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Determining PHEV Performance Potential – User and Environmental Influences on A123 Systems' Hymotion™ Plug-In Conversion Module for the Toyota Prius

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Abstract

A123Systems' Hymotion^{TM} 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 system uses a lithium ion battery pack with a rated energy capacity of 5.0 kWh and recharges by plugging into a standard 110/120V outlet. The system is designed to more than double the Prius fuel efficiency for 30-50km of charge depleting range. This paper will present efforts by A123 Systems and the Idaho National Laboratory in studying the on-road performance of this PHEV fleet. The performance potentials of various fleets will be compared in order to determine the major influences on overall performance.

Main performance parameters analyzed in this paper include fuel consumption, discharge energy rate, and charge depleting range. In order to describe the complex relationship between on-road and lab performance, noise factors are described which have varying effects on performance parameters. The noise factors described and analyzed include ambient temperature, driving mean speed, and driver aggressiveness. In addition to analyzing data from the entire fleet, five vehicles being used in different applications, duty cycles, and geographical locations are individually analyzed and compared to the entire fleet.

Keywords: PHEV, fleet, lithium battery

1 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 Plug-In Conversion Module (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 installed 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.

1.1 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.

Figure 1: Hymotion L5 PCM in the Toyota Prius

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.

Table 1: Hymotion L5 PCM Specifications

Battery Parameter	**A123Systems Hymotion PCM Battery**
Chemistry	A123 Systems L5 Lithium Ion Nanophosphate™
Nominal Voltage	~190 V
Battery Capacity	25Ahr / ~5.0kWhr
Weight	85kg (includes battery cells, on-board electronics, frame)

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. 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.

2 Data Collection and Analysis

2.1 Data Collection 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.

Table 2: Data Logger Parameters

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

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

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.

2.2 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 one year.

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.

2.3 Analysis Parameters

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

CHARGE DEPLETING RANGE – 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 behaviour. 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.

2.4 Overall Fleet Statistics

Table 1 – Overall Hymotion PHEV Fleet Statistics

Total Fleet Size Analyzed	36
Total Fleet Distance Travelled	320 937 km
Data Collection Time Range	8/10/2007 – 4/1/2009
Ambient Temperature Range	-27°C – +40°C
Drive Sessions	20 391
Charge Events	5002
Total Charge Energy	9.85 DC MWhr

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

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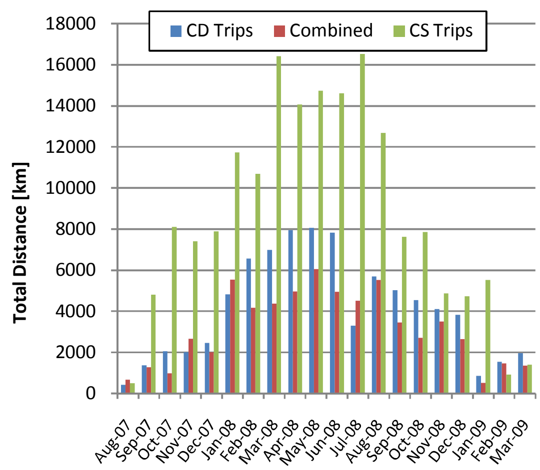
Data presented in this paper represents a subset of data collected from vehicles in the field, and comes only from Kvaser data loggers. Data shown in this paper are generally representative of the entire fleet, as judged by manual inspection of sampled data from both data loggers.

Figure 2: Overall Trip Data Composition



Five individual fleets will also be analyzed in order to add context to the overall analysis. These fleets, their location, and general use are found in Table 4. Shared fleet vehicles are owned and maintained by businesses, where the vehicles are also located and charged. These vehicles are rented by employees who need to travel offsite. The community rental vehicle is located and charged in a parking lot in Toronto as part of a rental fleet. The rental service is membership only and targets local residents looking for short duration rental periods to travel around the city. The vehicle in Manitoba is part of a private fleet but is allocated to an individual employee who utilizes the vehicle for daily use and commuting.

Table 4 – Individual Vehicle Description

Vehicle ID	Location	Application
CAL1	California, USA	Shared Fleet
CAL2	California, USA	Shared Fleet
CAL3	California, USA	Shared Fleet
TO1	Toronto, Canada	Community Rental
MAN1	Manitoba, Canada	Urban Personal Commuting

2.5 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.

