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Challenging battery aging myths – Insights from 7,000+ vehicles into battery life and vehicle residual value

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Executive Summary

The study investigates the legitimacy of concerns about premature degradation in EV batteries, fueled by prevailing claims in public discourse suggesting rapid capacity degradation and loss of residual value. Real-world data from over 7,000 EVs shows that most EV batteries maintain over 80% of their capacity even after 300,000 kilometers, outperforming pessimistic forecasts by far. An analysis of the underlying electrochemical processes shows that especially idle periods, which are typically not present in laboratory setups but highly prevalent under real-world conditions, can slow down the rate of degradation. Furthermore, technological advancements have led to increased confidence in battery longevity by manufacturers, as reflected in warranties of up to one million kilometers offered by automotive OEMs. Optimizing battery usage and providing accurate, independent health measurements further enhance consumer trust and facilitate the transition to electromobility. Additionally, second-life applications and recycling offer economic benefits, extending battery use beyond their vehicle lifespan.

Keywords: Electric Vehicles, Batteries, Measuring Methods & Equipment, Modelling & Simulation, Design for Second Life

1 Introduction

A key challenge in the transition to electromobility is obtaining credible information on electric vehicle (EV) battery lifespan. The narrative in public discourse often centers around the assumption of rapid capacity degradation in EVs, fueling a decline in confidence and reports of highly reduced resale values of used EVs [1], [2]. These claims have raised questions about the long-term viability of EV technology and the necessity for premature battery replacements. This study aims to address these concerns by analyzing real-world battery State-of-Health (SoH) data from EVs in relation to actual usage behavior. The study was conducted as a combined effort by P3, an international electromobility consultancy, and Aviloo, an industry-leader in battery health diagnostics. By providing a data-driven evaluation of battery performance, the aim is to offer insights into the durability of modern EV batteries and their economic implications.

2 Methodology

The study employs two complementary approaches. First, a qualitative analysis was conducted with 50 vehicles from the P3 electric vehicle fleet, chosen to analyze the influences of driving and charging behavior, manufacturer, and varied usage scenarios to identify the most critical influencing factors. A detailed questionnaire was evaluated for each driver, covering aspects such as parking conditions, charging rates and driving profiles.

As a second step, these findings were augmented by approximately 7,000 additional data points from Aviloo, an industry leader in battery diagnostics. The data points span vehicles with mileage ranging up to 300,000 kilometers and a spectrum of various models from EV manufacturers worldwide.

All data points are based on tests conducted with the Aviloo SoH Box, a system that connects to the OBD-II (On-Board Diagnostics) port of the vehicle and supplies battery health-relevant data in real time. The collected data is validated and analyzed, including compensation for influencing factors such as temperature and discharge rates. The SoH is calculated as a percentage by comparing the actual extractable energy to the energy available when the battery was new.

The extractable energy was measured uniformly for every vehicle until the vehicle display showed 0% State-of-Charge (SoC). Potential energy buffers available below 0% were not included in the calculations. This approach provides a realistic picture of battery health from the driver's perspective, especially in terms of available range. Original Equipment Manufacturers (OEMs) using larger buffers may appear to have slower battery aging compared to those with a smaller or no buffer. While this is fair from a user and second-hand buyer perspective, it is important to keep in mind when comparing SoH values across different OEMs.

Finally, the SoH data points were compared to theoretical forecasts for battery degradation from scientific literature. A two-stage linear aging model based on literary data [3], [4], [5], which was previously constructed bottom-up, was used to summarize prevailing assumptions regarding expected battery degradation into a single curve.

The integration of both qualitative and quantitative findings provides a robust database for analysis and enables a comprehensive assessment of battery aging. The direct comparison with expected values from literature allows for the validation and contextualization of the observed aging behavior.

3 Results and interpretation

3.1 Reduced SoH degradation rate at higher mileages

The analysis reveals a gradual decrease in SoH, with most EV batteries maintaining above 80% SoH even after 300,000 kilometers (Fig. 1). The data shows a behavior characterized by an initially higher degradation rate, which subsequently decreases and transitions into an asymptotic trend. An explanation for this behavior is the stabilization of the SEI (Solid Electrolyte Interphase) on the anode during the first charging and discharging cycles. During the formation of this layer, lithium is "consumed" or converted into degradation products, reducing the amount available for energy storage. After the SEI layer has stabilized, this capacity loss slows down significantly.

