EL ENVEJECIMIENTO DE LAS BATERÍAS DE UN VEHÍCULO ELÉCTRICO Y CÓMO LO PERCIBE EL CONDUCTOR

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ELECTRIC VEHICLE BATTERY AGEING AND HOW IT IS PERCEIVED BY ITS DRIVER.

ABSTRACT:
The electric vehicle is steadily entering into the automotive market. Most of these vehicles are equipped with Li-ion batteries to store the electric energy. Despite of the fast charge and the autonomy range, one of the major concerns of car manufacturers and users refers to the battery ageing.
Similarly to laptops and mobile phones, the batteries from electric vehicles performance reduces through its lifetime. This is the reason why the car manufacturers defined the end-of-life of a battery for automotive purposes when it has lost a 20% of its capacity to store energy.
This study analyzes the battery ageing of a Plug-in Hybrid electric vehicle. It presents some factors that impact on the capacity fade, some of the effects they have on the battery energy loss caused by ageing and how the energy loss is distributed.
Moreover, the driver's perception of the battery ageing will be evaluated and how the battery transmits these performance losses to the rest of components in the vehicle.
In fact, it has been observed that the capacity fade is transmitted almost entirely similarly to the loss of energy and power caused by the internal resistance increase. However, the incertitude brought by external factors, such as climatology, brake energy recovery or the driving conditions, makes it really difficult for the driver to perceive this battery degradation before it reaches the end-of-life

Keywords: Electric vehicle, Battery, Lithium, Ageing, Capacity.

RESUMEN:
El vehículo eléctrico está entrando en el mercado de la automoción de manera suave pero continuada. Los vehículos eléctricos que mayormente están ocupando este nicho de mercado utilizan baterías de Litio-ión para almacenar la energía eléctrica. A parte de la velocidad de carga y de la autonomía de este tipo de vehículos, una de las mayores preocupaciones que tienen, tanto los fabricantes de vehículos como los posibles compradores, hace referencia al envejecimiento de las baterías.
De un modo similar a lo que ocurre con las baterías de teléfonos móviles y ordenadores portátiles, las baterías de vehículos eléctricos van perdiendo prestaciones a lo largo de la vida del vehículo. Es por este motivo que los fabricantes de automóviles han definido que una batería ya no es apta para el sector de la automoción cuando esta ha perdido un 20% de su capacidad de almacenar energía.
En este estudio se analiza el envejecimiento de una batería de un vehículo híbrido enchufable a lo largo de su vida útil. Se muestran algunos factores que afectan a la pérdida de capacidad de la batería, sus efectos trasladados a pérdidas energéticas por envejecimiento y con qué proporción lo hacen.
Asimismo, se valora qué es capaz de percibir el conductor y cómo la batería transmite su envejecimiento al resto de componentes del vehículo.
De hecho, se observó que la pérdida de capacidad de la batería se transmite casi directamente, así como los efectos de la pérdida de potencia y energía debido al aumento de la resistencia interna. De todos modos, incertidumbre producida por factores externos, como son la climatología, las condiciones de conducción o la recuperación de energía al frenar, hacen que la percepción de la degradación de la batería antes de que esta alcance el final de vida por parte del conductor sea casi nula.

Palabras clave: Vehículo eléctrico, Baterías, Litio, Envejecimiento, Capacidad.

1.- INTRODUCTION

Electric vehicles (EV) are entering slowly but vigorously in the automotive market. Although in Spain its entrance is incipient, there are other countries in Europe, such as Norway, where the EV already reached 5.6% of the market share [1]. Most EV use Lithium ion batteries to store energy [2]. Similarly to other battery chemistries, EV battery degradation occurs along time and use, that is, losing capacity and power when they are in use or in a stand-by mode [3]. In particular, it is considered that these batteries are not useful for traction purposes when they have lost a 20% of its capacity [4], [5], where capacity refers to the amount of Amperes per hour (Ah) that a battery can deliver in a cycle.

An EV battery is built by the addition of cells connected in series forming modules. Several of these modules are, again, connected in series or parallel forming the battery pack.

Cell aging or state of health (SOH) depends on many factors, such as working temperature, depth of discharge (DOD), State of charge (SOC) or voltage and the intensity during charge and discharges (C-rate). Each of these factors produce different reactions and effects on cells. Generally speaking, the higher these values (SOC, T, DOD and C-rate) are, the faster aging occurs, although it is not always like this and they do not affect aging in the same proportion. For example, when temperature decreases below 0ºC, some aging mechanisms, as lithium platting, appear that rarely occur at higher temperatures [6], [7], [8]. In a practical way, battery aging originates losses in capacity, energy delivered, power and security. Fig.1 shows, schematically, the complexity and interactions of factors causing aging, the consequent physical/chemical reactions and the resulting effect on the battery performance.

