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Plug-in Fuel Cell Vehicle Technology and Value Analysis

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Abstract

Plug-in Hydrogen Fuel Cell Hybrid Electric Vehicles (PFCVs) offer reduced operating and manufacturing cost when compared to conventional hydrogen fuel cell hybrid electric vehicles (FCVs), and improved range and refueling time when compared to grid charged Battery Electric Vehicles (BEVs). As such, PFCVs provide opportunity to combine the advantages and mitigate the limitations of both FCVs and EVs. Although the PFCV concept has been presented conceptually in the past, no quantitative analyses of its prospective technical, environmental and economic characteristics have been performed until recently. Motivated by the basic promise of a new high-efficiency, zero-emission vehicle, the authors have conducted an initial assessment of PFCVs in comparison with FCVs, BEVs and internal combustion engine-battery hybrid electric vehicles (PHEVs). This study was coordinated by the Electric Power Research Institute (EPRI) and supported by the California Air Resources Board (CARB) and the Southern California Air Quality Management District (SCAQMD). The study approach included the identification of representative PFCV, FCV, BEV and PHEV vehicle configurations, the modeling of these configurations, and the determination of their energy use, well-to-wheel carbon dioxide emissions, and cost characteristics. Results show that, with economies of scale, PFCVs can offer a competitive alternative to conventional PHEVs with the added benefits of being 100% petroleum independent and having zero tailpipe emissions. Within the context of PFCVs, a wide range of design freedom is possible; this study suggests that low power fuel cells and high energy batteries provide optimal benefits for environmental and cost metrics. The optimal vehicle can be described as a hydrogen fuel cell, hybrid electric, range-extending vehicle (FCEREV).

Keywords: EREV, Fuel Cell, Hydrogen, PHEV, Simulation

1 Introduction

A plug-in fuel cell vehicle is an advanced technology electric vehicle concept with promise to help achieve key environmental and energy-strategic goals. In addition to being a zero-emission vehicle, the plug-in fuel cell vehicle combines the advantages of hydrogen fuel cell vehicles with those of grid-charged Battery Electric Vehicles (BEVs). It overcomes the range limitation and long refueling time of BEVs, considered by many to be the continuing barriers to their widespread acceptance. Compared to fuel cell vehicles, the plug-in fuel cell vehicle offers the customer lower fuel costs and home refueling with electricity from the grid. PFCVs offer the benefit of increased fuel cell operating efficiency while facilitating the market acceptance of FCVs in a phase of reduced availability of hydrogen infrastructure. This ability promises to reduce the cost and increase operating life of the fuel cell system, mitigating two of the most challenging issues faced by fuel cell vehicles.

Despite these potential advantages, the plug-in fuel cell vehicle has attracted little attention, and detailed analyses of the plug-in fuel cell vehicle have not yet been published [1][2][3][4]. As a consequence, it is not clear how the attributes of plug-in fuel cell vehicles compare with those of the most promising advanced vehicle technologies. Credible answers to these questions are needed before the potential of the plug-in fuel cell vehicle as an advanced electric technology vehicle option can be assessed.

2 Background

In 2011, a first phase of analysis was conducted of the technical, environmental and cost characteristics of three representative plug-in fuel cell vehicle (PFCV) configurations and similar-sized fuel cell vehicles (FCVs), BEVs and Plug-in Hybrid Electric Vehicles (PHEVs), the currently leading advanced electric technology vehicles [4]. Six vehicles were selected in the Phase 1 study to represent a range of production and research passenger vehicles based on a sedan-sized platform (~1800kg). Coordinated by the Electric Power Research Institute on behalf of the California Air Resources Board and the California South Coast Air Quality Management District, the Phase 1 study was conducted by an international team of experts in advanced technology electric vehicle design, development, demonstration and assessment, and supported by expertise in vehicle modeling. State-of-the-art simulation techniques were used to determine and compare vehicle performance, driving range, energy consumption, operating costs, and Well-to-Wheels (WTW) carbon dioxide equivalent (CO2-eq) emissions for representative driving cycles.

The conclusions of the Phase 1 study demonstrated a set of comparisons among PFCVs, FCV, BEVs and PHEVs on the basis of environmental and economic metrics. Graphic comparisons of the seven representative vehicles' updated simulation of WTW GHG emissions (using both California and U.S. electricity mixes) as well as near- and long-term fuel costs are shown in Figure 1 and Figure 2 respectively.

