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Investigation of battery end-of-life conditions for plug-in hybrid electric vehicles

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) capable of drawing tractive energy from the electric grid represent an energy efficient alternative to conventional vehicles. After several thousand charge depleting cycles, PHEV traction batteries can be subject to energy and power degradation which has the potential to affect vehicle performance and efficiency. This study seeks to understand the effect of battery degradation and the need for battery replacement in PHEVs through the experimental measurement of lithium ion battery lifetime under PHEV-type driving and charging conditions. The dynamic characteristics of the battery performance over its lifetime are then input into a vehicle performance and fuel consumption simulation to understand these effects as a function of battery degradation state, and as a function of vehicle control strategy. The results of this study show that active management of PHEV battery degradation by the vehicle control system can improve PHEV performance and fuel consumption relative to a more passive baseline. Simulation of the performance of the PHEV throughout its battery lifetime shows that battery replacement will be neither economically incentivized nor necessary to maintain performance in PHEVs. These results have important implications for techno-economic evaluations of PHEVs which have treated battery replacement and its costs with inconsistency.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are an advanced vehicle technology which has the capability to improve the near-term sustainability of the transportation energy sector. By storing energy on board the vehicle in the forms of both gasoline and electricity, PHEVs offer the potential to significantly reduce greenhouse gas emissions, reduce criteria emissions, and improve national energy security [1].

While PHEVs promise benefits to many elements of society, the market share that PHEVs will achieve in the near-term is dependent on their cost-competitiveness with conventional vehicles. The incremental cost of PHEVs relative to conventional internal combustion vehicles is primarily associated with the costs of electric drive train and battery energy storage system. Advancements in electric drive technologies and the maturation of battery manufacturing systems will drive down PHEV prices with government incentives used to narrow the price gap in the interim, but the role of battery lifetime on PHEV incremental cost is uncertain.

The recent studies which have sought to quantify the incremental cost of PHEVs relative to conventional ICE vehicles have been inconsistent in their assumptions as to whether PHEVs will require battery replacement during their useful life, a decision that has large effect on the lifecycle cost of a PHEV. In [2], the Electric Power Research Institute (EPRI) discusses the need for battery replacement by examining the distance required by battery warranties, the batteries usable state of charge (SOC), and how the vehicle's battery management system (BMS) handles degradation over time. Because the vehicles' lifecycle costs are sensitive to battery replacement, two sets of lifecycle costs are presented with each using different assumptions regarding replacement. A study by the Massachusetts Institute of Technology (MIT) assumes that no battery replacements will be necessary during a PHEV's useful life [3]. An Argonne National Laboratory (ANL) study presents lifecycle costs based on two different battery sizes; one in which a single battery replacement is required, and one sized such that replacement is not necessary [4]. EPRI's 2004 report [5] assumes no battery replacements in lifecycle analysis and justifies this claim with testing data, usage statistics, and technology improvement assumptions. The National Academy of Sciences (NAS) presents incremental costs of PHEVs without including the cost of battery replacement in a lifecycle costs analysis [6]. However, NAS does include battery life expectations that range from 3–8 years in the near term to 9–15 years by 2030; implying the need for battery replacement in a large percentage of PHEVs for years to come. In these 5 studies, the decision to include battery replacement in a lifecycle cost analysis increases the incremental cost of a PHEV by between 33% and 84%, as shown in Table 1.

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Table 1
Impact of the battery replacement assumption on the incremental cost of PHEVs for various PHEV cost studies.

Organization (year)	Vehicle configurations	% Increase in incremental cost for one battery replacement
EPRI (2001)	PHEV 20, 60	52–71%
ANL (2001)	PHEV 30	33–47%
EPRI (2004)	PHEV 20	57–64%
MIT (2007)	PHEV 10, 30, 60	44–75%
NAS (2010)	PHEV 10, 40	39–84%

In light of the large effect that battery replacement has on the lifecycle cost of PHEVs, a more detailed study of PHEV battery end-of-life (EOL) is required. This paper describes a comprehensive study of PHEV battery end of life including (1) analysis of battery EOL testing and metrics, (2) simulation of vehicle performance as a function of battery degradation and as a function of battery degradation management strategy, and (3) analysis of the economics of battery replacement. This paper will describe the ways in which the industry standard US Advanced Battery Consortium (USABC) battery lifetime is a poor surrogate for PHEV battery lifetime. Lithium ion battery degradation test results are then presented to illustrate the discrepancies between USABC battery lifetime and a PHEV specific battery lifetime. Two degradation control strategies (DCS) are then presented to demonstrate ways in which vehicle level efficiency and performance change with battery degradation. Discussion focuses on quantifying the benefit of battery replacement in terms of vehicle fuel consumption, performance and reduced ownership costs.

2. Background

The industry standard method for determining the lifetime and capabilities of automotive batteries is through USABC testing, but the applicability of USABC test procedures to the conditions of use of modern PHEVs is uncertain.

