Impact of Battery Weight and Charging Patterns on the Economic and Environmental Benefits of Plug-in Hybrid Vehicles

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ABSTRACT
Plug-in hybrid electric vehicle (PHEV) technology is receiving attention as an approach to reducing U.S. dependency on foreign oil and emissions of greenhouse gases (GHG) from the transportation sector. Because plug-in vehicles require large batteries for energy storage, battery weight can have a significant impact on vehicle performance: Additional storage capacity increases the range that a PHEV can travel on electricity from the grid; however, the associated increased weight causes reduced efficiency in transforming electricity and gasoline into distance traveled. We examine vehicle simulation models for PHEVs and identify trends in fuel consumption, cost, and GHG emissions for a range of battery capacities and distances traveled between charges. We find that PHEVs consume less gasoline than conventional hybrid electric vehicles (HEVs) when charged every 200 miles or less. Under frequent charges every 25 miles or less small capacity PHEVs consume less gasoline, are less expensive, and release fewer GHGs than HEVs or large capacity PHEVs. For moderate distances of 30-90 miles between charges, PHEVs release fewer GHGs, but HEVs are more cost effective, even under a $100 per metric ton carbon tax. However, future high fuel prices or low-cost batteries can extend the range for which PHEVs are cost-competitive to 50 miles or more, and public infrastructure for charging PHEVs will increase the number of drivers who can charge their vehicles frequently. We conclude that energy policy targeting PHEVs should account for vehicle design tradeoffs and expected charging patterns as well as economic and environmental competitiveness.

Keywords: plug-in hybrid electric vehicles; greenhouse gases, transportation

1 INTRODUCTION

Increasing concerns regarding high oil prices, oil dependency, and climate change have resulted in policymakers and the automobile industry evaluating alternative strategies for passenger transportation. Plug-in hybrid electric vehicle (PHEV) technology offers a possible approach to reducing life cycle GHG emissions and dependency on oil as a transportation fuel via the use of large rechargeable storage batteries that enable electricity from the grid to provide a portion of the propulsion requirements of a passenger vehicle (*1, 2, 3*). Since approximately 60% of the U.S. passenger vehicle miles are traveled by vehicles driving less than 30 miles per day (*4*), PHEVs may be able to displace a large portion of gasoline consumption with electricity. While the U.S. transportation sector is overwhelming powered by petroleum, oil-fired power plants only provide about 3% of U.S. electricity. We explore the impact of PHEV battery capacity on fuel consumption, cost, and GHG emissions benefits for a range of distances traveled between charges. The tradeoffs identified in this analysis can provide a space for policymakers, vehicle manufacturers, and the public on optimal decisions to maximize economic and environmental objectives with PHEVs.

The price differential between retail electricity and gasoline could make electric-powered travel more cost effective than gasoline, depending on the additional vehicle capital costs (*5*). However, the reduced fuel use, economic costs, and GHG emissions of PHEVs depend on the vehicle and battery characteristics, as well as recharging frequency and the source of electricity used for recharging. For example, the full life cycle GHG emissions associated with manufacturing and operating a PHEV could be close to that of traditional hybrids under the current U.S. mix of electricity generation (*3*). Trends in electricity generation, battery manufacturing, and vehicle design have critical implications on the relative advantages of PHEVs.

All PHEVs have a drivetrain that incorporates an electric motor and an internal combustion engine (ICE), and like conventional hybrid electric vehicles (HEVs) these components can be arranged in series, parallel, or split series/parallel configurations (*6, 7*). A split series/parallel powertrain, such as the one used in the popular Toyota Prius, uses a planetary gear system power split device and a separate motor and generator to allow the engine to provide torque to the wheels and/or charge the battery through the generator, depending on use conditions. The split drivetrain can take advantage of series and parallel benefits, but it requires more components. We take the split drivetrain configuration of the Prius as the baseline HEV and examine PHEV versions sized for 20, 40, and 60 miles of electric vehicle range with comparable performance characteristics.

The battery of a PHEV, which can be recharged using regular electrical outlets, would allow the vehicle to drive for a limited range using the energy from the electricity grid. A fully charged PHEV operates in *charge-depleting mode* until the battery is depleted to a target state of charge (SOC), typically 20%-25%, at which point the vehicle switches to *charge-sustaining mode*, using the engine to maintain the target SOC. A PHEV can be further categorized as 1) *range-extended* or 2) *blended*, depending on its energy management strategy in the charge-depleting state (*7*). A range-extended PHEV functions as a pure electric vehicle (EV) in charge-depleting mode, using only electrical energy from the battery for propulsion and disabling any engine operation. Blended PHEVs invoke a strategy where the motor provides primary power in charge-depleting mode, but the engine is used as needed to provide additional power. In the charge-sustaining state, all PHEVs operate similarly to a standard HEV, using the engine to maintain the target battery SOC. For simplicity and fair comparisons, we restrict attention to the range-extended PHEVs that run in pure EV mode in the charge-depleting range and switch to HEV-mode in the charge-sustaining range, since the performance of blended configurations can vary widely based on a broad range of control strategy parameters. Figure 1 shows a typical SOC pattern for a range-extended PHEV with an SOC sustaining target of 25%. The ability to operate in EV mode is advantageous for range-extended PHEVs because they are capable of operating for a time entirely on cheaper energy from the electricity grid and producing no tailpipe emissions (*8*).

