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Cost Benefit Analysis of Advanced Powertrains from 2010 to 2045

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Abstract

Through its Office of Planning, Budget and Analysis, the U.S. DOE Energy Efficiency and Renewable Energy (EERE) provides estimates of program benefits in its annual Congressional Budget Request. The Government Performance and Results Act (GPRA) of 1993 provides the basis for assessing the performance of Federally funded programs. Often referred to as "GPRA Benefits Estimates," these estimates represent one piece of EERE's GPRA implementation efforts—documenting some of the economic, environmental, and security benefits (or outcomes) from achieving program goals. PSAT, Argonne National Laboratory's vehicle system analysis tool, was used to evaluate the fuel economy of numerous vehicle configurations (including conventional, Hybrid Electric Vehicles (HEVs), Plug-in HEVs, electric), component technologies (gasoline, diesel, hydrogen engines as well as fuel cell) and timeframes (current, 2010, 2015, 2030 and 2045). The uncertainty of each technology is taken into account by assigning probability values for each assumption.

Keywords: simulation, HEV, PHEV, ICE, fuel cell

1 Introduction

Through its Office of Planning, Budget and Analysis, the U.S. DOE Energy Efficiency and Renewable Energy (EERE) provides estimates of program benefits in its annual Congressional Budget Request. The Government Performance and Results Act (GPRA) of 1993 provides the basis for assessing the performance of Federally funded programs. Often referred to as "GPRA Benefits Estimates," these estimates represent one piece of EERE's GPRA implementation efforts—documenting some of the economic, environmental, and security benefits (or outcomes) from achieving program goals. PSAT, Argonne National Laboratory's vehicle system analysis tool, was used to evaluate the fuel economy of numerous vehicle configurations (including conventional, Hybrid Electric Vehicles (HEVs), Plug-in HEVs, electric), component technologies (gasoline, diesel, hydrogen engines as well as fuel cell) and timeframes (current, 2010, 2015, 2030 and 2045). The uncertainty of each technology is taken into account by assigning probability values for each assumption.

2 Methodology

In order to evaluate the fuel efficiency benefits of advanced vehicles, the vehicles are designed based on the component assumptions. The fuel efficiency is then simulated on the Urban Dynamometer Driving Schedule (UDDS) and Highway Federal Emissions Test (HWFET). The vehicle costs are calculated from the component sizing. Both cost and fuel efficiency are then used to define the market penetration of each technology to finally estimate the amount of fuel saved. The process is highlighted in Figure1. This paper will focus on the first phase of the project: fuel efficiency and cost.

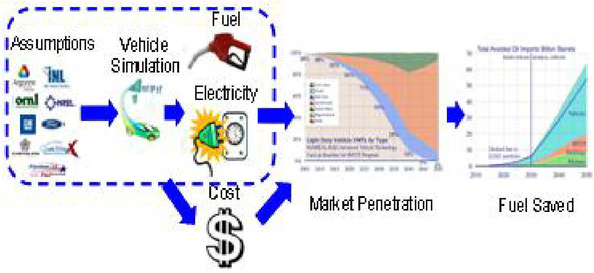

Figure 1: Process to Evaluate Vehicle Fuel Efficiency of Advanced Technologies

To properly assess the benefits of future technologies, several options were considered as shown in Figure 2:

- Four vehicle classes: midsize car, small SUV, medium SUV and pickup truck
- Five Timeframes: current, 2010, 2015, 2030 and 2045
- Five Powertrain configurations: conventional, Hybrid electric vehicle (HEV), Plug-in HEV (PHEV), fuel cell HEV and electric vehicle
- Four fuels: gasoline, diesel, ethanol and hydrogen

Overall, more than 700 vehicles were defined and simulated in PSAT. The current study does not include micro or mild hybrids and does not focus on emissions.

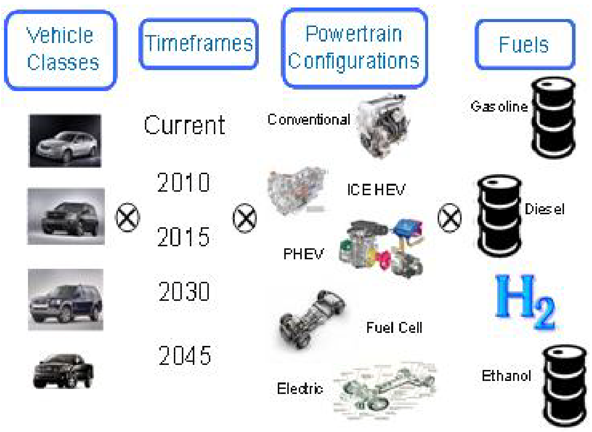

Figure 2: Vehicle Classes, Timeframes, Configurations and Fuels Considered

To address to uncertainties, a triangular distribution approach (low, medium and high) was employed as shown in Figure 3. For each component assumptions (i.e, efficiency, power density…), three separate values were defined to represent (1) 90th percentile, (2) 50th percentile and (3) 10th percentile. 90 percent probability means that the technology has a 90% chance of being available at the time considered. For each vehicle considered, the cost assumptions also follow the triangular uncertainty. Each set of assumption is however used for each vehicle, the most efficient components not being automatically the cheapest ones. As a result, for each vehicle considered, we simulated 3 options for fuel efficiency. Each of these three options also has three values representing the cost uncertainties.