To study the differences between real-world behavior and theoretical models, a trend line was calculated for the measured SoH data points ("Aviloo data trendline"). The progression of this line was then compared with the literature-based theoretical model ("Theoretical model"). As mileage increases, a growing deviation between real-world results and scientific forecasts becomes evident. Scientific forecasts are typically based on laboratory cycling without intelligent battery management systems (BMS). Further insights into the underlying electrochemical differences between laboratory and real-world data are provided in Chapter 4.1.

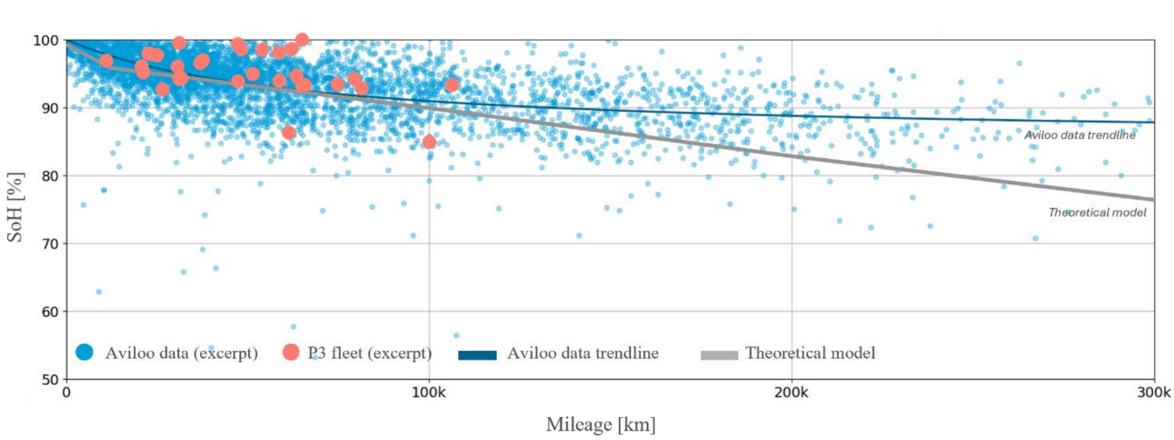

Figure 1: EV battery SoH data points up to 300,000 km

3.2 Similar degradation rate for both older and newer EV models

A surprising observation was that both older and newer EV models showed similar rates of battery degradation. Despite advances in battery technology, such as improved BMS, thermal regulation, and optimized cell designs, newer batteries continue to face the same underlying electrochemical challenges. In fact, with the shift towards high-performance charging and the adoption of high-nickel chemistries, modern batteries are subject to higher stress levels regarding material stability and heat dissipation.

However, these risks are increasingly offset by the use of advanced BMS and thermal management systems, which mitigate degradation by maintaining the battery within optimal operating windows and dynamically responding to external stress factors. This trend underscores the significant progress in battery engineering and control systems made in recent years. Continued improvements in cell chemistry, battery architecture, and operational safeguards have enhanced durability across a wide range of use cases. The widespread deployment of these technologies reflects growing confidence among manufacturers in their ability to manage long-term battery performance. [6], [7], [8], [9]

3.3 Wide range of observed SoH values

The data analysis highlights considerable variability in SoH values for similar mileages. This variation arises from multiple influencing factors, including charging habits and usage patterns (Fig. 2, Fig. 3). In addition, car manufacturers place varying degrees of importance on minimizing battery degradation, which lead to different strategies for dealing with battery aging. For example, the buffer provided by manufacturers can be used to significantly reduce the perceived aging experienced by drivers during the warranty period. Some vehicle manufacturers also use software updates to adjust charging performance, thereby influencing battery aging. [6]

Individual vehicle usage has a significant impact on battery longevity. Drivers who follow battery-friendly practices, such as primarily using AC charging, parking in moderate climates, and maintaining a gentle driving style, tend to experience slower capacity loss over time. Battery aging occurs not only during active use, such as charging and driving, but also when the vehicle is not in use. These two mechanisms are known as cyclic aging and calendar aging, respectively.