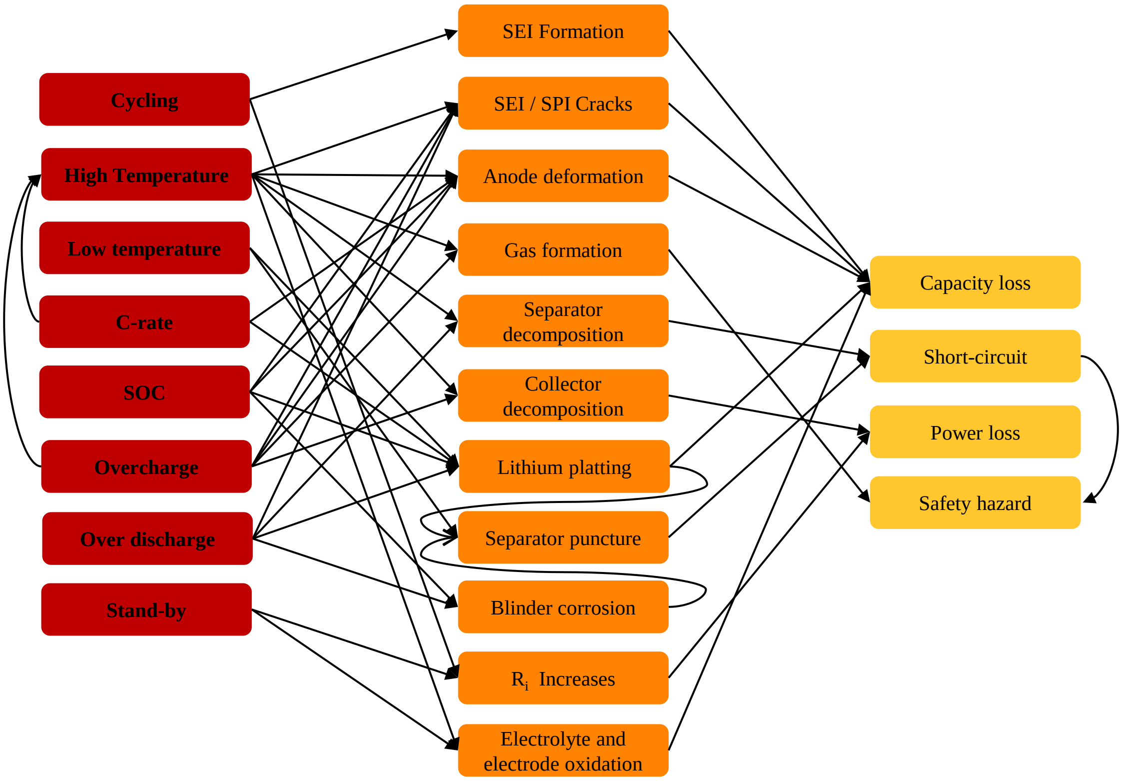

Fig.1: Relations between factors, reactions and effects on battery aging.

We classify these capacity, power and energy losses in three sections:
- Electrochemical and chemic/physical effects: The different elements in a battery suffer degradation while cycling. Little by little, the quantity of available lithium for electron exchange reduces, the electrode interstices get deformed by lithium ion intercalation, formation of dendrites may occur similarly to gas formation, lithium platting and many other aging mechanisms that worsen battery performance [8]. As an example, it has been observed that Lithium deposes in salt compounds in the anode, forming a thin film named Solid Electrolyte Interface (SEI), which difficult future ion intercalations [9].
- Unbalance: The energy loss caused by unbalance is not an effect of the battery itself but caused by its control unit or Battery Management System (BMS). All batteries need a BMS in order to have a controlled and safety functionality. In fact, not all cells in a battery degrade at the same rate, some do it faster and others slower. Thus, BMS should control the voltage of each one of them to ensure, for example, that there is no overcharge or over-discharge. If the difference among them is too wide, BMS imposes power restrictions and may even completely stop the charge/discharge. In this study case, the maximum unbalance is limited to 0.2V. This is the reason why some authors argument that the battery capacity is set by the worse performing cell [10].

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- Efficiency: During battery aging, for the reasons exposed above and presented in Fig.1, there is an internal resistance (R_i) increase. This resistance increase causes higher heat and power losses, thus, there is an efficiency reduction during both charge and discharge processes.

To offer longer guarantees to clients and ensure softer battery aging, EV manufacturers take into account these three effects by limiting and controlling the DOD working range, voltage, current and temperature. This is done by means of the BMS, who monitors these parameters for all cells and activates the refrigeration system in case of need [11].

Based on data obtained from a Plug-in Hybrid Electric Vehicle (PHEV) and on results from laboratory testing to verify battery SOH, this study analyzes the weight of each of these 3 categories affecting the capacity loss. Moreover, the study analyzes how these performance reduction is perceived by owners.

The studied PHEV is equipped with a battery having 84 Graphite-NMC (Niquel, Manganese Cobalt) cells of 37.3 Ah capacity to fulfill the requirements on maximum power, velocity and range. Each module contains 6 cells in series with a total energy of 11.6 kWh. Working temperature range is fixed between -40ºC and 50ºC, the maximum charge and discharge intensity is 320 and 500A respectively, although these values are never reached because of the additional limitations introduced for safety reasons.

Many other chemistries may be used on the anode and cathode apart from NMC, for example, Nickel Cobalt Aluminum oxide (NCA), iron phosphate (LFP) or titanate (LTO) among others. The combination of these materials offer more or less energy and power density, safety or endurance, depending on the requirements to fulfill. As all cells are connected in series, in the studied case, they have exactly the same current going through all of them. The only aging factor that may be different, considering the specific configuration of this battery and its location in the vehicle, is cell temperature. For this reason it is important to correctly design the refrigeration system. This study wants to show how the battery pack ages and how this battery aging is noticeable on driving performance.

