Trade-off between Fuel Economy and Cost for Advanced Vehicle Configurations

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Abstract

Internal combustion engine (ICE) hybrid electric vehicles (HEVs) have been recently introduced in the market place, offering higher fuel economy than current conventional vehicles. Concurrently, because of their high efficiency and low emission potential, fuel cell vehicles are undergoing extensive research and development. This paper compares conventional, ICE HEVs and fuel cell powertrain configurations from the fuel economy and cost points of view for the European, U.S., and Japanese markets. Several powertrain configurations, with different hybridization degrees, have been simulated using PSAT (Powertrain System Analysis Toolkit), and vehicle life cycle costs have been evaluated using the Automotive System Cost Model (ASCM) based on the average fuel price of each country.

Keywords: HEV, ICE, fuel cell, modeling, cost.

1 Introduction

Over several decades, the U.S. national laboratories have developed and used 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 vehicular life cycle from design and manufacturing through end-of-life. In addition, advanced batteries, fuel cells, engines, and many vehicle configurations have been modeled, developed and tested in DOE’s facilities. This combination of analytical, developmental, and testing experience has been supported through modeling and analysis at all levels, from individual components to the total vehicle from an efficiency point of view with PSAT(Powertrain System Analysis Toolkit) as well as a cost point of view with the Automotive System Cost Model (ASCM).

PSAT enables advanced vehicle designers to simulate fuel consumption and vehicle driving performance for many different vehicle configurations allowing them to quickly narrow their focus on the most fuel-efficient configurations and components. Argonne National Laboratory (ANL) developed this forward-looking model to study transient effects and the interactions among components with accurate simulations of driver-originated control commands. PSAT has been validated for several vehicle configurations and is primarily used to perform studies for the DOE and the FreedomCAR Partnership.

Once PSAT has been used to determine the most efficient configurations, the resulting choices will be evaluated from a total cost standpoint. ASCM, developed jointly by Oak Ridge National Laboratory (ORNL) and Ibis Associates, Inc., in collaboration with ANL, allows an early identification of key issues influencing vehicle life cycle cost. ASCM estimates the vehicle manufacturing cost at a level of five major subsystems (powertrain, chassis, body, interior, and electrical) and more than thirty-five components representing a specific manufacturing technology, to which vehicle operation costs are added for the vehicle life cycle cost estimation. The interrelationships among vehicle subsystems and their effect on vehicle manufacturing cost are also considered. The main objective of this model is to facilitate relative life cycle cost estimation via a uniform estimation methodology to allow comparison of alternative technologies considered by the FreedomCAR community. The model has the capability to evaluate seven specific vehicle configurations consisting of hybrid and fuel cell technologies for thirteen EPA light-duty vehicle classes.

2 PSAT Vehicle Model

PSAT [2], developed under MATLAB/Simulink, allows users to realistically estimate the wheel torque needed to achieve a desired speed by sending commands to various 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 model a driver who follows a predefined speed cycle. Moreover, as components react to commands as in reality, we can implement advanced component models, take transient effects into account (such as engine starting, clutch engagement/disengagement, or shifting) or develop realistic control strategies through a graphical user interface. Finally, PSAT has been used for several studies [3] after being validated within 5% accuracy by using testing results from several vehicles [4-5].

3 ASCM Cost Model

The basic design of the ASCM model is based on two primary elements: (a) a framework of equations and relationships used for component sizing, and (b) a database that populates the spreadsheet-based modeling framework as shown in Figure 1. Powertrain component sizing can either be done through Argonne National Laboratory's hybrid vehicle cost model algorithm adapted into the model or by directly inputting in the model the sizing information obtained from a performance model, PSAT in our case. The non-powertrain components are sized based on their functional relationships with powertrain components that are based on the first principles of physics, and using semi-empirical and empirical information available from the open literature. Operating costs such as financing, insurance, local fees, fuel, maintenance, repair, and disposal costs are considered in estimating the vehicle life cycle cost per vehicle, as well as per vehicle mile traveled. The database is designed to be dynamic, providing a centralized source of cost data for alternative technologies of advanced vehicle designs and concepts as they become available. The database contains mass and cost information for several advanced technologies for each vehicle component in a simple functional form. Data have been collected through past manufacturing cost analyses by Ibis Associates, Inc., direct interviews with OEMs and supplier engineers and designers, the published literature, and some internal cost estimates [6]. To date, the model has been validated using the representative current year models for thirteen EPA light-duty vehicle classes, and the estimated vehicle costs and masses were found to be within 5-10% of the published values [7]. The model has been used in the recent evaluation of the cost-effectiveness of alternative powertrains and body-in-white materials options for advanced technology vehicles [8].

