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Report on the Field Performance of A123Systems' Hymotion^{TM} Plug-In Conversion Module for the Toyota Prius

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ABSTRACT

A123Systems' Hymotion™ L5 Plug-in Conversion Module (PCM) is a supplemental battery system that converts the Toyota Prius hybrid electric vehicle (HEV) into a plug-in hybrid electric vehicle (PHEV). The Hymotion module is a lithium ion battery pack with 4.5 kWh of useable energy capacity. It recharges by plugging into a standard 110/120V outlet. The system was designed to more than double the Prius' fuel efficiency for 30 to 50 km of charge depleting range. The Hymotion L5 PCM is the first commercially available aftermarket product complying with NHTSA impact standards.

Since 2006, over 50 initial production Hymotion Plug-in Conversion Modules have been installed in private fleet vehicles across the United States and Canada and monitored for performance. With the help of the Idaho National Laboratory, which conducts the U.S. Department of Energy's (DOE) Advanced Vehicle Testing Activity (AVTA), A123Systems collected and analyzed real-time vehicle data from each fleet vehicle. This paper presents the results of this field evaluation.

INTRODUCTION

In an age of rising oil prices and a demand for energy independence, PHEV technology is on the forefront of automotive innovation. PHEVs combine a conventional internal combustion engine (ICE) with an electric motor and generator and a high capacity battery that can be plugged into any regular wall outlet. A123 Systems has released a commercially available PHEV aftermarket battery module which is used exclusively to convert the 2004-2009 model year Toyota Prius into a Plug-In Hybrid. Development of this product began in 2006 with more than 50 prototypes released into the field by 2008. Currently, the Hymotion L5 PCM has entered into full production with individual customers upgrading their Priuses into PHEVs. The data presented in this paper are only from the prototype fleet and do not include the current install base of production units.

In order to fully understand the benefits of this technology, A123Systems partnered with the Idaho National Laboratory and fleet customers to monitor the performance of the prototype PHEV fleet. This involved installing data loggers throughout the entire fleet to monitor both vehicle parameters, such as fuel consumption and vehicle speed, and battery parameters, such as power output and temperature. From this massive amount of data three performance metrics have been closely investigated: Fuel Consumption, Electricity Usage, and Charge Depleting Range. These metrics will be used to determine the overall performance of the Hymotion PHEV fleet.

HYMOTION™ L5 PCM

The Hymotion™ L5 PCM is a supplemental battery pack that is designed to fully integrate with the existing architecture in the 2004-2009 model year Toyota Prius. Adding the Hymotion PCM is the electrical equivalent of adding a secondary gasoline tank. It greatly expands the electrical energy capacity of the vehicle's energy storage system, making more electrical energy available to the Prius' electric motor. With this expanded electrical energy capacity, two operational improvements are made to the conventional Hybrid Electric Vehicle (HEV) operation:

- Increased all-electric acceleration range from 0-15km/h to 0-55km/h
- Operation in a charge depleting strategy as opposed to charge sustaining

All-electric acceleration up to 55km/h is the absolute maximum speed that can be reached before the ICE must turn on. This limit may be reduced based on both the maximum power output of the PCM battery and the overall condition of the PCM and vehicle system. For example, if the overall temperature of the PCM is above a certain threshold, the maximum power output will be limited, thereby decreasing the all-electric acceleration maximum speed. Alternately, if the vehicle is accelerating all-electrically up a steep incline, more power is required to accelerate the vehicle. Since the maximum power output of the PCM will be reached much earlier compared to accelerating on flat ground, the all-electric acceleration maximum speed will decrease.

No modifications are made to the powertrain system to allow for the increased all-electric range. The powertrain is already capable of accelerating the vehicle up to 55km/hr. In its regular stock configuration running in charge sustaining mode, the Prius has a small amount of energy available for acceleration, and once this limit is reached, the ICE will turn on. With the PCM Battery, more energy is available, and therefore the Prius will use this additional energy to accelerate the vehicle.

These improvements result in a fuel economy increase of more than double the standard Prius fuel efficiency. As measured utilizing EPA urban and highway dynamometer driving schedules, and taking the average of three consecutive runs, the Hymotion PHEV Prius is measured at 1.58L/100km City and 2.49 L/100km Highway[3]. This fuel consumption improvement is offset by charging the additional PCM battery from the grid – by plugging into any standard 110VAC 15 Amp circuit. Battery specifications are found in Table 1.

The PCM battery is installed in parallel with the existing OEM NiMh battery. Both batteries work together to drive the electric motor, but only the OEM battery accepts regenerative braking power. The only way to recharge the PCM battery is by plugging it into a wall outlet. While driving, once the PCM battery is fully depleted, charge depleting operation ceases, and the vehicle returns to charge sustaining operation – essentially a stock Prius.

