



Technology Improvement Pathways to Cost-Effective Vehicle Electrification

Preprint

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*To be presented at SAE 2010 World Congress
Detroit, Michigan
April 13-15, 2010*

Conference Paper
NREL/CP-540-47454
February 2010

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ABSTRACT

Electrifying transportation can reduce or eliminate dependence on foreign fuels, emission of green house gases, and emission of pollutants. One challenge is finding a pathway for vehicles that gains wide market acceptance to achieve a meaningful benefit. This paper evaluates several approaches aimed at making plug-in electric vehicles (EV) and plug-in hybrid electric vehicles (PHEVs) cost-effective including opportunity charging, replacing the battery over the vehicle life, improving battery life, reducing battery cost, and providing electric power directly to the vehicle during a portion of its travel. Many combinations of PHEV electric range and battery power are included. For each case, the model accounts for battery cycle life and the national distribution of driving distances to size the battery optimally. Using the current estimates of battery life and cost, only the dynamically plugged-in pathway was cost-effective to the consumer. Significant improvements in battery life and battery cost also made PHEVs more cost-effective than today's hybrid electric vehicles (HEVs) and conventional internal combustion engine vehicles (CVs).

INTRODUCTION

It has been well documented that the United States (U.S.) is faced with a transportation energy problem. The transportation sector is almost entirely dependent on a single fuel – petroleum. The future of the petroleum supply and its use as the primary transportation fuel threatens both personal mobility and economic stability. The U.S. currently imports nearly 60% of the petroleum it consumes and dedicates more than 60% of its petroleum consumption to transportation [1]. As domestic production of petroleum steadily declines and U.S. consumption continues to climb, imports will continue to increase. Internationally, the growing economies of China and India continue to consume petroleum at rapidly increasing rates. Many experts are now predicting that world petroleum production will peak within the next 5-10 years [2]. The combination of these factors will place great strain on the supply and demand balance of petroleum in the near future.

Hybrid electric vehicle (HEV) technology presents an excellent way to reduce petroleum consumption through efficiency improvements. HEVs use energy storage systems combined with electric motors to improve vehicle efficiency by enabling engine downsizing and by recapturing energy normally lost during braking events. A typical HEV will reduce gasoline consumption by about 30% over a comparable conventional vehicle. This number could approach 45% with additional improvements in aerodynamics and engine technology. Since their introduction in the U.S., HEV sales have grown at an average rate of more than 60% per year [3]. However, after 10 years of availability, they represent less than 1% of the total U.S. vehicle fleet [3]. There are 237 million vehicles on the road today and more than 16 million new vehicles sold each year [4]. Each new vehicle

(the vast majority of which are non-hybrids) will likely be in use for more than 15 years [5]. With continued growth in the vehicle fleet and in average vehicle miles traveled (VMT), even aggressive introduction rates of efficient HEVs to the market will only slow the increase in petroleum demand. Reducing U.S. petroleum dependence below present levels requires vehicle innovations beyond current HEV technology.

Plug-in electric vehicle (EV) and plug-in hybrid electric vehicle (PHEV) technologies are options with the potential to displace a significant portion of transportation petroleum consumption by using electricity for all or portions of given trips. Plug-in electric vehicles use an electric motor powered by an energy storage system and only use electricity from the utility grid. A plug-in hybrid electric vehicle is an HEV with the ability to recharge its energy storage system with electricity from the utility grid. With a fully-charged energy storage system, a PHEV will bias toward using electricity over liquid fuels. A key benefit of plug-in electric and plug-in hybrid electric technologies is that the vehicle is no longer dependent on a single fuel source. The primary energy carrier would be electricity generated using a diverse mix of domestic resources including coal, natural gas, wind, hydro, and solar energy. In the PHEV case the secondary energy carrier would be a chemical fuel stored on the vehicle (i.e., gasoline, diesel, ethanol, or even hydrogen).

EV and PHEV technologies are not without their own technical challenges. Energy storage system cost, volume, and life are the major obstacles that must be overcome for these vehicles to succeed. Nonetheless, these technologies provide a relatively near-term possibility for achieving petroleum displacement. One of the key factors in assessing the potential fuel use reductions of EVs and PHEVs is to assess their fuel use relative to specific configurations and component sizes (energy storage trade-offs) and how they compete with both conventional vehicles and other advanced technology vehicles, such as HEVs, in terms of cost, performance, and petroleum displacement potential. By doing this relative comparison, cost-effective pathways to vehicle sector electrification can be identified.

APPROACH

There are many possible pathways to cost-effective vehicle electrification. This study evaluates a variety of scenarios and technology improvements. Prior to the analysis the vehicle performance, cost, and battery life models were checked to match today's technologies and cost. Next, a variety of vehicle electrification scenarios were run. One scenario sized the battery to last for the life of the vehicle. A second assumed battery replacement: that the battery will be replaced during the life of the vehicle. A third scenario assumed opportunity charging: that the vehicle will be able to recharge after every trip rather than just at the end of the day. A fourth assumed both battery replacement and opportunity charging. These scenarios were then all rerun with improvements in battery cost or battery life. In each case they are all compared to conventional vehicles and HEVs.

ESTIMATING COST

A large share of the market needs to switch to electric vehicles to realize the national and global benefits of vehicle electrification. According to the J.D. Power and Associates 2008 Alternative Powertrain Study, most people will purchase a fuel saving vehicle if the fuel savings will pay back the extra upfront cost [6]. Alternatively, most would not be willing to purchase a fuel saving vehicle if it didn't provide payback [7]. Therefore, this study uses the cost-effectiveness as a metric to reflect the potential to successfully achieve the individual, national, and global goals.

The cost-effectiveness is estimated by comparing the net present vehicle and fuel cost of each electric vehicle against today's options. Since insurance, maintenance, and repairs have not been consistently higher or lower for advanced vehicles such as HEVs [8], they were not included.

Component costs were based on previous study estimates [9, 10] as shown in Table 1. The exception is the \$700/kWh [11] battery energy cost coefficient. This was calibrated to match estimates of a range of today's HEV, PHEV, and EV vehicles, as seen in Figure 1.

Table 1. Component manufacturing cost and markup factor applied to calculate price to consumer.

