



Battery Ownership Model: A Tool for Evaluating the Economics of Electrified Vehicles and Related Infrastructure

Preprint

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*Presented at the 25th International Battery, Hybrid and Fuel Cell
Electric Vehicle Symposium & Exposition
Shenzhen, China
November 5–9, 2010*

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5400-49127
January 2011

Contract No. DE-AC36-08GO28308

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Battery Ownership Model: A Tool for Evaluating the Economics of Electrified Vehicles and Related Infrastructure

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Abstract—Electric vehicles could significantly reduce greenhouse gas (GHG) emissions and dependence on imported petroleum. However, for mass adoption, EV costs have historically been too high to be competitive with conventional vehicle options due to the high price of batteries, long refuel time, and a lack of charging infrastructure. A number of different technologies and business strategies have been proposed to address some of these cost and utility issues: battery leasing, battery fast-charging stations, battery swap stations, deployment of charge points for opportunity charging, etc. In order to investigate these approaches and compare their merits on a consistent basis, the National Renewable Energy Laboratory (NREL) has developed a new techno-economic model. The model includes nine modules to examine the levelized cost per mile for various types of powertrain and business strategies. The various input parameters such as vehicle type, battery, gasoline, and electricity prices; battery cycle life; driving profile; and infrastructure costs can be varied. In this paper, we discuss the capabilities of the model; describe key modules; give examples of how various assumptions, powertrain configurations, and business strategies impact the cost to the end user; and show the vehicle’s levelized cost per mile sensitivity to seven major operational parameters.

Keywords: Battery, Economics, Electric Vehicle, Service Provider

1 Introduction

Reducing emissions such as greenhouse gases and criteria pollutants from transportation vehicles and switching to alternative fuels other than petroleum such as electricity, bio-fuels, and hydrogen are the goals of many countries around the world. The aim is to reduce the negative impact on climate change while achieving energy security, particularly for transportation. Hybridization and electrification of vehicles have the potential to decrease GHG emissions and lower and/or displace petroleum with alternative fuels with fewer environmental and security concerns. However, wide-scale consumer acceptance of alternatives to conventional gasoline-powered vehicles (CVs) such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicle (PHEVs), and pure electric vehicles (EVs) will depend on their cost-effectiveness and their functionality, including driving range and ease of refueling.

Each alternative powertrain technology has a unique petroleum reduction potential and incremental cost to the end user (either positive or negative) depending on the driving profile, vehicle performance and range requirements, and assumed cost of fuels; each of which may have a unique geographic profile.

Incorporation of battery technology into vehicle powertrains offers a significant petroleum reduction opportunity. The EV powertrain is especially attractive among electric traction drive vehicles in that it offers a complete transition from petroleum to electricity for transportation. However, the current costs of battery technology make the economics of pure EVs with range and performance equivalent to CVs challenging.

A number of technical and business strategies have been proposed and/or deployed to enable the transition to these alternative powertrain technologies, including: the electric utility utilization of the vehicle batteries as a distributed resource; battery leasing by a service provider

who takes on the risk and upfront cost of battery ownership; public infrastructure development to recharge electric vehicles while parked; fast-charge and/or battery swap stations that effectively extend EV range; and alternative car ownership models that allow users to own an EV but rent other vehicles for long-distance excursions. Each strategy has unique implications to the vehicle design, operating characteristics, and battery life. Accordingly, it can be challenging to compare different system options on a consistent basis.

To address this issue, the U.S. Department of Energy’s (DOE’s) NREL has developed a computer tool called the *Battery Ownership Model* (BOM). This paper describes the tool and gives an example of its use.

2 Modeling Overview

The purpose of the BOM is to calculate the cost of vehicle ownership under various scenarios of vehicle and component cost, battery and fuel price forecasts, driving characteristics, charging infrastructure cost, financing, and other criteria. The vehicle economics that are considered include vehicle purchase, financing, fuel, non-fuel operating and maintenance costs, battery replacement, salvage value, and any costs passed on by a third-party such as a service provider to account for the installation, use, and availability of infrastructure.

There are many reasons why an individual car buyer chooses one vehicle over another. Economics is an important factor for individual consumers, but there are many other factors that impact the purchasing decision as well. For end-users such as fleet owners, economics is one of the top factors for purchasing. In addition, the economics of technologies can aid policy makers in decision-making. Thus, there is a strong motivation to look at the economics of vehicle technologies to see how they compare against each other. As such, the primary output of the BOM is an economic indicator of end-user net present costs called “levelized cost per mile” (LCPM). The LCPM economic metric is defined as follows:

$$LCPM = \frac{\sum_{i=1}^N c_i \cdot d_i}{\sum_{i=1}^N vmt_i \cdot d_i} \quad (1)$$

The variable c is the cost to the end user during the given period, i . The discount factor for the given period is

d . Finally, the vehicle miles traveled for the given period is vmt . The total number of periods is represented by N .