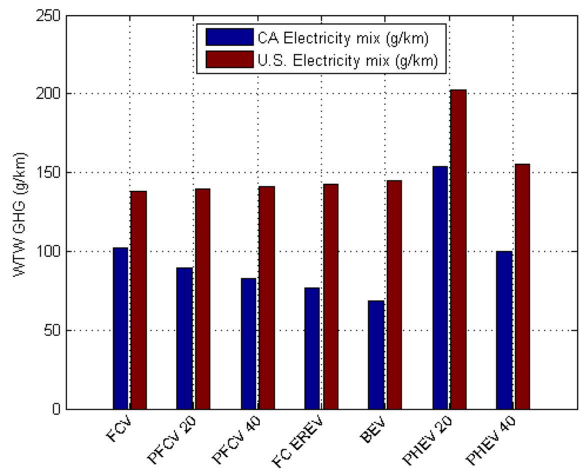

Figure 1: U.S. and California electricity mix WTW GHG emissions comparison for seven representative vehicles from Phase 1 study.

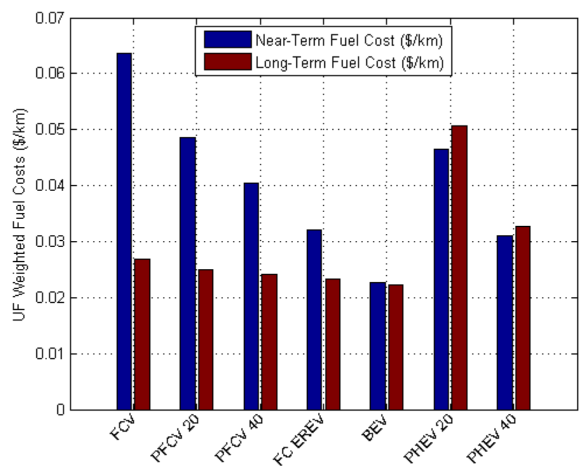

Figure 2: Near- and long-term fuel costs comparison for seven representative vehicles from Phase 1 study.

These results formed the motivation for an additional investigation of the design space encompassing PFCVs. Three goals were outlined for additional work:

- First, simulations performed for the previous results were subject to validation against expert opinion of theoretical performance. Additional analysis should provide benchmark for simulation results against production advanced technology vehicles.
- Second, these previous results show that increased battery energy (and thus increased CD range and AER) combined with fuel cells can be used to construct vehicles whose benefits increase with increased electrification. Additional analysis should define whether this trend continues by investigating a broader design space.
- Third, these previous studies were based on a set of vehicle designs defined by a committee of experts. It is unknown whether these designs are in fact representative of the performance characteristics of a particular vehicle technology (PFCV, PHEV, and BEV). Additional analysis should characterize the design space in more detail and should suggest Pareto-optimal design trends.

To expand upon the progression of vehicle designs towards increased electrification, the study presented in this paper provides additional analysis of the design space for BEVs, PHEVs, and PFCVs. The methods used for defining the vehicle architectures, models, simulations, and evaluation metrics are described in the following sections. Various results are presented to demonstrate comparative benchmark, and a characterization of the design space with increased breadth and detail. Discussion and conclusions focus on the ramifications of this work for further study of the characteristics of PFCVs.

3 Methods

Vehicle models and simulations have been developed to represent state-of-the-art hybrid architectures. The methods of formulating a design of experiments (DOE), determining vehicle components, simulation, and results analysis are outlined in the following sections.

3.1 Vehicle Models and Control

Two literature-based mathematical vehicle models were developed in Matlab/Simulink for this study; a plug-in hybrid electric vehicle with a conventional internal combustion engine, and a hydrogen fuel cell plug-in hybrid electric vehicle; the BEV model is based on the PFCV model with the hydrogen system removed. Each model was constructed with state-of-the-art quasi-static engine maps, motor maps, fuel cell polarization curves, and battery maps. Vehicle mass is calculated by summing the masses of vehicle components.

3.2 Conventional Plug-in Hybrid Electric Vehicle Model

The gasoline PHEV model is simulated to represent current and near-future technology PHEVs. The PHEV architecture and control strategy are described below.