Battery	\$22/kW + \$700/kWh + \$680
Motor and controller	\$21.7/kW + \$425
Engine	\$14.5/kW + \$531
Markup factor	1.75

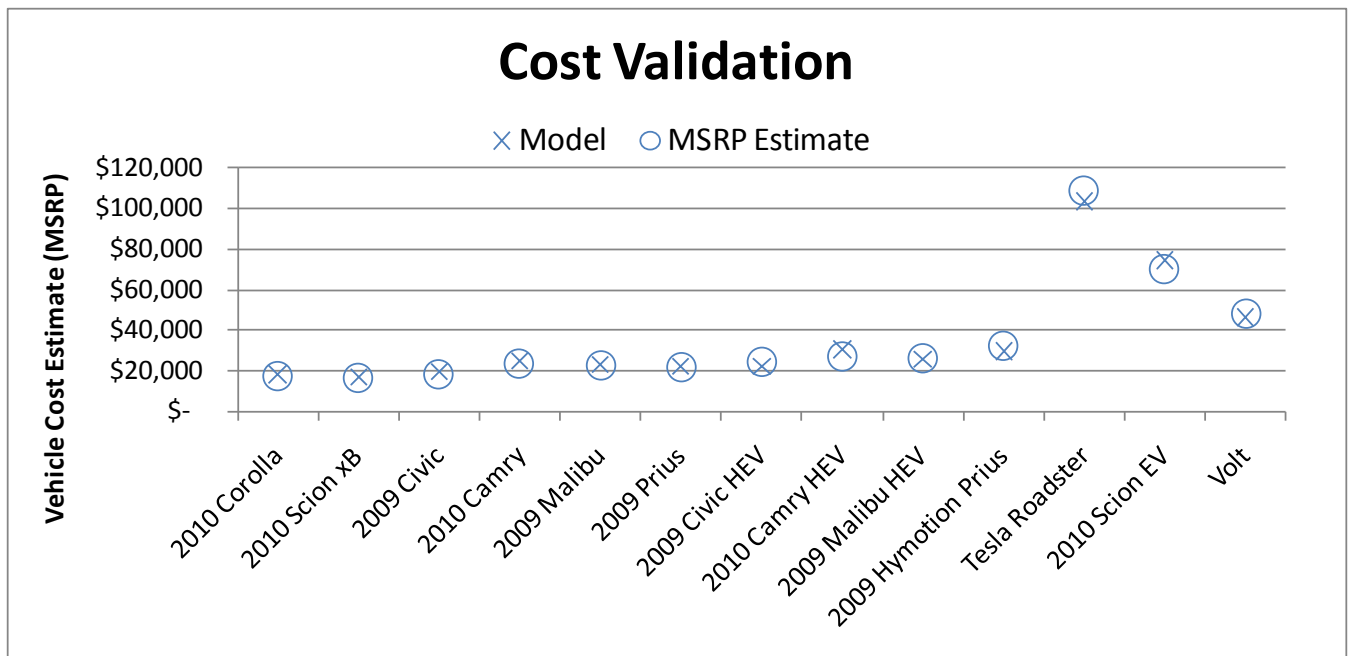


Figure 1. Vehicle cost validation.

The last three vehicle prices are much higher than the others. The Tesla Roadster is listed at \$109,000 [12]. The Scion EV, known as the E-Box, was a conversion of a roughly \$15,000 Scion by AC Propulsion for \$55,000 [13]. The estimated Volt manufacturer suggested retail price (MSRP) estimate of \$48,000 is based on the cost that would be required to make it profitable today [14], not the \$40,000 (\$32,500 after tax incentive) it is expected to sell for [14].

The conventional vehicle costs are used to estimate the HEV, PHEV, and EV costs. The engine cost is subtracted from the conventional vehicle price. Then the advanced vehicle component costs are added. This approach matched closely for a range of advanced vehicles with different component sizes.

UNIQUE IMPROVEMENTS

This study expands on previous efforts. As in previous studies, it accounts for the impact of larger batteries on cost, weight, and performance using a vehicle model. In addition, it improves on other aspects including the driving distance assumption, battery life, battery sizing, battery use strategy, and the method for estimating fuel economy. It also looks at another method of plugging-in, connecting electrically along the roadway while driving.

Distribution of Driving Distances

This study's assumption for driving distance between recharge expanded the constant distance assumption from other studies [15, 16] to a distribution of distances. This had important impacts on battery life, control strategies, and fuel economy. A constant distance is often used to represent a consistent commuting distance. Commuting, however, only represents one third of the miles driven [17]. Therefore, most driving may not be a consistent distance. To improve this assumption, this study uses a distribution of daily driving distances based on national statistics [17]. Figure 2 was generated using the 2001 National Household Travel Survey (NHTS) DAYPUB database and filtering consistent with SAE J2841. The frequency of occurrence assumed 2-mile bins, which was required to capture the maximum daily driving distance of 1200 miles. While long trips are infrequent, they are important because their length can make them a significant portion of the total miles traveled.

