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Platform Engineering Applied to Plug-In Hybrid Electric Vehicles

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ABSTRACT

Plug-in hybrid electric vehicle (PHEV) technology will provide substantial reduction in petroleum consumption as demonstrated in previous studies. Platform engineering steps including, reduced mass, improved engine efficiency, relaxed performance, improved aerodynamics and rolling resistance can impact both vehicle efficiency and design. Simulations have been completed to quantify the relative impacts of platform engineering on conventional, hybrid, and PHEV powertrain design, cost, and consumption. The application of platform engineering to PHEVs reduced energy storage system requirements by more than 12%, offering potential for more widespread use of PHEV technology in an energy battery supply-limited market. Results also suggest that platform engineering may be a more cost-effective way to reduce petroleum consumption than increasing the energy storage capacity of a PHEV.

INTRODUCTION

A plug-in hybrid electric vehicle (PHEV) is a hybrid electric vehicle (HEV) with the ability to recharge its energy storage system with electricity from an off-board power source. The key advantage PHEV technology has relative to hybrid electric and conventional vehicles is fuel flexibility. A PHEV uses the stored electrical energy to propel the vehicle and reduce petroleum consumption by the combustion engine.

A recent study by Simpson estimates that a PHEV with usable electrical energy storage equivalent to 20 miles of electric travel (PHEV20) would reduce petroleum consumption by 45% relative to a comparable conventional combustion engine vehicle.[1] The purpose of the previous study was to quantify the impacts of PHEV technology alone. Elements of platform engineering were not considered.

Platform engineering consists of enhancements that are not dependent on the powertrain technology and may include the use of lightweight materials, aerodynamic drag reduction, rolling resistance reduction, combustion engine efficiency improvement, and performance constraint relaxation. Each of these has the potential to improve overall vehicle efficiency. This paper will quantify the relative impacts of each platform engineering step on conventional, hybrid, and PHEV vehicle architectures.

APPROACH

This analysis employs a cost-benefit model detailed by Simpson.[1] It is a power-based model that iteratively solves for the component sizes (engine power, motor power, battery power, and energy) to meet performance constraints and energy consumption characteristics of the vehicle over standard driving profiles as a function of the equivalent electric range capability and the degree of hybridization. Consumption characteristics are calculated on the Urban Dynamometer Driving Schedule (UDDS) and the Highway Federal Test Procedure using a modified form of the SAE J1711 Recommended Practice as discussed by Gonder and Simpson.[2] The results are post-processed to determine the retail and operating costs of each vehicle scenario. The model runs quickly (a few seconds per vehicle scenario) and allows rapid exploration of the design space.

In the previous study by Simpson, the impacts of PHEV technology where isolated by including no improvements to engine and platform attributes. This study expands on the previous work by including improvements to engine and platform attributes. Conventional, hybrid, and plug-in hybrid vehicles can all benefit from platform engineering.

The retail cost models used in this analysis do not attempt to estimate the costs of implementing the platform engineering steps, but instead will reference the work of others as necessary. The models only account for changes in retail cost due to changes in the powertrain attributes. Retail cost is the manufacturer suggested retail price (MSRP) and is calculated from the sum of the component costs multiplied by manufacturer and dealer markups of 50% and 16.3% respectively.

Midsize sedans are high volume vehicles in today's marketplace. The baseline vehicle attributes for this analysis are representative of a typical midsize sedan, such as the Chevrolet Malibu or Toyota Camry. Table 1 summarizes the attributes of the baseline conventional vehicle.

Table 1: Midsize Sedan Platform and Performance Attributes

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

The previous study identified PHEVs with all-electric range capability on the UDDS to be the most cost-effective PHEV design scenarios.[1] Therefore, the scope of this study only considers PHEVs with all-electric range on the UDDS cycle. Both conventional combustion engine vehicles and charge-sustaining HEVs have been included for comparison. The impacts of five vehicle attributes influential in vehicle design and efficiency as detailed in Table 2 are evaluated in this study.

