

PERFORMANCE ANALYSIS OF THE HYMOTION PHEV FLEET

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ABSTRACT

Plug-In Hybrid Electric Vehicle (PHEV) technology is proving to be the next step in automotive powertrain technology, but because the current install base is quite small, very little is known about real-world installations and their performance. Although many simulations and small scale field studies have been conducted, an overall picture has still not been available to the public. Hymotion Canada – A123 Systems currently has the largest installed fleet of Toyota Prius Plug-In Hybrid Electric Vehicles in the world, and is in an opportune position to showcase the performance of this technology. Hymotion installs data loggers in most of its fleet in order to monitor the conditions of the Hymotion pack and to collect data on the overall performance of the vehicle. Parameters such as fuel economy, vehicle speed, and battery state of charge are collected and entered into a database for further analysis. With data being collected from installations located in very different climate conditions, from California to Manitoba; undergoing numerous loading conditions including daily highway commutes, steep grades, and inner city traffic, this paper will uncover the efforts behind the data collection initiative and will present preliminary figures and trends found in the first few months of development.

Keywords: Plug-In Hybrid Electric Vehicles, Fleet Operations, PHEV Fuel Economy

INTRODUCTION

Many independent studies have been conducted on PHEV systems using standardized fuel economy and emissions tests. Although these types of tests are very useful for comparison studies and product development, they do not demonstrate real world performance. The importance of real world data could not be ignored, which has led to substantial effort in data collection from the fleet. The data collection effort began in May 2007 and has been constantly expanding, starting with 4 data loggers in the field collecting information on 13 different parameters, and currently 30 data loggers collecting 24 parameters.

VEHICLE AND DATA LOGGER DESCRIPTION

Purpose

The data collection effort has two main purposes:

1. To identify overall fleet performance, utilization trends, and the identification of ideal operating conditions.
2. As a diagnostic and development tool.

This paper will only cover the collection of performance data from the fleet. Data is collected directly from the vehicle fleet and entered into a database. Numbers such as fuel economy, mean speed, and trip distance are calculated, which will be presented in this paper.

Vehicle description

The Hymotion L5 PHEV system utilizes A123 Systems’ Lithium-Ion Nanophosphate™ cells into a fully integrated package including an independent controller, power electronics package, and safety subsystems. The system has been designed to work exclusively with the Toyota Prius, where the PHEV system is placed in parallel with the existing NiMh battery pack. By utilizing the “Electric Vehicle” mode (EV mode) in the Toyota Prius, the vehicle operates in a charge depletion mode, allowing purely electric operation under steady acceleration up to 55 km/hr.

Data Logger Description

The data logger utilized is the Kvaser Memorator, which monitors the vehicle CAN bus via the OBD-II port on the Toyota Prius. All data is collected onto a standard SD flash disk which can then be downloaded into a database. This data logger was chosen for its unobtrusive size and ease of programming and downloading data.

Table 1: Data Logger Parameters

Parameter Logged	Unit	Sampling Frequency
Air inlet temperature to Hymotion pack	°C	2hz
Hymotion DC to DC converter temperature	°C	2hz
Hymotion Pack Current Draw	A	2hz
Hymotion Pack State of Charge	%	2hz
Hymotion Pack Voltage	V	2hz
Hymotion Pack maximum and minimum cell temperature	°C	2hz
Hymotion Pack maximum and minimum cell voltage	°C	2hz
Hymotion Pack maximum and minimum cell voltage location		2hz
Prius Battery State of Charge	%	2hz
Prius Battery Current Draw	A	2hz
Prius Battery Voltage	V	~1hz
Prius Battery Temperature	°C	n/a
All Current flow	A	4hz
Brake Pedal Position	%	0.5hz
Throttle Position	%	1hz
Vehicle Speed	km/h	2hz
Engine Speed	rpm	4hz
Fuel Volume	μL	Variable
Ambient Temperature	°C	n/a
Catalyst Converter Temperature	°C	2hz

Because the data logger monitors the vehicle CAN bus, it is capable of logging parameters from both the Prius and Hymotion CAN bus. Refer to Table 1 for a listing of the channels logged. The data logger parameter list has been under constant revision since this initiative begun therefore not all data will be presented here.