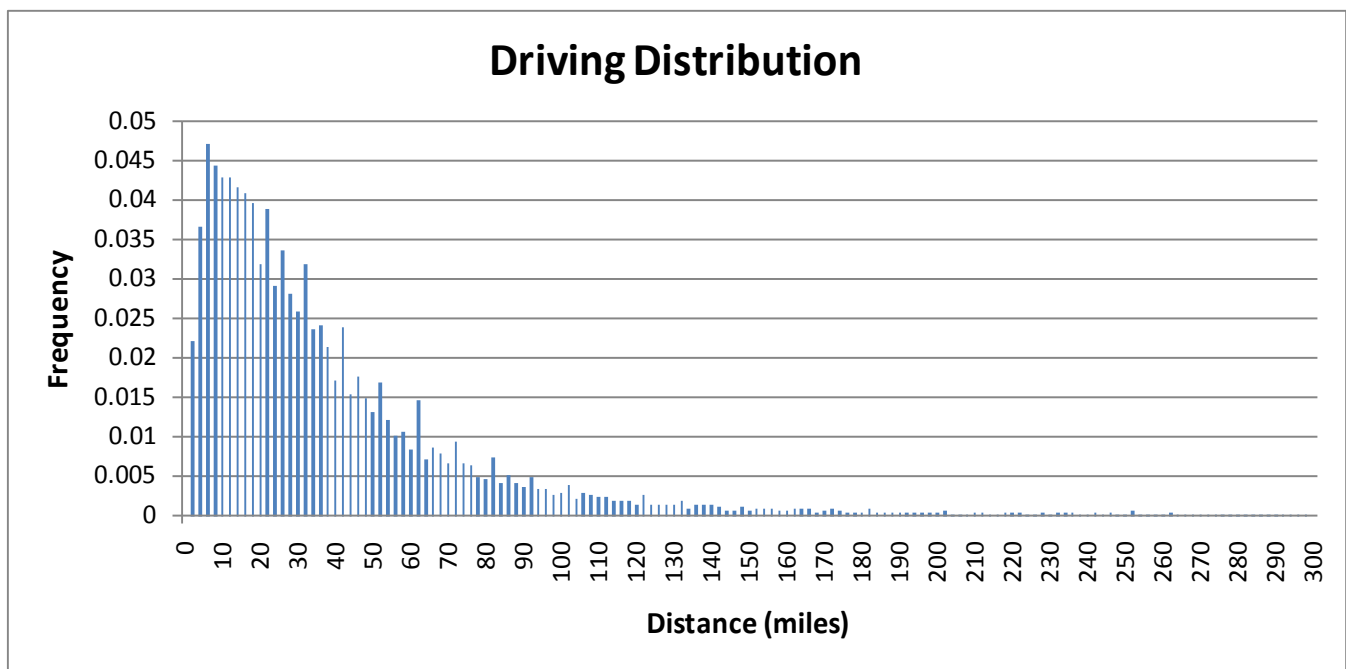


Figure 2. Distribution of daily driving distances.

The long trips reduce the average PHEV fuel economy. Therefore, it could be argued that PHEVs shouldn't be used for long trips. However, PHEVs still have high efficiency after the charge depleting range, similar to an HEV. Therefore, using them on long trips saves fuel relative to conventional vehicles to help capitalize on the higher initial cost.

EVs cannot travel many of the long distances without recharging. For daily driving distances greater than the electric range, this study assumes that the vehicle recharges each time it reaches its maximum range. This increases the frequency of daily driving distances at the maximum EV range, as seen in Figure 3. This is an optimistic assumption for EVs because it assumes greater use than is likely, and thus higher fuel cost savings, for EVs. It assumes greater use than likely would occur because people may use a different vehicle for long trips to avoid having to stop along the way and take the time to recharge.

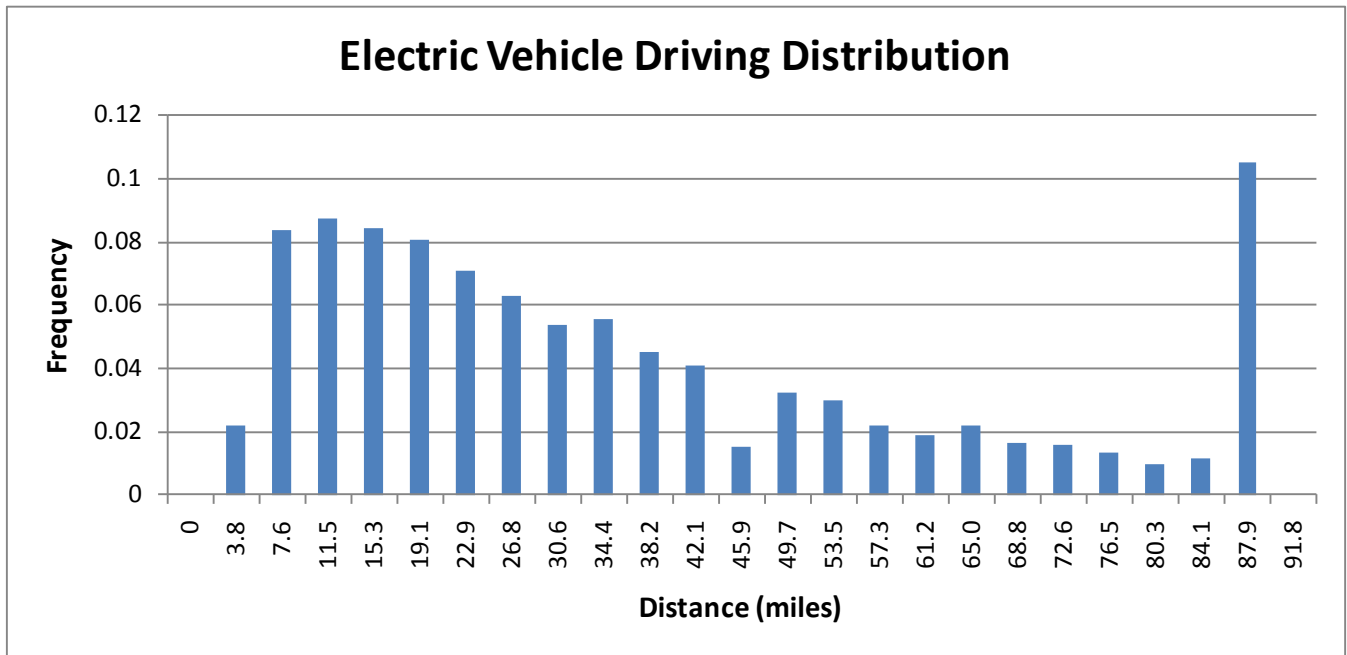


Figure 3. EV driving distribution between recharge events.

The opportunity charging scenario assumed charging after each trip instead of daily charging resulting in a different distribution of driving between recharges, as seen in Figure 4. The shift increases the amount of driving done electrically, especially for shorter range PHEVs.