Battery Parameter	**A123Systems Hymotion PCM Battery**
Chemistry	A123 Systems L5 Lithium Ion Nanophosphate™
Nominal Voltage	~190 V
Battery Capacity	25Ahr / 4.5kWhr
Weight	85kg (includes battery cells, on-board electronics, frame)

Table 1 – Hymotion PCM Specifications

DATA LOGGING HARDWARE

Two types of data loggers have been installed in the Hymotion PHEV fleet. The Kvaser Memorator is a CAN-bus data logger capable of collecting standard Toyota Prius vehicle and battery parameters, as well as the PCM battery parameters. All data is recorded onto SD flash cards, which are collected and transferred into the database.

The second data logger is the V2Green system. Developed as an interface between PHEVs and the electrical grid, the V2Green system has flexible data logging capabilities. It has all the functionality of the Kvaser system, and also includes off-board AC charging instrumentation and logging, GPS tracking, cellular and WiFi data transfer, and a web interface.

The list of basic data parameters collected is covered in Table 2.

Vehicle Operation	• Vehicle Speed • Engine RPM • Fuel Consumption • Accelerator and Brake Pedal Position • Engine Coolant Temperature • Ambient Temperature • Climate Control Status
Battery Operation (both OEM and Hymotion)	• Pack Current • Open Circuit Voltage • State of Charge • Coolant Air Temperature • Max/Min Cell Voltage • Max/Min Cell Temperature • Power Electronics Temperature

Table 2 – Data Logger Parameters

Data was collected during both driving and charging events. During charge, the Kvaser data logger only logs DC parameters from the Hymotion PCM, thereby missing some of the losses associated with rectifying the AC input into the battery charger. The V2Green system measures AC parameters directly, from the plug, giving a more accurate picture of charge energy and power.

FLEET COMPOSITION

The first 50 prototype PHEV conversions were spread across North America with large concentrations in California, Seattle, North and South Carolina, and Toronto. Extreme seasonal weather was experienced in Phoenix, AZ and Winnipeg, Manitoba. The most complete set of data was from the Toronto fleet of 9 Hymotion PHEV Priuses covering a span of almost one year.

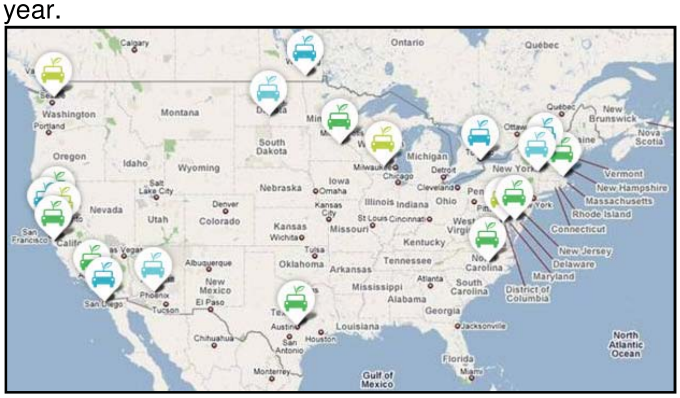

Figure 2 - Geographical Distribution of Hymotion PHEVs

The majority of these vehicles were parts of existing company vehicle fleets. These vehicles were generally used for day to day activities such as visiting off-site facilities. Variability in usage was wide-spread, and vehicles were not usually assigned to individuals but were shared among a pool of users. A few vehicles were assigned to individual employees and were used for commuting to and from work.

ANALYSIS PARAMETERS

Because of the unique nature of PHEV operation, a detailed description of how parameters were calculated is described below:

CHARGE DEPLETING DISTANCE – The total amount of distance required to completely discharge a fully charged PCM battery.

CHARGE DEPLETING MODE – When the vehicle is being driven and the PCM battery has charge and is being discharged, the vehicle is considered to be in charge depleting (CD) mode. Charge depleting mode can include both series all-electric and parallel electric motor and gas engine operation.

CHARGE DEPLETING TRIP – If greater than 95% of the total distance of a trip is driven in charge depleting mode, then the entire trip is considered to be a charge depleting trip.

CHARGE SUSTAINING MODE – When the vehicle is being driven and the PCM battery does not have charge or is turned off, the vehicle is considered to be in charge sustaining (CS) mode.

CHARGE SUSTAINING TRIP – If greater than 95% of the total distance of the trip is driven in charge sustaining mode, then the entire trip is considered to be a charge sustaining trip.

COMBINED TRIP – If between 5% and 95% of the total trip distance there is a transition from charge depleting to charge sustaining modes, then the entire trip distance is considered to be a combined mode trip.

AGGRESSIVENESS FACTOR – The aggressiveness factor is meant to capture aggressive driving behavior. Since the data logger does not capture driver torque demand, the next simplest aggressiveness indicator available in the data set is accelerator pedal usage. Using qualitative observations from data sets, it was found that as the driver tips into the accelerator pedal past 40% of overall travel, the gasoline engine tends to come on to increase overall power output. Therefore, the aggressiveness factor used in this paper is calculated by finding the proportion of the trip when accelerator pedal position is greater than 40% of its overall travel and is expressed as a percentage of the trip.

