DRAFT - January 7, 2015

Status Report

Electric Vehicles and the Environment Informal Working Group (EVE IWG) Battery Performance and Durability

Table of Contents

1. Background

At EVE 16, a small drafting group was tasked with summarizing the views of the EVE IWG on battery durability. This document is an initial draft that is meant to:

(a) outline the overall topic of battery durability as it relates to the EVE mandate,

(b) summarize initial findings of the group as represented by comments and discussion that took place in EVE 16, and

(c) promote discussion of how the EVE IWG might move forward on the topic of battery durability for electrified vehicles.

2. Battery Durability and the EVE Mandate

The EVE mandate on battery durability stems from the recognition that the environmental performance of electrified vehicles may be affected by degradation of the battery system over time. This is important in particular because governmental regulatory compliance schemes often credit electrified vehicles with a certain level of expected environmental benefit, which might fail to be realized over the life of the vehicle if sufficient battery degradation occurs. Because battery degradation is not currently subject to uniform standards, there is a desire to understand the potential for battery degradation to affect environmental performance of electrified vehicles, and to consider the need for regulations to ensure that battery durability of an electrified vehicle is sufficient to maintain the expected environmental performance for the life of the vehicle.

Here, electrified vehicles are defined to include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) with all-electric range (AER) and/or blended mode operation, and hybrid electric vehicles (HEVs). Electrified vehicles of all types will herein be referred to as xEVs.

Members of the IWG have pointed out that battery durability per se is not the primary issue for the EVE IWG, but rather the effect that battery durability can have on the environmental performance of xEVs. Therefore, usage scenarios outside the normal expected duty cycle of an xEV application (such as durability under mechanical stress or other abuse conditions), or issues of durability that do not relate to environmental performance, will not be considered.

3. Initial Findings

Discussions among the members of the IWG have taken place for some time. Members appear to be in general agreement on some points, while others continue to be discussed.

3.1 Points of Agreement

At EVE 16, the EVE IWG appeared to generally agree on the following points.

(1) Electrified vehicle durability is an important performance parameter for the long term environmental impact of electrified vehicles. Battery durability is an important factor in electrified vehicle durability and is therefore relevant to the problem at hand.

(2) Electrified vehicle manufacturers are aware of the issues posed by battery durability, and currently manage battery durability to meet customer demands and expectations regarding the durability of the vehicle, and to provide appropriate warranty terms.

(3) It is possible to establish the durability of a battery, as evidenced by the fact that individual manufacturers have found it possible to establish durability metrics for their electrified vehicle products with sufficient confidence to bring the products to market while providing for customer satisfaction and warranty terms.

(4) Not every manufacturer is establishing (or managing) durability in the same way. Electrified vehicles on the market today have largely been validated for battery durability by means of a wide variety of testing regimens, often determined in an ad hoc manner and conducted as part of a long term research program. There is a lack of standard methods that are generally accepted to be effective at reliably predicting battery durability for arbitrary usage scenarios across all battery chemistries and configurations. For example, while accelerated aging is a well-established approach for generating durability data, converting such data to a reliable forecast of durability in actual use is still an unsettled issue. As a result, different manufacturers are likely to perform different suites of tests to become individually satisfied with their prediction of durability rather than using a single accepted suite of tests. Differences in the chosen test regimen could also be due to product differentiation or different customer or geographic influences.

(5) There are at least four major vehicle operating conditions that affect battery durability:

(a) Discharge rates, as determined by vehicle duty cycle, or activity and inactivity;

(b) Charge rates, as determined by type and frequency of charging;

(c) Battery temperature during operation; and

(d) Time (calendar life).

3.2 Discussion Items

The following topics were discussed at EVE 16 and will continue to be discussed within the IWG.

3.2.1 Distinction Between Types of Battery Degradation

Members of the IWG noted that battery degradation may manifest itself as a reduction in energy capacity and/or a reduction in power capability. These two types of performance degradation may carry different implications for environmental performance, and therefore should be considered individually.

