vehicles. Among all existing alternatives, the Plug-In Hybrid Electric Vehicle (PHEV) may be one of the most promising [1][2].

A PHEV is a Hybrid Electric Vehicle (HEV) having the ability to recharge its battery pack from an electrical off-board source such as the utility grid (Fig. 1). As with a conventional HEV, a PHEV can drive in a charge-depleting mode to reduce its fuel consumption.

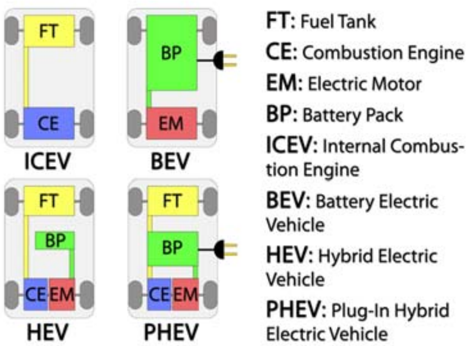


Fig. 1: ICEV, BEV, HEV and PHEV architectures

Depending on the technology used, it can also drive solely on electricity. PHEVs combine the advantages of both HEVs and Battery Electric Vehicles (BEVs) while mitigating their drawbacks. PHEVs battery capacities are usually larger than those of HEVs resulting in low fuel consumption. Despite higher fuel consumption, PHEVs battery cost and recharging time are reduced when compared to BEVs without penalizing driving range.

PHEVs are seen as a promising solution for reducing greenhouse gas (GHG) emissions. In 2007, the Electric Power Research Institute (EPRI) jointly with the Natural Resources Defense Council (NRDC) presented a nationwide (USA) scenario-based modeling analysis of the GHG emissions impacts of PHEVs over the timeframe of 2010 to 2050 [3]. The study accounted for the emissions from the generation of electricity to charge PHEV batteries and from the production, distribution and consumption of gasoline and diesel motor fuels. Various PHEV fleet penetration rates were also taken into account. In terms of GHG emission reduction, the study finds that PHEVs offer a 40% to 65% improvement over conventional ICEV and a 7% to 46% improvement over HEVs. Even in the case where PHEV penetration rates are low and CO2 emissions from electricity production are high, cumulative GHG emissions were still reduced.

PHEV adoption could also lead to a significant reduction in the consumption of petroleum fuels. Thanks to its larger battery pack and ability to charge from the grid, PHEVs can have very low fuel consumption. A 4 month nationwide study in the U.S. [8] reports fuel economy numbers ranging from 2.4 to 4.5 L/100 km, measured over various trip distances on a PHEV fleet of 7 vehicles. Table 1 below reports fuel consumption for our Toyota Prius PHEV (*PHEVα*, see section 3), obtained from experimental tests for various driving profiles conducted in summer 2008. The lowest fuel consumption numbers are obtained by using the Prius' all-electric mode for speeds below 50 km/h.

Another feature of a PHEV is its vehicle-to-grid (V2G) capability. Equipping PHEVs with a bi-directional connection to the electrical grid offers new opportunities for both transport and power generation sectors. A PHEV fleet represents a considerable distributed energy storage capacity that can exchange energy with the utility grid and then allow for a better use of existing electric production capacities [2]. While parked, the energy contained in a PHEV battery pack can be used during peak power periods or for ancillary services [4]. Similarly, the V2G technology may be used to support emerging renewable power source as storage for intermittent energy sources like wind energy [4].

Table 1: *PHEVα* measured fuel consumptions for various driving profiles (summer 2008).

Distance after full recharge [km]	Mean speed [km/h]	Mean fuel cons. [L/100 km]
22	15	1.6
25	48	2.6
41	75	2.8
45	73	1.9
47	94	3.5
47	71	2.5

Up to now, PHEVs are not commercially available. Though many major car manufacturers are developing the technology (General Motors, Toyota, Chrysler, etc.), few companies currently offer PHEV upgrades from existing HEVs platforms (some conversion companies include: Hymotion, Hybrid Plus, OEMtek, etc.). A comprehensive state of art on PHEVs as well as the description of some existing PHEV conversions can be found in [2].

