

Cost-Benefit Analysis of Plug-In Hybrid Electric Vehicle Technology

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COST-BENEFIT ANALYSIS OF PLUG-IN HYBRID ELECTRIC VEHICLE TECHNOLOGY¹

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Abstract

Plug-in hybrid-electric vehicles (PHEVs) have emerged as a promising technology that uses electricity to displace petroleum consumption in the vehicle fleet. However, there is a very broad spectrum of PHEV designs with greatly-varying costs and benefits. In particular, battery costs, fuel costs, vehicle performance attributes and driving habits greatly-influence the relative value of PHEVs. This paper presents a comparison of the costs (vehicle purchase costs and energy costs) and benefits (reduced petroleum consumption) of PHEVs relative to hybrid-electric and conventional vehicles. A detailed simulation model is used to predict petroleum reductions and costs of PHEV designs compared to a baseline midsize sedan. Two powertrain technology scenarios are considered to explore the near-term and long-term prospects of PHEVs. The analysis finds that petroleum reductions exceeding 45% per-vehicle can be achieved by PHEVs equipped with 20 mi (32 km) or more of energy storage. However, the long-term incremental costs of these vehicles are projected to exceed US\$8,000, with near-term costs being significantly higher. A simple economic analysis is used to show that high petroleum prices and low battery costs are needed to make a compelling business case for PHEVs in the absence of other incentives. However, the large petroleum reduction potential of PHEVs provides strong justification for governmental support to accelerate the deployment of PHEV technology.

Keywords: Plug-in Hybrid; Hybrid-Electric Vehicles; Battery, Secondary Battery; Modeling, Simulation; Energy Security.

1 Introduction to Plug-In Hybrid-Electric Vehicles

Plug-in hybrid-electric vehicles have recently emerged as a promising alternative that uses electricity to displace a significant fraction of fleet petroleum consumption [1]. A plug-in hybrid-electric vehicle (PHEV) is a hybrid-electric vehicle (HEV) with the ability to recharge its electrochemical energy storage with electricity from an off-board source (such as the electric utility grid). The vehicle can then drive in a charge-depleting (CD) mode that reduces the system's state-of-charge (SOC), thereby using electricity to displace liquid fuel that would otherwise have been consumed. This liquid fuel is typically petroleum (gasoline or diesel), although PHEVs can also use alternatives such as biofuels or hydrogen. PHEV batteries typically have larger capacity than those in HEVs so as to increase the potential for petroleum displacement.

1.1 Plug-In Hybrid-Electric Vehicle Terminology

Plug-in hybrid-electric vehicles are characterized by a "PHEV_x" notation, where "x" typically denotes the vehicle's all-electric range (AER) – defined as the distance in miles that a fully charged PHEV can drive before needing to operate its engine. The California Air Resources Board (CARB) uses the standard Urban Dynamometer Driving Schedule (UDDS) to measure the AER of PHEVs and provide a fair comparison between vehicles [2]. By this definition, a PHEV₂₀ can drive 20 mi (32 km) all-electrically on the test cycle before the first engine turn-on. However, this all-electric definition fails

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to account for PHEVs that might continue to operate in CD-mode after the first engine turn-on. Therefore, the author uses a definition of PHEV_x that is more appropriately related to petroleum displacement. By this definition, a PHEV₂₀ contains enough useable energy storage in its battery to displace 20 mi (32 km) of petroleum consumption on the standard test cycle. Note that this definition does not imply all-electric capability since the vehicle operation will ultimately be determined by component power ratings and their control strategy, as well as the actual in-use driving cycle.

1.2 The Potential of Plug-In Hybrid-Electric Vehicles

The potential for PHEVs to displace fleet petroleum consumption derives from several factors. First, PHEVs are potentially well-matched to motorists' driving habits – in particular, the distribution of distances traveled each day. Based on prototypes from the last decade, PHEVs typically fall in the PHEV₁₀₋₆₀ range [3]. Figure 1 shows the US vehicle daily mileage distribution based on data collected in the 1995 National Personal Transportation Survey (NPTS) [4]. Clearly, the majority of daily mileages are relatively short, with 50% of days being less than 30 mi (48 km). Figure 1 also shows the Utility Factor (UF) curve for the 1995 NPTS data. For a certain distance D , the Utility Factor is the fraction of total vehicle-miles-traveled (VMT) that occurs within the first D miles of daily travel. For a distance of 30 mi (48 km), the utility factor is approximately 40%. This means that an all-electric PHEV₃₀ can displace petroleum consumption equivalent to 40% of VMT, (assuming the vehicle is fully recharged each day). Similarly, an all-electric PHEV₆₀ can displace about 60%. This low-daily-mileage characteristic is why PHEVs have potential to displace a large fraction of *per-vehicle* petroleum consumption.