Table 2: Platform Engineering Parameter Values

Attribute	Baseline	Alternative
Vehicle Glider Mass	905kg	815kg
Peak Engine Efficiency	34%	37%
0-60mph Acceleration Time	8s	10s
Aerodynamic Drag Coef.	0.30	0.27
Rolling Resistance Coef.	0.009	0.008

Finally, the previous work by Simpson assumed that the usable window of the energy storage system in a PHEV would be specified to ensure 15-year life of all components based on statistical daily driving behaviors and limited battery cycle life data. The usable battery state of charge varied from 37% for PHEV20 to 73% for a PHEV60. Limiting the usable state of charge for shorter range PHEVs increases the total energy requirements and vehicle retail cost. High vehicle retail cost could be a challenging barrier to PHEV market penetration. The ability to fully utilize the onboard storage system capacity will be critical for reducing retail cost and maximizing operating efficiency. In this paper, the focus is on long-term scenarios, so it is assumed that all PHEVs will be able to utilize 70% battery depth of discharge.

RESULTS

The individual impacts of each of the five platform engineering improvements—mass reduction, engine efficiency improvement, acceleration constraint relaxation, aerodynamic drag reduction, and rolling resistance reduction—have been applied to a PHEV20 vehicle. The results provide insight into the relative benefits of each for a specific powertrain. All of the attributes are then applied together to the conventional, HEV, and PHEV designs considered to quantify the combined potential benefits and identify how these benefits vary by powertrain design scenario.

Figures 1 and 2 summarize the impacts of each platform engineering attribute and are discussed in the sections below. Energy costs were calculated assuming 15,000 miles/year, $3/gal gasoline, and $0.09/kWh electricity.

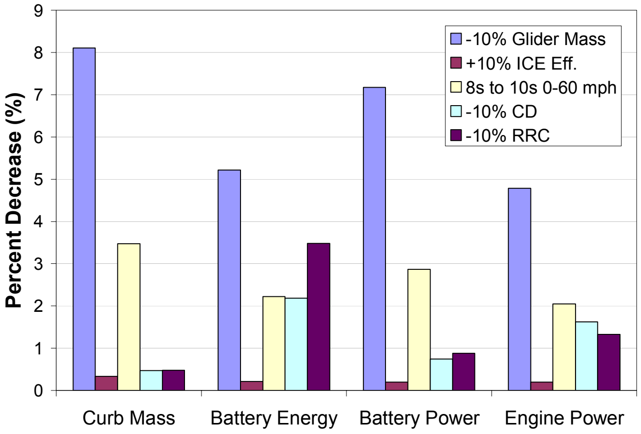

Figure 1: Platform Engineering Impacts on Powertrain Attributes of a PHEV20

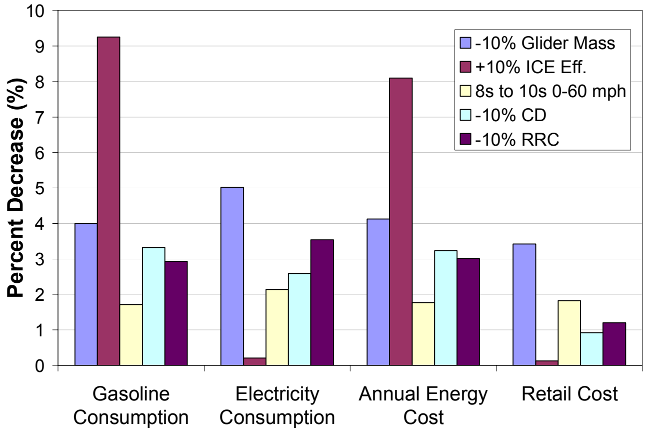

Figure 2: Platform Engineering Contributions to Costs and Consumption for a PHEV20

MASS REDUCTION

Reducing the mass of the vehicle is one of the most effective ways to increase vehicle efficiency. Today's typical sedan weighs ~1600 kg and is often used to move a single ~75 kg person. The additional mass of the vehicle adds function, comfort, and convenience but leads to large amounts of wasted energy.

Honda employed dramatic mass reduction technologies in developing the Insight HEV. Through the extensive use of aluminum, the body-in-white weighs ~40% less than a comparable conventional vehicle.[3] The Insight was the most fuel efficient vehicle commercially available.

The mass of the vehicle glider in this study was reduced by 10% from 905kg to 815kg to assess the impact of mass reduction on a PHEV. A reduction of 90kg is significant but is achievable through the use of lightweight steels.[4] More extensive use of aluminum and composites can provide even greater weight savings (120 to 150kg) but are also more costly (~$500).[4]

A reduction in glider mass of 10% allowed the engine power requirement to be reduced by 4.8%, and the battery energy requirement was reduced by 5.2% (Figure 1). Both of these along with the actual glider mass reduction and compounding effects lead to a reduction in total curb mass of 8.1%. The mass reduction affects both electrical consumption and gasoline consumption nearly equally, and the net result is that the operating energy cost drops by 4.1% (Figure 2). The retail cost savings due to powertrain impacts alone of mass reduction was $1031 or 3.4%. Based on the literature, the savings is greater than the cost to implement a 10% reduction in glider mass.