As there are many other elements in a vehicle that consume energy, the capacity loss perceived by drivers depends on other factors rather than just battery SOH. For example: driving habits (more or less aggressive), trips or climate conditions (when using other auxiliary acclimatization systems) [12], [13]. An analysis of these aspects will allow us to weight the variables involved in the loss of EV performance perceived by drivers.

2.- MATERIAL AND METHODOLOGY

To obtain the necessary data used in this study, we took advantage of two main experimental data sources. The first data harvesting is focused on information logged from different trips done by the PHEV. This vehicle was leased for short periods of 3 weeks to several people that had the opportunity to charge it at home. The second data mining sources are the results from experimental laboratory maintenance tests done to the vehicle and battery when it had loss close to 10 and 20% of its capacity.

The first data collection was done extracting on-board EV information: This vehicle was a plug-in hybrid prototype equipped with data loggers that capture and store data from current (A), cell and battery voltage (V), module and battery temperature (ºC) and accumulated current (Ah) at every second, allowing data exploitation afterwards. In order to compare equivalent trips, we selected those that began with a fully charged battery and that where sufficiently long to completely discharge it. 16 trips were finally selected having similar characteristics. Evidently, the vehicle did many more trips with different durations and conditions apart from the ones described in this study. Fig.2 shows one of these complete discharge trip profiles. It can be observed that discharge is not constant (left axe), having voltage fluctuations (right axe) due to regenerative braking, which absorbs energy.

In the case of study, as in many other EVs, the studied PHEV had battery limitations. Thus, our vehicle considers that the battery is discharged when it achieves 26% SOC. At that moment, the vehicle leaves the 100% electric mode and works like a hybrid vehicle, that is, the internal combustion engine (ICE) starts to run. This fact is also appreciable in Fig.2, when discharge reaches 26% SOC, capacity starts to recover energy little by little. Thus, during its functionality, this PHEV never reaches 0% SOC , never does full discharges and the maximum DOD allowed is 74%.

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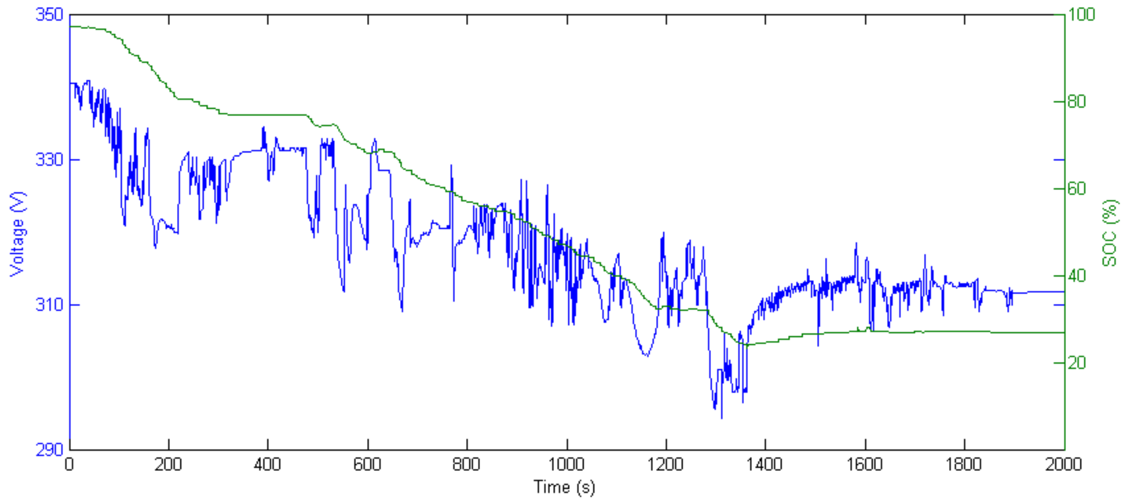

Fig. 2. Example of the studied PHEV battery discharge in one of the selected trips.

The analysis of data from the vehicle relates the capacity discharged (Ah) against DOD in all 16 trips. Small recharges from regenerative braking are also included in the global Ah discharge of a battery along a trip. Therefore, to determine the capacity loss due to aging, we had to first calculate the available capacity of the battery during a trip (Cap) subtracting the regenerative braking small recharges (Q_{ch}) to the total energy discharged (Q_{dch}) (Eq.1). Having the net energy discharge per trip, this value was normalized using the nominal capacity equivalent to a 100% DOD. This was simply done dividing capacity (Cap) by trip's DOD. The result is the real capacity of the battery at this moment (Cap_{Norm}) as shown by Eq.2.

$$Cap = Q_{dch} - Q_{ch} \qquad (1)$$

$$Cap_{Norm} = \frac{Cap}{DOD} \qquad (2)$$

This approximation allowed us to observe how battery capacity decreases, as expected, through time and use. SOH, being a unidimensional value that represents the state of health of batteries in relation of their initial capacity can be estimated based on different factors and parameters. In this study, SOH was obtained by the ratio of battery capacity at the actual state (Cap_{Norm}) between capacity at the beginning of the project (Cap_{ini}) (Eq.3), which is a common way to evaluate and estimate SOH. However, as described later on, R_i measurements are also usable for this purpose.