In order to differentiate between data collection events, data files needed to be created for individual driving and charging events. To do this, triggers are setup in the data logger software which triggers the creation of a new data file based upon message retrieval. When the data logger receives a vehicle speed message, the data logger starts a new logging event and file, and the file is time stamped with both date and time. The data file ends when the vehicle speed message is terminated. Charging logging events are triggered via the detection of charging current to the Hymotion pack.

Data Collection

The current install base of data loggers in Hymotion PHEV Prius' is 30 spread throughout North America. With this number of data loggers, a huge effort was required to collect data from the field. Even though the data logger is capable of collecting over two months worth of day to day driving events with the included flash disk, a collection period of one month was chosen. This was to create a sense of routine for the customer and to also allow for a reasonable period of time to detect problems with either the data logger or PHEV system. Two methods of data collection from the field were determined to be the least intrusive and straightforward for the customer:

1. Each month a replacement flash disk is sent to the customer with a self addressed envelope for return of the old flash disk.
2. Creation of a secure FTP server which the customer can use to upload their files manually.

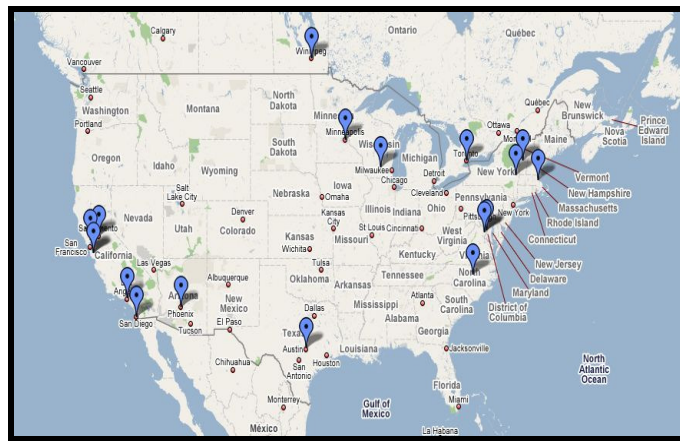


Figure 1: Map of current data logger install base

The data collection effort has only just begun, with the majority of data loggers installed in the month of August 2007. Data has been collected from a small number of sites whose data will be presented in this paper. As the infrastructure is developed to collect data from all sites, the amount of data will grow from the current 2.5 gigabytes from 7 vehicles over 4 months, to close to 100 vehicles.

DATA ANALYSIS

Simple analysis on parameters important to this study was conducted. The calculation of total distance traveled, mean speed, and fuel economy would provide the basis for comparison between the different parameters and also a starting point for comparisons under different conditions. Each of these values are calculated for operation under PHEV only, while there was charge remaining in the Hymotion pack, in addition to calculation performed for an entire trip. Other calculated values include energy consumed over a trip from the Hymotion pack, ambient temperature, and a loose method of determining the level of driving aggressiveness.

The aggressiveness factor was only developed as a quick and easy way of determining how aggressive the driver is. It is calculated by finding the percentage of time the driver presses the throttle more than 40% over its travel. Other methods of distinguishing aggressive driving behavior have yet to be tested, but could take the form of a load histogram or based on several different variables.

Scripts were written to automatically calculate all parameters and plot the results. Refer to Figure 2 for an automatically generated plot of a single trip. These types of plots are very useful for examining trips on a micro level but are not of much help when looking at the overall performance over a wide range of conditions. Another set of scripts were written to process large batches of data files in order to quickly calculate only the necessary parameters, such as mean speed, PHEV pack range, and trip fuel economy.

DATA POOL

Unfortunately, at the time of writing, the pool of data only consisted of seven vehicles, three of those being used as Hymotion test vehicles. Although the amount of data is significant, at almost 12000 km of driving distance, the diversity of the data leaves much to be desired. Hymotion test drivers tend to drive much more “conservatively” in attempts to derive maximum performance from the PHEV pack, as opposed to everyday drivers who drive with more “normal” (ie. aggressive) behavior.