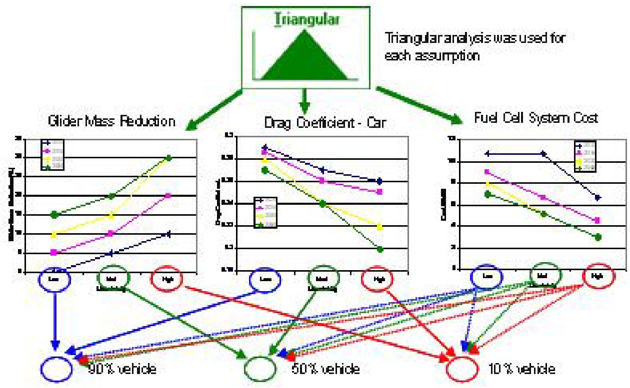

Figure 3: Uncertainty Process

The following paragraph describes the assumptions and their associated uncertainties for each component technology.

3 Vehicle Technology Projections

3.1 Engines

Several state-of-the-art engines were selected for the fuels considered: gasoline, diesel, E85 FlexFuel and hydrogen. The gasoline, diesel and E85 FlexFuel engines used for current conventional vehicles were provided by automotive car manufacturers, while the port-injected hydrogen engine data was generated at ANL [5]. The engines used for HEVs and PHEVs are based on Atkinson cycles, generated from test data collected at ANL's dynamometer testing facility [4]. Different options were considered to estimate the evolution of each engine technology. While linear scaling was used for gasoline and E85 (HEVs application only) and diesel engines, direct injection with linear scaling was considered for the hydrogen fueled engine [5] and non-linear scaling based on AVL's work [6] was used for gasoline and E85 (conventional applications). For the non-linear scaling, different operating area where improved by different amounts, resulting in changing the constant efficiency contours. The peak efficiencies of the different fuels and technologies are shown in Figure 4.

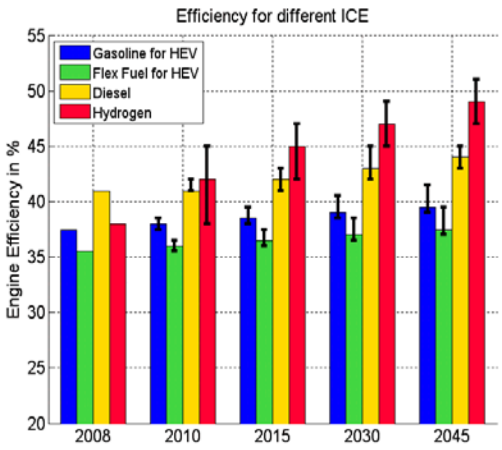

Figure 4: Engine Efficiency Evolution

3.2 *Fuel Cell Systems*

The fuel cell system model is based on the steady-state efficiency map shown in Figure 5. The system is assumed to be gaseous hydrogen. In simulation, the additional losses due to transient operating conditions are not taken into account.

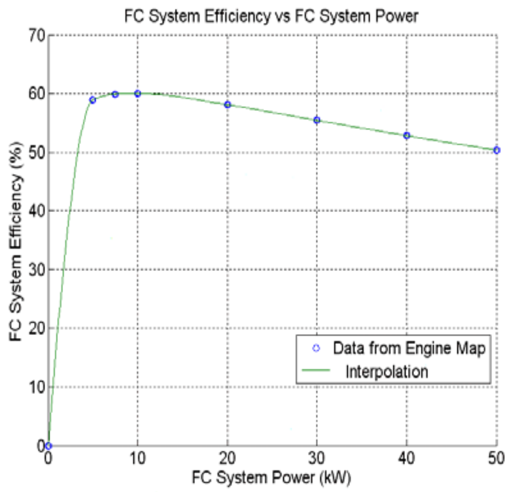

Figure 5: Fuel Cell system efficiency versus Fuel Cell system power from the system map

Figure 6 shows the fuel cell system peak efficiencies as well as its associated cost. The peak fuel cell efficiency is assumed to be currently at 55% and rapidly increase to 60% by 2015. The value of 60% has already been demonstrated in laboratories and consequently is expected to be implemented soon in vehicles. The peak efficiencies remain constant in the future as most research is expected to focus on reducing cost. The costs are projected to decrease from 108 $/kW currently (values based on high production volume) to an average of 45$/Kw in 2030 (uncertainty from 30 to 60 $/kW).

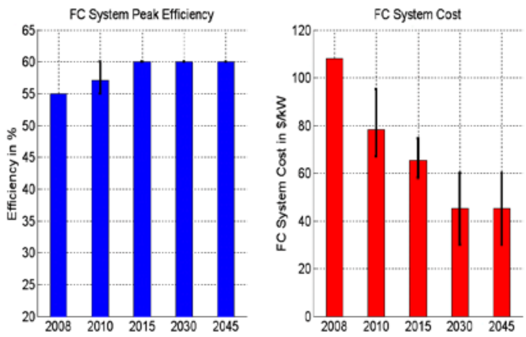

Figure 6: Fuel Cell System Efficiency and Cost

3.3 *Hydrogen Storage Systems*

The evolution of hydrogen storage systems is vital to the introduction of hydrogen powered vehicles. Figure 7 shows the evolution of the hydrogen storage capacity.

