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Improving Petroleum Displacement Potential of PHEVs using Enhanced Charging Scenarios

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Abstract

Plug-in hybrid electric vehicles (PHEVs) have the potential to displace a significant amount of petroleum relative to conventional vehicles. It is anticipated that home charging at night (roughly once a day) would be the usual mode of operation for PHEVs. Opportunity charging could provide additional electric range. Our analysis have shown that a PHEV-20 with opportunity charging during the day would reduce fuel consumption by 71% whereas a PHEV-40 with only night charging reduces fuel by 66% relative to a conventional vehicle. A PHEV-20 with smaller battery reduces the initial purchase cost; however, our analysis shows that charging more frequently could reduce the life of the battery.

Keywords: Battery, charging, cycle life, electricity, PHEV (plug in hybrid electric vehicle).

1 Introduction

The United States faces a transportation energy problem. The transportation sector depends almost entirely on a single fuel—petroleum. The future of petroleum supply and its use as the primary transportation fuel threatens both personal mobility and economic stability. The United States currently imports nearly 60% of the petroleum it consumes and dedicates more than 60% of its petroleum consumption to transportation [1]. With ever-climbing U.S. petroleum consumption despite steadily declining domestic production, the petroleum import percentage will grow. International pressures also continue to increase as the growing economies of China and India consume petroleum at rapidly increasing rates. Many experts now predict that world petroleum production will peak within the next 5 to 10 years, greatly straining the petroleum supply and demand balance in the international market [2].

Hybrid electric vehicle (HEV) technology presents an excellent way to reduce petroleum consumption through efficiency improvements. HEVs use energy storage systems (ESS) combined with electric motors to improve vehicle efficiency by enabling the use of smaller-sized engines and by recapturing energy normally lost during braking events. A typical HEV can reduce gasoline consumption by about 30%-45% over a comparable conventional vehicle [3]. However, even aggressive introductions of efficient and affordable HEVs to the market will only slow the increase in petroleum demand due to vehicle life and annual travel trends. Reducing U.S. petroleum dependence below present levels requires vehicle innovations beyond current HEV technology.

Plug-in hybrid electric vehicle (PHEV) technology provides the potential to displace a significant portion of transportation petroleum consumption by using electricity for portions of trips. A PHEV is an HEV with the ability to "plug-in" so as to recharge its ESS with electricity from the utility grid. With a fully charged ESS, the vehicle will bias toward using electricity rather than liquid fuels. A key benefit of plug-in hybrid technology is that the vehicle no longer depends on a single fuel source. The primary energy carrier would be electricity generated from a diverse mix of domestic resources including coal, nuclear, natural gas, wind, hydroelectric, and solar energy. The secondary energy carrier would be a chemical fuel stored on the vehicle (i.e., gasoline, diesel, ethanol, or even hydrogen). Although PHEVs must still overcome technical challenges related to ESS cost, size, and life, the technology nevertheless provides a relatively near-term petroleum displacement option [6]. The combination of fuel savings potential, consumer usage patterns, charging scenarios, battery life attributes, and battery costs all need to be balanced and optimized to find the best low-cost solution for displacing fuel using PHEV technology. This paper integrates a recently developed battery life assessment method to sets of PHEV simulations to better understand the impacts of charge management scenario options, the potential to reduce battery size, while providing equivalent or greater fuel savings.

NREL is involved in significant PHEV-related research and development, including PHEV batteries and their interactions with the electricity grid. NREL has simulated the performance and performed cost/benefit analysis of PHEVs, developed PHEV batteries requirements for the US Department of Energy and the United State Advanced Battery Consortium, performed thermal testing of PHEV batteries, has used its PHEV test bed (Prius converted to plug-in with EnergyCS or Hymotion conversion kits) for field testing, studied the grid interaction with PHEVs, and also developed models for PHEV battery cost, life and performance trade-off studies. This paper uses the results and insight from these parallel studies to explore charging scenarios and environmental conditions that balance between cost, life, and fuel saving.