OVERALL FLEET STATISTICS

Total Fleet Size Analyzed	36
Total Fleet Distance Travelled	256 356 km
Data Collection Time Range	8/10/2007 – 10/31/2008
Ambient Temperature Range	-27℃ - +40℃
Drive Sessions	14 727
Charge Events	4105
Total Charge Energy	8.19 DC MWhr

Table 3 – Overall Hymotion PHEV Fleet Statistics

Not all vehicles are represented over the entire date range presented, as Hymotion PCM customer installation dates were widely distributed. A123Systems kicked off its joint data collection effort with INL in January 2008. The majority of data prior to that was collected solely by A123 Systems. This explains the spike in total data collected in Figure 3.

Data presented in this paper represents a subset of data collected from vehicles in the field, and comes only from Kvaser data loggers. Data shown in this paper are generally representative of the entire fleet, as judged by manual inspection of sampled data from both data loggers.

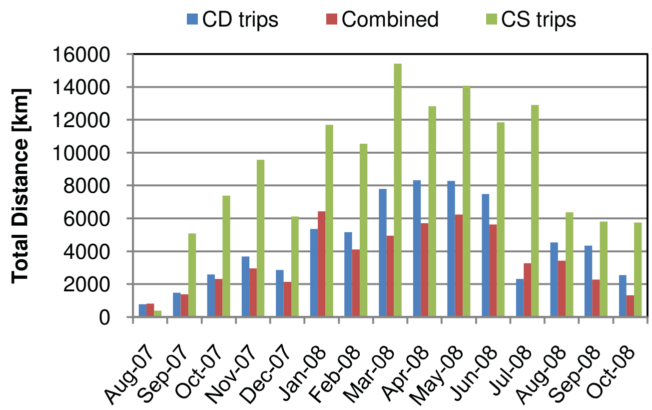

Figure 3 – Overall Data Trip Composition

PERFORMANCE METRICS

Determining PHEV performance from fleet data presents unique challenges. From habits learned working with conventional vehicles and HEVs, there is a temptation to present overall fleet fuel consumption as a singular measure of fleet performance. However, additional metrics are needed to define PHEV performance. As bi-fuel vehicles, PHEVs displace gasoline fuel with electricity. Therefore, in addition to the standard fuel consumption metric of L/100km, electrical energy consumption must be measured. This paper presents electrical energy consumption in units of Whr/km, Additionally, PHEVs operate in two modes: charge depleting or charge sustaining. Gasoline fuel consumption is significantly reduced during charge depleting mode, when the plug-in battery pack is discharged to propel the vehicle. Once the PCM battery is fully discharged, the vehicle transitions to charge sustaining mode. It is important to identify when this transition occurs, in terms of distance driven. This metric is called the charge depleting range. Furthermore, the frequency with which the vehicle is charged, relative to the distance driven between charging events, determines the proportion of distance driven in charge depleting versus charge sustaining mode. The proportion of charge depleting to charge sustaining operation will affect the overall balance between gasoline and electrical fuel consumption.

In addition to examining multiple performance metrics, it is important to identify the effects of noise factors on performance. Fuel consumption and charge depleting range in PHEVs are found to be extremely sensitive to noise factors, such as ambient operating conditions, driving aggressiveness, climate control operation, driving patterns, and aging. With the exception of aging – the overall age of the fleet is too low to demonstrate these effects – all of the above performance metrics will be examined in an attempt to draw a true picture of overall PHEV fleet performance.

Another major noise factor is related to the emissions startup sequence for the vehicle. In order to maintain exhaust emissions levels equal to that of the stock vehicle, the emissions engine and catalyst warm-up cycle is maintained. For very short trips less than 3km, these gasoline engine startups disproportionately affect fuel consumption. Therefore, these trips have been removed from their respective datasets. This is denoted in most plots below.

BASIC DISTRIBUTIONS

Since the main advantage of PHEVs is a dramatic improvement in gasoline fuel consumption (hereafter referred to simply as fuel consumption), Figure 4