The BOM consists of nine modules that are described in subsequent sections. The model is currently written in Microsoft Excel. A schematic of how the different modules (in oval) fit together can be seen in Figure 1.

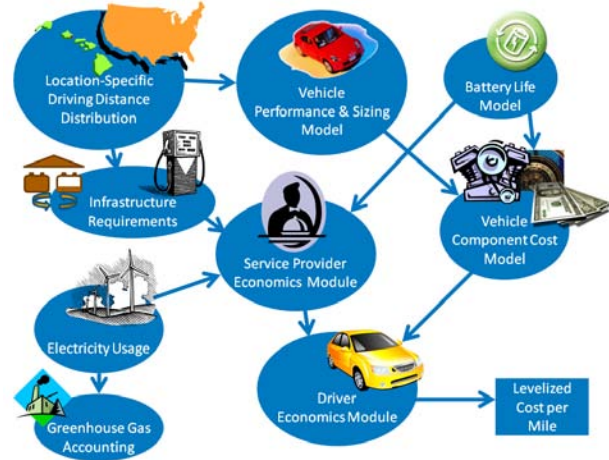


Figure 1: Overview of the battery ownership model

2.1 Location-Specific Data Module

Four pieces of information are obtained based on location: a probability density function for daily driving distance, forecasts for annual vehicle miles traveled (VMT) per person, and location-specific forecasts for cost of fuel over time. For this paper, we present data for electricity and gasoline, though other fuels such as diesel, biodiesel, or ethanol (E85) could be used as well.

The probability density function of daily VMT is obtained from the 2001 National Household Transportation Survey (NHTS) [1]. The NHTS can be used to predict the probability density function for daily driving distance. A trip distance distribution for the entire United States is shown in Figure 2.

Location-specific forecasts for gasoline and electricity costs over time were obtained from the Energy Information Administration (EIA) short-term energy outlook and annual energy outlook [2, 3]. The EIA projections are made for multiple scenarios. Two forecast scenarios for gasoline price are presented in Figure 3, “reference” and “high oil price” (using terminology from [2]). The forecasts for the entire United States are a sales-weighted average of prices for all grades of gasoline and include federal and state taxes (but not county and

local taxes). A forecast of commercial electricity prices is given for several regions in Figure 4: the states of Hawaii, California, and Colorado are shown in contrast to the national average forecasted electricity price. Note the large difference in electricity price by region.

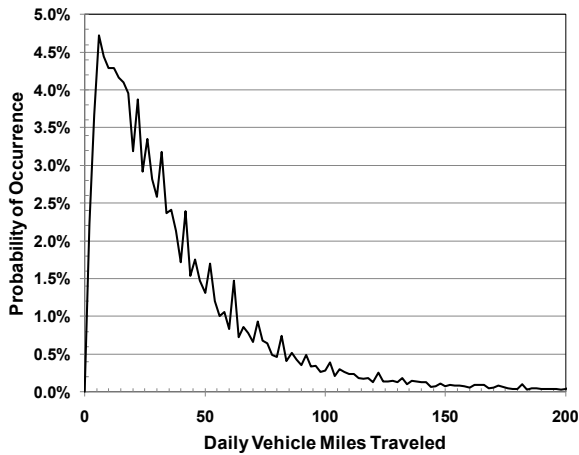


Figure 2: Probability of daily vehicle miles traveled

2.2 Vehicle Performance and Sizing Module

This module simulates the fuel consumption (gasoline, electricity, or other fuel) and acceleration performance of a given vehicle using attributes such as weight, frontal area, drag coefficient, powertrain type (CV, HEV, PHEV, or EV), and driving profile. An optimization routine included in this module optimizes vehicle component sizes (engine power, motor power, battery energy, and battery power) to meet minimum performance requirements at the lowest cost. NHTS driving distance distributions along with location-specific annual VMT are used to predict the number and depth of battery discharges. This distribution of discharges is used with a battery life model to predict battery life. This analysis is repeated for different battery power and energy levels until the minimum cost of ownership is found for a given scenario. When comparing vehicles with different powertrain configurations, we use this module to size components so that they have similar acceleration performance and meet range requirements to give a fair comparison based on similar utility to the end user.