1.1 Review of Previous Results

The cost benefit ratio of several PHEV design scenarios relative to conventional and hybrid vehicles was presented by Simpson [5] and a comparison of the fuel savings benefit variability over real-world driving profiles was presented by Gonder [2]. ADVISOR^{TM}, a vehicle systems simulation package was used along with 227 unique real-world driving profiles to demonstrate the spectrum of fuel savings benefits that result from a broad distribution of driving behaviours. Although differences exist across driving profiles, when evaluated as a fleet, the simulations showed a savings of ~0.9 gallons of gasoline per day per vehicle or 66% for the PHEV-40 and 55% for the PHEV-20 design. Under long-term cost assumptions, the PHEV-20 was estimated to cost ~$3000 less than the PHEV-40 design scenario.

In a study conducted in collaboration with Xcel Energy, the real-world simulation results [2] were used to generate estimates of the utility load profile from charging PHEVs under several scenarios [1]. The utility integration study included four scenarios, "baseline" with one unmanaged charge per day, "delayed" with all charging delayed until after 10pm, "utility load valley filling" where all charging is optimally controlled to occur during the lowest utility demand period, and "opportunity" where charging occurs anytime the vehicle is parked. In recent publications, the expected performance of plug-in hybrid electric vehicles over real driving profiles based on travel survey data were presented (Figure 1) and it is shown that although consumer driving is more aggressive than standard test and design profiles, there is still significant potential for fuel savings with plug-in hybrid technology.

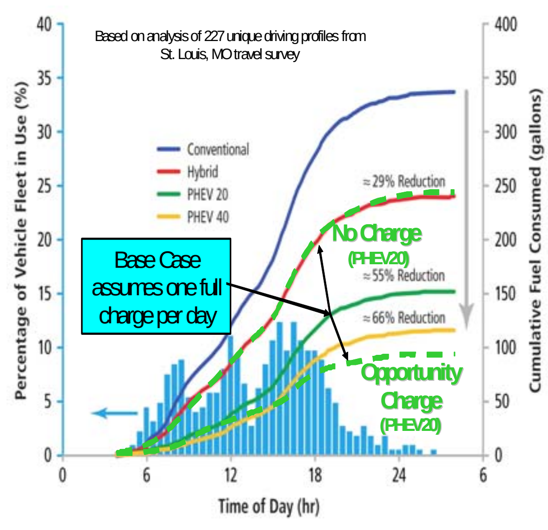

Figure 1: Plug-in hybrid simulations over collection of real driving profiles lead to greater than 50% petroleum displacement

The opportunity charge scenario proved to provide the greatest vehicle petroleum displacement while other scenarios provided a potentially more desirable scenario from utility operations perspective by lower operating costs and emissions impacts. The vehicle energy storage system encounters very different operating characteristics under each scenario. The battery life impacts of differences in usage profiles were not quantified. Research focus is now on the impact factors and opportunities for cost reduction of the plug-in hybrid system

1.2 Review of Battery Life Modelling

Battery life modelling is complicated as life is affected by many factors, including the temperature and state of charge (*SOC*) during storage, the depth of each discharge cycle, the frequency of cycling, and the rate of cycling. For automotive applications, the battery is often deemed to be at the end of its useful life when it has degraded to 80% of its original power or energy capacity [7]. The PHEV duty cycle may be the most difficult that a battery may see. In HEV usage, the ESS is maintained in a mid to high SOC level and cycling is quite shallow. In electric vehicle (EV) applications, the ESS is cycled deeply however, this cycling may only occur every few days rather than daily as in a PHEV. If a PHEV is charged more than once a day, the duty cycle may be even more severe. Battery life modelling coupled with vehicle systems simulations provides an opportunity for quantifying these differences.

Most commonly, battery cycle life is projected by extrapolating degradation-per-cycle measured during accelerated cycling tests [16]. Battery calendar life, or years in life, is projected by extrapolating a model fit to degradation measured with time during storage at normal and elevated temperatures [14]. True battery life, however, is dependent upon both storage and cycling, and it is important when exploring real world scenarios that the battery ageing model combine both cycling and storage effects.