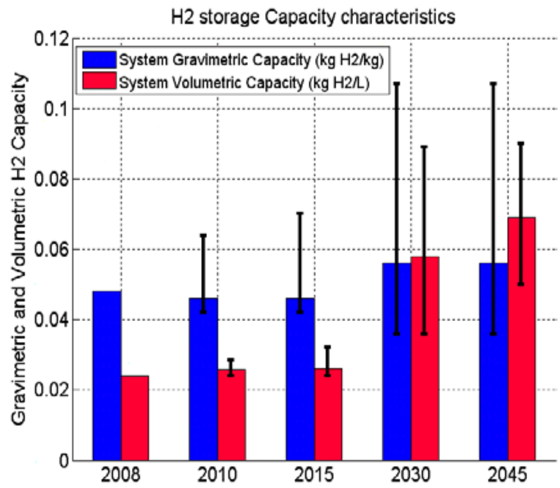

Figure 7: Hydrogen storage capacity in terms of Hydrogen quantity

One of the requirements for any vehicle in the study is to be able to travel 320 miles on the Combined Driving Cycle with a full fuel tank. If we wanted to simulate current vehicles with a hydrogen storage system allowing a drive of 320 miles, the amount of hydrogen needed, and thus the corresponding fuel tank mass, would be too large to fit in the vehicles. As a result, different ranges were selected:

- Reference, 2010 and 2015 : 190 miles
- 2030 and 2045 : 320 miles

3.4 Electric Machines

Figure 8 shows the electric machine peak efficiencies considered. The values for the current technologies are based on state-of-the-art electric machines currently used in vehicles [7]. The electric machine data from the Toyota Prius and Toyota Camry were used for the power split HEV applications, while the Ballard IPT was selected for series fuel cell HEVs. Since the component is already extremely efficient, most of the improvements reside in cost reduction as shown in Figure 9.

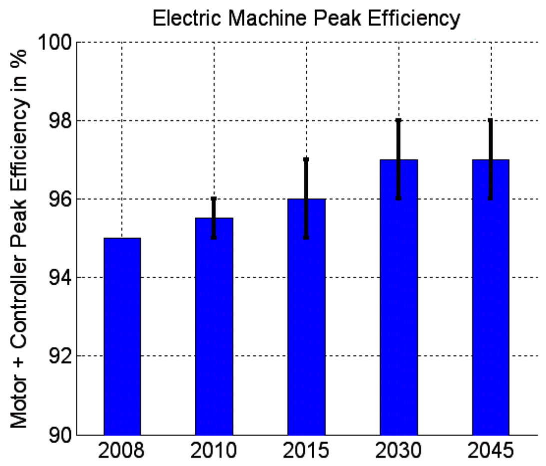

Figure 8: Electric Machine Peak Efficiency

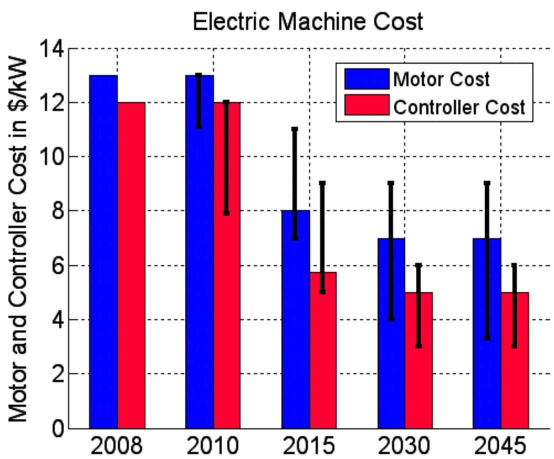

Figure 9: Electric Machine Cost

3.5 Energy Storage System

Energy storage systems are a key component to advanced vehicles. While numerous studies are currently being undertaken with ultracapacitors, only batteries were taken into account in the study. All current vehicles are defined using NiMH technology. The Li-ion technology is introduced for the high case in 2010 and for the medium and high case in 2015 before becoming the only one considered for later timeframes. For HEV applications, the NiMH is based on the Toyota Prius battery pack and the Li-ion is based on the 6Ah from Saft. For PHEV applications, the VL41M battery pack from Saft has been characterized. Due to the fact that each vehicle is size for both power and energy in the case of a PHEV, a sizing algorithm was developed to design the batteries specifically for each application [8].

To ensure that the battery has similar performance at the beginning and end of life, the packs were oversized both in power and energy as shown in Figure 10. In addition, for PHEV applications, the State-of-charge (SOC) window (difference between maximum and minimum allowable SOC) increases over time, allowing a reduction of the battery pack as shown in Figure 11.