Although very attractive in theory, the PHEV success is not simply a question of technology: it must be commercially viable. In the literature, the potential and performance of PHEVs are typically evaluated using simulations, models [3-6], or laboratory tests such as standardized fuel consumption and emission tests [7]. However, the PHEV technology cost-benefit equation is strongly influenced by a range of factors that cannot easily be taken into account in simulations, or reproduced in laboratory. For example, models or test benches cannot easily consider factors such as climate, driver habits, battery technology and costs, which will likely affect the price, performance and the attractiveness of PHEVs. Similarly, it's difficult to evaluate the real impact on electrical loads using assumptions on consumer charging behavior. Up to now, very few real-world field studies can be found in the literature. For example, [8] presents fuel economy and charge depletion data collected from a PHEV fleet of 7 vehicles. Given this scarcity, there is a need for more real-world, large-scale tests.

This paper describes the PHEV-Québec field-test, a recently launched major study on PHEVs, which will conduct real-world tests to examine their market potential, simultaneously accounting for technical, financial, human-behavior, and environmental factors. We will do this by evaluating a fleet of PHEVs driven by their owners in Quebec City. Moreover, using the university's own electrical grid, we will account for vehicle-to-grid interactions. After the presentation of the project's main focus, some experimental results are discussed, including a comparison of the performance of a PHEV and a similar HEV.

2. PHEV-Québec test program main focuses:

The objective of the program is to respond to the lack of real-world experimental studies on PHEVs. Our fleet will consist of PHEVs owned by their drivers and operated in and around Quebec City and Université Laval (both are in the province of Quebec in Canada, Fig. 3 is a map of the campus.) and accounting for V2G interactions using an independent 22 MW electrical network.

Fig. 2 shows the 3 main focuses of our test studies as well as the principal aspects that are going to be analyzed. Ongoing works and test procedures are detailed in this section.

A. Engineering concerns.

The price and performance of PHEVs will have a strong influence on public acceptance and therefore the technology's marketability. As a consequence, future PHEV systems will have to offer characteristics that match customer expectations at lowest reasonable price. From an engineering perspective, human behavior, technical and climate aspects greatly affect the price and performances of a PHEV. PHEV-Québec examines the influence of such factors (Fig. 2) to evaluate various PHEV technologies.

The battery technology used in a PHEV will affect its overall price and performances. The majority of existing commercial PHEV conversions uses Li-Ion batteries (Hymotion systems, Hybrid Plus, OEMtek use Li-Ion Nanophosphate) mostly for their high energy density and good cycle life. Unfortunately, this battery technology is also rather expensive. As a consequence, the price of a PHEV system is mostly defined by the cost of its battery energy installed in the vehicle. Current commercial conversions costs range between 10 000 and 20 000 USD. This research is going to consider various types of battery technologies as well as different battery pack size to identify the optimal battery cost to fuel economy trade-off. Our first PHEV has been equipped with a 5.6 kWh Li-Ion Manganese battery pack to balance performances and affordability.

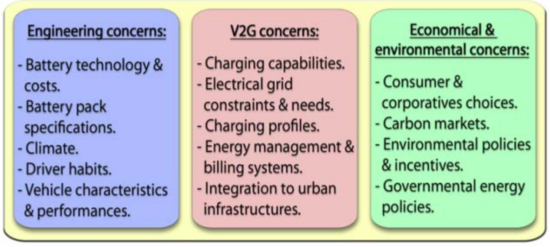


Fig. 2: PHEV-Québec test program main focuses.

The climate will also affect the performances of a PHEV. Battery performance is often influenced by the temperature. In a PHEV, this can result in higher fuel consumption as shown in [9]. Our study will be conducted in a climate with a large temperature gradient allowing for various test conditions.

The performances of a PHEV are also significantly affected by the driver's behavior. In [8], field tests performed using 7 similar PHEVs show variations in fuel economy numbers over similar trip distances: this is especially true for short trips (frequent start-stop sequences) and is explained by the variance in drivers throttle aggressiveness. Similarly, the optimal size of a PHEV battery pack depends on how the driver uses the car. Our field-tests of PHEVs using driver/owners, will help us make statistical inferences, identify driving trends and determine optimal PHEV systems patterns.