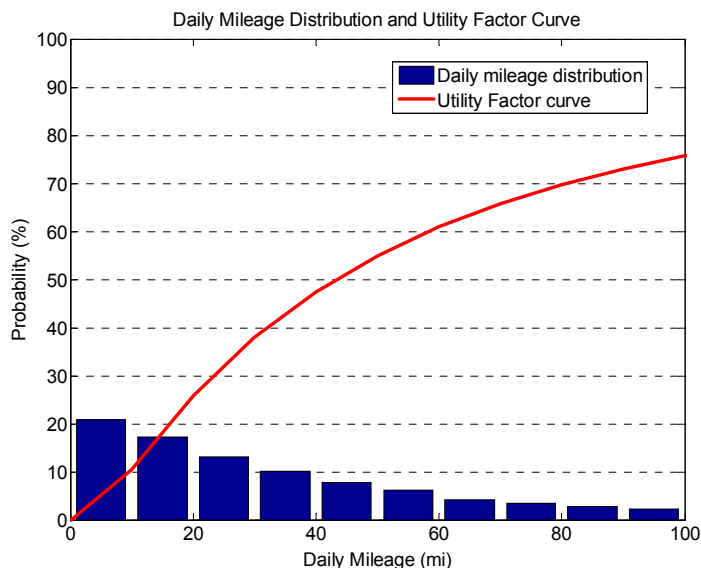


Figure 1: Daily mileage distribution for US motorists based on the 1995 National Personal Transportation Survey

However, for PHEVs to displace *fleet* petroleum consumption, they must penetrate the market and extrapolate these savings to the fleet level. A second factor that is encouraging for PHEVs is the success of HEVs in the market. Global hybrid vehicle production is currently several hundred thousand units per annum [5]. Because of this, electric machines and high-power storage batteries are rapidly approaching maturity with major improvements in performance and cost having been achieved. Although HEV components are not optimized for PHEV applications, they do provide a platform from which HEV component suppliers can develop a range of PHEV components.

Finally, PHEVs are very marketable in that they combine the beneficial attributes of HEVs and battery electric vehicles (BEVs) while mitigating their disadvantages. Production HEVs achieve high fuel economy, but they are still designed for petroleum fuels and do not enable fuel substitution/flexibility. PHEVs, however, are true fuel-flexible vehicles that can run on petroleum or electrical energy. BEVs do not require any petroleum, but are constrained by battery technologies resulting in limited driving ranges, significant battery costs and lengthy recharging times. PHEVs have a smaller battery which mitigates battery cost and recharging time while the onboard petroleum fuel tank provides driving range equivalent to conventional and hybrid vehicles. This combination of attributes is building a strong demand for PHEVs, as evidenced by the recently launched Plug-In Partners Campaign [6].

PHEVs have the potential to come to market, penetrate the fleet, and achieve meaningful petroleum displacement relatively quickly. Few competing technologies offer this potential combined rate and timing of reduction in fleet petroleum consumption [7]. However, PHEV technology is not without its challenges. Energy storage system cost, volume, and life are major obstacles that must be overcome for these vehicles to succeed. Increasing the battery storage beyond that of HEVs increases vehicle cost and presents significant packaging challenges. Furthermore, the combined deep/shallow cycling in PHEV batteries is uniquely more demanding than that experienced by HEVs or BEVs. PHEV batteries may need to be oversized to last the life of the vehicle, further increasing cost. Given that HEVs are succeeding in the market, the question relevant to PHEVs is, “What incremental petroleum reductions can be achieved at what incremental costs?” These factors will critically affect the marketability of PHEVs through their purchase price and cost-of-ownership. This paper presents the results of a study designed to evaluate this cost-benefit tradeoff.

2 Modeling PHEV Petroleum Consumption and Cost

The reduction of per-vehicle petroleum consumption in a PHEV results from two factors:

1. Petroleum displacement during CD-mode, which as previously discussed relates to the PHEV_x designation based on the added battery energy capacity of the vehicle.
2. Fuel-efficiency improvement in charge-sustaining (CS) mode due to hybridization, which relates to the degree-of-hybridization (DOH) or added battery power capability of the vehicle. HEVs, which do not have a CD-mode, are only able to realize savings via this second factor.

For a PHEV_x, these two factors can be combined mathematically as follows:

$$\frac{FC_{PHEV_x}}{FC_{CV}} = [1 - UF(x)] \frac{FC_{CS}}{FC_{CV}} \quad (1)$$

where FC_{PHEV_x} is the UF-weighted fuel consumption of the PHEV_x, FC_{CV} is the fuel consumption of the reference conventional (non-hybrid) vehicle and FC_{CS} is the PHEV_x's CS-mode fuel consumption. Note that this expression becomes approximate for PHEVs without all-electric capability because use of the utility factor in this way assumes that no petroleum is consumed in the first x miles of travel.

Figure 2 uses Equation 1 to compare the petroleum reduction of various PHEV designs. We see there are a variety of ways to achieve a target level of petroleum reduction. For example, a 50% reduction is achieved by an HEV with 50% reduced fuel consumption, a PHEV20 with 30% CS-mode reduction and by a PHEV40 with 0% CS-mode reduction (this last example is unlikely since PHEVs will show CS-mode improvement due to hybridization, notwithstanding the increase in vehicle mass from the larger battery). To demonstrate the feasible range of CS-mode reduction, Figure 2 compares several contemporary HEVs to their conventional counterparts (in the case of the Toyota Prius, a comparison is made to the Toyota Corolla which has similar size and performance). At the low end of the spectrum, the “mild” HEV Saturn Vue achieves a modest reduction of less than 20%. The “full” HEV Toyota Prius achieves the highest percentage reduction (40%) of all HEVs currently on the market although, in addition to the platform enhancements employed in production hybrids, it also uses an