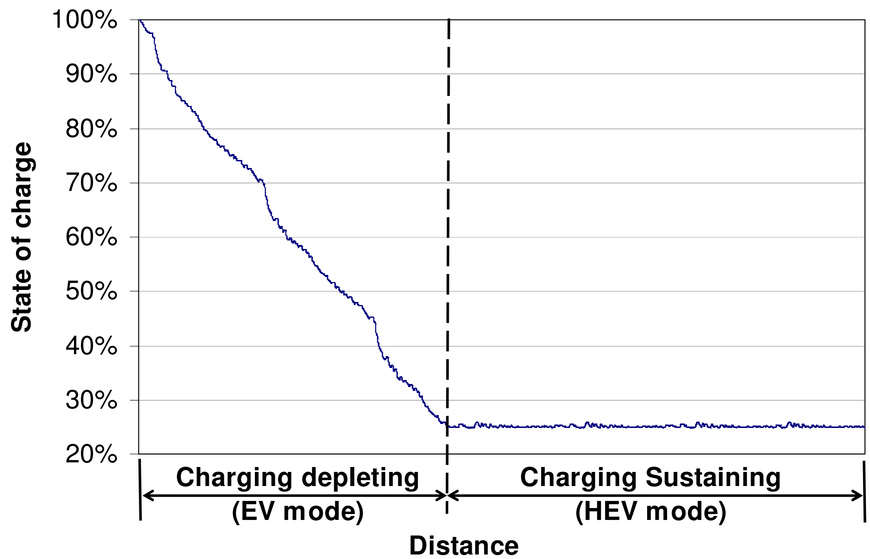

FIGURE 1 Typical SOC of a range-extended PHEV

Since PHEVs rely on large batteries for any economic or environmental benefits relative to traditional hybrids and ICE vehicles, the characteristics, design issues and costs associated with PHEV batteries play an important role in the potential adoption of PHEVs. Overviews of the current state of battery technology for PHEV applications as well as future goals are provided in (*8, 9, 10*). The two dominant battery technologies considered likely candidates for PHEV applications are nickel-metal hydride (NiMH) and lithium-ion (Li-ion) batteries. NiMH batteries have performed well in existing hybrids and electric vehicles (*11*) and have proven reliable in automotive applications. However, their relatively low energy density implies large, heavy batteries for extended electric travel. Li-ion batteries have higher energy densities, but concerns regarding calendar life, safety, and degradation under high temperature still need to be solved (*8, 9*). In spite of these technical difficulties, Li-ion battery has been widely evaluated for its great potential as a PHEV energy storage device (*8, 9, 10*), thus we focus on Li-ion batteries in this study.

Due to data constraints, previous studies evaluating the GHG benefits of PHEVs assumed that the additional weight of potentially large storage batteries did not affect the gasoline fuel economy or the electrical requirements for propulsion (*3*). However, it has been shown that ICE vehicle weight affecting CO_2 emissions (*12*) and increased weight of HEVs causes fuel economy dropped (*13*). Hence, technical sensitivity analysis is warranted to explore the impact of additional battery and potential structural weight on fuel consumption, greenhouse gas emissions, and operating costs of PHEVs.

2 METHOD

2.1 Effects of large batteries on PHEV performance

Conventional vehicles that hold more fuel can travel farther without refueling. Similarly, PHEVs with larger battery capacity can travel farther on electricity before drawing on liquid fuel. However, batteries have a considerably lower energy density than liquid fuel: When a vehicle is filled with 10 gallons of gasoline, it contains approximately 360 kWh of energy embodied in the fuel. The vehicle weighs an additional 28 kg, and it gradually loses those that weight as the fuel is combusted in the engine. A PHEV battery pack may contain 5-27 kWh and weigh 100-600 kg plus the additional structural weight required to carry these batteries, and the vehicle must carry this weight even after the battery is depleted. Additional battery weight decreases the attainable efficiency in miles per kWh in EV mode as well as miles per gallon in HEV mode (i.e.: once the battery is depleted to its lower target SOC). Thus, while increased battery capacity extends EV range, it decreases efficiency in both in EV and HEV modes.

Because extra battery weight may require additional structural support in the vehicle body and chassis, we investigate the effects of additional weight required to support each additional kg of battery and impose a parameter called the *structural weight multiplier*. Via informal discussions with several automakers, we estimate the range of this multiplier is from +0x (no additional weight required) to +2x (two kg of additional structural weight required per kg of battery). The requirement for the additional structural weight is dependent on the vehicle type and its design. We assume that one kg of additional structural weight is required for each kg added to the vehicle (+1x case) as our base case, and we investigate the +0x and +2x cases for the purpose of sensitivity analysis. We also account for the structural weight of larger electric motors required to maintain target performance characteristics in heavier vehicles. Particularly we size the motor of each vehicle such that it can accelerate from 0-60 miles per hour (mph) (0-100 km per hour) in a time comparable to the Prius (10.5 seconds) when the vehicle is in charge sustaining mode.

2.2 Plug-in hybrid vehicle simulation

We use the Powertrain System Analysis Toolkit (PSAT) vehicle physics simulator (*14*) to model and examine design tradeoffs between battery capacity and PHEV benefits. For the PHEV simulations in our study, we used the model year 2004 Toyota Prius as a baseline for engine, body and powertrain configurations. Additional battery capacity was added to the base configuration in order to attain a set of EV range requirements, and the electric motor was scaled to maintain target HEV acceleration time at low SOC. The PSAT split hybrid control strategy for maximum engine efficiency was modified so that the vehicle operates in EV mode without engaging the engine until the battery reaches 25% SOC, after which the vehicle switches to HEV mode and operates like a Toyota Prius, using the split control strategy with a target SOC of 25% and SOC operating range of 20-30%.

In this study, the PHEV design variables are the number of battery cells and the size (power scaling factor) of the electric motor. The engine model is a 1.4 liter four-cylinder engine with a 57 kW maximum power. The base motor is permanent magnet type with a maximum peak power of 52 kW and a weight of 40 kg including a 5kg controller. Performance map and weight characteristics of larger motors needed for the PHEV cases are predicted using a linear scaling parameter. The battery model is based on a Saft Li-ion battery package, where each module is comprised of three cells. The weight of each cell is 0.378 kg, and its capacity is 9.6 Wh with a nominal output voltage 3.6 volt. Accounting for the weight of packaging using a factor of 1.25, the weight of one 3-cell module is 1.42 kg. The total battery size and capacity was scaled by specifying an integer number of battery modules. Additional structural weight in the body and chassis required to support the weight of battery and motor are controlled by the structural weight multiplier. For comparison of the performance between PHEV and HEV, we use the current Prius model as our HEV base case but replace its original NiMH battery and control strategy with Saft Li-ion module and simplified split control strategy in order to make more direct comparisons with PHEV variations. The detailed configurations of the base HEV are shown in the last column of Table 1.