3.2.1 Architecture

The PHEV was modeled with a post-transmission parallel architecture. The spark ignition direct injection engine map has a peak efficiency of 31%, idles at 1000rpm and reaches redline at 7000rpm. The torque of the engine is scaled to meet the desired engine power and the engine mass is scaled linearly with power. The batteries are 3.6V nominal lithium-ion cells with 100 cells in series. Internal resistance is scaled to match battery power and capacity is scaled to match the desired energy. The mass of the pack is calculated as a function of both the specific power and specific energy. The permanent magnet electric motor model has a base speed of 3000rpm, a maximum speed of 8000rpm and a max efficiency of 92%. The torque of the motor is scaled to match the desired motor power, and the mass is scaled linearly with power. The Continuously Variable Transmission (CVT) is modeled as a controllable variable gear ratio with a constant efficiency of 90%; the limits of the CVT are designed around the vehicle's maximum speed and the speed at which the engine can turn on (5mph). The final drive gear ratio is sized so that both the engine and electric motor reach their maximum operating speed at the vehicle's maximum speed of 85mph. The engine is clutched out and turned off at speeds below 5mph.

3.2.2 PHEV Supervisory Control Strategy

The PHEV is controlled using a charge depleting/charge sustaining strategy, and the engine is controlled on an ideal opperating line. The torque demand is baised to the electric motor so that the vehicle responds quickly to changes in driver demands and utelizes primarily electric power. The engine can be turned on through two mechanisms; 1) a power request that occures when the electric motor isn't capable of meeting the power demand, or 2) an energy request which occures when the battery state of charge must be maintained. When the engine is on, its demand is calculated by summing vehicle power demand and the battery SOC correction factor demand.

3.3 Plug-in Hydrogen Fuel Cell Hybrid Electric Vehicle Model

The hydrogen PFCV model incorporates a Polymer Electrolyte Membrane (PEM) fuel cell with electric vehicle components to simulate zero-emissions vehicles.

3.3.1 Architecture

The hydrogen fuel cell PHEV model differs from the ICE parallel vehicle models because it is purely an electric drive vehicle. This model utilizes the same motor and battery presented in the previous section, with identical scaling. The fuel cell is modeled through a static system polarization curve with a maximum efficiency of 60% at 0.1A/cm^2 and maximum power at 0.7A/cm^2 [5]. The DC/DC converter is modeled with an efficiency of 90%.
The Battery Electric Vehicle (BEV) model is based on the PFCV model for this study. In the BEV, the fuel cell and DC/DC converter are removed from the PFCV system, allowing for battery-only operation.

3.3.2 PFCV Supervisory Control Strategy

The supervisory control strategy for the PFCV is similar to that of the PHEV with the exception of the fuel cell control. The fuel cell can be turned on through two mechanisms: 1) a power request which occures when the battery isn't capable of meeting the power demand, or 2) an energy request which occures when the battery state of charge must be increased. When the fuel cell is on, its power demand is calculated by summing vehicle power demand and the battery SOC correction factor demand.

3.4 Drive Cycles

The vehicle models were simulated on a combination of drive cycles which include the Supplemental FTP (US06 divided into city and highway segments), Urban Dynamometer Driving Schedule (FU505), and Highway Fuel Economy Driving Schedule (HWFET). The data from each simulated cycle is weighted and used to determine the fuel and energy consumption, performance, range, etc. The weight of each cycle is as follows; 14.1% US06 City, 28.8% FU505, 44.5% US06 Highway, and 12.5% HWFET. This combination of drive cycles is chosen to be more representative of U.S. driver behavior than the EPA's city/highway drive schedule and is therefore a better metric on which to evaluate vehicle designs.

3.5 Design Space Investigated

A full-factorial design of experiments was performed on the PHEV, PFCV and BEV design spaces. Vehicle designs are characterized by three design variables for this study: total vehicle power (kW), battery energy capacity (kWh), and degree of hybridization. For a parallel architecture vehicle, like the modeled PHEVs, the total tractive power is the sum of the electrical and mechanical drivetrain powers. For electric drive vehicles, like the PFCV model, the total tractive power is the electric motor power rating. The degree of hybridization is defined in Equation 1. With this definition, a vehicle with DOH of one represents an electric vehicle while a DOH of zero represents a conventional vehicle. Finally, the batteries are sized so that they are capable of sourcing the electric motor's peak power draw. With these three design variables and sizing rules all drivetrain component sizes are defined. Table 1 shows the ranges over which each of these design variables were varied in the design of experiments.

$$DOH = \frac{Power_{Total} - Power_{Fuel\ Converter}}{Power_{Total}} \quad (1)$$

Table 1: Ranges of design variables investigated for each of the vehicle architectures simulated.