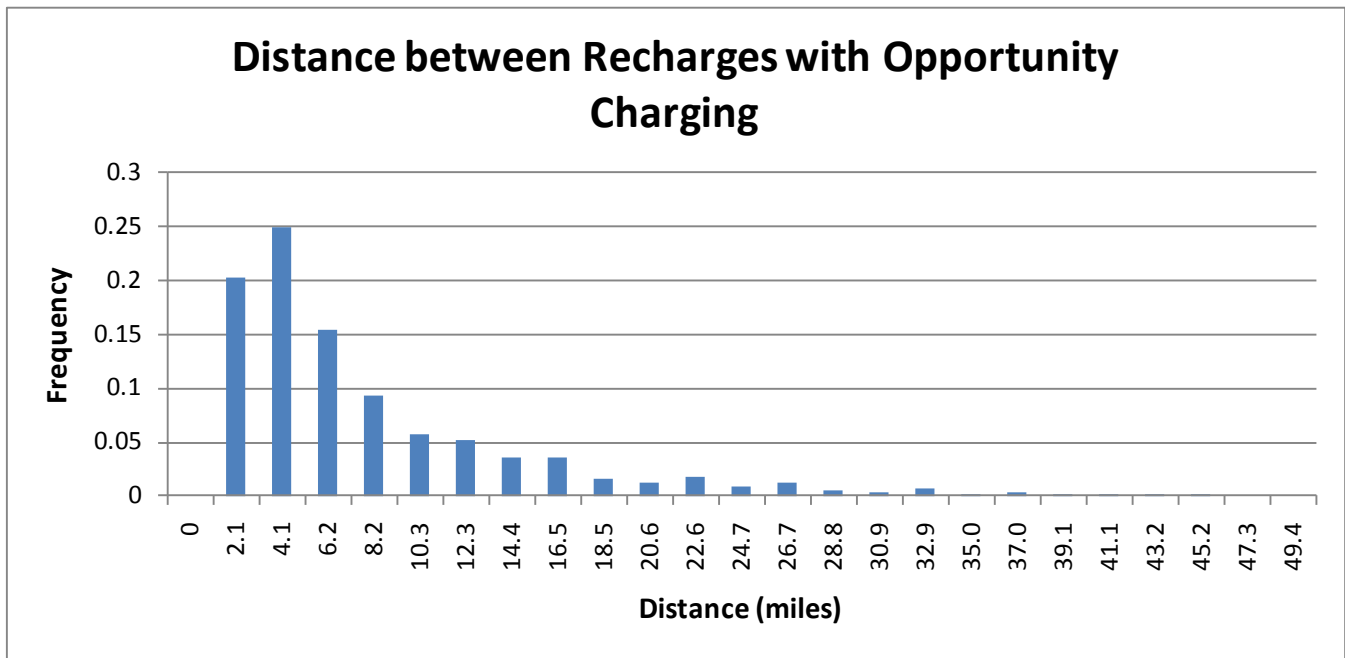


Figure 4. Distribution of distances between recharge events with opportunity charging.

Battery Life and Sizing

The driving distribution has important implications on battery life and sizing. For PHEVs and EVs, the trip length is used to estimate the level of discharge to the battery based on the vehicle's charge depleting efficiency. Each discharge causes a specific level of battery wear based on data from Johnson Controls [18], as seen in Figure 5. Using the trip driving distribution data, battery discharge efficiency, and battery cycle life data, the average charge depleting wear per mile was calculated. The acceleration and regenerative braking cycle wear per mile based on the drive cycle simulations, which can account for as much as 5% of the wear for low range PHEVs, was then added to calculate the total wear per mile.

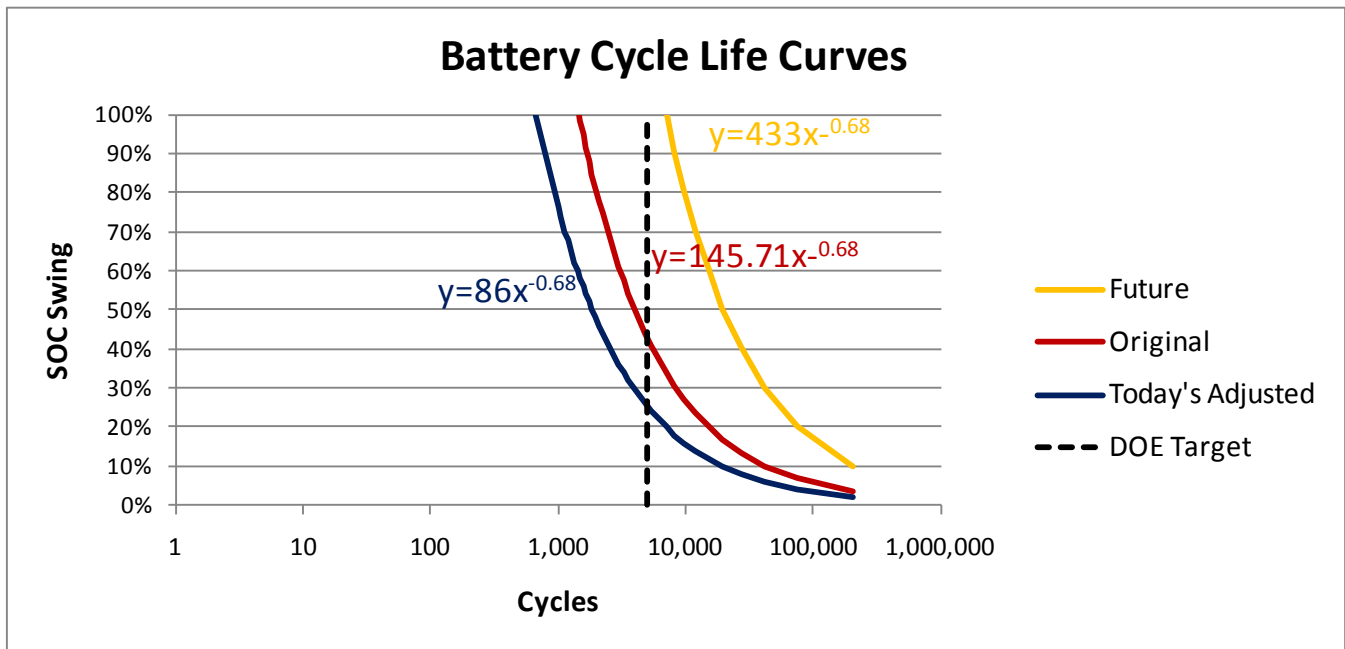


Figure 5. Original and modified battery cycle life curves.

The original battery life curve in Figure 5 represents the published data. Since this data does not consider calendar, temperature, or power level effects for the current technology case, the trend was adjusted to match published Nissan Leaf [19] and Chevy Volt [20, 21] battery life expectations. The future case was adjusted to match the 7,000 cycle life published by A123 [22], which is similar to the U.S. Department of Energy's (DOE) target [23]. It is used for the future improved case because again the published data does not include the calendar, temperature, or power level effects that would occur for a vehicle application.