Over four months of data is available from the Hymotion test vehicles, whereas only a month of data from each of the customer vehicles was available. Additional difficulties arose from the constantly evolving list of data parameters, adding another level of complexity to the automated scripts and parameter comparison. The capability to collect charge data has not dispersed throughout the entire fleet; important information such as charge time and duration are missing for this study.

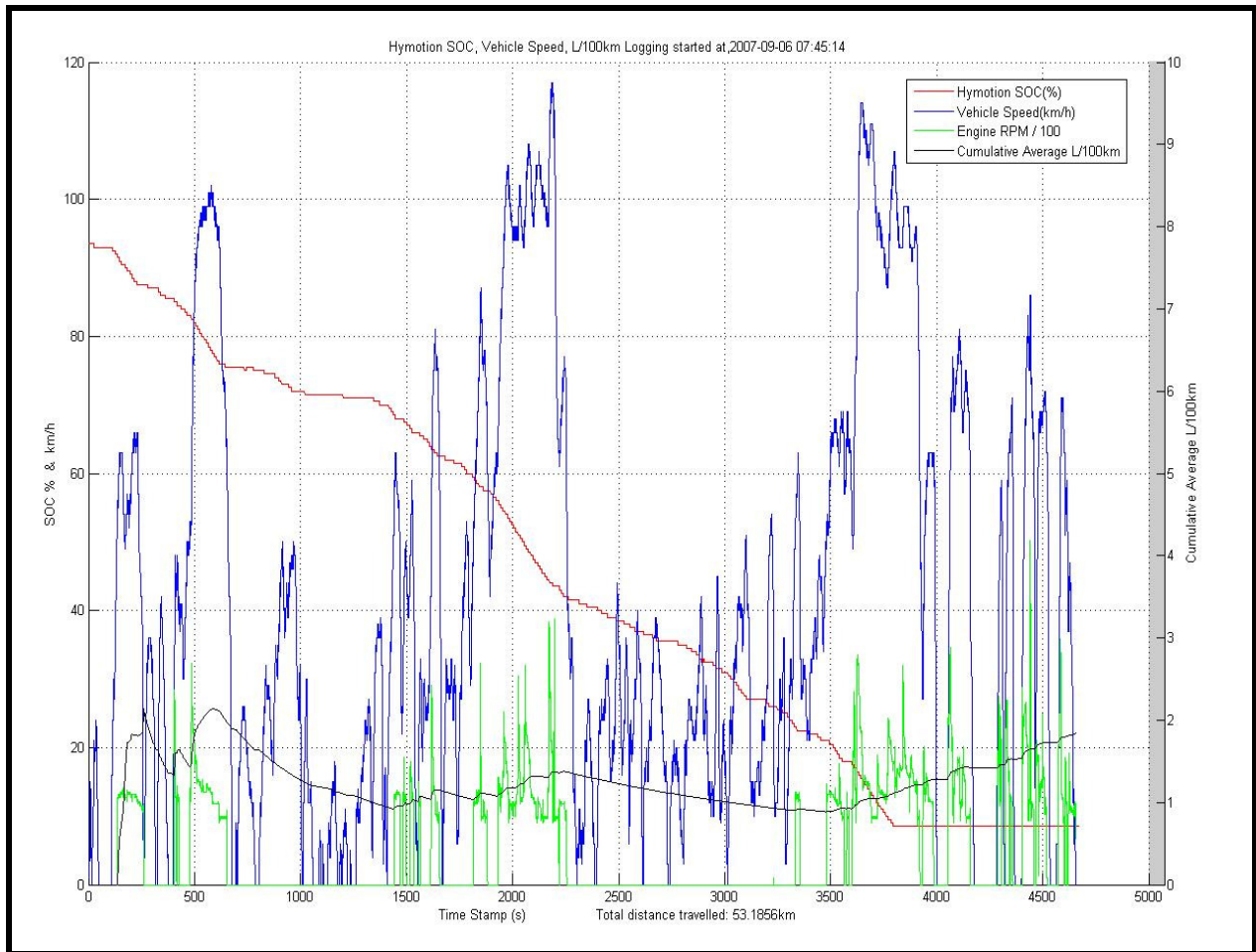


Figure 2: Example Plot from Test Data

RESULTS

PHEV trips were first divided into trip distances, as can be seen in Table 2. For each trip distance range, mean values and standard deviations were calculated and tabulated. Engine on time fraction and PHEV energy consumption meet expectations, as both increase in relation to increasing trip distance. Theoretically, fuel economy should follow the same trend, and decline with greater trip distance, and does to some extent except for the first few distance groups. A possible explanation for the variance is throttle aggressiveness as more aggressive behavior is observed over the shorter trips.

Over short distances, throttle aggressiveness can have a much greater effect on the overall trip as opposed to long distance driving where a longer period of time is spend at constant lower throttle positions. Also, the standard deviation for shorter trip distances is higher compared to the long distance trips. If a better method of deriving driving behavior can be used, these variations can probably be filtered out.

Referring to Figure 3, the same PHEV fuel economy numbers are compared to a dataset where the vehicle was only running in HEV mode (where no charge remained in the PHEV pack). The

size of the HEV dataset was smaller than the PHEV dataset, but was still large enough to form a valid comparison. The most obvious conclusion is that PHEV operation far out performs HEV operation over all distances.

Table 2: PHEV Trip Distance Mean Numbers

Trip Distance (km)	Fuel Economy (L/100 km)	Engine ON Fraction (%)	Total PHEV Energy Consumed (kWh)	Throttle Over 40% Time Fraction (%)
Form: Mean/Standard Deviation				
1-5	4.47 1.57	38.87 17.32	0.383 0.185	0.078 0.087
5-10	3.55 1.11	38.23 16.35	0.763 0.205	0.045 0.036