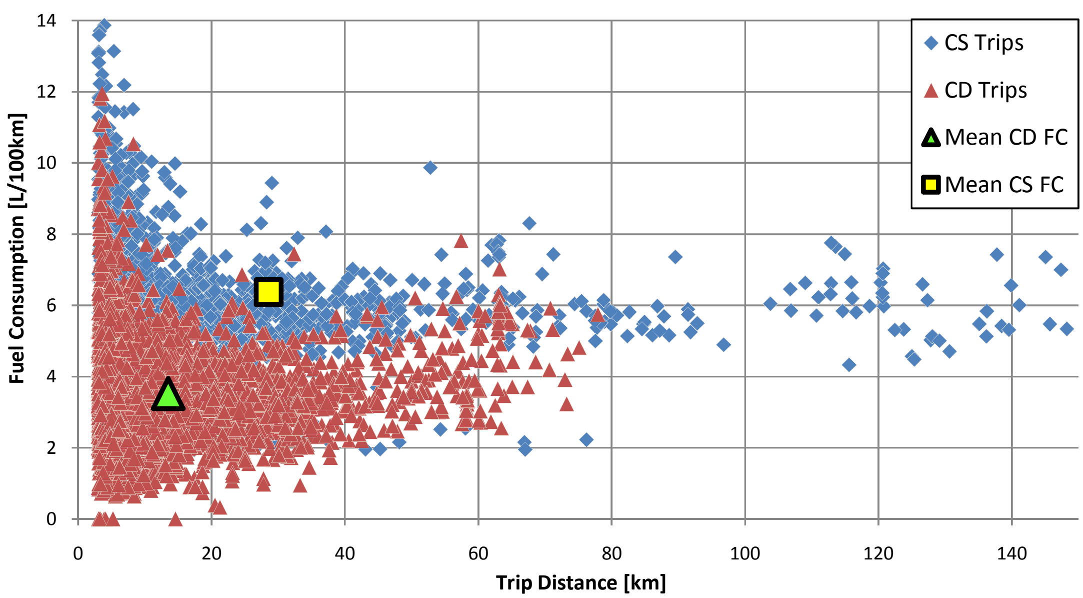
In addition to examining multiple performance metrics, it is important to identify the effects of noise factors on performance. Fuel consumption and charge depleting range in PHEVs are found to be extremely sensitive to noise factors, such as ambient operating conditions, driving aggressiveness, climate 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.

3 Basic Distributions

Since the main advantage of PHEVs is a dramatic improvement in gasoline fuel consumption (hereafter referred to simply as fuel consumption), Figure 2 presents a comparison of fuel consumption results for all trips greater than 3 km,

Figure 2: Fuel Consumption vs. Trip Distance, >3km, >5°C



with an average ambient temperature greater than 5°C. Two points on the graph are also highlighted: Overall means for both operating modes. Overall Mean Charge Depleting fuel consumption was 3.53L/100km with a mean trip distance of 13.66km. Overall Mean Charge Sustaining fuel consumption was 6.37L/100km with a mean trip distance of 28.55km. 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 ~80km 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. Table 5 compares individual vehicles with the overall mean reinforcing the variability in usage for these vehicles.

Table 5: Trip Distance and Fuel Consumption

	Mean CD FC [L/100km]	Mean CD Distance [km]	Mean CS FC [L/100km]	Mean CS Distance [km]
Overall	3.53	13.6	6.37	28.5
CAL1	3.19	12.8	6.40	19.5
CAL2	3.76	21.3	5.54	42.2
CAL3	3.05	19.8	5.11	27
TO1	3.93	14	6.13	22.5
MAN1	2.44	7.6	5.87	50

Energy drawn from the PCM battery is shown in Figure 3, plotted against charge depeleting trip distances. Since the total amount of usable 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 one entire trip, a theoretical maximum discharge rate can be calculated. This is also plotted in Figure 3. Variability in trips less than 10km are again due to noise factors, such as mean speed and aggressiveness. The overall mean charge depleting discharge rate is -82Whr/km as plotted in Figure 3.