The USABC was formed in January of 1991 in an effort to promote the long term research and development of electrochemical energy storage systems. Currently operating under the guidance of the US Council for Automotive Research (USCAR), USABC promotes collaboration between leaders of industry and academia in order to accelerate the development of high power and energy batteries for use in electric, hybrid, and fuel cell vehicles [7].

As part of its mission, the USABC publishes test procedures to guide the development of electrochemical energy storage systems. During its inception in the early 1990s, battery electric vehicles (BEVs) were receiving considerable attention from US automakers in anticipation of their commercial release. As such, USABC established battery testing procedures designed primarily for all-electric BEVs. These USABC standards established battery EOL for BEVs as the stage at which specific failure criteria is met (e.g., capacity and/or power degradation). Specifically, when either:

(1) “the net delivered capacity of a cell, module, or battery is less than 80% of its rated capacity when measured on the DST (Reference Performance Test); or
(2) the peak power capability (determined using the Peak Power Test) is less than 80% of the rated power at 80% DOD,”

with DOD (depth of discharge) defined as:

“the ratio of the net ampere-hours discharged from a battery at a given rate to the rated capacity.”

USABC last updated its battery EOL testing procedures in January of 1996 [8]. Since that time, vehicles have become far more sophisticated in their measurement and management of battery SOC; to the point that the USABC definition of EOL must be reexamined.

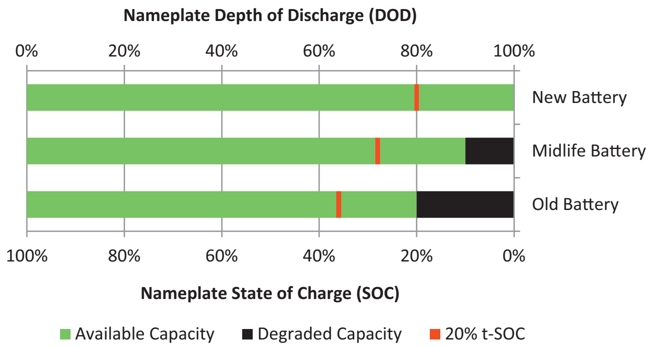

Fig. 1. Variation of t-SOC as a result of capacity degradation. As the battery degrades, the degraded capacity occupies a greater fraction of nameplate SOC, whereas t-SOC is normalized to the available capacity.

Conventionally SOC and DOD (where, DOD = 1 − SOC) are nameplate capacity-based, using a method known as Coulomb Counting to determine the percent of remaining charge relative to nameplate capacity [9]. Capacity-based SOC measurement is widely used in testing environments due to its high degree of stability and consistency; however, this method can be misleading as it does not represent the actual thermodynamic “state” of the battery [10] including Peukert effects, temperature effects, self-discharge, and capacity degradation. Modern BMS are now capable of taking these variables into account to determining a battery’s thermodynamic SOC (t-SOC), where the t-SOC is a characterization of the battery with respect to its instantaneous chemical composition and extent of reaction [11]. The discrepancy between SOC and t-SOC in batteries of various ages can be seen in Fig. 1.

Advancements in BMS systems have important ramifications for how modern PHEVs and EVs manage their batteries as the batteries degrade over the vehicle’s lifetime. Electric vehicles built in the 1990s were designed to maintain their original range over their lifetime and as a result experienced accelerated power degradation once capacity degradation necessitated the use of the battery under low t-SOC. Because PHEVs do not have so strict a requirement on battery capacity (as they are able to drive under a hybrid mode), PHEV DCS are now capable of preventing a battery from being depleted to the point where this accelerated degradation occurs. This allows PHEVs to operate within a t-SOC “window” that supplies adequate battery power while avoiding the accelerated degradation which occurs at extreme t-SOC. The lower limit that a DCS places on t-SOC is especially critical to PHEVs as they will operate at low t-SOC for travel in charge sustaining mode.

3. Battery test methods

To evaluate the difference between battery test procedures which use conventional SOC definition and one which uses a definition of t-SOC, we present an experimental study of battery degradation under both scenarios.

Between 2005 and 2009, a PHEV battery pack was degraded in the laboratory over 4323 charge–discharge cycles using a PHEV-specific test profile. The battery test profile was developed to simulate the duty cycle of a PHEV battery in charge depleting (CD) mode, in charge sustaining (CS) hybrid mode, and in recharging mode. The battery test profile was derived from a dynamic vehicle-level simulation of a portion of the INRETS URB1 vehicle test cycle. The battery test cycle replicates the urban driving conditions likely to be the most demanding to the battery (low speed, high acceleration and charge-sustained HEV mode at low battery SOC). Details of the battery and vehicle characteristics can be found in [12–14].

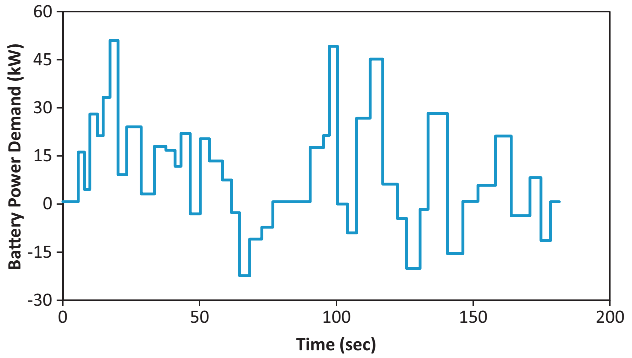

Fig. 2. PHEV CD test profile used to define PHEV-specific battery degradation test procedure.