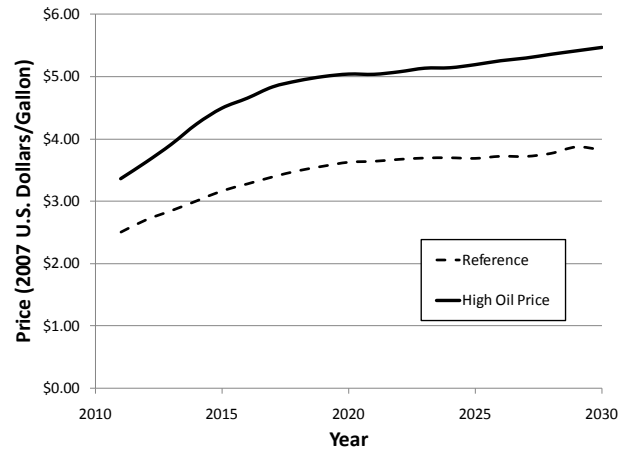


Figure 3: Gasoline price forecast for the United States

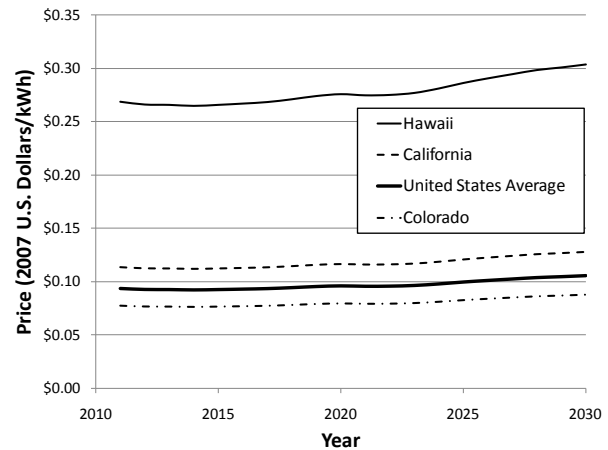


Figure 4: Commercial electricity price forecasts

2.3 Vehicle Component Cost Module

This module predicts the component cost and price of various components that make up a vehicle. Vehicle cost is the sum of the “glider” cost (the vehicle chassis and partial drivetrain without the powertrain), the powertrain cost, and the battery cost, if applicable. Manufacturing costs are translated to end user price using a markup factor. A markup factor of 1.75 was determined to give a good fit when comparing the model-predicted prices with actual vehicle manufacturer’s suggested retail price (MSRP) as shown in Figure 5. Lower markup factors may be possible for wholesale large-quantity purchases such as for a service provider who provides batteries and infrastructure to an EV end-user.

The price of the CV is calculated by adding the cost of the glider to the cost derived using the formula for the engine in Table 1. The cost of the HEV is the cost of the glider plus engine, battery, motor, and power electronics. The cost equation for the PHEV is similar to that of the

HEV although the component sizes are different and the PHEV power electronics must include an on-board charger. The EV cost is the cost of the glider, motor, power electronics, charger, and batteries; these equations are presented in Table 1. An example set of cost relationships were obtained from [4] with the exception of the battery energy cost coefficient, which was calibrated to match the MSRP over a range of advanced vehicles of different component sizes (see Figure 5). In Table 1, P_b represents the battery peak power capability in kW, E_b represents the battery total energy capacity in kWh, P_m is the peak power of the electric motor in kW, and P_e is the peak power of the internal combustion engine in kW.

Table 1: Component cost model

Battery	$\frac{\$22.00}{kW} \cdot P_b + \frac{\$700.00}{kWh} \cdot E_b + \680.00
Motor & Power Electronics	$\frac{\$21.70}{kW} \cdot P_m + \425.00
Engine	$\frac{\$14.50}{kW} \cdot P_e + \531.00

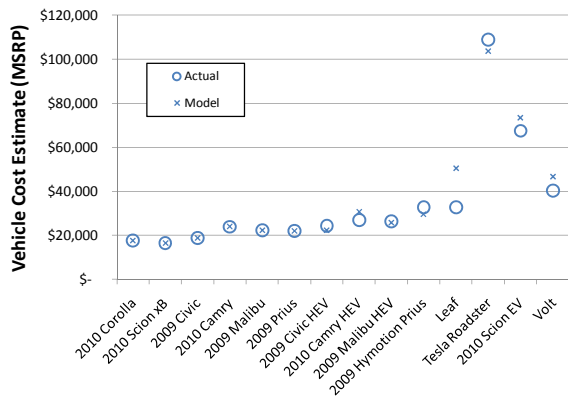


Figure 5: Comparison of vehicle MSRP versus model prediction

As can be seen from Figure 5, the largest discrepancies occur between the MSRP/announced price and predicted price of EVs although our model predictions are neither consistently high nor consistently low. Because MSRP is a combination of manufacturing cost and markup, it is difficult to say whether the lack of good fit for EV data reflects a choice by the original equipment manufacturer

to reduce their markup factor [5-9], the achievement of lower initial battery costs [10], or some combination of the two.

