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Fuel Economy Sensitivity to Vehicle Mass for Advanced Vehicle Powertrains

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ABSTRACT

In 2002, the U.S. Department of Energy (DOE) launched FreedomCAR, which is a partnership with automakers to advance high-technology research needed to produce practical, affordable advanced vehicles that have the potential to significantly improve fuel economy in the near-term. Advanced materials (including metals, polymers, composites, and intermetallic compounds) can play an important role in improving the efficiency of transportation vehicles. Weight reduction is one of the most practical ways of increasing vehicle fuel economy while reducing exhaust emissions. In this paper, we evaluate the impact of vehicle mass reduction for several vehicle platforms and advanced powertrain technologies, including Internal Combustion Engine (ICE) Hybrid Electric Vehicles (HEVs) and fuel cell HEVs, in comparison with conventional vehicles. We also explain the main factors influencing the fuel economy sensitivity.

INTRODUCTION

Over several decades, the Center for Transportation Research at Argonne National Laboratory (ANL) has developed and applied a number of computer models in support of the U.S. Department of Energy's (DOE's) advanced automotive R&D program to address the energy usage throughout the life cycle of a vehicle, which ranges from design and manufacturing through recycling. In addition, advanced batteries, fuel cells, engines, and many vehicle configurations have been developed and/or tested in DOE's facilities at ANL. This combination of analytical, developmental, and testing experience has been supported by modeling and analysis of the vehicle powertrain through a powerful and flexible vehicle simulation tool, the Powertrain System Analysis Toolkit (PSAT).

PSAT [1,2], developed with MATLAB/Simulink, is a vehicle-modeling package used to simulate performance and fuel economy. It allows one to realistically estimate the wheel torque needed to achieve a desired speed by sending commands to different components, such as throttle position for the engine, displacement for the clutch, gear number for the transmission, or mechanical braking for the wheels. In this way, we can model a driver who follows a predefined speed cycle. Moreover, as components in PSAT react to commands realistically, we can employ advanced component models, take into account transient effects (e.g., engine starting, clutch engagement/disengagement, or shifting), and develop realistic control strategies. Finally, by using test data measured at Argonne's Advanced Powertrain Research Facility, PSAT has been shown to predict the fuel economy of several hybrid vehicles within 5% on the combined cycle.

One of the FreedomCAR goals [3] is to reduce the mass of a vehicle's by up to 50%. While other studies have discussed the impact of weight reduction on fuel economy [4,5], more research needs to be done to quantify the fuel economy sensitivity to mass reduction of advanced drivetrain configurations, vehicle platforms and drive cycles

METHODOLOGY

The fuel consumption sensitivity to mass was determined for two different cases:

- *Without powertrain resizing:* The drivetrain maximum power was fixed. In this case, the vehicle mass was reduced by increments of 10%.
- *With powertrain resizing:* The drivetrain maximum power was recalculated to maintain the performance. In this case the glider mass was reduced by increments of 10% and the fuel converter (engine or fuel cell) power was adjusted while the battery size was held constant, thus yielding a different degree of hybridization for each case.

The same control strategy was used for both cases. The fuel consumption metric used to calculate the sensitivies was the unadjusted combined fuel consumption. More specifically, the city (UDDS) and highway (HWFET) cycles, both simulated as hot starts, were run and the results of each cycle were combined by using the 55/45 weighting factors.

FUEL CONSUMPTION SENSITIVITY WITHOUT POWERTRAIN RESIZING

This section describes the effect of reducing vehicle mass by increments of 10% on fuel consumption without component resizing. For this paper, fuel consumption sensitivity is defined as:

$$\frac{dm_{fuel}}{dm_{vehicle}} \qquad (1)$$

Where m_{fuel} is the total fuel mass consumed on the combined cycle and $m_{vehicle}$ is the mass of the vehicle.

VEHICLE DEFINITION

Vehicles representative of the compact, midsize and SUV classes were sized for performance times (IVM-60mph) of 10 s. For each vehicle class, four powertrains were simulated:

- Conventional,
- Pre-transmission parallel hybrid (electric machine located in-between the clutch and the gearbox),
- Fuel cell vehicle, and
- Fuel cell hybrid vehicle.

The reference vehicle characteristics are highlighted in Appendix 1.

RELATIONSHIP BETWEEN POWER-TO-WEIGHT RATIO AND PERFORMANCE

The power-to-weight ratio of a vehicle is a good predictor of performance time, assuming a fixed drivetrain architecture. Figure 1 shows the Initial Vehicle Movement (IVM) time (the time at which the vehicle moves one foot) to the time at which the vehicle reaches 60 mph as a function of the vehicle specific power. The vehicle mass was reduced by increments of 10% to generate the curves.

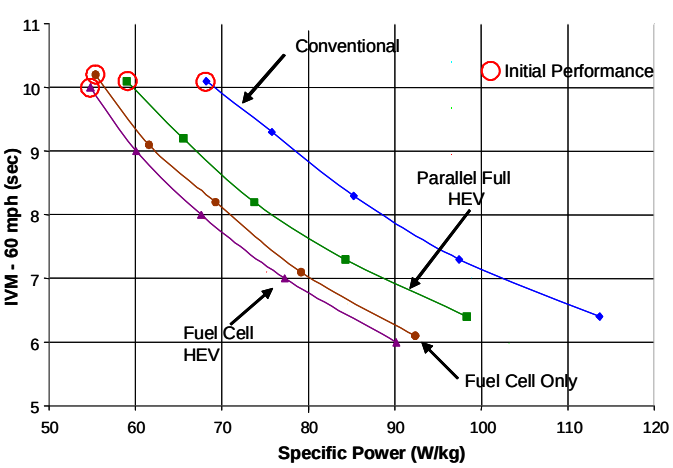

Figure 1: IVM - 60 mph Power-to-Weight Ratio of the Midsize Vehicle

One notices that parallel HEV and fuel cell powertrains require a lower power-to-weight ratio than conventional vehicles to achieve the same performance. This finding is expected since the electric motor provides its maximum torque at low speed, which gives the vehicle a faster initial acceleration during a performance test.

Because of greater model uncertainties for high-performance vehicles, a powertrain with an IVM-60 faster than 6 s and specific power greater than 120 W/kg were not represented in this study.

COMPACT VEHICLE PLATFORM

Of the configurations simulated in this study, the conventional and the parallel hybrid appears the most sensitive to a change in vehicle mass, as shown in Figure 2. The next most sensitive configuration is the fuel cell vehicle, followed by the hybrid fuel cell vehicle, which showed the least sensitivity to a decrease in body mass. All the results are provided in Appendix 3.