This PHEV specific test profile is made up of a series of CD, CS and charging modes to simulate the types of battery usage which are common to PHEVs.

3.1. Charge depleting mode testing

The CD mode begins with a fully charged battery. The 181.5 s EV test profile (see Fig. 2) was repeatedly applied to the battery until the battery voltage drops below a pre-defined threshold for 10 consecutive seconds. This threshold was determined at the beginning of the life cycle test to ensure that the battery SOC at the end of the charge depleting mode was approximately 25%. Cycling the batteries from 100% to 25% SOC represents an aggressive approach by current standards. The Chevrolet Volt utilizes a t-SOC window of 80–30% in an effort to mitigate capacity degradation [15]. Employing such a window in this set of testing could significantly reduce the rate of capacity degradation.

3.2. Charge sustaining mode testing

The CS mode starts at the completion of the CD mode. The 181.5 s HEV test profile (see Fig. 3) was continually applied to the battery until the total duration of the CD mode and the CS mode reached a combined 2.6 h (equivalent to a 50 mile trip). The battery was then allowed to rest for 15 min before the next mode.

In the CS mode, the battery SOC should remain constant. The test profile was adjusted to ensure a zero net energy transfer between the battery and the test equipment. A minor offset was applied to the test profile at the beginning of the life cycle test to guarantee a constant SOC during the CS mode. Throughout the course of the test, the SOC drifted as the battery's internal resistance changed due to degradation effects. When the balance of capacity in ampere-hours exceeded a pre-defined parameter at the end of any test profile, the SOC was readjusted automatically.

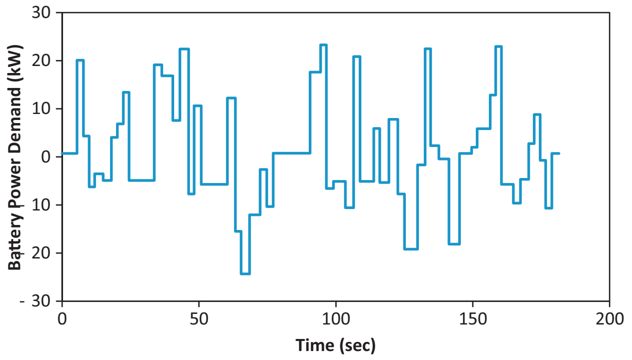

Fig. 3. PHEV CS test profile used to define PHEV-specific battery degradation test procedure.

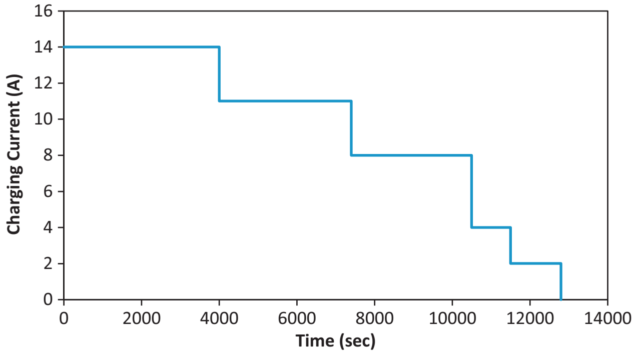

Fig. 4. PHEV charging profile used to define PHEV-specific battery degradation test procedure.

Table 2
SCE EVTC battery degradation test equipment.

Make	Model	Description
AeroVironment Inc., Simi Valley, CA	ABC-150	Battery Cycler
Neslab, Oak Park, IL	HX-300	Recirculation Chiller
National Instruments, Austin, TX	PCi-CAN2 Series 2	CAN Communication Interface Card
AeroVironment Inc., Simi Valley, CA	SmartGuard Type E	12-bit data acquisition system

3.3. Battery charging mode testing

After completion of the simulated driving profile, the battery was charged using the manufacturer's suggested charge algorithm (see Fig. 4) at the highest rate that would not present any detrimental effect to the battery life (3.5 h for a full charge). At the completion of this mode, a rest period lasting approximately 1 h was applied to allow for chemical and thermal stabilization before the start of a new test cycle.

3.4. Details of test methods

This test profile was adapted by Southern California Edison (SCE) to the test equipment at their Electric Vehicle Technical Center (EVTC) (see Table 2). The 7.3 h cycle was applied to 3 PHEV modules (see Table 3 for specifications) continuously from March 2005 to August 2009 for a total of 4323 cycles.

Reference Performance Tests (RPTs) were conducted before the start of the life cycle test, and at periodic intervals every 240 test cycles (equivalent to approximately 2 months of testing) to characterize the performance of the battery. The following tests are included in each RPT:

- A constant current discharge at a rate of C/1.
- A constant current discharge at a rate of C/3.
- A peak power test.
- A Hybrid Pulse Power Characterization (HPPC) Test (performed in the dual mode configuration).