The life estimates are used to size the battery for the different scenarios. As the battery cycle life curves show, decreasing the depth of discharge will increase the number of cycles that battery can sustain. Therefore, to increase the battery life to match the vehicle life, or to match the vehicle life with one replacement, the model iterates on depth of discharge to find the smallest battery that will last the required amount. Finding the smallest battery to meet the requirements minimizes the battery size and thus total vehicle cost.

Battery Use Strategy

The driving distribution assumption impacts not only battery life but also the PHEV battery use strategy. Assuming a constant driving distance may suggest that the best control strategy very selectively depletes the battery over the entire distance [24]. However, assuming that people drive a distribution of distances and that consumers don't enter in information about their trip every time they get in the vehicle, a better control strategy displaces gasoline as quickly as possible to minimize gasoline use before the trip ends.

Fuel Economy

A vehicle model is used to predict fuel economy. To gain confidence in the model, component sizes and vehicle characteristics were entered into the model for a variety of vehicles. As seen in Figure 6, the model predicted the fuel economy [25] within 10% except for the Hymotion Prius [26]. This overestimation was accepted to account for the non-ideal implementation of an aftermarket conversion vehicle.

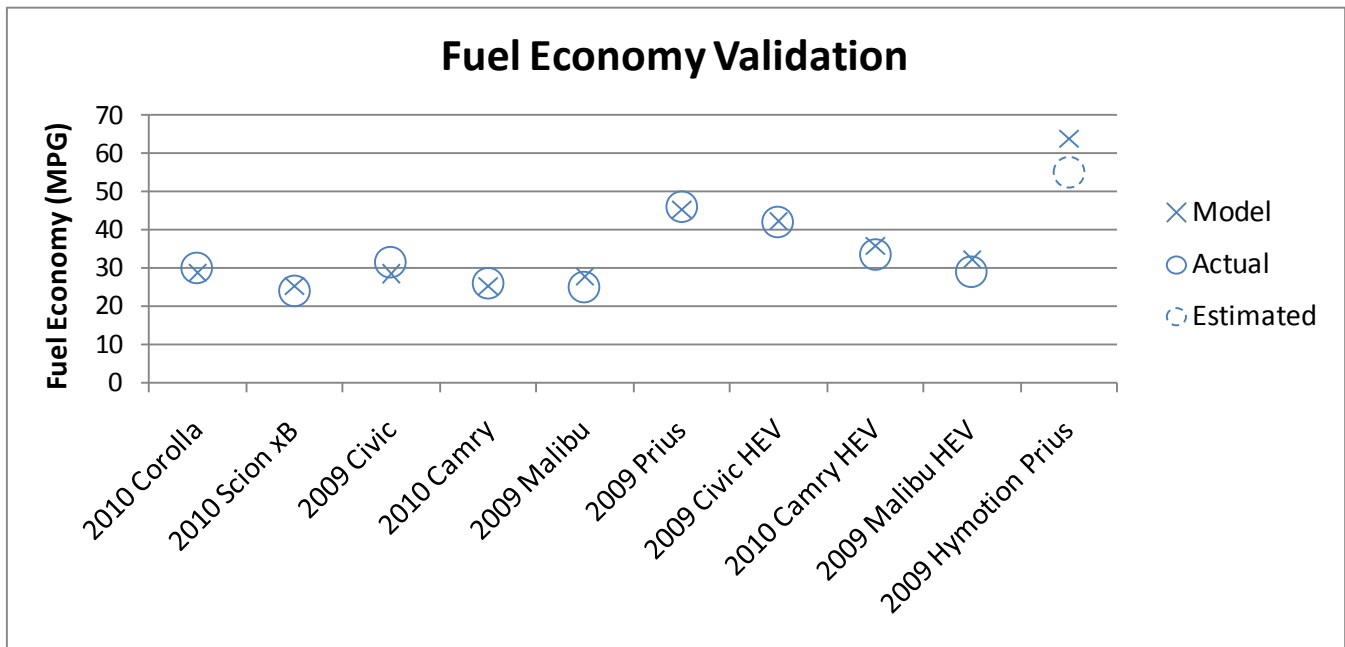


Figure 6. Vehicle model fuel economy validation.

The method to estimate PHEV fuel economy also builds from previous studies. A recent paper discusses a few methods on how to estimate in-use PHEV fuel economy [27]. The approaches involve repeating a drive cycle enough times to deplete the battery and then running one charge sustaining cycle. The charge depleting and charge sustaining fuel economies can then be calculated, adjusted to better represent in-use fuel economy, and combined based on the utility factor (UF), or the percent of driving that would likely occur in charge depleting mode. This study used a slight variation from the approach described in the paper to remove fuel economy variations caused by the test approach.

Dynamic Plug-in

This study also expands on the type of plug-in hybrid vehicle evaluated. It assesses a vehicle that plugs-in dynamically, connecting electrically along the roadway while moving, similar to the way trolley buses or streetcars currently do, although research to improve the connection approach would be required. Since the vehicle is connected while driving, it doesn't need a large battery to gain PHEV fuel economy benefits, although it does need infrastructure along a small fraction of roadway. The fraction of infrastructure is small because most travel occurs on just a few roads. The interstate, for example, makes up 1% of the miles of roadway but carries 22% of the vehicle miles traveled [28, 29]. This scenario assumes that 50% of the distance driven is connected dynamically. It also assumes an additional \$1,000 cost to the consumer for the dynamic connection, the same fuel cost per mile as an HEV when not connected dynamically, and the charge depleting fuel cost per mile of a PHEV when connected.

ADDITIONAL ASSUMPTIONS

Additional assumptions used in this study are listed in Table 2.

Table 2. Additional assumptions used in the study.

