

A Comparative Assessment of Electric Propulsion Systems in the 2030 US Light-Duty Vehicle Fleet

Matthew A. Kromer and John B. Heywood

Massachusetts Institute of Technology

Copyright © 2008 SAE International

ABSTRACT

This paper quantifies the potential of electric propulsion systems to reduce petroleum use and greenhouse gas (GHG) emissions in the 2030 U.S. light-duty vehicle fleet. The propulsion systems under consideration include gasoline hybrid-electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs), fuel-cell hybrid vehicles (FCVs), and battery-electric vehicles (BEVs).

The performance and cost of key enabling technologies were extrapolated over a 25-30 year time horizon. These results were integrated with software simulations to model vehicle performance and tank-to-wheel energy consumption. Well-to-wheel energy and GHG emissions of future vehicle technologies were estimated by integrating the vehicle technology evaluation with assessments of different fuel pathways.

The results show that, if vehicle size and performance remain constant at present-day levels, these electric propulsion systems can reduce or eliminate the transport sector's reliance on petroleum. However, continued reliance on fossil-fuels without effective carbon capture and sequestration for producing electricity and hydrogen constrain the GHG emission and energy reductions to about 60% below that of present-day spark-ignition technology.

INTRODUCTION

Electric and hybrid-electric propulsion systems have the potential to help manage impending environmental and energy challenges in the transport sector. This opportunity arises both because they offer highly efficient on-road operation and, depending on the vehicle technology in question, because they enable the transportation sector to shift to fuels that can be produced from domestic, non-GHG emitting sources.

The rising interest in developing electric powertrains is not merely a function of negative externalities. In parallel with these increasing external pressures, electric powertrains have made significant strides towards competing with conventional technology on their own merits. For example, over the last decade, both battery

and fuel-cell technology have simultaneously improved performance while decreasing cost. At the same time, even with continued developed, new propulsion systems may not offer the same low-cost or utility as conventional vehicles for decades.

The research presented in this paper informs this discussion by quantifying the energy, petroleum, and greenhouse-gas reduction benefits of several proposed propulsion systems in the context of the 2030 US light-duty vehicle fleet. In addition, other discriminators, such as vehicle cost, technological risk, and performance, are evaluated. Previous work [1] quantified these characteristics for a series of "conventional" automotive technologies that are currently on the road: a naturally-aspirated spark-ignition engine using gasoline (NA-SI); a turbo-charged spark-ignition engine (Turbo SI); a compression-ignition engine using diesel fuel (Diesel); and a gasoline hybrid-electric vehicle (HEV).

This paper extends the analysis to several more forward-looking technologies: a plug-in gasoline hybrid-electric vehicle (PHEV); a fuel-cell hybrid-electric vehicle running on pure hydrogen (FCV); and a battery-electric vehicle (BEV). In addition, the previous analysis of the hybrid vehicle is revisited and extended to include cost estimates and maintain consistency with the new evaluation. These results are integrated with the results of the previous study to present a unified assessment of 2030 vehicle technology.

Several propulsion system technologies were omitted from this evaluation because an initial review of the costs, benefits, and technical challenges indicated that they did not offer a high enough value proposition for a mass-market in the US context over an extended time horizon. These technologies include a fuel-cell vehicle using an onboard reformer and an internal combustion engine running on compressed natural gas (CNG), and a diesel hybrid-electric vehicle (discussed further below).

While different transportation fuels are analyzed in the context of new propulsion systems, it should be noted that this paper focuses primarily on propulsion systems, not fuels. As such, bio-fuels such as ethanol or bio-diesel are not included in the analysis.

METHODOLOGY

The full lifecycle greenhouse gas (GHG) emissions and energy use, which characterizes the energy and emissions associated with fuel use over the vehicle lifetime, were characterized for each propulsion system in three stages:

- 1. The “well-to-tank” energy, which accounts for the energy used in refining and transporting fuel from the primary source to the vehicle tank, were calculated using DOE-EIA [2] and ANL-GREET [3] projections.
- 2. The “tank-to-wheel” (or in-use) energy and petroleum use of different propulsion systems were calculated using ADVISOR software simulations of proposed 2030 vehicles operating over standard EPA drive cycles (see the Definitions section for details on specific drive cycles).
- 3. The “cradle-to-grave” energy and GHG emissions – those impacts associated with manufacturing and recycling vehicles – are not a focus of this study. However, previously published estimates [4] are included in the total lifecycle results.