The first three tests were performed using the methods of the USABC Electric Vehicle Test Procedure Manual [8]; the HPPC test was performed using the methods the PNGV Battery Test Man-

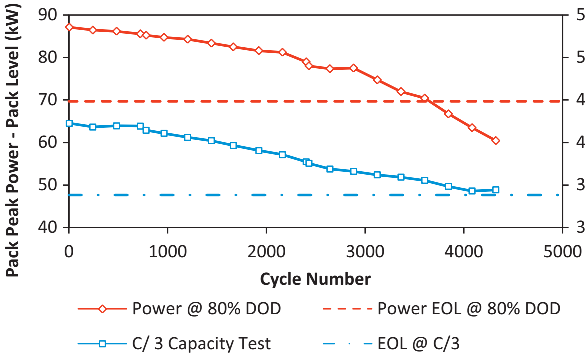

Fig. 5. Energy and power measurements as a function of cycle number.

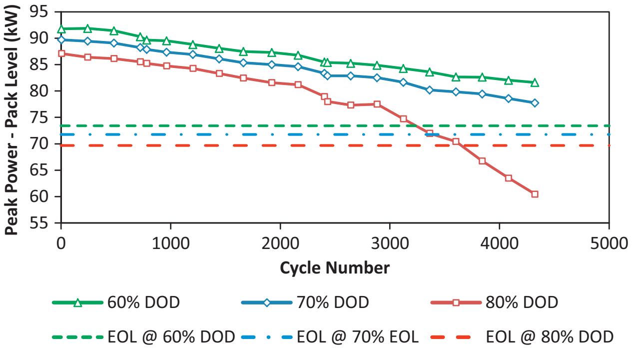

Fig. 6. Power degradation at various levels of capacity based DOD as a function of cycle number.

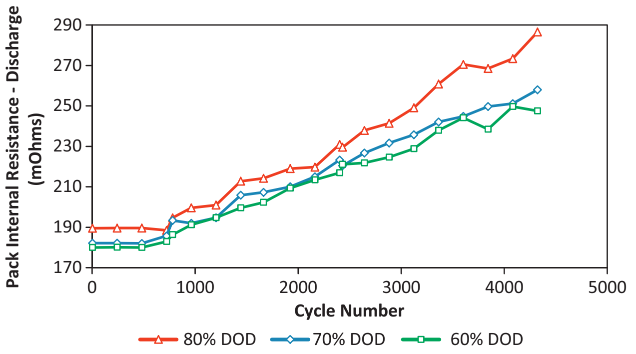

Fig. 7. Pack internal discharge resistance as a function of cycle number.

ual [16]. A preliminary cycle, including a discharge at a constant current rate of C/3 down to 60% DOD and a full recharge, was performed prior to each RPT. A 30 min rest was included in between each charge and discharge.

4. Experimental results

The results of these RPTs are now presented as a function of cycle number to demonstrate the degradation of Lithium Ion batteries under PHEV-specific test procedures. Battery EOL as calculated using the USABC capacity-based SOC can be contrasted with the battery EOL as calculated using t-SOC. In all of these results, no effort is expended to post hoc separate cycling-based degradation from calendar life degradation.

4.1. Battery degradation test results using capacity-based SOC

This section presents testing results which illustrate how capacity degradation and power degradation develop under USABC tests which use a capacity-based SOC definition.

Fig. 5 presents the battery RPT test results as measured during the battery degradation test. As shown in Fig. 5, battery power degrades non-linearly with cycle number. This non-linear effect is especially evident after approximately 2400 cycles. Under the USABC testing procedure, the battery under test will reach EOL at approximately 3650 cycles due to power limit. The energy EOL is not reached in 4323 cycles under the USABC test at the C/3 discharge rate.

The effect that t-SOC has on power degradation rate can be seen in Fig. 6 where degradation at various capacity based SOC are compared. Power can be seen to degrade at comparable rates for the three DODs until approximately 2400 cycles. At that point, power measured at 80% DOD begins to rapidly degrade while power measured at 70% and 60% DOD continues to degrade linearly.

Table 3
PHEV battery module specifications.

Manufacturer	Saft
Battery chemistry	Lithium Ion
Number of cells/pack	102
Number of modules/pack	17
Nominal pack voltage (VDC)	367
Cell capacity (Ah)	41 @ C/3
Pack energy (kWh)	15.5 @ C/3
Peak pack power (kW)	100
Module dimensions (mm)	190 × 123 × 242
Pack weight (kg)	136
Total system weight (kg)	180
Charger	3.3 kW conductive 208-240 VAC input
Cooling	Circulated liquid at 25 °C, continuous 0.5 l min^{-1} flow
Battery monitoring	SAFT BMS with voltage, current, and temperature sensing

A similar effect can be seen in Fig. 7 which shows the battery internal resistance as a function of SOC and cycle number. Again, the pack internal resistance at low capacity-based SOC is increasing nonlinearly with cycle number after approximately 2400 cycles.