10-15	3.29 1.19	46.4 13.65	1.122 0.319	0.035 0.029
15-20	2.98 0.85	42.2 18.3	1.61 0.418	0.021 0.022
20-25	2.75 0.60	44.9 16.9	2.13 0.56	0.014 0.013
25-30	3.19 0.87	48.7 16.0	2.23 0.59	0.013 0.011
30-35	2.33 0.53	48.7 12.7	2.45 0.40	0.013 0.007
35-40	2.86 1.14	53.3 14.7	3.20 0.68	0.007 0.002
40-50	3.44 0.84	66.0 11.2	3.08 0.72	0.009 0.009
50-60	3.53 0.63	66.5 11.8	3.29 0.76	0.006 0.004
60-80	3.33 0.95	63.0 14.2	3.67 0.33	0.005 0.002
>80	3.69 0.51	71.5 12.2	3.9 0.45	0.005 0.003

Referring to Table 3, the same set of data was divided into mean speed groups. For each group, mean fuel economy and engine on times were calculated. A better correlation is found between trip mean speed and fuel economy, with engine on time matching the relationship.

The relationship between mean speed and fuel economy is even more apparent when the data set is further focused. By separating out trips where the PHEV pack starts fully charged and is drained completely, and only plotting mean speed and fuel economy over the range where charge

remained in the pack, a better picture of the relationship is revealed. Refer to Figure 4. Therefore, as mean speed increases in PHEV mode, overall fuel economy declines.

Table 3: PHEV Mean Speed Fuel Economy and Engine ON Time

Trip Mean Speed (km/h)	Fuel Economy (L/100km)	Engine ON Fraction (%)
Form: Mean/Standard Deviation		
20-30	2.45 0.67	28.8 5.64
30-40	2.77 0.84	40.5 6.8
40-45	2.43 0.92	44.3 6.35
45-50	2.38 0.55	48.9 5.32
50-55	2.98 0.72	57.8 10.1
55-60	3.09 0.74	60.3 6.6
60-65	3.09 0.87	64.2 9.25
65-70	3.30 0.42	66.4 4.5
70-75	3.14 0.44	73.8 5.5
75-80	3.48 0.5	76.3 5.5
80-85	3.26 0.64	79.9 4.29
85-90	3.36 0.6	76.9 6.9
>90	3.75 0.75	77.1 11.9

According to the data, and ignoring thermal, efficiency, and noise losses, a PHEV pack can provide approximately 3.9-4.1 kWh of energy on one charge. For distances greater than 50km, some of the trips completely drained the PHEV battery pack. But, to get a better idea of overall PHEV pack capacity limits, performance must also be related to mean speed over the PHEV pack range. Again, only taking trips where a full charge is completely depleted, PHEV pack mean speed and range are plotted against each other in Figure 5. Therefore, PHEV pack range decreases with increasing mean speed.