	PFCVs	BEVs	PHEVs
Battery Energy (kWh)	5-30	15-45	5-30
Degree of Hybridization	0.2-0.9	1.0	0.2-0.9
Vehicle Power (kW)	80-180	80-180	80-180

3.6 Analysis Metrics

The selected analysis metrics allow for inclusion of economic, environmental, and consumer acceptability assessment, they include fueling cost, WTW greenhouse gas emissions and performance.

Analysis metrics use best current practices for vehicle comparison studies [4][6] and for well-to-wheel CO_2 emissions calculations [7][8]. The analysis metrics used in this paper are based on low fidelity models that will be refined in future studies. Future work will include detailed analysis of a broader set of analysis metrics including infrastructure investment and projected manufacturing costs as well as detailed analysis of WTW energy use and emissions.

3.6.1 Fueling Costs

Consumer fueling cost is calculated on a utility factor weighted fuel use basis. Near-term (2012) and long-term (2020) electricity and gasoline prices are estimated from the 2012 Annual Energy Outlook [9]. Hydrogen near-term and long-term costs are estimated from DOE targets [10]. Electricity costs are determined from residential rates, assuming that a majority of charging will occur at a vehicle owner's home. The long term scenario assumes that the costs of gasoline, electricity and hydrogen evolve in different ways over a period of approximately 10 years: gasoline prices increase under the impact of resource competition; electricity prices remain relatively stable due to embedded capacity and the continued availability of off-peak power for battery charging; and costs of hydrogen production and transportation decline with economies of scale.

Table 2: fueling cost analysis conversion metrics

	Gasoline ($/kWh)	Electricity ($/kWh)	Hydrogen ($/kWh)
Near-term (2012)	0.093	0.113	0.266
Long-term (2020)	0.107	0.111	0.089

3.6.2 WTW GHG Emissions

GREET was used to estimate upstream Greenhouse Gas (GHG) emissions from each fuel source. Both United States (U.S.) and California (CA) electricity mixes are used [11]. CA electricity has lower upstream GHG content due to its large fraction of renewables and nuclear power. The CA electricity mix is estimated to be more representative of future generation emissions across the world as increased amounts of renewable energy are utilized. Hydrogen upstream GHG emissions assume 100% natural gas (NG) reformed hydrogen as NG is expected to be the feedstock for hydrogen production in the foreseeable future. Downstream GHGs are calculated from the carbon content of the fuel.

Table 3: GHG emissions analysis conversion metrics

	Gasoline (g/kWh)	Electricity (g/kWh)	Hydrogen (g/kWh)
PTW GHGs	261.0	0.0	0.0
WTP CA GHGs	60.2	343.0	369.1
WTP U.S. GHGs	64.3	721.4	402.1

3.6.3 Performance (Power to Weight Ratio)

Performance of each vehicle is approximated using a power to weight ratio (P/W). Vehicles with high P/W will have high performance while low performance vehicles have a low P/W ratio.

4 Results

Simulation of each vehicle within the design space, across architectures, yields data that has been analyzed to determine optimal vehicle design. Simulation results are intended to provide benchmarking to state-of-the-art production vehicles, increase the breadth of the investigated design space, and identify trends within the design space to locate optimal designs. Simulation results are intended to present technology and value assessments across the simulated design space as well as in comparison with current production and previously investigated vehicles.

4.1 Vehicle Benchmarking

The intention of vehicle benchmarking is to show that each simulated technology performs within an acceptable error of existing production vehicles and therefore provide confidence in trends and tradeoffs identified in the results of this study. As such, the benchmark simulations do not represent the exact architecture and control of the selected benchmark vehicles. The benchmark vehicles are simulated using manufacturer component specifications applied to the models described in this study. The benchmarking vehicles are: GM Chevrolet Volt (PHEV), Nissan Leaf (BEV), and Honda FCX Clarity (FCV). Benchmark vehicle performance values have been obtained from certified EPA testing data.