2.4 Battery Cycle Life Module

This module estimates the cycle life of a battery based on usage and state-of-charge range. In the future, we hope to expand this model to include the effects of charge rate and temperature. For the EV, trip length is used to estimate the level of battery discharge based on the vehicle's energy use per mile. Each discharge causes a specific level of battery wear, based on data from Johnson Controls [11], as seen in Figure 6. Using trip driving distance distribution data, battery discharge efficiency, and battery cycle life data, the average charge-depleting wear per mile can be calculated. The wear per mile due to accelerating and braking, which is based on assumed speed versus time drive profiles input into vehicle simulations, is then added to calculate the total wear per mile.

Three curves are presented in Figure 6 to demonstrate the battery life model. The curve labeled “Case 1” represents data published in [11]. These data were obtained at the cell level and do not consider calendar life, temperature, or power level effects on life. Case 2 was created by adjusting case 1 to match published data for the Nissan Leaf [12] and Chevy Volt [13] battery life expectations. Case 3 reflects an advanced battery with a 7,000-cycle life at 100% depth of discharge [14]. For reference, Figure 6 also indicates the DOE target of 5,000 cycles of battery life assumed to be at 80% state-of-charge swing [15].

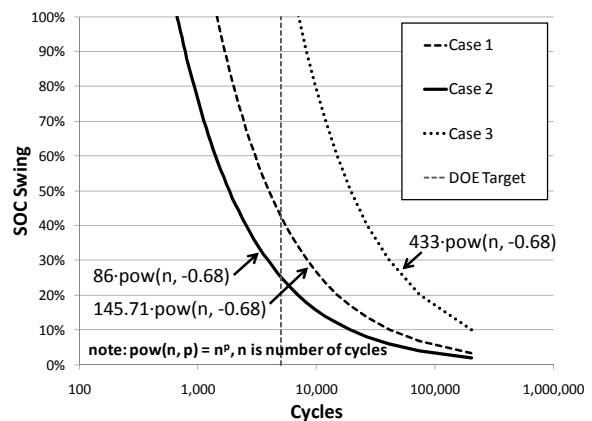


Figure 6: Battery cycle life dependence on SOC swing.

2.5 Electricity Usage Module

This module calculates the total electricity required to recharge EVs from the electric utility grid to determine the electricity cost burden on the end user or on a service provider. EVs and PHEVs can be recharged from charge points for all daily driving distances below the vehicle's range. For daily driving distances above the vehicle's electric range, PHEVs must rely on their internal combustion engines and EVs must rely on some other manner of infrastructure if they are to be used over approximately the same driving profiles as conventional vehicles. For example, a battery swap station may be used to exchange a depleted battery pack for a fully charged one. EV fast charging may provide a similar service.

We can also simulate opportunity charging in this module, which is defined as the ability to recharge any time the vehicle is parked. By using charge points, opportunity charging can, among other things, reduce the dependence on more expensive infrastructure items such as battery swap stations and fast charge stations.

More work is needed to assess the exact charging efficiency from grid to battery and impact on the grid by EV supply equipment, battery swap stations, and battery fast charge stations over the EV's life.

2.6 Infrastructure Requirements Module

This module estimates the amount and cost of the needed infrastructures for different EV business approaches such as EV direct ownership and EV service provision scenarios. In the EV direct ownership, the driver purchased the vehicle and its battery and pays for the electricity and other cost. An EV service provider is assumed to do the following: lease batteries, provide a charge point network for home and opportunity charging when parked, provide battery swap stations, and may even provide access to alternate transportation technologies for long trips. In this EV service provider scenario, the driver purchases the EV without the battery pack, reducing upfront cost.

The frequency of use and benefit of various forms of EV support technology depend very much on the specifics of how the aggregate users of the infrastructure are traveling between recharging events. Our model takes driving distance probability (such as Figure 2) and an

EV's range and calculates the "distance driven between recharge events." Distances greater than the EV range are transformed into n trips approximately equal to the EV range, which implies a stop at a fast charging unit or battery swap station plus an additional trip of r miles where n is the integer quotient of the intended trip distance and the EV range; r is the remainder.