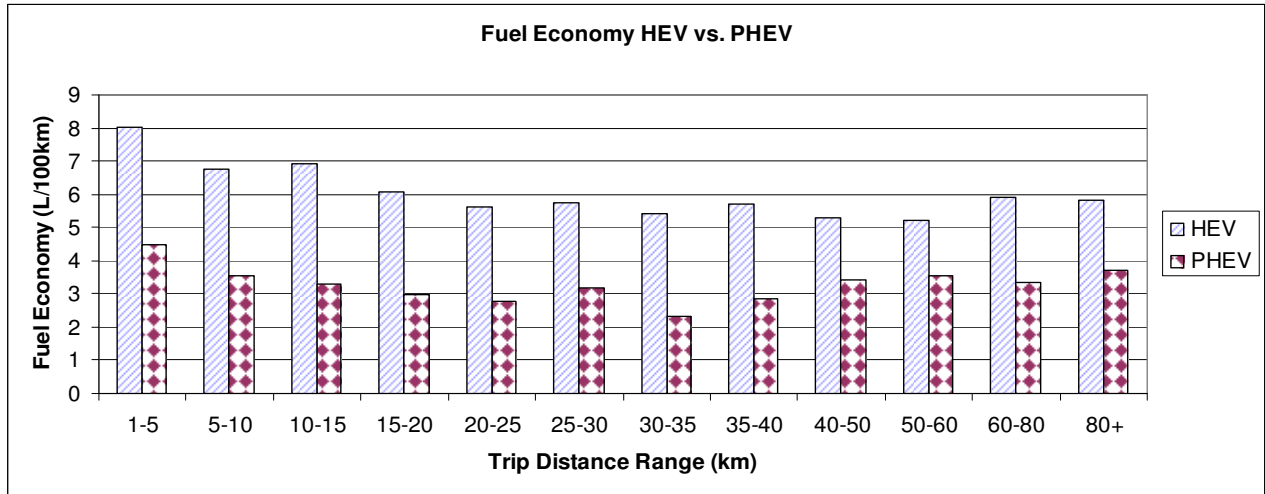


Figure 3

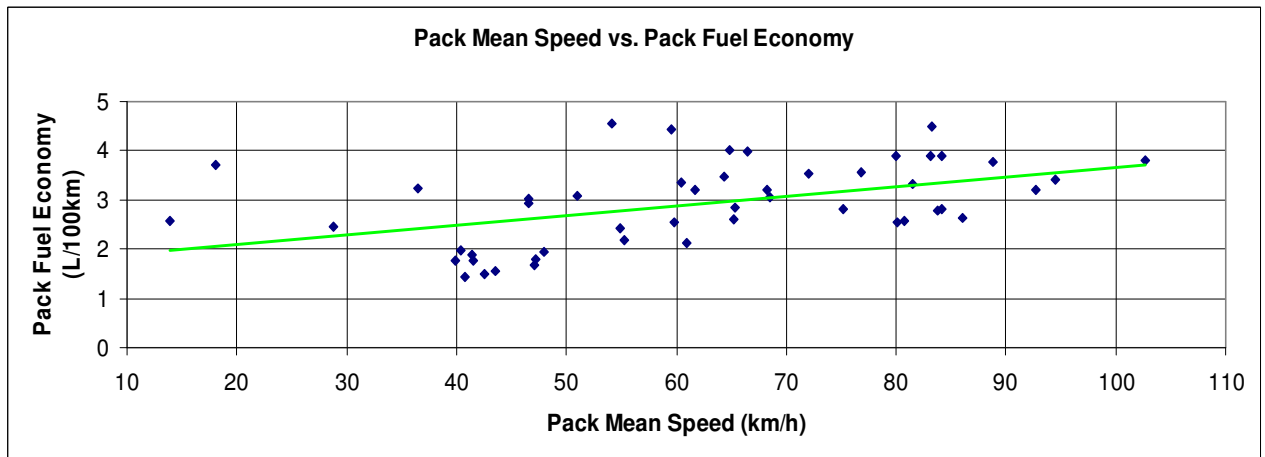


Figure 4

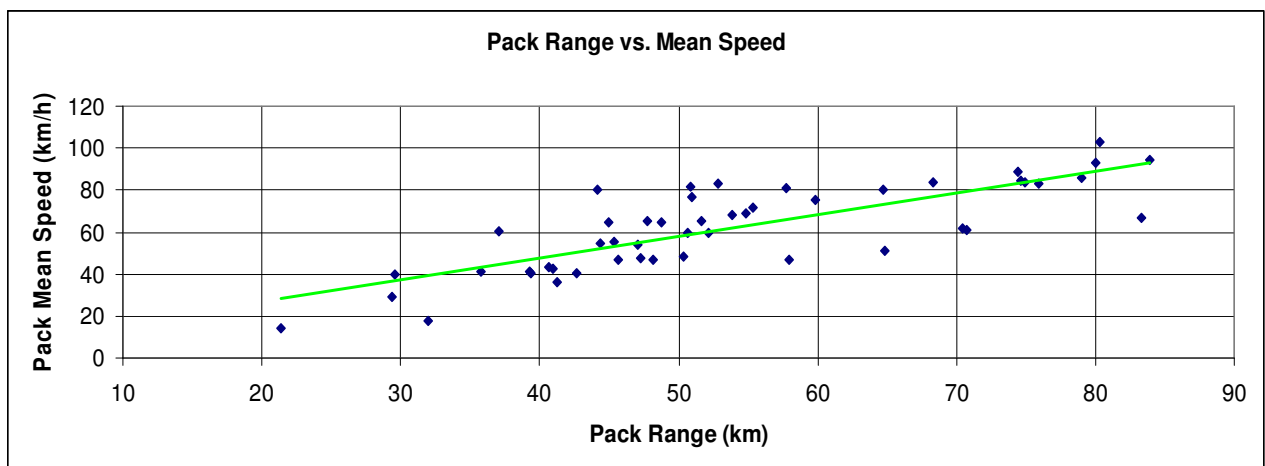


Figure 5

FUTURE WORK

Although these initial results are quite positive, they only represent the beginning of a massive data collection effort. The first 30 data loggers already in the field will be expanded to close to 100 by the beginning of 2008. Also, as this project progresses, seasonal data will also be collected and performance differences between summer and winter can be determined.

To deal with the immense logistics effort of collecting data from fleets across North America and entering the data into a fully automated database, Hymotion will begin a partnership with Idaho National Labs (INL) to share responsibility for this massive project. INL will assist in data collection and archiving while Hymotion will oversee data analysis and reporting. This partnership will greatly expand upon the types of figures reported in this paper.

On the data analysis front, as variations in the structure of data collected from the field begins to disappear, better usage statistics can be calculated. Figures such as number of charge cycles, time of day to begin charge, ambient temperature relationships, and average trip lengths can be found. Data logging channels will also be expanded to cover HVAC parameters. These figures will further focus the optimal usage pattern for PHEV technology.

Alternative data logging hardware is also being explored. Several options include the logging of real-time GPS location, cellular data transmission, and grid tie data transmission.

CONCLUSION

Clear relationships were identified between mean speed and PHEV charge depletion range and fuel economy. A third relationship between trip distance and fuel economy was also established. As more data is collected, these relationships can be further validated and focused.

Although a large amount of data has already been collected, covering over 12000 km, this performance analysis is only the beginning. By expanding data collection efforts from currently 30 data loggers to close to 100, a very broad range of data will be available to further develop an understanding of PHEV performance.

AKNOWLEDGEMENTS

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