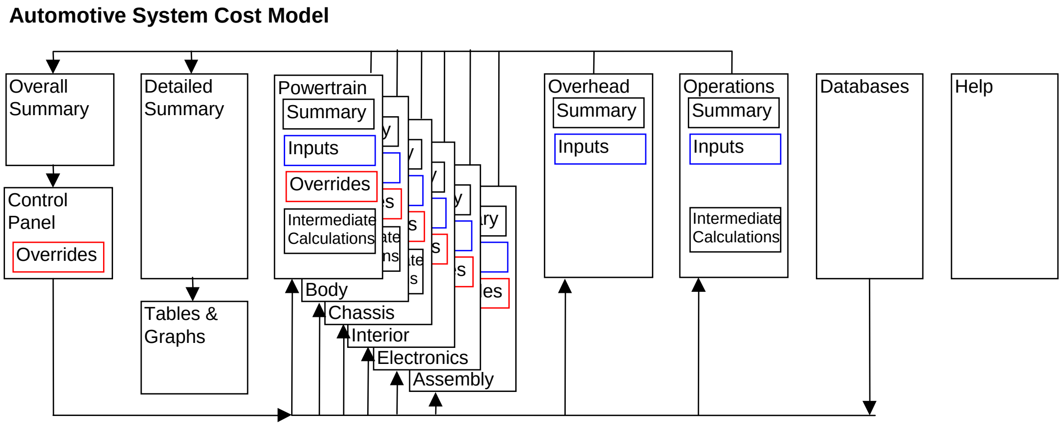

Figure 1: ASCM modeling framework

4 Vehicles Definition

The reference vehicle is based upon a generic SUV (sport utility vehicle) platform (similar to Ford Explorer) whose selected characteristics are listed in Table 1.

	Units	Vehicle Assumptions
Vehicle mass	kg	2035
Glider mass	kg	1258
Engine		V6, SOHC, 210 hp
Frontal area	m2	2.46
Drag coefficient	NA	0.41
Rolling resistance	NA	0.0084
Wheel radius	m	0.368
Acceleration (0–60 mph)	s	10
Combined fuel economy	mpg	21

Table 1: Baseline Reference Vehicle Characteristics

From the reference vehicle, several powertrain configurations have been simulated for near-term (2010) technologies including:

- Conventional vehicle with diesel engine and manual and automatic transmissions,
- Starter-alternator parallel hybrid with gasoline and diesel engines and
- Pre-transmission parallel hybrid with gasoline and diesel engines.

Series engine hybrid configurations have not been included in the study because the components could not be sized within reasonable power constraints to achieve sufficient acceleration.

5 Methodology Assumptions

5.1 Vehicle

To provide a fair comparison among several competing powertrain technologies, the following major assumptions have been made:

- The components of each configuration have been sized to achieve performance similar to that of the reference vehicle (0–60 mph in 10.5 s +/-0.2 s and maximum speed >100 mph).
- Since the results for a powertrain configuration or technology depend on the driving schedule; each of the options was simulated on the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HWFET), the Normalized European Driving Cycle (NEDC), and the Japan 10-15 Mode. The driving cycles have been selected to allow easy evaluation of each powertrain application anywhere in the world.
- Vehicle aerodynamic drag, tire rolling resistance, and glider mass have been kept constant throughout the configurations. The differences between each vehicle were only due to their powertrain configurations and control strategies.
- No cold start was taken into account. It should be noted that this would favor diesels and fuel cells, which currently have cold temperature deficiencies related to gasoline.

Under the FreedomCAR program, specific goals for fuel cell efficiency and specific power were set to 60% and 325 W/kg, respectively [1]. The goal for internal combustion engine brake efficiency was set to 45%. Although no technology was specified for this goal, it was assumed in this study to be the peak brake efficiency for the diesel engine. To simulate near-term advanced vehicles in PSAT, the goals were supplemented with other assumptions, listed in Table 2. To take into account the uncertainties regarding near-term technologies, each component has been assigned low and high targets. These vehicles were defined such that they represent both slow and rapid progress in technology. When available, FreedomCAR goals have been used for the rapid technology case.

	Slow Technology	Rapid Technology
Vehicle Characteristics		
Body mass (kg)	1258	1063
Frontal area (m2)	2.46	2.3
Drag coefficient	0.41	0.38
Rolling resistance	0.0084	0.006
Component Power Density (kW/kg)		
Gasoline ICE	0.8-1.6	1-1.8
Diesel ICE	0.6-0.72	0.8-0.9
Hydrogen ICE	0.7	0.8
Fuel cell	0.28	0.322
Motor	2	2.2
Battery	1.8	1.8
Component Peak Efficiencies (%)		
Gasoline ICE	35	38
Diesel ICE	40.5	45
Hydrogen ICE	38	42
Fuel cell	55	60
Gearbox	96	97

Table 2: Major Vehicle Component FreedomCAR goals

5.2 Cost

The following major assumptions have been made in the vehicle life cycle cost estimation of competing powertrain technologies, and major powertrain component cost assumptions were based on the FreedomCAR goals expressed in $/kW, as shown in Table 3.

