<u>DRAFT – May 2017</u>

Status Report

Options for EVE on Battery Durability

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1. Background

At EVE 22, a general discussion of topics related to battery durability took place among the members of the IWG. This led to the identification of several potential directions or approaches for continuing work on the topic of battery durability. At this time, significant uncertainties remain as to the feasibility of developing a GTR, or its most appropriate structure. The immediate work of the IWG is primarily seen as continuing investigation and research into this question.

This informal report documents the main topics of the discussion and the approaches that were discussed. The approaches presented here are not meant to be exhaustive, nor are they mutually exclusive with one another. Going forward it may be appropriate to consider directions that were not discussed, or to combine elements of several of the approaches described here.

2. Review of Major Topics Discussed

2.1 Manufacturer Practices for Establishing Durability

Members discussed some of the approaches that manufacturers take to establish durability. It was suggested that a primary goal of a manufacturer in this regard is to become comfortable that the durability of an electrified vehicle product will be sufficient to meet their business objectives (largely, to maintain customer satisfaction (range, fuel economy, reliability, etc) while minimizing warranty service costs for the useful life of the product). This commonly involves extensive testing at the cell level, pack level, vehicle level, or any combination, over a long period of time. Manufacturers individually determine the testing regimen that they consider to be appropriate. The regimen typically calls for identification and control of factors such as: driving cycle, SOC swing, temperature, number of cycles, and so on. Because the effectiveness of any chosen regimen at predicting the degradation of the battery in actual use is often uncertain, manufacturers commonly follow up these efforts by investigating actual degradation among vehicles sold into the market to help validate and further develop their testing regimen.

Members recognized that manufacturers use a wide variety of test regimens and usage profiles; they differ among manufacturers; that the effectiveness of these various regimens have not been fully validated by field testing due to the relatively short time these products have been on the market, and that there is no conclusion as to which regimens/profiles are most effective at predicting useful life. The making of such a conclusion may vary with different chemistries and different vehicle applications, making it potentially very difficult to identify a single regimen that would apply equally well to every type of light-duty vehicle or battery.

As a thought exercise, a member described the ideal case, in which battery degradation would be measured by subjecting a battery to actual use, in an actual vehicle, for its full useful lifetime of perhaps 10 years. Such an approach, although clearly not practical, would establish durability accurately and would treat all battery chemistries and battery designs equally. But because it is not practical, the problem then becomes one of, “How shall the vehicle be tested in an accelerated manner, and how shall the outcome of the test be transformed into a reliable prediction of its actual useful life?" This problem, while more feasible, is complicated by the possibility that the relationship between the outcome of an accelerated test and the actual useful life may not be the same for each battery chemistry. That is, the effect of accelerating the test may differ among chemistries, even if useful life in normal usage would be the same. For example, a cell with a lithium titanate anode has a structure that may make it less susceptible to the effects of increased heating and more rapid intercalation cycles associated with accelerated testing; however, this chemistry has a lower energy density than others which discourages its widespread use in BEVs. Thus there was some concern that if we were to adopt a single test profile without regard to chemistry, it may disadvantage chemistries that would perform well under actual use but fail to evaluate well under an accelerated profile.

2.2 Deterioration Factors

It was also suggested that manufacturer practices toward establishing durability, combined with the presence of vehicles so certified on the market for a number of years, implicitly suggests that manufacturers are internally identifying battery deterioration factors (DFs) that they consider to be reasonable (for the purpose of satisfying their business objectives) and achievable (as evidenced by the outcome of the testing regimen they undertook). That is, because many manufacturers have placed electrified vehicle products on the market and warranted them accordingly, it suggests that (a) they have some idea of the degradation that is likely to occur, and (b) they believe that their business objectives will be met with this level of degradation. This suggests that they also believe that the testing regimen they undertook to support these conclusions is reasonably representative of actual performance in use.