Simulations were performed to test 20-, 40-, and 60-mile EV range PHEVs under three cases of structural weight multipliers +0x, +1x, and +2x. The simulated driving cycle specified to measure fuel efficiency in HEV mode and electricity efficiency in EV mode is the Environmental Protection Agency (EPA) Urban Dynamometer Driving Schedule (UDDS) (*15*), which has been used for fuel economy evaluation and emissions certification of passenger vehicles. In each test, the number of battery modules needed to reach the target EV range was first determined. To compare equivalent-performance vehicles, motor size (power) was then adjusted to achieve a 0-60 mph acceleration time specification of 10.5 +0.0/-0.5 seconds, which is approximately the acceleration performance of a Toyota Prius. This procedure was repeated iteratively until convergence to a vehicle profile that satisfied both targeted electrical range and acceleration for each case, accounting for weight.

2.3 Economic and GHG parameters

The calculations of PHEV operation cost in the study are based on \$0.11 per kWh of delivered retail electricity and \$3.00 per gallon of retail motor gasoline, which were similar to U.S. prices in 2007 (*16*). The total operating cost to travel a particular distance is the sum of the cost of the electricity needed to charge the battery and the cost of the gasoline used. For distances less than the EV range, the battery was only charged as much as needed for the trip. For distances greater than the EV range, the battery was fully charged. Moreover, in order to calculate the vehicle cost, we estimated the vehicle base cost, excluding the Li-ion battery, using the Prius MSRP less its NiMH battery cost of \$3,900 (*17*), resulting in a vehicle base cost of \$17,600. The base battery cost is assumed to be \$1,000 per kWh (*18*), and variations are examined in a sensitivity analysis.

Life cycle GHGs are expressed in kg CO_2-equivalent (CO_2-eq) with a 100-year timescale. The emissions calculations in this study assume 0.670 kg of CO_2-eq emitted per kWh of electricity, 11.34 kg of CO_2-eq per gallon of gasoline and 8,500 kg CO2-eq per vehicle for vehicle manufacturing (excluding emissions from battery production) (*3*). We further assume each kWh of Li-ion battery capacity produced and manufactured creates 120 kg CO2-eq at the battery plant gate (*3*). These values represent the U.S. average life cycle emissions, including combustion and the upstream fuel cycle impacts. For gasoline, 8.81 kg CO_2-eq / gal is generated in combustion and 2.54 CO_2-eq / gal is emitted in the supply chain (*19, 20*).

TABLE 1 Impact of Battery and Structural Weight on Plug-in Hybrid Performance, Fuel consumption, Greenhouse Gas Emissions, and Operation Costs

		Structural weight factor	+0x			+1x			+2x			HEV
		Design EV range (mile)	20	40	60	20	40	60	20	40	60	
Vehicle design	Engine	Engine power (kW)	57	57	57	57	57	57	57	57	57	57
		Weight (kg)	114	114	114	114	114	114	114	114	114	114
	Motor	Motor power (kW)	59	64	70	62	75	92	67	93	133	52.35
		Motor weight (kg)	39	43	47	41	50	62	45	62	89	35
		Controller weight (kg)	6	6	7	6	7	9	6	9	13	5
		Structural weight (kg)	0	0	0	7	17	30	22	62	123	0
		Total weight (kg)	45	49	53	55	75	101	74	133	225	40
	Battery	Number of cells	243	513	804	252	576	978	264	667	1260	75
		Battery volume (m^3)	229	484	758	238	543	923	249	629	1189	71
		Battery capacity (kWh)	5.2	11.1	17.4	5.4	12.4	21.1	5.7	14.4	27.2	1.6
		Battery weight (kg)	115	243	380	119	272	462	125	315	596	35
		Structural weight (kg)	0	0	0	84	237	427	179	560	1121	0
		Total weight (kg)	115	243	380	203	509	889	304	875	1716	35
	Vehicle	Vehicle weight (kg)	1604	1735	1878	1702	2028	2434	1821	2452	3385	1519
Simulation results	EV mode	EV efficiency (mile/kWh)	5.18	4.86	4.65	4.98	4.33	3.81	4.78	3.75	2.96	-
		Simulation EV range (mile)	20.4	40.4	60.6	20.3	40.4	60.4	20.4	40.5	60.4	-
	HEV mode	HEV Efficiency (mpg)	50.2	49.3	48.5	49.1	47.4	45.2	48.3	44.9	39.9	52.8
		HEV 0-60 mph time (sec)	10.1	10.2	10.2	10.2	10.4	10.4	10.3	10.4	10.3	10.5
Estimated costs and GHG emissions	Op. cost ($/mile)	EV mode	0.021	0.023	0.024	0.022	0.025	0.029	0.023	0.029	0.037	-
		HEV mode	0.060	0.061	0.062	0.061	0.063	0.066	0.062	0.067	0.075	0.057
	Op. GHG ems. (kg/km)	EV mode	0.129	0.138	0.144	0.134	0.155	0.176	0.140	0.179	0.227	-
		HEV mode	0.226	0.230	0.234	0.231	0.239	0.251	0.235	0.252	0.284	0.215

3 RESULTS AND DISCUSSION

The final PHEV configuration and simulation results are shown in Table 1, which reveals that additional weight affects EV range, EV-mode electrical efficiency, HEV-mode gasoline fuel efficiency, operation cost per mile, and GHG emissions per mile. Greater motor power is needed to achieve baseline acceleration performance as the vehicle weight increases, although the weight of the larger motor itself is small compared to the additional battery weight. Increased weight also requires more batteries to achieve a target EV range, creating a compounding effect. Further, the additional battery volume of large capacity PHEVs may cause design feasibility issues.