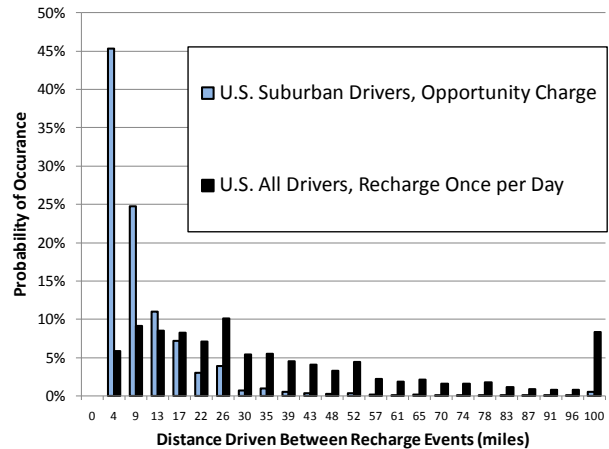


Figure 7: Probability density function: daily driving distance

As an example, consider an EV with a range of 100 miles (EV100) and the data from Figure 2. If we assume recharging only occurs once per day, we get the histogram labeled "U.S., All Drivers, Recharge Once per Day" in Figure 7. With once-per-day charging across the U.S. driving population (including urban and rural drivers), these data indicate approximately 8% of recharging events would require range-extending infrastructure such as fast charge units or battery swap stations. On the other extreme, if we assume the vehicle has access to ubiquitous opportunity charging such that the vehicle can recharge after every trip and we target drivers living in suburban areas (that is, excluding urban and rural residents), we get the histogram titled "U.S. Suburban Drivers, Opportunity Charge." In this case, only approximately 0.5% of recharging events would require range-extending infrastructure. Note that under the ubiquitous opportunity charging assumption, recharge events typically occur more than one time per day.

2.7 Service Provider Economics Module

As mentioned previously, the service provider can provide one or more of a range of EV services. If the service provider offers recharging infrastructure, to various degrees, this can allow a shorter range EV to drive

similar driving distances as other vehicles due to the presence of opportunity charging and battery swap stations and/or fast charge stations. The cost of all services offered by a service provider must be recouped through some manner of service fee. This fee would cover, for example, battery purchases over the life of the vehicle, the cost to install and maintain EV charging infrastructure, and sufficient additional funds to cover the operating expenses (including the cost of electricity) and profit margin of the service provider business itself. The purpose of the service provider economics module is to compute the fee required to cover all costs by the service provider plus profit margin which is specified using a return on equity metric which is given as an input.

The module uses estimates for the service provider customer market growth versus time. The EV service provider’s customer growth projections can be taken from sources such as [16]. Infrastructure costs are forecast based on the ratios of the number of charge points and swap stations needed per vehicle in the system. That is, the infrastructure investment lags the customer demand, although supply and demand in real markets are more dynamically linked (particularly for new technology adoptions).

2.8 Greenhouse Gas Accounting Module

GHG reduction is a primary goal for many proponents of EVs. The Greenhouse Gas Accounting Module tracks GHG emissions from vehicle production and disposal as well as the fuel cycle, which includes well-to-wheels fuel production and use. As shown in Figure 8, EVs can lead to substantial GHG reductions if electricity is produced from a low-carbon fuel mix. EVs have lower lifecycle GHG emissions than CVs in all states examined in Figure 8, and they have lower emissions than HEVs or PHEVs when charged with average U.S. electricity or electricity from a state such as California that generates a substantial portion of its electricity using renewable resources and natural gas.

GHG emissions from the vehicle production phase are from [17] for the CV and the EV and extrapolated for the HEV based on battery capacity, power of the electric drivetrain, and power of the gasoline drivetrain. Gauch et al. [17] assumes that electricity used in vehicle production

is generated from the European Union fuel mix, which is 4% less GHG-intense than U.S. electricity and therefore slightly under- represents the GHGs coming from vehicle production in the U.S. GHG emissions from disposal are assumed to be 20% of production energy use [18].

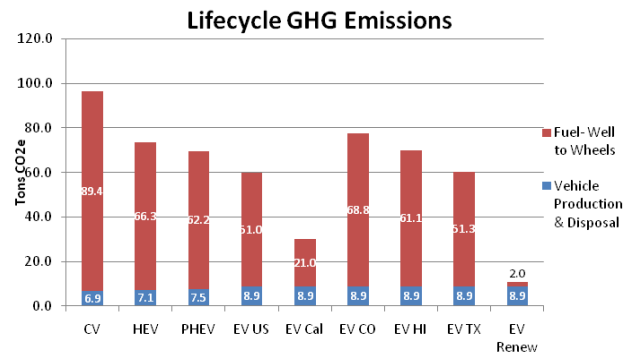


Figure 8: Lifecycle GHG emissions for vehicles

GHG emissions from the vehicle fuel include 25 pounds carbon dioxide equivalent (CO₂e) per gallon of gasoline drilled, refined, transported, and used [19]. Lifecycle emissions for electricity account for producing electricity from various primary fuel sources [20], which are weighted according to each state’s electricity generation primary fuel distribution [21]. Electricity transmission losses of 6.5% [22] and battery charger losses of 14% [23] are also accounted for.