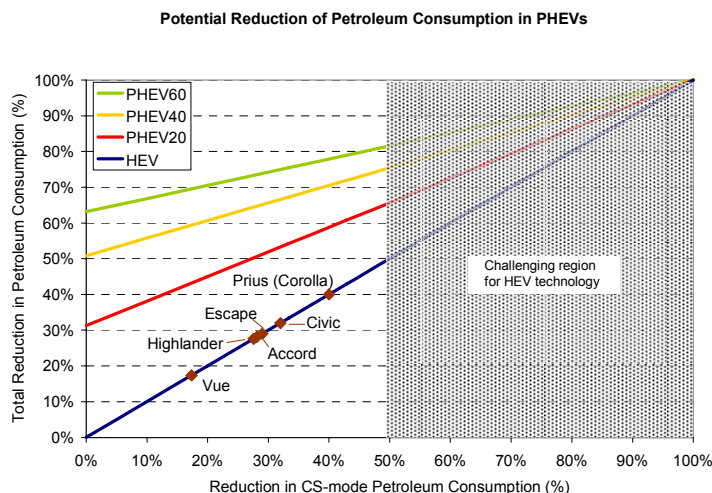


Figure 2: Potential per-vehicle reduction of petroleum consumption in PHEVs

advanced (Atkinson-cycle) engine technology. Note that none of the production HEVs achieve the 50% reduction discussed in the above example, suggesting that there is an upper limit on the benefit of hybridization alone. Reductions exceeding 50% are available through CD-mode operation in a PHEV, although increasing PHEV_x ranges can be seen to provide diminishing returns due to the nature of the Utility Factor curve (Figure 1).

The PHEV design space in Figure 2 characterized by CS/CD-mode fuel consumption has a matching space characterized by battery power/energy. Improving CS-mode fuel consumption implies an increase in DOH and battery power, while increasing CD-mode benefit implies an increase in PHEV_x and useable battery energy. Moving in either direction incurs additional vehicle costs. However, the link between battery specifications, CS/CD-mode reductions, and vehicle costs is not obvious and must be explored through detailed vehicle fuel consumption and cost modeling. Therefore, a model was developed to predict the petroleum reductions and costs of contrasting PHEV designs compared to a reference conventional vehicle. The details of this model are presented in the following sections.

2.1 Modeling Approach and Scope of the Study

The PHEV cost-benefit model includes several sub-models. First, a *performance model* calculates component sizes necessary to satisfy the performance constraints listed in Table 1. Second, a *mass balance* calculates the vehicle mass based on component sizes determined by the performance model. Third, an *energy-use model* simulates the vehicle's gasoline and electricity consumption over various driving cycles. The vehicle performance and energy-use models are coupled to vehicle mass, so the model is able to capture mass compounding in the sizing of components. Fourth, a *cost model* estimates the vehicle retail price based on the component sizes. All costs are reported in 2006 US dollars. Finally, the *results post-processing* performs calculations to report the vehicle energy consumption and operating costs in meaningful ways. The model is implemented in an iterative Microsoft Excel spreadsheet.

The energy-use model is a detailed, second-by-second, dynamic vehicle model that uses a reverse-calculation approach [8]. It is also characterized as a power-flow model since it models component losses/efficiencies as functions of device power, rather than as functions of torque/speed or current/voltage as in more detailed models. This reverse-calculation, power-flow method provides rapid estimation of vehicle energy usage and enables the coupled, iterative spreadsheet described above. A solution is obtained in only a few seconds, meaning that the design space can be explored very quickly and thoroughly. Several hundred PHEV designs were therefore included in the study.

The model performs simulations of both conventional vehicles (CVs) and HEVs (including PHEVs) so that side-by-side comparisons can be made. The performance and energy-use models were validated for a Toyota Camry sedan and Honda Civic Hybrid. In both cases, errors of less than 5% were observed in the estimates of vehicle performance and energy use.

Two powertrain technology scenarios (Table 2) were included in the study. The near-term scenario (2005-2010) represents vehicles produced using current-status powertrain technologies, whereas the long-term scenario (2015-2020) allows for advanced technologies expected to result from ongoing R&D efforts and high-volume production levels. The long-term scenario does not, however, include advanced engine technologies since the author wanted to isolate the impact of improved electric drive and energy storage technologies on the relative cost-benefit of PHEVs.

2.2 Vehicle Platform, Performance and Cost Assumptions

All vehicles included in the study satisfied the same performance constraints and used a vehicle platform identical to the baseline CV. The baseline CV was a midsize sedan (similar to a Toyota Camry or Chevrolet Malibu) and relevant parameters are presented in Table 1. Most parameters were calculated from sales-weighted average data for the top selling US midsize sedans in 2003 [9]. Some parameters, such as rolling resistance, accessory loads, passing acceleration, and gradeability, were engineering estimates. The baseline manufacturer's suggested retail price (MSRP) of US\$23,392 was

used in combination with the powertrain cost model to estimate the baseline “glider” cost (i.e. vehicle with no powertrain). The cost of a 121 kW CV powertrain was estimated at US\$6,002, leading to an estimated baseline glider cost of US\$17,390.

Table 1: Vehicle Platform and Performance Assumptions for Midsize Sedan

Platform Parameters		
Glider Mass	905 kg	
Curb Mass	1429 kg	
Test Mass	1565 kg (136 kg load)	
Gross Vehicle Mass (GVM)	1899 (470 kg load)	
Drag coefficient	0.3	
Frontal area	2.27m ²	
Rolling resistance coefficient	0.009	
Baseline accessory load	800 W elec. (4000 W peak)	
Performance Parameters		
Standing acceleration	0-97 kph (0-60 mph) in 8.0 s	
Passing acceleration	64-97 kph (40-60 mph) in 5.3 s	
Top speed	177 kph (110 mph)	
Gradeability	6.5% at 88 kph (55 mph) at GVM with 2/3 fuel converter power	
Vehicle attributes		
Engine power	121 kW	
Fuel consumption	10.6 / 6.7 / 8.8 L per 100km (urban / highway / composite)	
MSRP	\$23,392	