$$SOH = \frac{Cap_{Norm}}{Cap_{ini}} \qquad (3)$$

In order to verify that the extracted data from the vehicle was robust enough, some laboratory tests were executed to the same PHEV battery. These tests consist in capacity tests at 1C (meaning a total discharge of a battery that takes 1h), together with pulse tests, which are 100 and 160A current pulses during 18 seconds at 50% SOC that are used to determine R_i values. These tests were performed in a climate chamber under controlled temperature (23ºC) following the process described by Schweiger, et al. [14] that is similar to most of tests and laboratory studies [15], [16]. For these tests, the battery was outside the vehicle and it was controlled by laboratory instrumentation instead of the common BMS. For this reason, it could be discharged below the 26% SOC limit and determine the real capacity if the battery.
From the capacity test, the first thing to notice is the useful capacity loss caused by unbalance between cells, as shown in the results section.

On the other hand, heat energy losses (Q_{heat}) also influence in the final energy consumption. In fact, heat emitted by batteries is not so easy to evaluate, as there are reversible and irreversible energy losses. However, Joule effect (Eq.4) is the one having higher impact at low C-rates [17]. Therefore, to calculate heat losses it is necessary to know R_i values, which is the main reason to perform pulse tests. R_i values are obtained following the Ohm rule, that is, dividing voltage

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drop (ΔV) against current going through the battery during the pulse (Eq.5). This calculations can be done either during discharge or charge pulses after 2, 10 and 18 seconds. Some authors divide Ri in three components: Ohmic resistance, charge transference and diffusion [18]. Moreover, it should be noticed that R_i varies according to SOC and temperature [19], so calculations should make special attention to these parameters when using equations 4 and 5.

$$Q_{heat} = R_i \cdot I^2 \qquad (4)$$

$$R_i = \frac{\Delta V}{I} \qquad (5)$$

In fact, R_i increases together with battery aging, as reported by pulse tests done at 90%, and 80% SOH further in this study. Moreover, these results allow an evaluation of the heat loss increase and power loss due to aging.

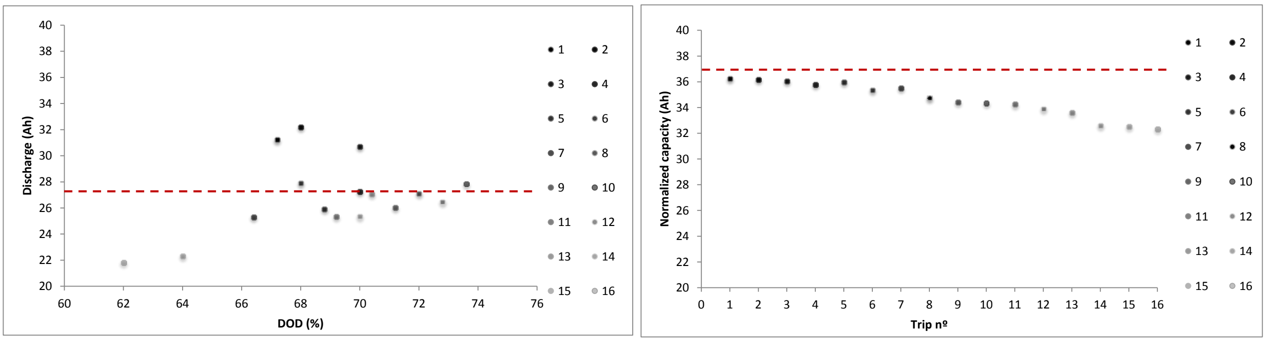
Being all cells monitored, we obtain real data of each one of the cells in the battery, being able to see the evolution of R_i and capacity. This monitoring allow us to identify the existence or not of degradation tendencies in some modules against others and, in consequence, determine if the refrigeration system was well defined.

Once the vehicle performance losses are determined and based, again, on data from the aforementioned 16 trips, we will analyze the variations in perception due to driving habits and auxiliary consumption devices. Therefore, in addition to temperature effects, we will analyze the quantity and variability of the regenerative braking, observing how this factor increases incertitude to appreciate aging.

3.- RESULTS

Once data acquisition and methodology is defined, we proceed to explain and present the obtained results. The main objective of the study is to determine how the capacity loss is transmitted to EV drivers. This section begins with the results obtained from on-board data.

Figure 3 shows the relation between discharged Amperes-hour (Q_{dch}) against DOD for the selected 16 trips. Trips are numbered from 1 to 16 in order of occurrence, that is, the first trip that completely discharged the battery in the EV takes number 1, while number 16 represents the last (more recent) trip that the EV did with a complete discharge, corresponding to a heavily aged battery. Battery aging is caused by the accumulation of effects all along vehicle use, this 16 trips allow us to observe it. Two tendencies can be identified (*Fig. 3*a): in the first place we can state that, effectively, higher DODs imply more energy exchange. Secondly, (*Fig. 3*a) shows how trips done at the beginning of the project (darker dots) have generally more energy exchange than the once done lately (light grey dots). Thus, we can sense the capacity loss. Additionally, *Fig. 3*a also shows the huge variability reported by regenerative braking, which is eliminated by normalization applying equations 1 and 2. *Fig. 3* b presents the normalized capacity of these 16 trips that, effectively, shows a decreasing useful battery capacity tendency as the PHEV drives and battery ages.



a) b)

Fig. 3: a) Relation between discharged current per trip (Ah) against its corresponding DOD per trip. Discontinuous line represents the theoretical capacity of the battery without regenerative braking. b) Normalized capacity of cells on each of the analyzed trips (37Ah is the base nominal capacity identified by a discontinuous red line).