Existing HEVs provide an excellent platform for testing PHEVs as the conversion mainly consists in adding/changing a battery pack and some electronics. Although every HEV can be converted into a PHEV, certain types of vehicles seem somewhat more popular for conversions. Hymotion, Hybrid Plus, and OEMtek, as well as many other conversion projects tend to favor the Toyota Prius principally for its popularity but also for its unique HEV architecture. This research intends to develop a PHEV fleet mainly constituted of Toyota Prius conversions.

B. V2G concerns.

The plug-in capability brings a new dimension to both transport and power generation markets: To plug-in where electricity is available and to put it back to the grid if necessary. Previous work has been done (as in [4]) to evaluate PHEV/ V2G viability. This research focuses on real-world bidirectional network viability. The latter is addressed according to PHEV-Québec requirements and worldwide standards. Specific

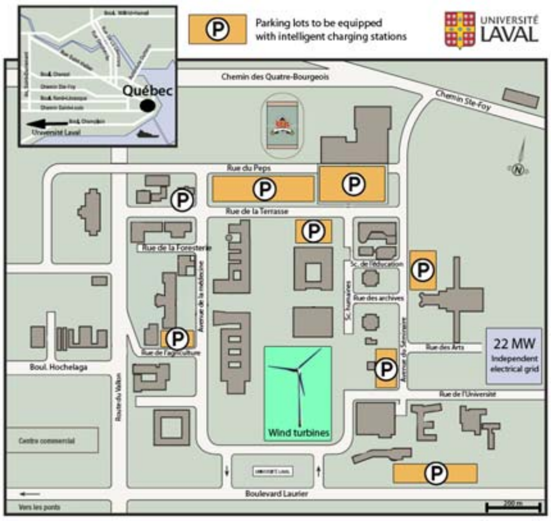


Fig. 3: Intelligent charging stations to be installed on the Université Laval's campus.

Fig. 4: PHEV-Québec charging station initial design.

aspects (Fig. 2) are taken into account in our viability evaluation as described below.

As explained above, this research is performed using Université Laval's campus infrastructure (Fig. 3). It has the following characteristics:

- 22MW capacity;
- Isolated from the public grid;
- Many parking lots;
- Installed wind turbines;
- 6MW controllable load resistor (boiler).

The campus is going to be equipped with charging stations, which will be placed as depicted in Fig. 3. Their number will gradually increase to 50 over the next 4 years.

The PHEV-Québec's charging stations must allow both a slow charging (overnight charge) and bi-directional fast-charging rates. The first one allows recharging PHEVs that are equipped with conventional 120VAC outlets complying with Level 1 SAE standards [10]. To achieve fast charging complying with various battery pack sizes (i.e. various PHEV systems), charging stations should also be equipped with SAE Level 3 plugs. Every charging station has to be supplied with the necessary power electronics for bidirectional energy exchanges.

In this research, charging stations will be equipped with an interface for energy management and a billing system. For the needs of the study, an embedded communication system is also mandatory for gathering charging data.

A study of existing commercial chargers and charging stations (solutions proposed by Brusa, Coulomb Technologies, Epyon, Elektromotive, DBT, Fuji Heavy Industries has been investigated) has showed that none of them completely meets our technical requirements. Therefore, PHEV-Québec is developing its own charging station. Further details about its design will be addressed in a future paper. An initial design is depicted on Fig. 4.

The charging stations will also have to comply with Hydro-Québec (Québec's public utility) distributed power generation standards to achieve bidirectional energy exchanges. Therefore, the station will have to satisfy E.12-05 and E.12-06 standards requirements [11] [12]. The IEEE 1547 standard [13] for interconnecting distributed resources will also be considered.

Fig. 5 shows a diagram representing the electrical interconnections between one charging station and the Université Laval's electrical grid as they are defined above.

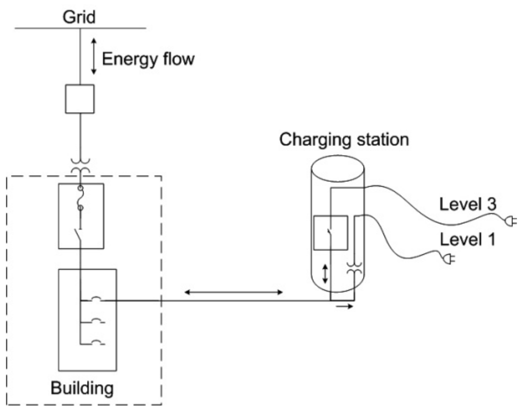


Fig. 5: Electrical interconnections between a charging station and the grid.