Both excessively high and low temperatures accelerate aging mechanisms during use, such as the growth of electrolyte interphase layers on both electrodes, lithium plating, and structural breakdown. The ideal scenario for cycling (charging and discharging) is to maintain the temperature within a moderate range of 20–50°C. [10], [11] Frequent fast charging (at high C rates, >3–4 C) stresses the chemical structures due to high currents, voltages, and temperatures [8], [12]. The analyzed data supports the assumption that frequent use of fast charging contributes to accelerated degradation. Regular cycling at medium depth of discharge (DoD), i.e., between 20% and 80%, is advantageous. Driving the vehicle completely empty and recharging it to 100% leads to higher loads within the batteries and thus accelerates aging [10]. Strong accelerations and long journeys at high speeds cause high currents to flow, which increases the temperature and puts more strain on the battery, while moderate driving behavior affects battery aging less. Finally, the SoC also affects chemical processes in the battery. High SoC and corresponding voltage levels accelerate battery aging, especially during extended periods of inactivity. For prolonged times of non-use, it is recommended to park the vehicle with a low (~10%) to moderate (~50%) SoC. Maintaining a high SoC (>80%) during inactivity intensifies degradation processes. The findings suggest that optimizing both battery design and usage behavior can extend battery life significantly. [6]

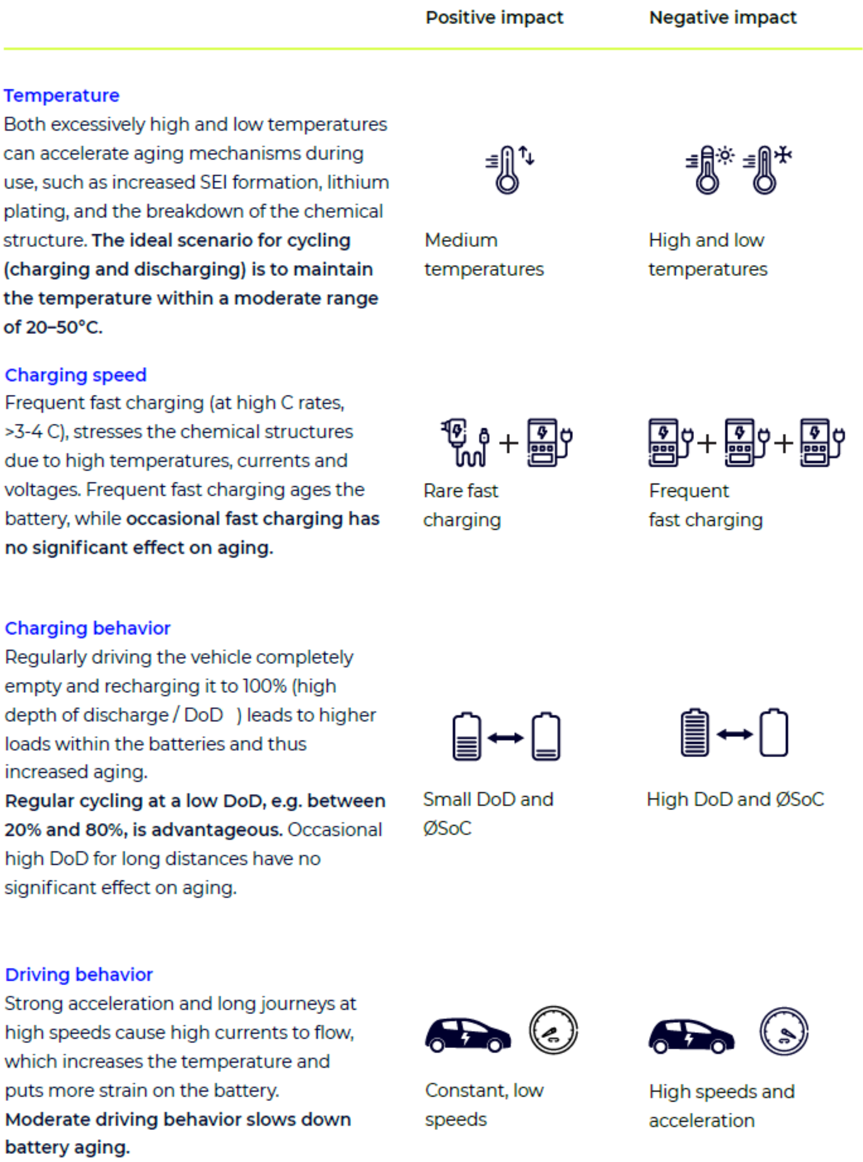

Figure 2: Influencing factors on cyclic aging (usage)