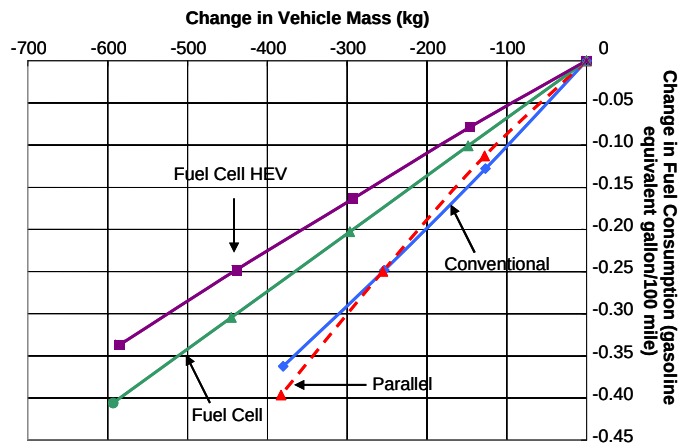

Figure 2 Change in Fuel Consumption Gasoline Equivalent due to Mass Reduction for the Compact Vehicle – Combined Cycle

The following paragraphs look at the parameters influencing the sensitivity.

Effect of Driving Cycles

Driving cycles have an impact on fuel economy sensitivity, as shown in Figures 3 and 4. Note that the powertrains are more sensitive to the UDDS (maximum fuel consumption change > 0.5) than the HWFET (maximum fuel consumption change of 0.3). However, because the trends are similar, we will explain sensitivity changes based on the UDDS cycle only.

The difference between the sensitivities of fuel consumption for the hybrid and the conventional vehicles can be explained by examining how both stricter engine control and regenerative braking affect fuel consumption sensitivity.

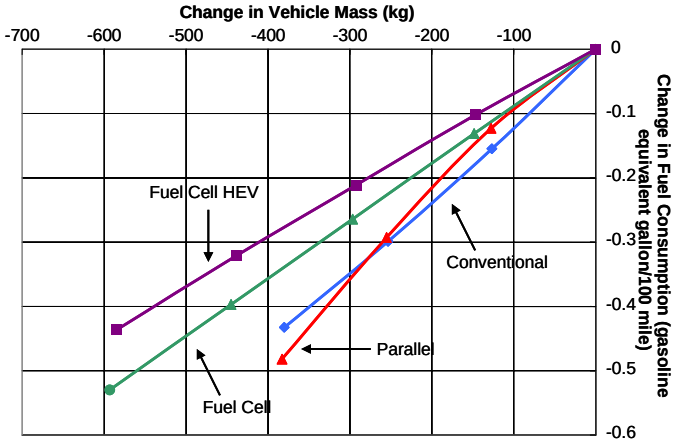

Figure 3 Change in Fuel Consumption Gasoline Equivalent due to Mass Reduction for the Compact Vehicle – UDDS Cycle

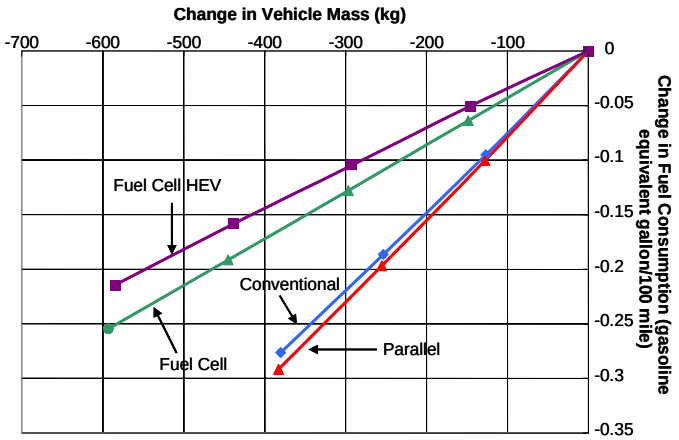

Figure 4 Change in Fuel Consumption Gasoline Equivalent due to Mass Reduction for the Compact Vehicle – HWFET Cycle

Effect of a Change in Mass on Fuel Converter Efficiency

Engine efficiency in a conventional vehicle is more sensitive to a reduction in vehicle mass than any of the other powertrains studied.

Figure 5 shows a rapid decrease in average engine cycle efficiency for the conventional vehicle. As the vehicle mass is reduced and the drivetrain size remains fixed, the engine operating point will shift in the map to lower torques, where the engine is less efficient.

However, the trend is actually reversed for the parallel hybrid. The control strategy of the parallel HEVs turns the engine on based on a wheel demand power threshold. As the control strategy parameters were maintained, with a lower mass, the engine turned on less often, increasing the percentage in electric vehicle (EV) mode. The control strategy used for the parallel HEV strictly limited the operation of the engine to its most efficient region. So when the engine was on, it would run at an engine power higher than what was needed to satisfy the road demand. Engines keep operating in similar area thanks to the electric motor, which is one of the reason why HEVs are less sensitive to drive cycle characteristics than conventional vehicles.

Figure 5 also shows that the efficiency of the fuel cell system was less sensitive to a change in mass than to engine efficiency for both fuel cell vehicles. The hybrid fuel cell vehicle has small degree of hybridization (10%), and so the behavior was similar to that of the non-hybrid fuel cell vehicle.

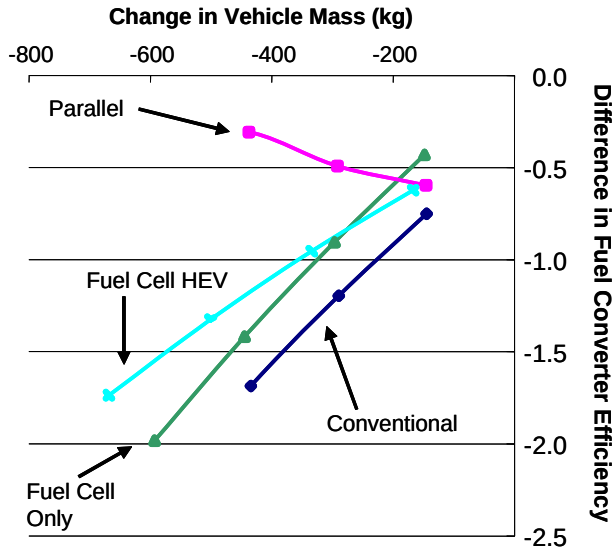

Figure 5: Change in Fuel Converter Efficiency versus Mass Reduction for the Compact Vehicle - UDDS Cycle

Effect of a Change in Mass on Regenerative Braking

As the mass of the vehicle is changed, the regenerative braking of the hybrid is affected, as demonstrated by Figure 6, which shows three curves:

- The decrease in recoverable energy at the wheels is the total energy stored in the inertia of the vehicle. Assuming perfect regen efficiency, all of this inertial energy could be recovered.
- The increase in percent regenerative braking is the actual fraction of the total inertia energy that actually charges the energy storage system (ESS).
- The increase in the fraction of recoverable energy at the wheels.

As the vehicle mass is reduced, the amount of available energy that can be recovered diminishes. A 10% reduction in vehicle mass yields a 7% reduction in overall recoverable energy.

With a decrease in vehicle mass, less battery power is required to recover the stored energy. Because the battery was not initially sized to collect the entire available regenerative braking power, some energy was being wasted through the friction brakes. As the vehicle is made lighter, the battery captures the same amount of energy because it is saturated. However, there is less power in excess of the battery size, and so, the battery is

capturing a larger fraction of the total braking power, as shown in Figure 7.