Based on the simulation results of EV and HEV efficiency under fixed 0-60mph acceleration specifications, Figure 2 shows the net effects of increasing EV range on vehicle weight, operation cost per mile and operation-associated GHG emissions per mile. We found that relationships are fairly linear in this range, and increasing the target EV range of a PHEV by one mile results in an additional 4.1 kg of vehicle weight (1.9-6.9 kg), an increase of \$0.17 and 1.03 kg CO_2 per 1000 miles for pure EV mode (up to \$0.36 and 2.16 kg CO_2), and an increase of \$0.13 and 0.49 kg CO_2 per 1000 miles for pure HEV mode (up to \$0.33 and 1.24 kg CO_2), depending on structural weight assumptions. The linear regression functions for the +1x structural weight case are:

$$\begin{aligned} c_{\text{OP-EV}} &= 0.017 d_{\text{EV}} + 1.86 \\ c_{\text{OP-HEV}} &= 0.013 d_{\text{EV}} + 5.83 \\ v_{\text{OP-EV}} &= 0.103 d_{\text{EV}} + 11.3 \\ v_{\text{OP-HEV}} &= 0.049 d_{\text{EV}} + 22.1 \end{aligned} \tag{1}$$

where $c_{\text{OP-EV}}$ and $c_{\text{OP-HEV}}$ are the operation cost per 100 mile under EV and HEV mode respectively, $v_{\text{OP-EV}}$ and $v_{\text{OP-HEV}}$ are operation GHG emissions in kg CO_2-eq per 100 mile in EV and HEV mode respectively, and d_{EV} is the EV range in miles. It should be noted that while costs and GHG emissions both increase with EV range in EV and HEV modes, this does not imply that total cost and emissions will increase, since PHEVs with larger EV ranges can travel more miles on low cost, low GHG electricity. In the following sections, we examine the effect of EV range and distances traveled between charges on fuel economy, operating cost, and GHG emissions.

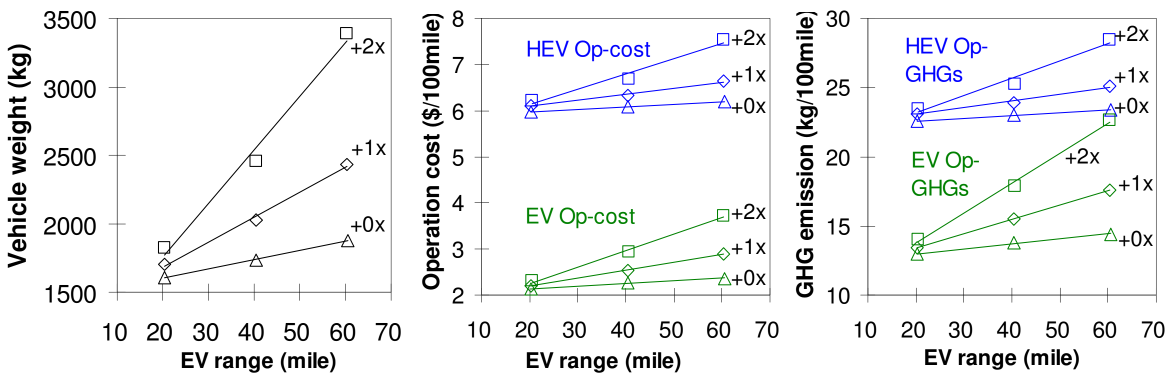

FIGURE 2 EV range effect on vehicle weight, operation cost and GHG emissions

3.1 Fuel economy

The results of hybrid-mode fuel economy (HEV efficiency) in Table 1 show that as the target EV range increases from 20 miles to 60 miles, hybrid mode fuel efficiency decreases 8% from 49.1 miles per gallon (mpg) to 45.2 mpg in the +1x base case due to increased weight. Larger capacity PHEVs can travel for a longer electrical range without burning gasoline, but they consume more gasoline than smaller PHEVs once the battery is drained. This effect is reduced under lower structural weight assumptions and amplified for larger structural weight. The average fuel consumption per mile g is calculated as:

$$g = \frac{1}{d}\left(\frac{d_{\text{HEV}}}{\eta_{\text{HEV}}}\right) \tag{2}$$

where d is the distance traveled between charges, d_{HEV} is the distance traveled in HEV mode, and η_{HEV} is the fuel efficiency in HEV mode. Figure 3 shows the average fuel consumption per mile for each case as a function of the distance traveled between charges. Below the EV range in each case, the vehicle consumes no gasoline. Beyond the EV range, fuel is consumed at a greater rate for the heavier vehicles. The graph shows that larger capacity PHEVs consume less gasoline as long as the vehicle is charged every 300 miles or less (~220 miles in the +2x case and > 400 miles in the +0x case). Given such long distances, it is clear that larger capacity PHEVs will reduce gasoline consumption in most use conditions.

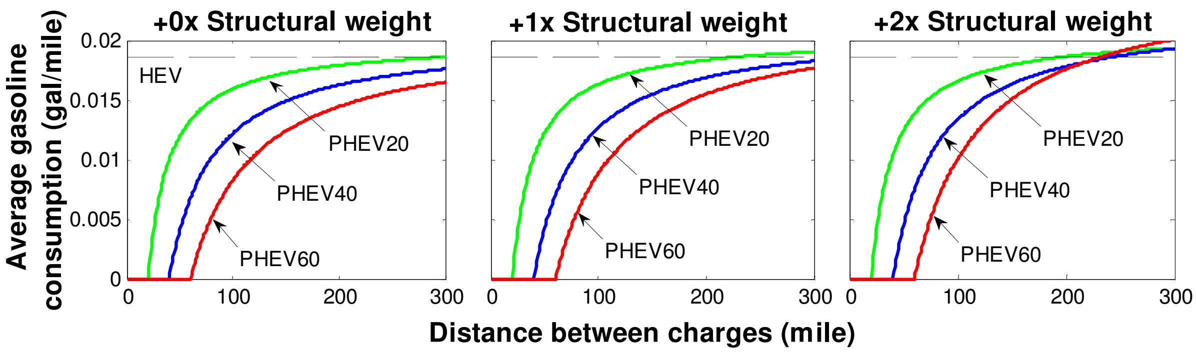

FIGURE 3 Average fuel consumptions per mile

3.2 Cost per distance traveled

The average operation cost represents the average consumer expense per mile associated with fuel. The equation of the average operation cost c_{OP} is given by:

$$c_{\mathrm{OP}} = \frac{1}{d}\left(\frac{d_{\mathrm{EV}}}{\eta_{\mathrm{EV}}} c_{\mathrm{ELEC}} + \frac{d_{\mathrm{HEV}}}{\eta_{\mathrm{HEV}}} c_{\mathrm{GAS}}\right) \tag{3}$$

where d_{EV} and d_{HEV} are the distances traveled in EV mode and HEV mode and η_{EV} and η_{HEV} are the EV electrical efficiency and HEV gasoline efficiency. The cost estimation section in Table 1 shows the average operation cost per mile for EV mode and HEV mode for the three structural weight multiplier cases, assuming an electricity cost c_{ELEC} of \$0.11 per kWh and a gasoline cost c_{GAS} of \$3 per gallon. Larger capacity PHEVs are heavier, thus increasing the operation cost in both EV and HEV mode; however, they also extend the distance that the vehicle operates in the less-expensive EV mode. The average total cost per mile is then calculated by adding the average operation cost and the life-time average vehicle cost per mile with ignoring the time value of money here for simplicity. The equation is given by:

$$c_{\mathrm{TOT}} = c_{\mathrm{OP}} + \frac{1}{d_{\mathrm{LIFE}}}\left(c_{\mathrm{VEH}} + c_{\mathrm{BAT}}\kappa\right) \tag{4}$$

where d_{LIFE} = 150,000 miles is the assumed vehicle lifetime mileage, c_{VEH} = \$17,600 is the vehicle base cost (excluding the battery), c_{BAT} = \$1,000 per kWh is the battery cost in unit capacity, and κ is the battery capacity in kWh. The resulting graphs are shown in the first row of Figure 4. The curves in three structural weight cases represent that PHEV20 has slight cost advantage for short distances travel between changes and HEV is cheaper for longer driving distances, while the PHEV40 and PHEV60 are more costly, especially as structural weight increases.

We further perform a sensitivity analysis by considering scenarios of high gas prices, a hypothetic CO_2 tax, and low-cost batteries. Figure 4 shows the responses to a high gasoline price of \$6 per gallon. Compared to the base case of \$3 per gallon, the high gasoline price increases the cost-competitiveness of the PHEVs, making the PHEV20 a clear economic choice for trips less than 50 miles. However, the larger PHEVs remain dominated by alternatives. The second scenario is a CO_2 tax on life cycle GHG emissions, including production and use phases (details in Section 3.3), with a high taxation rate of \$100/metric ton imposed (*21*). The graphs in Figure 4 show that the CO_2 tax offsets the base cost curves and increases the overall costs of all vehicles, but the regulation increases economic competitiveness of PHEVs only slightly. The third scenario examines the availability of low-cost battery technology. Assuming a low-cost battery with \$250 per kWh (*9*) available for hybrid vehicle applications, Figure 4 shows that the cost differences among various hybrid vehicles are significantly reduced, and PHEVs becomes more economically competitive. However, the large PHEV (PHEV60) is still more expensive than conventional HEV in the tested range of 100 miles. Overall, under various scenarios and different structural weights, small PHEV possesses superior cost performance for short charging intervals.