A 2006 2.5L Toyota Camry was used as the basis for the future propulsion systems. The Camry was chosen as a “typical” passenger car because it represented the best-selling vehicle during the model year in question. In addition, its performance and weight are close to the US car fleet average.

For consistency across vehicle platforms, vehicle performance and size were held constant at present-day levels. In this context, “performance” is defined in terms of both 0-60 MPH acceleration times and the vehicle’s ability to meet the US06 drive cycle, which represents an aggressive driving pattern. Vehicle size was defined in terms of vehicle frontal area.

Holding these parameters constant is at odds with historical trends, which have yielded a steady increase in both vehicle size and performance over the last 25 years. However, keeping these characteristics at present-day levels allows us to quantify the efficiency gains enabled by technological progress using conventional technologies. These gains are obtained without sacrificing the size and performance attributes that are important to consumers.

The future (2030) vehicles include a number of evolutionary, non-powertrain improvements which are applied consistently across different vehicle technologies. These include improved aerodynamics, reduced rolling resistances, and some weight reduction. The logic behind these improvements is detailed in [1].

A detailed breakdown of vehicle and vehicle component assumptions is available in Table 11 and Table 12 in the appendix; further details and discussion of these assumptions are available in [5].

VEHICLE TECHNOLOGY PROJECTIONS

ENGINE & MOTOR ASSUMPTIONS - The engine operating maps for future vehicles are based on those developed in [1], scaled to meet vehicle performance constraints. Electric motor specifications are configured to meet DOE efficiency and weight targets [6], and are also scaled to meet performance constraints and maximize vehicle efficiency.

BATTERY ASSUMPTIONS – Battery characteristics are based on extrapolated versions of present-day lithium-ion batteries, scaled to meet weight and performance projections based on an evaluation of lithium-ion technology. To date, automakers have been hesitant to introduce lithium-ion batteries for automotive applications due to concerns over their safety and longevity. As a result, nickel-metal hydride (NiMH) batteries currently dominate the hybrid vehicle market. At the same time, lithium-ion batteries offer a significant weight reduction and better scale economies than NiMH (which could lead to lower costs); they also promise greater opportunity for continuing improvements into the future [7,8].

Over the time horizon in question, it is assumed that the safety and durability issues with lithium-ion chemistries will be addressed: these improvements may be achieved through some combination of more stable materials, such as future incarnations of LiFePO₄ or LiMn₂O₄ chemistries currently under development; oversized battery packs; and external control circuitry [9, 10, 11].

Battery Energy and Rate Performance – Although specific electrode and electrolyte materials are not postulated for the future battery system, the system is based on manufacturer data for the Saft VLE module, which uses a Li[Co₂Ni₈]O₂ cathode and graphite anode [12]. The future model includes several adjustments to the present-day performance characteristics: first, the future battery was assumed to maintain its rate capability at high depth-of-discharge – a development that is consistent with recent advances in phosphate-based chemistries [13].

Table 1: Battery Weight as a function of electric range and specific energy.

Range (Miles)	Specific Energy (Wh/kg)				Battery Weight (kg)
	100	120	150	225	
0 (HEV)	10	8	7	4	
10	32	27	21	14	
30	82	68	55	36	
60	165	138	110	73	
200	480	400	320	213	

Second, the future models include evolutionary improvements in battery specific power and specific energy. It is assumed that specific energy improves by a factor of 1.5 over present day lithium-ion battery packs –

a rate of about 2% per year – for both high-power and high-energy batteries. It should also be noted that, in absolute terms, battery weight is a relatively minor factor for all of the vehicle technologies except the battery-electric vehicle (Table 1).

While the specific energy and specific power of lithium-ion batteries is likely to improve, this rate of improvement is unlikely to continue along historical trajectories of 5-7% per year (Figure 1).