For a conventional vehicle, 100% of the power required to spin the inertia of the vehicle is supplied by the engine, whereas for a hybrid configuration, the electric powertrain supplies a significant fraction of the power delivered to the inertia. Thus, as mass is added or removed from a hybrid powertrain, the fuel converter — being partially screened from the effects of the added mass by the regenerative braking — does not "see" the full change in mass.

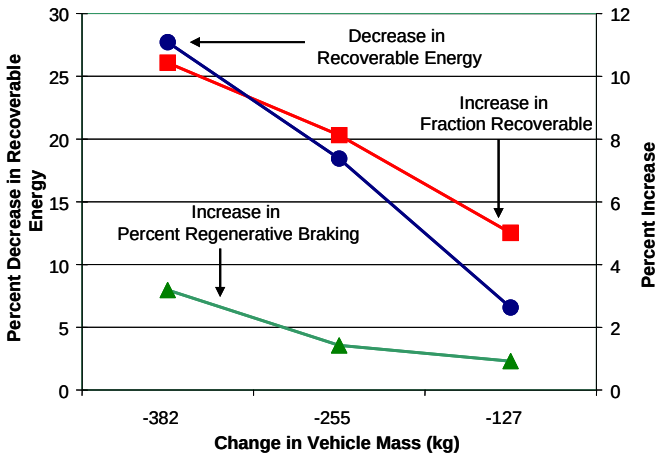

Figure 6: Change in Regenerative Braking due to a Reduction in Vehicle Mass for the Parallel Vehicle - UDDS Cycle – Compact Vehicle

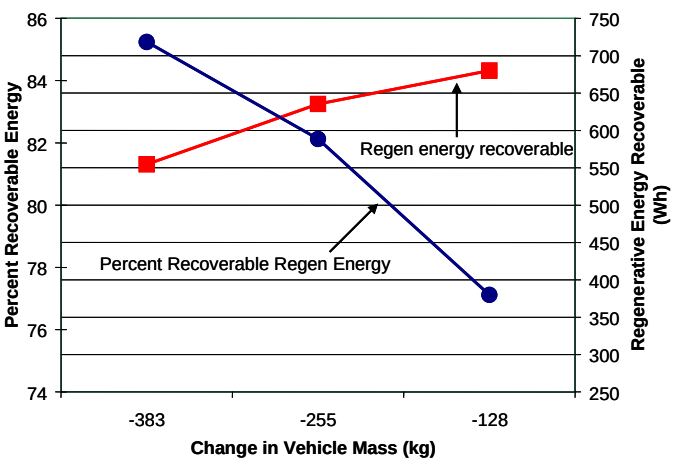

Figure 7: Recoverable Energy for the Parallel Vehicle - UDDS Cycle – Compact Vehicle

The power delivered to the inertia of a hybrid vehicle can be divided into three pathways as shown in Figure 8: (1) a path directly from the fuel converter to the inertia, (2) an indirect path from the fuel converter through the electrical system to the inertia, and finally (3) a path from an apparent external source to the inertia of the vehicle. This apparent source is supplied by the free energy that is recovered from the inertia of the vehicle using regenerative braking. The inertial energy left the powertrain system, so that when the energy is recovered to the powertrain system, it appears to come from an external source. Any mass added or removed from the vehicle can be portioned among these three pathways, further illustrating that the fuel converter is not affected by the total inertia but rather by a fraction of the total that has a magnitude dependent on the hybridization degree of the vehicle.

By considering the effect on regenerative braking of changing the mass of a vehicle in isolation without considering the subsequent changes in component efficiencies, one can reason as follows. Decreasing the mass of a hybrid vehicle decreases the loss of inertia, which decreases fuel consumption; however, the lower mass also decreases the energy recovered from regenerative braking, and this decrease in recovered energy offsets the benefit from decreased inertia. Thus, the total benefit of reducing inertia is diminished for a hybrid. It can also be reasoned that increasing the mass of a hybrid will increase the recovered energy, which will offset the deficit of higher vehicle mass. Thus, the total deficit of increased inertia is diminished for a hybrid.

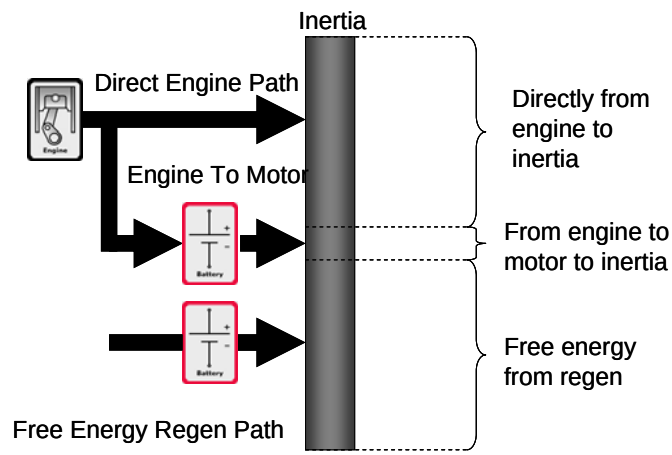

Figure 8: Impact of Mass Reduction on Repartitioning of Inertia

The power of the battery pack in the Toyota 2005 Prius is effectively sized to encompass 100% of the power during each braking event on the UDDS cycle. This is evidenced by the lack of significant mechanical brake application during the cycle. The mechanical brakes are applied at low speed/low power because of the limitations of the electric machine. The question can be asked, what happens if the mass is increased beyond the recovery capacity of the battery, so that the battery cannot encompass 100% of the power for every braking event?

One can hypothesize that the previous discussion still holds, even if the mass is increased beyond the recovery capacity of the battery because, overall, the same trend is still true. An increase in mass leads to an increase in regenerative braking recovery. An increase in mass increases the magnitude of all braking events, and most of braking events do not saturate against the battery power limit. One can argue that not until every braking event saturates against the battery power limit would the characteristic of decreased sensitivity disappear for the hybrid. However, this saturation effect does have a

higher-order effect and should be studied further in much greater detail than presented in this paper.

Effect of Powertrain Efficiency

We have shown in the previous paragraphs that both fuel converter efficiency and regenerative braking influence fuel consumption sensitivity to a mass change. As both parameters are related to average powertrain efficiency, as shown in Equation 2, it is natural to consider powertrain efficiency as a main factor of sensitivity:

$$\hat{\eta}_{powertrain} = \frac{E_{OUT}}{E_{IN}} = \hat{\eta}_{power_source} * \hat{\eta}_{trans} * \hat{\eta}_{fd} \qquad (2)$$

with power source peak efficiency including fuel converter, electric machine and regenerative braking.

Figure 9, however, highlights the fact that powertrain efficiency only cannot explain the difference in sensitivity among the different powertrains as parallel and conventional configurations have different efficiencies but show similar sensitivities.

