Factors Affecting the Fuel Consumption of Plug-In Hybrid Electric Vehicles

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Abstract— Plug-in hybrid electric vehicles (PHEVs) have proven to significantly reduce petroleum consumption when compared to conventional internal combustion engine vehicles by utilizing onboard electrical energy storage for propulsion. Through extensive testing of PHEVs, analysis has shown that fuel consumption of PHEVs is more significantly affected than conventional vehicles by the driver's inputs, as well as by the environmental inputs around the vehicle. Six primary factors have been identified that significantly affect fuel consumption and electrical energy consumption of PHEVs. In this paper, these primary factors are analyzed from the on-road driving and charging data of the Hymotion Prius PHEV. The data consist of 1.8 million miles of driving and charging from over 200 PHEVs in 23 states, Canada, and Finland.

The Idaho National Laboratory tests PHEVs as part of its conduct of the U.S. Department of Energy's Advanced Vehicle Testing Activity. The Advanced Vehicle Testing Activity is part of the U.S. Department of Energy's Vehicle Technology Program. In collaboration with its more than 90 PHEV testing partners, Idaho National Laboratory has collected data on 12 different PHEV models (as distinguished by battery manufacturer), while conducting fleet, track, and dynamometer testing for the U.S. Department of Energy's Advanced Vehicle Testing Activity.[1]

Keywords— PHEV, Fuel Consumption, On-Road, Testing

1. Introduction

The U.S. Department of Energy's Advanced Vehicle Testing Activity, in collaboration with 80 testing partners throughout the United States, Canada, and Finland, has collected data from over 1.8 million miles of plug-in hybrid electric vehicle (PHEV) driving and charging events.[1] A map of the testing partner locations is shown in Figure 1. Analysis of this extensive data, performed by the Idaho National Laboratory, has identified six primary factors that significantly impact fuel consumption and electrical energy consumption of PHEVs. For this paper, the six primary factors are analyzed for the Hymotion Prius PHEV and the results of the analysis are discussed.

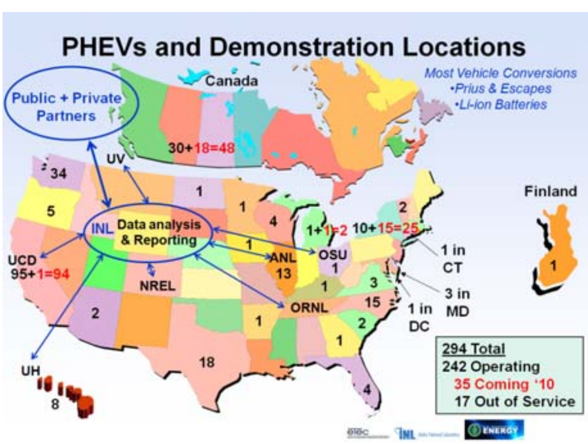

Figure 1: Locations of collaborative PHEV demonstration and test partners.

2. Vehicle Description

The analysis for this paper was performed on data obtained from the Hymotion Prius PHEVs operating in the demonstration fleet discussed previously. The Hymotion Prius PHEV uses A123 Systems' Hymotion L5 PCM (plug-in conversion module), which is a 5 DC kWh supplemental battery pack that is designed to fully integrate into a 2004 through 2009 Toyota Prius.[2] With the additional onboard battery capacity of the Hymotion L5 PCM, charge depleting operation is used in an effort to significantly reduce petroleum consumption. Figure 2 shows a picture of one of over 200 Hymotion Prius PHEVs used as part of the collaborative fleet data collection activity.

Figure 2: Hymotion Prius PHEV conversion with integrated A123 Systems' Hymotion L5 PCM.

3. Six Primary Factors

Six primary factors have been identified that significantly impact PHEV fuel consumption and electrical energy consumption. These six factors are listed below. Some of the factors are unique to PHEVs while others are common for all types of vehicles.

3.1 Usable Electrical Energy

Usable electrical energy is dictated by battery capacity, rate of depletion, and state of charge at the beginning of each trip. With less electrical energy available for use, the powertrain must use more petroleum to generate the demanded power output. With minimal usable electrical energy, a PHEV operates similarly to a hybrid electric vehicle (HEV).

3.2 Vehicle Accessory Utilization

Air conditioner systems and defroster systems are capable of consuming a significant amount of additional energy that does not contribute to the propulsion of the vehicle.