That new infrastructure allows us to study PHEVs in a real V2G environment, offering the possibility to analyze real bidirectional energy exchanges. It will also provide comprehensive data on customers charging behaviors given energy price ($/kWh) fluctuations.

C. Socio-economical and environmental concerns.

Though much has been said regarding the economic and social benefits of PHEVs [5][6][14], surprisingly little research has attempted to investigate the complex interactions that will determine these benefits. The demand for PHEVs and their impact will be endogenously determined. In particular, once the vehicles are on roads, new markets will develop, others will be affected (e.g., energy and carbon markets), our infrastructure demands will change, and new government regulations will be implemented. These changes will, in turn, “feed-back” and change the economic viability of the vehicles.

Moreover, a number of studies have estimated the environmental benefits of the wide adoption of PHEVs [3][14]. However, no study has estimated these benefits using real PHEVs that operate in real-driving conditions as the drivers’ primary vehicle over a long period of time. Further, no study has made detailed estimates of the financial impact on drivers (e.g., effects on income variability, credit worthiness, and consumption patterns).

One of the goals of PHEV-Québec is to shed-light on these complex interactions. Our large-scale real-world laboratory is used to uncover the factors which influence the financial and environmental benefits of PHEVs for different classes of drivers. The latter constitute the initial-values in various market penetration scenarios. Those allow us to simulate the impact of the vehicles on emissions, the infrastructure, energy markets, and on the spatial-temporal dynamics of the financial benefits of PHEVs.

These above topics requiring more than just a technical expertise, this research calls for a multidisciplinary approach. Therefore, PHEV-Québec test program is composed with engineers as well as financial analysts from Université Laval in Québec city. This team is also working in partnership with the battery manufacturer Modular Energy Devices and the cooperative financial institution, Desjardins to produce affordable PHEV systems for participants. Started mid-2008, the project is currently at the end of its pilot phase, mainly consisting in feasibility tests and partner funding search. One HEV has already been converted into a PHEV and 4 others PHEV conversions are currently in progress. Charging stations are also under development. The goal of 5 years is to reach a PHEV fleet of 50 vehicles with charging stations spread on the university campus, connected to our own independent electrical network.

3. Pilot-project preliminary results: performance comparison between a PHEV and a HEV.

As explained above, this research has reached the end of its pilot phase. During this phase, experimental studies have been conducted considering the specifications of our pilot-project PHEV system (*PHEVα*) based on a Toyota Prius 2005 (Fig. 6). Our preliminary studies were mainly focused on engineering concerns and studying the performances of *PHEVα* for different driving profiles in various climate conditions. Ongoing studies on V2G, socio-economical and environmental concerns will be addressed in further papers. Performance tests performed in summer 2008 showed low fuel consumptions for *PHEVα* for various driving profiles (see Table 1). Recent work has been done to compare *PHEVα* performance to that of a conventional Toyota Prius HEV in different driving situations. After a short description of our project PHEV system, this section presents the results of this comparison.

A. PHEVα characteristics.

PHEV-Québec preliminary studies have been performed with a PHEV system especially designed for the project. The latter consists of a 2005 Toyota Prius (Fig. 6), principally selected for its ability to be run solely on electricity (the all-electric mode can be imposed for speeds under 50 km/h) and well-documented conversion procedure. The Prius original Ni-MH battery pack (1.3 kWh) has been replaced

Fig. 6: Toyota Prius 2005 PHEV (*PHEVα*).

with a high power Li-Ion Manganese battery pack (5.6 kWh) provided by Modular Energy Devices. The latter has been chosen to balance performance and affordability. It is composed of five Li-Ion battery modules, each with a nominal voltage of 48 V, a capacity of 24 Ah and a weight of 23.3kg. Modular Energy Devices' modules are series connected and equipped with internal battery management and safety features. As shown in Fig. 7, each of them communicates serially to a master control unit (MCU) that monitors voltage, temperature and current. The MCU ensures that the car behaves as a PHEV for battery pack level over a state of charge (SoC) of around 20%. At this limit, the MCU makes sure that the car acts as a standard HEV. It also broadcasts battery modules data (voltage, temperature, current) on the vehicle CAN bus. Finally, the PHEV is equipped with an onboard 800 W charger to recharge the battery pack from a conventional 120VAC outlet (Level 1). *PHEVα* system has been installed in the Prius trunk in the spare tire storage area (Fig. 8).

