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HEV to PHEV Conversion Compatibility

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***Abstract*—This paper includes some of the information gathered regarding the feasibility of converting a series-parallel configured electric vehicle to a plug-in hybrid electric vehicle versus using a series configured electric vehicle to a plug-in hybrid electric vehicle. It will explain the theory behind how a series configured hybrid electric vehicle (HEV) might be a better option due to the power rating of the electric motor. Using ADVISOR (Advanced Vehicle Simulator) it will explain test results and form conclusions regarding the efficiency of a series-parallel configured HEV vs. a series configured HEV as it relates to their feasibility of conversion to a plug-in hybrid electric vehicle (PHEV).**

***Keywords*—Hybrid Electric Vehicl; Plug-in Hybrid Electric Vehicle**

I. Introduction - Theory of a Plug-In Hybrid Electric Vehicle

The idea behind having a plug-in hybrid electric vehicle (PHEV) is to charge the vehicle overnight so that a person who is commuting short distances during the day can significantly reduce gas consumption thus lowering the personal cost of gasoline consumption [1, 2]. The problem is associated with the vehicle's configuration. A series-parallel configured vehicle has an electric motor that isn't sized to the maximum power output required by the driver. If this type of configuration is converted to a plug-in hybrid electric vehicle then the motor would need to be replaced with a motor with a higher power rating. This would increase the weight of the vehicle significantly since a surplus of batteries would need to be added in conjunction with the larger sized motor.

The PHEV generally operates in two modes which are charge depleting and charge sustaining [3]. The common conception is that the vehicle would be charged at night or at any other time the vehicle is not in use. This would generate a high state of charge (SOC). When the vehicle initially starts the power demand is still low and the vehicle is capable of being driven entirely on battery power. This decreases the SOC of the battery. This mode is called charge-depletion mode [4]. After a pre-specified SOC is reached the vehicle enters charge-sustaining mode at which time the battery SOC levels off with minimal fluctuations. After charge-sustaining mode is reached the vehicle begins to operate like any other hybrid electric vehicle (HEV) [5].

It may be a better option to have a series configuration when converting a hybrid electric vehicle to a plug-in hybrid electric vehicle because the electric motor is already rated for the maximum power output the driver demands.

II. Simulation of a Plug-In Hybrid Electric Vehicle

Data taken using ADVISOR (Advanced Vehicle Simulator) is shown below for a Japanese Prius model where the motor type is adjusted. The vehicle's data is taken over a drive cycle which involves accelerating, braking, and accelerating again. This pattern simulates a person driving in slow conditions such as a neighborhood, stopping at a stop sign, and also entering a highway where greater speeds are required.

The goal of this experimentation is to gain a better understanding of the relationship of the motor size to fuel economy in a series-parallel configured hybrid electric vehicle so that conclusions can be made on how efficient converting a series-parallel hybrid to a plug-in series-parallel hybrid might be. The reason the motor size is varied in the experiment is due to the motor power rating in a typical series-parallel hybrid which isn't sized for the maximum power output demanded by a driver. Advisor can simulate a sample of what a typical driver's power demand might be.

The computer simulation occurs over a complete drive cycle and involves periods of acceleration and braking. The program simulates a typical driver's power demand by taking into account what the driver would encounter while on the road including traffic lights or stop signs where the power demand drops to zero and the braking can be used to recharge the batteries. It also simulates the vehicle entering a freeway where a high power will be demanded by the driver.

The motors simulated through ADVISOR exist in the physical world and so the motor sizing in the simulation will change to discrete values because motors offered for the Japanese Prius assume values that do not allow a smooth distribution of data points.