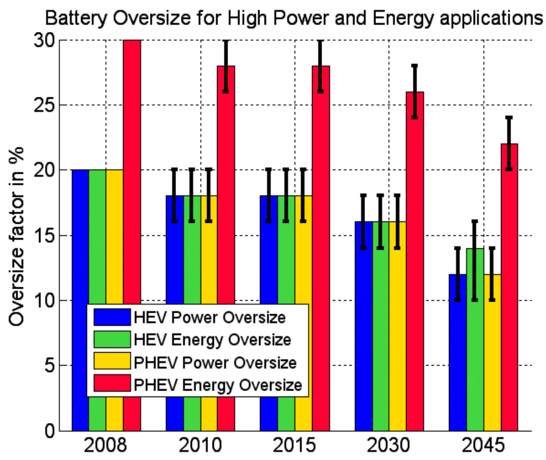

Figure 10: Battery Over Sizing

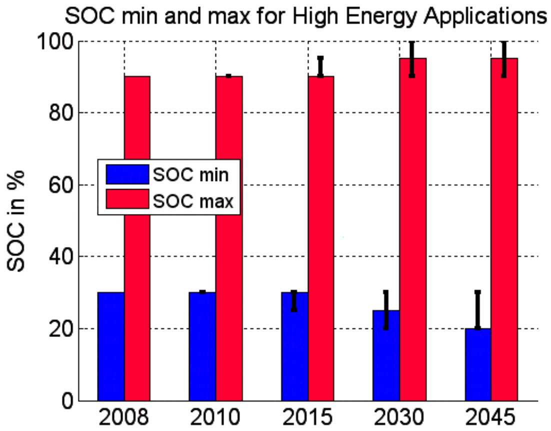

Figure 11: Battery SOC Window

Figure 12 and 13 show the cost of the battery packs for both high power applications ($/kW) and high energy applications ($/kWh).

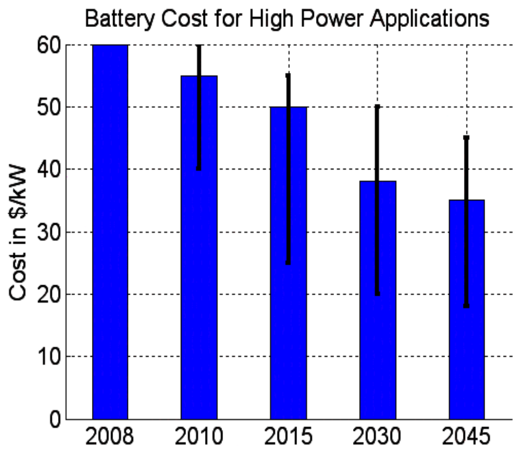

Figure 12: High Power Battery Cost Projections

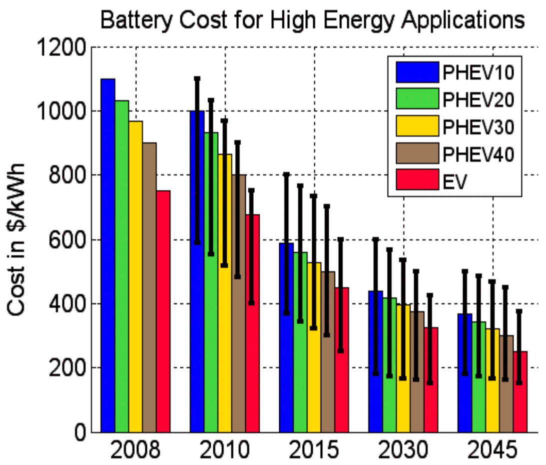

Figure 13: High Energy Battery Cost Projections

3.6 Vehicle

As previously discussed, four vehicles classes were considered as shown in Table 1.

Table 1 : Vehicle characteristics for different vehicle classes

	Glider Mass (Ref) in kg	**Frontal Area (Ref) in m^2**	**Tire**	**Wheel Radius in m**
Midsize car	990	2.2	P195/65/R15	0.317
Small SUV	1000	2.52	P225/75/R15	0.35925
Midsize SUV	1260	2.88	P235/70/R16	0.367
Pickup	1500	3.21	P255/65/R17	0.38165

Due to the improvements in material, the glider mass is expected to significantly decrease over time. The maximum value of 30% was defined based on previous studies [9] that calculated the weight reduction that one could achieve when replacing the entire chassis frame by aluminum. Despite the fact that frontal area is expected to differ from one vehicle configuration to another (i.e., the electrical components will require more cooling capabilities), the values were considered constant across the technologies. Figure 14 and 15 show the reduction in both glider mass and frontal area.

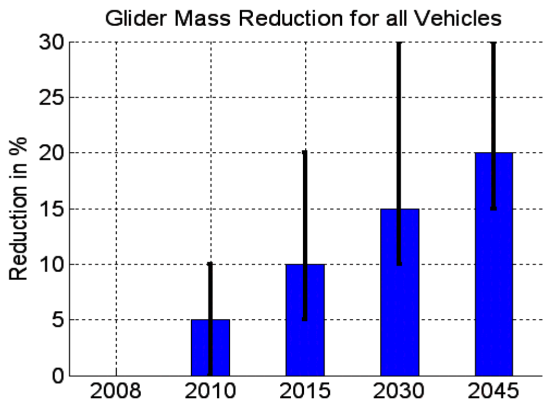

Figure 14: Glider Mass Reductions

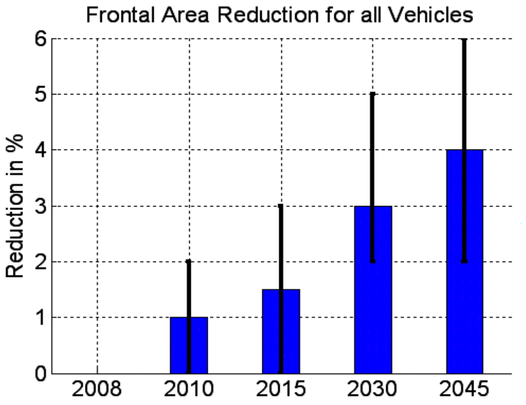

Figure 15: Frontal Area Reductions

4 Vehicle Powertrain Assumptions

All the vehicles have been sized to meet the same requirements:

- 0-100 km/h in 9 sec +/-0.1
- Maximum grade of 6% at 105 km/h at Gross Vehicle Weight
- Maximum vehicle speed >160 km/h

For all cases, the engine or fuel cell powers are sized to perform the grade without any assistance from the battery. For HEVs, the battery was sized to recuperate the entire braking energy during the UDDS drive cycle. For the PHEV case, the battery power is defined to be able to follow the UDDS in electric mode while its energy is calculated to follow the trace for a specific distance. Due to the multitude of vehicles considered, an automated sizing algorithm was defined [10].

Input mode power split configurations, similar to the Toyota Camry, were selected for all HEV and PHEV applications using engines. The series fuel cell configurations use a two-gear transmission to be able to achieve the maximum vehicle speed requirement. The vehicle level control strategies employed for each configuration have been defined in previous publications [11, 12, 13, 14, 15].

5 Component Sizing

As shown in Figure 16, the engine power is decreasing over time for all the powertrains. The power split HEV is the one with the highest engine power reduction: 20% from reference to 2045 average case whereas the conventional decreases only by 13%. The engine power is higher when the AER range increases. This is due to the fact that the power is sized on acceleration and grade and that the different PHEV (for the same fuel) only vary from one to the other by having a bigger battery (and thus a heavier car).

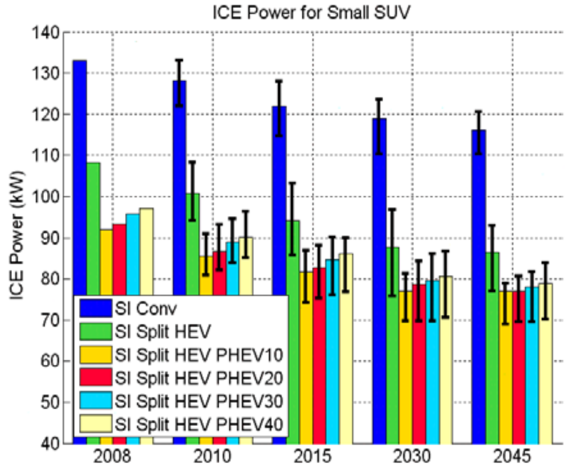

Figure 16: Engine Power for Gasoline Powertrains for Small SUV

The ICE power linearly changes with the vehicle mass as shown in Figure 17. The hydrogen and diesel points are on the same line but they do not cover the same mass range. Also, if the hydrogen had the same travel distance range than the other fuels, its line would be shifted up and left. Two points from the hydrogen series remain on the same line as the gasoline engine. These two points correspond to the 2008 and 2010 low case values where the ICE used is not direct injection. Consequently, the ICE power is higher for these two cases. For every 100kg less on the vehicle mass, the engine power decreases by approximately 10kW.

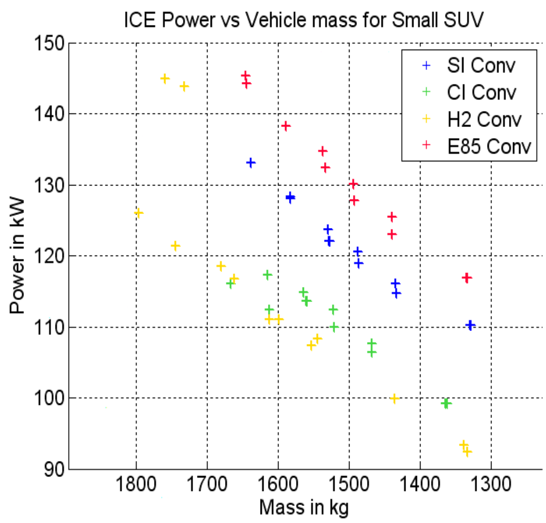

Figure 17: ICE Power as a function of Vehicle mass for Conventional.

Figure 18 shows the electric machine power for the gasoline HEVs and PHEVs. As one notices, PHEVs require higher power due to the fact that one of their requirements is the ability to follow the UDDS in electric mode. It is important to note that the fact that the vehicles have the ability to drive the UDDS in electric mode, the control strategy employed during fuel efficiency simulation is based on blended operation. However, the power does not increase significantly compared to HEVs as the input mode power split configuration was considered. A decrease of 10 to 20kW can be expected by 2045 due to other component improvements.