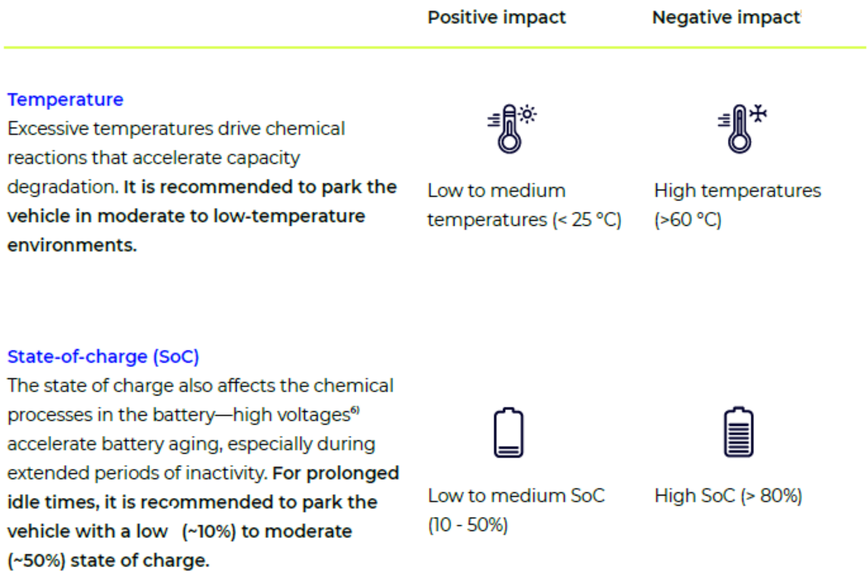

Figure 3: Influencing factors on calendar aging (time, "non-use")

4 Further implications

4.1 Discrepancy in laboratory vs. real-life settings

A key finding of the study is the deviation in SoH observed between the real-world results and findings reported in literature. To identify electrochemical phenomena not adequately captured by laboratory environments, a meta-analysis of the underlying electrochemical processes was conducted.

In laboratory settings, battery cells are typically subjected to accelerated aging through standardized cycling protocols [13], [14]. These protocols often involve constant load cycles, consisting of repeated full discharge followed by full charge cycles, with minimal or no rest phases to shorten the duration of the aging process. However, this approach contrasts with the real-world usage of EVs, where operating conditions are highly dynamic and transient. EV battery usage is characterized by rapid alternations between charge and discharge, unsteady driving profiles, and a broad spectrum of driving behaviors and situations. Moreover, real-world conditions include significant idle periods of up to 97% in which the vehicle is not in use [15]. [16]

Several studies, e.g., Schreiber et al. [16], investigated the electrochemical differences arising from these distinct cycling conditions, despite the nominally equivalent energy throughput. A recurring conclusion in the literature is that the rest phases, which are largely omitted in laboratory experiments but prevalent in real-world driving, facilitate substantial recovery within the battery cell [13], [17], [18]. A key driver facilitating these recovery effects is summarized as the re-establishment of equilibrium within the cell, which is disrupted with progressive cycling (Fig. 4) [16], [19]. Some recovery effects include the re-homogenization of electrolyte distribution within the anode, the resolution of concentration gradients of the conducting salt in the electrolyte, caused by electrolyte motion-induced salt inhomogeneity (EMSI), and the anode overhang effect [16], [20]. The cell in immaculate condition is in a homogenous state, with no major gradients in electrode lithiation or conducting salt concentration. With onset of cycling, the effects begin to cause inhomogenizations and gradients within the cell. Continued cycling results in a more pronounced form of these inhomogenizations, whereas a termination of the cycling process enables partial re-homogenization.