Figure 1 displays what happens when the electric motor is replaced with several different motor types. The energy storage unit used in this simulation is the Japanese Prius model. The graphical data displayed in Figure 1 shows

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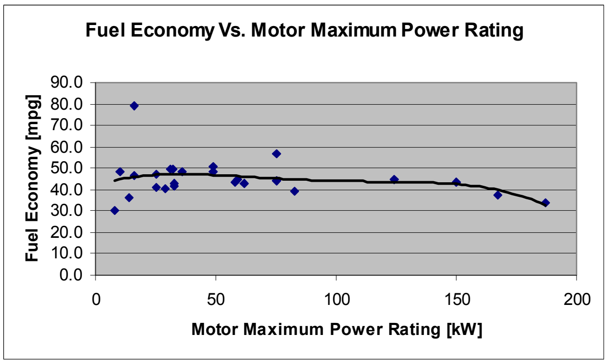

Figure 1. Fuel economy of a Japanese Prius vs. motor power rating

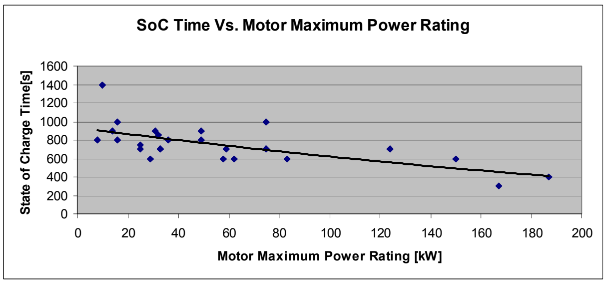

Figure 2. State-of-charge time vs. motor maximum power rating

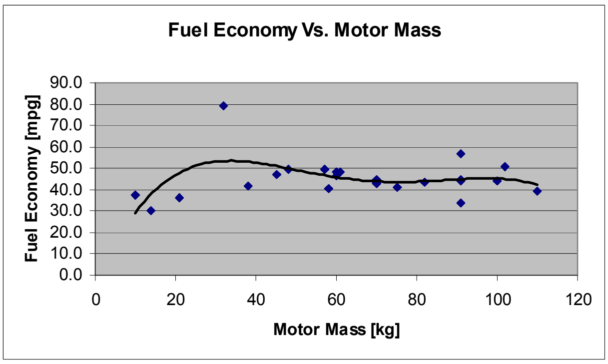

Figure 3. Fuel economy vs. electric motor mass

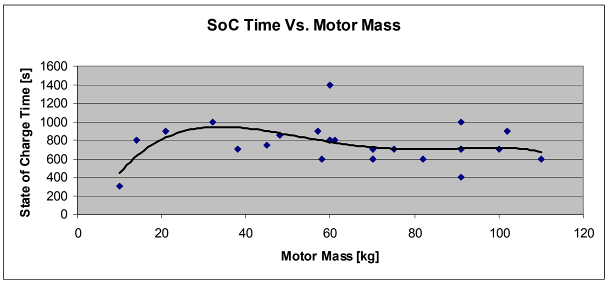

Figure 4. State-of-charge time vs. motor mass

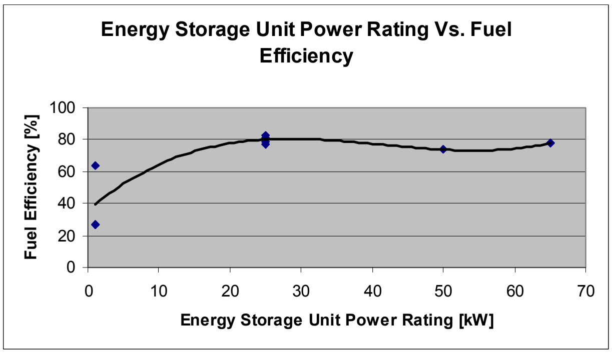

Figure 5. Fuel Efficiency vs. power rating of the energy storage unit

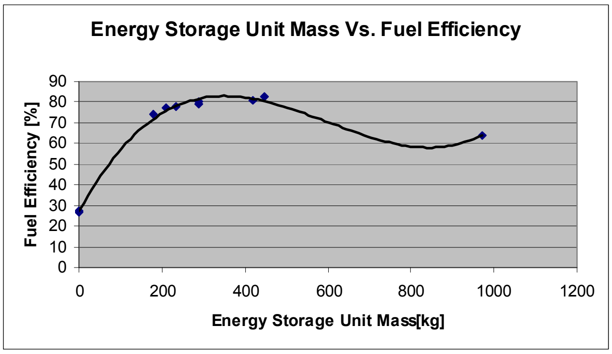

Figure 6. Fuel efficiency as a function of the mass of the energy storage unit

that there might be a slight increase in fuel efficiency as the motor power rating increases until around 100 horsepower where the fuel efficiency begins to decrease.

Each simulation begins with the battery at a state-of-charge of 70%. The "State of Charge Time" indicated in Figure 2 shows the amount of time required for the battery state-of-charge to stabilize at 50%. This is also the amount of time it takes for the vehicle to move from charge-depletion mode to charge-sustaining mode. Figure 2 shows that as the motor maximum power rating increases, there is a slight downward trend in the time it takes to reach charge-sustaining mode.

Figure 3 shows that as motor mass increases, fuel economy increases until the motor mass reaches 60 kg. At values exceeding 60 kg, the fuel economy is more constant.

III. SIMULATION OF ENERGY STORAGE UNIT AND CORRELATION WITH FUEL EFFICIENCY

The following data was taken from the same model of vehicle and the drive-train is that of a Japanese Prius. The energy storage units are replaced with units of varying size and weight.

Figure 5 displays the overall fuel efficiency of a Japanese Prius over the 1396 second drive cycle as a function of energy storage unit power rating. Notice that the power ratings of the available energy storage unit's are very discrete. Low power ratings for energy storage units can yield a wide range of efficiencies from values of a typical non-hybrid to full-hybrid models. As the energy storage unit power rating increases, the efficiency saturates.