This acceleration in degradation rate which is evident in all test results at low capacity-based SOC can be attributed to a significant change in the t-SOC that power is being measured at. As the battery capacity degrades, an 80% DOD corresponds to a lower and lower t-SOC condition, as seen in Fig. 8. At approximately 2400 cycles, the degraded battery capacity forces the 80% DOD power test to occur at a t-SOC below 15%. This low t-SOC region has high impedance reaction pathways, increasing the internal resistance of the battery system and decreasing its peak power. In other words, the USABC test procedure mixes the effects of battery capacity degradation with those of battery power degradation; as the battery capacity degrades, the low SOC power tests begin to occur at lower and lower t-SOC.

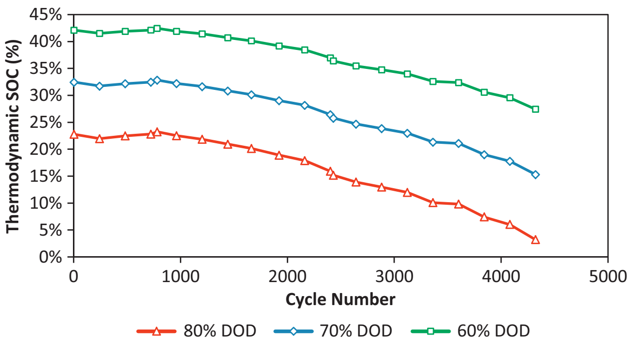

Fig. 8. Thermodynamic SOC relative to capacity based DOD as a function of cycle number.

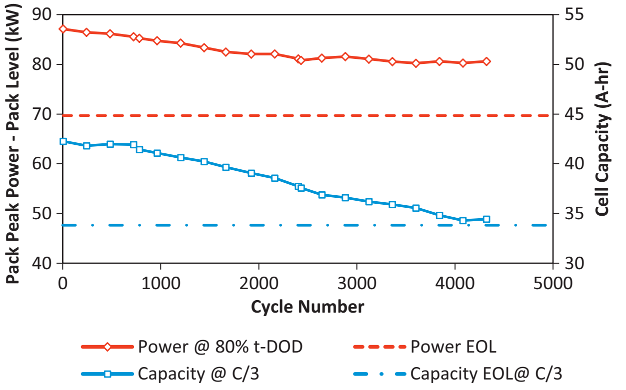

Fig. 9. Energy and power measurements made at 80% DOD and 80% t-DOD as a function of cycle number.

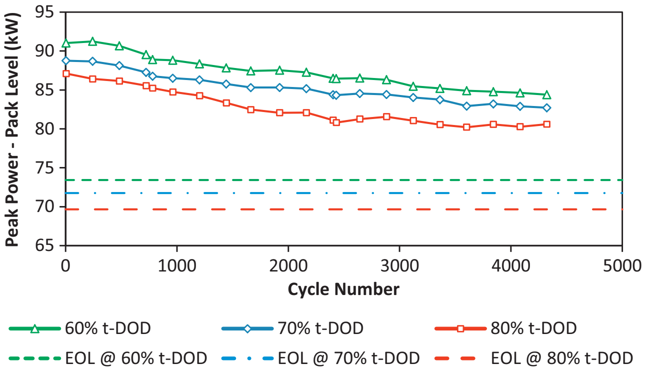

Fig. 10. Power degradation measured at various t-DOD as a function of cycle number.

These types of results will be familiar to students of battery degradation under USABC procedures, but the results' relevance for evaluating battery EOL must be considered carefully. For BEVs, these USABC EOL definitions can be relevant because BEVs are expected to maintain a constant driving range (approximately proportional to battery nameplate capacity) throughout their lifetime. In addition, battery power at the vehicle's maximum range is important for the usability, drivability and consumer acceptability of the BEV. For PHEVs, the battery performance plays a more minor role in these functions of the vehicle. Because PHEVs can vary their energy management and control strategy by varying engine turn-on conditions and charging power demands, they can maintain the usability, drivability and consumer acceptability and can avoid battery EOL despite degrading battery capacity.

4.2. Battery degradation test results using t-SOC

In this section, we analyze the same battery degradation test data so as to understand the ability of an advanced DCS to extend the life of PHEV batteries beyond USABC EOL. For this analysis, results of the previously presented RPTs were recalibrated to represent low power testing at 20% t-SOC, as opposed to the USABC-required 20% SOC testing procedure. It should be noted that results presented in this section reflect testing that occurred for CD cycling from 100% to 25% SOC. This analysis does not account for differences in degradation rates as a result of CD cycling from 100% to 25% t-SOC. While cycling based on t-SOC is believed to extend battery life, an additional 5 years of testing would be necessary to fully account for the unique degradation mechanisms associated with test procedure based solely on t-SOC.

Fig. 9 shows power and energy degradation measured at 20% t-SOC. This adjustment causes power to degrade more linearly as compared to the degradation presented in Fig. 5. Instead of battery EOL being determined by power degradation, it is now dictated by energy degradation. This extends the battery life from approximately 3650 cycles to over 4400 cycles, an increase of over 20%.