Comparison of simulated and tested vehicle performance shows that simulated vehicles operate within 10% of commercially available vehicles on the basis of charge-depleting fuel economy, charge-sustaining fuel economy, and charge-depleting range. Figure 3 shows the benchmarking result. The results show near-equivalent error across fuels, providing a fair comparison of vehicle technologies.

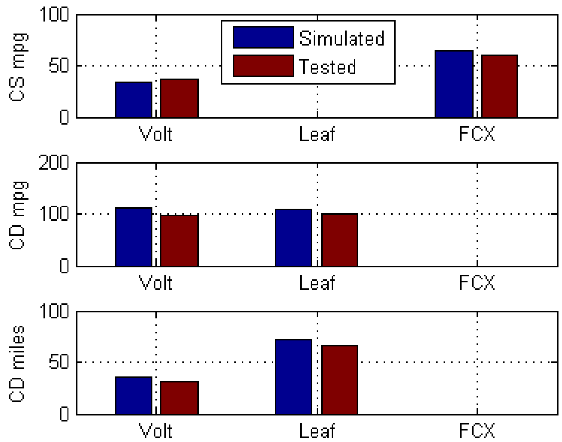

Figure 3: Benchmarking of simulations against commercially available vehicles

4.2 Increased Breadth of Design Space

The design variables investigated in this study cover a wide range of vehicle designs. Figure 4 shows all vehicle designs investigated, across architectures, along with the seven representative vehicles from the Phase 1 study. It can be observed in Figure 4 that the design space explored for this study greatly expands the breadth and detail of the design space simulated over the Phase 1 study.

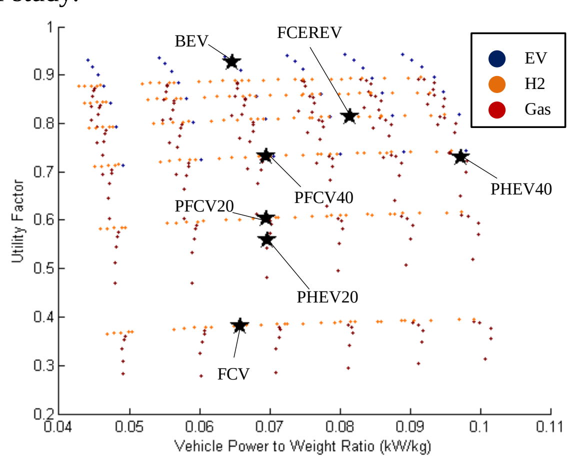

Figure 4: Vehicle design space power to weight ratio vs. utility factor.

Figure 5 and Figure 6 show "worst case" and "best case" vehicle design space evaluations respectively. U.S. WTW GHG emissions and near-term costs are considered a worst case for PFCVs due to high hydrogen costs and relatively dirty electricity generation. CA WTW GHG emissions and long-term costs are more favorable for PFCV designs as CA offers more renewable energy sources (likely representative of future electricity generation) and are designated "best case".

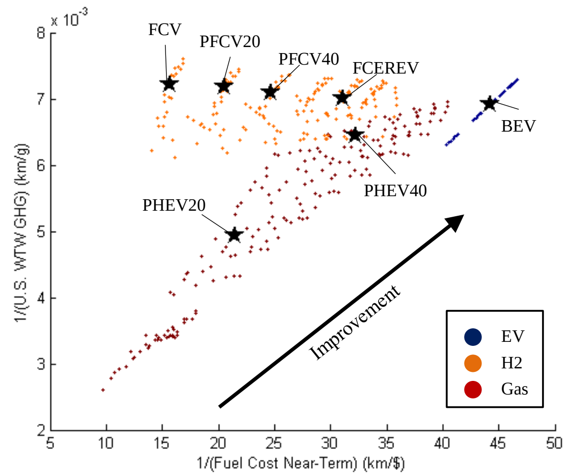

Figure 5: Vehicle designs near term fuel costs vs. U.S. electricity mix WTW GHGs, "worst case" scenario.