As can be seen in Figure 6, the mass of the energy storage unit greatly affects the overall fuel efficiency of the vehicle during the 1396 second drive cycle. An upward trend in efficiency occurs as the energy storage unit mass increases up to around 400 kg. No data points exist between 450 kg and 900 kg, but the data point near 1000 kg indicates that there might be a downward trend in fuel efficiency once the energy storage unit reaches larger masses.

IV. Simulation of Plug-In Hybrid Electric Vehicle in Charge-Depletion Mode

The next simulation in ADVISOR is performed during only the charge-depletion mode of the drive cycle. The time of each simulation is dependent on the motor as each motor discharges the energy-storage-unit differently.

Figure 7 displays the gas mileage of various motors over a range in which the vehicle is in charge-depletion mode. The time period of the simulation is 1396 seconds, but is not periodic within that time. Therefore a vehicle that is in charge depletion mode for 900 seconds will undergo the same demanded velocity as a vehicle in charge depletion mode for 1000 seconds for only the first 900 seconds. The vehicle in charge depletion mode for 1000 seconds will then undergo extra demand until it enters charge-sustaining mode. Figure 7 shows that the gas mileage is fairly constant until motor power rating reaches 150 kW. Then a slight downward trend in gas mileage occurs.

Figure 8 displays the simulation results for the charge-depletion mode. It shows that gas mileage is fairly constant regardless of the mass of the motor.

The last simulation involves running the various motors through the full driving cycle beginning in charge-sustaining mode. The simulation time is the full cycle of 1396 seconds. Each energy storage unit in the simulation is initially set to 50%. This allows us to determine the efficiencies of a hybrid electric vehicle which operates constantly in charge-sustaining mode vs. the efficiencies of a plug-in hybrid electric vehicle as simulated in the previous simulation.

Figure 9 suggests that gas mileage of a hybrid electric vehicle may increase as motor size increases up to 75 kW, but then may fall off at values exceeding 75 kW.