ENGINE EFFICIENCY

Efficiency of the combustion engine in both conventional and hybrid vehicles is critical. Losses in the engine are the single greatest source of inefficiency in vehicles. Hybrid vehicle technology attempts to reduce these losses by allowing engines to operate under greater loads and eliminating low load and idle operation.

In the baseline scenario, a peak engine efficiency of 34% is assumed. This is typical of today's standard gasoline combustion engines. The peak efficiency occurs near 50% of rated power and is significantly lower at lower-load fractions. The engines in the Prius, Camry, and Ford Escape HEVs all use an Atkinson combustion cycle to increase engine efficiency. To determine the relative benefits of engine efficiency improvements in a PHEV, the engine efficiency was increased by 10% from 34% for the baseline to 37% for the engineered scenario.

PHEVs use very little if any gasoline in their initial charge-depleting operating mode but are fully dependent on gasoline in the charge-sustaining operating mode. Changing engine efficiency does not affect component sizing requirements. Therefore, improving engine efficiency simply reduces operating energy costs by reducing gasoline consumption. Gasoline consumption dropped by 9.3% and operating cost dropped by 8% Figure 2). Increasing engine efficiency had negligible impact on the powertrain attributes and thus provides little retail cost savings due to powertrain impacts. It is likely that engine efficiency improvements will be more effectively applied in short-range (equivalent energy of 20 miles or less) PHEVs. If the average daily consumer travel distance is ~30 miles, the engine of a PHEV with 20 miles of energy will be used in charge-sustaining mode (battery state of charge is maintained within a fairly small nominal window) more often as compared to PHEVs with 40 or more miles of energy.

The cost of implementing engine efficiency improvements is uncertain. Lipman and Delucchi [5] suggest that VTEC (variable valve timing and lift electronic control) technology could be implemented at a cost of $360. Since engine efficiency improvements had little impact on retail cost the incremental costs may need to be offset by the reduced operating costs or by reduced retail cost impacts of other platform engineering steps.

PERFORMANCE CONSTRAINT RELAXATION

The baseline performance constraints for acceleration, top speed, and gradeability are detailed in Table 1. For hybrids these define the limits of downsizing the engine. For the midsize sedan, 8.0s 0-60mph acceleration capability is slightly better than the average of ~8.5s. Toyota has demonstrated with their first and second generation Prius models introduced in the United States that vehicles can be introduced and can achieve significant market penetration with less than class average acceleration. The MY2004 Prius was introduced with 0-60mph acceleration time of 10s.

For a PHEV20, reducing the 0-60mph acceleration requirement from 8s to 10s reduces the engine size by 2% (Figure 1). Engine size reduction leads to mass reduction and as a result the battery energy requirement is reduced. The combined impact is ~3.5% reduction in curb mass. Both petroleum and electricity consumption are reduced by 2% (Figure 2). Because both engine and battery sizes can be reduced, the retail costs are reduced by almost 2% or $550. There should be no offsetting technology costs to implement a reduced performance vehicle.

AERODYNAMICS

The impacts of aerodynamic drag are speed dependent and contribute substantially during highway operation. As the powertrain efficiency is improved through hybridization, aerodynamic losses begin to represent a greater share of total losses. A typical midsize sedan will have a drag coefficient of 0.3-0.35. The Honda Insight, Toyota Prius, and Honda Civic HEVs all have lower than class average drag coefficients of 0.25, 0.26, 0.28.[6] The overall body design substantially impacts the aerodynamic drag losses. However, other simpler elements, like the rear spoiler employed on the Civic and Saturn Vue hybrids and aerodynamic hubcaps as employed on the Civic and Insight, also can contribute. Honda went so far as to include body panels to enclose the rear wheels and an enclosed underbody for the Insight.

For this study, the aerodynamic drag coefficient is reduced from 0.3 to 0.27. This is a moderate but significant reduction and within the realm of existing hybrid vehicles. The 10% improvement in aerodynamics leads to a 1.6% reduction in engine power requirement and 2.2% reduction in energy storage capacity requirement (Figure 1). Together, they provide a retail cost reduction of slightly less than 1% or $278 (Figure 2). No attempt has been made to quantify the additional costs of implementing a 10% reduction in aerodynamic drag. Lipman and Delucchi [5] suggest that this can be accomplished for under $176 for a midsize sedan. Aerodynamics biggest impact comes in reducing the energy consumption costs by 3.2%.