The final basic distribution, shown in Figure 4, plots Charge Depleting Fuel Consumption vs. Discharge Energy 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, there are many noise factors that mask this relationship.

4 Noise Factors

4.1 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,

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

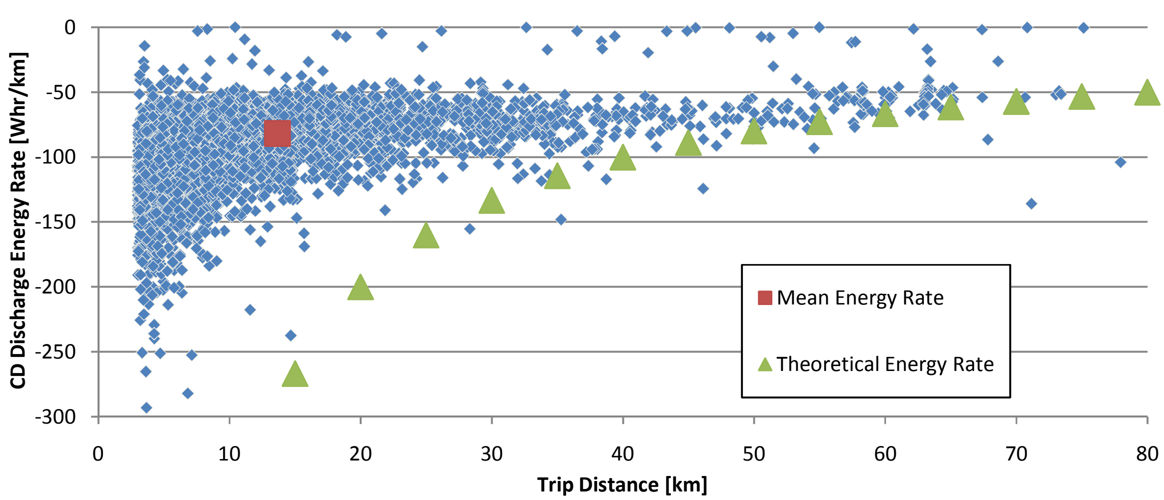
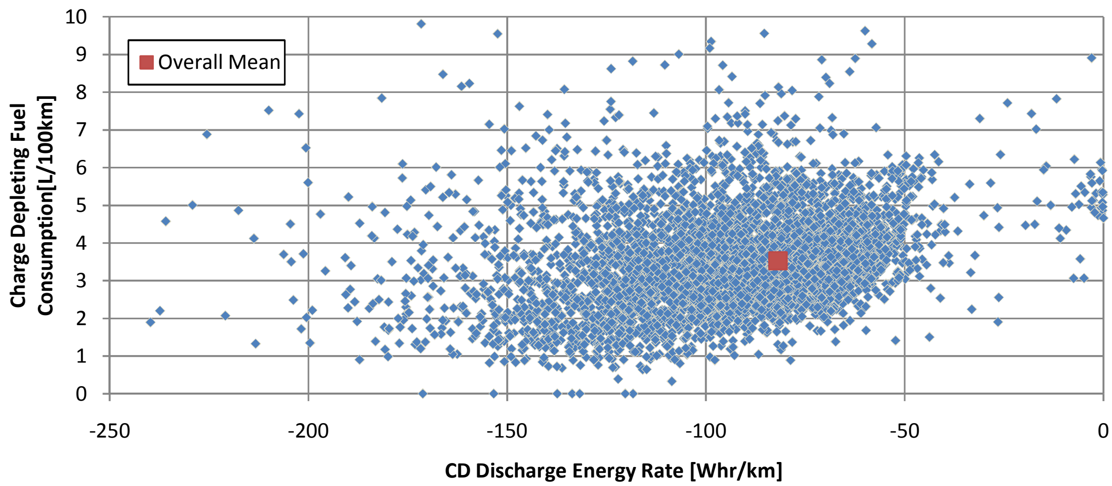


Figure 4: CD Fuel Consumption vs. Discharge Energy Rate, >3km, >5°C



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.