- Cost estimates were based on the sizing information for various vehicle components provided by PSAT, and hence mainly the powertrain component costs varied among the scenarios. The glider mass changed only between the slow and rapid technology cases, where aluminum space frame for body-in-white and aluminum panels at the aluminum price of $1.00/lb were assumed to achieve the lower value in the latter case.
- For the 2010 rapid technology case, the FreedomCAR 2010 cost goals have been assumed as shown in Table 3. Either the intermediate FreedomCAR cost goals (wherever available) or the best available expert judgments, considering the current state of technology, were used for the slow technology case. These cost goals were based on a large annual production volume of 500,000 vehicles. In addition, a higher emission control electronics cost for diesel engines and a lower transmission cost for direct-drive fuel cell vehicles were assumed.
- Non-powertrain components sizing, and thereby costs, did not vary among the scenarios, and the cost model was calibrated to be representative of a current mid-sized SUV similar to the Ford Explorer model available in the market today.
- Manufacturing overhead and dealer costs were added to the manufacturing cost to estimate vehicle manufacturer’s suggested retail prices (MSRP), which were assumed to be 45% and 26% of the manufacturing cost, respectively. A higher percentage value in the former cost category indicates a higher profit margin associated with light trucks and SUVs.
- Consistent assumptions were made among the various scenarios for the operation cost estimation for a lifetime vehicle operation of about 160k miles, with the major difference being in fuel and maintenance and repair costs. Fuel economy estimates were based on PSAT, and the United

Kingdom was considered as representing for the European market. Domestic and foreign (i.e., Japan and Europe) fuel prices were based on the U.S. Department of Energy, Energy Information Administration forecasts, but the past 10-year trend was used in the latter case for the 2010 prices. Maintenance and repair costs were assumed to be slightly higher for hybrid vehicles based on the available field data, whereas they were assumed to be similar to conventional vehicles for fuel cell vehicles.

	Slow Technology	Rapid Technology
Gasoline ICE ($/kW)	23	21
Diesel ICE ($/kW)	27	21
Hydrogen ICE ($/kW)*	60	45
Fuel Cell ($/kW)*	75	45
Motor ($/kW)	5	4
Battery ($/kW)	30	20
Emission control ($/kW)**	6	4
U.S. fuel price ($/gge)***	1.40/1.21	1.37/1.17
Europe fuel price ($/gge)***	3.31/4.44	2.64/3.53
Japan fuel price ($/gge)***	2.94/2.14	2.32/2.13
Hydrogen ($/kg)	2.50	1.50

***** Hydrogen storage system included in the price

******Emission control costs are assumed to be constant for gasoline and diesel

*******Two fuel prices under each scenario correspond to gasoline and diesel prices, respectively

Table 3: Major Vehicle Component Cost Assumptions (2010)

6 Study Results

6.1 Fuel Economy

Figure 2 shows simulated U.S. Combined cycle fuel economy test results including the uncertainty error band, as each technology has been considered in terms of a lower and upper bounds for vehicle weight and efficiency associated with slow and rapid technology development described above. Regarding the uncertainty band (Figure 2 - 4), the rapid technology case is represented by the upper tick mark, and the slow technology one by the lower tick mark. The following results consider the average values:

- The diesel conventional vehicle with manual transmission achieves higher fuel economy than the gasoline starter-alternator configuration and is close to the gasoline full hybrid (36.5 mpgge vs. 37.8 mpgge).
- Hydrogen ICE hybrids provide a better fuel economy than gasoline hybrids (41.7 mpgge vs. 37.8 mpgge on average), but lower than of diesel hybrids (46.8 mpgge).
- Hybrid fuel cell vehicles would provide a fuel economy ratio improvement up to 2.2 compared to conventional gasoline vehicles.
- It has been shown in previous papers [9] that excessive hybridization of the fuel cell powertrain when using NiMH or ultracapacitors may diminish the gain in fuel economy. Indeed, (1) the smaller battery configuration recovers most of the regenerative braking and (2) decreasing the fuel cell system power leads to a decrease in the average efficiency of the fuel cell system. For the same hybridization degrees considered, this is not the case when Li-ion are considered, where a higher degree of hybridization for the fuel cell powertrain leads to a fuel economy increase due to their improved performance compared to NiMH or ultracapacitors.
- Considering that batteries are expected to be less costly than fuel cells, a greater degree of hybridization will also help reduce the cost of fuel cell vehicles while maintaining (or even improving) their fuel economy.

- A fuel cell vehicle with high degree of hybridization will also be better in dealing with cold-start issues.