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Presented results until now evidence that the battery transmits all its losses to the vehicle. To delve further into the analysis it is time to present the results obtained on laboratory testing facilities. *Fig. 4* shows in the same picture the capacity tests results obtained during EV maintenance at the beginning of the project, when the battery had lost near a 10 % of its capacity and when it achieved its EoL (20% capacity loss). To clarify, *Fig. 4* also shows the working zone of the battery in the PHEV, which limit is fixed at 26% SOC. Additionally, *Fig. 4* identifies with letters *A* and *B* the unused capacity at the beginning and at the EoL (2^{nd} maintenance).

In absolute terms, the capacity loss is lower when the battery reaches the 26% SOC in comparison to a full discharge, identified in *Fig. 4* as *a* and *b*, where *a* is smaller than *b* and also smaller than *A* and *B* respectively. *Fig. 4* also presents the energy loss for the same discharged capacity at different instants, that is, the energy loss is equivalent to the area between the final capacity curve (green) against the initial capacity (red). That is caused by the lower efficiency and the R_i increase caused by aging. Finally, the lower voltage values from aged battery testing indicate a reduction in power the battery offers.

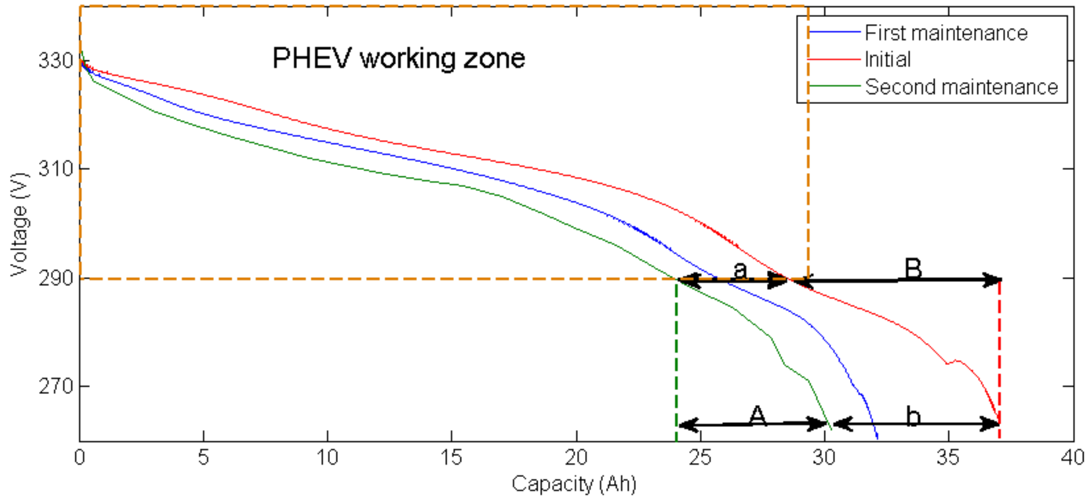

Fig. 4: Characteristic discharge curves of the analyzed PHEV battery at the beginning of the project and during first and second maintenance tests. Dashed square marks the working zone in the PHEV, while the rest of the curves is achieved only under laboratory conditions.

From these laboratory maintenance capacity tests and following equation 3 we obtain 88 and 82.8% SOH for the first and second maintenance test respectively.

During discharge maintenance testing, discharge stopped before reaching the minimum discharge voltage, that is when the battery had still 2 and 2,8 % SOC respectively. This prompt stop is caused by cell unbalance (*Fig. 5*), when the BMS detects wide enough voltage differences between cells it firstly reduces the discharge rate, reason why there is change in the discharge voltage behavior near 273V battery voltage or 3.35V cell voltage, to finally completely stop the discharge when the difference between cell nº4 and 72 (*Fig. 5 left*) overpassed the limits. From (*Fig. 5* right) it can be appreciable that even in cells within the same module there was a significant difference in voltage.

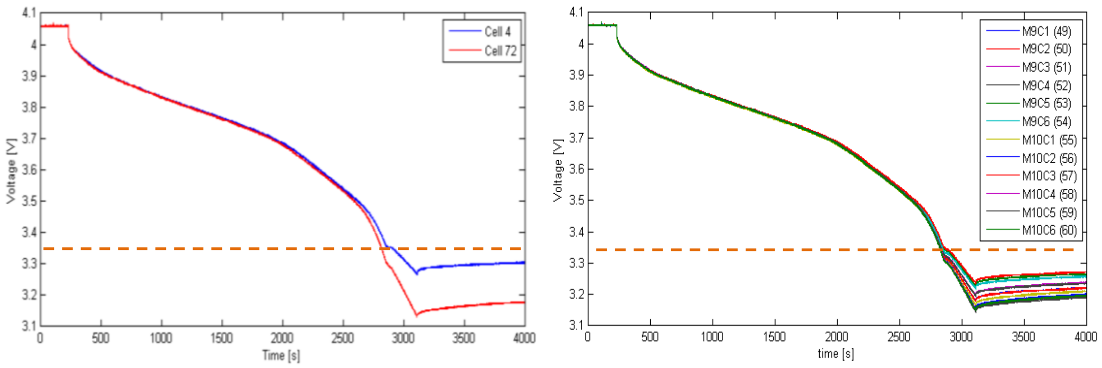

Fig. 5: left: Maximum cell unbalance during discharge, corresponding to cells nº4 (4th cell from module1) and cell nº72 (6th cell from module 11). Right: Second maintenance characteristic tension curve from cells in modules 9 and 10.