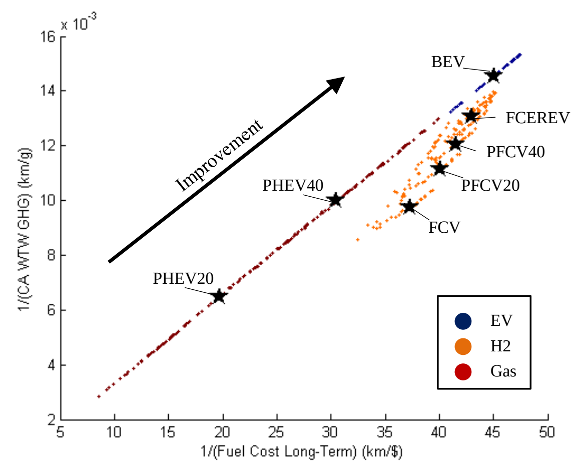

Figure 6: Vehicle designs long term fuel costs vs. CA electricity mix WTW GHGs, "best case" scenario.

For each of the scenarios, it can be observed that BEVs minimize both fueling costs and WTW GHG emissions. Additionally, improved vehicle designs are available beyond the seven architectures investigated from the Phase 1 study.

The existence of improved vehicle designs beyond the Phase 1 investigated vehicles suggests that further investigation of the design space should be performed to correctly characterize the potential of each vehicle technology.

5 Increased Vehicle Design Detail

Analysis of the simulated design space leads towards interest in the optimal vehicles represented. For each of the three vehicle design variables (and for each of the three vehicle architectures) Pareto optimal designs at each increment are determined based on the two analysis metrics (WTW GHGs and fueling costs). Pareto optimal design fronts represent the non-dominated edge of the design space for the two analysis metrics, and can provide design tradeoff transparency to assist in vehicle design decision making.

5.1 Vehicle Characteristics for Reducing WTW GHG Emissions

As mentioned, U.S. and CA electricity mix metrics are used in this study to compare different electricity generation scenarios. Figure 7, Figure 8, and Figure 9 show the WTW GHG emission based Pareto-optimal vehicle designs evaluated against DOH, vehicle power, and battery energy capacity respectively. For the CA scenario, BEVs offer the lowest WTW GHG emissions across all design variables. PFCVs offer slight improvements over BEVs and PHEVs for some U.S. WTW GHG based vehicle designs as hydrogen is leveraged by CO_2 intensive electricity generation. Increased use of hydrogen is preferable over electricity for low DOH and low energy capacity PFCVs. Figure 7, Figure 8, and Figure 9 show Pareto-optimal PFCVs as having lower emissions than Pareto-optimal gasoline PHEVs across all design variable ranges.

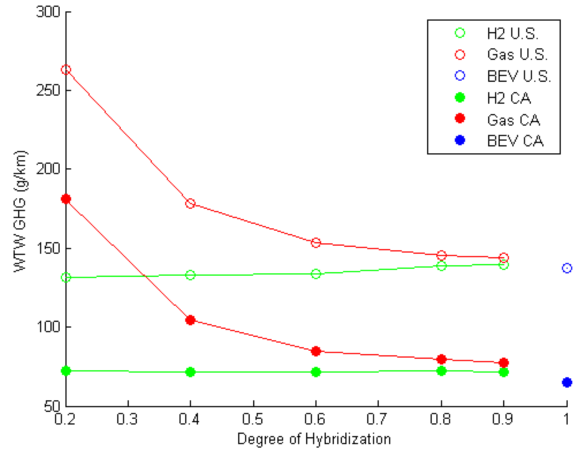

Figure 7: Pareto-optimal vehicles for U.S. and CA GHG emissions, by degree of hybridization.

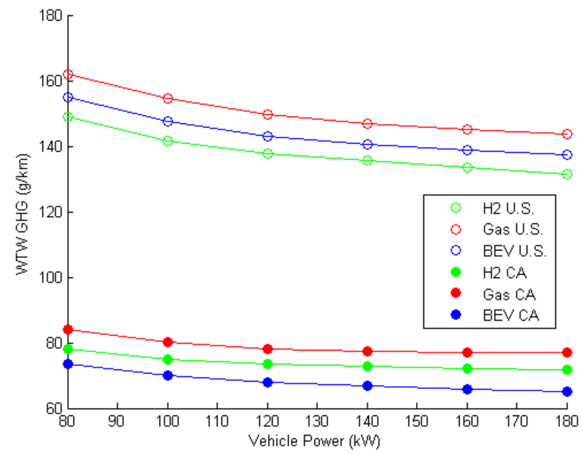

Figure 8: Pareto-optimal vehicles for U.S. and CA GHG emissions, by total vehicle power.