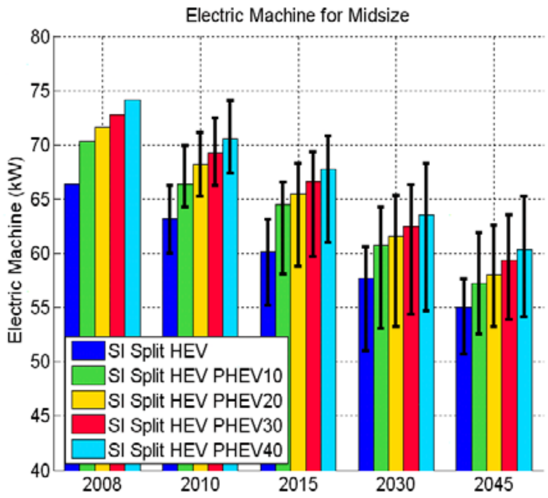

Figure 18: Electric Machine Power for Gasoline HEV and PHEVs for Midsize Vehicle

Figure 19 and 20 show the battery power and energy requirements for HEV, PHEV and EV applications. The sensitivity of battery power to vehicle mass increases with the degree of electrification (i.e, higher for EV, then PHEV and finally HEVs). From an energy point of view, every 100 kg decrease for a PHEV40 (i.e, 40 miles on electric only on the UDDS), the energy requirements decrease by approximately 2 kWh.

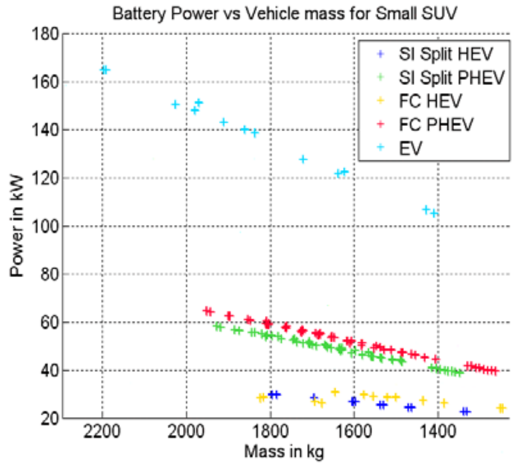

Figure 19: Battery Power

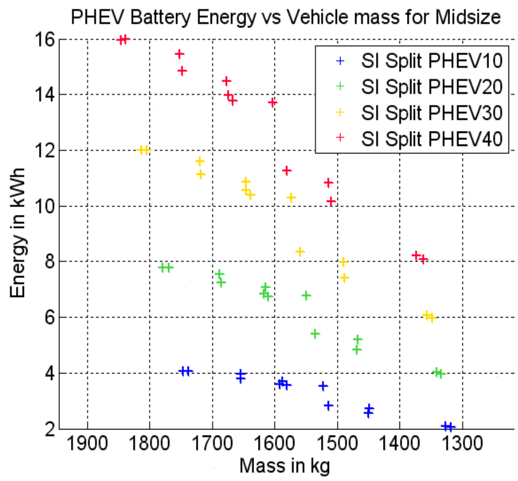

Figure 20: Battery Energy

6 Vehicle Simulation Results

The vehicles were simulated on both the UDDS and HWFET drive cycles. The fuel consumption values and ratios presented below are based on unadjusted values. The cold start penalties were defined for each powertrain technology option based on available data collected at ANL's dynamometer facility and available in the literature. The following cold start penalties (on the 505 cycle at 20C) were maintained constant throughout the timeframes:

- Conventional : 15%
- Split HEV: 18%
- Split PHEV: 14%
- Fuel Cell HEV: 25%
- Fuel Cell PHEV: 15%
- Electric Vehicle: 10%

6.1 Impact of Different Fuels on Conventional Vehicles

Figure 21 shows the evolution of the fuel consumption for different fuels on a conventional midsize vehicle. All the results are presented in gasoline fuel equivalent. As expected, the diesel engine achieve better fuel efficiency than the gasoline, but the difference between both technologies narrows with time as greater improvements are expected for gasoline engine, especially at lower loads than for their diesel counterparts with technologies such as low temperature combustion, variable valve timing, downsizing…

Hydrogen engine are penalized by the additional weight of the hydrogen storage system. With the introduction of direct injection hydrogen engine technology combined with improved storage, they can compete with other fuels. It is moreover important tom notice the large uncertainty related to hydrogen vehicles.

Ethanol engine are currently being designer to run on several fuels. When specifically designed to run on ethanol, the vehicles running on ethanol have the potential to achieve the best fuel efficiency.

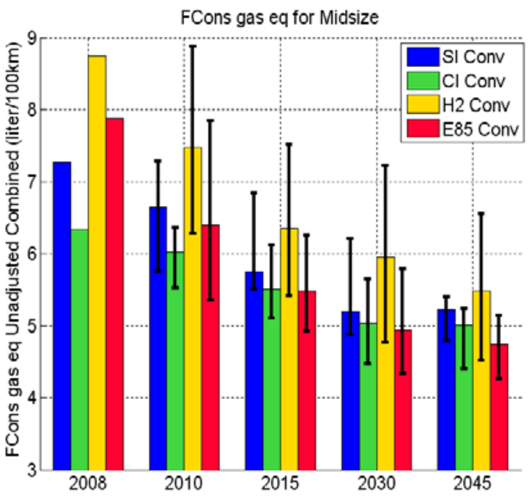

Figure 21: Fuel Consumption Gasoline Equivalent Unadjusted for Conventional Midsize Cars

Figure 22 shows the vehicle cost ratios between the different fuels for conventional vehicles. Diesel engines are expected to remain more expensive than their gasoline counterparts while hydrogen engine vehicles become competitive in the long term due to less expensive storage.