Further evidence of the effect of measuring power degradation at uniform t-SOC can be seen in Fig. 10. Power can now be seen to degrade at similar rates for all three t-DOD with degradation rate remaining relatively constant throughout testing.

Fig. 11 shows the effect that t-DOD measurements have on internal resistance as batteries degrade. Internal discharge resistance can now be seen to increase more uniformly and linearly for all conditions of t-DOD.

These results indicate that the USABC test procedure underestimates the cycle life capability of battery systems which can compromise on the requirement to discharge to a capacity-based SOC. Battery systems in PHEVs should be able to use an advanced DCS to avoid battery discharges at very low t-SOC, thereby increasing the battery cycle life.

5. Implications of battery degradation on PHEV fuel consumption, performance, and lifecycle cost

The results of the experimental battery degradation tests show that PHEVs can increase their battery cycle life and power capability by implementing a DCS which allows the battery to reduce its maximum capacity-based DOD during operation so as to maintain a constant minimum t-SOC. These changes to the battery DCS should minimize increases in fuel consumption, performance and lifecycle cost of the PHEV.

To determine the effects of battery degradation and DCS on these PHEV attributes, a light commercial vehicle was modeled and simulated as a blended-mode capable, parallel PHEV20. A Modelica-based vehicle simulation environment representing the LFM vehicle model presented in [17] was used to relate battery degradation to changes in vehicle performance. These simulations assume that calendar life degradation in practice is insignificantly different from calendar life degradation in the laboratory, that module-level performance degradation dominates over pack level effects such as module imbalance, and that the rate of battery degradation is independent of control strategy.

Simulations were performed using two DCSs: a "Static DCS" and a "Dynamic DCS". The Static DCS maintained the SOC window in the battery such that the energy available for discharge remained constant over the battery's life (equivalent to maintaining a constant, minimum capacity-based SOC over the lifetime of the vehicle). The Dynamic DCS allowed for a constant percentage of thermodynamic capacity to be utilized in CD mode such that the energy available for discharge was a function of the actual energy available in the battery instead of rated capacity (equivalent to measuring and

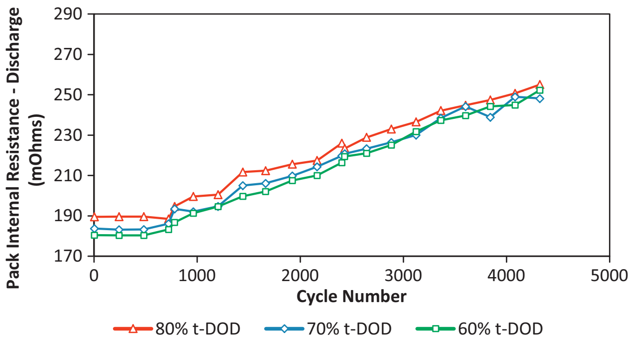

Fig. 11. Pack internal discharge resistance as a function of cycle number.

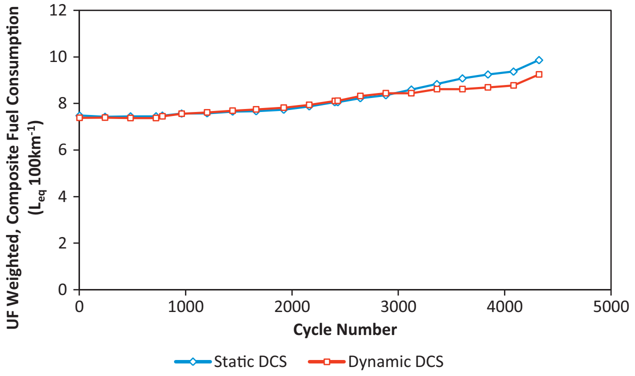

Fig. 12. PHEV20 fuel consumption as a function of cycle number.

recalibrating the minimum t-SOC continuously over the lifetime of the vehicle). The Dynamic DCS ensured that the vehicle entered charge sustaining mode at 25% t-SOC.

The vehicle model employed in these simulations represents a limited-production vehicle which was designed so that the battery was not oversized in terms of its power output, thereby minimizing incremental costs. As such, any loss of battery power from original specifications would be immediately visible at the vehicle level. Modern PHEVs are designed with some battery power margin to allow for battery degradation without affecting the electrical power capability of the drivetrain. As such, these degradation simulations represent a worst-case scenario.

5.1. Vehicle fuel consumption simulations

Using the two DCSs, we can see in Fig. 12 how fuel consumption is affected by battery degradation. PHEV fuel consumption is presented in this paper using an equivalent liter per 100 km metric where electric power consumption in the vehicle is converted to gasoline consumption using the lower heating value for gasoline. CD and CS fuel consumptions are weighted based on vehicle's utility factor (UF) using the methods of SAE J1711 [18]. PHEV UF is calculated as the ratio of the distance a PHEV travels in CD mode to the total distance traveled prior to a charging event. SAE J2841 [19] is used to calculate UF based on CD range. Finally, composite fuel consumption is calculated by weighting urban and highway fuel economy based on EPA standards (55% urban and 45% highway measured using federal driving schedules) [20].