Hall et al. [10] recently demonstrated the importance of collecting real-time cycling data as well as accelerated cycling data for a lithium ion battery with nickel-cobalt-aluminium (NCA) cathode. They found that accelerated cycling results (4 cycles/day) tended to over-predict actual NCA battery life when compared to 5 years of real-time cycling data (1 cycle/day) for a geosynchronous orbit satellite application. Differences between accelerated cycling and real-time cycling degradation could not be wholly explained by correcting for calendar effects.

2 Approach

Vehicle systems simulation enables the rapid exploration of vehicle design and control options. Battery life models provide the ability to quantify differences in battery usage scenarios. Real-world driving profiles are extremely valuable for understanding both the real fuel savings potential of PHEVs and highlighting the design challenges of incorporating sufficient power capability, energy storage sizing, and fleet charging strategies. This study uses all three modelling and data resources to compare two PHEV scenarios:

a. PHEV-40 with a single evening charge and
b. HEV-20 with opportunity charging throughout the day.

2.1 Vehicle Simulation Model

Vehicle system simulation enables modelling and evaluation of many vehicle powertrain and control scenarios. ADVISOR was used to simulate the operation of conventional, hybrid, and plug-in hybrid electric vehicle options for this study. Inputs to this model include details about the powertrain components, the vehicle attributes, the control strategy, and the driving profile. Results provide detailed information on the time dependent operation of all of the components and the overall performance of the vehicle. For this study, of primary interest are the fuel consumption and the energy storage system operational details. Table 1 shows the attributes of the vehicle simulated.

Table 1: Simulated Vehicle Attributes

	Units	Conventional	Hybrid	PHEV20	PHEV40
Engine Power	*kW*	121.7	82	79.4	81.9
Motor Power	*kW*	n/a	39	43.6	48
ESS Power	*kW*	n/a	50	47	51.8
ESS Energy (total)	*kWh*	n/a	1.9	9.4	18.5
Curb Mass	*kg*	1429	1399	1488	1567
Fuel Economy (urban/highway)	*mpg*	26	39.2	54	67.4
Electric Consumption (urban/highway)	*Wh/mi*	n/a	n/a	95	157
All Electric Range (urban)	*miles*	n/a	n/a	22.3	35.8

Key assumptions were:

- The baseline vehicle is based on a Malibu/Camry-like mid size vehicle,

- The PHEV has ability to operate on the electric drivetrain alone during urban driving,
- Controls operate the PHEV in charge depletion mode between 95% to 30% SOC,
- The strategy implements a charge sustaining operation between 25% to 35%,
- The baseline scenario begins to recharge the battery after the end of the last driving trip,
- The opportunity scenario begins recharge any time the vehicle key is turned off,
- The battery is recharged at a constant 1.4kW utility load with an 85% efficient charger.

The battery life impacts of two PHEV scenarios, one with 40 miles of range and a single daily charge and one with 20 miles of range and ability to charge at all parked times were considered. A PHEV-40 is designed to provide ~40 miles of electric drive capability on an urban driving profile. On driving profiles requiring more power than that encountered in urban driving or for distances longer than 40 miles, the petroleum-fueled engine supplements the battery power and energy capability. Likewise, the PHEV-20 has ~20 miles of urban electric drive capability. Based on assessment of NHTS data a 40 mile vehicle satisfies 68% of consumer daily driving needs with a single daily charge. A 20 mile range would cover 42% of the daily miles [18]. With additional recharge opportunities the 20 mile PHEV should provide equal or greater fuel displacement depending on the driving profile attributes.

2.2 Driving Profile Database

The driving profile database for this study includes one full day of driving data for 227 unique vehicles that were collected using GPS data loggers as part of a metropolitan travel survey in St. Louis Missouri in 2002. Expansion factors to weight these cycles to be representative of the entire survey population were not applied. A typical driving profile includes several individual driving trips defined by elapsed time and vehicle speed. Parked times and durations are also included. Figure 2 shows the distribution of daily distances in this data set.