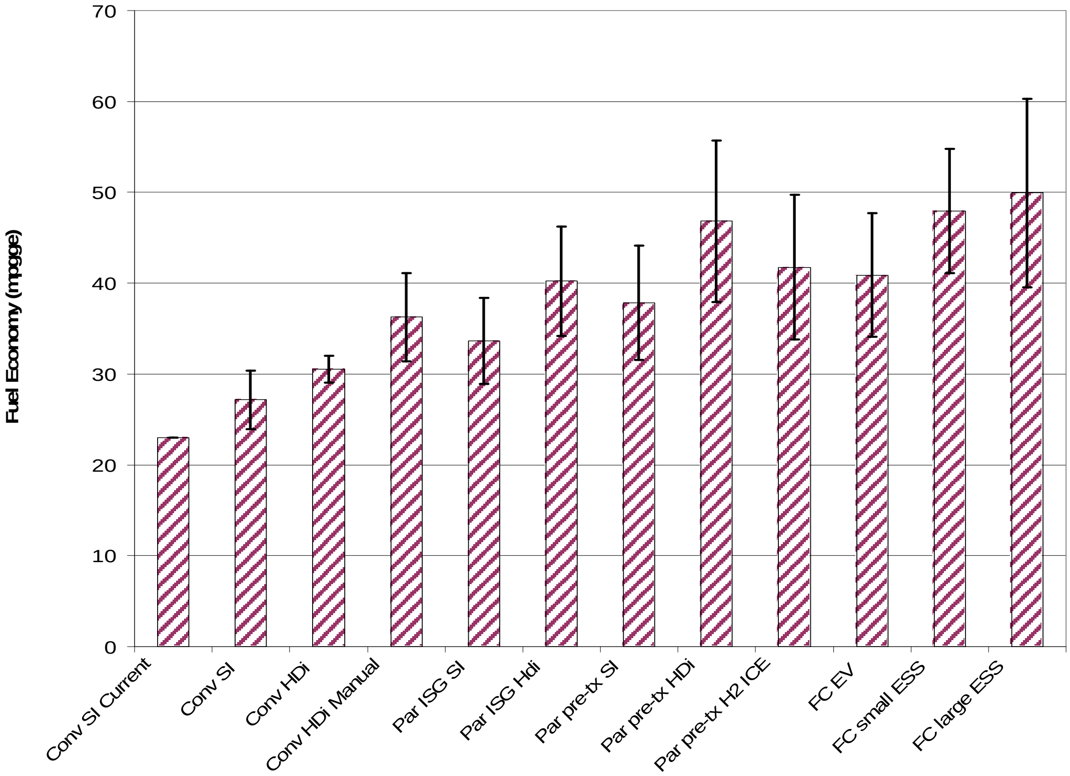

Figure 2: Fuel Economy Results Using U.S. City/Highway Combined Driving Cycles

Figures 3 and 4 illustrate the impact of drive cycle on both diesel and fuel cell configurations. One notices that:

- As expected, the fuel economy gains due to hybridization are greater with a low speed cycle including long stop times. For example, fuel economy of the parallel integrated starter alternator (ISG) hybrid increased by 5% for the HWFET, 12% for the UDDS, 18% for the NEDC, and 25% for the Japan10-15, compared to the conventional diesel configuration.
- An increase in degree of hybridization decreases the impact of drive cycle variation on vehicle fuel economy. Indeed, for the diesel configurations, when comparing the HWFET and Japan10-15 drive cycles, the fuel economy drops by 40% for the conventional, 25% for the ISG and only 10% for the full hybrid. This result is also valid for the fuel cell configurations.
- Parallel pre-transmission diesel hybrids achieve higher fuel economy (mpg) than any fuel cell configuration for both the NEDC and the Japan10-15 cycles, whereas fuel cell vehicles perform better for the UDDS and the HWFET cycles.