2.9 Driver Economics Module

The overall cost of each powertrain technology to the end user is calculated using LCPM. Costs can be divided into two main categories—vehicle financing (including tax incentives) and vehicle operating costs (including fuel input, insurance, general maintenance, and service provider fees if applicable). Maintenance and insurance costs are assumed to be the same for all vehicle powertrains (CV, HEV, PHEV, and EV). We assume end users for all powertrains pay some percentage of the upfront costs (nominally 20%) as a down payment with the remaining fraction to be financed over some period (nominally 5 years). Fuel costs are based on the location-specific electricity and gasoline cost projections (see section 2.1). Battery replacement costs for HEVs and EVs are calculated from section 2.4. The vehicle is assumed to be resold at the end of the vehicle ownership analysis period. Vehicle resale value is based on data for actual vehicles such as the Toyota Corolla [24]. Battery

resale (or reuse) values can be specified as well although the results are less sensitive the further into the future the resale event takes place.

3 Results and Discussion

All currency reported in the results section is in year 2007 United States dollars. Due to space limitations, in this section we provide some example results. Detailed scenario and business strategy analysis will be reported in other studies.

3.1 Levelized Cost per Mile Validation

As a means of validation, we compared our LCPM prediction for various CVs with existing data sources. This comparison appears in Figure 9. The reference gasoline forecast case for U.S. average conditions is assumed along with 5 years of ownership. The data labeled as “AAA” is referenced from online documentation [25]. The Ward’s data [26] were adjusted to the U.S. average annual VMT of 12,375 miles/year in 2005 [27]. Data listed as “IRS mileage reimbursement” correspond to the federal reimbursement rate of 55 cents per mile (in 2008) used to calculate the deductible costs of operating an automobile for business, charitable, medical or moving purposes when filing tax returns [28].

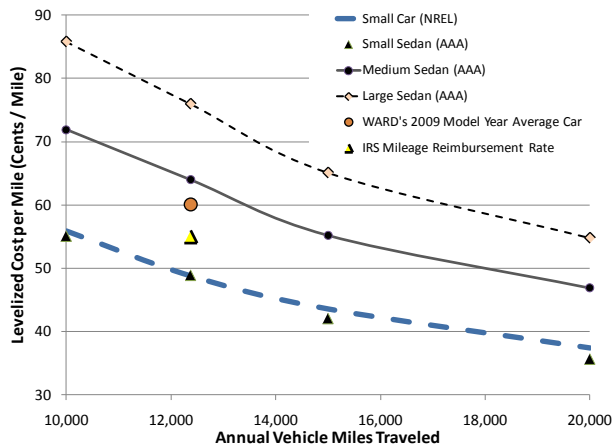


Figure 9. Comparing levelized cost per mile from various sources with our model

The NREL-predicted LCPM compares well with the data provided by AAA for a small car. Depending on the type of vehicle driven and how far it is driven each year, LCPM can vary significantly. At the 2005 U.S. average VMT of 12,375 miles/year, LCPM varies between \$0.49 per mile and \$0.76 per mile. It is noteworthy to compare

the cost of advanced technology vehicles against the range of what people spend for conventional transportation.

3.2 Scenario Analysis

In this section, we present an example demonstrating some of the capabilities of our model. An midsize car is assumed to be owned by one owner for 15 years. Four powertrain options for this vehicle are examined: a CV, HEV, a PHEV with 40 miles of electric range (PHEV40), and an EV with 100 miles of electric range (EV100). The driving distribution from Figure 2 is assumed. The EV is directly owned by the end user and assumed to be charged once per day at home. Due to time and space constraints, an EV with a service provider option is not addressed in this paper. The components in each vehicle powertrain are sized by the program to yield equivalent acceleration performance: 0 to 60 mph in ~10 seconds. Note, however, that the EV100 does not have the same utility as the other vehicles due to the lack of a service provider infrastructure such as fast charging or battery swap for extended range operation. For all powertrain options, we assume the vehicle owner makes a down payment of 20% of the upfront purchase costs with a total sales tax rate of 7% and finances the balance over 5 years at a loan rate of 8%. Inflation is assumed at 2.5%. The end user is assumed to value money at an annual 8% discount rate. Seven design variables are examined as shown in Table 2.