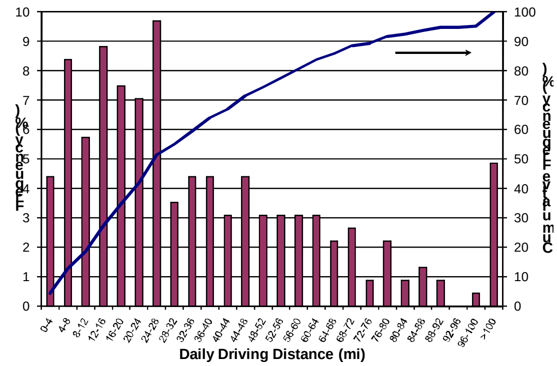

Figure 2: St. Louis driving profile data set daily driving distance distribution

2.3 Battery Ageing Model

Battery performance degradation has been shown to be dependent on a number of operational parameters including number of cycles N_i at a given state of charge swing ΔSOC_i, time t, voltage exposure $V(t)$, temperature exposure $T(t)$ and charge current rate $I(t)$. With sufficient data, the dependency of capacity fade and resistance growth on each operational parameter can be established. Physical or empirical models can be fit to data to interpolate/extrapolate results for different scenarios.

In order to explore the impact of PHEV consumer use scenarios on battery performance degradation, the present work uses an empirical model [8] fit to data presented by Hall et al. for a Saft VES-140 Li-ion cell with carbon/NCA chemistry [10-12]. Operational parameters explored in that study included end of charge voltage, depth of discharge, temperature, and number of cycles per day. Cycling conditions included the afore-mentioned real-time and accelerated cycling conditions as well as storage.

Hall et al. found that storage degradation time dependency could be well-described by a $t^{1/2}$ model, consistent with a diffusion-limited corrosion reaction mechanism that builds a film layer at the electrode surface. They also found that small ΔSOC cycles tended to suppress the film layer growth somewhat, while large ΔSOC cycles tended to degrade the positive electrode active material and cause additional resistance growth and capacity loss. The addition of cycling degradation was well-correlated by adding a t or N dependency to the $t^{1/2}$ storage model.

Full details of the present carbon/NCA chemistry degradation model may be found in [8]. The model captures both storage- and cycling-induced resistance growth with

$$R = a_1 t^{1/2} + a_{2,t} t + a_{2,N} N \qquad (1)$$

Results of various storage and cycling tests were used to fit coefficients $a_1(\Delta SOC,T,V)$ and $a_2(\Delta SOC,T,V)$ and capture ΔSOC, $T(t)$ and $V(t)$ dependencies. Depth of discharge dependency was fit using empirical formulas. Temperature and voltage dependencies were fit with physically-justifiable Arrhenius and Tafel relationships, respectively. Separate t- and N-dependent terms (rather than t-only or N-only) in (1) are necessary to describe degradation under both real-time and accelerated cycling conditions.

To describe capacity fade, the model assumes Li loss to be the dominant mechanism on storage, and active site loss to be the dominant mechanism on cycling [13]. Available Li capacity C_{Li} is described as

$$C_{Li} = d_0 + d_1\, a_1\, t^{1/2} \qquad (2)$$

while active site capacity is described as

$$C_{sites} = e_0 + e_1 (a_{2,t} t + a_{2,N} N) \qquad (3)$$

Actual measured or useable capacity is taken as the lesser of (2) or (3)

$$C = \min(C_{Li}, C_{sites}) \qquad (4)$$

The VES-140 cells [10-12] are nearly a decade old and might not reflect the life capability of present day PHEV battery technology. It is also possible that these cells, intended for aerospace application, use more expensive materials and last longer than present day PHEV cells. In order to account for both of these possibilities, several battery degradation model parameters were adjusted to match recent published data for vehicle electric drive batteries also with carbon/NCA chemistry.