Voltage slope against time or discharge increases in the low SOC zone, where unbalance is more visible, defining an instability working zone.

Fig. 6 relates the capacity loss against battery SOC, appreciating that capacity loss is proportional to SOC, that is, it increases linearly with the discharged capacity. The only irregularities are found when the BMS intercedes in the normal discharge, at low SOC, and they are caused by sudden changes and SOC estimations more than real variations.

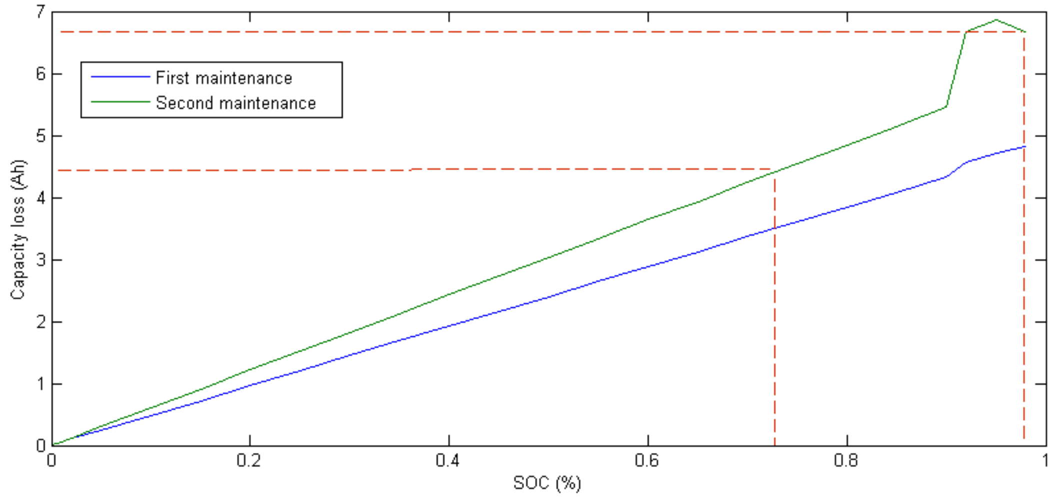

Fig. 6: Evolution of the battery capacity loss against SOC.

Therefore, energy losses under a 1C complete discharge laboratory test on a 82% SOH battery are close to 6.7Ah. However, the energy loss transmitted to the driver corresponds to 4.4Ah, as discharge stops at 26% SOC in the vehicle.

Once electrochemical and unbalance losses are identified, this study proceeds with the analysis of cell aging taking R_i as indicator along time. Fig. 7 shows how all cells have a resistance increase between 0.1 and 0.2 mOhm between the initial measurements and the ones obtained in the first and second 100A pulse maintenance tests. Knowing that initial R_i measurements were close to 1.2 mOhms, R_i increase represents a 19%, which is equivalent to the heat loss increase that battery suffers.

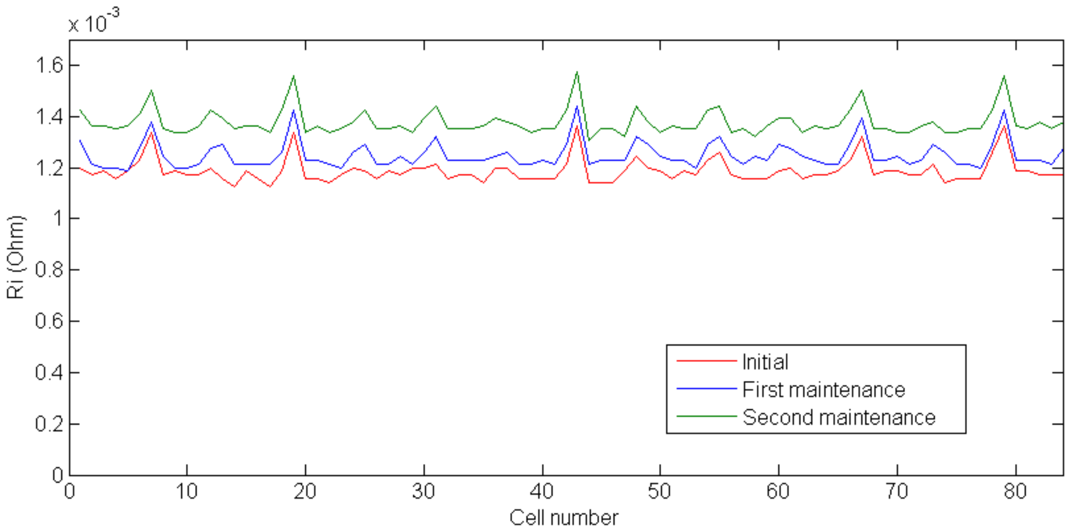

Fig. 7: Internal resistance of all the cells forming the battery under a 100A pulse after 18 seconds.