Fig. 12 shows that the Dynamic DCS is able to reduce the increase in vehicle fuel consumption over the life of the battery pack. Over the 4323 cycles tested the Dynamic DCS fuel consumption increases by 25% compared to an increase of 32% using the Static DCS. This effect is due in part to the Dynamic DCS allowing the vehicle to operate in a higher SOC window where available battery power is superior. While the Dynamic DCS offers lower fuel consumption, it is also more susceptible to losses in CD range. Over the tested cycles, the Composite UF for the Dynamic DCS decreases by 13% while the Static DCS increases by 11%. While an increase in CD Range for degraded batteries may seem counterintuitive, it is a result of the Static DCS maintaining the SOC window in CD mode. As the peak power of the battery decreases with use, additional distance is necessary to deplete a constant amount of battery capacity.

Additional understanding of battery degradation's effect on fuel consumption can be garnered by examining its effects on specific modes of operation and drive schedules. Figs. 13 and 14 display fuel consumption for the simulated PHEV20 broken into CD versus CS operation and urban versus highway drive schedules respectively. In both instances the scenario that relies more heavily on battery power is more efficient over the life of the battery. However, CD and urban fuel consumption increase more rapidly than CS and highway fuel consumption because of their reliance on battery power. In all cases the Dynamic DCS is able to maintain fuel consumption more effectively (see Table 4).

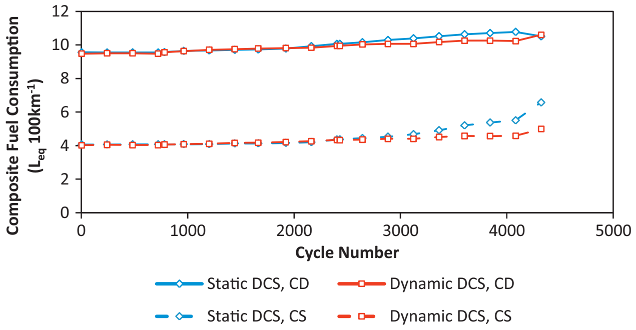

Fig. 13. Composite fuel consumption as a function of cycle number.

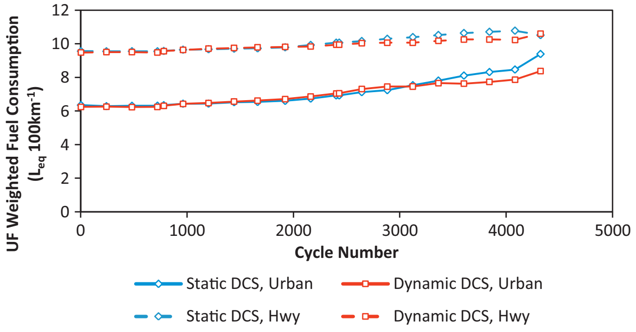

Fig. 14. UF-weighted fuel consumption as a function of cycle number.

5.2. Vehicle performance simulations

Regarding performance, Fig. 15 shows full-throttle standing acceleration times to 60 mph (96 kph) for the simulated PHEV20 as its battery degrades. It can be seen that in a blended parallel architecture, the simulated PHEV20 is able to maintain its acceleration time well for high SOC. However, acceleration does suffer slightly at low SOC. The acceleration time at 30% SOC and 30% t-SOC increased by 57% and 36% respectively over the 4000+ cycles tested. While this increase is measureable, the vehicle would still be very drivable after 4000+ cycles, becoming relatively sluggish only at low SOC.

The vehicle level effects of battery degradation have been presented in this section. We have shown PHEV fuel consumption to increase by 32% and 25% respectively for the Static DCS and the Dynamic DCS over the course of 4323 CD cycles. For comparison,

Table 4
Changes in equivalent fuel consumption, composite utility factor (UF) and acceleration time between cycle 1 and cycle 4323 for the simulated PHEV20 using Static and Dynamic DCS (superior metric for each DCS marked in bold).

	Δ Static DCS	Δ Dynamic DCS
UF weighted, composite L_{eq} 100 km^{-1}	32%	**25%**
Composite CD L_{eq} 100 km^{-1}	62%	**24%**
Composite CS L_{eq} 100 km^{-1}	23%	**14%**
UF weighted urban L_{eq} 100 km^{-1}	48%	**34%**
UF weighted highway L_{eq} 100 km^{-1}	**10%**	12%
Composite utility factor	**11%**	−13%
0–60 mph (96 kph) @ 90% SOC (t-SOC)	0%	0%
0–60 mph (96 kph) @ 60% SOC (t-SOC)	12%	**3%**
0–60 mph (96 kph) @ 30% SOC (t-SOC)	57%	**36%**

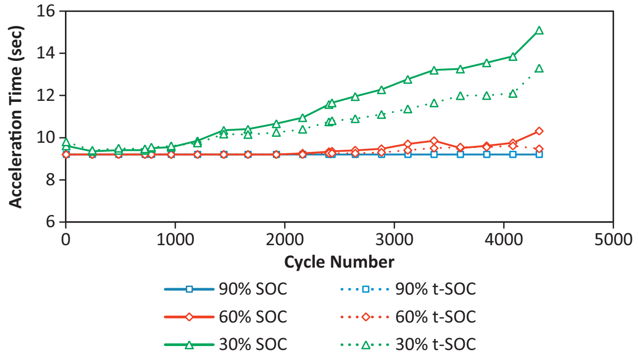

Fig. 15. Full throttle standing acceleration to 60 mph (96 kph) time as a function of cycle number for multiple SOC.

testing conducted at Idaho National Laboratory has shown HEV fuel consumption to increase by 4.2–14.7% over the course of 160,000 miles [21]. Acceleration times were simulated for 90%, 60%, and 30% SOC and t-SOC with increases in acceleration time presented in Table 4.