The model used for scenario analysis matches the following actual measured ageing results. After 4.5 years storage at 40^{o}C and 50% SOC, the battery will have lost 10% capacity [14]. After 13.7 years at 35^{o}C, the resistance will have grown 110% [15]. Following 2700 PHEV power profile cycles consisting of ΔSOC = 75% deep discharge and numerous shallow cycles at 25^{o}C, the battery resistance will have grown 50% and capacity will have faded 8% [16 and 17].

3 Results

Vehicle simulations were conducted for five vehicles and charge scenarios. These included conventional, HEV, PHEV-20 baseline charge, PHEV-40 baseline charge, and PHEV-20 opportunity charge. The total fleet fuel savings relative to the conventional case are shown in Figure 3.

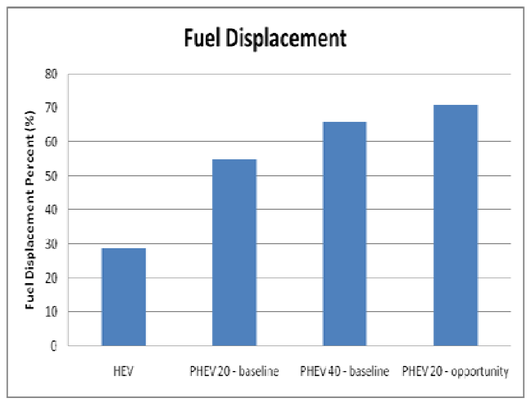

Figure 3: Fuel displacement potential of various hybrid scenarios over the conventional vehicle

3.1 Driving Profile Impact

The driving profile characteristics can affect the relative benefits of the PHEV-20 opportunity charging scenario to the PHEV-40 baseline charge scenario. Cycles with more short trips and parked time between trips provides more opportunity for recharging the depleted battery while cycles with only a few long trips provide less overall benefit of opportunity charging.

Figure 4 provides an example of the simulation details for a single driving profile simulation. The chart shows the vehicle speed profile, the cumulative fuel consumption, and the varying battery state of charge for each of the vehicle and charge scenarios. This specific vehicle travelled ~55 miles over the course of one day. The opportunity charge capability extended the electric only range on this driving profile by over 30 miles for the PHEV-20. Fuel savings relative to the HEV for the opportunity charge case was 1.5 gallons while the fuel savings for the single charge per day PHEV-40 case was ~1 gallon. The ESS *SOC* history for each of the three scenarios is also provided. The HEV SOC scenario varies between a very narrow range. The PHEV-40 with a single evening charge incurs a single full discharge and charge. The PHEV-20 with opportunity charge capability incurs multiple cycles. These cycling scenarios will have very different impacts on battery life. Additionally, this is only a sample, a single cycle selected from the 227 unique driving profiles. Relative benefits will vary with driving profile attributes.

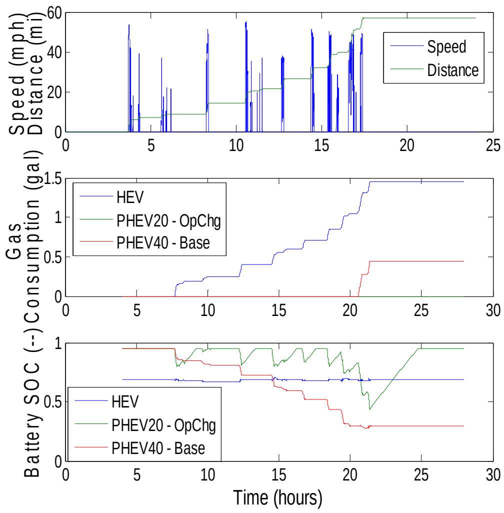

Figure 4: Gasoline consumption and state of charge behaviour greatly impacted by battery size and charging scenario

Assessing the SOC characteristics of the entire fleet can also be completed. Figure 5 shows the ESS SOC information for the entire vehicle driving profiles in the data set. The amount of time spent in each SOC range is compared for each charge scenario. The opportunity charge scenario results in more time in the highest SOC range of any of the scenarios. The PHEV-40 baseline spends time in both low SOC and high SOC ranges. The battery in the HEV scenario spends nearly all of its time in the mid-range SOC. The battery operating characteristics resulting from these simulations provide input information for the evaluation of the cycling impacts on battery life.