Vehicle miles traveled per year [30]	12375
Vehicle type	Compact Car
Vehicle life (years) [31]	15
Gasoline price (average 2008 price) [32]	\$3.21
Electricity price (\$/kWh) [33]	\$0.10
Sales tax [34]	7.8%
Discount rate	8%
Battery cost reduction per year	3%
Battery salvage value (percent of future manufacturing cost)	20%
Percent of distance dynamically plugged-in	50%
Dynamic connection cost to the consumer	\$1,000
Low power PHEV battery power (kW)	21
High power PHEV battery power (kW)	45

RESULTS

CURRENT BATTERY TECHNOLOGY

The improvements in assumptions and approach led to unique results. Using today's battery assumptions, while the gasoline consumption decreases significantly, no electrification pathways were cost-effective compared to HEVs or CVs except one, as indicated by the red line in Figure 7. The vehicles listed on the figure follow the naming convention of vehicle type, charge depleting range, and then battery power level. For example, the PHEV10 Low Power stands for plug-in hybrid electric vehicle with 10 miles of charge depleting range using a low power battery. Increasing battery power had little effect on fuel consumption results because in both cases the battery power can provide most of the driving on the test cycles, so the fuel economy only differs slightly. For the electric powered vehicles, the electricity cost is relatively low, reflecting the low cost of electricity and the high efficiency of batteries and motors. The gasoline, on the other hand, is a large expense, especially for the conventional vehicle. Even so, the extra battery costs in PHEVs and EVs outweighed the gasoline cost savings.

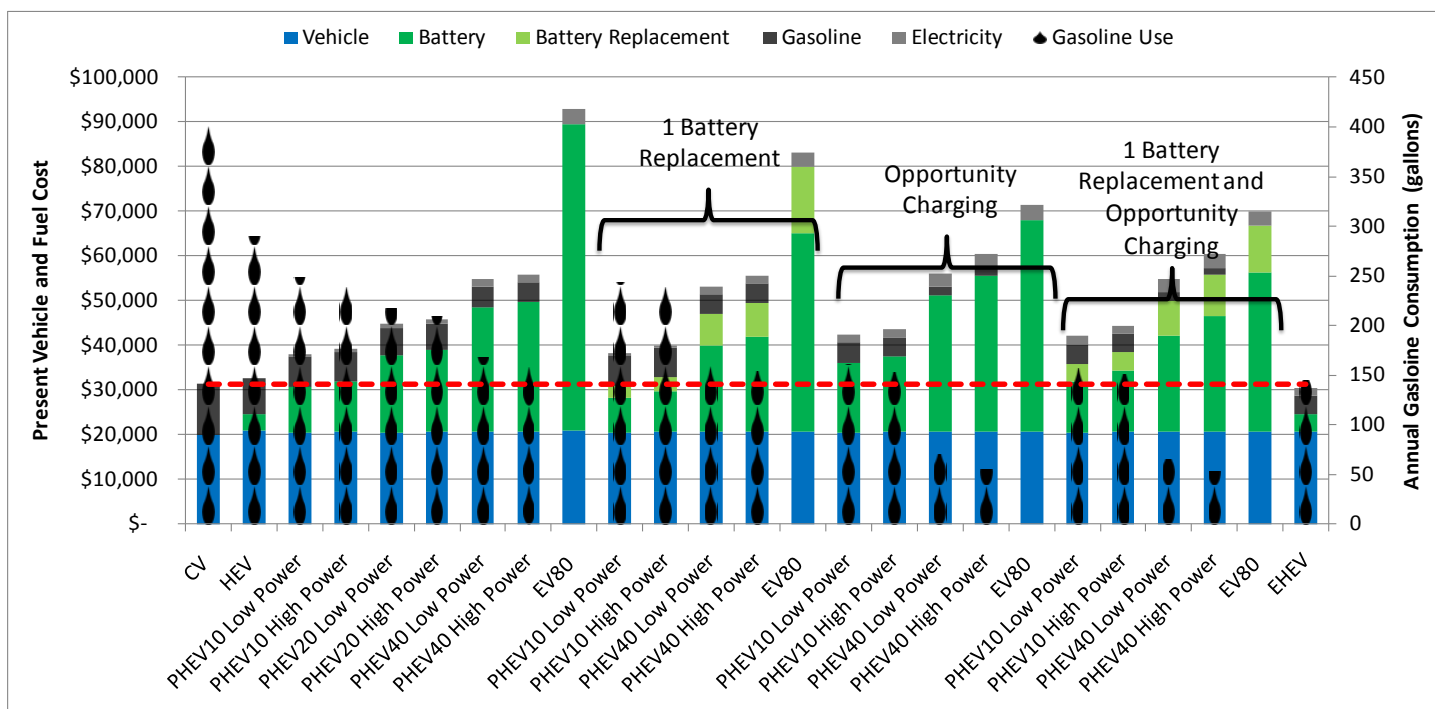


Figure 7. Cost-effectiveness of vehicle electrification using today's assumptions.

Battery replacement had minor overall improvements in cost-effectiveness. These cases reduced the size of the battery but used it more aggressively to reduce upfront cost and weight and take advantage of lower future battery costs. The advantages, however, were mostly balanced out by the increase in battery wear. For a smaller battery to provide the same electric range and regenerative braking, it must use a greater portion of the battery energy, and thus have greater depths of discharge. Since battery wear increases non-linearly with depth of discharge, each battery has to be larger than half of the single battery case. For example, in the high power PHEV10 case, a 5.9 kWh battery would last the life of the vehicle using 34% of the energy. Having one replacement, however, required more than half of a 5.9 kWh battery. It required purchasing two 3.7 kWh batteries using 54% of the energy to meet the life requirement. Although it was assumed that future batteries cost less and that there is a time value of money advantage to purchasing the second battery, these advantages did not make up for the total added cost of buying more total battery energy. The nonlinear wear trend balanced out the advantages for little overall gain.

Opportunity charging further decreased the gasoline consumption, and thus gasoline cost, of PHEVs, but at a greater increase in battery cost. Opportunity charging reduced gasoline consumption for the PHEV10 by 35%. A 35% reduction amounted to roughly a \$2,400 reduction in present fuel cost. Although the fuel cost went down, opportunity charging increased the use of the battery. In order to sustain the additional use and wear, the battery energy had to be increased from 5.9 kWh to 10 kWh. This added more than \$5,500 to the vehicle cost. Including the additional electricity cost, opportunity charging increased the total by \$4,400.