3.3 Ambient Temperature

The ambient temperature can reduce the efficiency of many powertrain components by significantly increasing fluid viscosity. For vehicles that utilize battery energy storage systems (ESS), the temperature can greatly affect the power output capability of the ESS, thus reducing its system effectiveness. In cold ambient temperatures, the need for cabin heat to warm the driver and passengers increases the time of engine operation, increasing fuel consumption.

3.4 Engine Startup/Warm up

Engine startup/warm up includes control strategies to improve cold start emissions and control routines to quickly supply cabin heat. These control strategies, while necessary for emissions control and consumer acceptance, increase fuel demand.

3.5 Route Type

Route type includes city and highway driving that can affect fuel consumption because the route can involve stop and go driving or ascending and descending steep grades.

3.6 Driver Aggressiveness

Driver aggressiveness impacts fuel consumption of nearly all vehicles; however, the impact is greater for high-efficiency powertrains such as HEVs and PHEVs.

Because many of the impact factors are independent from the other factors, it is highly possible for multiple factors to simultaneously impact fuel and electrical consumption. To accurately determine the extent of the impact for each factor, each factor must be isolated from the other impact factors. To accomplish this, fleet data are analyzed for the specific factor during periods of operation when the other five factors are within a set of nominal conditions and the sample size is greater than fifty trips. The nominal conditions are shown in Table 1. Because of random driver and environmental conditions that are present, normal distributions of data can be assumed with average values representing a majority of the respective recorded data.

Table 1: Nominal conditions of primary factors used for PHEV fleet data analysis.

Primary Factors	Nominal Conditions
Usable Electrical Energy	Trip entirely in charge depleting or in charge sustaining mode
Vehicle Accessory Utilization	No accessories on
Ambient Temperature	15 to 30°C
Engine Startup / Warm up	Initial engine temperature >50°C and trip duration > 0.2 hours
Route Type	Urban driving
Driver Aggressiveness	Less than 20% of time of the drive greater than 40% pedal position
Driver Aggressiveness	Less than 20% of time of the drive greater than 40% pedal position

4. Usable Electrical Energy

For vehicle propulsion, the amount of wheel energy is determined by the road loads on the vehicle. To create the necessary wheel energy, the powertrain, which can be comprised of a wide variety of configurations, is required to generate the required power to satisfy the desired wheel energy. For PHEVs, the powertrain uses fuel and electrical energy to produce the required output power. Because of current technology constraints of onboard ESS, the available electrical energy for use by PHEVs is much less than the available fuel energy available onboard the vehicle. For a given powertrain energy requirement, increased contribution from the onboard electrical energy storage system lessens the amount of fuel demanded to fulfill the driving requirement.

For the Hymotion Prius PHEV, the ESS enables charge depleting operation in which fuel consumption is reduced as shown in Figure 3 by displacing fuel energy with electrical energy. But charge depleting operation is only possible if there is energy available for use in the ESS from prior recharging. The energy storage system is recharged from off-board electrical energy. If the energy storage system is not fully charged prior to a trip, fuel consumption will be increased due to decreased usable electrical energy, as shown in Figure 3. At high initial states of charge, sufficient electrical energy is available to displace a large portion of the fuel consumed; however, at decreasing initial states of charge, the fuel displacement benefit is reduced.

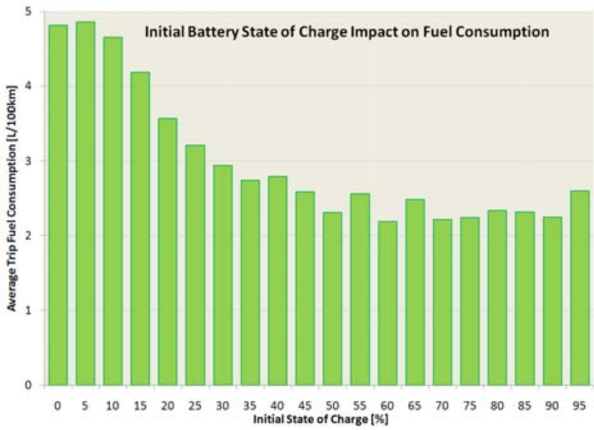

Figure 3: Fuel consumption impact dependant on ESS initial SOC.