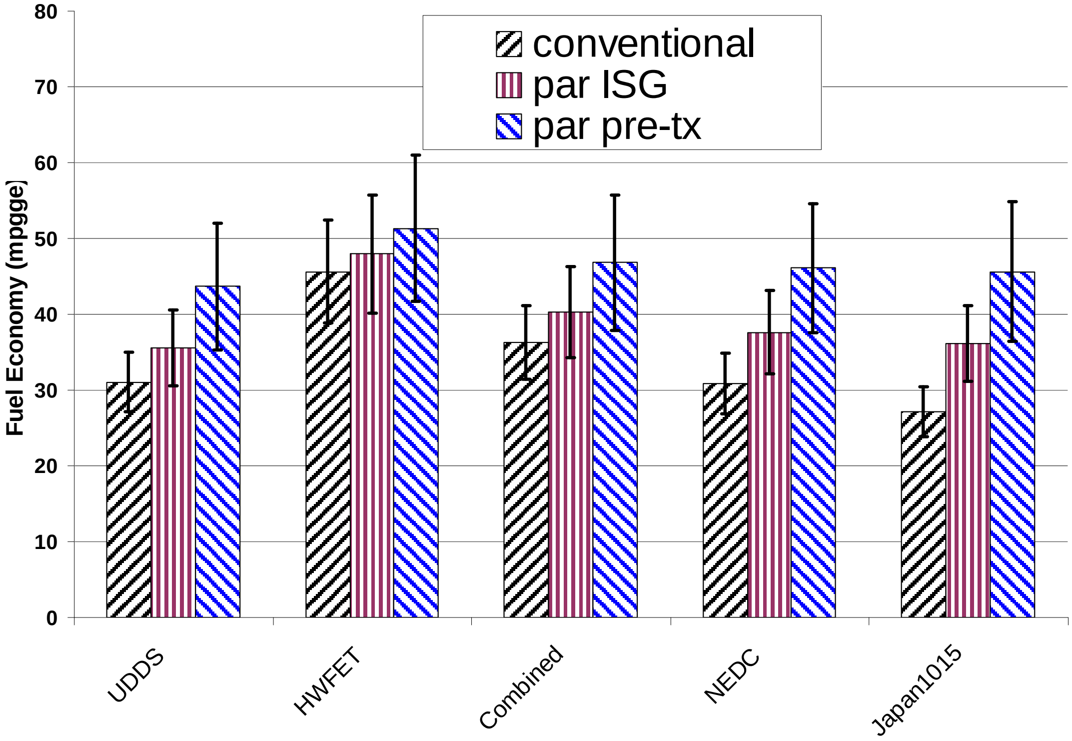

Figure 3: Drive Cycle Impact on Diesel Configurations

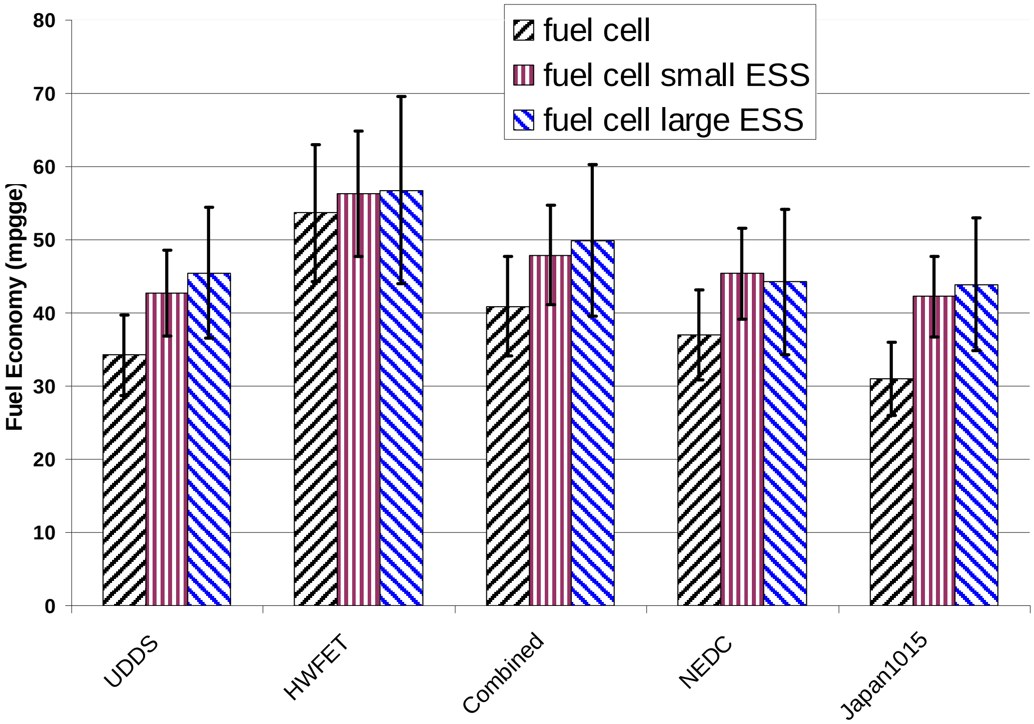

Figure 4: Drive Cycle Impact on Fuel Cell Configurations

6.2 Cost

Figure 5 shows the domestic vehicle purchase cost ratios in 2010 using the U.S. combined cycle fuel economy and its fuel prices. Regarding the uncertainty band (Figure 5 - 7), the rapid technology case is represented by the lower tick mark, and the slow technology one by the upper tick mark. The cost ratios in these figures were estimated based on the conventional gasoline (SI) engine considered in the analysis here. The following observations related to the cost-effectiveness of various vehicle configurations considered are based on the average values and can be summarized as follows:

- As anticipated, initial purchase price of fuel cell vehicles will be significantly higher than that of hybrid vehicles in the U.S. as shown in Figure 5. Higher hybridization of fuel cell vehicles and the use of the hydrogen ICE hybrid vehicles offer the least cost options for the fuel cell vehicles, a cost reduction in the range of 3.5-6%.
- Conventional hybrid vehicles purchase price will approach being similar to that of conventional vehicles by 2010, with the exception of pre-transmission parallel hybrid with gasoline and diesel engines, which will be slightly higher. The incremental cost range for this vehicle type is estimated to be around 3% of the conventional SI vehicle in 2010, mainly due to higher electric drive and traction battery costs.
- Vehicle purchase price is estimated to contribute around 50% of the vehicle life cycle cost. As its contribution does not vary much (from 50 to 54%) for different vehicle configurations, one can conclude that fuel cost contributes to a relatively smaller share of the total vehicle life cycle cost as fuel efficiency increases. This is true even with vehicles with significantly higher fuel economy potential such as fuel cell vehicles.
- Even on the life cycle cost basis (Figure 5), hydrogen fueled vehicles are the least cost effective ones, including the fuel cell vehicles with higher hybridization degree. The hydrogen ICE vehicles are the least cost effective among these vehicles.
- A combination of relatively lower purchase price increase and higher fuel economy result in lower life cycle costs compared to the 2010 conventional SI vehicle for diesel engine-based vehicle configurations with the exception of pre-transmission parallel diesel hybrids. The SI-based vehicle configurations are anticipated to have similar life cycle cost as the conventional vehicle.

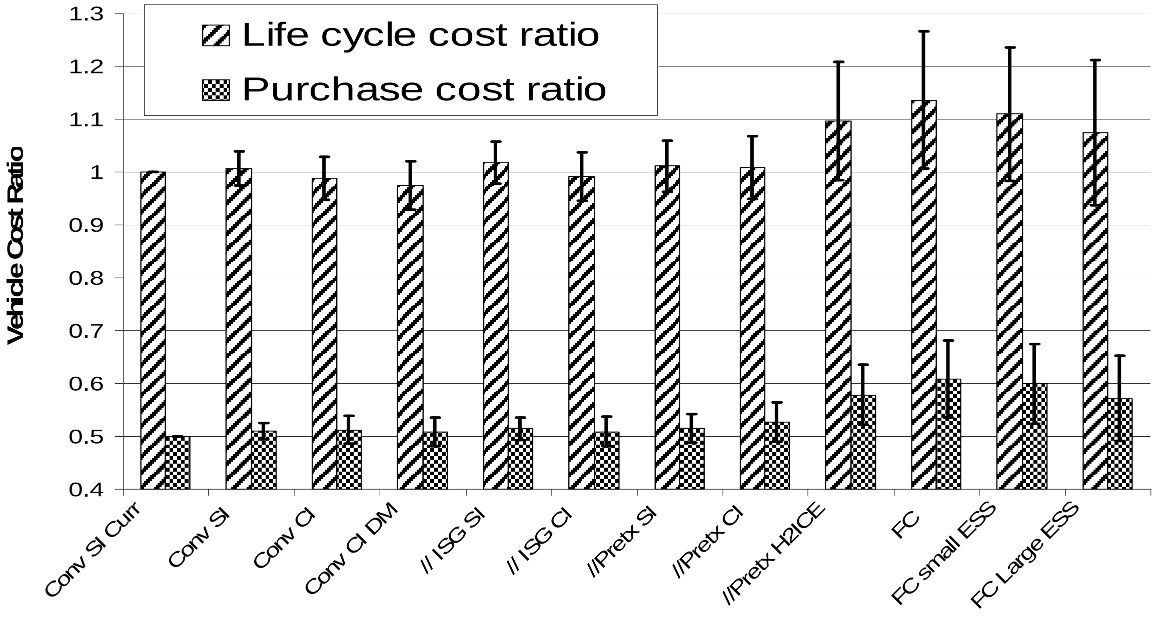

Figure 5. Vehicle Purchase and Life Cycle Cost Ratios Using U.S. Combined Drive Cycle and Fuel Price

When considering rapid technology, based on FreedomCAR goals, fuel cell hybrid vehicles achieve a lower cost ratio than the ICE hybrids. In addition, all the vehicle configurations, except the fuel cell only, have the potential to lower the life cycle cost compared to current conventional gasoline vehicles.