ROLLING RESISTANCE

The energy efficiency impacts of rolling resistance are mass dependent and thus affect vehicle efficiency both during urban and highway operation. Again, reduced rolling resistance tire technology has been employed on several of today's HEVs, including the Insight, Prius, and Vue. A report published by Green Seal indicates that low-rolling-resistance replacement tires with acceptable performance and handling characteristics for the midsize car class have values of 0.0102 to 0.0081.[7] Therefore, the reduction from 0.009 to 0.008 rolling resistance coefficient as evaluated in this report is feasible and should have minimal additional cost for implementation. The Green Seal report also highlights that the cost of these quality low-rolling-resistance tires can vary greatly but in general cost nearly the same or just slightly more than traditional tires.

Reduced rolling resistance provides improved operating efficiency across the full operating spectrum allows the battery energy requirement to be reduced by 3.5%. Some mass reduction is observed in addition to a reduction in engine size of 1.3% (Figure 1). Petroleum consumption is reduced by 3% and electricity consumption is reduced by 3.5% (Figure 2). As a result, operating energy costs are also reduced by 3%. The overall system cost is reduced by 1.2% or $362. Because the cost of implementing low-rolling-resistance tires is minimal, these powertrain cost savings could potentially be used to offset the cost of other more costly platform engineering steps.

COMBINED EFFECTS OF PLATFORM ENGINEERING

The impacts of each step of platform engineering has been summarized individually by their contributions to vehicle design and energy efficiency, which impact retail cost and operating cost respectively. The last step in this analysis is to apply all of the platform engineering steps together into a single vehicle and compare it to the base vehicle.

Relative to the base vehicle, the curb mass of the PHEV20 with platform engineering is reduced by 12.5%. The substantial reduction in mass allows both the engine power and battery energy requirements to be reduced by 9.7% and 12.6% respectively. Figure 3 shows that the actual glider mass reduction, the acceleration performance relaxation, and the mass compounding account for more than 75% of the total vehicle mass reduction.

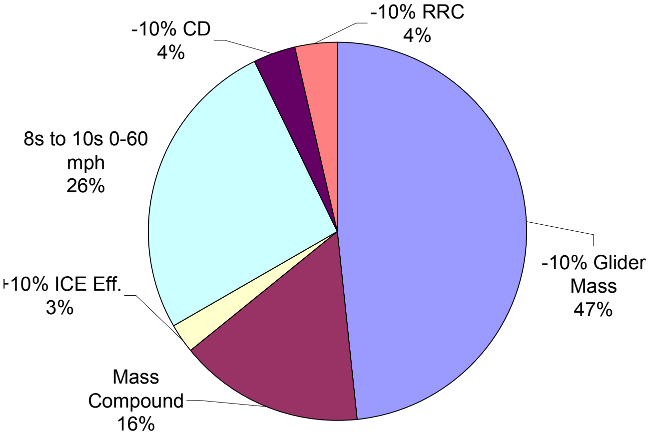

Figure 3: Contributions to Total Mass Reduction

Achieving substantial mass reduction in combination with reducing aerodynamic and rolling resistance losses dramatically reduces the energy capacity requirements for a PHEV. In Figure 4, a PHEV20, 30, and 40 can all reduce their energy capacity by more than 12.5% while the PHEV10 achieves slightly less than 12% reduction. Assuming that the energy battery manufacturing industry for hybrid vehicles will be supply limited, platform engineering becomes extremely important for achieving the greatest reduction in petroleum consumption with a limited supply of energy batteries.