5.3. Vehicle lifecycle cost simulations

Given the present state of battery technology, battery costs, energy prices, and personal driving patterns, it is highly unlikely that the majority of PHEV owners will be interested in battery replacement as a means of financial savings.

The fuel consumption results of the vehicle simulations were input into a vehicle total cost of ownership model. Inputs to the model include the changes in fuel consumption relative to battery degradation presented earlier in this paper, projections for future US energy prices [22], projections for lithium-ion battery prices [23], and a constant value of 15,000 for vehicle miles traveled (VMT) per year. VMT was modeled as being constant over time in order to represent the behavior of a high mileage driver maintaining the use of a PHEV over several years. This is meant to simulate the use of a PHEV most likely to benefit from a battery replacement. The presented model does not assign a salvage value to batteries that are replaced. While a future market for the second use of automotive batteries has been discussed [24], the current absence of such a market makes salvage value projections uncertain.

Fig. 16 presents the results of a present value cost of ownership model reflecting the financial benefit of replacing a PHEV battery pack. The incremental costs of battery replacement after 10 years of ownership are not recuperated over a 25 years lifetime of the vehicle.

Using this model, battery replacement in a 10-year old PHEV would have a payback period of greater than 15 years, potentially exceeding the life of the vehicle. While the payback period is sensitive to model parameters (degradation rate, replacement year, etc.), the conclusion that battery replacement is not economically incentivized is robust to a variety of scenario definitions. The potential financial benefit anticipated as a result of battery replacement is not expected to be sufficient incentive for a consumer or fleet manager to invest in a multi-thousand dollar battery pack replacement.

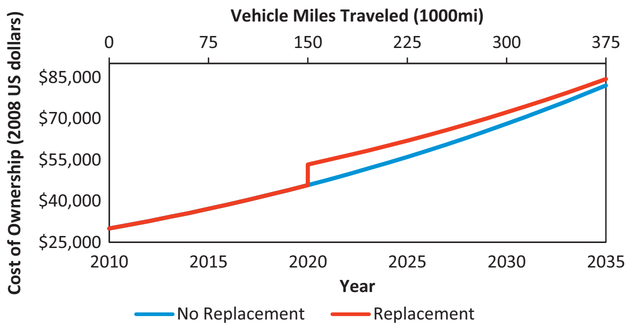

Fig. 16. Cost of ownership model demonstrating the cost of battery replacement in PHEVs.

It is also unlikely that consumers will be interested in battery replacement for improved performance or increased drivability. While acceleration times have been shown to increase at low SOC, the simulated PHEV20 was still able to complete urban and highway drive cycles in CS mode at 4323 cycles with adequate performance, including the aggressive US06 drive cycle. Replacement based on vehicle performance degradation would only be anticipated after the battery pack has endured far more than 4323 CD cycles.

6. Conclusions

A variety of studies assume that PHEV battery life can be predicted by the USABC cycle life test procedure; this assumption has dramatic effects on PHEV lifecycle cost and consumer acceptability. This study has shown how a DCS can be designed to extend battery life in PHEVs beyond USABC EOL. The effects of battery degradation on a blended parallel PHEV have been presented both in terms of vehicle efficiency and performance. In light of these effects, it is unlikely that the USABC definition for battery EOL will be predictive of how consumers and vehicle manufactures will approach battery replacement in PHEVs.

PHEVs differ from BEVs in that a direct relation between battery performance and vehicle performance does not exist. PHEVs can be designed to sense degradation and subsequently increase the degree to which they are blended to make up the power difference necessary to meet performance requirements. With this understanding, PHEV battery replacement would only make sense when a significant improvement in efficiency and/or performance could be achieved. In terms of fueling costs, replacement would be justified when the present value of fuel savings a battery replacement would provide is greater than the present value of replacement cost. This definition does not provide economic justification for pack replacement, even in scenarios involving significant battery degradation. In terms of battery replacement to restore as-new acceleration performance, the justification for battery replacement based on improvement in vehicle performance is more subjective. While the improvement in acceleration a battery replacement provides can be quantified, the amount of improvement that justifies an expensive battery replacement is an individual decision.

Finally, as a result of the disconnect between existing testing procedures and modern PHEV battery requirements and control capabilities, USABC should consider revising testing procedures for the specific application of PHEVs. Future work should anticipate the desire of automotive manufactures to design intelligent DCS that allow for adequate performance over the vehicle's life while avoiding battery replacement.

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