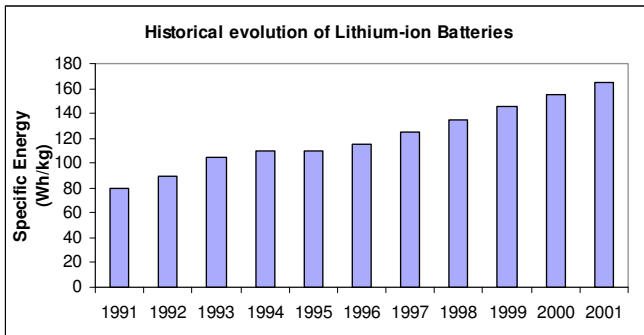


Figure 1: Improvement in lithium-ion battery specific energy

This assumption reflects two important realities:

1. Fundamental constraints on lithium-ion chemistry limit improvements in an absolute sense. In this light, 300 Wh/kg has been cited as a plausible upper-bound on high-energy lithium-ion batteries over a two-decade time horizon [14]; this represents roughly a doubling of the capacity of present-day cells.
2. As discussed above, development in the automotive context will focus primarily on demonstrating improved safety and durability, which is likely to entail some sacrifice in terms of energy capacity.

Specific battery characteristics were defined for each vehicle configuration to reflect the tradeoff between battery energy and rate capability. These characteristics are based on the power-to-energy ratio needed to meet vehicle performance, range, and regenerative braking requirements. In addition, the battery duty cycle (quantified as the state-of-charge envelope in which the vehicle operates) was tailored to reflect the frequency of a typical discharge cycle.

The current state-of-art and projected evolution of battery energy (measured over a 3-hour discharge, or C/3 rate) and peak power is shown in Figure 2. The current battery technology was characterized from company literature for a typical high-energy lithium-ion battery (the Saft VL45E cell [12]); a high-power lithium-ion battery (the A123 ANR26650 cell [15]); and the high-power NiMH battery pack used in the Toyota Prius. The specific energy and specific power of the battery pack is assumed to be 25% lower than that of an individual cell.

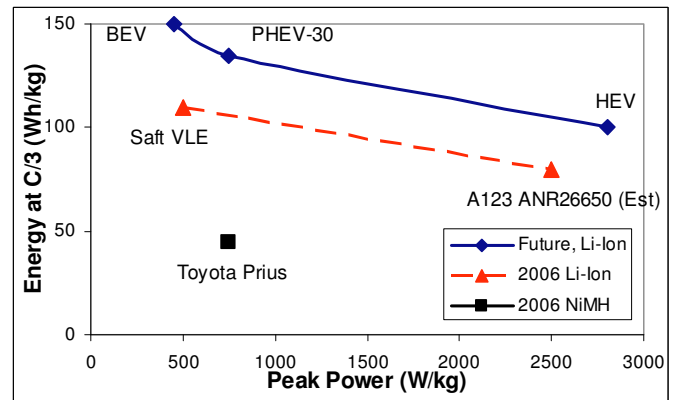


Figure 2: Battery Specific Power & Energy

Battery Costs – Battery cost is a function of both the battery energy content and its rate capability. Rate capability may be expressed as a ratio of battery power to battery energy. Hence, the battery cost may be expressed as follows:

$$\text{Battery Cost} = (\text{Cost}_{\text{High Energy}}) \times f(\text{Power-to-Energy Ratio})$$

Where $\text{Cost}_{\text{High Energy}}$ represents a base cost for a high-energy battery (a power-to-energy ratio of 2:1 – similar to that used in a full battery-electric vehicle), and $f(\text{Power-to-Energy Ratio})$ is a scale factor that is a function of the battery power-to-energy ratio.

Hence, projecting future battery costs, there are two important trends to account for: advances which lower the base cost of high-energy batteries, and advances which lower the cost of high-power relative to high-energy units.

The high-energy cost term is assumed to undergo incremental reduction which loosely tracks the improvements in battery specific energy, but also reflects an expectation that cheaper active materials and packaging will be developed. Consistent with [16], the following assumptions were used: 1.) Material costs for the high-energy battery were assumed to decrease at a rate of 2.5% per year (over 20 years); 2.) Manufacturing costs and margin remain unchanged from present-day values; 3.) Present-day high-energy battery is assumed to cost \$300/kWh; and 4.) Materials costs constitute roughly one-half of this total. These assumptions yield a specific cost \$250/kWh. However, because these cost projections are highly speculative, an optimistic case was developed in which the high-energy battery cost is assumed to go to \$200/kWh.