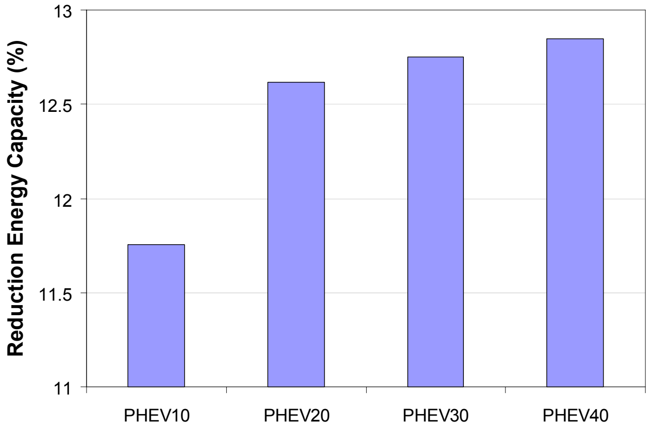

Figure 4: Platform Engineering Reduces PHEV Energy Capacity Requirements

Platform engineering affects the design and efficiency of all vehicle architectures not just PHEVs. Two scenarios for four vehicle architectures are depicted in Figure 5. All four vehicles—conventional, hybrid, PHEV20 and PHEV40—were modeled with the baseline assumptions and with platform engineering implemented. The plot shows the estimated retail cost of each scenario with respect to the annual petroleum consumption of each. The consumption is calculated assuming 15,000 miles of travel per year.

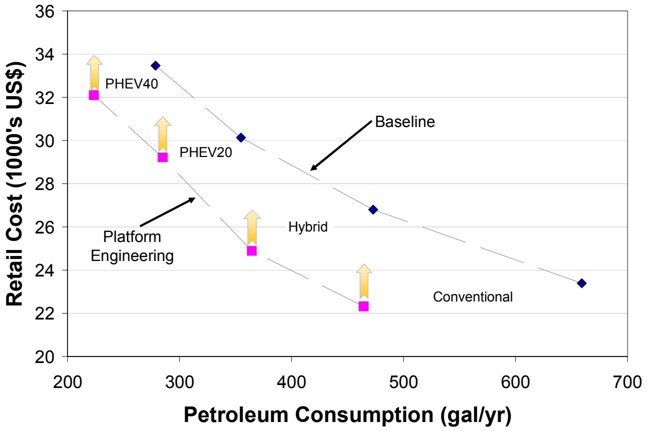

Figure 5: Cost and Consumption Impacts of Platform Engineering

For the platform engineered vehicles, gradiated arrows are drawn to indicate the unquantified additional costs to implement the technology improvements in the vehicle. For each case, moving from the diamond to the corresponding square, there is a retail cost savings due to changes in powertrain ranging from slightly less than $1000 for the PHEV20 to close to $2000 for the HEV. Ideally, the powertrain cost savings would more than offset the platform engineering costs. Based on the literature cited, the cost to implement the platform engineering steps discussed is likely to be ~$1000 with a large window of uncertainty.

The PHEV20 and PHEV40 in the baseline case reduce petroleum consumption by 46% and 58% respectively. Application of platform engineering continues to reduce the petroleum consumption of these vehicles. The PHEV20 with platform engineering achieves nearly the same petroleum consumption reduction as the PHEV40 baseline vehicle. The conventional vehicle with platform engineering achieves petroleum reduction slightly greater than the hybrid baseline. Likewise, the hybrid with platform engineering achieves nearly the same consumption reduction as the baseline PHEV20.

From the chart it seems that PHEVs don't have as much to gain with regard to petroleum consumption from platform engineering steps. However, platform engineering helps PHEVs not only reduce petroleum consumption by 20%, but also reduces their electrical consumption by more than 12.5%. Platform engineering is a cost effective way of making vehicles much more efficient regardless of the source of the energy.

CONCLUSION

Previous analysis used vehicle systems simulation to determine the vehicle design attributes and consumption characteristics for a full spectrum of PHEV scenarios. This study extends the results of the previous work by applying platform engineering and quantifying its impacts on PHEV design and benefits. The impacts of mass reduction, improved engine efficiency, relaxed performance constraints, aerodynamic drag, and rolling resistance improvements were evaluated when applied to conventional, hybrid, and PHEVs.

Various degrees of platform engineering are already employed in energy-efficient vehicles. The magnitude of the improvements considered in this study is similar to those included in available vehicles.

Mass reduction and relaxed performance constraints allow the combustion engine to be downsized. Engine downsizing coupled with improved engine efficiency, aerodynamics, and rolling resistance greatly enhance overall vehicle efficiency. For PHEVs, the improved vehicle efficiency due to platform engineering reduces energy storage system capacity by more than 12%. Platform engineering allows a limited supply of batteries to be used in more PHEVs and thus have a greater impact on total petroleum consumption.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

PHEV*x*: A plug-in hybrid electric vehicle with a usable energy capacity equivalent to x miles of electric operation on a standard urban driving profile. It may or may not travel x miles all-electrically depending on the operating strategy