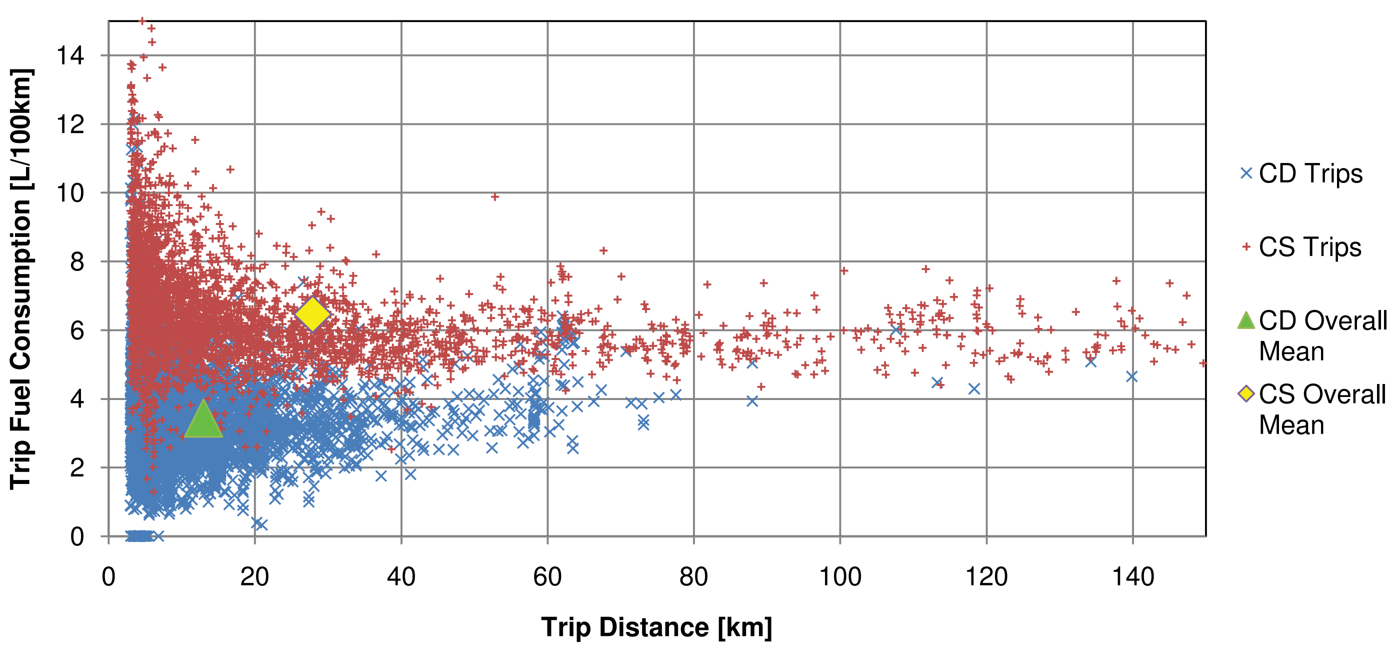

Figure 4 - Fuel Consumption vs. Trip Distance, >3km, >5℃

presents a comparison of fuel consumption results for all trips greater than 3 km, with an average ambient temperature greater than 5℃. Two points on the graph are also highlighted: Overall means for both operating modes. Overall Mean Charge Depleting fuel consumption was 3.44L/100km with a mean trip distance of 12.97km. Overall Mean Charge Sustaining fuel consumption was 6.46L/100km with a mean trip distance of 27.87km. The concentration of trips around their respective overall results confirms an improvement in fuel consumption in charge depleting mode. Note the trip distance limitation of Charge Depleting trips to a max of ~100km due to the limited charge capacity of the PCM battery. This plot also demonstrates the high variability in fuel consumption. Although the concentrations of data points give an idea of fleet performance, it does not take into account all the noise factors previously mentioned. In order to better understand why PHEV performance is so variable, these noise factors will be more closely examined.

Energy drawn from the PCM battery is shown in Figure 5, plotted against charge depeleting trip distances. Since the total amount of discharge energy in the PCM battery is fixed (~4 kWhr), as the trip distance increases, the discharge rate decreases. If it is assumed that the entire energy capacity of the PHEV battery is depleted over the trip distance, a theoretical maximum discharge rate can be calculated. This is alsoc plotted in Figure 5. Variability in trips less than 10km are again due to noise factors, such as mean speed and aggressiveness.

The final basic distribution, shown in Figure 6, plots Charge Depleting Fuel Consumption vs. Discharge Rate. This plot conveys the basic principle of charge depleting operation – displacement of gasoline usage with electricity. As the electric drive is used more frequently during charge depleting operation, the ICE is used less frequently. Therefore, as the electrical discharge rate increases, fuel consumption should theoretically decrease proportionately. But, as previously mentioned,