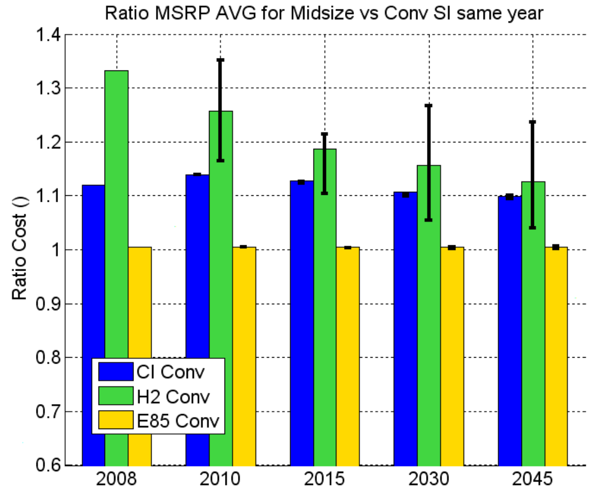

Figure 22: Conventional Vehicle Cost Ratio Compared to Gasoline Conventional of the Same Year

6.2 Evolution of HEVs vs Conventional Vehicles

The comparisons between power split HEV and conventional gasoline vehicles (same year, same case) in Figure 23 show that the ratios stay roughly constant for diesel, gasoline and ethanol. Indeed, the gasoline HEV consumes between 25 and 28% less fuel than the gasoline conventional, whereas the diesel HEV is between 35 and 38% and the ethanol HEV is between 19 and 21%. However, the hydrogen case shows more significant variations. In 2008, the hydrogen power split vehicle consumes roughly 25% less fuel than the gasoline conventional but in 2045 average case, this advantage rises up to 43% and even 47% in the high case. This confirms that hydrogen vehicles will benefit more of hybridization in the future. To summarize, the advance in component technology will equally benefit conventional and HEVs, except for the hydrogen engine due to additional benefits of the hydrogen storage.

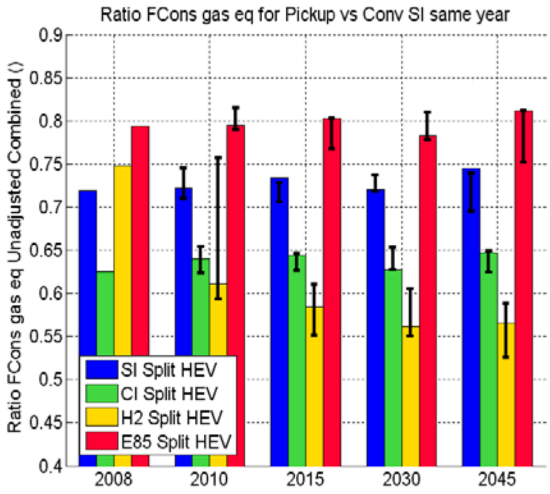

Figure 23: Ratio of Fuel Consumption gasoline equivalent Unadjusted Combined in comparison to the conventional gasoline same year, same case, for Pickup.

Figure 24 shows the vehicle cost ratio between HEV and conventional vehicles. As expected, HEVs remain more expensive than conventional vehicles, but the difference significantly decreases due to faster reduction in battery and electric machine cost than for engines.

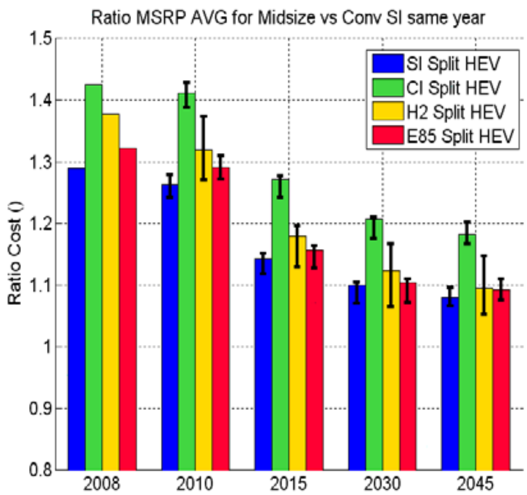

Figure 24: HEV Vehicle Cost Ratio Compared to Gasoline Conventional Vehicle of the Same Year

6.3 *Evolution of HEVs vs FC HEVs*

Figure 25 shows the fuel consumption comparison between HEVs and FC HEVs for the midsize car case. First, one notices that the fuel cell vehicle technology will continue to provide better fuel efficiency than the HEVs with ratios above 1. However, the ratios vary over time depending upon the fuel considered. The gasoline HEV sees its ratio increase over time due to the fact that most improvements considered for the engine occur at low power and consequently do not significantly impact the fuel efficiency in hybrid operating mode. Both diesel and ethanol HEVs follow the same trend than the gasoline.