Capacity degradation and power degradation often occur in conjunction with each other because some of the underlying mechanisms are common to both. Further, either type of degradation may be accompanied by increased internal resistance, which can reduce charging and discharging efficiency, and either increase the need for battery cooling or increase the temperature at which the battery operates.

3.2.1.1 Capacity Degradation

Capacity degradation refers to loss of energy storage capacity over time. For example, a battery capable of providing 20 kWh of usable capacity at beginning-of-life might provide only 16 kWh at end-of-life. Manufacturers have sometimes defined battery end-of-life by reference to capacity degradation. For example, a battery might be considered to be at end-of-life when its capacity reaches 80% of its original capacity (as in the above example).

In the case of BEVs and PHEVs, capacity degradation is important to environmental performance because it directly affects the capability for the vehicle to deliver all-electric mileage. Unless the manufacturer over-specifies battery capacity to allow for future capacity degradation, electric driving range will be reduced over the life of the vehicle. This is significant to environmental performance because a reduced driving range may reduce the degree to which all-electric vehicle mileage may displace conventional vehicle mileage (also referred to as utility factor). In the case of BEVs, reduction of the utility factor reduces the degree to which electric mileage is likely to displace conventional vehicle mileage, because the vehicle may become usable only for shorter and shorter trips. In the case of PHEVs, it reduces all-electric mileage (in charge-depletion mode) in favor of conventionally-fueled mileage (in charge-sustaining mode).

Capacity degradation may also be associated with increased internal resistance, leading to reduced charge and discharge efficiency. This can therefore affect the upstream emissions of BEV and PHEV AER miles by increasing energy use per mile.

To reduce the effect of capacity degradation on range, manufacturers may choose to slightly oversize the battery to allow for a widening of the state-of-charge (SOC) window as capacity degrades. Others may choose to design for a beginning-of-life range, and account for degradation by warranting the battery to a specified degree of capacity retention over a specified period of time. Implicitly, the consumer is therefore expected to understand that a potential reduction in electric range may be experienced during the life of the vehicle. Commonly, acceptable capacity retention is formally or informally defined to be approximately 70% to 80% of original capacity.

Despite the potential for loss of electric range over time, regulatory practice does not uniformly account for it. For example, US EPA range labeling rules for BEVs and PHEVs effectively treat driving range as a beginning-of-life criterion, by measuring range at beginning-of-life and omitting any adjustment for future capacity degradation.

In the case of HEVs, capacity degradation may affect the ability of the system to effectively manage power flows of the internal combustion engine, and so may affect fuel economy and/or vehicle power output.

3.2.1.2 Power Degradation

Battery power degradation has a strong potential to affect both the environmental performance and the acceleration performance of the vehicle over time.

In the case of BEVs and many longer-range PHEVs, the large capacity of the battery often brings along with it a greater power capability than needed for vehicle acceleration, with the power rating of the electric propulsion motor acting as the limiting factor. Power fade in these batteries is less likely to affect acceleration performance. Power fade in smaller batteries, particularly those of HEVs and shorter-range PHEVs, may have a noticeable effect on acceleration performance. It may also have an effect on the ability of the battery to effectively manage power flows from the internal combustion engine, causing more propulsion energy to be derived from the engine and increasing loads on the engine. Therefore it may be preferable to consider battery power as an end-of-life criterion so that expected levels of performance may be maintained for the life of the vehicle.

Power degradation may also be associated with increased resistance, leading to reduced charge and discharge efficiency for all xEVs. As with capacity degradation, this can have an impact on the upstream emissions of BEV and PHEV AER miles by increasing energy use per mile, and can have an impact on CO_2 emissions for HEVs.

3.2.2 Need for Distinction between HEVs, PHEVs and BEVs

Members noted that battery degradation can have significantly different implications for the environmental performance of different types of xEVs. Therefore it was suggested that the effort should focus separately on battery degradation with respect to HEVs, PHEVs and BEVs.