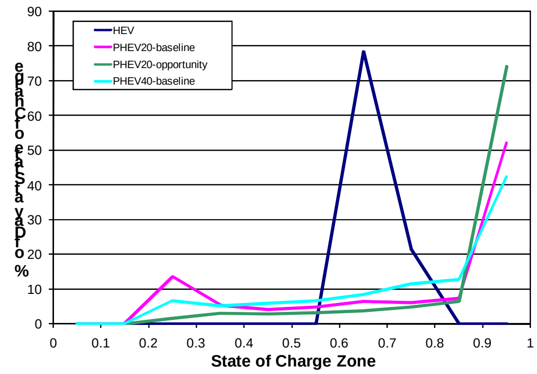

Figure 5: SOC for several PHEV and charge scenarios

3.2 Battery Aging with Different Charging Scenarios

The battery ageing model is used to simulate resistance growth and capacity fade for the 227 different one-day vehicle driving profiles. Vehicle simulations were performed for the two different vehicle/charging scenarios to generate battery cycling profiles:

a. PHEV-40 with a single evening charge and
b. HEV-20 with opportunity charging throughout the day.

For a given vehicle driving profile, cases (a) and (b) impose very different cycles on the battery. The PHEV20 battery is quickly cycled to its maximum ΔSOC depth due to its smaller capacity. Under the opportunity charging scenario, it is also charged/discharged with more cycles per day. A constant temperature of 30°C is used for all simulations. Previous work [8] found that this condition closely matches ambient temperature fluctuations in Phoenix, Arizona, commonly used as a worst case climate for vehicle design.

It is important to note that all Li-ion batteries have different characteristics and will degrade differently dependent on chemistry, materials, and manufacturing techniques. Furthermore, the 15 year scenarios explored using the model are significantly extrapolated forward in time compared to datasets used to fit the model. The present battery degradation projections are not meant to represent definitive outcomes for a particular Li-ion battery, but instead are intended to illustrate differences between the two different charging scenarios and demonstrate a variety of possible end-of-life outcomes. The results may aid the interpretation of battery degradation measured for actual vehicle fleets.

Figure 6 shows the model-projected battery resistance growth and capacity fade at the end of 15 years of cycling for the 227 different vehicle driving profiles. Resistance growth generally exceeds 100%, consistent with model parameter assumptions discussed in Section 2.3. The large resistance growth indicates that these batteries would need to be sized with substantial excess power at beginning of life in order to maintain useable energy and thus electric driving range for 15 years at this high temperature condition of 30^{o}C. Capacity fade ranges from 10% to 15% in most cases. Approximately 25% of the PHEV-20/opportunity charge cases experience severe capacity fade, greater than 13.5%. These most severe PHEV cases, however, encounter 2 to 3 deep discharges per day and over the 15 years accumulate far more cycles than the typical goal of 5000 deep discharge cycles for PHEV batteries [7].