B. *Field Test Procedure*

The performance comparison has been performed following a strict test procedure involving our PHEV as well as a non-converted Toyota Prius 2005 (Fig. 9). Those cars were both equipped with a data acquisition system in order to evaluate the car performances. The datalogger used (Fig. 10) allows us to record some battery parameters such as DC bus voltage and current from installed sensors. It is also equipped with a CAN Bus interface enabling the monitoring of selected vehicle broadcasted parameters such as the speed or the fuel injector flow. A GPS receiver is also used to record the car position. The data logging process was achieved at a sample rate of 100 ms for sufficient accuracy.

The mean fuel economy and battery energy use over a driving cycle are chosen as performance criterion in this comparison. The mean fuel economy (L/100km) is calculated from a time integration of the car fuel injectors flow (L/h) over travel duration. Fuel injector flow data are broadcasted on each vehicle CAN bus. The battery energy use refers to the amount of battery energy recharged from the electrical grid and consumed during a travel. It also reflects the battery depth of discharge (DoD) which greatly affects the battery cycle life. This parameter is only recorded for the PHEV since the HEV cannot be recharged. Current and voltage sensors connected to the battery pack allow the calculation of the battery power fluctuation. The latter is then integrated over time to estimate the battery energy (kWh).

The comparison has been performed on 3 different trips to represent typical driving profiles (Urban, Mixed Urban-Highway and Highway). Before each test, the PHEV battery pack was fully recharged. Both cars were parked indoors for three hours before each test. For a proper comparison, the all-electric mode has never been imposed by the drivers during the experiment. The field tests were conducted in December 2008 in snowy conditions and temperatures between -10°C and 0°C. During each field test, the HEV and PHEV were closely following each other and trying to preserve the same speed.

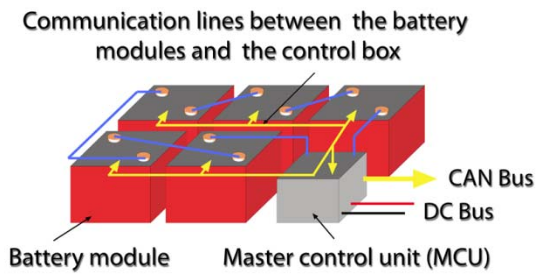


Fig. 7: *PHEVα* battery modules and MCU.

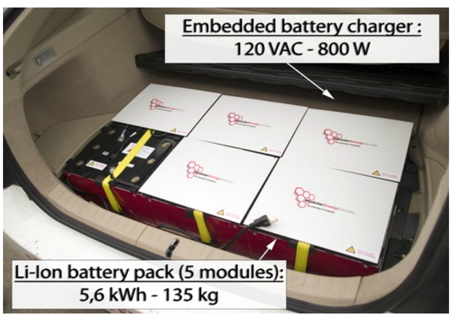


Fig. 8: *PHEVα* battery modules and control box.

Fig. 9: *PHEVα* and a conventional Prius HEV used in this performance comparison.