Battery degradation in an HEV could have different implications for environmental performance than for a BEV which has no internal combustion engine. When the battery of a BEV degrades, there could be loss of range (and a resulting change in utility factor) without a significant change in upstream emissions from the vehicle itself. When the battery of a PHEV or HEV degrades, it may result in a change in CO_2 emissions due to more frequent use of the conventional powertrain. It is even conceivable that potential HEV powertrains could be designed that rely on battery assistance in such a way that criteria pollutant emissions could be affected by loss of battery capacity or power (although it is not clear that any such designs are currently in production).

In the case of HEVs, consumers are most likely to experience the effect of battery degradation as a loss of fuel economy and/or power, while in a BEV or PHEV it is likely to be experienced primarily as a loss of electric range. At this time, shortfalls in fuel economy are more likely than shortfalls in power or driving range to trigger regulatory penalties or recalls. Either is likely to result in loss of customer satisfaction.

HEVs also differ from PHEVs and BEVs in that the battery is smaller and so has a smaller thermal mass. This means that only a short soak is necessary for an HEV battery to reach ambient temperature conditions, while a larger PHEV or BEV battery may take many hours. This leads to different implications for the impact of trip length on environmental performance and battery durability. For example, frequent short trips in cold weather with an HEV may involve on average a colder battery operation temperature than for BEVs and PHEVs which may retain their internal temperature for a longer time between trips. Also, since BEVs and PHEVs are charged from an external source, they offer the possibility of charge station warming to further prevent battery cooling while soaking in cold weather.

Further, it was noted that requirements for durability may depend on specific vehicle applications within each xEV type. Different vehicle classes may have different battery durability needs.

3.2.3 Timeliness of Regulation and Potential Impact on Innovation

Members of the IWG noted that the relative infancy of the xEV battery industry suggests that it may be premature to establish detailed regulations for battery durability.

One member noted that the industry is still seeking improved battery chemistries, and that no currently available xEV batteries have yet achieved the levels of specific energy, energy density, or cost targeted by the United States Advanced Battery Consortium (USABC). It was suggested that to establish guidelines for durability before battery technology has fully stabilized could potentially discourage the emergence of certain technology options. For example, establishing a requirement that the original battery last the life of the vehicle might discourage research into potentially more cost-effective battery chemistries that might require scheduled replacement. This also might preclude some approaches to metal-air chemistries, such as aluminum-air and zinc-air, that have proposed regular replacement of electrode material or electrolyte as an alternative to station charging. Since it is acceptable for other vehicle components that affect environmental performance to last less than the full life of the vehicle (for example, tires), it was suggested that a battery durability regulation should not necessarily presume that the battery must last the full life of the vehicle either.

Members also discussed whether there is sufficient urgency or pressing motivation to proceed with a GTR at this time. It was noted that there seem to be relatively few examples of battery degradation having a marked effect on environmental performance outside of the bounds established by current warranty practice and regulatory frameworks. That is, the lack of explicit regulation of battery durability does not at this time appear to be resulting in widespread underperformance of environmental expectations. In the few cases that have occurred, the effects have been corrected by existing mechanisms such as recalls, consumer rebates, etc.

Some members expressed the opinion that management of battery durability is best left as a warranty issue between manufacturers and consumers, on the grounds that degradation in environmental performance would likely be accompanied by sufficient loss of utility (in terms of fuel economy, power, or driving range) that manufacturers are already motivated to manage battery durability in order to offer competitive warranty terms and maintain customer satisfaction.

3.2.4 Complexity of Establishing Battery Durability

At EVE 16, FEV presented the results of a literature review of the factors affecting battery durability. From this presentation it was clear that the problem of establishing battery durability for arbitrary usage scenarios, chemistries, and configurations is extremely complex.

Specifically, IWG members noted the following considerations:

(a) The factors which affect battery durability vary among different chemistries and usage conditions, and have differing importance to environmental performance.