Opportunity charging decreased the EV cost. Unlike the PHEV, which drives more on the battery with or without opportunity charging, the EV has to cover all of its distance on the battery with or without opportunity charging. Opportunity charging increased the frequency of recharging, reducing the depth of discharges and the amount of wear, and thus reducing the amount that the battery has to be oversized to last the required life. Specifically, it

reduced the battery size from 47 kWh to 32 kWh. This reduced the battery cost and the vehicle cost overall, but the EV still exceeded the cost of all the other vehicle types.

Combining battery replacement and opportunity charging increased the use of the high cost battery to better leverage the investment. With the current battery life assumption, however, little to nothing was gained by adding battery replacement to the opportunity charging cases.

One case may warrant further investigation because it reduced total cost to the consumer and it reduced fuel use. This is labeled EHEV, for electrified HEV. This case assumes that an HEV could connect to an external source of energy along some roadways while moving, similar to the way trolley buses or streetcars do in some cities such as Boston, Cambridge, Philadelphia, and San Francisco [35], though it would require research to improve the connection. Although it would require infrastructure along a small percentage of heavily traveled roadways [28, 29], if the design can be flexible for both mass transit and private vehicles, then cities may install it for the mass transit benefit alone [35]. On the consumer side, the EHEV is cost-effective even with the extra \$1,000 cost to the consumer for the connection mechanism. The cost is low because it gains the low cost electric mode operation similar to a battery PHEV without the cost, wear, efficiency losses, and weight of a large battery.

REDUCED BATTERY COST

An additional pathway to cost-effective vehicle electrification is to reduce battery cost. As seen in Figure 8, if the battery energy cost comes down around DOE targets [23] to \$300/kWh, PHEVs get close to breaking even with today's vehicles. Battery replacement didn't add any further advantages for the PHEVs. Opportunity charging, however, significantly reduced gasoline consumption for the PHEVs for little additional cost.

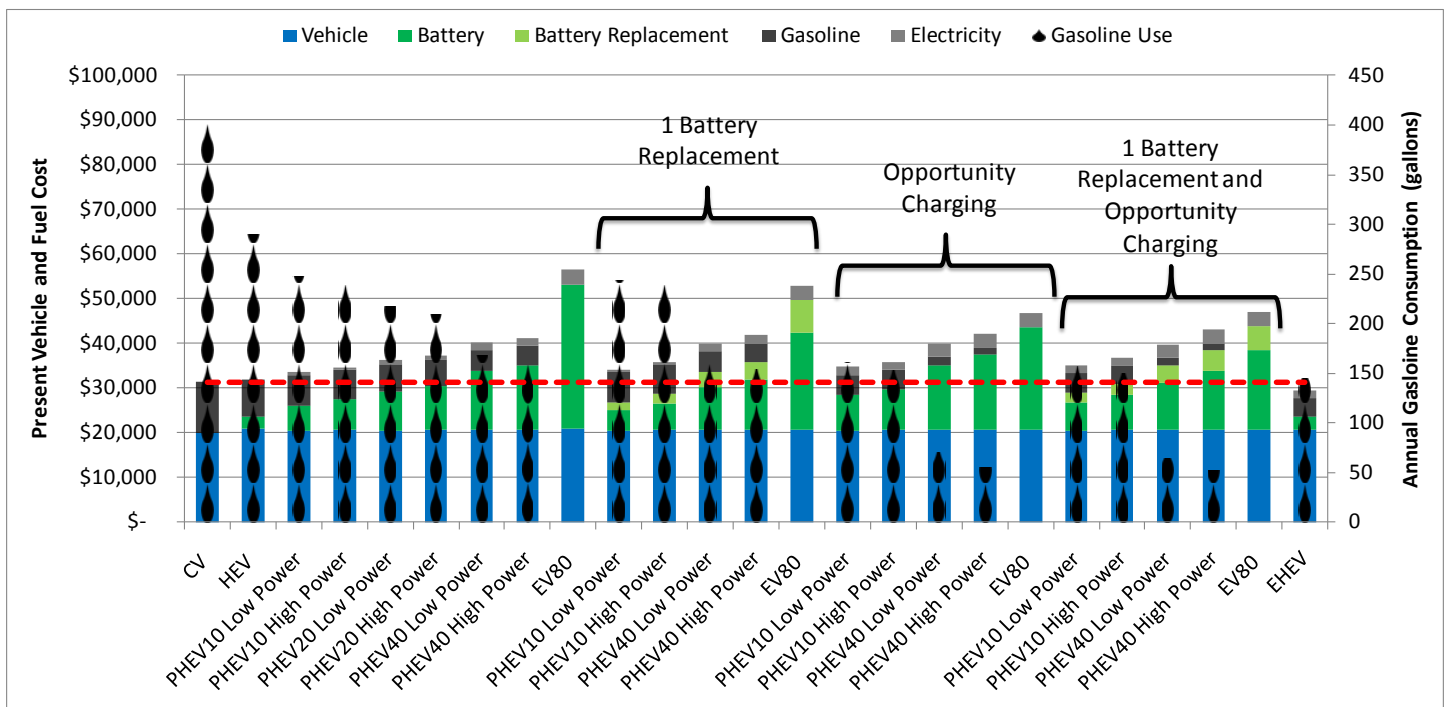


Figure 8. Cost-effectiveness of vehicle electrification with battery energy cost at \$300/kWh.

IMPROVED BATTERY LIFE

A third pathway to cost-effective vehicle electrification is to improve battery life. As seen in Figure 9, PHEVs became cost-effective by improving the battery life as illustrated previously in Figure 5. Unlike reducing battery cost, improving battery life makes opportunity charging slightly more cost-effective, providing more potential to reduce gasoline consumption further.