5. Vehicle Accessory Utilization

In the Hymotion Prius PHEV, air conditioner operation is the primary accessory that impacts fuel consumption and electrical energy consumption. The air conditioner compressor is driven by a high voltage electric motor (same as in the Toyota Prius) and is operated during cabin cooling and windshield defroster operation. Figure 4 shows the relative number of driving trips in which the air conditioner compressor was operating across a range of ambient temperatures. For example, nearly all driving trips (about 90%) above 30°C ambient temperature utilized the air conditioner, whereas trips below 0°C had very low utilization of the air conditioner (about 0%). Figure 4 also shows the groupings of driving trips that utilized the air conditioner for windshield defrost and cabin air cooling. The utilization decreases for cabin air cooling as the ambient air temperature decreases from 30°C; however, windshield defroster utilization peaks just below 10°C with a utilization range from 0 to 15°C ambient temperature.

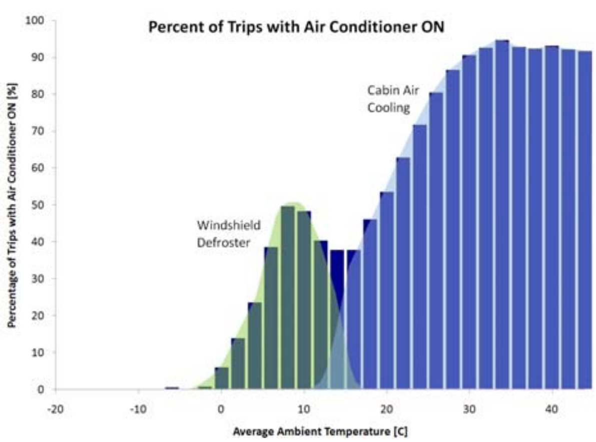

Figure 4: Percent of trips with air conditioner operation at various ambient temperatures.

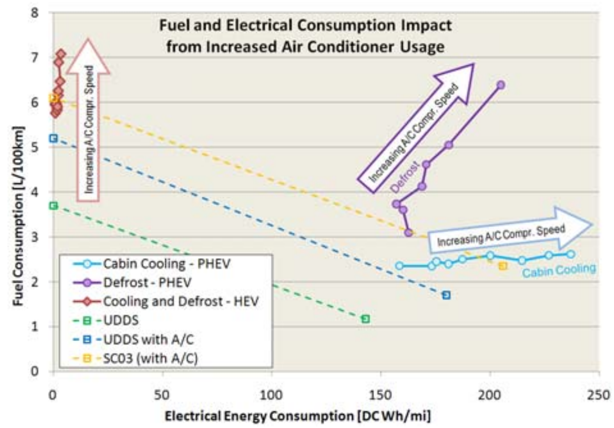

Figure 5: Fuel and electrical energy consumption impact of increasing compressor speed.[3]

Air conditioner compressor speed is closely related to the power draw from the air conditioner system. Compressor speed is available from the data collected on the Hymotion Prius PHEV fleet operation, whereas air conditioner system power draw is not available. Therefore, air conditioner compressor speed will be the metric used for comparison to determine the impact of air conditioner utilization throughout this analysis. Figure 5 shows the impact of increased air conditioner compressor speed on fuel consumption and electrical energy consumption. During charge depleting operation, with the air conditioner operating for cabin air cooling, electrical energy consumption significantly increases as fuel consumption slightly increases. This seems logical because the air conditioner compressor is driven by a high-voltage electric motor and, as electrical load increases on the energy storage system, electrical energy consumption also increases. When air conditioner operation is required for operation of the windshield defroster, both fuel consumption and electrical energy consumption significantly increase. This is due to increased engine operation during defroster operation relative to cabin cooling air conditioner operation. Because the defrost operation is primarily utilized between 0 and 15°C ambient temperature, two primary impact factors are concurrently effecting fuel consumption. As for charge sustaining operation, fuel consumption increases as compressor speed increases because all loads ultimately are powered from fuel energy. For comparison, Figure 5 shows the results of three chassis dynamometer tests of the Hymotion Prius PHEV.[3] With increasing cabin cooling load (from UDDS to UDDS with A/C to SC03), electrical energy consumption significantly increases and fuel consumption slightly increases.

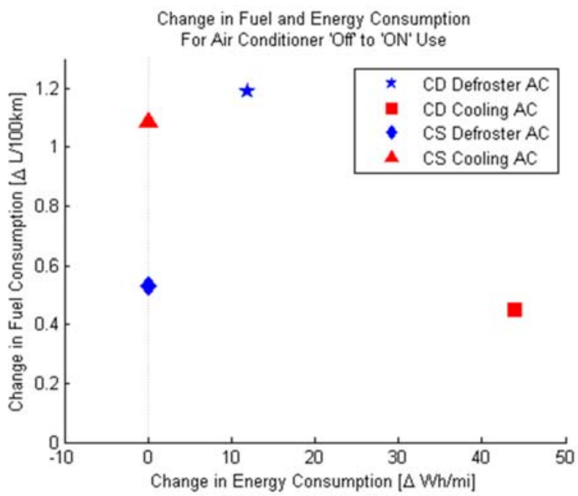

Figure 6: Average fuel and electrical consumption as impacted by use of the air conditioner for defroster and cooling purposes.