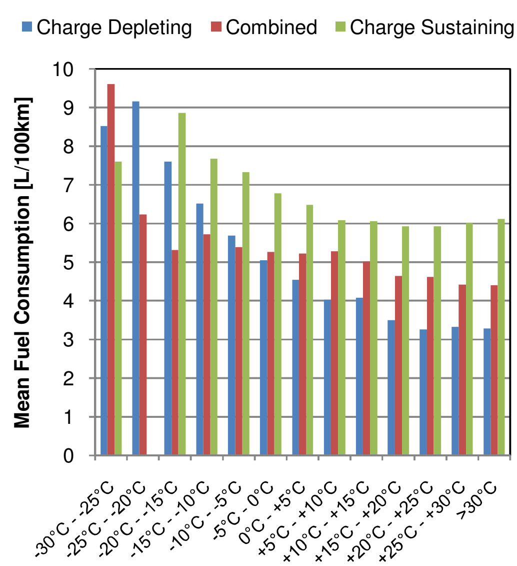
For air conditioning, the compressor is driven by an electric motor capable of drawing more than 2kW of power, which could otherwise be used to drive the wheels. During charge depleting operation, with this additional load, the ICE will turn on more frequently to offset that load, resulting in increased fuel consumption. Table 6 demonstrates the effect of ambient temperature on individual vehicle charge depleting fuel consumption.

Table 6: Ambient Temperature Vehicle Comparison

	Overall CD FC [L/100km]	Mean Ambient Temp.	CD FC > 5°C [L/100km]	CD FC < 5°C [L/100km]
CAL1	3.19	19°C	3.19	n/a
CAL2	3.76	18.8°C	3.76	n/a
CAL3	3.05	19.4°C	3.05	n/a
TO1	4.77	10.3°C	3.93	4.93
MAN1	4.05	4.7°C	2.44	6.26

MAN1, located in Manitoba, by far experiences the coldest weather among the five vehicles, with a mean ambient temperature of 4.7°C, almost 15°C colder throughout the entire year compared to the vehicles in California. For MAN1, overall fuel consumption almost triples below 5°C. The vehicle in Toronto, although experiencing far less cold temperatures, still sees a 20% increase in fuel consumption below 5°C. None of the vehicles in California were driven in ambient temperatures below 5°C.

Figure 5: Mean Fuel Consumption vs. Ambient Temperature Bins, >3km



Over the entire fleet, Figure 5 plots mean fuel consumption for each of the operating modes, in separate temperature bins. 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 charge depleting fuel consumption of more than 60%.

4.2 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.

Table 7: Mean Speed Vehicle Comparison

	CD FC > 5°C [L/100km]	Mean CD Speed [km/hr]	Mean CD Range [km]	Mean Discharge Rate [Whr/km]
CAL2	3.76	49.3	62	-69
CAL3	3.05	50.2	59	-71
CAL1	3.19	37	48	-77
TO1	3.93	30.6	42	-95
MAN1	2.44	26	38	-118

Table 7 demonstrates the mean speed – discharge rate relationship. Of the five vehicles, MAN1 had the lowest overall charge depleting mean speed, indicative of urban driving. Since overall power requirements for driving at low speed can be handled by the PCM, the overall discharge rate increases. Therefore, as the discharge rate increases, the PCM battery is discharged faster, thereby decreasing the overall charge depleting range. This is opposite for CAL2 whose overall mean speed is almost double of MAN1. Since the ICE will turn on to supply the additional power required to drive at faster speeds, the overall discharge rate of the PCM battery decreases. Therefore, CAL2's overall charge depleting range increases and mean discharge rate decreases.