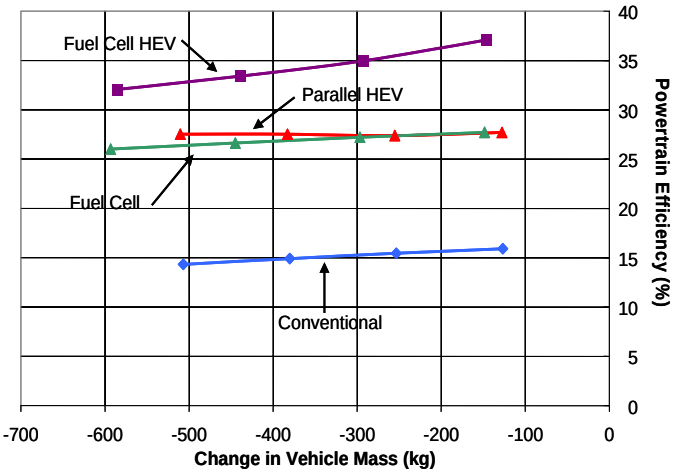

Figure 9: Powertrain Efficiencies for the Compact Vehicle — UDDS Cycle

MIDSIZE VEHICLE PLATFORM

For the compact vehicle, the simulation results show that the fuel economies of the conventional and the parallel were more sensitive to a reduction in mass than either the fuel cell or hybrid fuel cell vehicles. The results for the midsize vehicle follow the trend shown in Figure 10.

Note that the order of the powertrain sensitivity may change when considering the percentage change in fuel economy rather than the change itself, as shown in Figure 11. For the midsize vehicle, the conventional powertrain, despite showing the highest fuel economy change, has also the lowest percentage change.

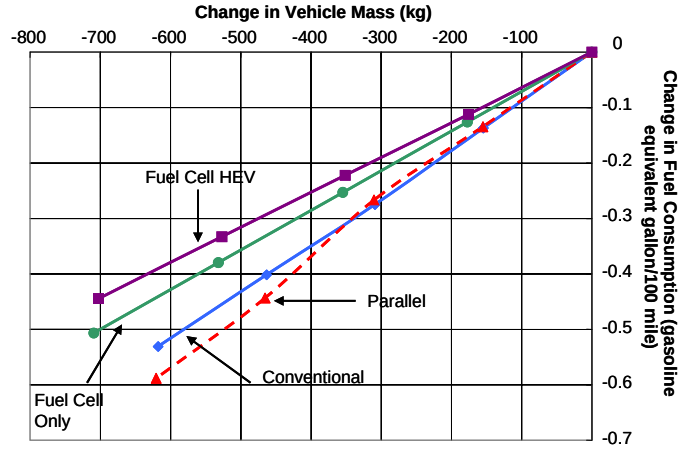

Figure 10: Change in Fuel Consumption Gasoline Equivalent due to Mass Reduction for the Midsize Vehicle — Combined Cycle

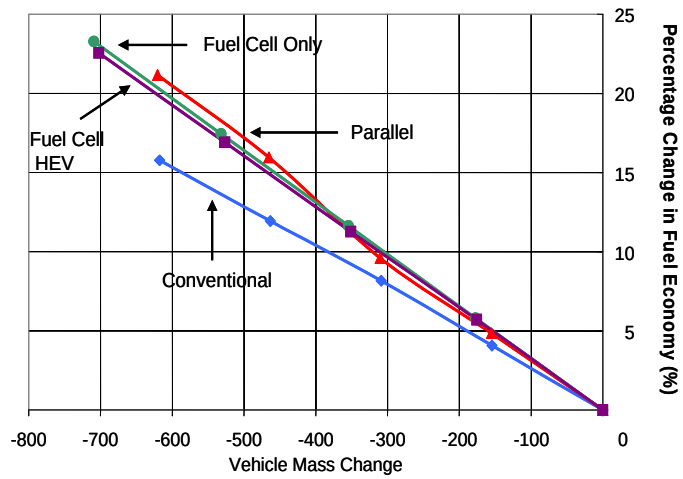

Figure 11: Percentage Change in Fuel Economy Gasoline Equivalent due to Mass Reduction for the Midsize Vehicle — Combined Cycle

A comparison of the fuel converter efficiency for each vehicle in Figure 12 shows that the conventional vehicle has the greatest drop in engine efficiency followed by the fuel cell vehicles. In contrast, the parallel vehicle actually reverses the trend by having a slight increase in engine efficiency. Comparing Figure 12 with Figure 5 shows that these efficiency trends are the same for both the compact and midsize vehicles.

Because the trends are similar among vehicle classes, the SUV will only be used as part of the platform comparison.

PLATFORM COMPARISON

Figure 13 shows that the sensitivity of a conventional vehicle's fuel economy to a mass reduction is nearly the same across vehicle platforms.

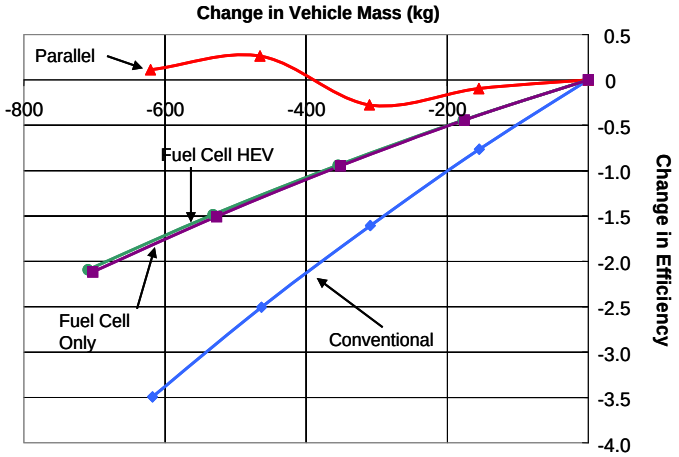

Figure 12: Change in Fuel Converter Efficiency versus Mass Reduction for the Midsize Vehicle — UDDS Cycle

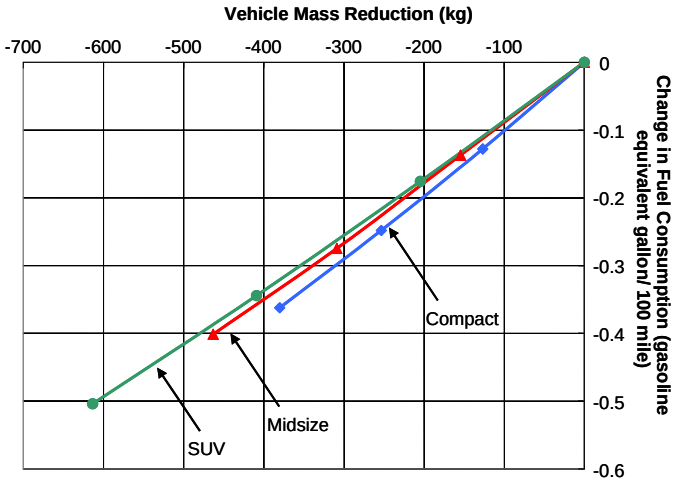

Figure 13: Change in Combined Fuel Consumption Gasoline Equivalent vs. Change in Mass for the Conventional Vehicle for Each Vehicle Class

Figure 14 shows the change in fuel converter efficiency for the conventional vehicles. As one can expect, the SUV has the lowest reduction because of its large engine.