A comparison of air conditioner operation for cabin cooling and windshield defrost for both charge depleting and charge sustaining operation is shown in Figure 6. The points on the figure show the change in fuel and electrical consumption for air conditioner operation compared with no operation. The averages for each data set over the available temperature ranges are shown in Figure 6. Because the windshield defroster is only used at lower ambient temperatures, trips with an average ambient temperature below 15°C are presented as "Defroster AC." Similarly cabin cooling air conditioner operation is only used for higher ambient temperatures; therefore, trips above 15°C are presented as "Cooling AC." From the analysis, an increase in fuel consumption is observed for all instances of air conditioner operation regardless of vehicle mode (charge depleting or charge sustaining) or air conditioner operation type (cabin cooling or defrost). For variation in air conditioner operation type (defrost and cabin cooling), Figure 6 shows cabin cooling has the greatest impact on fuel consumption in charge sustaining operation, whereas defrost has the largest impact on fuel consumption in charge depleting operation. This effect is caused by an engine-on command for charge depleting defroster operation. For cabin cooling air conditioner operation, electrical power is required because the air conditioner compressor is driven by a high-voltage electric motor. For charge depleting operation, cabin cooling air conditioning operation uses more electrical energy from the energy storage system. For charge sustaining operation of the cabin cooling air conditioning, the additional energy requirement ultimately comes from additional fuel consumption because, by definition, the battery system has no net energy output during charge sustaining-operation.

Figure 7 shows the average air conditioner compressor speed for each driving trip in which the air conditioner system is used with respect to ambient temperature. Above 15°C, the average compressor speed for each trip exponentially increases with respect to ambient temperature. This is due to increased cooling load requirements at high ambient temperature to keep the passenger compartment cool. Below 15°C, compressor operation is for windshield defroster operation, and the average compressor speed is typically 1,000 RPM. This shows that windshield defroster operation requires a reduced and more consistent amount of power for proper operation across the operating temperature range.

Also shown in Figure 7 is the total occurrence (number of trips) for each average compressor speed for a given ambient temperature as indicated by color. Note the high occurrence, shown in dark red, of windshield defrost operation between 5 and 15°C, and contrast that with the low occurrence (shown in green and blue) of high speed compressor operation at high ambient temperatures (30°C). This means that even though the there is a large percentage of trips at high ambient temperature that use the air conditioner system (shown in Figure 4), the occurrence of those trips is rather low compared to the typical operation of the vehicle (shown in Figure 7).

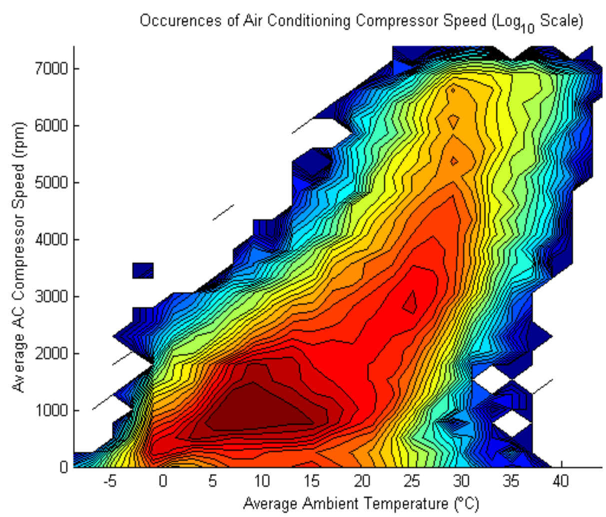

Figure 7: Percent of trips with air conditioner operation at various ambient temperatures.