Table 2: Powertrain Technology Scenarios for the Cost-Benefit Analysis

	Near-Term Scenario	Long-Term Scenario
Battery		
Chemistry	NiMH	Li-Ion
Module cost	Twice that of long-term scenario	\$/kWh = 11.1 x P/E + 211.1 [14]
Pack cost	\$ = (\$/kWh + 13) x kWh + 680 [14]	Same
Module mass	NiMH battery design function [15], see Figure 6	Li-Ion battery design function [15], see Figure 6
Pack mass	Tray/straps + thermal mgmt = 0.06 kg/kg [15] Harness + bus bars = 0.14 kg/kW [15]	Same
Efficiency	Equivalent circuit model based on P/E ratio, see Figure 5	Same
SOC window	SOC design window curve, see Figure 4	Same (assumes Li-Ion cycle life = NiMH)
Motor		
Mass	kg = 21.6 + 0.833 x kW [13]	kg = 21.6 + 0.532 x kW [14]
Cost	\$ = 21.7 x kW + 425 [14]	\$ = 16 x kW + 385 [14]
Efficiency	95% peak efficiency curve, see Figure 5	Same
Engine		
Mass	kg = 1.62 x kW + 41.8 [9]	Same
Cost	\$ = 14.5 x kW + 531 [14]	Same
Efficiency	34% peak efficiency curve, see Figure 5	Same

2.3 Powertrain Architecture

The two things that differentiate a PHEV from an HEV are the inclusion of a CD operating mode and a recharging plug. Therefore, a PHEV can be implemented using any of the typical HEV architectures (parallel, series, or power-split). For this study, a parallel architecture was assumed with the ability to declutch the engine from the powertrain (Figure 3). This parallel layout provides greater flexibility in engine on/off control compared to Honda’s integrated motor assist (IMA) parallel system [10]

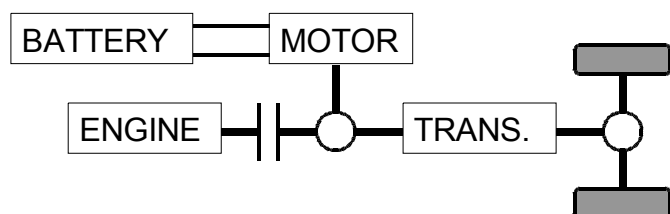


Figure 3: Parallel HEV powertrain architecture

where the engine and motor are always connected. To create more flexibility in engine on/off control, it was also assumed that all accessories (including air conditioning) would be powered electrically from the battery.

2.4 Component Sizing

Battery

The battery is the first component sized by the model and the two key inputs are the PHEV_x designation and the battery power-to-energy (P/E) ratio. The useable battery energy is calculated using an estimate of the vehicle's equivalent electrical energy consumption per unit distance multiplied by the target PHEV_x distance. The electrical energy consumption is estimated using the PAMVEC model [11]. The total battery energy is then calculated based on the SOC design window. Finally, the rated battery power is calculated by multiplying the total battery energy by the input P/E ratio and then de-rating by 20% to account for battery power degradation at end-of-life.

To achieve similar battery cycle life, different PHEV_x ranges require different SOC design windows. The daily mileage distribution (Figure 1) means that a PHEV10 is far more likely to experience a deep cycle than a PHEV60. Therefore, the SOC design window must be chosen such that the average daily SOC swing is consistent across the range of PHEVs. Figure 4 shows the SOC design windows assumed in the PHEV cost-benefit model, based on cycle-life data presented by Rosenkrantz [12] and a target battery life of 15 years (assuming one full recharge each day). Figure 4 also shows the resulting average daily SOC swing which is consistent across the range.

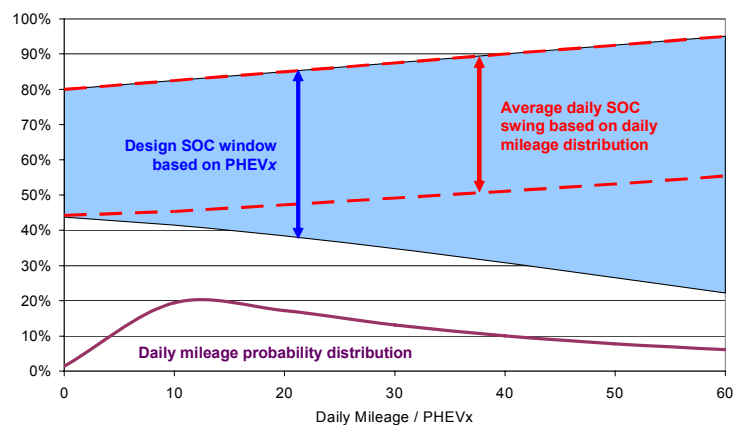


Figure 4: SOC design window for PHEVs

Electric Motor

The motor power is matched to the battery power, but with the resulting motor power being slightly smaller after accounting for electric accessory loads and motor/controller efficiency.

Engine

Several steps are required to size the engine. First, the required peak power of the engine plus motor is calculated using the PAMVEC model [11]. This power is typically dictated by the standing acceleration performance and for the baseline midsize platform is approximately 120kW. The motor power is then subtracted from the total to provide a requirement for the engine power. This produces some “engine downsizing,” but there are downsizing limits imposed by other performance constraints. Continuous performance events (gradeability and top speed) determine the minimum permissible engine size. Gradeability performance is limited to 2/3 of peak engine power due to engine thermal management and noise, vibration, and harshness (NVH) considerations. For the baseline midsize platform, the minimum engine size is approximately 80kW.