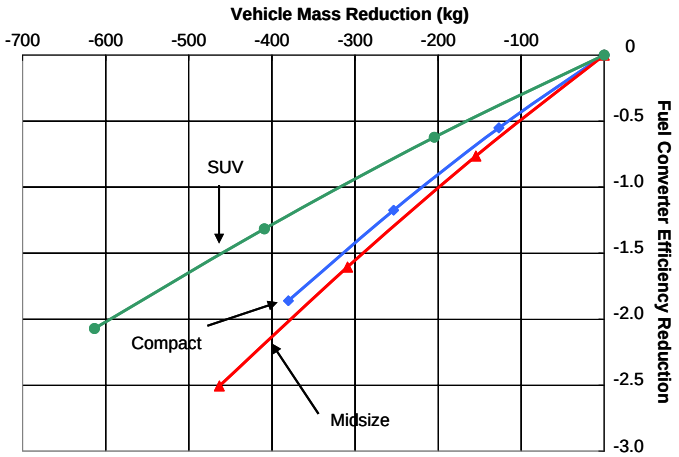

Figure 14: Change in Fuel Converter Efficiency for the Conventional Vehicle

FUEL ECONOMY SENSITIVITY WITH POWERTRAIN RESIZING

This section describes the effect of decreasing the glider mass (not the vehicle mass as previously done) in increments of 10% on fuel consumption when the drivetrain is resized to retain constant performance. As the vehicle mass is decreased, the fuel converter is downsized to keep the similar performance (IVM-60mph = 9 s). The battery for the hybrid configurations is held constant. Thus, for the hybrids, as the vehicle mass is decreased, the degree of hybridization increases. Results are given only for the midsize platform. The vehicles are described in Appendix 2.

For the case of mass reduction with resizing, the conventional vehicle appears to be the most sensitive to changes in vehicle mass, followed by the parallel hybrid with the fuel cell and fuel cell HEV vehicles as the least sensitive, as illustrated by Figure 15.

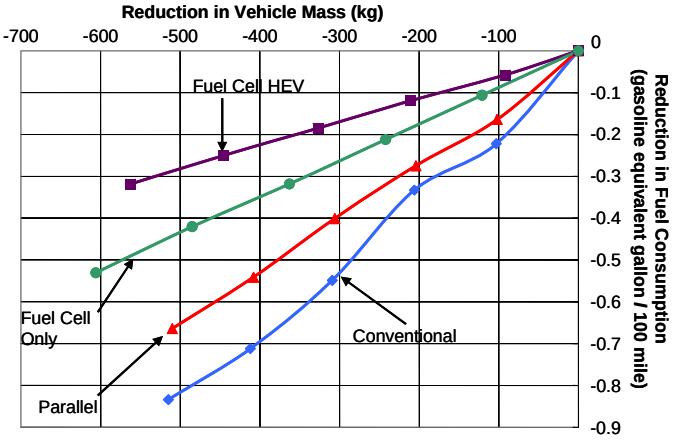

Figure 15: Reduction in Combined Fuel Consumption vs. Percent Reduction in Vehicle Mass

As an attempt to explain these differences, one can start by comparing the fuel converter average efficiencies among the vehicles, as was done in the previous section.

The average efficiency for each fuel converter is shown in Figure 16. In this case, fuel converter efficiency for the parallel hybrid vehicle, as well as for the conventional and fuel cell vehicles, is insensitive to a reduction in vehicle mass. This result is expected, because the fuel converters are downsized as the vehicle mass is reduced. Thus, the reduced operating regime of the fuel converter still covers the same fraction of the fuel converter map, resulting in approximating the same average cycle efficiency.

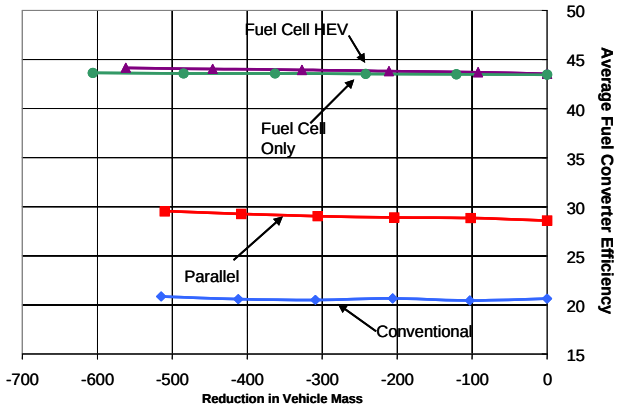

Figure 16 Average Fuel Converter Efficiency on UDDS Cycle vs. Reduction in Vehicle Mass

FUEL ECONOMY SENSITIVITY TO MASS REDUCTION DEFINITION

In the previous paragraphs, we described the parameters influencing the sensitivity on the basis of the results of simulation. The following paragraph reiterates their impact on the basis of equations. All the parameters used in these equations are instantaneous values.

We can rewrite equation 1 in terms of energy rather than mass of fuel consumed:

$$\frac{dE_{fuel}}{dm_{vehicle}} = LHV \times \frac{dm_{fuel}}{dm_{vehicle}} \tag{3}$$

A general equation for the sensitivity of fuel consumption to changes in vehicle mass for a pre-transmission hybrid vehicle can be determined by starting with an expression for the vehicle's balance of power:

$$\eta_{driveline}\eta_{fcv}P_{fuel} + \eta_{driveline}P_{ess} = P_{veh} \tag{4}$$

where $\eta_{driveline}$ is the instantaneous efficiency of the driveline (transmission and final drive for parallel HEVs and also electric machine for fuel cell HEVs). η_{fcv} is the instantaneous fuel converter efficiency. P_{fuel} is the instantaneous power contained in the fuel flowing into the fuel converter. P_{ess} is the instantaneous power from the electrical system that is added mechanically to the drivetrain for the case of a parallel engine hybrid or added electrically for the case of a fuel cell hybrid. P_{veh} is the instantaneous vehicle load. P_{veh} can also be expressed as shown in Equation 5.

$$P_{veh} = m_{vehicle}av + C_{rr}m_{vehicle}gv + \frac{1}{2}C_d A\delta v^3 \tag{5}$$

Taking the derivative with respect to mass of equation 4 gives:

$$\begin{aligned}&\eta'_{driveline}\eta_{fcv}P_{fuel} + \eta_{driveline}\eta'_{fcv}P_{fuel} + \eta_{driveline}\eta_{fcv}P'_{fuel} + \ldots \\ &\eta'_{driveline}P_{ess} + \eta_{driveline}P'_{ess} = P'_{veh}\end{aligned} \tag{6}$$

Solving for P'_{fuel} gives:

$$\begin{aligned}P'_{fuel} &= \frac{P'_{veh} - \eta'_{driveline}\eta_{fcv}P_{fuel} - \eta_{driveline}\eta'_{fcv}P_{fuel} - \ldots}{\eta_{driveline}\eta_{fcv}} \\ &\frac{\eta'_{driveline}P_{ess} - \eta_{driveline}P'_{ess}}{\eta_{driveline}\eta_{fcv}}\end{aligned} \tag{7}$$

Integrating both sides with respect to time gives:

$$\begin{aligned}\frac{dE_{fuel}}{dm_{vehicle}} &= \int_{a\geq 0}\frac{P'_{veh}}{\eta_{driveline}\eta_{fcv}}dt - \int_{a\geq 0}\frac{\eta'_{driveline}\eta_{fcv}P_{fuel}}{\eta_{driveline}\eta_{fcv}}dt - \ldots \\ &\int_{a\geq 0}\frac{\eta_{driveline}\eta'_{fcv}P_{fuel}}{\eta_{driveline}\eta_{fcv}}dt - \int_{a\geq 0}\frac{\eta'_{driveline}P_{ess}}{\eta_{driveline}\eta_{fcv}}dt - \int_{a\geq 0}\frac{\eta_{driveline}P'_{ess}}{\eta_{driveline}\eta_{fcv}}dt\end{aligned} \tag{8}$$

which, as was shown by equation 3, is a scaled version of the fuel consumption's sensitivity to a change in vehicle mass. Equation 8 consists of five terms that show the major factors contributing to the sensitivity of a hybrid vehicle's fuel consumption to a change in mass.