The power-to-energy scale factor is assumed to decrease significantly from present-day values due to improved cell engineering and materials advances. Hence, whereas present-day high-power lithium-ion batteries incur a factor of 4.5 to 5 cost penalty compared to high-energy batteries with an equivalent energy content [17], the future high-power battery uses a factor of 3 cost penalty.

The estimated battery costs as a function of power-to-energy ratio is shown in Figure 3; the present-day curve is based on the estimates from Ford Motor Company of power-to-energy ratio cost multiplier [17], and the \$300/kWh base cost from [16]. A complete summary of battery characteristics in tabular form for different vehicle configurations is included in Table 12.

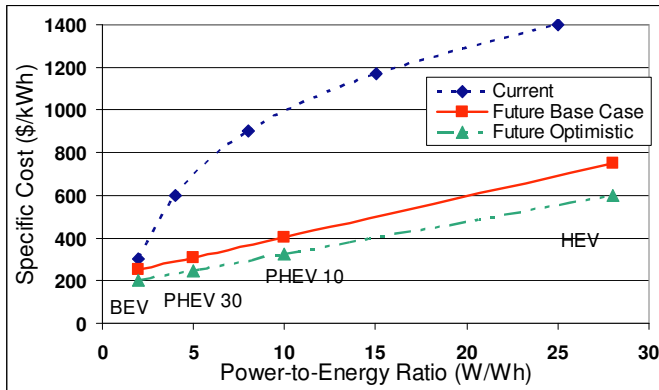


Figure 3: Estimated battery specific cost as a function of rate capability.

HYBRID-ELECTRIC VEHICLE (HEV) ASSUMPTIONS – The hybrid vehicle simulations and costs are based on a vehicle that employs a single-motor parallel hybrid architecture. The hybrid system (including battery, motor, and controller) was sized to be powerful enough to capture most of the vehicle’s regenerative braking requirement under “typical” driving conditions. In practical terms, sensitivity analysis of the HWFET, FTP, and US06 drive cycles showed that a hybridization ratio¹ of 25% was necessary and sufficient to meet this requirement.

Projecting forward, viable improvement paths for the hybrid vehicle include both evolutionary improvements in vehicle components, such as improved efficiency or lighter weight; and improved vehicle design and integration, which can improve regenerative braking capability and further optimize engine operation.

The future vehicle model incorporates elements of each of these improvement pathways. In particular, an important benefit of hybridization that, to date, has been only partially exploited, is the ability to actively optimize engine operating points by avoiding engine operation under low-torque, low-efficiency conditions. In [1], several paths were postulated by which this improved optimization could occur:

1. A single-motor parallel hybrid with an advanced transmission that can decouple engine or motor operation from the wheels and a control strategy that switches off the engine under low-load conditions.
2. A dual-motor power-split hybrid (similar to the Toyota Prius) with improved generators and motors that can decouple engine operation from vehicle speed.

¹ Hybridization Ratio = $P_{\text{Motor}} / (P_{\text{Motor}} + P_{\text{Engine}})$

3. A high-efficiency mechanical CVT with a parallel hybrid architecture.

The hybrid vehicle model is based on the first option, as it is likely cheaper than the power-split architecture and more efficient than the CVT. However, all of the options achieve comparable results.

In addition to this advanced optimization, evolutionary improvements in vehicle components were incorporated into the ADVISOR vehicle models as described in the previous section; the vehicle braking system was configured to direct 90% of braking energy down the regenerative path; and the vehicle controls were configured to switch the engine off under low load conditions – a proxy for the type of control strategy postulated in path (1) above (and, in theory, similar to the behavior of a power-split system).

Comparison of Gasoline Hybrid to Diesel Hybrid – In addition to the gasoline hybrid, we performed a preliminary evaluation of a diesel hybrid vehicle. However, vehicle simulations showed only a marginal benefit when compared to the future gasoline hybrid – on the order of 5%. The lower-than-expected benefit arises due to several factors:

1. As discussed in [1], the efficiency of the 2030 gasoline SI engine approaches that of the 2030 diesel engine.
2. Diesel vehicles achieve higher efficiency in part because they are more efficient than SI engines under part load conditions. Because one of the benefits of hybridization is that it minimizes these part-load losses, hybridizing a diesel offers a lesser benefit.