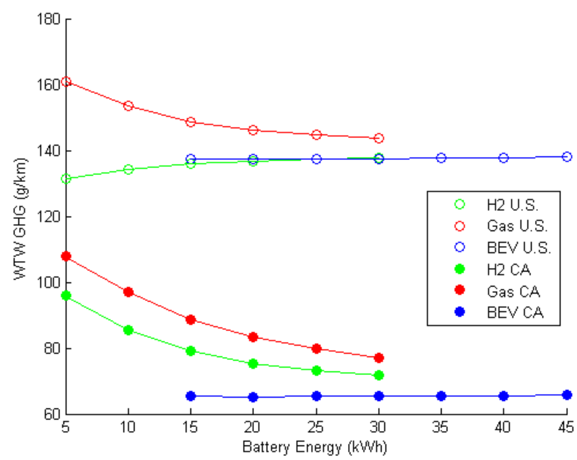

Figure 9: Pareto-optimal vehicles for U.S. and CA GHG emissions, by battery energy storage capacity.

5.2 Vehicle Characteristics for Reducing Consumer Fueling Costs

Fueling cost scenarios for 2012 (near term) and 2020 (long term) have been used to evaluate the costs that consumers would incur on a per-kilometer basis assuming driving patterns similar to the four cycles listed in Section 3. Near-term and long-term Pareto optimal vehicle designs are shown in Figure 10, Figure 11, and Figure 12 for each of the three fuels investigated. BEV's show the lowest fueling costs for all of the observed cases, followed by long term PFCVs and then near and long term PHEVs. PFCVs have the highest near-term fueling cost per kilometer due to high hydrogen costs in 2012. Fueling costs converge towards the fueling costs of BEVs as electrification increases.

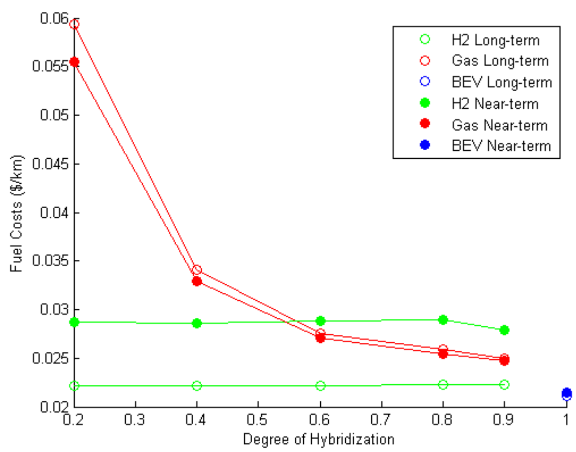

Figure 10: Pareto-optimal vehicles for near term and long term fuel costs, by degree of hybridization.

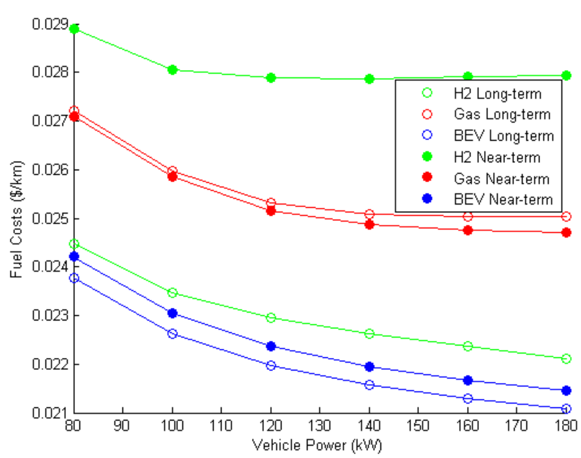

Figure 11: Pareto-optimal vehicles for near term and long term fuel costs, by total vehicle power.