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Although for small differences, *Fig. 7* shows that, effectively, R_i increase is homogeneous in all cells, confirming that this methodology is also useful to estimate SOH under laboratory testing. As stated in the introduction, the only factor that may cause diversity on cell aging was a different working temperature between cells. Data presented in *Fig. 7* indicates that the cooling system was well designed, maintaining similar working temperature for all cells.

As 19% of heat loss increase might cause alarm, we proceed to calculate these heat losses under different discharge profiles by equation 4.

Adding all cell R_i we obtain the whole battery internal resistance, which value is used for heat calculations. Thus, for a 1C discharge (equivalent to 37A current), heat losses from our PHEV battery make 0.099kWh, which represents less than 1% of the total energy discharged. Thus, 19% increment due to the internal resistance increase signifies only 0.019% energy loss increase.

$$Q_{heat} = R_i \cdot I^2 = 0{,}0728 \cdot 37^2 = 99{,}66 \text{ W} \qquad (4)$$

Under these circumstances, internal resistance increase does not seem such a serious problem. However, as Joule law follows a quadratic equation, heat losses increase dramatically at higher current rates. Thus, under a 4C discharge rate (equivalent to 148 A) these losses rise up to 0.39kWh, accounting for 3.4% of the total energy provided by the battery, and together with the R_i increase it ends up at 4.1% heat energy losses.

Regarding the different current loads from a trip, we could identify current peaks above 250A, which would represent additional losses. Having all the details of all trip, as all parameters were captured for each second, we proceed to calculate the exact heat energy losses of all these trips. Results show up that, in average, heat energy losses using a fresh battery represent around 2.7% of the energy exchanged during a trip, having a dispersion range that goes from 3.2% to 1.9%. These variations are caused basically to driving habits (more aggressive driving means more power, thus, higher losses) and to the driving cycle or profile (urban, highway, mountain…). Taking these results, a 20% R_i increase means an average heat loss increment of only 0.57%, which is almost unappreciable by drivers.

On the other hand, the R_i increase has an additional effect on the maximum power the battery may provide. Hence, the aforementioned 250A peaks, which represent 5.5% of energy loss because of heat on a fresh battery, take an additional 1.1% due to R_i increase that can be directly translated to power losses.

Apart from the variability caused by heat losses, there is another factor intrinsic in driving that may disturb the correct perception of range and performance losses of battery and vehicle. This is the regenerative braking. To appreciate the effects of this factor, we studied the energy recovered on all trips, observing that they range between 1 and 3 Ah (*Fig. 8* a). Eliminating the 3 first trips from the study, as they recovered energy raised above 5Ah caused principally from the ICE activation during the last miles of the trips (as it happened in *Fig. 2*), we obtained an average energy recovery of 2.06Ah, which is equivalent to a 8% (*Fig. 8* b) of the total energy discharged with an standard deviation of 0.78Ah representing an additional 3% variation. Moreover, the 0.78Ah deviation accounts for a 38% of the total energy recovered from regenerative braking, meaning that this variability is notable.

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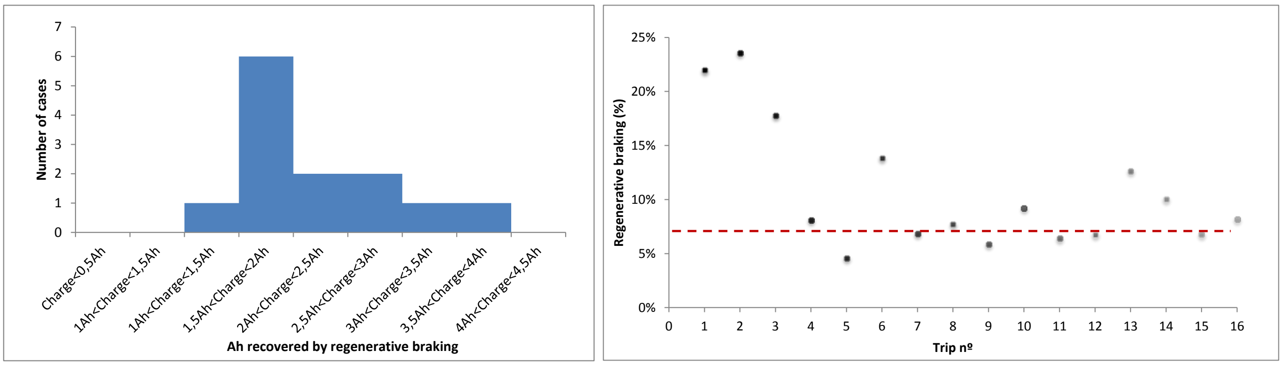

a) b)

Fig. 8: a) Histogram by Ah recovered on regenerative braking. b) Ratio of the recovered energy in front of total energy (y-axis) on each analyzed trip (abscissa axis). The dotted line marks the average energy recovered per trip and lighter dots indicate more recent trips.

Indeed, it is interesting to notice that trip nº 5 (*Fig. 8* b), which had a total discharge of 27.2 Ah at SOH 96.5%, is the one having less regenerative braking energy recovery. This fact puts trip nº 5 at the same level, in terms of capacity and driver perception, than trip nº 13, which is one of the trips that more energy recovered, having the battery at 90% SOH. Therefore, the 3% deviation from energy recovery by regenerative braking really disturbs driver's capability to perceive the battery capacity loss due to aging, being even easy to camouflage up to a 6% SOH.