Members also discussed the concept of a "conscientious manufacturer," one that performs the necessary testing to become satisfied that deterioration over the full useful life will be reasonable, as opposed to a hypothetical manufacturer that fails to sufficiently investigate or design for full useful life. It would be a perverse outcome if both manufacturers gain equal environmental credit when the second manufacturer's vehicles may soon fail to fulfill the expected environmental performance. Because conscientious manufacturers are likely incurring higher costs (due to additional testing costs as well as manufacturing a more durable battery), part of the goal of regulation of durability should be to ensure that less diligent manufacturers are held to the same standard.

To the degree that existing manufacturers have been "conscientious," the DFs that they are achieving in the field are likely to say something about the range of reasonable and attainable DFs of existing battery technology. It may be possible to identify these DFs by observing the degradation in vehicles that have aged.

Conscientious manufacturers are likely to base their battery durability design decisions on what they believe to be sufficient to maintain customer satisfaction, marketability, and stay within targeted warranty costs. If it is also true that the battery specification and the DF they design to also results in acceptable environmental performance over the full useful life, then the testing practices of a conscientious manufacturer might be seen to exemplify adequate testing practices to ensure environmental performance. Continued observation of the performance of vehicles in the field could provide empirical evidence as to the battery DFs that are naturally resulting from the design decisions of these manufacturers.

While manufacturers already design for customer satisfaction and warranty cost with respect to some anticipated product lifetime, this product lifetime might potentially differ from the useful life for which WLTP might seek to ensure environmental performance. Therefore, the group should consider whether this existing manufacturer motivation is necessarily sufficient to ensure environmental performance for the time period a GTR would seek to ensure. Also, because battery degradation is not perceived immediately by the consumer at point of sale, it was suggested that market forces may be less effective at upholding it than for other attributes such as power or utility.

The group also briefly discussed the concept of determining a DF by means of simulation rather than empirical research. This could involve the low-level modeling of cell deterioration mechanisms, resulting in an expected degree of deterioration resulting from simulation of a specific test profile or set of profiles.

2.3 Aging of a Battery for Test Purposes

The group discussed the similarities and differences between batteries and emissions-reducing catalysts, both of which experience changes in performance due to aging. It was recognized that vehicle emissions are commonly tested on a vehicle fitted with a bench-aged catalyst in order to represent performance at the end of useful life, suggesting that a similar approach might be possible with respect to batteries, by testing an electrified vehicle with an aged battery. It was pointed out that catalyst aging is well understood and involves a limited number of aging mechanisms that are represented well by bench aging, while battery aging is a more complex, highly path dependent process that results from a larger variety of mechanisms, which have greatly varying degrees of influence on degradation depending on how a battery is used.

The group also discussed the possibility of certifying by testing a vehicle in a special test mode that provides a software emulation of an aged battery. The software emulation would electronically limit the power and/or usable capacity of the battery to a level representative of a vehicle at the end of its useful life. The degree of power and capacity limitation would be determined by use of a DF (to be determined).

2.4 Differing Impact of Battery Degradation Among Electrified Vehicle Types

Participants in the discussion also observed that the impact of battery degradation on the environmental performance to which a vehicle has been certified may differ among electrified vehicle types. These differences should be considered when identifying durability requirements and approaches forward.

For reference, some of the differences among HEVs, PHEVs, and PEVs in regard to the impact on environmental performance are outlined below. This list is not likely to be complete but is presented for discussion.

(a) HEV

(i) loss of battery power or capacity, leading to increased engine load or more frequent usage/cycling of engine, leading to increased criteria pollutants

(ii) loss of battery energy efficiency, leading to increased energy consumption/CO_2

(b) PHEV

(i) loss of battery capacity, leading to reduced electrically-powered driving, leading to increased usage/cycling of the engine, leading to increased criteria pollutants and tailpipe CO_2 (applies to both blended and series PHEVs)

(ii) loss of battery power, leading to increased cycling of the engine, and associated startup and cold start emissions (primarily blended PHEV)

(iii) loss of battery energy efficiency, leading to increased energy consumption/CO_2

(c) PEV

(i) loss of battery capacity, leading to loss of electric range, leading to potentially less usage of vehicle and therefore less displacement of conventionally fueled driving (reduced utility factor). Note: this is likely to be more significant for shorter range vehicles than for longer range vehicles.