1. All five terms are scaled by the same factor $\frac{1}{\eta_{driveline}\eta_{fcv}}$, which shows the important role fuel converter and driveline efficiency play in determining the sensitivity: the greater the fuel converter and driveline efficiencies, the lower the sensitivity. Thus, one can predict that a fuel cell configuration with a high fuel-converter efficiency and a fixed-ratio transmission will have a lower sensitivity than a parallel hybrid with an engine and a gearbox.

2. The first term, which depends on the power demanded at the wheels of the vehicle, clearly shows the dependence of the fuel consumption mass sensitivity on the characteristics of the cycle. P'_{veh}, when referring back to equation 5, can be expressed as $P'_{veh} = av + C_{rr}gv$. Aggressive cycles (large a*v) and high rolling-resistance values will enhance sensitivity.

3. The second and fourth terms can be grouped, yielding a new term showing the dependence of the fuel consumption sensitivity to the driveline efficiency's variation. Because of the negative sign, if $\eta'_{driveline}$ has a direct relationship to mass (that is, an increase in mass gives an increase in driveline efficiency), then this term will decrease the overall sensitivity. If it is the opposite, then this term will increase it.

4. The third term depends on the sensitivity of the fuel converter efficiency. If η'_{fcv} has a direct relationship to mass, then it will reduce the overall sensitivity. If η'_{fcv} has an inverse relationship, it will increase sensitivity. For the engine, the relationship is direct as increasing the engine load tends to increase its efficiency. For the fuel cell, this relationship could be either depending on the fuel cell sizing.

5. The last term, term five, depends on the change in the electrical power as the mass is changed, which accounts for the regenerative braking. P_{ess} can be decomposed into two modes: when it is positive (propelling the vehicle) and when it is negative (battery is being charged using the fuel converter). Considering the charge-sustaining mode, the regenerative braking part of P_{ess} is the dominant factor impacting the sensitivity. A decrease in mass will lead to less regenerative braking and consequently decrease the sensitivity.

6. In our analysis, idle fuel consumption does not affect the sensitivity of cycle fuel consumption to a change in vehicle mass, because idle fuel consumption does not change significantly with vehicle mass.

Table 1 summarizes the main factors influencing the fuel consumption sensitivity to mass as well as their relative effects. For one to determine the overall fuel consumption sensitivity trend, the magnitude of each term needs to be known. Because these sensitivities are difficult to estimate and depend on specific design characteristics of the hybrid, such as hybridization degree and control strategy, only trends are represented in the table. For the "powertrain" efficiency shown in column two, the rankings are well established. For instance, it is clear that the fuel converter in a fuel cell configuration will have a higher efficiency than the engine in a conventional configuration. Also, the fuel converter efficiency in hybrids will tend to be higher than the fuel converter efficiency in their conventional counterparts.

PERCENTAGE FUEL ECONOMY REDUCTION COMPARISON

The results for the first case (when drivetrain is not resized) are shown in Tables 2 and 3. Table 4 shows the case where the powertrain is resized. For each reduction in the percentage of vehicle mass (10–30%), the reduction of the percentage of fuel is shown on the basis of both fuel economy (mpgge) and fuel consumption (L/100km). Even if the fuel cell configurations appear to have the lowest fuel economy sensitivity to a change in vehicle mass, they demonstrate the greatest variation of fuel economy/consumption.

Configuration	$P'_{vehicle}$	$\eta_{driveline}\ \eta_{fcv}$	$\eta'_{driveline}$ & η'_{fcv}	P'_{ess}
Conventional	+	0	-	0
Parallel	+	-	0	-
Fuel Cell	+	- -	-	0
Fuel Cell HEV	+	- - -	0	-

Table 1: Trends of the Main Factors Influencing Fuel Economy Sensitivity to Mass (+ increases the sensitivity, - decreases the sensitivity, 0 has no effect)

Configuration	10% Vehicle Mass Reduction		20% Vehicle Mass Reduction		30% Vehicle Mass Reduction	
	% based on mpgge	% based l/100km	% based on mpgge	% based l/100km	% based on mpgge	% based l/100km
Conventional	4.9	4.7	10	9.1	15.3	13.3
Parallel	5.1	4.9	12.1	10.8	20.8	17.2
Fuel Cell	5.7	5.4	12.1	10.8	19.4	16.2
Fuel Cell HEV	4.9	4.7	10.7	9.7	17.3	14.7

Table 2: Percentage Reduction in Fuel Economy and Consumption by Configuration, Compact Platform — when Powertrain Is Not Resized

Configuration	10% Vehicle Mass Reduction		20% Vehicle Mass Reduction		30% Vehicle Mass Reduction	
	% based on mpgge	% based l/100km	% based on mpgge	% based l/100km	% based on mpgge	% based l/100km
Conventional	4.2	4.1	8.9	8.2	13.5	11.9
Parallel	5.1	4.8	10.6	9.6	19	16
Fuel Cell	6.2	5.8	13.2	11.6	21.1	17.4
Fuel Cell HEV	6.1	5.7	12.7	11.3	20.3	16.9

Table 3: Percentage Reduction in Fuel Economy and Consumption by Configuration, Midsize Platform — when Powertrain Is Not Resized

Configuration	10% Glider Mass Reduction			20% Glider Mass Reduction			30% Glider Mass Reduction		
	% vehicle mass	% based on mpgge	% based l/100km	% vehicle mass	% based on mpgge	% based l/100km	% vehicle mass	% based on mpgge	% based l/100km
Conventional	6.6	6.6	7	13.3	10	11	19.9	16.4	19.6
Parallel	6.5	6	6.3	13	10	11	19.6	14.5	17
Fuel Cell	5.2	4.7	5	12	9.5	10.4	18.6	14.2	16.5
Fuel Cell HEV	6.7	3.2	3.3	13.3	6.6	7	20	10.2	11.4

Table 4: Percentage Reduction in Fuel Economy and Consumption, based on Reduction in Glider Mass, by Configuration — Midsize Platform — when Powertrain Is Resized

CONCLUSION

Several vehicle platforms and powertrain configurations were considered to assess the sensitivity of fuel economy to mass variation.