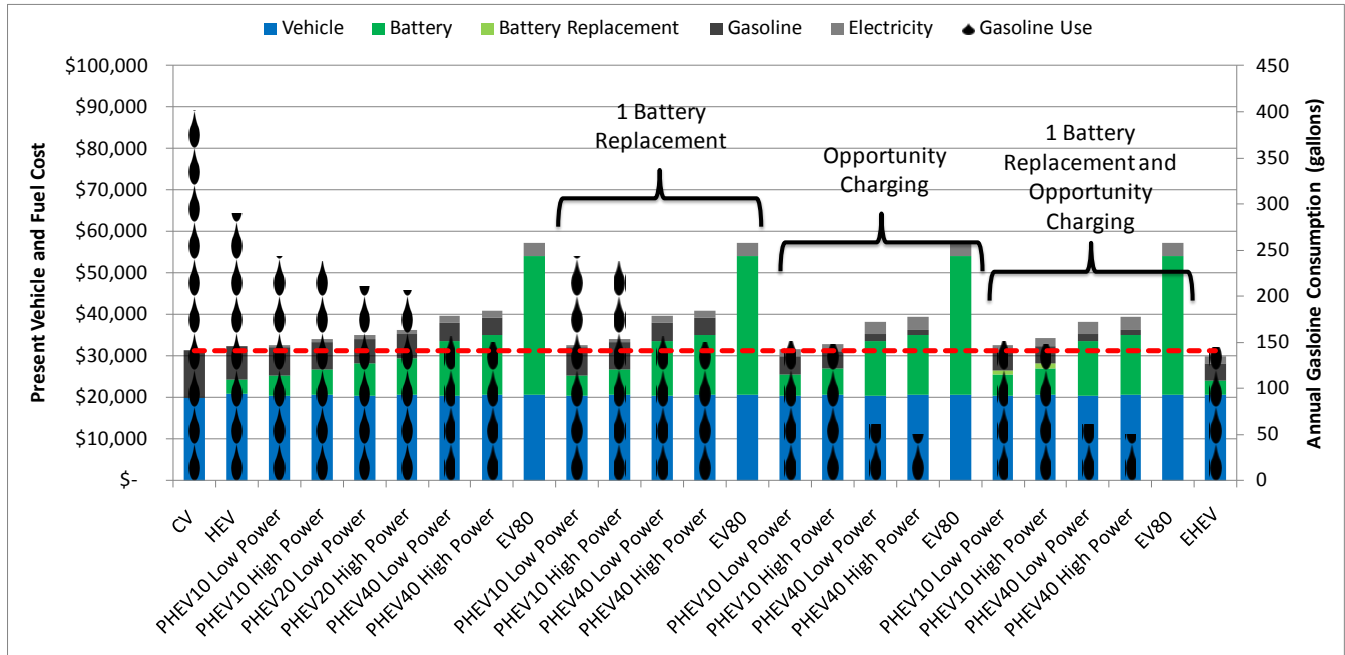


Figure 9. Cost-effectiveness of vehicle electrification with improved battery life.

CONCLUSIONS

Electrifying transportation can reduce or eliminate dependence on foreign fuels, emission of green house gases, and emission of pollutants. However, finding a cost-effective pathway to gain widespread adoption and provide a significant impact is challenging. Three possible pathways include improving battery life, reducing battery cost, or connecting to the grid more directly.

Using current battery cost and life, PHEVs and EVs were not cost-effective for many different configurations. PHEVs with 10, 20, or 40 miles of electric range, with low or high electric power, with or without battery replacement, and with or without opportunity charging were all less cost-effective than conventional vehicles and HEVs. EVs' cost-effectiveness improved with battery replacement and opportunity charging, but not enough.

One approach with current battery technology could be cost-effective. If an acceptable method for plugging in while traveling along the roadway can be devised, it may provide a cost-effective pathway to vehicle electrification. This approach benefits from the low electric fuel cost of a large battery without the high cost, cycling wear, weight, and efficiency loss. Even with assuming a \$1,000 price for the connection device, the cost to the consumer was still lower than for today's conventional and hybrid vehicles. This pathway requires infrastructure, but only along a small fraction of heavily traveled roadways to gain the same gasoline saving benefits as battery PHEVs.

Significant battery improvements can also provide cost-effective pathways to vehicle electrification. If today's battery energy cost component goes down from \$700/kWh to \$300/kWh, PHEVs start becoming cost-effective. PHEVs also become cost-effective if battery life improves by a factor of 10.

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ACKNOWLEDGMENTS

The authors gratefully acknowledge the support for this work provided by Lee Slezak and Patrick Davis in the Vehicle Technologies Program of the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy.

DEFINITIONS/ABBREVIATIONS

CD: Charge depleting

The PHEV mode of operation where electricity from the grid is being used by the battery.

CVs: Conventional vehicles

DOE: Department of Energy

EHEV: Electrified hybrid electric vehicles

EVs: Electric vehicles

HEVs: Hybrid electric vehicles

kW: Kilowatts

kWh: Kilowatt hours

MPG: Miles per gallon

MSRP: Manufacturer Suggested Retail Price

NHTS: National Household Travel Survey

PHEVS: Plug-in hybrid electric vehicles

This vehicle is plugged in dynamically. It is similar to an HEV but it connects to an outside source of electricity while moving.

UF: Utility Factor

The percent of travel done in charge depleting mode based on driving distance statistics and the charge depleting range.

REPORT DOCUMENTATION PAGE

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1. REPORT DATE (DD-MM-YYYY) February 2010		2. REPORT TYPE Conference Paper		3. DATES COVERED (From - To)		
4. TITLE AND SUBTITLE Technology Improvement Pathways to Cost-Effective Vehicle Electrification: Preprint			5a. CONTRACT NUMBER DE-AC36-08-GO28308			
			5b. GRANT NUMBER			
			5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S) A. Brooker, M. Thornton, and J. Rugh			5d. PROJECT NUMBER NREL/CP-540-47454			
			5e. TASK NUMBER FC102300			
			5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393			8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-540-47454			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S) NREL			
			11. SPONSORING/MONITORING AGENCY REPORT NUMBER			
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT (Maximum 200 Words) This paper evaluates several approaches aimed at making plug-in electric vehicles (EV) and plug-in hybrid electric vehicles (PHEVs) cost-effective including opportunity charging, replacing the battery over the vehicle life, improving battery life, reducing battery cost, and providing electric power directly to the vehicle during a portion of its travel. Many combinations of PHEV electric range and battery power are included. For each case, the model accounts for battery cycle life and the national distribution of driving distances to size the battery optimally. Using the current estimates of battery life and cost, only the dynamically plugged-in pathway was cost-effective to the consumer. Significant improvements in battery life and battery cost also made PHEVs more cost-effective than today's hybrid electric vehicles (HEVs) and conventional internal combustion engine vehicles (CVs).						
15. SUBJECT TERMS plug-in hybrid electric vehicles; PHEV; electric vehicles; EV; battery; electric range						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)	