Aging, presented by the lighter line in Fig. 9, represents the average energy loss perceived for a random trip. Adding and subtracting the variety of factors that affect the useful capacity of an EV battery, we can outline an uncertainty zone around real battery aging. This zone, identified by a dark blue stripe around aging in Fig. 9, adds ± 5% uncertainty margin, which means that the perception of the battery capacity might vary a 10% depending on the driving habits or the particular conditions of trips. Hence, when the battery has lost a 20% of its capacity, the perception of aging is defined by the difference between the less favorable trip when the battery was new and fresh and the most favorable trip when the battery reached the EoL. That is, the gap between red dotted lines in Fig. 9, which value is 7.57%. It should be noticed that the uncertainty zone is centered on the capacity transmitted loss, that is, the one that does not considers the unbalance effects as they remain outside the stable working zone of EVs.

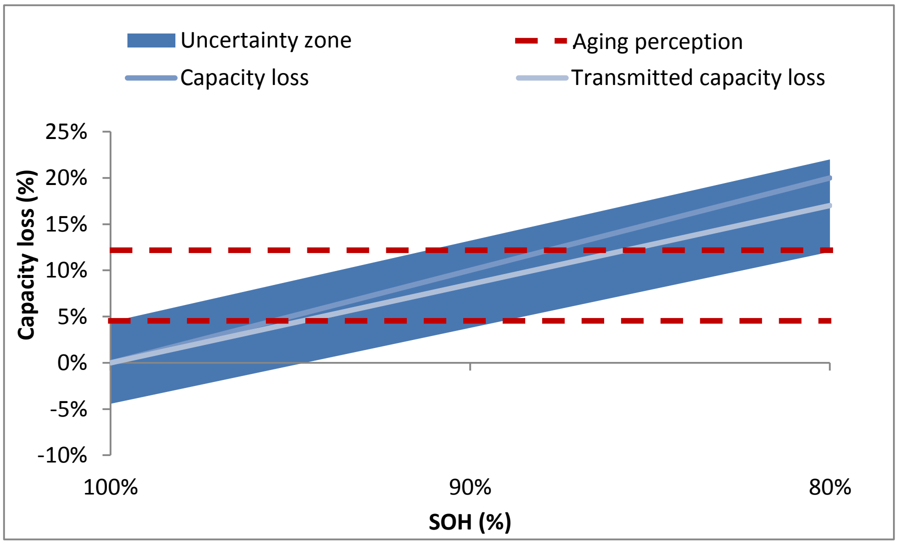

Fig. 9: Real (pale blue) and transmitted (light line) capacity loss and the uncertainty zone. Dashed lines indicate the perception range of degradation.

Hereby, it is observed that battery transmits its energy losses but these losses are hardly appreciable by drivers due to the inherent driving dynamics and changing conditions.

4.- DISCUSSION

This paper presented how battery electrochemical energy losses have a linear relation with discharges, thus, these losses (representing 96.5% of the total energy losses from a battery) impact directly on EV range and performances.

We could observe the instability zone at low SOC, where unbalance between cell voltages often occurs. However, as EV manufacturers limit the working voltage range of the whole battery using the BMS, this instability zone is never reached when driving. Therefore, the useful capacity loss due to instability, which is near a 3% in the studied PHEV, does not affect the driver's battery aging perception.

During a trip or comparing discharges among trips, battery current demand is not constant, neither continuous. In consequence, we can state that the driver's capability to perceive battery capacity losses is severely reduced not having a stable and repetitive base to compare with.

Heat loss is one of the factors affecting the capability to perceive aging as it varies from one trip to another. From the different trips analyzed, we could stablish a 2% variability on useful battery capacity due to heat losses.

Another factor adding uncertainty to perceive battery aging that appears while driving corresponds to regenerative braking, which was calculated to be a 3%.

Consequently, at the EoL, when EV batteries had lost 20% of its initial capacity, the driver will perceive much less than that. While working in the voltage stable zone, the capacity loss is reduced to a 17% as cell unbalance is eliminated. To this value, uncertainties should be added, such as the ones from regenerative braking and heat losses, which represent a ± 5%. In fact, this variability also occurs at the beginning of the EV and battery life, when it may seem that the EV battery has more or less capacity that what it really has depending on the driving conditions. Thus, driver's EV battery aging perception is reduced to 7.57% against the 20% real capacity loss, which represents only a 38% of what really happens.

Finally, we should notice that, as the study is based on battery energy capacity and not on mileage driven, there will surely appear additional factors affecting and hampering driver's perception of aging, such as EV auxiliaries' consumption. Maybe the best example of auxiliary consumption load is the acclimatization system, which consumption varies depending on the year season or the hours in which the car runs. For example, a new EV bought in winter using cabin heating systems will have less driving range than another EV near to the EoL driving during spring, when temperatures are soft and pleasant. In fact, driving at very cold temperatures around -20ºC reduces EV driving range to less than half, which has nothing to do with aging.

In summary, we can state that, although batteries transmit directly their losses to the EV, there are many other factors perturbing driver's capacity loss perception. By defining an EoL of batteries at 80% SOH we assume that battery capacity loss or aging will hardly be appreciated by EV drivers, offering relative relief to car manufacturers and possible EV clients.

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