Given that the diesel hybrid price premium includes both the additional cost of a diesel engine and the additional cost of a hybrid power train, the *long-term* cost/benefit of such a vehicle does not appear justified – particularly as spark-ignition performance approaches that of the diesel and particularly if lower cost plug-in hybrids can enter the market.

Sensitivity to Air-Conditioning Loads – In present-day hybrid vehicles, a high base-load (typically air-conditioning) has a greater impact on fuel consumption than in a conventional vehicle. To some extent, this shortcoming reflects an intrinsic constraint on hybrid technology. In an NA-SI vehicle, accessory loads can be partially offset by higher engine efficiencies enabled by the higher engine load; and by engine braking, which acts as a form of regenerative vehicle braking. In contrast, the hybrid vehicle already uses both of these methods to improve fuel efficiency without a base load; as such, their impact is marginal when a base load is added. In addition, the hybrid may incur additional losses from charging and discharging the battery.

The impact of air-conditioning load can be mitigated both by reducing the thermal load on the vehicle, and by improving compressor performance. NREL has estimated that improvements to vehicle design can reduce compressor load by 75% with continued development [35].

To quantify the impact of base loads on a future hybrid, ADVISOR simulations were run using a 1.5 kW accessory load. These simulations assume that the accessory load is the same for both the hybrid and the conventional vehicle: although hybrids are typically equipped with higher efficiency electric compressors, these systems tend to also be more expensive than the belt-driven compressors used in conventional vehicles. It was concluded that, on a cost-equalized basis, the compressors in conventional vehicles could approach these efficiencies.

The 1.5 kW load is consistent with a 3.5 kW thermal load served by a compressor with a coefficient-of-performance of 2.3. The thermal load assumes a 50% reduction in thermal load from that estimated for a present-day vehicle in [35] at 95F and 40% relative humidity.

Figure 4 shows the magnitude of the air-conditioning load for the NA-SI and gasoline hybrid vehicles across different drive cycles. The bar segments illustrate how this load is met. The bar segments corresponding to “engine braking” and “improved efficiency” do not represent actual additional energy expenditure by the vehicle; rather, they show the fraction of the cooling load that is met by reducing losses elsewhere in the driveline.

As shown, the NA-SI is able to meet a large fraction of its accessory load by using recaptured energy and boosting engine efficiency, particularly in urban driving conditions.

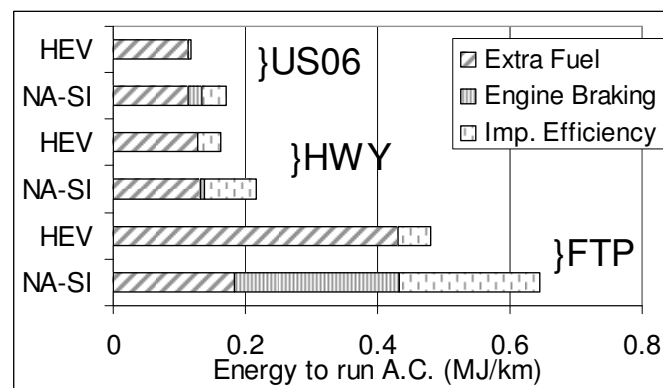


Figure 4: Air-conditioning energy use in conventional and hybrid vehicles.

The fuel-consumption penalty of a high base-load is also mitigated by the fact that these conditions comprise only a fraction of the time the vehicle is in use. A recent EPA study estimated that, on an aggregate, national basis, the average air-conditioning load is equivalent to operating under the high load condition used in vehicle simulations 15% of the time [36]. This load factor

accounts for periods when air conditioning is not in use, and for periods where it operates at less than full load.