An inhomogenization of electrolyte distribution within the anode starts to develop when the cell is continuously cycled without intermediate relaxation periods. This in turn leads to the anode becoming increasingly inhomogenously lithiated due to a local depletion of available active lithium. These variations in available lithium result in an incomplete utilization of active material, which becomes measurable electrochemically in a reduced capacity or SoH degradation of the cell. As cycling progresses, this phenomenon may ultimately lead to lithium plating. [16]

The EMSI effect describes the phenomenon of an inhomogeneous $LiPF_6$ salt distribution within the electrolyte, leading to regions with high and low salt concentrations. This discrepancy is caused by the motion of electrolyte within the cell due to the expansion and contraction of active materials during cycling. EMSI-induced gradients become especially pronounced under fast charging. [20]

The anode overhang effect, also referred to as the passive anode effect, is facilitated by the typical practice of designing the anode slightly larger than the cathode. This is done to prevent the anode potential from dropping below the potential of metallic lithium and to mitigate the risk of lithium plating. This anode overhang, which lacks a corresponding cathode counterpart, can serve as either a source or a sink for lithium and therefore plays a critical role in moderating local lithium concentration gradients. [21]

Inhomogeneities related to the electrolyte, conducting salt and/or lithium distribution are triggered less by dynamic load patterns or may even partially re-homogenize under such conditions. This relaxation during idle phases in real-world conditions helps equalize lithium distribution across the electrodes, slowing degradation. A hypothesis is that aside from full idle periods, low-intensity load peaks in dynamic scenarios may also serve as intermediate breaks, thereby reducing cell inhomogenization compared to static laboratory cycling. [16]

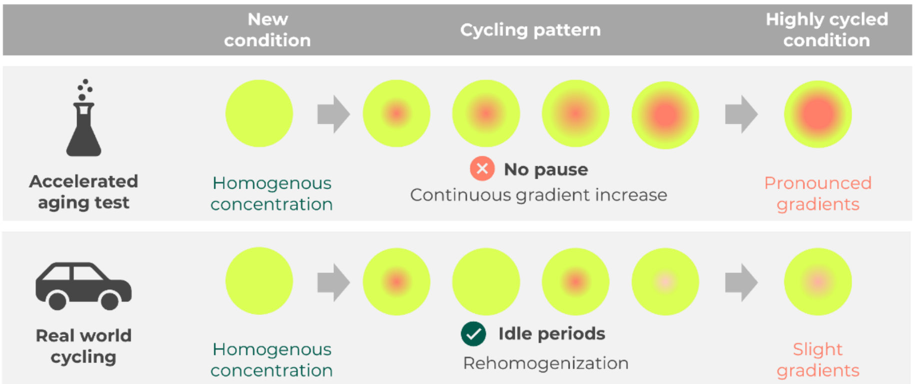

Figure 4: Discrepancies in cell homogenization between laboratory and real-world cycling. Idle periods, which are typically not prevalent in accelerated laboratory cycling protocols, can aid the re-homogenization of lithium gradients within electrolyte and anode

4.2 OEM warranty periods for EV batteries

In recent years, vehicle manufacturers have strengthened their expertise and confidence in battery systems through growing experience and continuous technological advancements. As a result, they now offer increasingly robust warranties. The warranty assures a residual capacity of at least 70% up to a certain age or mileage, whichever is reached first. If this capacity falls below the guaranteed threshold, the warranty covers repair measures such as replacing the entire battery pack or individual modules, including the use of refurbished components, to restore the guaranteed capacity.

Standard warranties typically cover eight to ten years or 160,000 to 200,000 kilometers until 70% SoH is reached [22]. Some exceptions, such as Lexus, now offer warranties of ten years or one million kilometers. These extended warranties reflect a belief in the long-term viability of battery technology. Moreover, the likelihood of a significant drop in SoH during the warranty period is exceedingly low, as the data shows that most batteries remain well within acceptable performance ranges, due to batteries with a long service life and efficient control through battery and thermal management systems. In cases where battery repairs are needed, manufacturers often replace either the entire pack or individual modules using refurbished parts. [23]

4.3 Residual value degradation and potential Second Life applications

Even when EV batteries have reached the end of their automotive life, they often retain considerable value for a Second Life with lower requirements. This study explores the concept of battery lifecycle phases, dividing them into End-of-Warranty (EOW), End-of-First-Life (EOFL), and End-of-Second-Life (EOSL) stages (Fig. 5).