Overall, the conventional and parallel hybrid configurations are the most sensitive configurations, the conventional being the most sensitive when performance is maintained. Because of the high efficiency of their fuel converter, fuel cell configurations (with or without energy storage systems) are the least sensitive.

The parameters influencing fuel consumption sensitivity to mass have been described, both from simulation results and equations. The process demonstrated the influence of the drive cycle, the powertrain, and fuel converter efficiencies, as well as regenerative braking.

The achievement of the FreedomCAR goals, including high fuel converter efficiencies and energy storage development, would allow higher regenerative braking and lead to a lower sensitivity for all vehicle configurations, especially for the conventional vehicle.

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APPENDIX 1 – NO RESIZING

Compact Vehicle Assumptions

		Conventional	Parallel	Fuel Cell	Fuel Cell HEV
Power					
IC Engine	kW	113	82	0	0
Fuel Cell	kW	0	0	84	72
Electric Motor #1 : Peak Power	kW	0	16.5	84	80
High Power Energy Storage	kW	0	21	0	8
Transmission					
Transmission Type		Auto 4spd	Manual 5spd		
Final Drive Ratio		4.07	4.07	4.07	4.07
High Power Energy Storage (NiMH)					
Number of Cells			124		47
Cell Capacity (C/3)	Ah		6		6
Weights					
Glider (Body & Chassis)	kg	740	740	740	740
ICE	kg	70.6	51.3	0	0
FC System	kg	0	0	168	144
High Power Energy Storage	kg	0	16.2	0	6.1
Motor Controller	kg	0	3.3	16.8	16
Motor	kg	0	16.5	84	80
Other	kg	592.4	584.7	610.2	611.9
Cargo & Driver	kg	136	136	136	136
Total Mass Used In Simulation	kg	1267	1276	1483	1462
Specific Power					
Powertrain	W/kg	89.2	80.7	56.6	54.7
Vehicle					
Frontal Area	m2	2.18	2.18	2.18	2.18
Coefficient Drag	/	0.3	0.3	0.3	0.3
Rolling Resistance	/	0.008	0.008	0.008	0.008
Wheel Radius	m	0.307	0.307	0.307	0.307
Peak Efficiencies (0-100)					
IC Engine	%	33.5	33.5		
FC System	%			50	50
Accessory Power					
Mechanical	W	300	250	0	0
Electrical	W	300	350	600	600

Midsize Vehicle Assumptions

		Conventional	Parallel	Fuel Cell	Fuel Cell HEV
Power					
IC Engine	kW	105.3	76	0	0
Fuel Cell	kW	0	0	97	85.5
Electric Motor #1 : Peak Power	kW	0	15.5	97	95
High Power Energy Storage	kW	0	19	0	9.5
Transmission					
Transmission Type		Auto 5spd	Manual 5spd		
Final Drive Ratio		4.44	4.44	4.44	4.44
High Power Energy Storage (NiMH)					
Number of Cells			112		56
Cell Capacity (C/3)	Ah		6		6
Weights					
Glider (Body & Chassis)	kg	988	988	988	988
ICE	kg	65.8	47.5	0	0
FC System	kg	0	0	194	171
High Power Energy Storage	kg	0	14.6	0	7.3
Motor Controller	kg	0	3.1	19.4	19
Motor	kg	0	15.5	97	95
Other	kg	626.2	618.3	610.6	611.7
Cargo & Driver	kg	136	136	136	136
Total Mass Used In Simulation	kg	1544	1551	1773	1756
Specific Power					
Powertrain	W/kg	68.2	59.0	55.4	54.8
Vehicle					
Frontal Area	m2	2.2	2.2	2.2	2.2
Coefficient Drag	/	0.3	0.3	0.3	0.3
Rolling Resistance	/	0.008	0.008	0.008	0.008
Wheel Radius	m	0.317	0.317	0.317	0.317
Peak Efficiencies (0-100)					
IC Engine	%	33.5	33.5		
FC System	%			50	50
Accessory Power					
Mechanical	W	300	250	0	0
Electrical	W	300	350	600	600

SUV Vehicle Assumptions

		Conventional	Parallel	Fuel Cell	Fuel Cell HEV
Power					
IC Engine	kW	170	124	0	0
Fuel Cell	kW	0	0	126	121.5
Electric Motor #1 : Peak Power	kW	0	25	126	135
High Power Energy Storage #1	kW	0	31	0	13.5
Transmission					
Transmission Type		Auto 5spd	Manual 5spd	NA	NA
Final Drive Ratio		3.55	3.55	3.55	3.55
High Power Energy Storage #1					
Number of Cells			97		42
Cell Capacity (C/3)	Ah		28		28
Weights					
Glider (Body & Chassis)	kg	1258	1258	1258	1258
ICE	kg	212.5	77.5	0	0
FC System	kg	0	0	252	243
High Power Energy Storage #1	kg	0	82.8	0	35.8
Motor Controller #1	kg	0	5	25.2	27
Motor #1	kg	0	25	126	135
Other	kg	438.5	445.7	455.8	464.2
Cargo & Driver	kg	136	136	136	136
Total Mass Used In Simulation	kg	2045	2030	2253	2299
Specific Power					
Powertrain	W/kg	83.13	73.40	55.93	58.72
Vehicle					
Frontal Area	m2	2.46	2.46	2.46	2.46
Coefficient Drag	/	0.41	0.41	0.41	0.41
Rolling Resistance	/	0.0084	0.0084	0.0084	0.0084
Wheel Radius	m	0.368	0.368	0.368	0.368
Peak Efficiencies (0-100)					
IC Engine	%	33.5	33.5		
FC System	%			50	50
Accessory Power					
Mechanical	W	700	500	0	0
Electrical	W	500	700	1200	1200

APPENDIX 2 – RESIZED POWERTRAIN VEHICLE ASSUMPTIONS (MIDSIZE PLATFORM)

		Conventional						Parallel					
Percentage glider mass reduction		0	10	20	30	40	50	0	10	20	30	40	50
Power													
IC Engine Power	W	118000	111000	105000	98000	91000	84000	85000	80000	73666	67744	62038	55235
Fuel Cell Power	W												
Electric Motor #1 : Peak Power	W							17000	17000	17000	17000	17000	17000
High Power Energy Storage #1 Power	W							21250	21250	21250	21250	21250	21250
Transmission													
Transmission Type		Auto 5spd	Auto 5spd	Auto 5spd	Auto 5spd	Auto 5spd	Auto 5spd	Manual 5sp	Manual 5sp	Manual 5sp	Manual 5sp	Manual 5sp	Manual 5spd
Final Drive Ratio		4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44
High Power Energy Storage NiMH													
Number of Cells ESS #1								125	125	125	125	125	125
Cell Capacity (C/3) ESS #1	Ah							6	6	6	6	6	6
Weights													
Glider (Body & Chassis)	kg	988	889.2	790.4	691.6	592.8	494	988	889.2	790.4	691.6	592.8	494
ICE Mass	kg	73.8	69.4	65.6	61.3	56.9	52.5	53.1	50	46	42.3	38.8	34.5
FC System	kg												
High Power Energy Storage	kg							16.3	16.3	16.3	16.3	16.3	16.3
Motor Controller	kg							3.4	3.4	3.4	3.4	3.4	3.4
Motor	kg							17	17	17	17	17	17
Other	kg	354.2	354.4	354	354.1	354.3	354.5	347.2	347.1	346.9	347.4	346.7	346.8
Cargo & Driver Mass	kg	136	136	136	136	136	136	136	136	136	136	136	136
Total Mass Used In Simulation Mass	kg	1552	1449	1346	1243	1140	1037	1561	1459	1356	1254	1151	1048
Power Density													
Powertrain	W/kg	76.0	76.6	78.0	78.8	79.8	81.0	65.3	66.5	66.9	67.6	68.7	68.9
Vehicle													
Frontal Area	m2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Coefficient Drag	/	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Rolling Resistance	/	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Wheel Radius	m	0.317	0.317	0.317	0.317	0.317	0.317	0.317	0.317	0.317	0.317	0.317	0.317
Peak Efficiencies (0-100)													
IC Engine eff	%	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335
FC System eff	%												
Accessory Power													
Mechanical Power	W	300	300	300	300	300	300	250	250	250	250	250	250
Electrical Power	W	300	300	300	300	300	300	350	350	350	350	350	350