6. Ambient Temperature

The ambient temperature in which a vehicle is driven impacts fuel consumption of nearly all vehicles due to changes in viscosity of lubrication fluids for the powertrain and driveline and operational changes (e.g., transmission shift schedule and engine idle speed) for improved drivability. For PHEVs, the ambient temperature has similar and additional impacts, including increased engine operating time to provide cabin air heat at low ambient temperatures and reduced battery performance at very high ambient temperatures. Figure 8 shows fuel consumption of the Hymotion Prius PHEV fleet over a wide temperature range in charge depleting and charge sustaining operation. Note the increase in fuel consumption in extremely low ambient temperature and high ambient temperature. This trend of increased fuel consumption tracks with the percentage of electric only operation as shown in Figure 9. At low ambient temperatures, the engine operates more to provide cabin air heat for passengers and longer engine warm up times are required.

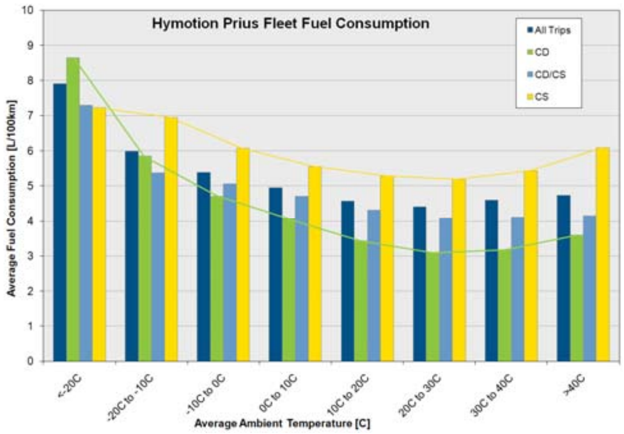

Figure 8: Fuel consumption impact of ambient temperatures.

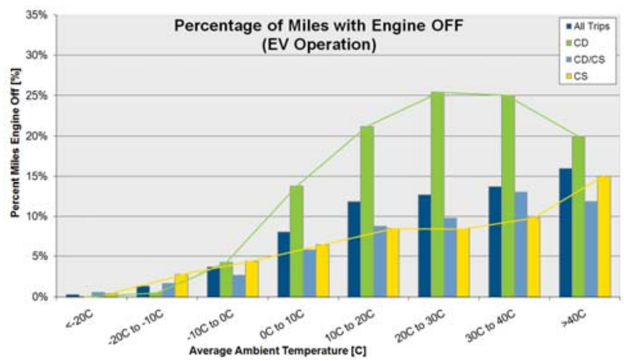

Figure 9: Electric Only operation with respect to ambient temperatures.

7. Engine Startup

At initial startup, increased fuel and electrical energy consumption occurs due to engine warm up in the Hymotion Prius PHEV. During engine warm up, different engine control strategies are used to ensure tailpipe emissions' compliance and smooth operation; however, as a result, more fuel is consumed to warm the engine. This also results in less power output from the engine during this warm up state; therefore, more electrical energy is required to meet the driver's demand. For trips with higher initial engine temperature, this increased fuel and electrical energy consumption is reduced as seen in Figure 10. The warm up period is rather brief (2 to 4 minutes); longer trips show less overall impact to fuel and electrical energy consumption due to a significant portion of driving occurring after the warm up period. As trip duration increases, the overall impact of engine warm up time to fuel and electrical energy consumption is diminished (Figure 10).

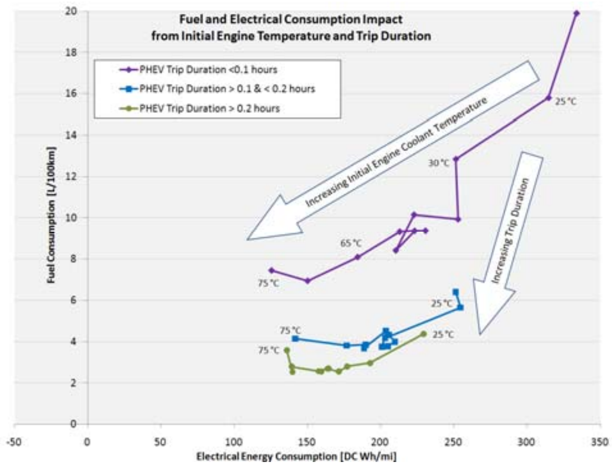

Figure 10: Fuel and electrical energy consumption impact by initial engine coolant temperature and trip duration.