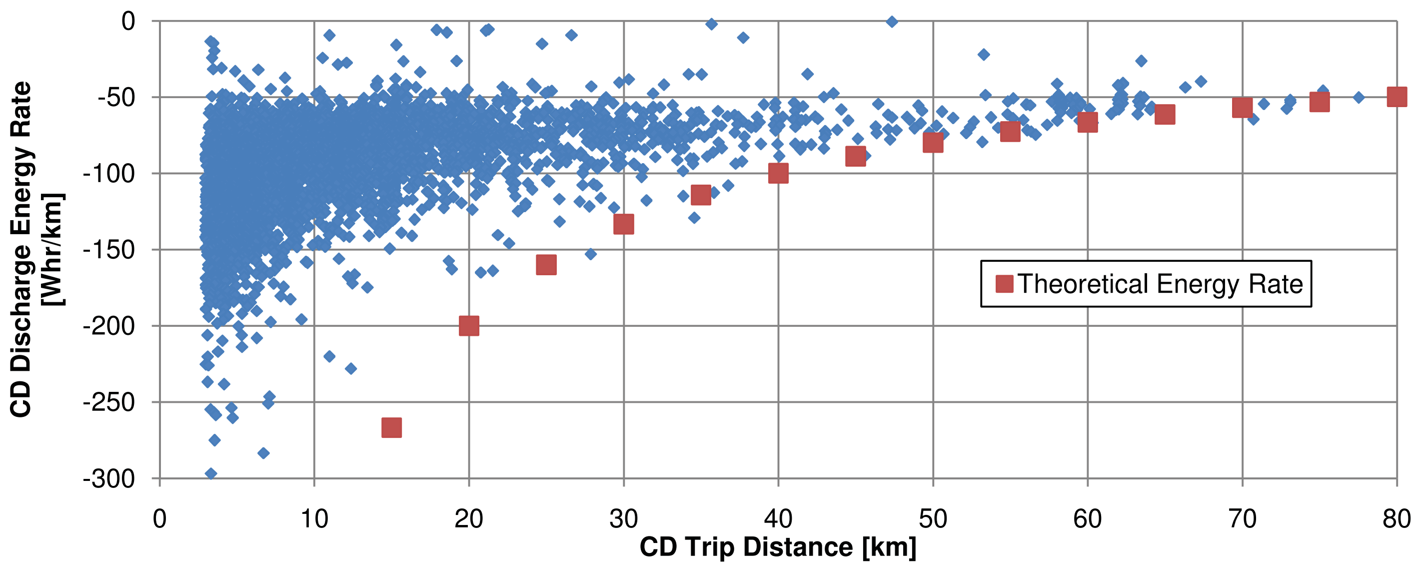

Figure 5 - CD Energy Rate vs. CD Trip Distance, >3km, >5°C

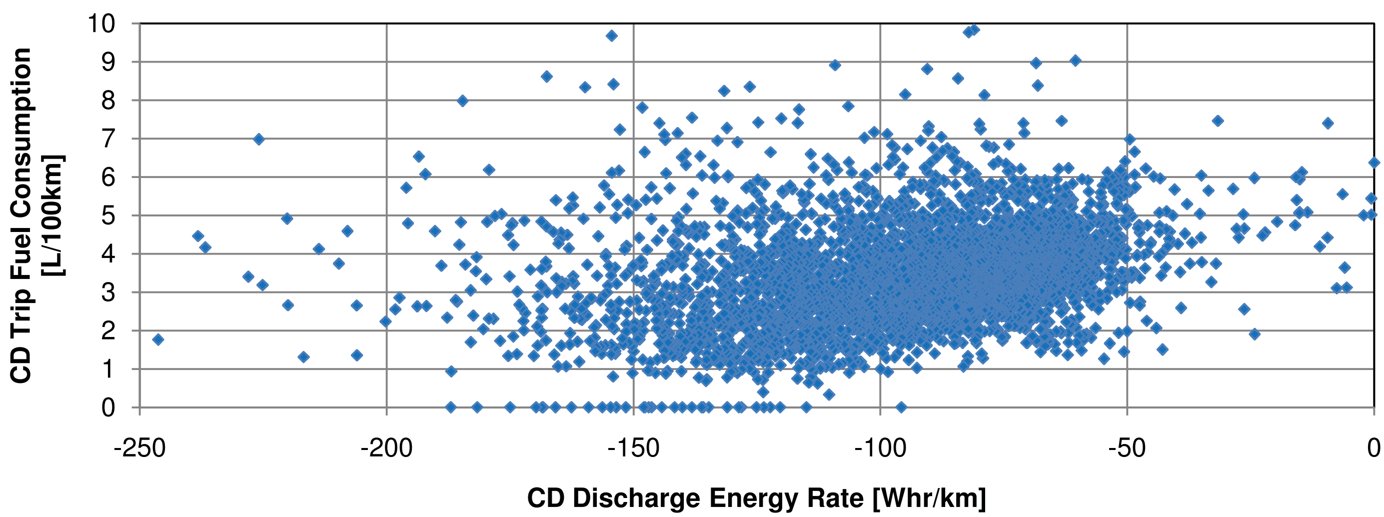

Figure 6 – CD Fuel Consumption vs. CD Energy Rate, >3km, >5°C

there are many noise factors that mask this relationship.

NOISE FACTORS

AMBIENT TEMPERATURE – Ambient temperature is a major noise factor influencing PHEV performance. As with all motorized vehicles, variations in temperature will change material performance properties, lubrication will be less effective, and increased electrical resistance will increases losses. An increase in the density of air will decrease aerodynamic performance.

In PHEVs, the driver's use of climate control will dramatically affect performance. The internal combustion engine is the heat source for defrosting the windshield and heating the cabin in the Toyota Prius. Any elevated requirement for heat by the climate control system drives the engine to turn on. This is especially detrimental to fuel consumption during charge depleting operation, as full fuel consumption reduction performance depends on minimal engine operation.

For air conditioning, the compressor is driven by a small electric motor capable of drawing more than 2kW of power, which could otherwise be used to drive the wheels. During charge depleting operation, with this additional load, the ICE will turn on more frequently to offset that load, resulting in increased fuel consumption. Figure 7 demonstrates the effect of ambient temperature on overall fuel consumption.