		Fuel Cell						Fuel Cell Hybrid					
Percentage glider mass reduction		0	10	20	30	40	50	0	10	20	30	40	50
Power													
IC Engine Power	W												
Fuel Cell Power	W	110000	103000	96000	89000	82000	75000	96365	89670	83174	76500	70200	63792
Electric Motor #1 : Peak Power	W	110000	103000	96000	89000	82000	75000	105920	99225	92729	86055	79755	73347
High Power Energy Storage #1 Power	W							9555	9555	9555	9555	9555	9555
Transmission													
Transmission Type													
Final Drive Ratio		4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44
High Power Energy Storage NiMH													
Number of Cells ESS #1		6	6	6	6	6	6	56	56	56	56	56	56
Cell Capacity (C/3) ESS #1	Ah							6	6	6	6	6	6
Weights													
Glider (Body & Chassis)	kg	988	889.2	790.4	691.6	592.8	494	988	889.2	790.4	691.6	592.8	494
ICE Mass	kg												
FC System	kg	220	206	192	178	164	150	192.7	179.3	166.3	153	140.4	127.6
High Power Energy Storage	kg							7.3	7.3	7.3	7.3	7.3	7.3
Motor Controller	kg	22	20.6	19.2	17.8	16.4	15	21.2	19.8	18.5	17.2	16	14.7
Motor	kg	110	103	96	89	82	75	105.9	99.2	92.7	86.1	79.8	73.3
Other	kg	338	338.2	338.4	338.6	337.8	338	339.9	340.2	339.8	339.8	339.7	340.1
Cargo & Driver Mass	kg	136	136	136	136	136	136	136	136	136	136	136	136
Total Mass Used In Simulation Mass	kg	1814	1693	1572	1451	1329	1208	1791	1671	1551	1431	1312	1193
Power Density													
Powertrain	W/kg	60.6	60.8	61.1	61.3	61.7	62.1	59.1	59.4	59.8	60.1	60.8	61.5
Vehicle													
Frontal Area	m2	2.2	2.2	2.2	2.2	2.2	2.18	2.2	2.2	2.2	2.2	2.2	2.2
Coefficient Drag	/	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Rolling Resistance	/	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Wheel Radius	m	0.317	0.317	0.317	0.317	0.317	0.307	0.317	0.317	0.317	0.317	0.317	0.317
Peak Efficiencies (0-100)													
IC Engine eff	%												
FC System eff	%	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Accessory Power													
Mechanical Power	W												
Electrical Power	W	600	600	600	600	600	600	600	600	600	600	600	600

APPENDIX 3 – SIMULATION RESULTS

All the fuel economy values are unadjusted for the Combined Drive cycle and expressed in miles per gallon of gasoline equivalent (mpgge).

No Resizing – Compact Platform

	Conventional		Parallel		Fuel Cell Only		Fuel Cell Hybrid	
Mass Reduction	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)
0%	9.9	36.6	9.9	43.4	10.0	53.3	10.1	59.4
10%	9.0	38.4	9.0	45.6	8.9	56.3	9.1	62.3
20%	8.1	40.3	8.1	48.6	7.9	59.8	8.1	65.8
30%	7.2	42.2	7.2	52.4	7.0	63.6	7.0	69.7
40%	6.3	44.4	6.3	56.7	6.1	74.3	6.0	68.0

No Resizing – Midsize Platform

	Conventional		Parallel		Fuel Cell Only		Fuel Cell Hybrid	
Mass Reduction	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)
0%	10.1	29.7	10.1	36.0	10.2	46.0	10.0	50.8
10%	9.3	31.0	9.2	37.8	9.1	48.8	9.0	53.8
20%	8.3	32.4	8.2	39.8	8.2	52.0	8.0	57.2
30%	7.3	33.7	7.3	42.8	7.1	55.7	7.0	61.1
40%	6.4	35.3	6.4	45.6	6.1	59.9	6.0	65.6

No Resizing – SUV Platform

	Conventional		Parallel		Fuel Cell Only		Fuel Cell Hybrid	
Mass Reduction	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)	IVM – 60mph (sec)	Fuel Economy (mpgge)
0%	9.9	20.3	9.9	26.4	10	33.8	10.1	32.1
10%	9	21	8.9	27.8	8.9	35.9	9.1	34.1
20%	8.1	21.8	8	29.4	7.9	38.3	8.0	36.3
30%	7.2	22.6	7	31.2	6.9	40.9	7.0	38.7
40%	6.3	23.3	6.1	33.1	6	43.8	6.0	41.5

Resizing – Midsize Platform – Fuel Economy (mpgge)

Mass Reduction	Conventional	Parallel	Fuel Cell Only	Fuel Cell Hybrid
0%	30.4	36.1	49.9	44.6
10%	32.0	38.4	52.0	46.8
20%	33.7	40.1	54.5	49.3
30%	35.7	42.2	57.4	51.9
40%	37.9	45.0	60.6	54.9

APPENDIX 4 – TERMS AND ABBREVIATIONS

m_{fuel}	fuel mass
$m_{vehicle}$	vehicle mass
$\hat{\eta}_{powertrain}$	average powertrain efficiency
$\hat{\eta}_{power_source}$	aggregate power source efficiency
$\hat{\eta}_{trans}$	average transmission efficiency
$\hat{\eta}_{fd}$	average final drive efficiency
E_{IN}	powertrain input energy
E_{OUT}	powertrain output energy
E_{Fuel}	fuel energy
LVH	fuel lower heating value
$\eta_{driveline}$	instantaneous driveline efficiency
η_{fcv}	instantaneous fuel converter efficiency
P_{Fuel}	instantaneous fuel power
P_{Veh}	instantaneous vehicle power
P_{Ess}	instantaneous energy storage system power
a	vehicle acceleration
V	vehicle linear speed
C_{rr}	rolling resitance coefficient
g	gravity
Cd	drag coefficient
A	frontal area
δ	air density