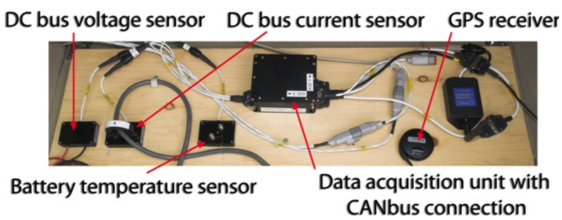
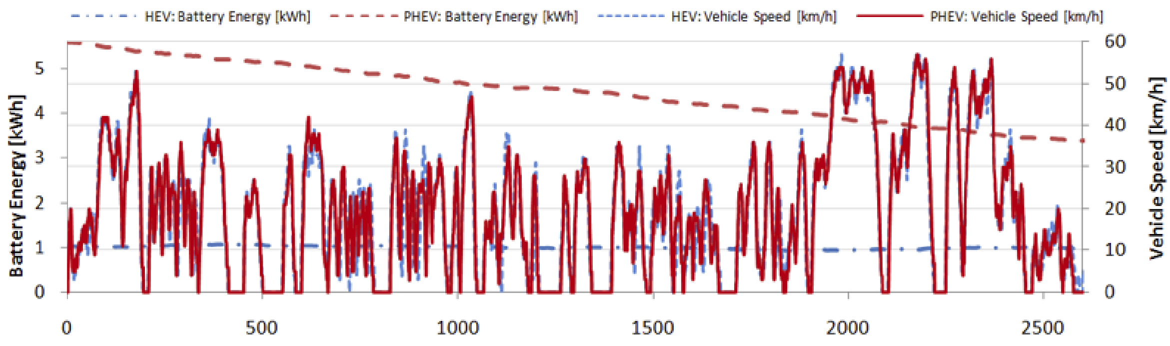
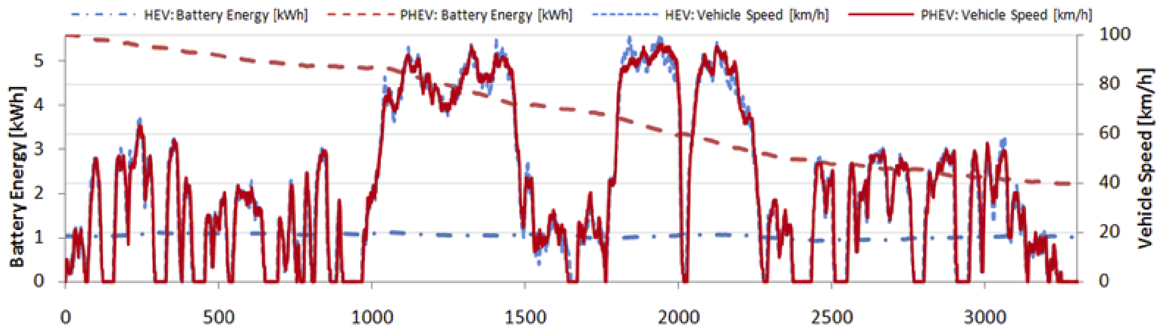


Fig. 10: The onboard data acquisition system.

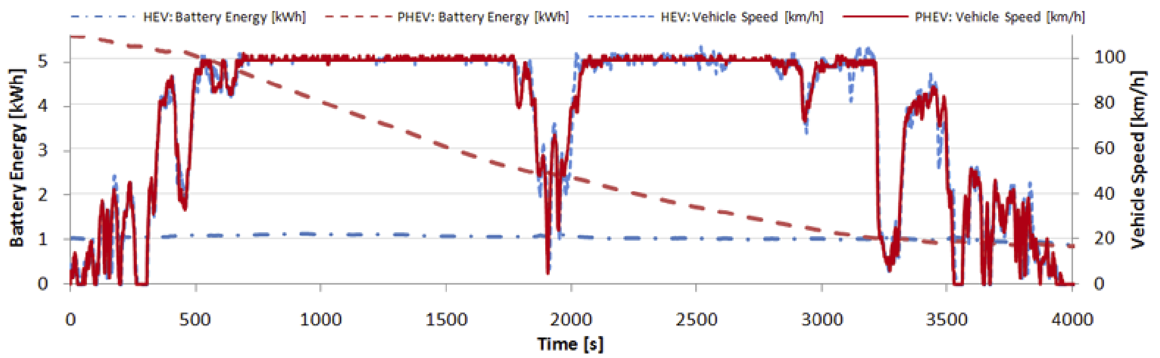
Fig. 11: The performed driving profiles along with their battery use for the PHEV and HEV test cars.



a. Urban driving cycle



b. Mixed urban/highway driving cycle



c. Highway driving cycle

C. Experimental Results

The data recorded (Fig. 11) during the field tests reveal the three expected driving profiles. The urban profile (Fig. 11 a.) is characterized by low vehicle speeds and frequent starts and stops. The highway profile (Fig. 11 c.) mainly consists of high and rather constant speeds while the mixed cycle (Fig. 11 b.) is a combination of the latter two. Very little difference can be seen between the PHEV and HEV speed profiles, which attest to the strict test procedures.