Because of the larger improvements considered for the hydrogen engine, the hydrogen power split shows the best fuel consumption improvement compared to the fuel cell technology. . Indeed, in 2008, the hydrogen HEV vehicle consumes nearly 40% more fuel than the Fuel Cell HEV vehicle but in 2045 average case, this difference is reduced to 10%. If we consider the UDDS fuel consumption instead of the Combined values, we find that the hydrogen power split is only 2.5% more fuel consuming than a Fuel Cell HEV in 2045 high case.

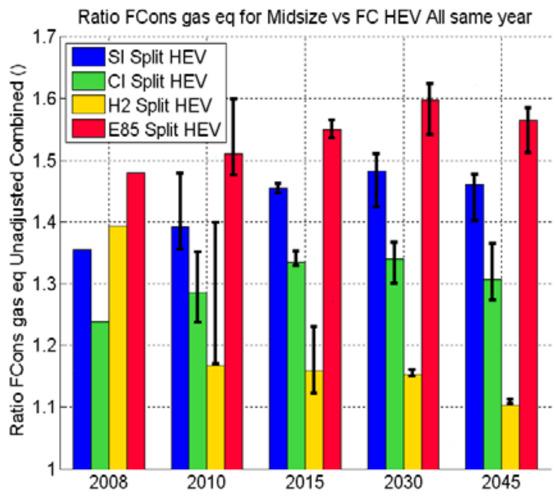

Figure 25: Ratio of Fuel Consumption gasoline equivalent Unadjusted Combined in comparison to the Fuel Cell HEV same year, same case, for Midsize.

Figure 26 shows the vehicle cost comparison between HEVs and FC HEVs. As one notices, the cost difference between both technologies is expected to decrease over time with a ratio between 0.9 and 1 in 2030 and 2045.

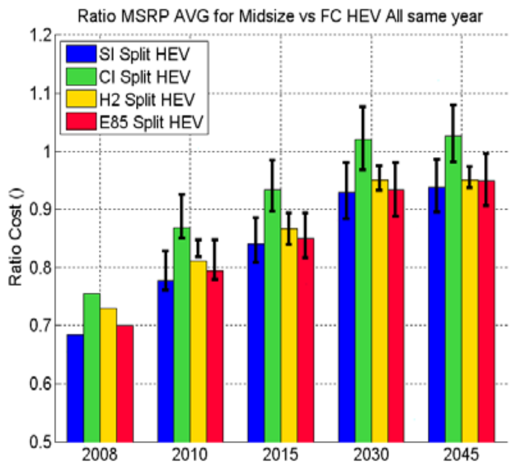

Figure 26: HEV Vehicle Cost Ratio Compared to FC HEV Vehicle of the Same Year

6.4 *Evolution of Hydrogen Fueled Vehicles*

In 2008, FC HEVs consume about 49% less fuel than gasoline conventional vehicles and this difference in fuel consumption is increasing in the next timeframes to reach 54% in 2030 average case. In 2045, the trend is changing. In 2045 average case, the fuel cell vehicle will consume 51% less fuel than the gasoline conventional vehicle. This value is still higher than for the reference year which means that the gasoline conventional vehicle will not improve its fuel consumption faster than FC HEV.

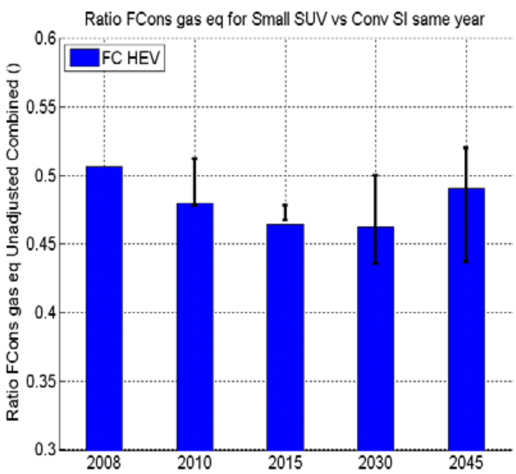

Figure 27: Ratio of Fuel Consumption gasoline equivalent Unadjusted Combined in comparison to the gasoline conventional same year, same case, small SUV.

7 Conclusion

More than 700 vehicles were simulated for different timeframes (up to 2045), powertrain configurations and component technologies. Both their fuel economy and cost were assessed to estimate the potential of each technology. Each vehicle was associated with a triangular uncertainty. The simulations highlighted several points:

- The discrepancy between gasoline and diesel engine for conventional vehicles is narrowing with the introduction of new technologies such as VVT, low temperature combustion…
- From a fuel efficiency perspective, HEVs maintain a relative constant ratio compared to their conventional vehicle counterparts. However, the cost of electrification is expected to be reduced in the future, favoring the technology's market penetration.
- Ethanol vehicles will offer the best fuel consumption among the conventional powertrains in the near future, thus the interest of bio-fuels development.
- Fuel cell HEVs have the greatest potential to reduce fuel consumption
- Hydrogen engine HEVs, through direct injection, will offer significant fuel improvements and due to lower cost than fuel cell systems appears as a bridging technology which would help the infrastructure

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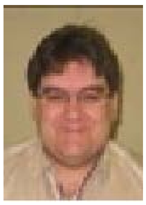

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