In charge sustaining mode motor mass has an unexpected effect on gas mileage. It seems that as the electric motor mass increases from 10 kg to 50 kg, the gas mileage increases. After 50 kg the gas mileage is fairly constant.

V. Conclusions

A comparison of Figures 7 and 8 allow us to conclude that the relationship of motor mass to motor maximum power ratings are not linear. From the simulations conducted using ADVISOR, it can be concluded that a hybrid electric vehicle in a series-parallel configuration would have better efficiency if it were fitted with a larger electric motor. Replacing the electric motor in the process of converting a series-parallel configured vehicle to a plug-in is a very large and expensive operation and would negate any savings from fuel costs. From this it may be concluded that a series hybrid may be a better option in converting a hybrid electric vehicle to a plug-in hybrid electric vehicle because it is already fitted with a large electric motor capable of handling the power demand of the driver.

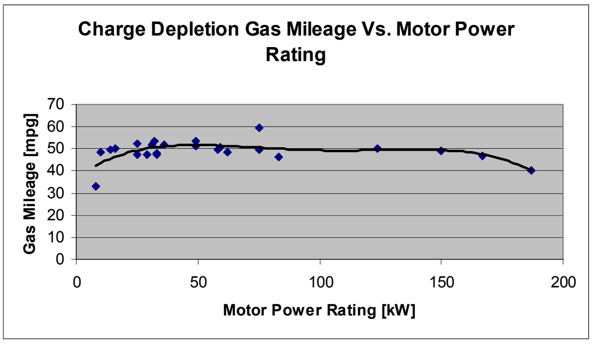

Figure 7. Motor power rating vs. gas mileage in charge-depletion mode

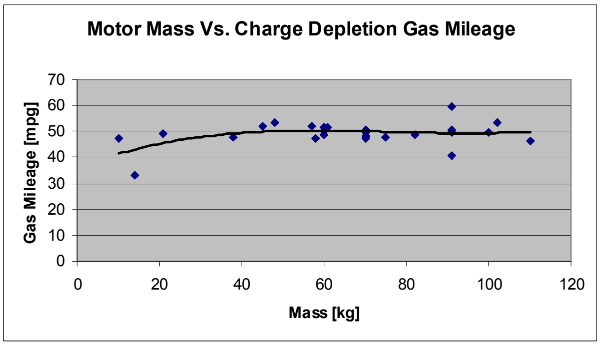

Figure 8. Motor mass vs. gas mileage while in charge-depletion mode

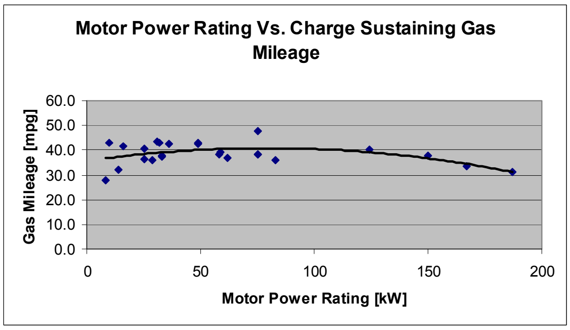

Figure 9. Motor power rating vs. gas mileage in charge-sustaining mode

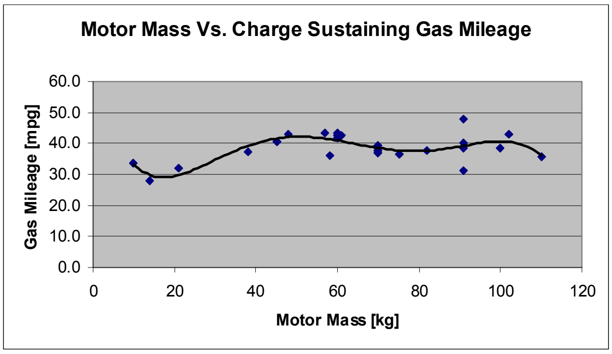

Figure 10. Gas mileage as a function of motor mass

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