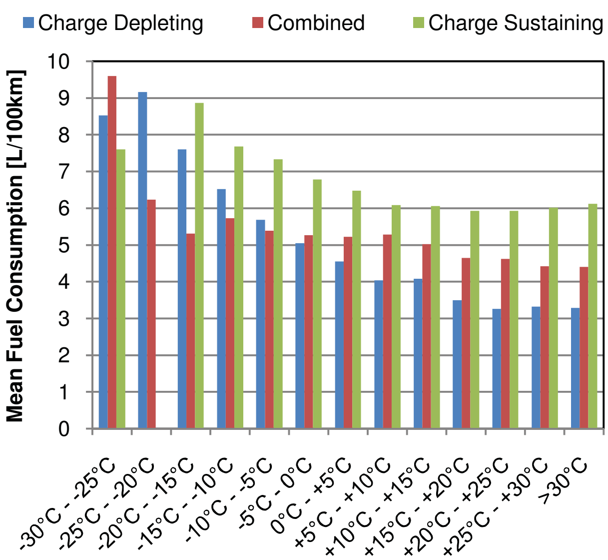

Figure 7 – Mean Fuel Consumption vs. Ambient Temperature Bins for All Modes of Operation

Note that as ambient temperature decreases mean fuel consumption begins to converge over all the different type of trips. Although not directly accounted for, this could be caused by the climate control system (cabin heater/defroster) being activated throughout the entire trip, thereby forcing the ICE to remain on to generate heat. From the lowest to highest ambient temperatures, there is a reduction in mean fuel consumption of more than 60%.

MEAN SPEED – As vehicle speed increases, a greater amount of power is required to accelerate the vehicle. Additionally, higher power is required to meet road load power demand and maintain speed. In charge depleting operation, the Prius will attempt to utilize the electric motor as often as possible, up to the maximum all-electric speed of 55km/hr. It will also attempt to drive all-electric under constant speed conditions, as long as load variations remain steady. If an increased amount of power is required, which cannot be met by the electric motor, the ICE will turn on. At that point, power requirements are split between the ICE and electric motor, thereby decreasing the overall electric motor demand. In high power demand situations, the electric motor may maintain maximum power output, while the internal combustion engine meets the remaining power demand. Therefore, as speed and power demand increases, ICE power demand increases and electric motor demand decreases or is maintained.

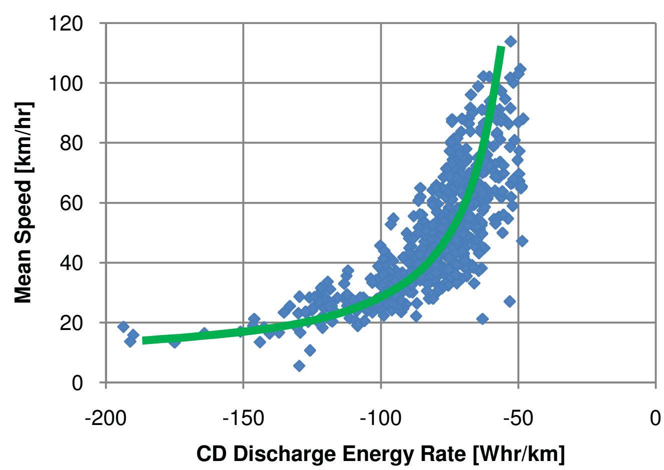

Figure 8 - CD Discharge Energy Rate vs. Mean Speed

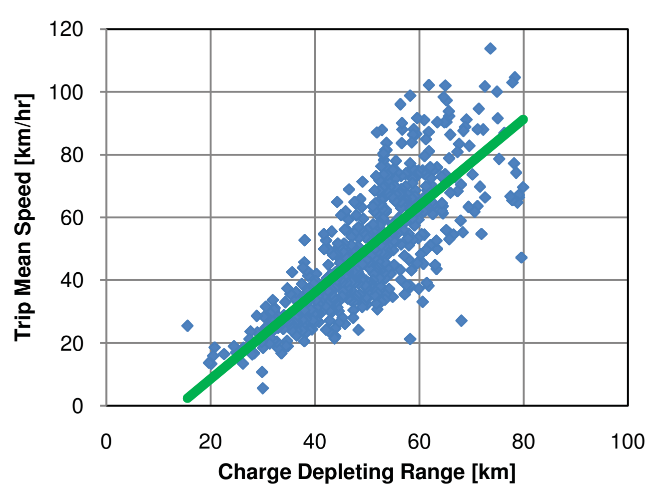

Figure 9 - Charge Depleting Range vs. Mean Speed

Figure 8 demonstrates how an increase in overall trip mean speed results in a decrease in discharge energy rate. Therefore, as mean speed increases and discharge rate decreases or stays the same, the overall charge depleting range will increase, as shown in Figure 9. In order to calculate charge depleting range, starting with a trip where the PCM battery was fully charged, consecutive trips running in charge depleting mode are added together until the PCM battery runs out of energy. The distance covered over all these trips are totaled up to the point where the PCM battery ran out of energy. This same set of data was used to plot Figure 8 – mean speeds and discharge rates were averaged over all trips.