Table 2 shows the mean fuel economy and battery energy use for the three different cycles. The PHEV shows a fuel economy gain of 35% over the HEV in the urban cycle and the battery pack ends up with a 40% DoD. The performance gain is a bit higher for the mixed cycle (39%), with a DoD rate of 60%. For the highway cycle, the battery ends up almost fully depleted with a 84% DoD and has the lowest fuel economy gain of 29%. This is

Table 2: Mean fuel economy [L/100km] and battery energy use [kWh] over each driving cycle

		Urban cycle (14,5 km)	Mixed cycle (35,6 km)	Highway cycle (84,3 km)
Mean Fuel Economy	PHEV [L/100 km]	5.00	3.62	3.88
	HEV [L/100 km]	7.72	5.93	5.46
	Gain	35%	39%	29%
Battery Energy Use	PHEV [kWh]	2.22	3.38	4.73
	PHEV DoD	40%	60%	84%

mostly explained by the fact that the PHEV system acts as a standard HEV when its battery energy level falls around 20%. This characteristic can be observed from Fig. 11 c. (from 3200 s) when the PHEV battery pack energy level stabilizes.

PHEVα's longest battery cycle life would be obtained with the urban driving profile as it achieves the lowest DoD (40%). However, *PHEVα* highest fuel economy is realized with the mixed cycle, achieving the best mean fuel economy (3.62 L/100km) and performance gain (39%) over the HEV. The highway cycle is the only profile that uses all the available PHEV battery energy before completing the trip.

Analyzing those results shed-light on an important point concerning the development of a PHEV system: of the size of the PHEV battery pack should be chosen based on the drivers driving profile to minimize both fuel consumption and battery energy use (i.e. DoD).

One can also notice that the corresponding fuel economy for both vehicles is higher in the urban cycle than those observed in higher distance tests. This may be related to the vehicle cold start phase, where the vehicle must use the ICE to warm its fluids to operational temperatures, resulting in a higher use of fuel as shown by [7].

Tests conducted during summer 2008 (Table 1) already show lower fuel consumption for *PHEVα* for similar driving profiles. However, it should be reemphasized that the difference may have been more pronounced if the Prius all-electric mode would have been used during the experiment.

D. Project pilot phase conclusions and lessons.

The data gathered in the field tests leads to some preliminary conclusions and lessons:

- For each driving profile, the PHEV fuel consumption was lower than that of the HEV in the same driving conditions. It shows that our PHEV system seems to work as expected with performance gains ranging from 29 to 39%.
- Future PHEV battery packs should be selected to balance fuel economy gains and DoD limits given the driver's driving profile.
- The cold start sequence seems to have an impact on fuel economy, especially for shorter trips. The installation of an engine heater would be an interesting feature to test in future PHEV systems.

4. General conclusion.

This paper discusses a recently launched, field-test of PHEVs, the PHEV-Québec test program. Our research aims to examine engineering issues and the potential and market viability of PHEVs, while accounting for technical, financial, human-behavior and environmental factors. A real V2G infrastructure is under development to allow us to experiment with bidirectional energy flows between PHEV charging stations and Université Laval's independent electrical grid. Data gathered during these field tests are going to be used as initial parameters in market penetration scenarios to evaluate environmental and financial benefits of PHEVs.

PHEV-Québec is currently at the end of its pilot phase. This document has presented a comparison of the performance of the project's pilot-phase PHEV with that of a similar HEV. The PHEV system shows fuel economy gains over the HEV ranging from 29% to 39% for three typical driving profiles: Urban, Mixed Urban-Highway and Highway. The analysis also illustrates the importance of both fuel consumption and battery energy use as performance criterion for the future design of PHEV systems. PHEV- Québec is now enlarging its PHEV fleet by performing HEV conversions. Charging stations are also currently under development and will soon be implemented on the University's campus.

Acknowledgement

The authors would like to acknowledge the support of the Institut du Transport Avancé du Québec (ITAQ), the cooperative financial institution Desjardins and Modular Energy Devices.

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