Table 2: Design Variables Examined in this Study

Variable	Min	Max
D1: GHG Market Cost (2007 U.S. Dollars/Ton CO2e-Year)	0.00	28.53
D2: Federal Tax Incentive (2007 U.S. Dollars)	0	7,500
D3: Gasoline Cost Forecast	EIA Reference	EIA High-Oil-Price
D4: Annual Distance Driven (Miles/Year)	9,059	15,691
D5: Vehicle Auxiliary Load (W)	700	2,200
D6: Battery Energy Cost Coefficient (2007 U.S. Dollars / kWh)	350	700
D7: Battery Life Coefficient	86 (low cycle life)	433 (high cycle life)

The design variables include cost for GHG emissions in dollars per ton of CO₂ equivalent emitted per year, the amount of federal tax incentive offered to buyers of the EV100 and PHEV40, the EIA gasoline forecast scenario used: reference or high-oil price case (see Figure 3), the annual VMT per year, the magnitude of accessory loads on the vehicle from 0.7 to 2.2 kW, the battery energy cost coefficient, and finally, the battery life coefficients representing different battery life curves (see Figure 6, cases 2 and 3).

Over the range of design variables examined, the model predicts fuel economy to be between approximately 26 and 32 mpg for the CV, 35 and 44 mpg for HEV, and between 248 and 353 Wh/mile for the EV100. The PHEV40 has aggregate fuel consumption between 54 and 74 mpg gasoline and 103 to 128 Wh/mile electricity. Accessory load is a major driving factor behind the change in fuel consumption rate of electric traction drive vehicles as has been observed elsewhere [29].

The range of variation in vehicle levelized cost ratio over the full factorial of all simulated runs is given in Figure 10. Vehicle levelized cost ratio is the vehicle's LCPM divided by the CV LCPM for a given scenario. The majority of the EV100's cost is due to the cost of the battery pack. Therefore, it is not surprising that the EV100 shows a large variation in cost ratio over the design variables examined. All vehicles, including the EV100, achieve a cost ratio below 1.0 over some of the scenarios (the minimum EV100 cost ratio is 0.99).

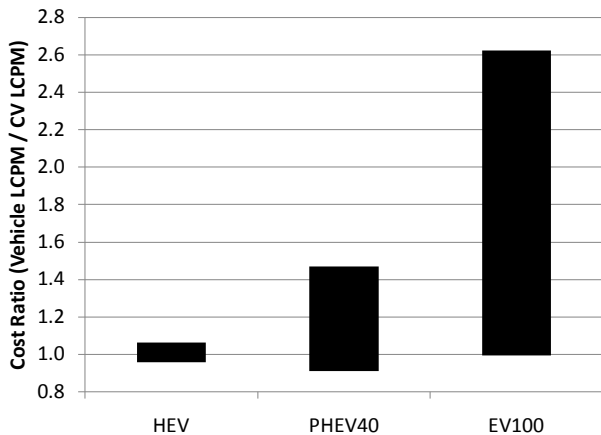


Figure 10: Range of the ratio of vehicle levelized cost ratio

Figure 11 shows the sensitivity of the vehicle levelized cost ratio to the design variables listed in Table 2.

Sensitivity to a given design variable is determined by taking the full factorial results for the levelized cost ratio and taking the absolute value of the difference between the average cost ratio at the high setting of the design variable and at the low setting of the design variable. All sensitivity values were then divided by the largest of all sensitivities seen to normalize the maximum sensitivity to a value of one. The sensitivity of vehicle levelized cost ratio to design variable interactions with each other is not plotted. The EV100 vehicle levelized cost ratio is most sensitive to battery costs followed by battery cycle life. After that, the presence of a federal tax incentive, assumptions on gasoline cost, annual distance driven, and magnitude of vehicle auxiliary loads all have approximately equal effect on the EV100 levelized cost ratio. GHG market cost does not seem to be a large economic driver in and of itself over the range of assumptions examined.