The life cycle cost impacts of drive cycle on both diesel and fuel cell configurations are also considered for only two foreign markets (i.e., Europe and Japan) by assuming its fuel prices as shown in Figures 6 and 7. The following observations consider the average values:

- The cost-effectiveness due to hybridization is dependant upon the drive cycle, being especially favorable in the case of slow speed and stop-and-go Japanese drive cycle, as shown in Figure 7. The life cycle cost reduction is estimated to be around 7% for a fuel cell with a large energy storage system due to the higher degree of hybridization compared to fuel cell only. Similarly, it has been shown that an increase in degree of hybridization reduces the impact of driving cycle variations on fuel cell cost-effectiveness. A higher degree of fuel cell vehicle hybridization has resulted in a less than 1% difference in life cycle cost for the NEDC and Japan10-15 drive cycles considered in Figures 6 and 7.
- The cost-effectiveness of diesel vs. fuel cell vehicle configurations in Britain and Japan can be seen in Figures 6 and 7, since the respective countries' fuel prices and drive cycles have been considered in this analysis. The life cycle cost ratio difference among various vehicle configurations in Britain is less pronounced than in Japan, with hybrid fuel cell vehicles having a slight cost advantage in the former case. Due to a low-speed drive cycle that includes long periods of zero speeds, diesel technologies appear to be the most cost-effective in Japan. For example, the pre-transmission parallel hybrid with diesel engines is estimated to provide an 11% reduction in vehicle life cycle cost in that country. Since no consideration has been made here to apply fuel taxes to hydrogen as they are applied to conventional fuels today in Japan and Europe, inclusion of taxes would cause diesel vehicles to be even more attractive.

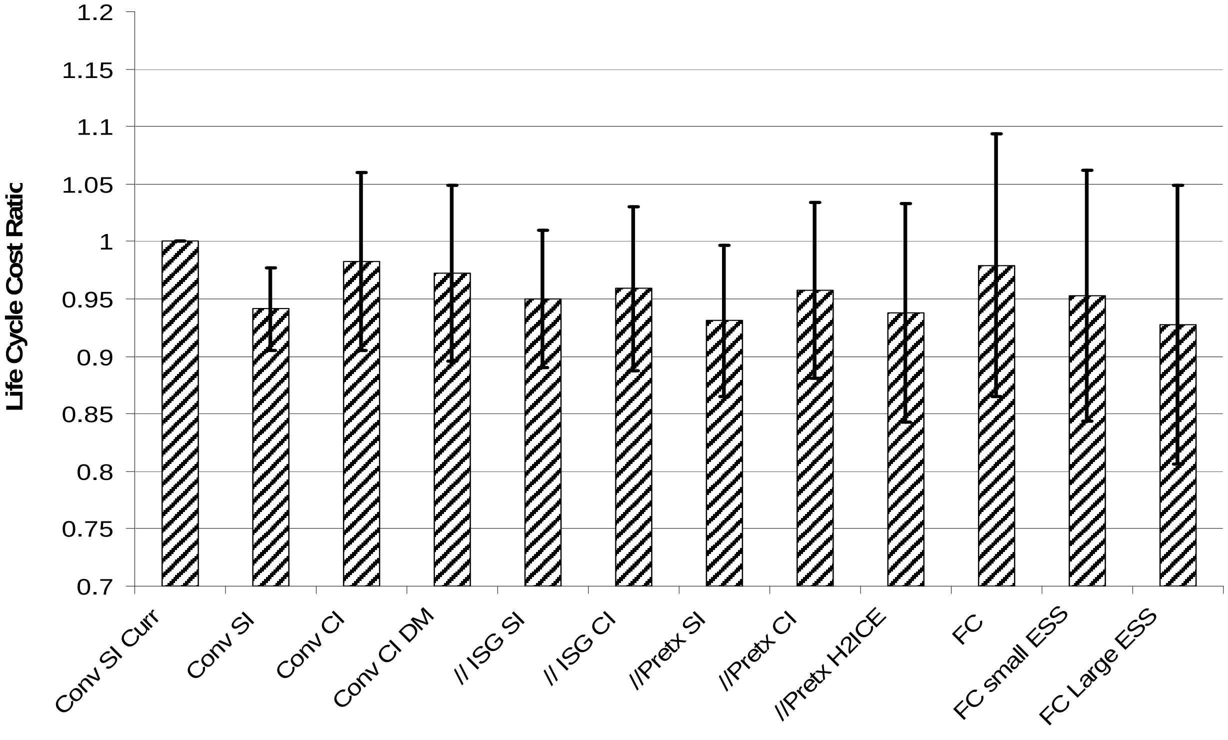

Figure 6: Vehicle Life Cycle Cost Ratios Using European Drive Cycle and Fuel Price