Fuel flow and fuel consumption for two trips with different initial and final trip temperatures over similar trip routes is shown in Figures 11 and 12. As the engine coolant temperature during the trip increases, the fuel volume used during the trip is reduced. It can be seen by comparing Figures 11 and 12 that the colder the initial engine temperature, the longer it takes for the engine to warm up, thus increasing the fuel flow and total volume consumed. Also of importance to note is trips starting at especially cold temperatures (such as the below freezing trip in Figure 11) have an increased fuel consumption rate even during low demand driving conditions. As the engine coolant temperature increases, the engine operation and fuel flow becomes more dependent on driver demand. This reduction with increasing engine coolant temperature is the same effect shown in Figure 10 where longer trips have lower average fuel consumption

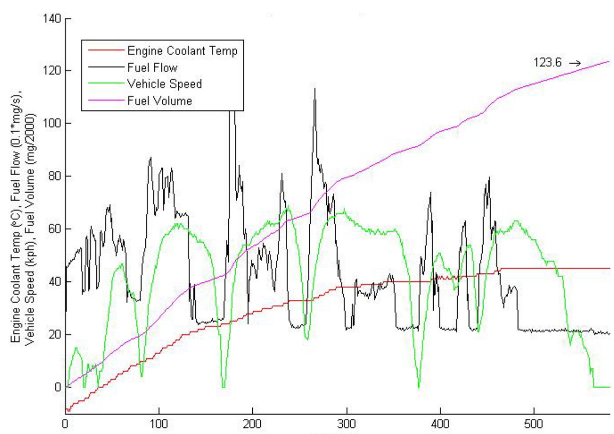

Figure 11: Driving data from a trip with initial engine coolant temperature of -8°C.

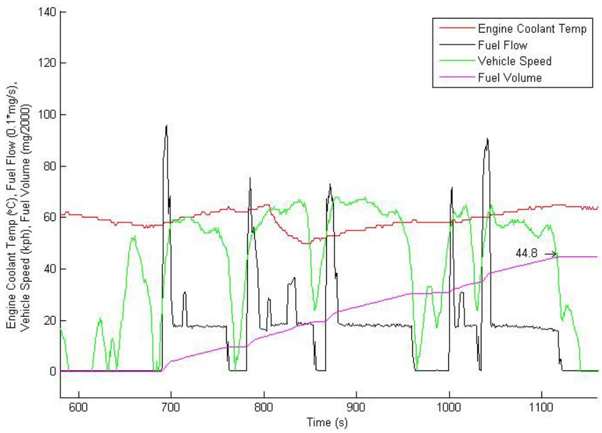

Figure 12: Driving data from a trip with initial engine coolant temperature of 61°C.

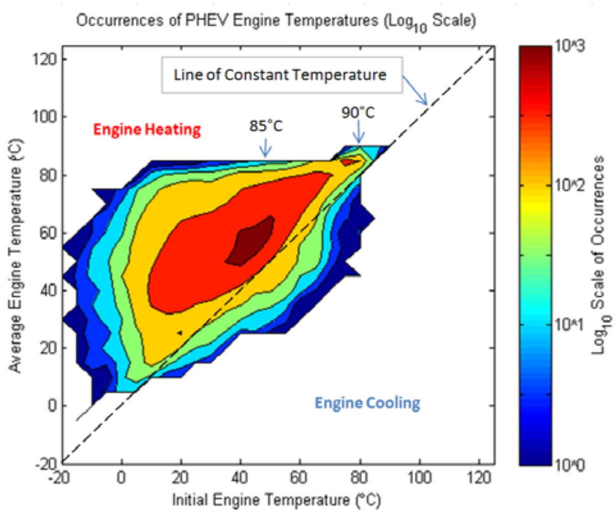

Figure 13: Number of occurrences of initial and average engine temperature during charge depleting operation.

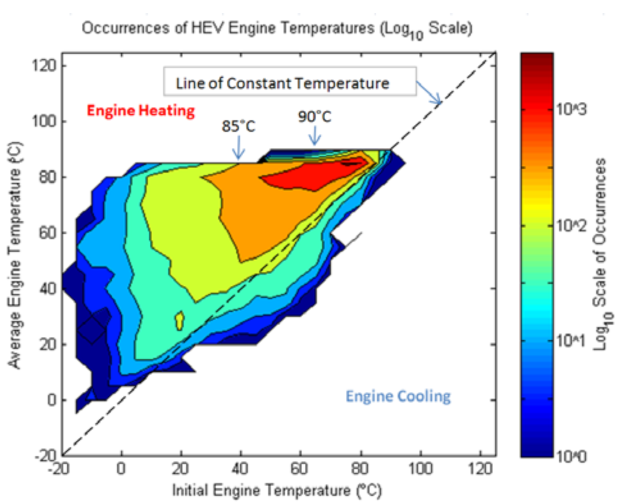

Figure 14: Number of occurrences of initial and average engine temperature during charge sustaining operation.