(ii) loss of battery power, leading to degraded performance, leading to potentially less usage of vehicle and therefore less displacement of conventionally fueled driving (reduced utility factor).

(iii) loss of battery energy efficiency, leading to increased energy consumption/upstream CO_2

3. Approaches for Continuing Work on Battery Durability

The topics that were discussed suggest several possible approaches for proceeding with the goals of the EVE IWG:

Approach A: Pursue Development of Durability Test Profiles

Approach B: Seek to Identify Default Deterioration Factors (DFs)

Approach C: Investigate Testing with Aged or Age-Emulated Battery

Approach D: Seek to Establish Default DF by Simulation

3.1 Approach A: Pursue Development of Durability Test Profile(s)

3.1.1 Description

Under this approach, the EVE IWG would investigate the potential for durability test profiles to be developed for the testing of vehicles or batteries, for use by a manufacturer to demonstrate compliance with a durability standard. In this sense, a "test profile" is any combination of factors known to affect battery degradation, including but not limited to factors such as: driving cycle, ambient temperature (during use and storage), internal battery temperature (related to thermal management effectiveness and driving cycle), charging rate at the charger, frequency and type of charging, calendar time, idle storage time, etc. If suitable test profiles are identified that are shown to be effective at predicting useful life durability by means of a prescribed test, future GTR development might focus on defining a prescribed testing protocol that includes these profiles. Alternatively, such a test profile might be used in conjunction with battery simulation to determine analytically derived DFs.

An important consideration here is that manufacturer design choices for the battery system and the vehicle overall (such as effectiveness of thermal management, usable SOC swing, BMS balancing practices, battery thermal mass and insulation, placement within the vehicle, etc.) also have strong implications for durability under a given set of test conditions, meaning that a suitable test likely must be performed at the vehicle level rather than the battery level in order to capture these influences.

3.1.2 Feasibility requirements for this approach

For a solution of this type to be feasible, the following conditions are likely required and should be explored by the IWG:

(a) There must exist one or more accelerated test profiles applicable to a vehicle or a battery that would effectively and fairly predict degradation over a specified useful life (kilometers and years).

(b) The test profile must be possible for a manufacturer to complete within a reasonable amount of time (e.g. 1 year or less).

(c) The test profile should not disadvantage chemistries that work well in real-world use, but respond poorly to accelerated testing. That is, the transformation from a test outcome to a predicted degradation must either be the same for all chemistries and designs, or must be identified uniquely for each chemistry and design.

3.1.3 Potential EVE activities under this approach

EVE work under this approach would initially be exploratory and of a research nature. Its purpose would be to further understand the possibility and practical potential for such a profile to be identified and developed as a supporting component of a future GTR. The end goal would not necessarily be to take this approach to develop a GTR, but possibly to inform a GTR with a different structure. Even if this approach does not result in taking of this direction, EVE anticipates that it will be valuable as an educational exercise, i.e. as one member stated, “we could learn a lot by trying to do this.”

At EVE22, members from JRC agreed to develop a proposal of what a potential battery durability test profile under this approach might look like.

Prediction of useful life degradation and identification of test profiles for this purpose is a very active area of research. EVE should continue to identify and collect this research and invite investigators to present at future EVE meetings.

3.2 Approach B: Seek to Identify Default Deterioration Factors (DFs)

3.2.1 Description

Under this approach, the IWG would work to identify default DFs for use in vehicle certification, most likely by observing vehicles in use, and also considering the need to uphold environmental performance.

Under a hypothetical certification approach, vehicles would be tested for environmental performance at or near beginning-of-life (BOL). Environmental performance at end-of-life (EOL) would be estimated by applying a default DF to represent expected degradation at EOL. A manufacturer could petition for use of a different DF upon presentation of evidence to support it.