Figure 6: CD Mean Speed vs. Discharge Rate

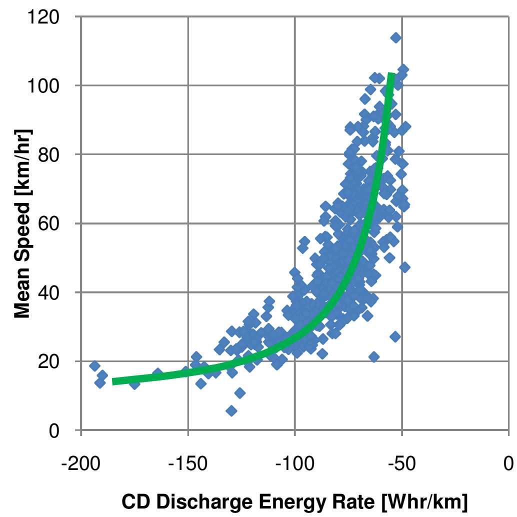
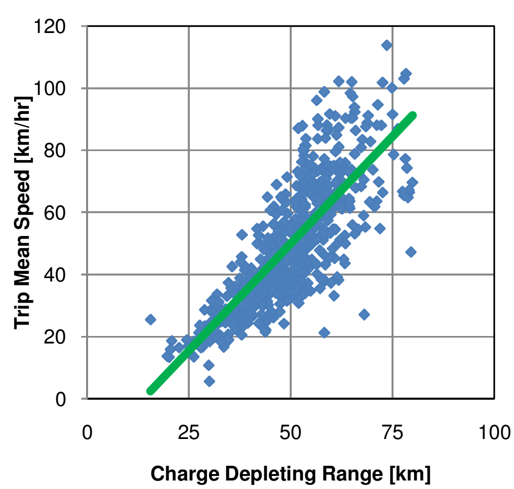


Figure 6 demonstrates how an increase in overall trip mean speed results in a decrease in discharge energy rate. Therefore, as mean speed increases and discharge rate decreases or stays the same, the overall charge depleting range will increase, as shown in Figure 7. In order to calculate charge depleting 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.

Figure 7: Charge Depleting Range vs. Mean Speed



The distance covered over all these trips are totalled up to the point where the PCM battery ran out of energy. This same set of data was used to plot Figure 7 – mean speeds and discharge rates were averaged over all trips.

4.3 Driver Aggressiveness

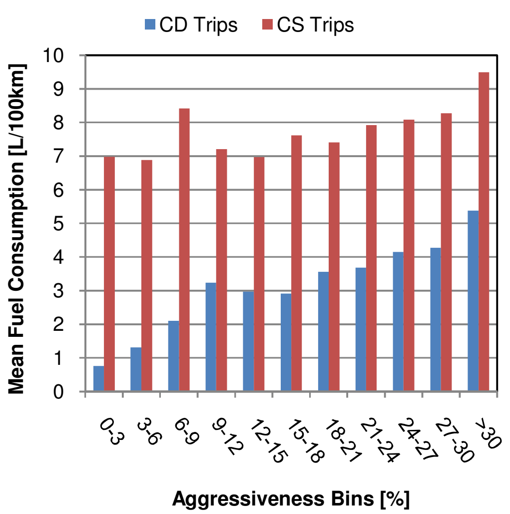
The least predictable noise factor is driver aggressiveness. Since the driver aggressiveness factor is based upon accelerator pedal position, there is also a correlation to load demand. As the driver tips into the accelerator pedal, this is interpreted by the vehicle as increased load demand. As previously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

Table 8: Aggressiveness Vehicle Comparison

	CD FC >5°C [L/100km]	Mean Aggressiveness
MAN1	2.44	10.7
CAL3	3.05	14.9
CAL1	3.19	19.7
CAL2	3.76	21.4
TO1	3.93	24.5

Table 8 demonstrates the relationship between fuel consumption and aggressiveness for individual vehicles. MAN1, with the lowest mean aggressiveness also had the lowest overall charge depleting fuel consumption. The opposite is true for TO1, which had the highest mean aggressiveness and fuel consumption of all five vehicles.

Figure 8: Mean Fuel Consumption vs. Aggressiveness, >3km, >5°C, <30km/hr



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 8 plots aggressiveness for the entire fleet, plotting mean fuel consumption over aggressiveness bins. The trips plotted in the figure are specifically urban trips where speeds are lower and the effects of aggressiveness are more evident. The least aggressive driving bin records mean charge depleting fuel consumption approximately 80% less than the most aggressive. This effect is less evident in charge sustaining mode, as the gas engine already provides a greater proportion of power.

5 Charge Behaviour

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, two parameters related to charge behaviour are tabulated in Table 9. In order to demonstrate the overall effects of charge behaviour, fuel consumption is calculated over all trips for each vehicle, instead of focusing on only charge depleting, charge sustaining, or combined modes of operation. CD:CS Distance Ratio is the ratio of trip distances travelled between charge depleting and sustaining modes of operation over the entire data set for each vehicle. Distance Between Charge is the distance travelled by the vehicle between each charging event. This distance may be composed of a single trip or multiple trips before charging.