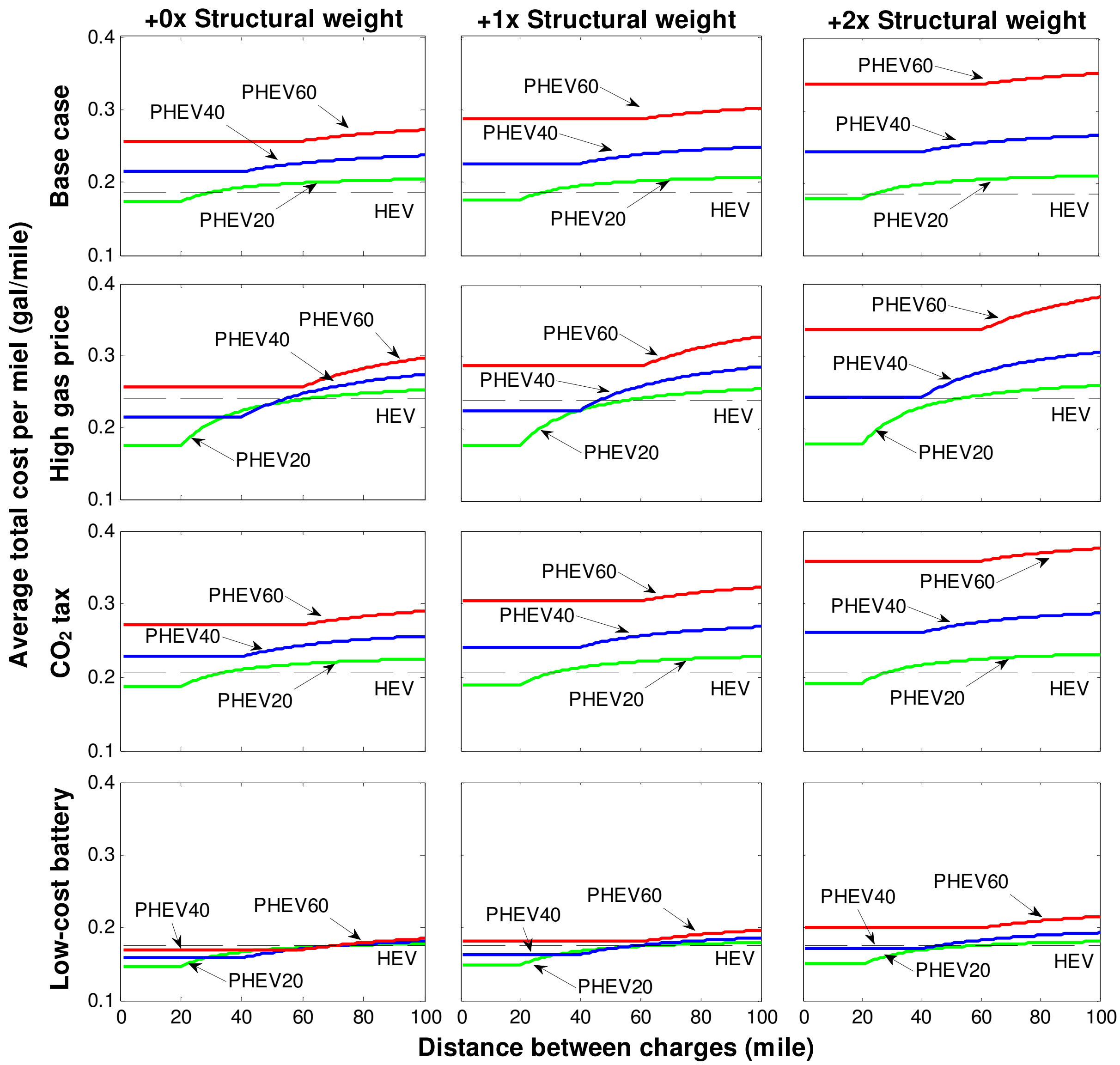

FIGURE 4 Average cost per mile under various scenarios

3.3 GHGs per distance traveled

Greenhouse gas emissions were calculated including combustion and supply chain emissions associated with electricity v_{ELEC} = 0.670 kg CO_2-eq / kWh and gasoline v_{GAS} = 11.34 kg CO_2-eq / gal, as described previously. The average operation-associated GHG emissions per mile v_{OP} is calculated by:

$$\nu_{\text{OP}} = \frac{1}{d}\left(\frac{d_{\text{EV}}}{\eta_{\text{EV}}}\nu_{\text{ELEC}} + \frac{d_{\text{HEV}}}{\eta_{\text{HEV}}}\nu_{\text{GAS}}\right) \tag{5}$$

Table 1 lists GHG emissions per mile for each case in both EV mode and HEV mode. The data show that the average life cycle GHG emissions associated with driving in HEV mode are roughly 1.2 to 1.7 times as those associated with EV mode. The total GHG emissions per mile includes the operation GHG emissions plus the emissions associated with vehicle and battery manufacturing:

$$\nu_{\text{TOT}} = \nu_{\text{OP}} + \frac{1}{d_{\text{LIFE}}}\left(\nu_{\text{VEH}} + \nu_{\text{BAT}}\kappa\right) \tag{6}$$

where ν_{VEH} = 8,500 kg CO_2-eq is assumed the life cycle GHG of a vehicle not including battery and ν_{BAT} = 120 kg CO_2-eq per kWh is the life cycle GHG emissions of batteries (*3*).