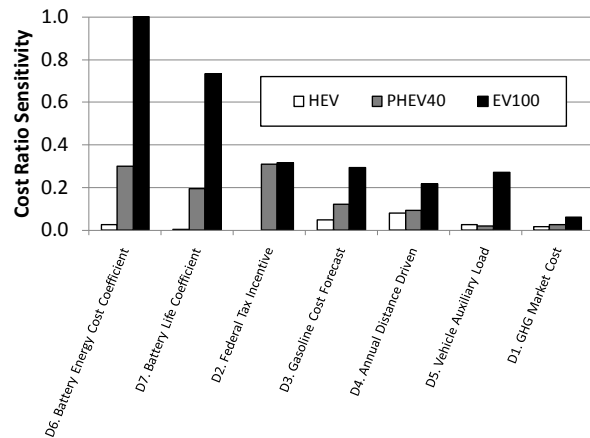


Figure 11: Sensitivity of vehicle levelized cost ratio to design variables

4 Conclusion

Multiple new powertrain configurations, infrastructure options, and business strategies are being suggested for future electric drive vehicles. To comparatively investigate these business approaches, NREL developed a new techno-economic model called the *Battery Ownership Model*. The model uses the present value metric of levelized cost per mile of owning and operating an EV under various business strategies and compares it with those of CV, HEV, and PHEVs. This paper focused on giving an overview of the model and illustrated some of the model inputs. We also presented an example analysis that investigated the sensitivity of vehicle levelized cost

ratio to seven design variables. The vehicle levelized cost ratio for an EV with a 100-mile range was found to be most sensitive to battery cost and cycle life with accessory loads, annual distance traveled, the existence of a tax incentive, and gasoline cost assumptions all having a secondary though approximately equal effect over the range of design variables examined.

In future work, we plan to use our model to further explore the techno-economic trade-offs of EV technologies, including consideration of service provider infrastructure options, markets such as taxis or long-distance commuters, alternative vehicle ownership scenarios, optimal EV range in the presence of infrastructure, optimal battery life and replacement schedules, larger vehicle size classes, further depth and emphasis on battery costs and associated projections, and vehicle usage and recharging strategies (e.g., opportunity charging). The present model currently has the capability to analyze all of these. In addition, since the battery is such a critical element for this model, we would like to enhance our battery cycle life model to better predict when batteries will fail and what residual value they will have at end of life. One area that the BOM will continue to omit is non-monetary benefits to the driver such as reduction in fossil fuel dependence, reduced GHG emissions, pride of driving green technology, reduction in the number of visits to gas stations, and the instant torque response of EVs. Inclusion of these externalities increases the value proposition of EVs to the driver over and above what we see from pure economics.

In summary, NREL's *Battery Ownership Model* was constructed to calculate the present value of costs to the end user of advanced electric traction drive vehicles and related infrastructure on a consistent basis over multiple scenarios. The results of the model show that there are scenarios where HEVs, PHEVs, and even EVs can be less expensive than CVs, and it also highlights which parameters have the largest influence over the vehicle levelized cost per mile. Furthermore, the BOM is equipped to answer many pressing questions that drivers, third party service providers, EV marketers, and policymakers have as they turn a transportation electrification system into reality.

5 Acknowledgements

We would like to acknowledge the U.S. Department of Energy's Vehicle Technologies Energy Storage, and particularly David Howell, for sponsoring this work. We would also like to thank NREL's Laboratory Program Manager for Transportation Research, Terry Penney, and the NREL Energy Storage Task Leader, Ahmad Pesaran, for their support and guidance.

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1. REPORT DATE (DD-MM-YYYY) January 2011			2. REPORT TYPE Conference Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Battery Ownership Model: A Tool for Evaluating the Economics of Electrified Vehicles and Related Infrastructure: Preprint				5a. CONTRACT NUMBER DE-AC36-08GO28308		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) M. O'Keefe, A. Brooker, C. Johnson, M. Mendelsohn, J. Neubauer, and A. Pesaran				5d. PROJECT NUMBER NREL/CP-5400-49127		
				5e. TASK NUMBER FC08.6400		
				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-5400-49127		
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) Electric vehicles could significantly reduce greenhouse gas (GHG) emissions and dependence on imported petroleum. However, for mass adoption, EV costs have historically been too high to be competitive with conventional vehicle options due to the high price of batteries, long refuel time, and a lack of charging infrastructure. A number of different technologies and business strategies have been proposed to address some of these cost and utility issues: battery leasing, battery fast-charging stations, battery swap stations, deployment of charge points for opportunity charging, etc. In order to investigate these approaches and compare their merits on a consistent basis, the National Renewable Energy Laboratory (NREL) has developed a new techno-economic model. The model includes nine modules to examine the levelized cost per mile for various types of powertrain and business strategies. The various input parameters such as vehicle type, battery, gasoline, and electricity prices; battery cycle life; driving profile; and infrastructure costs can be varied. In this paper, we discuss the capabilities of the model; describe key modules; give examples of how various assumptions, powertrain configurations, and business strategies impact the cost to the end user; and show the vehicle's levelized cost per mile sensitivity to seven major operational parameters.						
15. SUBJECT TERMS Battery; Economics; Electric Vehicle; Service Provider						
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)	