DRIVER AGGRESSIVENESS – The least predictable noise factor is driver aggressiveness. Since the driver aggressiveness factor is based upon accelerator pedal position, there is also a correlation to load demand. As the driver tips into the accelerator pedal, this is interpreted by the vehicle as increased load demand. As previously mentioned, as power demand increases, this often drives the ICE to turn on to supplement power.

This relationship is confirmed by aggressiveness factors measured during emissions dynamometer cycles. The Urban Dynamometer Drive Schedule run in charge depleting mode records fuel consumption of approximately 1.58L/100km. The aggressiveness factor of this cycle was 5.7%. This is compared to the US06 cycle which is representative of high speed aggressive driving. Recorded fuel consumption was 4.2L/100km with an aggressiveness factor of 34.8%.

Figure 10 shows the dramatic effect that driving aggressiveness has on charge depleting fuel consumption. The most aggressive driving bin records mean fuel consumption 5 times greater than the least

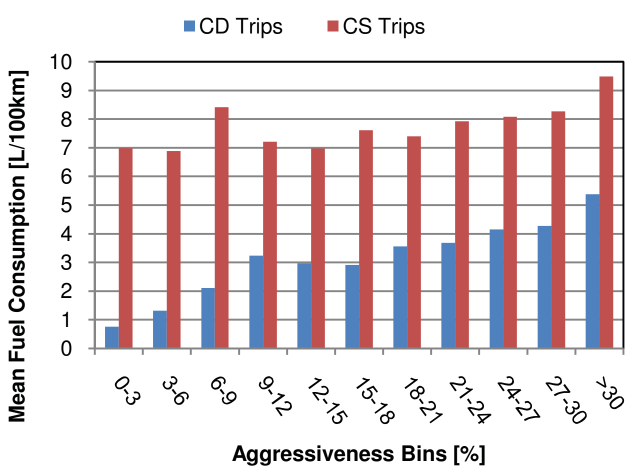

Figure 10 - Aggressiveness vs. Fuel Consumption, >3km, >5°C, >30km/hr

aggressive. This effect is less evident in charge sustaining mode, as the gas engine already provides a greater proportion of power. The trips plotted in the graph are specifically urban trips where speeds are lower and the effects of aggressiveness are more evident.

SUMMARY – All three of these factors – ambient temperature and the related use of climate control, driving speed, and driving aggressiveness, have a measureable effect on fuel consumption, primarily because they can create conditions which drive the ICE to turn on. While it may seem obvious to point out, the simplest way to reduce fuel consumption is to keep the ICE off. Figure 11 illustrates this relationship. As a greater proportion of the overall trip is driven in all-electric, or EV mode, there is a decrease in fuel consumption. Only trips with a mean speed less than 30 km/hr are plotted in order to isolate those trips where all electric operation can actually be utilized.

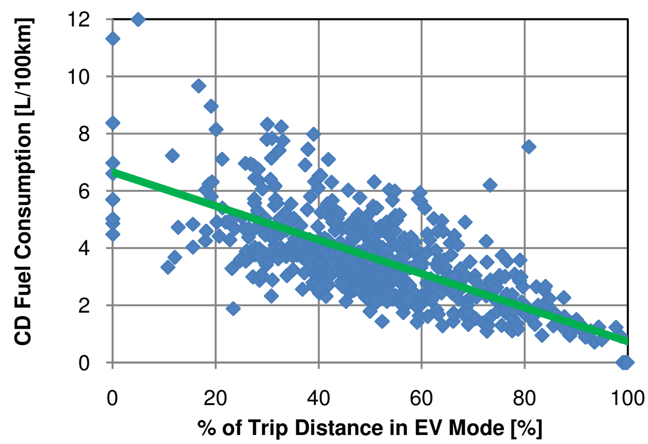

Figure 11 - EV Mode vs. CD Fuel Consumption, >3km, >5°C, <30km/hr

CHARGE BEHAVIOR

As previously demonstrated, there is a decrease in fuel consumption in charge depleting mode when compared to charge sustaining mode. In order to achieve charge depleting operation, there must be charge in the PCM battery. Although this statement seems obvious, many fleet vehicles drive for days without being recharged, essentially driving as a stock Prius. To highlight the effect of frequently recharging the PCM battery, Figure 12 plots the distance driven between charge events versus overall fuel consumption over that entire distance, along with minimum and maximum values. This distance may be composed of a single trip or multiple trips before charging.

The plot shows an increase in fuel consumption as the distance between charging increases. Mean fuel consumption approaches the stock fuel consumption of the Prius in charge sustaining mode. Note the large variations in the minimum fuel consumption for distances below 40 km. Again, this is due to the many noise factors involved with charge depleting fuel consumption.