There could be separate DFs for power degradation and capacity degradation. Appropriate DFs could be identified by various means including battery modeling, survey of empirical degradation data from vehicles in the field, etc. The goal would be to select a DF that reasonably represents the behavior of these technologies over time, without an unacceptable loss of environmental performance.

DFs might be developed by observing vehicles in use, to identify the DFs they achieve during useful life in the hands of average customers. Assuming that customer satisfaction and reliability is also being upheld, and that environmental performance is seen to be maintained to a degree EVE accepts as “reasonable for environmental goals,” EVE might accept these DFs as minimum acceptable performance. Alternatively, if these DFs are not seen to be upholding environmental goals, more stringent DFs could be specified.

Manufacturers that can make a case for using a different DF would be provided a mechanism to do so. For example, suppose that the default DF for capacity loss is 70% capacity at EOL. Now suppose that two PEV manufacturers offer the same driving range using the same chemistry and battery design, but the first uses 95% SOC swing, while the other uses only 85%. The second vehicle is likely to experience less degradation due to the more conservative SOC swing. Applying the same default DF to both would disadvantage the second manufacturer, even though its vehicle might degrade less. In such a case, the second manufacturer might present a proposal for a less stringent DF based on their relatively conservative SOC swing. Procedures for evaluating and approving such a proposal would need to be laid out carefully.

As an illustrative example, it was noted at EVE 22 that the U.S. EPA range label rule provides a default procedure by which range is calculated as 70% of the range measured under the two-cycle test protocol. There is also an optional procedure to derive a custom factor that may be higher. This rule thus provides some precedent for the concept of using a default DF supplemented by an optional procedure. It seems likely that the 70% figure was suggested first as a qualitative proposal (based on qualitative evidence), and after stakeholder comment was accepted as reasonable and adopted. A similar approach might be taken to propose default DFs for various chemistries, vehicle types, market applications, etc.

3.2.2 Feasibility requirements for this approach

For a solution of this type to be feasible, the following conditions are likely required and should be explored by the IWG:

(a) A population of in-use vehicles with sufficient age and mileage must exist and be accessible for testing to the degree necessary to accurately determine their level of battery degradation (both power and capacity) and project it into the future.

(b) Alternatively, sufficient evidence must exist from other sources to develop proposed DFs based on qualitative observations.

(c) It must be possible to gather sufficient evidence in a reasonable time frame. That is, it is probably not practical to wait until recently introduced vehicles have been in the field for a full 15 years.

(d) There should be reason to believe that what is learned in this manner, presumably by reference to vehicles currently in the field, will remain applicable to later generations of vehicles. That is, while the Nissan Leaf is likely to be the first fleet to see 15 years of use, this vehicle may not be representative of prevailing chemistries or designs going forward.

(e) The concept of allowing more lenient DFs in view of manufacturer submissions of supporting evidence must be feasible to implement uniformly in an EU regulatory setting.

3.2.3 Potential EVE activities under this approach

The EVE IWG would continue to gather empirical information regarding battery power and capacity degradation observed in real in-use vehicles. This could include review of published sources, invitations for manufacturers and researchers to present data to the group, or the commissioning of independent vehicle testing.

The IWG would periodically consider whether these sources have begun to paint a cohesive picture of real-world battery durability being achieved in the field. Over time, if the data appears to converge sufficiently, it may be possible to propose a set of default DFs based on this data. Once having proposed default DFs, the group may then discuss the implications of using these DFs as part of a certification process. This would probably serve to identify additional issues, practicalities, and concerns.

The IWG would also consider the need for different DFs for different types of vehicles. For example, the concept of deriving an EOL range for a PEV by applying a DF to a BOL range test result is fairly straightforward. However, the DF applicable to PEV capacity degradation may not be applicable to an HEV because capacity deterioration has a fundamentally different effect on the ability of an HEV to achieve environmental goals (for example, an HEV does not have all-electric range; instead, deterioration affects the ability of the engine and electrical system to work together as designed). Part of this EVE activity would likely involve completing the matrices described in Section 4.