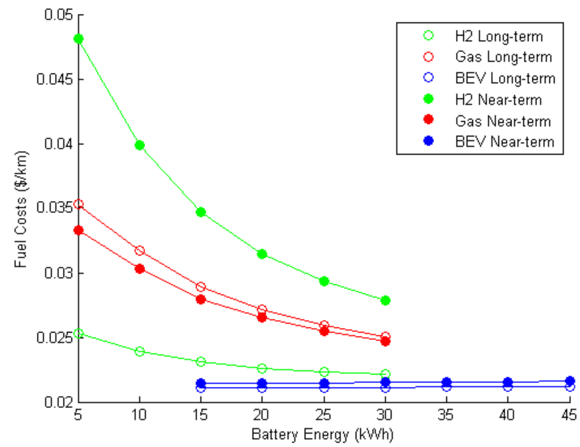

Figure 12: Pareto-optimal vehicles for near term and long term fuel costs, by battery energy storage capacity.

6 Discussion

The results of the design space exploration for PFCVs, BEVs, and PHEVs show the strengths of increased electrification with regard to WTW GHG emissions and fueling costs in all scenarios simulated. Investigation of Pareto-optimal vehicle designs reveals that all exhibit high power to weight ratios; suggesting desirable driving responsiveness. Although BEVs show the lowest emissions and fueling costs for a majority of the observed vehicle designs, they suffer from reduced total driving range and long refueling times when compared to PFCVs and PHEVs. The leading vehicle design for each fuel type is displayed in Table 4.

Table 4: Leading BEV, FC-EREV, and ICE-PHEV design comparison.

	BEV	FC-EREV	ICE-EREV
Battery Energy (kWh)	20	30	30
Degree of Hybridization	1.0	0.9	0.9
Vehicle Power (kW)	140	180	180
Near-term fuel cost ($/km)	0.0219	0.0279	0.0247
Long-term fuel cost ($/km)	0.0215	0.0222	0.0250
U.S. WTW GHG (g/km)	140.45	139.44	143.71
CA WTW GHG (g/km)	66.77	71.66	77.09

For the leading vehicles, the BEV shows the most desirable performance. The PFCV and PHEV offer tradeoffs in costs, with the PFCV offering lower emissions. Both the leading PFCV and PHEV designs are characterized by high degrees of hybridization (0.9) and large battery capacity (30kWh), demonstrating that the most desirable PFCVs and PHEVs can be characterized as EREVs.

PFCVs show potential to offer low WTW GHG emissions, low refueling costs, and comparable dynamic performance in comparison with optimal BEV and PHEV designs. The benefit of PFCVs over comparable performance BEVs or PHEVs is an increased renewable energy use potential without sacrificing total driving range, performance, or refueling times. These results are consistent with conclusions from the Phase 1 study.

7 Conclusions

This paper has provided increased breadth and detail for three vehicle architecture design spaces. Analysis of the technology-specific design trends concludes:

- Vehicle benchmark simulations have provided proof of prevalent and accurate technology representations that are closely matched with production vehicle tested performance.
- Additional vehicle designs beyond those observed in the Phase 1 study can offer increased benefits, dominantly when applying increased electrification.
- Diminishing returns on WTW GHG reduction and fueling costs exist at very high battery energy capacity vehicles, particularly above 30kWh. This trend suggests the correct breadth of the design space was investigated.
- In the near term, PFCVs can be expected to cost substantially less to operate than FCVs.
- Over the longer term hydrogen and gasoline prices are expected to converge, allowing highly efficient hydrogen use in fuel cells to offer reduced consumer fueling costs.
- When charged with "low-CO_2" electricity, mid-size PFCVs cause substantially lower well-to-wheel greenhouse gas emissions than FCVs, with EVs, FC-EREVs and ICE-EREVs producing the lowest emissions.

Taken together these conclusions indicate that PFCVs could increase the acceptance and accelerate the introduction of fuel cell-powered vehicles. PFCVs promise lower operating costs and reduced well-to-wheels releases of CO_2. PFCVs also offer potential for increasing the penetration of electricity in transportation in the longer term because they overcome the limited driving range and long recharge times of EVs with little increase in operating costs.

To increase confidence in the fundamental promise of PFCVs the authors and EPRI have proposed a substantially more detailed study to fully explore the attributes and value of PFCVs in comparison with other leading advanced-technology electrified vehicle technologies, and for the more likely scenarios for future transportation energies and environmental constraints. This EVS26 paper includes the most up-to-date results from this ongoing work on PFCVs.

8 Acknowledgements

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