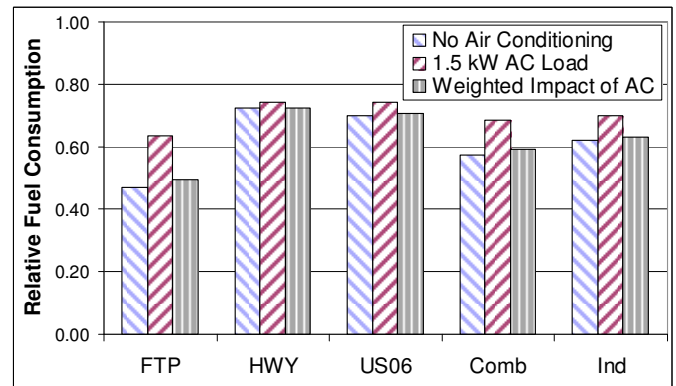


Figure 5: 2030 HEV Fuel-Consumption, relative to the 2030 NA-SI vehicle

As shown in Figure 5, when this limited time-in-use is accounted for and the results are aggregated across different drive cycles, the impact of the high base load is relatively minor. For example, over the combined, adjusted cycle, the base-load incurs a penalty on the order of 3%. However, the impact of air conditioning use during hot weather, particularly in urban driving conditions is significant. While in the aggregate this may be a small fraction of vehicle-miles, it suggests that the benefits of the hybrid vehicle are reduced for parts of the country for which these conditions are the norm.

PLUG-IN HYBRID (PHEV) ASSUMPTIONS – In the context of this assessment, a plug-in hybrid (PHEV) is defined as a hybrid-gasoline electric vehicle with the ability to recharge from the grid. The vehicle uses a lithium-ion battery pack in a parallel hybrid configuration similar to that assumed for the conventional hybrid. Above a threshold battery state-of-charge, the PHEV operates in “charge depleting” (CD) mode, in which it freely draws down the onboard battery to meet vehicle power demands. Once it reaches this minimum SOC threshold, the vehicle switches to “charge sustaining” (CS) mode. Charge-sustaining mode is functionally equivalent to vehicle operation in a conventional HEV.

Estimating Petroleum Use In a Plug-In Hybrid – Because a plug-in hybrid draws its power from two different energy sources, a methodology for estimating the fraction of petroleum-sourced and electricity-sourced energy must be defined. The utility factor (UF) has been defined by the SAE J1711 standard as the fraction of vehicle miles traveled in charge-depleting mode [18].

The tank-to-wheels energy (E_{Total}), petroleum (E_{Petrol}), and electricity (E_{Elec}) use are calculated from the petroleum consumption in charge-depleting and charge-sustaining mode, and the energy use in charge-depleting and charge sustaining mode (PC_{CS} , PC_{CD} , E_{CS} , and E_{CD} , respectively):

$$E_{Total} = (E_{CD})(UF) + (E_{CS})(1-UF)$$



 Document Sharing Hub

$$E_{\text{Petrol}} = (PC_{\text{CD}})(UF) + (PC_{\text{CS}})(1-UF)$$

$$E_{\text{Elec}} = E_{\text{Total}} - E_{\text{Petrol}}$$

The rate of petroleum consumption and rate of energy consumption in both driving modes were estimated using ADVISOR vehicle simulations. The utility factor was estimated by using the mid-range values from a survey of several different sources [18, 19, 20, 21], as shown in Figure 6.

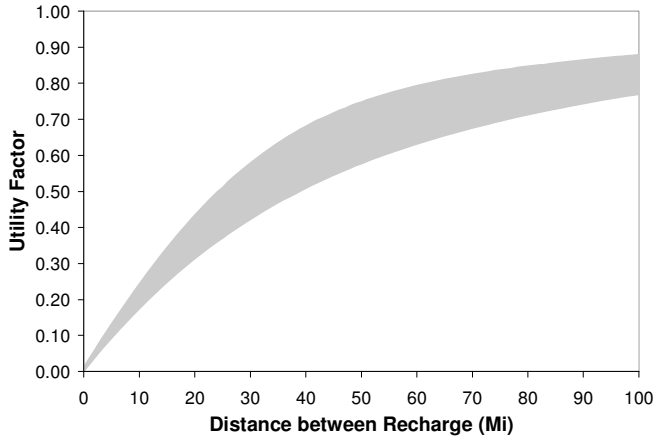


Figure 6: Utility factor as a function of distance between recharge [18, 19, 20, 21].