3.3 Approach C: Investigate Testing with Aged or Age-Emulated Battery

3.3.1 Description

Under this approach, the IWG would investigate the possibility of a test protocol that involves testing a vehicle that has been configured to act like a deteriorated vehicle (by means of a special test mode that activates software changes, or a special test configuration involving specific hardware changes).

One approach that was discussed is the possibility of testing a vehicle with an aged battery. Procuring a properly aged battery would be a difficulty. While the ideal aged battery would be one that has been used for the full useful life in the hands of a typical customer (e.g. 240,000 km in 15 years), this is obviously not practical, meaning that alternatives must be considered to emulate such an ideally aged battery.

One option is the use of a battery that has been aged in an accelerated way that is understood as being a good surrogate for a true useful-life-aged battery. The testing profile for this purpose would need to be developed and validated. To ensure that the test is representative, EVE would seek to identify an appropriate aging regimen, and/or outline the requirements for supporting a proposed regimen as being representative.

A second option is the use of a new battery that has been hardware modified to represent the behavior of an aged battery. That is, the battery would have less capacity, less power, and possibly higher resistance, to match what is anticipated to be the state of the battery at EOL.

A third option is a software limitation of the stock battery, in which a controller test mode limits the capacity and power of the battery to behave as it is expected to behave at EOL. It seems it would be fairly simple to limit power and capacity, but may be more difficult to emulate reductions in energy efficiency of the battery.

3.3.2 Feasibility requirements for this approach

For a solution of this type to be feasible, the following conditions are likely required and should be explored by the IWG:

(a) For the “test with an aged battery” approach, a suitable aging/test profile (perhaps the result of Approach A) would need to be developed in order to age the battery.

(b) The feasibility requirements under Approach A (Section 3.1) therefore also apply.

(c) For the hardware- or software-emulated aging approach, a set of default DFs (as developed under Approach B) would also be needed in order to define the operating limits of the age-emulation.

3.3.3 Potential EVE activities to consider this approach

EVE work under Approach A (developing a test profile) would also inform this approach, because the test profile may be applicable to battery bench aging as well as vehicle testing.

EVE work under Approach B (developing default DFs) also are directly applicable.

EVE could also investigate the techniques by which manufacturers currently provide dyno-testing modes that alter the operation of a vehicle for dynamometer testing, and consider the applicability of this mechanism for invoking software-limitation of a battery for test purposes.

3.4 Approach D: Determine DF by Simulation

3.4.1 Description

Under this approach, the IWG would consider developing a battery simulation model that is sufficiently detailed to predict the degradation that would result from application of arbitrary lifetime usage profiles. This would then be used to determine default DFs for various vehicle types and applications. This would be an alternative to Approach B, where DFs would be developed from empirical data. The model would likely be a very low-level model capable of using inputs such as battery chemistry, cell design, BMS, thermal management capabilities, etc. and predict degradation that would result from application of a test profile.

3.4.2 Feasibility requirements for this approach

For a solution of this type to be feasible, the following conditions are likely required and should be explored by the IWG:

(a) It must be possible to develop such a model with the resources available to EVE.

(b) The model must be applicable to a wide variety of chemistries and designs likely to be used by manufacturers going forward.

(c) The DFs thus derived by this analytical method should be possible to validate by comparison to empirical field or test data.

3.4.3 Potential EVE activities to consider this approach

The IWG could invite speakers to describe the state of the art in low-level battery modeling and its capability of modeling degradation resulting from use.

4. Matrix of Environmental Goals and Vehicle Types

With regard to any of these Approaches (A through D), it is likely that different types of electrified vehicles will present different requirements and may therefore be best suited to different approaches. Environmental goals, durability requirements, and implications of degradation are likely to differ substantially among different types of vehicles.

This issue is best illustrated by a matrix (Figure 1) which was discussed at EVE22 and previous meetings. Environmental goals are shown on the horizontal, and vehicle types on the vertical.

	Air pollutants	**CO_2**	**Range**
HEV	?	?	N/A
PHEV	?	?	?
PEV	N/A	?	?