2.5 Component Efficiencies, Masses, and Costs

Engine and Electric Motor

As discussed in section 2.1, the PHEV energy-use model is a reverse-calculation, power-flow model that simulates component losses/efficiencies as a function of output power. Both the engine and electric motor efficiencies are modeled using polynomial expressions for component input power as a function of output power. The engine curve is based on a 4-cylinder, 1.9L, 95kW gasoline engine. A 3rd-order polynomial was fitted to data from an ADVISOR simulation [8] using this engine. The

motor curve is based on a 50kW permanent magnet machine and a 9th-order polynomial was fitted to data from an ADVISOR simulation using this motor. Both efficiency curves are shown in Figure 5.

The engine and motor masses and costs are modeled as linear functions of rated output power. The engine mass function is derived from a database of 2003 model-year vehicles [9]. The near-term motor-controller mass function is based on the 2006 current status listed in the FreedomCAR and Vehicle Technologies Program Plan [13]. The long-term motor-controller mass is based on technology demonstrated in the GM Precept concept vehicle [14]. The engine cost function is based on manufacturers' data provided to the EPRI Hybrid-Electric Vehicle Working Group (HEVWG) [14]. The near-term and long-term motor cost functions are also based on data reported by EPRI [14].

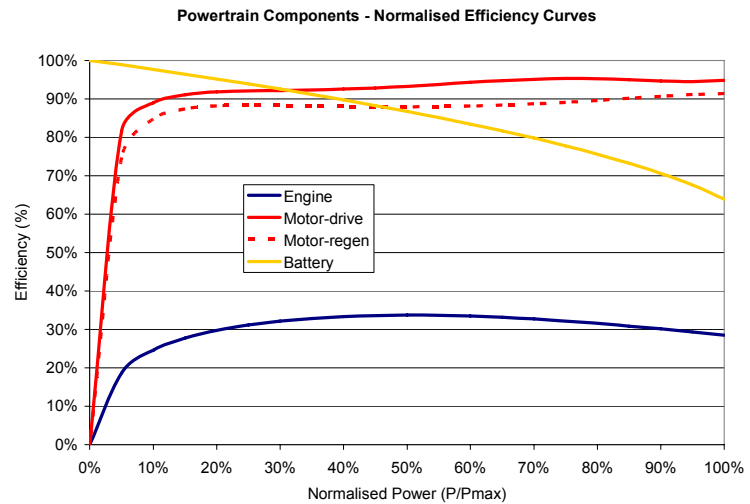


Figure 5: Efficiency curves used in the PHEV cost-benefit model

Battery

Battery efficiency is modeled using a normalized function for efficiency vs. input power (Figure 5). This relationship was derived from an equivalent circuit model using realistic values for nominal open-circuit voltage and internal impedance. Battery-module mass for both NiMH and Li-Ion technology is modeled using battery design functions developed by Delucchi [15] and shown in Figure 6. The added mass of battery packaging and thermal management was also based on [15].

Battery-module-specific costs (\$/kWh) vary as a function of power-to-energy ratio (Figure 6). The long-term Li-Ion cost curve is based on estimates from EPRI [14]. After speaking with battery suppliers and other experts, it was estimated that the near-term specific cost of NiMH modules was approximately double that of EPRI's long-term prediction. The costs of battery packaging and thermal management are also based on those listed in [14].

Recharging Plug and Charger

PHEVs are assumed to be equipped with an inverter-integrated plug/charger with 90% efficiency and an incremental manufactured cost of US\$380 over the baseline inverter cost [14].

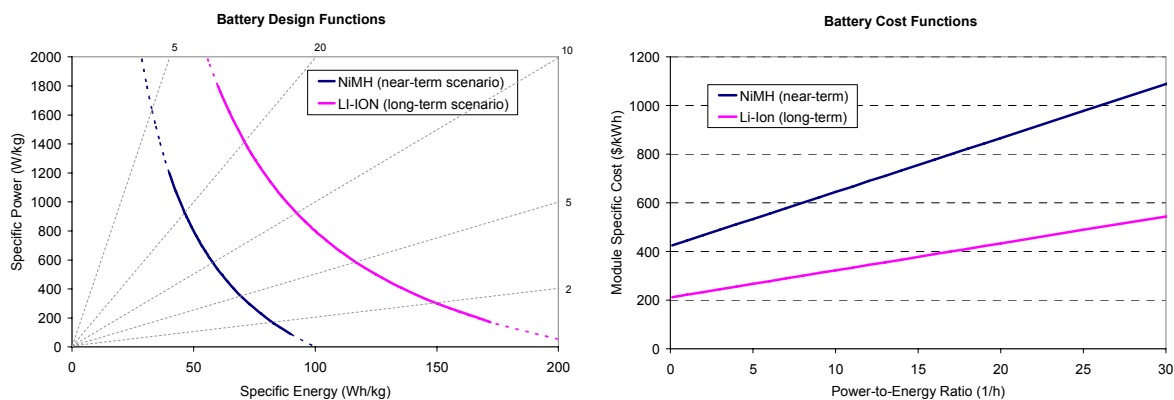


Figure 6: Battery design functions and module cost curves assumed for NiMH and Li-Ion technology

Retail Markup Factors

The component cost functions in Table 2 model the manufactured cost of components. To convert these to retail costs in a vehicle, various markup factors are applied. A manufacturer's markup of 50% and dealer's markup of 16.3% are assumed based on estimates by EPRI [14]