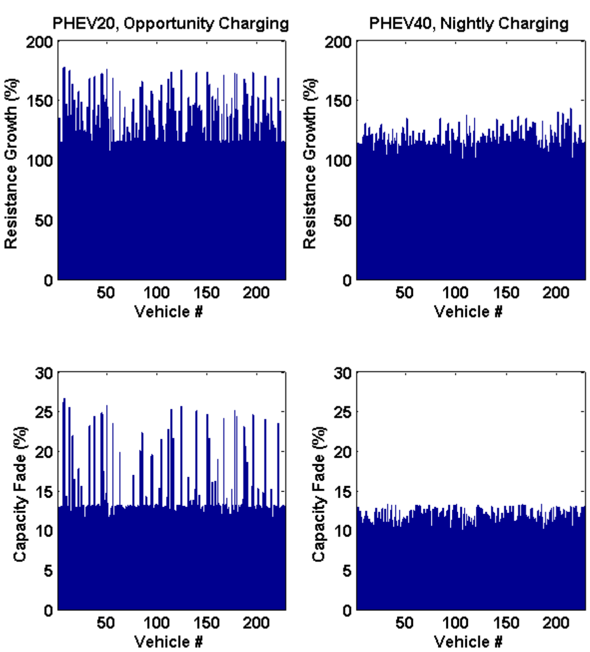

Figure 6: Capacity fade and resistance growth for PHEV20 opportunity charging (left column) and PHEV40 nightly charging (right column) scenarios for various vehicle driving cycles. Results are at the end of 15 years at 30^{o}C (comparable to Phoenix, AZ condition) for each of the 227 different drive cycle profiles.

Figure 7 shows battery degradation versus average daily SOC. All results are at the end of 15 years of cycling per each of 227 different vehicle driving cycles. A general increasing trend in degradation is observed with average SOC, consistent with the increased voltage exposure for those batteries. For both the PHEV-20/opportunity charge and PHEV-40/nightly charge cases, a minimum line of degradation with average SOC is observed. This line corresponds to shallowly or infrequently cycled batteries where the storage degradation effect dominates. For the PHEV-40, the dominant cycle is once per day. This cycling is benign enough such that, in all but one PHEV-40 case, Li loss at 30^{o}C controls capacity fade (2) rather than active site loss (3). For the PHEV-20, with much more frequent daily cycling, capacity fade is more often controlled by active site loss, indicated by the large variability in the possible capacity fade outcomes.

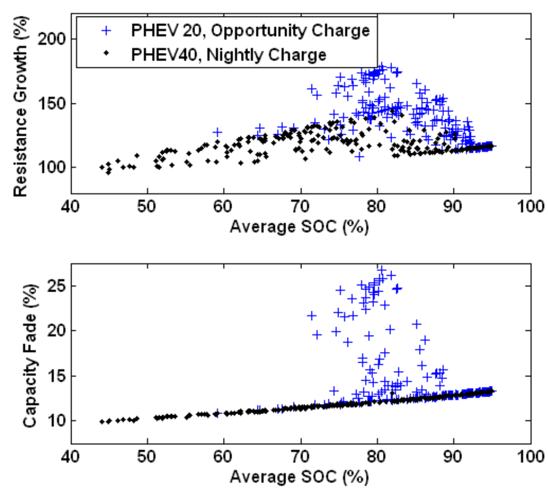

Figure 7: Resistance growth and capacity fade at the end of 15 years at 30^{o}C for 227 different vehicle driving cycles. The increasing trend with average SOC is due to the generally higher voltage exposure for those cases.

Resistance growth, rather than being controlled by either storage or cycling, is affected by both storage and cycling. In Figure 8, a minimum line of resistance growth versus average SOC is again observed in the 227 different vehicle driving profiles. These are all cases where storage effects dominate. For both PHEV-20/opportunity charge and PHEV-40/nightly charge cases, cycling further increases resistance growth compared to the storage-dominated cases. The PHEV-20 case, with more frequent daily cycling, shows roughly double the variability in resistance growth at the end of 15 years compared to the PHEV-40 case.

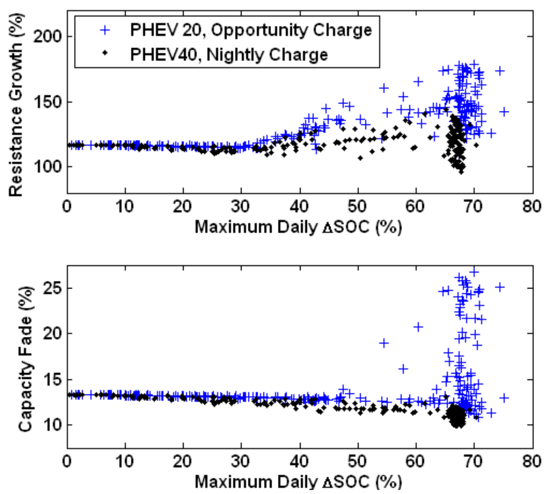

Figure 8: Resistance growth and capacity fade at the end of 15 years at 30°C for 227 different vehicle driving cycles. Resistance growth and capacity fade can either increase or decrease with maximum daily ΔSOC swing due to competing degradation mechanisms of voltage exposure and cycling stress.