Figure 1. Matrix of environmental goals and vehicle types

4.1 Regulatory Objectives

At EVE22 it was suggested that, as a minimum requirement going forward, the IWG should populate the matrix by identifying which cells in the matrix represent a WLTP objective for regulation.

For example, the lower right cell of the matrix represents maintenance of driving range in a PEV. Is maintenance of driving range in a PEV an environmental issue of interest to WLTP? And is it a goal of WLTP for EVE to develop a GTR to ensure that the driving range of a PEV is maintained to some standard for the useful life of the vehicle?

As another example, the bottom center cell represents CO2 emissions (or energy consumption) of a PEV. Is CO2 emission of a PEV likely to change sufficiently during useful life that it should be an environmental issue of interest to WLTP? And if so, is it a goal of WLTP for EVE to develop a GTR to ensure that CO2 emission level is maintained to some standard for the life of the vehicle?

Figure 2 below shows some considerations of regulatory objectives as discussed at EVE22. This matrix requires further consideration and discussion and is presented only as a starting point.

	Air pollutants	CO_2/energy consumption	Range
HEV	Yes? Requirement for in-use compliance (5 year, 100,000 km) already in place in EU	Yes? Loss of power, capacity, or efficiency could reduce FE (e.g. Honda where FE fell due to premature degradation)	No? Not applicable. HEVs do not have significant range
PHEV	Yes? Requirement for in-use compliance (5 year, 100,000 km) already in place in EU	Yes? Loss of power or capacity could increase use of ICE	Probably Yes? (if CO2/FE compliance value involves a UF for electric vs fueled miles)
PEV	No? Not applicable (unless via upstream emissions)	Maybe? Loss of battery efficiency would increase upstream CO2; loss of power or capacity may affect ICE miles displaced (shorter range BEVs particularly)	Maybe? (is range maintenance an environmental concern? Are existing market forces sufficient or is regulation required?)

Figure 2. Working draft matrix of regulatory objectives

4.2 Durability Requirements

The IWG should also consider identifying specific durability requirements/standards for each cell, as suggested in Figure 3. For example, what is the definition of useful life (in kilometers and years), and does it differ for the various cells? This task was previously discussed with WLTP; at this time, WLTP has not yet provided a matrix of durability standards to EVE.

	Air pollutants	CO_2/energy consumption	Range
HEV	5 year, 100,000 km? (already in place in EU)	?	N/A
PHEV	5 year, 100,000 km? (already in place in EU)	?	?
PEV	N/A	?	?

Figure 3. Working draft matrix of durability requirements

The matrix of Figure 3 requires further consideration and discussion and is presented only as a starting point.

4.3 Approaches

Having identified regulatory objectives and durability requirements, the IWG would be better prepared to identify the most suitable Approaches (A through D) applicable to each cell.

Figure 4 shows a sample matrix of potential approaches. For example, for the "PEV/Range" cell at lower right, Option B (Develop Default DFs) may be quite suitable, because PEV range is related directly to capacity, so a capacity DF could easily be applied mathematically to transform a BOL range to an EOL range. Option C (Test with Aged Battery) could also be suitable.

But for the "HEV/CO2" or "Air pollutants" case, performance is tied both to changes in capacity and power, and depends on how well the ICE and electrical components are able to work together. In this case, applying a power or capacity DF to predict a future change in emissions seems less straightforward than for range. It may be better served by considering Approach A (Develop a Test Profile) or Approach C (Aged or Age-Emulated Test).

The Figure 4 matrix requires further consideration and discussion and is presented only as a starting point.

	Air pollutants	**CO_2/energy consumption**	**Range**
HEV	Approaches A, C	Approaches A, C	N/A
PHEV	Approaches A, C	?	Approaches B, C, D
PEV	N/A	?	Approaches B, C, D

Figure 4. Potentially most relevant approaches for EVE IWG (Draft)

Approach A: Pursue Development of Durability Test Profiles

Approach B: Seek to Identify Default Deterioration Factors (DFs)

Approach C: Investigate Testing with Aged or Age-Emulated Battery

Approach D: Seek to Establish Default DF by Simulation