2.6 Powertrain Control Strategy

A generic control strategy was developed for the spectrum of PHEV designs. This control strategy consists of four basic elements. The basis of the strategy is an SOC-adjusted engine power request:

$$P_{engine-request} = P_{driveline} - k(SOC - SOC_{target}) \quad (2)$$

When the SOC is higher than the target, the engine power request is reduced to promote CD operation. Alternatively, when the SOC is lower than the target, the engine power request is increased to recharge the battery. The adjustment is governed by the factor k which is set proportional to total battery capacity. An electric-launch speed of 10 mph (16 kph) is also specified, below which the strategy tries to operate the vehicle all-electrically by setting the engine power request to zero. However, both the SOC adjustment and electric launch can cause the power ratings of the motor to be exceeded. Therefore, a third element of the strategy is to constrain the engine power request to within acceptable limits such that no components are overloaded. Finally, there is engine on/off control logic. The engine is triggered on whenever the adjusted engine power request becomes positive. Once on, however, the engine can only turn off after it has been on for at least 5 minutes. This final constraint is designed to ensure the engine warms up thoroughly so that repeated cold starts are avoided.

The aim of this control strategy is to prioritize discharging of the battery pack. Given the nature of the daily mileage distribution, this approach ensures that the maximum petroleum will be displaced. However, the strategy does not explicitly command all-electric operation. Rather, it discharges battery energy at the limits of the battery/motor power capabilities and uses the engine as needed to supplement the road load power demand. Therefore, the vehicle behavior that results is totally dependent on the power ratings of components. Vehicles with higher electric power ratings will have all-electric capability in more aggressive driving, whereas vehicles with lower electric power ratings will tend to operate in a "blended" CD-mode that utilizes both motor and engine. For more discussion of all-electric vs "blended" operation, the reader is directed to [16].

2.7 Driving Cycles

The cost-benefit model simulates CVs, HEVs, and PHEVs over two cycles – the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET) – used by the US Environmental Protection Agency (EPA) for fuel economy and emissions testing and labeling [17].

2.8 Fuel Economy Measurement and Reporting

The PHEV fuel economies and operating costs are measured and reported using a procedure based on a modification of the Society of Automotive Engineers' (SAE) *J1711 Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles* [18]. This procedure measures the fuel and electricity use in both CD and CS-modes and weights them according to the Utility Factor (UF), assuming the PHEVs are fully-recharged each day. Further discussion of this procedure for fuel economy measurement and reporting is provided in [17].

3 Results

PHEV2, 5, 10, 20, 30, 40, 50, and 60 vehicles were considered in the study. Also, an HEV0 was modeled as a PHEV2 with its charger/plug removed. P/E ratios were chosen to vary DOH (defined as the ratio of motor power to total motor plus engine power) across a range of approximately 10%–55%. Note that the engine downsizing limit corresponds to a DOH of approximately 32%, and that DOH higher than this results in excess electric power capability onboard the vehicle.

Figure 7 shows the battery specifications for the spectrum of PHEVs in the long-term scenario. The total battery energy varies from approximately 1.5 kWh for the HEV0/PHEV2 to approximately 25kWh for the PHEV60. The battery power varies from approximately 10–100kW across the range of DOH. Figure 7 includes dashed lines of constant P/E ratio, which varied from approximately 1–50. Figure 7 also indicates the minimum battery power requirement (approximately 45kW) for the PHEVs to have all-electric capability on the UDDS test cycle. The battery specifications for the near-term scenario are similar to Figure 7 but have increased power and energy requirements due to mass-compounding from the lower specific energy of NiMH batteries.

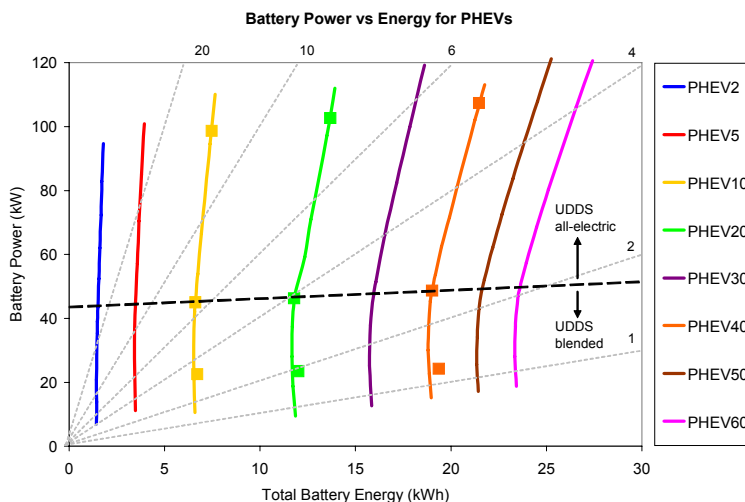


Figure 7: Battery specifications for the spectrum of PHEV designs (long-term scenario)

Figure 8 presents the reductions in annual petroleum consumption and incremental costs for the spectrum of PHEVs in the long-term scenario. Taking a macroscopic view, we see that increasing PHEV_x provides increasing reduction in petroleum consumption. Relative to the baseline CV, which consumes 659 gal (2494 L) of petroleum based on 15,000 mi (24,100 km) each year, the HEVs reduce petroleum consumption by 20%–28%. The PHEVs reduce petroleum consumption further, ranging from 21%–31% for the PHEV2s up to 53%–64% for the PHEV60s. However, these increasing reductions come at increasing costs.