Figure 9: Mean Fuel Consumption vs. Distance Between Charging Events, >3km, >5°C

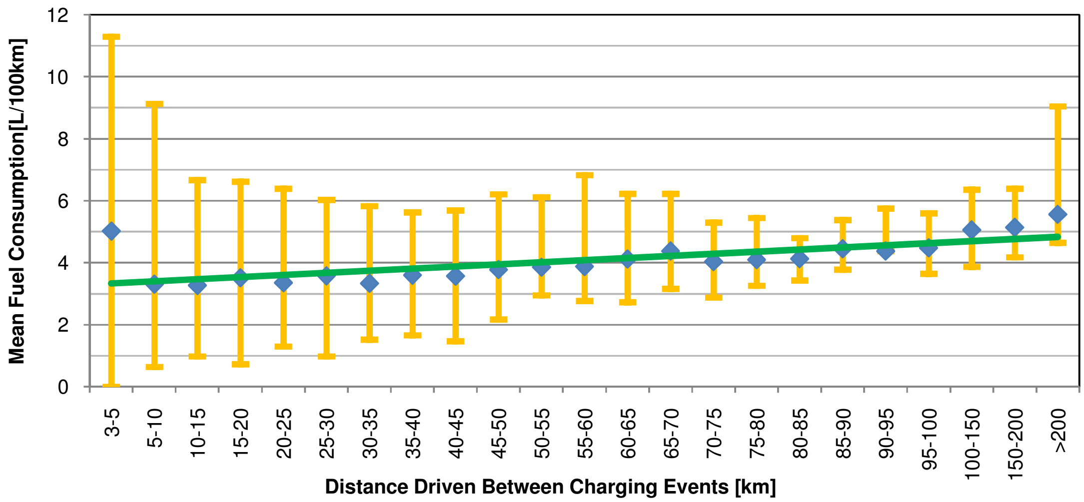


Table 9: Charge Behaviour Comparison

	Overall FC > 5°C [L/100km]	CD:CS Distance Ratio	Mean Distance Between Charge [km]
CAL1	3.77	4.05	19.9
MAN1	3.92	2.13	35.3
CAL3	3.92	1.73	63.1
CAL2	4.63	0.902	87.3
TO1	5.78	0.14	150.3

Of the five vehicle sample, CAL1 charged the most frequently, driving in charge depleting mode four times more than in stock charge sustaining mode, and recording the lowest overall fuel consumption. As CD:CS ratio decreases and the mean distance between charge increases, overall fuel consumption increases. TO1 charged the least frequently of all five vehicles and recorded overall fuel consumption similar to standard stock operation.

Figure 9 plots the distance driven between charge events versus overall fuel consumption over that entire distance, along with minimum and maximum values, for the entire fleet. The plot shows an increase in mean fuel consumption as the distance between charging increases, approaching the stock fuel consumption of the Prius in charge sustaining mode. This is the same relationship shown in the five vehicle sample. 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 7 that charge depleting range is usually in the 30-60 km range. As seen in Figure 9, 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.

6 Conclusions

PHEVs offer significant fuel consumption improvements. Data from customer fleets show that, on average, the Toyota Prius with the Hymotion™ L5 Plug-in Conversion Module (PCM), operating in charge depleting mode, 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. Additionally, 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 (6.37L/100km) and charge depleting operation (3.53L/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 range.

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 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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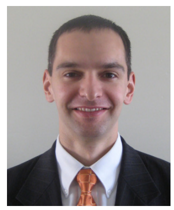
Huang – Yee Iu is currently employed at A123Systems as a Test Engineer with the following specializations: Mechanical, abuse, compliance, and qualification testing of large format battery packs for automotive applications; data collection and analysis of plug-in hybrid fleets; and battery life model analysis and development. He holds a Bachelor of Applied Science in Mechanical Engineering from the University of Toronto and is a University of Toronto Formula SAE five year alumni and three time winner of Formula Student UK.



John Smart is the lead PHEV test engineer at the Idaho National Laboratory. Prior to this position, he worked at Ford Motor Company in Powertrain Product Development. Mr. Smart holds a Bachelor of Science degree in Mechanical Engineering from Brigham Young University.

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