After a battery's first life in a vehicle ends, it can be repurposed for use in stationary storage systems or other applications where performance and energy density requirements are less stringent. By extending the battery's usefulness beyond its automotive life, second-life applications contribute to a more sustainable and economically viable lifecycle. The final stage, EOSL, is reached when the battery can no longer serve any purpose and is sent for recycling. Previous findings of battery longevity suggest that EV value loss may slow down in the future. Based on battery condition and potential for secondary applications, substantial residual value is expected at the end of its first life in an EV. Even if the battery is no longer usable, it retains value due to the presence of valuable metals.

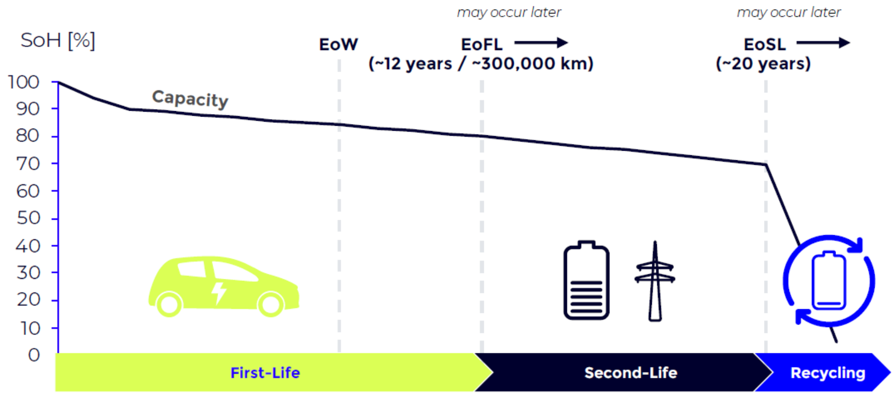

Figure 5: Exemplary progression of the SoH through the lifecycle phases of an EV battery

5 Conclusion

In conclusion, this study provides valuable insights into the real-world health performance of EV batteries, presenting a data-driven perspective on battery longevity that is more optimistic than previously assumed. The study demonstrates that EV batteries maintain a long service life even when used intensively. With mileages of over 300,000 kilometers, most batteries retain more than 80% of their original capacity and are therefore usable far beyond the usual warranty period.

Improved cell chemistries, thermal management, and BMS technology provide better protection against premature aging, enabling manufacturers to offer warranties of more than ten years or over 200,000 kilometers. Even at the end of their service life in the vehicle, the batteries remain usable. If a battery system or components are removed from an EV, there are numerous options for reuse, which means that a significant residual value is retained.

In comparison with theoretical models, the real-world data shows a higher longevity, especially at higher mileages. Key factors contributing to this discrepancy have been elaborated, such as EMSI and inhomogeneous anode lithiation, highlighting why even advanced testing protocols may underestimate actual battery durability.

Moreover, the study emphasizes the importance of accurate, independent SoH measurements, enabling both manufacturers and consumers to make better-informed decisions regarding the use and resale of electric vehicles. It also demonstrates the significant influence of user behavior (e.g., by parking at medium SoC, charging with low currents and moderate driving behavior) and BMS technology in extending battery life.

Acknowledgments

This study was conducted as a collaborative effort between P3, an international consultancy specializing in electromobility, and Aviloo, an industry-leader in battery diagnostics. Additionally, we would like to express our gratitude to the battery research team at the Technical University of Munich (TUM), centered around Markus Schreiber, whose research into electrochemical processes proved highly insightful for this work.

The study was conducted independently. No external payments, incentives, or funding were received in connection with its execution. The results presented reflect an unbiased analysis, free from any commercial influence.

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Presenter Biography

Markus Hackmann is the managing director of P3 and responsible for the area of electromobility. After completing his engineering studies at the University of Newcastle upon Tyne, he joined P3 in 2006 and has since been working on numerous projects in the field of electromobility technology strategies, lithium-ion batteries, and charging of electric vehicles. Since a few years and with the breakthrough of electromobility, numerous projects with utility and grid operators have been added. Likewise, Markus and the P3 team work with numerous investors on the topic of technical due diligence. The P3 electromobility team currently consists of over 200 consulting engineers.