Figures 13 and 14 show the number of occurrences of initial and average engine temperatures for charge depleting and charge sustaining operation respectively. The engine operates within different coolant temperature ranges depending on vehicle operating mode. During charge sustaining operation, the engine is required to operate more often and at higher load, which increases the average operating temperature because all propulsion energy ultimately comes from fuel energy. For trips starting in charge sustaining mode, many are preceded by charge depleting trips in which the engine approaches typical operating temperature. In contrast, it is less likely that a charge depleting trip was preceded by a significant driving event; therefore, charge depleting trips typically begin with much lower initial engine coolant temperature. The occurrences of initial and average engine temperatures lead to an understanding that, on average, vehicles operated in charge sustaining mode operate at more fuel-efficient engine temperatures more often than vehicles operated in charge depleting mode. However, these effects are usually negated by electrical energy offsets to the total energy consumption by depletion of the battery during charge depleting operation. Additionally, in Figures 13 and 14, it is shown that the typical peak operating temperature is about 85°C, but for trips with a high initial temperature, the engine can reach about 90°C. The "Engine Heating" and "Engine Cooling" divisions of Figures 13 and 14 represent trips where the initial engine temperature is lower and higher than the average engine temperature, respectively. Engine cooling occurs when the engine is off for a significant amount of time during the trip such that the engine coolant temperature decreases over the duration of the trip.

8. Route Type

The characteristics of the route driven also impact the overall fuel and electrical energy consumption of the Hymotion Prius PHEV. Driving in stop-and-go traffic in an urban environment or cruising at high speed on a freeway will result in different fuel and electrical consumption. Mountainous driving up and down steep grades also can have a significant impact. A few parameters that are used to aid in characterization of the route type are average vehicle speed, vehicle stops per distance traveled, and percent idle time (percent of trip time when vehicle speed is zero). A strong correlation between average vehicle speed and stops per kilometer for this PHEV fleet data is shown in Figure 15. Highway driving on freeways consists of high average vehicle speeds and a low number of stops per distance traveled. Urban driving consists of a moderate number of stops per distance traveled and lower average vehicle speeds. Delivery route-type driving has a very high number of stops per distance traveled, and very low average vehicle speeds. For comparison, dynamometer drive cycle route characteristics are shown on Figure 15.[3]

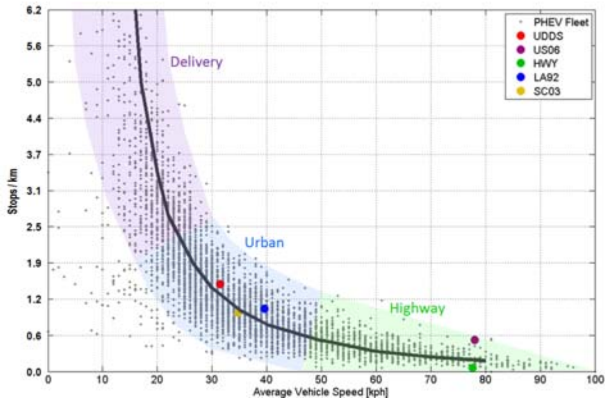

Figure 15: Relationship between average vehicle speed and stops per mile for the fleet

For the Hymotion Prius PHEV, the impact of the driving route characteristics changes near a 35-kph average vehicle speed and 1.2 stops per kilometer as shown in Figure 16. At average vehicle speeds lower than 35 kph, the fuel and electrical energy consumption decrease dramatically with increasing average vehicle speed. This trend is due to less stop and go driving, which results in the powertrain operating in regions of higher efficiency. Above average vehicle speeds of 35 kph, the fuel consumption increases while electrical energy consumption decreases with increasing average vehicle speed. This trend results from an increasing percentage of the wheel energy being delivered by fuel energy.