Recall from Figure 4 that charge depleting range is usually in the 30-60 km range. As seen in Figure 12, as the distance between charge events enters the 50km+ range, mean fuel consumption variations begin to stabilize and approaches the fuel consumption of the stock vehicle.

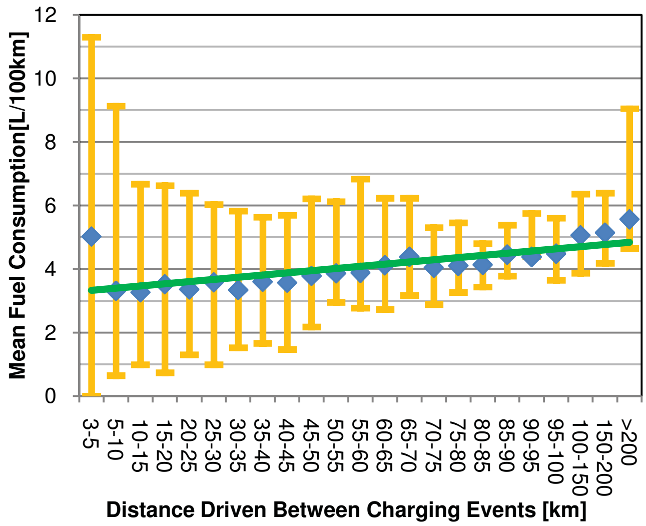

Figure 12 - Mean Fuel Consumption vs. Distance Driven Between Charging Events, >3km, >5C

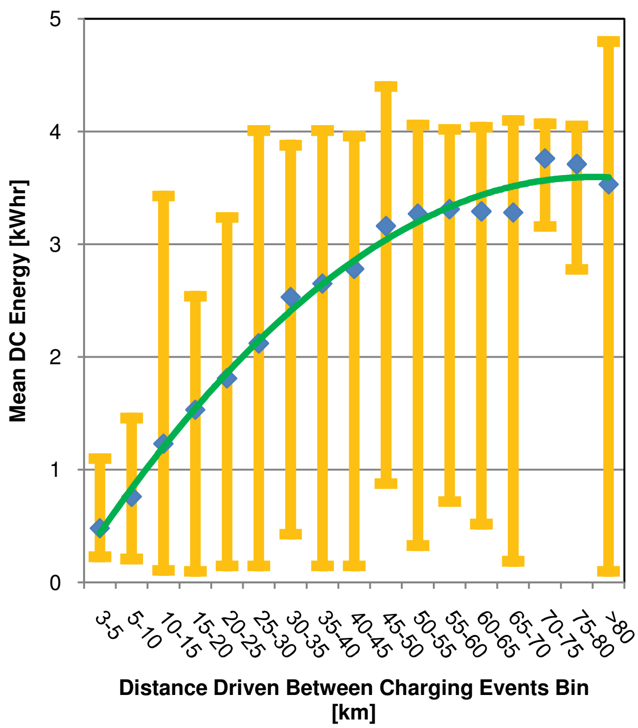

Figure 13 - Mean DC Energy vs. Distance Driven Between Charging Events

Charge Depleting range is also demonstrated in Figure 13, which shows the total amount of energy discharged from the PCM battery in relation to the distance between charging events. As the distance increases beyond the charge depleting range – or in other words, the maximum energy capacity – the maximum total discharge energy plateaus around 4 kWhrs. Note the low minimum discharge energies over the entire distance range. This is due to short "opportunity" charges, where the pack was not fully charged prior to being driven.

CONCLUSION

PHEVs offer significant fuel consumption improvements. Data from uncontrolled customer fleets show that, on average, the Toyota Prius with the Hymotion^{TM} L5 Plug-in Conversion Module (PCM) can achieve approximately half the overall fuel consumption of a base HEV Prius. This performance improvement is realized by offsetting fuel consumption with electricity from the grid. PHEV fuel consumption, electrical energy consumption, and charge depleting range are significantly affected by noise factors. Analysis based on these fundamental principles led to the following conclusions:

- After filtering only cold start warm-ups and low ambient temperature, a significant reduction in overall mean fuel consumption can be seen between charge sustaining operation (6.46L/100km) and charge depleting operation (3.44L/100km).

- Three main noise factors affect PHEV performance: Ambient Temperature, Driver Aggressiveness, and Mean Speed.

    - From the coldest to hottest ambient temperatures, there is a reduction in mean fuel consumption of approximately 60%.

    - From the most to least aggressive driving, mean fuel consumption is reduced by approximately 80%.

    - As mean speed increases, there is a greater reliance on the internal combustion engine to provide power – thereby decreasing the overall discharge energy rate and increasing charge depleting distance.

- To achieve a PHEV's potential for gasoline fuel displacement, it must operate in charge depleting mode. It is important to look beyond individual driving trips and consider the overall distance driven between off-board charging events. Increasing charging frequency relative to driving distance will result in a greater proportion of charge depleting operation, thereby reducing overall vehicle fuel consumption.

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