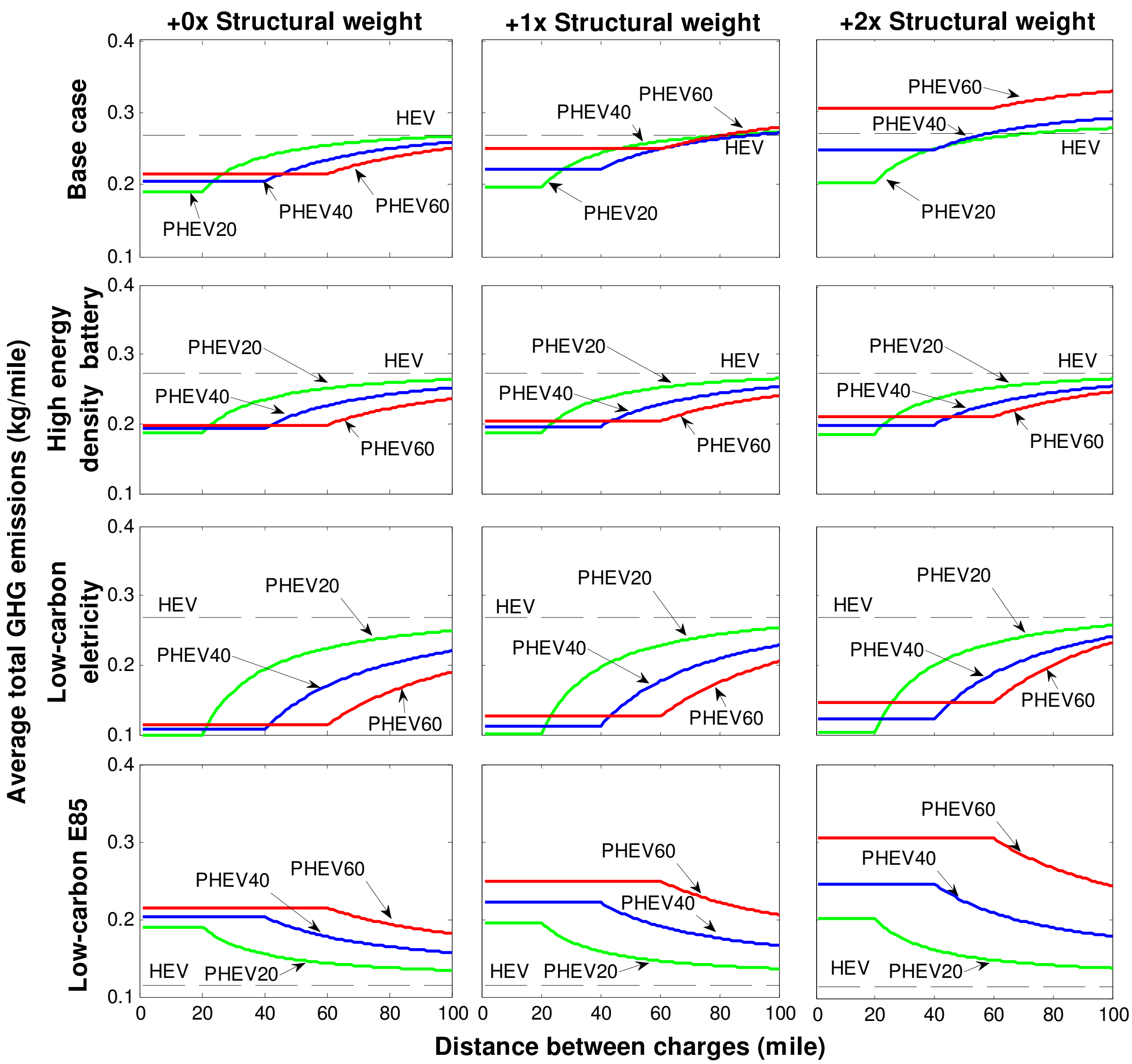

FIGURE 5 Average total GHG emissions under various scenarios

The resulting total GHG emissions are shown in Figure 5. Inclusion of manufacturing emissions affects the larger capacity PHEVs most; however, general trends are similar, and the PHEV20 dominates for small trips. We further conduct the sensitivity analysis with three scenarios, including high energy density battery technology, low-carbon electricity and a low-carbon cellulosic ethanol blend fuel (85% ethanol with 15% gasoline, E85). The graphs in Figure 5 show the total GHG emissions using a target battery with a high specific energy of 140 Wh/kg (*22*). High energy density implies reduced battery weight, which lowers emissions associated with all PHEVs such that they dominate HEVs. This trend demonstrates importance of reducing battery weight and improving energy density to make larger PHEVs environmentally competitive. The second scenario uses low-carbon electricity with an average emissions 0.20 kg per kWh. Use of low carbon electricity sources greatly increases environmental competitiveness of PHEVs. The final scenario assumes that cellulosic E85 fuel is used to replace gasoline in HEVs and PHEVs. We assume that low-carbon ethanol in E85 is processed from low-input switchgrass biomass (*23*) with GHG emissions of 120 CO_2-eq per liter. Further, we account for a 27% drop on the HEV fuel economy when using E85 fuel, due to the energy density differences between ethanol and gasoline (*24*). Figure 5 shows that the cellulosic E85 fuel results in HEVs emitting less CO_2 than PHEVs. Generally, PHEVs will offer reductions in CO_2 emissions over a wide range of distances between charges; however, the degree of benefit and the relative competitiveness of larger capacity PHEVs will depend on battery technology and infrastructural choices for electricity generation and liquid fuel production.

3.4 Vehicle selection decisions

Figure 6 summarizes the best vehicle choice for minimizing fuel consumption, cost, or greenhouse gasses as a function of the distance the vehicle will be driven between charges. We focus on the +1x structural weight case and examine sensitivity of results to potential future trends that can be influenced by policy. For short distances between charges, the PHEV20 is the robust choice for minimizing gasoline consumption, cost, and emissions except in the case of low-carbon cellulosic E85 fuel replacing gasoline. A low-carbon liquid fuel implies that PHEVs will increase carbon emissions relative to HEVs and conventional vehicles; however, the E85 case uses GHG emissions figures from (*23*), which may be optimistic given recent findings on land use implications for CO_2 (*25, 26, 27*). If cellulosic ethanol results in greater CO_2 per mile than average electricity, results are similar to the other cases. For moderate to long distances of 55-100 miles between charges, HEVs are more cost effective even under a $100 carbon tax, while PHEVs release fewer GHG. However, high gas prices or inexpensive batteries can make PHEVs economically competitive over a wider range. High density batteries or low carbon electricity could make larger PHEVs more environmentally competitive at these distances, but they would remain less cost effective than HEVs. HEVs (or conventional vehicles, not shown) remain the clear economic choice for drivers who do not charge their vehicles frequently.