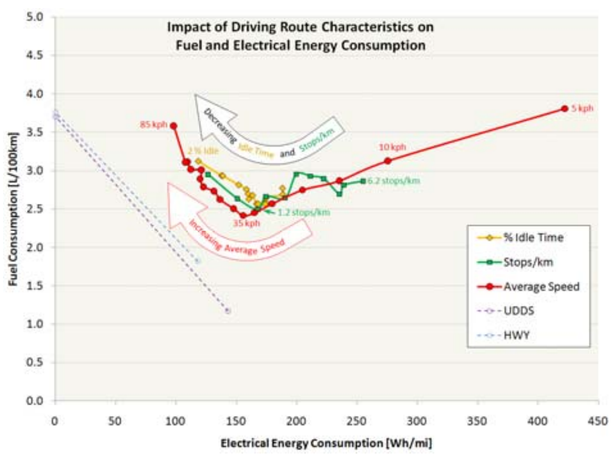

Figure 16 – Impact of average speed, idle time, and stops per mile of fuel and electrical energy consumption.[2]

The route characteristics of stops per mile and percent idle time track with a similar effect as average vehicle speed. This is due to the nature of typical driving. As average vehicle speed increases, the number of stops and total time stopped decreases. For comparison with the fleet data results, two dynamometer drive cycle results are shown in Figure 16 for the Hymotion Prius PHEV over the UDDS and the HWFET (HWY) cycles. Fuel consumption increases while the electrical energy consumption decreases when comparing the UDDS to the HWFET cycle. This is due to the increase in average vehicle speed from 32 kph to 78 kph, and the decrease in stops per mile from 1.5 to 0.06 for the UDDS and the HWFET respectively.

9. Driver Aggressiveness

Because of the power limitations of the electric drive components in the Prius powertrain, the internal combustion engine will add tractive power when road load exceeds the electric drive component power limitations. Relative driver torque request was measured by recording the accelerator pedal position throughout the driving trips. The aggressiveness factor presented here is the percent of time the accelerator pedal is depressed greater than 40% of full pedal range of travel. Early testing of the Hymotion Prius PHEV revealed that at low speeds, accelerator pedal positions greater than about 40% would cause the engine to turn on in charge depleting mode. Figure 17 shows the trend of increased fuel consumption and decreased electrical energy consumption for trips with increasing aggressiveness for a given range of average trip speed. Each point presented is the average electrical energy and fuel consumption of all trips within the given trip aggressiveness and average speed ranges.

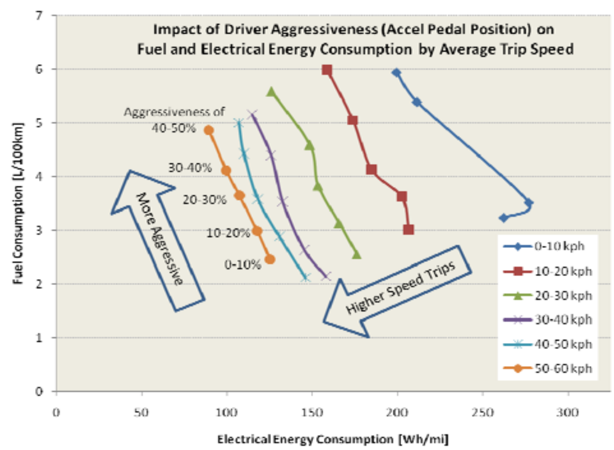

Figure 17 – Effects of driver aggressiveness on fuel and electrical energy consumption.

Driver aggressiveness is composed of characteristics involving vehicle acceleration and vehicle speed. Therefore aggressiveness has some elements that are synergistic with the driving route, specifically trip average speed. For a fixed aggressiveness range, the trend of higher speed trips having decreased fuel consumption and electrical energy consumption below 35 kph is shown in Figure 17. Above 35 kph, the trend changes to increased fuel consumption and decreased electrical energy consumption for increasing vehicle speed. This is the same trend shown in Figure 16. For a fixed-speed range, the trend is for higher fuel consumption with increasing aggressiveness due to more engine operation and higher engine torque request. While the fuel consumption increases, electrical energy consumption decreases due to the increased engine operation fulfilling a larger percent of the torque request.

10. Summary

Six primary factors that impact the fuel consumption and electrical energy consumption of PHEVs were identified from the analysis of 1.8 million miles of PHEV driving and charging data from the Hymotion Prius PHEVs. The six factors include available electrical energy, driver aggressiveness, route type, engine start-up, ambient temperature, and accessory utilization.

Through analysis of these six primary impact factors, it was determined that driving at moderate speeds (about 35 kph) in an urban environment without the air conditioner, in a non-aggressive manner, at ambient temperature near 25°C, and after plugging in the vehicle often will result in very low fuel consumption. Because very few drivers actually drive in this manner, continued advances in powertrain technology, energy storage system technologies, and vehicle architectures are needed to continue improvements in petroleum displacement.

11. Acknowledgments

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