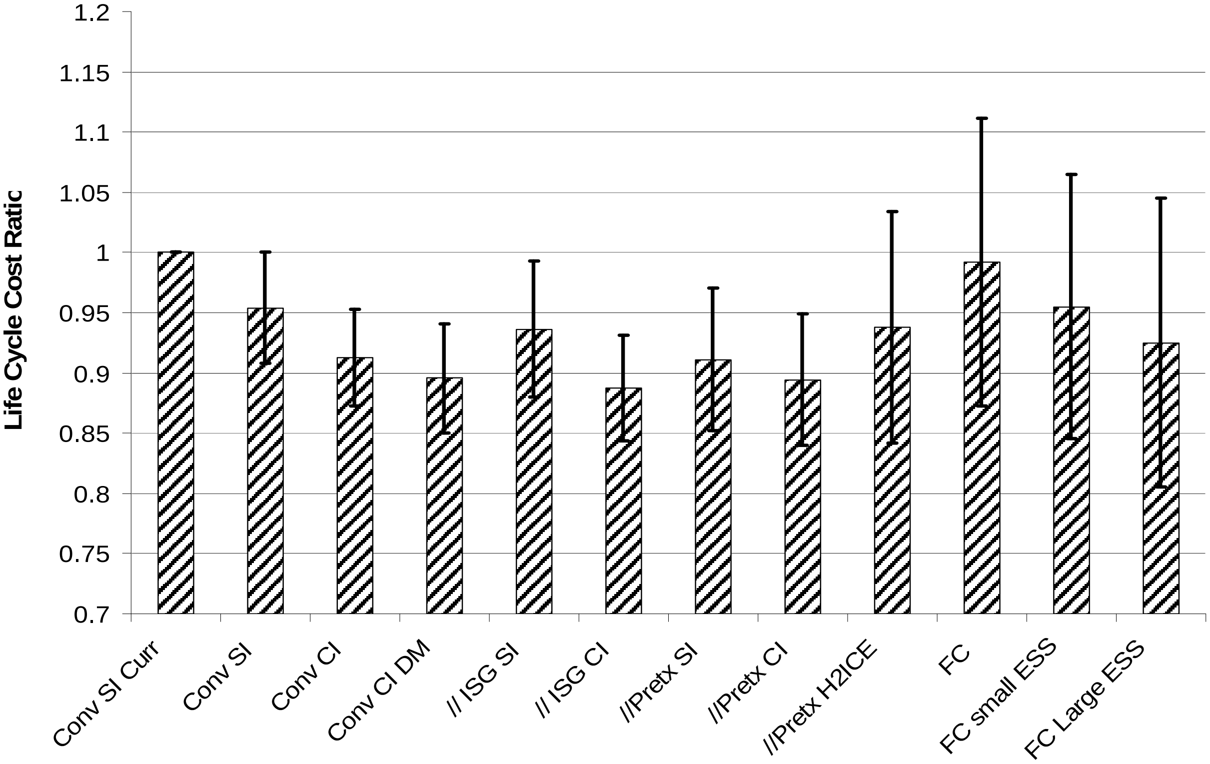

Figure 7: Vehicle Life Cycle Cost Ratios Using Japanese Drive Cycle and Fuel Price

7 Simulation Results Summary

Near-term technologies based on FreedomCAR goals have been compared and their potential has been evaluated from both fuel economy and cost perspectives, using PSAT and ASCM. For the cases examined here and the set of assumptions used, several implications can be deduced:

- Given the wide range of possible technology development outcomes covered in these future vehicle scenarios, these results have significant uncertainties associated with them as reflected in the error bars on the results charts. However, we believe the trends presented to be relatively robust although developments in individual technologies may change the relative performance of a specific vehicle configuration.
- The FreedomCAR goals support and enhance the chances of the emergence of fuel cell technology as their power density is increased and their cost is significantly decreased compared to their ICE counterparts. These goals take into account the developing nature of fuel cell technology compared to the 100-year history of ICE engine commercialization in vehicular applications.
- The goals also favor diesel compared to gasoline ICE as it was assumed that both technologies will not have significantly different costs, and diesel emissions issues will be solved.
- Fuel cell configurations with a high degree of hybridization provide higher efficiency and lower cost compared to other fuel cell configurations when Li-ion technology is used as the energy storage system independent of U.S., European, or Japanese driving cycles.
- When gasoline and diesel ICE hybrids are compared, the former vehicle configuration is cost competitive with conventional vehicles on a life cycle basis but the latter provides a lower overall life cycle cost.

- As fuel efficiency improves, the fuel price contributes to smaller share of life cycle cost and a substantial fuel economy change is required to influence the relative cost-effectiveness of all vehicle configurations.
- When considering an average technology growth, ICE hybrids appear competitive from a cost point of view compared to conventional configurations, while fuel cell vehicles remain more expensive.
- When considering the rapid technology case (based on FreedomCAR goals), fuel cell hybrid vehicles achieve a lower cost ratio than the ICE hybrids. The FreedomCAR Partnership allows fuel cells to become a viable technology to reduce U.S. foreign oil dependency by providing high fuel economy at acceptable cost.
- By focusing on the development of hydrogen-fueled future vehicle technologies, the FreedomCAR partnership is laying the technological foundation for increasing domestic energy security and establishing a viable pathway to sustainable transportation using non-petroleum fuel resources at comparable life cycle costs to future conventional vehicles.

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