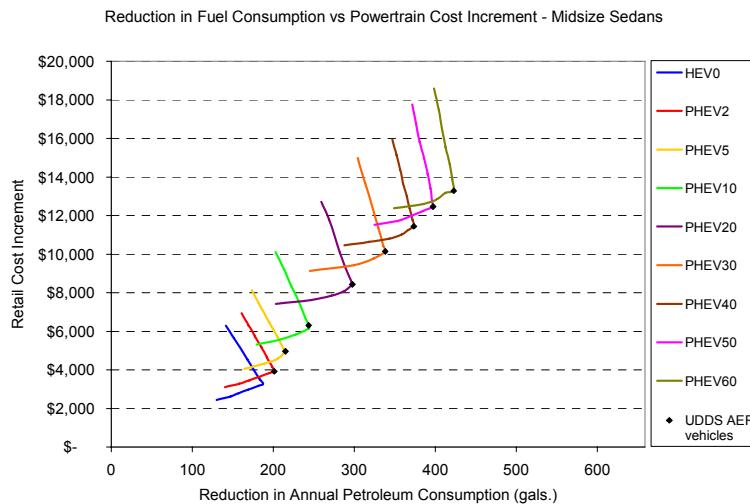


Figure 8: Incremental costs and annual petroleum consumption for the spectrum of PHEV designs (long-term scenario)

The HEV0s are projected to cost US\$2,000–\$6,000 more than the baseline CV, whereas the PHEV60s are projected to cost US\$12,000–\$18,000 more. The near-term trend is quite similar to Figure 8, except that petroleum reductions are slightly reduced and vehicle cost increments are much larger due to the greater mass and significantly higher cost of near-term NiMH batteries.

Looking closely at Figure 8, we see a repeated trend in the relative cost-benefit of PHEVs with varying DOH, and there is an optimum DOH for each PHEV_x. For the HEV0s, the optimum DOH (32%) coincides with the limit of engine downsizing. For the PHEVs, the optimum DOH is higher (35%) to coincide with the minimum battery power required for all-electric capability on the UDDS cycle (the maximum power requirement on the HWFET cycle is lower). This all-electric capability allows vehicles to avoid engine idling losses that would otherwise be incurred due to engine turn-on events subject to the 5-minute minimum engine on time constraint. The optimum HEVs and PHEVs for the near-term and long-term scenarios are summarized in Tables 3 and 4.

It must be emphasized that these optimum DOH are highly-dependent on the vehicle platform/performance attributes and the nature of the driving pattern. The analysis should be repeated for other baseline vehicles (e.g. sport-utility vehicles) to see how the PHEV designs will vary. Furthermore, PHEVs should be simulated over real-world driving cycles to identify differences in the petroleum displacement and all-electric operation compared to standard test cycles. Such further analyses should provide the understanding needed to optimize PHEVs for the market.

Table 3: Near-Term Scenario PHEV Specifications – Optimum DOH Vehicles

Vehicle	Curb Mass (kg)	Engine Power (kW)	Motor Power (kW)	DOH	Battery Energy (kWh)	P/E Ratio (1/h)	SOC Window	Fuel Cons. (L/100km)	Elec. Cons. (Wh/km)	Retail Cost (US\$)
CV	1429	122	---	---	---	---	---	10.3	---	23,392
HEV0	1451	78	38	33%	1.5	33.4	37%	7.5	---	28,773
PHEV2	1451	78	38	33%	1.5	33.4	37%	7.3	7	29,435
PHEV5	1505	80	42	35%	3.6	15.9	39%	7.1	17	31,447
PHEV10	1571	82	44	35%	6.9	8.6	41%	6.7	33	34,180
PHEV20	1678	85	47	35%	12.7	4.9	47%	6.0	60	38,935
PHEV30	1759	89	49	36%	17.2	3.8	53%	5.4	84	42,618
PHEV40	1824	91	51	36%	20.8	3.3	59%	4.8	104	45,655
PHEV50	1880	94	52	36%	23.9	2.9	66%	4.5	118	48,162
PHEV60	1923	96	53	36%	26.4	2.7	73%	4.1	133	50,184

Table 4: Long-Term Scenario PHEV Specifications – Optimum DOH Vehicles

Vehicle	Curb Mass (kg)	Engine Power (kW)	Motor Power (kW)	DOH	Battery Energy (kWh)	P/E Ratio (1/h)	SOC Window	Fuel Cons. (L/100km)	Elec. Cons. (Wh/km)	Retail Cost (US\$)
CV	1429	122	---	---	---	---	---	10.3	---	23,392
HEV0	1412	77	36	32%	1.5	32.8	37%	7.4	---	26,658
PHEV2	1412	77	36	32%	1.5	32.8	37%	7.2	7	27,322
PHEV5	1445	78	41	34%	3.5	15.7	39%	7.0	17	28,365
PHEV10	1481	79	42	35%	6.6	8.5	41%	6.5	32	29,697
PHEV20	1531	81	43	35%	11.8	4.9	47%	5.7	58	31,828
PHEV30	1569	82	44	35%	15.9	3.7	53%	5.0	78	33,533
PHEV40	1598	83	45	35%	19.0	3.2	59%	4.5	96	34,839
PHEV50	1618	84	45	35%	21.6	2.8	66%	4.1	108	35,857
PHEV60	1636	84	46	35%	23.6	2.6	73%	3.7	120	36,681

3.1 Economics of PHEVs

The PHEV cost-benefit analysis also includes a simple comparison of cost-of-ownership over the vehicle lifetime. The comparison includes the retail cost of the vehicle and the cost of its annual energy (fuel and electricity) consumption, but does not account for possible differences in maintenance costs (for a more thorough analysis of total PHEV lifecycle costs, the reader is directed to [14]). Figure 9 presents economic comparisons for the near-term and long-term scenarios. In calculating annual petroleum and electricity consumption, all vehicles are assumed to travel 15,000 mi (24,100 km) per year to be consistent with the assumptions of the US EPA. The near-term cost of retail gasoline is assumed to be US\$3 per gallon (US\$0.79 per L), whereas a higher gasoline cost of US\$5 per gallon (US\$1.32 per L) is assumed for the projected scenario. The cost of retail electricity is held constant at US\$0.09 per kWh based on the 2005 US average retail price and historical trends [19]. No discount rate was applied to future cash flows.