Plug-In Hybrid Configuration and Sizing – A plug-in hybrid may be configured in a number of different ways to optimize across different dimensions, such as fuel use, electric range, and vehicle cost. Because electric range is the primary cost driver and primary source of fuel consumption benefit, plug-in hybrids with a 10-, 30-, and 60-mile range² were modeled. The vehicle's electric range was defined as the distance the vehicle can travel under electric power over the combined, adjusted FTP/HWFET drive cycle.

All of the plug-in hybrid configurations are designed with a parallel hybrid architecture similar to that assumed for the conventional hybrid vehicle. While a series plug-in hybrid architecture may be an attractive option, particularly for vehicles with a high electric range, this assessment adopts a parallel architecture as a natural outgrowth of the already-extant hybrid market.

To size vehicle components, the plug-in hybrid's total power was fixed to: 1.) Meet the US06 drive cycle in both charge-depleting and charge-sustaining mode and 2.) Meet a minimum acceleration requirement in charge-depleting mode.

Plug-In Hybrid Control Strategy and Hybridization – Specific tradeoffs regarding how to size the system and use stored electric energy were explored by varying the hybridization ratio and the vehicle control strategy. The hybridization ratio, defined as the ratio of the peak power of the motor relative to the power of the total powertrain³, was varied from 25% to 55%. In addition, two different

control strategies were evaluated: an *all-electric* strategy, in which the gasoline engine remains off during charge-depleting mode (necessitating a more highly hybridized vehicle); and a *blended* strategy, in which the engine is available to meet peak power demands during charge-depleting mode (allowing for a less-powerful electric propulsion system), but remains off at other times [34]. During blended mode, engine operation was constrained by a minimum engine-on time as a way to minimize the number of cold engine starts.

Downsizing the electric powertrain (using a lower hybridization ratio) is desirable because it minimizes system cost and could have a performance benefit. The reasons for the potential performance benefit is that to meet the same performance criteria as a vehicle using a blended control strategy, an all-electric vehicle would require electric propulsion that is powerful enough to meet the vehicle's entire driving load *in addition to* an engine that switches on during hybrid operation. On the other hand, all-electric operation minimizes the number of cold-starts and total engine operation time; as such, it minimizes both fuel-consumption and criteria pollutant emissions.

Table 2: Plug-In Hybrid Vehicle Configurations

Electric Range (Mi)	Control Strategy	Hybridization Ratio
30	All-Electric	55%
30	Blended	44%
30	Blended	36%
30	Blended	36%

The vehicle configurations that were simulated are summarized in Table 2. All configurations were evaluated using the PHEV-30 platform.

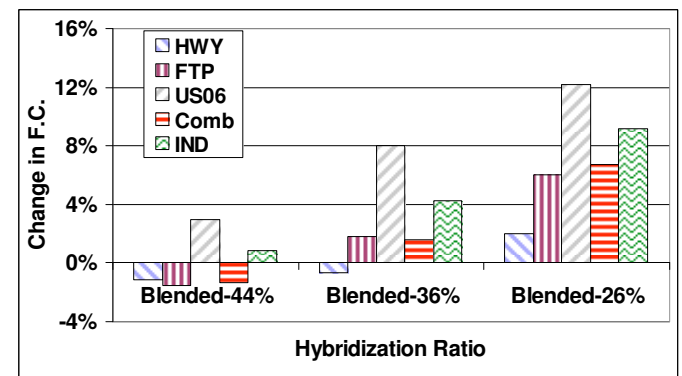


Figure 7: Change in fuel consumption due to varying hybridization ratio, relative to a 55%-hybridized vehicle using an all-electric control strategy.

The results of this sensitivity analysis are shown in Figure 7, Figure 8, and Figure 9. Figure 7 shows the estimated aggregate impact (including charge-depleting and charge-sustaining mode) of the various vehicle configurations across different drive cycles. The results are shown relative to the all-electric vehicle (55% hybridization ratio). Figure 8 and Figure 9 show cumulative petroleum consumption as a function of driving distance for the different vehicle configurations;

² 16, 48, and 96 kilometers, respectively

³ Hybridization Ratio = $P_{\text{wtrMotor}} / (P_{\text{wtrMotor}} + P_{\text{wtrEngine}})$