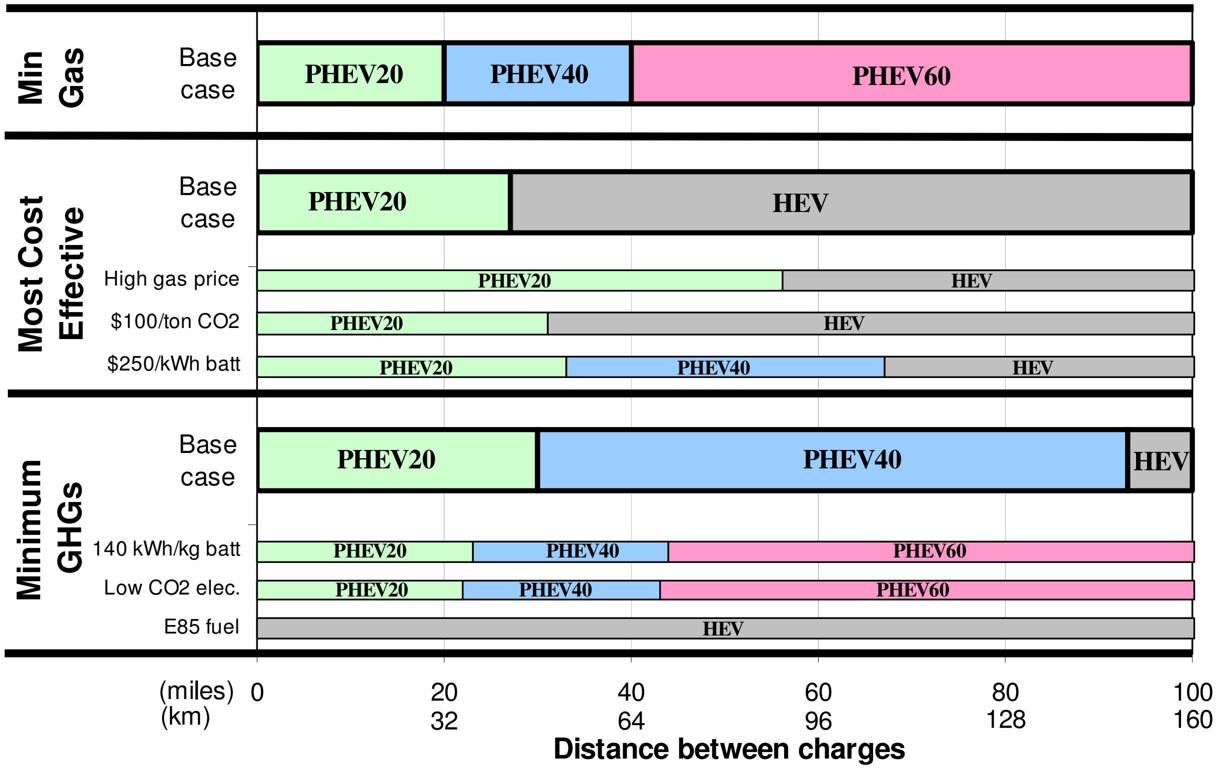

FIGURE 6 Ranges of best vehicle choices for minimum gasoline consumption, cost, and greenhouse gas emissions

4 SUMMARY AND CONCLUSIONS

Our study results indicate that battery weight is a key factor affecting the cost, emissions, electrical efficiency and fuel economy of PHEVs. The best choice of PHEV battery capacity depends on the distance that the vehicle will be driven between charges, the weight of the batteries, and the structural weight needed to support them. Because nearly 50% of U.S. passenger vehicle miles are traveled by vehicles driving less than 20 miles per day (*3, 4*), there exists potential to reduce cost and GHG emissions by sizing battery capacity properly: Our results suggest that a low-capacity PHEV sized for about 20 miles of EV-mode travel would be a robust choice for minimizing gasoline consumption, cost, and greenhouse gas emissions. Indeed, planned production PHEVs, including the Toyota Prius plug-in (*28*), the Saturn Vue plug-in (*29*), and the Chevy Volt (*30*), have target EV-ranges between approximately 8 and 40 miles.

Three potential complications arise when sizing PHEVs based on the number of miles that drivers travel: 1) if the variance in miles traveled per day is large, then a capacity designed for the average distance may be suboptimal; 2) it is unclear whether it is safe to assume that drivers will consistently charge their vehicles once per day – irregular charging behavior could lead to significantly longer distances between charges than the average daily distances would suggest; and conversely, 3) widespread installation of charging infrastructure in public parking places would enable charging more than once per day, enabling shorter distances between charges.

Higher density batteries would mitigate some of the loss in energy efficiency associated with increased EV range. The default battery examined in the PSAT model is a SAFT Li-ion module with a pack energy density of 46 Wh/kg. Based on the future goal for a PHEV battery with a 40-mile EV range (*22*), a target pack energy density of 140 Wh/kg was used for the optimistic case evaluation in the study. If this goal were achieved, the battery weights in this analysis would be reduced 50-70%, improving fuel economy up to 5%, operating costs by up to 20%, and GHGs by up to 30%.

These results lead us to make several recommendations: First, ignoring the effect of battery weight on vehicle efficiency may overestimate the benefits of PHEVs, particularly for larger, heavier batteries and cases that require substantial structural weight. This effect calls for greater attention and technical sensitivity analysis in PHEV studies. Battery weight can lower a vehicle's fuel economy by as much as 20% when operating in hybrid mode. While the importance of hybrid-mode fuel efficiency is mitigated for frequent charges, it dominates when vehicles are driven longer distances. Automakers may be able to reduce PHEV weight by incorporating batteries into existing frame and shell elements where possible, which could contribute substantially to reducing the effect of structural weight. Second, battery cost is currently very high, and government incentives or technological breakthroughs may make the difference as to whether or not early PHEVs will be adopted at a significant scale. Lemoine et al. argue that in order for PHEVs to be economically competitive with conventional vehicles and HEVs (accounting for lower PHEV fuel costs and higher purchase prices), lower battery pack costs would be necessary, with current battery prices exceeding $1000/kWh (*18*). We show that a targeted mass-production battery cost of $250/kWh (*9*) can make PHEVs economically competitive for drivers who travel up to 65 miles between charges. In comparison, advanced batteries with higher energy densities would reduce GHG emissions but may not significantly improve the economic competitiveness of PHEVs. Policies that encourage research into improving energy density alone may have difficulty promoting market penetration of PHEVs, while policies that target cost-reducing innovations would encourage adoption of PHEVs. However, because goals of reducing cost, GHG emissions and fuel consumption are well-aligned for drivers who will charge frequently, economic interest may lead to environmental solutions for these drivers if policies promote appropriate infrastructure and initial sales, for example through government fleet purchases.

Further research is needed to determine appropriate projections for the distribution of miles that PHEV drivers will travel between vehicle charges. Infrastructure advancements, such as automatic charging connections installed in garages or designated public parking spaces, may help to ensure frequent charging and increase the number of drivers for whom small capacity PHEVs are competitive; however, in the near-term it may be unrealistic to assume that consumers will charge their vehicles every night, despite the economic benefit. Because economic, environmental, and fuel consumption implications of PHEVs are sensitive to this variable, research to better understand and predict driver behavior is warranted. Finally, the role of government incentives and consumer preferences in bringing PHEV technology to market will have a substantial impact on PHEV designs chosen by automakers (*31*). Examining the relative importance to consumers of attributes such as purchase cost, operating cost, acceleration, and charging requirements will shed greater light on which vehicles may emerge as successful in the competitive marketplace.

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