In the near-term scenario, the HEV achieves a lower cost-of-ownership than the CV after approximately 10 years. However, the PHEVs never achieve a lower cost-of-ownership than the CV nor the HEV over the 15-year vehicle lifetime. The long-term scenario provides a significant contrast, with the HEV providing lower cost than the CV after approximately 4 years and the PHEVs providing lower cost than the HEV after approximately 12 years.

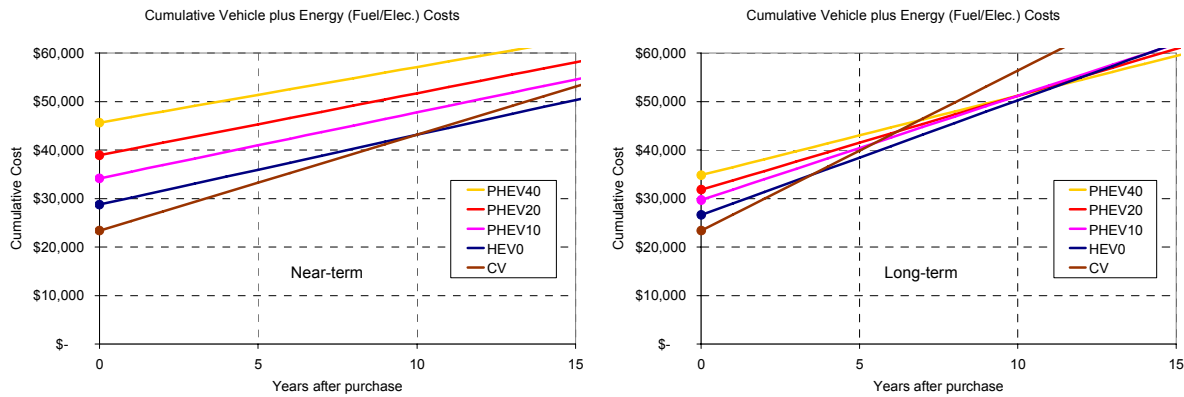


Figure 9: Economic comparison of PHEVs in the near-term and long-term scenarios

Several observations can be made from these comparisons. It is clear that these “payback” analyses are sensitive to the cost of gasoline and also the vehicle retail costs, which are strongly affected by the battery cost assumptions in each scenario. It is also clear that the economics of PHEVs are not promising if gasoline prices remain at current levels and battery costs cannot be improved. However, it does seem that a compelling business case for plug-in hybrids can be made under a scenario of both higher gasoline prices and projected (lower) battery costs, at least from the perspective of the simple consumer economic comparison presented here.

Despite the uncertainty of PHEV economics, there are other factors that may justify the incremental PHEV cost. Examples include tax incentives; reductions in petroleum use, air pollution, and greenhouse emissions; national energy security; reduced maintenance; fewer fill-ups at the gas station; convenience of home recharging; improved acceleration from high-torque electric motors; a green image; opportunities to provide emergency backup power in the home; and the potential for vehicle-to-grid applications. Alternative business models—such as battery leasing—also deserve further consideration since they might help to mitigate the daunting incremental vehicle cost and encourage PHEV buyers to focus on the potential for long-term cost savings.

4 Conclusion

This paper has presented a comparison of the costs (vehicle purchase costs and energy costs) and benefits (reduced petroleum consumption) of PHEVs relative to HEVs and CVs. Based on the study results, there is a very broad spectrum of HEV-PHEV designs with greatly varying costs and benefits. Furthermore, the PHEV cost-benefit equation is quite sensitive to a range of factors. In particular, battery costs, fuel costs, vehicle performance, and driving habits have a strong influence on the relative value of PHEVs. Given the large variability and uncertainty in these factors, it is difficult to predict the future potential for PHEVs to penetrate the market and reduce fleet petroleum consumption.

However, the potential for PHEVs to reduce *per-vehicle* petroleum consumption is clearly very high. Reductions in excess of 45% are available using designs of PHEV20 or higher. This compares favorably with the 30% maximum reduction estimated for HEVs. However, it seems likely that the added battery capacity of a PHEV will result in significant vehicle cost increments, even in the long term. For the projected scenario in this study, a retail cost increment of US\$3,000 was estimated for a midsize sedan HEV. In contrast, the long-term cost increments for a midsize PHEV20 and PHEV40 were estimated at US\$8,000 and US\$11,000 respectively. Without knowing the future costs of petroleum, it is impossible to determine the future economics of PHEVs. But it does seem likely, based on the results of this study, that it will be quite a challenge to justify the PHEV capital cost premium on the basis of reduced lifetime energy costs alone. Other incentives and business models may be required to create an attractive value proposition for PHEV motorists. However, the large petroleum reduction potential of PHEVs offers significant national benefits and provides strong justification for governmental support to accelerate the deployment of PHEV technology.

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