(b) Battery aging is very path dependent, making it difficult to reliably model the actual life of an in-use battery by means of a single simplified test protocol.

(c) Influences on durability that occur during vehicle operation are not necessarily the same as those that occur while parked. For example, a vehicle parked in a hot environment for long periods of time may experience degradation due to elevated battery temperature, while a vehicle being actively operated in the same environment may avoid degradation because the battery is being actively cooled.

(d) Ambient temperatures have mixed relevance to battery durability. Manufacturers have the option to actively manage the temperature of the battery itself so that actual battery cell operating temperatures are rarely the same as ambient air temperatures.

(e) Some members noted that any steps to predefine battery aging conditions may lead manufacturers to optimize performance for test conditions rather than for the range of actual usage likely to be experienced by customers.

3.2.5 Quantitative Methods of Predicting Battery Durability

The IWG acknowledged that some quantitative methods exist that may be relevant to the problem of predicting battery durability.

3.2.5.1 High Precision Coulomb Counting

The IWG acknowledged research conducted by Jeff Dahn's group at Dalhousie University, in which high-precision coulomb counting is used to predict future degradation rates by measuring loss of charge in early cycling of battery cells. It was noted that this method is best suited to cell-level analysis in a research environment and so does not appear to be readily adaptable to vehicle-level testing. However, it might potentially be relevant if a GTR were to specify cell-level testing as a means for manufacturers to establish evidence of future battery durability. Because this method primarily attempts to quantify the future rate of formation of solid-electrolyte interphase (SEI) on a carbon-based Li-ion anode, it presumably would not reflect other mechanisms of degradation, nor mechanisms that would apply to non-carbon anodes or non-Li-ion chemistries.

3.2.5.2 Formulas for Battery Degradation

Shortly after EVE 16, some members of the IWG circulated an article describing a Pennsylvania State University project[1], funded by Volvo, in which a formula was developed for battery degradation using inputs describing state of charge, how often the battery charges or discharges completely, operating temperature, and current. Like the high-precision coulomb counting approach, this appears to be another method to track formation of SEI and its corresponding effect on battery capacity and power degradation. While the article does not describe the formula in detail, the existence of this example suggests that it may be relevant to consider the potential for such formulas to be developed and integrated into a GTR.

3.2.5.3 Measurement of Total Energy Delivered

Members of the IWG have also discussed the possibility of defining durability in terms of the total amount of energy that a battery must deliver during its useful life in order to achieve the environmental performance expected in a given application. Evidence of this capability might then be established by testing the ability of a battery to deliver this energy through a series of appropriately specified charge and discharge cycles. The potential capability of such a test to deliver reliable estimates of durability for arbitrary usage cycles, chemistries and configurations has not been examined.

4. Options for Proceeding

Within the framework of EVE, several options exist for the IWG to proceed on the topic of battery durability:

Option 1: Recommend that a GTR is appropriate for electrified vehicle durability, and note that it will take time to obtain the information required. For example, information relating to the effect of vehicle duty cycle, vehicle charging, operating temperature, and calendar time will need to be collected to inform this action. Proceeding in this direction may require initiating a new mandate and/or forming another IWG.

Option 2: Extend the mandate of the EVE to continue research into electrified vehicle durability. This would involve gathering data to inform a potential future GTR.

Option 3: Recommend to the GRPE that it is premature at this time to develop a GTR for electrified vehicle durability, but the question should be revisited in the future.

At EVE 16, the IWG discussed these options. The IWG then recommended preparation of this status report and recommendations for the GRPE regarding electrified vehicle durability, while engaging all stakeholders in the development of the report and the recommendation.

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[1] http://news.psu.edu/story/378093/2015/10/30/research/simple-mathematical-formula-models-lithium-ion-battery-aging

Drafting, review and submission of the report is to take place within the timeline outlined in the EVE roadmap. This draft report will be discussed at EVE 17 in January 2016 to promote further discussion of an appropriate way to proceed.