Figure 8 displays resistance growth and capacity fade at the end of 15 years at 30°C versus the maximum daily ΔSOC, that is the deepest discharge encountered each day for the 227 different cycles. Figure 8 shows that both resistance growth and capacity fade can either increase or decrease with maximum daily ΔSOC swing, dependent upon the severity of the cycling. The increasing trend is due to the higher severity of cycling degradation caused by increasing ΔSOC. This cycling-dominated degradation is much more common for the PHEV-20/opportunity charge case compared to the PHEV-40/nightly charge case. The decreasing trend with ΔSOC seen for other simulation results is due to the higher voltage exposure experienced by batteries that are cycled very little and instead spend much of their life near full charge. For these cycles, degradation is largely storage-dominated.

4 Conclusions

The PHEV duty cycle of a full discharge on a daily basis for 10-15 years in an automotive environment may be one of the most difficult life performance challenges for batteries. Both cycling and calendar ageing affect the power and capacity fade rates of a battery. A model has been developed to estimate the combined impacts of cycling and calendar aging influences, including time spent at high SOC, time spent at high temperature, and depth of discharge and frequency of cycling.

Batteries account for a significant portion of PHEV initial cost. Manufacturing cost of a PHEV-20 is expected to be on the order $3000 less than a PHEV-40 due to its smaller battery. While a PHEV-20 may seemingly have less potential for petroleum displacement due to its smaller electric range, recharging between trips can enable greater utilization of its smaller battery. Vehicle simulations for 227 different real-world driving profiles find that a PHEV-20, charged at every opportunity, can displace 5% more fuel than a PHEV-40 that is only charged once each night. This PHEV-20 opportunity charging scenario, however, places more frequent deep discharge cycles on the battery compared to the PHEV-40 nightly charging scenario and can be expected to degrade the PHEV-20 battery at a faster rate.

Simulations of battery ageing for PHEV-20 opportunity-charge and PHEV-40 nightly-charge scenarios for 227 driving cycles illustrate a large variety of possible outcomes dependent upon the manner in which a battery is cycled and stored. With more severe cycling, 25% of the simulated PHEV-20 opportunity-charged fleet experiences substantially greater degradation than the PHEV40 nightly-charged fleet after 15 years of cycling at 30°C (NCA chemistry). In some situations, cycling can reduce degradation by reducing time spent at high SOC, however this effect is generally small when compared to the cumulative stress of multiple deep discharge cycles per day. Both storage- and cycling-dominated degradation outcomes are possible dependent upon how the battery is used.

Acknowledgments

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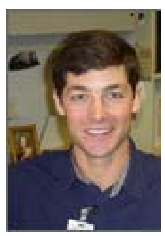
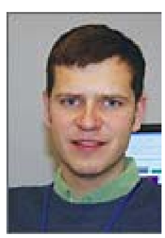


Tony Markel is a Senior Engineer at NREL and applies computer modeling and simulation to the evaluation of advanced automotive systems. He is currently researching several innovative technologies for hybrid electric vehicles and enjoys applying optimization tools to real world analysis problems. He holds a M.S. in mechanical engineering from the University of Colorado.



Kandler Smith is a Senior Engineer at NREL, working in the areas of battery thermal management and electrochemical modelling. He holds a Ph.D. in mechanical engineering from Penn State. His Ph.D. research developed electrochemistry-based real-time algorithms that enable expanded battery power and energy capability.

Ahmad Pesaran is a Principal Engineer at NREL and leads the energy storage team. Ahmad manages several projects for Department of Energy and industrial partners, which include thermal characterization and analysis of batteries, modelling and simulation for hybrid and plug-in hybrids.