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Status Report

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

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1. Background

This document summarizes the views of the EVE IWG on electrified vehicle battery durability, a topic of Part A of the EVE mandate. This document is intended to serve three primary goals:

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

(b) to summarize initial findings of the working group, as represented by comments and discussion that took place at EVE 17 and prior meetings, and

(c) consider the available options for moving forward on the topic of electrified vehicle battery durability.

2. Battery Durability and the EVE Mandate

The EVE mandate on electrified vehicle 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. The IWG has been charged with the task of gathering information related to this topic, and to make recommendations concerning the possibility of establishing a GTR for this purpose. If development of a GTR were to be recommended, it would likely be concerned with establishing specific durability performance requirements for electrified vehicles, and specifying one or more test protocols for use by manufacturers to demonstrate that these performance requirements are met.

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, although there was no consensus on the most effective way of handling this topic.

(2) Electrified vehicle manufacturers are aware of the issues posed by battery durability, and currently manage battery durability by agreements and warranties between the manufacturer and the user/consumer.

(3) As evidenced by the presence of electrified vehicles in the market, manufacturers have found it possible to establish the durability of specific battery implementations sufficiently to bring the products to market with some degree of confidence that customary provisions for customer satisfaction and warranty terms will be met.

(4) The presence of existing products with warranty terms does not automatically mean that manufacturers have successfully predicted battery durability for these products. Manufacturers continue to rely on long-term, ongoing experimental lab research and tracking of vehicles in use to verify that the methods used to establish durability were effective and to modify durability metrics as this experience dictates. As a result, it cannot be said that the metrics to determine durability for arbitrary battery implementations are fully developed even for a single manufacturer.

(5) Not every manufacturer is establishing durability in the same way. Manufacturers employ a wide variety of testing regimens often tailored to specific product configurations, applications, customer groups, and geographic considerations. 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.

(6) There are at least five major vehicle operating conditions that affect battery durability, each differing in importance depending on whether the application is BEV, PHEV, or HEV:

(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) State of charge (SOC) window used in system operation of the battery;

(d) Battery temperature during operation; and

(e) Time (calendar life).

3.2 Discussion Items

The following topics 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. When speaking of battery lifetime, it is important to consider whether it is power degradation or capacity degradation that causes a battery to be judged as having reached end-of-life. Whether energy or power degradation is life limiting depends on the application and vehicle type. Hence, this must be considered by an eventual regulation in order to be relevant in achieving the environment benefits intended.

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 when first manufactured might be found to provide only 16 kWh at a later stage of its life. Manufacturers have sometimes defined battery end-of-life by reference to a specific degree of capacity degradation that is considered to provide a minimum acceptable performance to the consumer. For example, if a manufacturer of a BEV feels that consumers will be dissatisfied with loss in driving range after a battery degrades to 80 percent capacity, it might define this point as end-of-life for warranty purposes, although the vehicle may still be capable of operating with a reduced range.

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. Even though the vehicle may still operate with a reduced driving range, it 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 BEV or PHEV 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. These are not universal and largely depend on manufacturer assumptions regarding minimum acceptable performance and customer satisfaction, and are thus somewhat arbitrary and may differ among manufacturers. Establishing an appropriate end-of-life criterion on the basis of capacity degradation also depends on the vehicle type, system design factors, and how the battery is used.

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. For PHEVs, however, manufacturers are indirectly compelled to account for degradation in range, in that it directly affects the calculated in-use emissions later in life. PHEV GHG emissions are calculated using the SAE J1711 procedure, which accounts for utility factor, a function of all-electric range. If range degrades during useful life, the utility factor correction would change and thus, the calculated GHG emissions would increase. Because vehicles are considered noncompliant if their emissions exceed the certified emission level by more than 10 percent during the useful life, manufacturers that do not factor capacity degradation into their PHEV designs risk exceeding the GHG standards in-use. Accordingly, for PHEVs, manufacturers typically use a combination of battery oversizing and an energy management strategy that provides for a consistent range throughout the useful life.

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, 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 proposed quantitative methods exist that may be relevant to the problem of predicting battery durability. These methods are discussed below in order to establish that research is being actively conducted in this area, without suggesting that they are directly applicable to the problem of predicting actual battery durability for vehicle applications. Since these methods are still in research stage and still undergoing verification and development, it would be premature to apply them as a regulatory norm for battery durability determination.

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. 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

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

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, and therefore has the same limitations.

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.

Of the three methods listed above, IWG members have expressed greatest confidence in "measurement of total energy delivered" as the most viable method for battery durability assessment. Further research would be required to evaluate the applicability of this method and to determine what the appropriate test conditions should be and to validate the test results for vehicles of varying degree of electric propulsion as well as different usage conditions.

4. Options for Proceeding

In summary, the IWG has noted that battery durability is an important factor in electrified vehicle durability and environmental performance. Electrified vehicle durability is currently managed by means of agreements between manufacturers and customers, for example, warranty agreements and expectations of utility and customer satisfaction. This basis promotes customer-facing aspects of vehicle durability such as performance, fuel economy, and reliability, which in some cases align with environmental benefit. The lack of explicit regulation of battery durability does not at this time appear to be resulting in widespread underperformance of environmental expectations. However, these existing practices do not necessarily guarantee that the level of environmental benefit expected by governmental regulatory compliance schemes will be maintained for the life of the vehicle.

Within the framework of EVE, several options exist for the IWG to proceed on the topic of battery durability. The 3 options below are not listed in any order of preference by the IWG.

<u>Option A</u>: 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 B: 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 C: 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.

At EVE-17 (Geneva, January 2016), members discussed the need to coordinate EVE IWG work on battery durability with WLTP. It was generally agreed that WLTP would be responsible for establishing durability performance requirements, while the EVE IWG would be responsible for recommending test procedures.

WLTP has therefore been tasked with providing durability performance requirements to the EVE IWG. After this has occurred, the EVE IWG will address the possibility of developing applicable test procedures. At EVE-18 (Shanghai, April 2016), the EVE IWG will initiate this work by discussing the matrix of possible performance requirements and potentially applicable test procedures.