Automotive Lead-Acid Batteries – A Review and "Outside View" on the Perspective for the (European) Automotive Batteries

2024-09-19

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Study Overview

Targets:

- Analyse the current state of automotive lead acid battery performance
- Study the main performance limitations, especially regarding:
  - 17.5% DoD units *(EN 50342)*
  - 50% DoD cycles *(EN 50342)*
- Compare data from lab tests and the field, i.e., real-life vehicle application
- Identify potential solutions for performance improvements

Data Set:

- Technologies: AGM, EFB, SLI
- Manufacturers: Covering > 85% of total market share in Europe
- Lab test data: Ca. 40 test series of usually 6 or more automotive batteries → Σ > 300 batteries
- Field data (i.e., field returned vehicle batteries): > 150 batteries
- Timeframe: 4 years (2018 to 2022)

Methodology

Data evaluation was started in Excel, but quickly ran into obstacles and limitations

- Limited use for visualizing e.g. more than one categorical variable in one graph
- More complex visualizations often hard to implement or even impossible

Is there a better option?

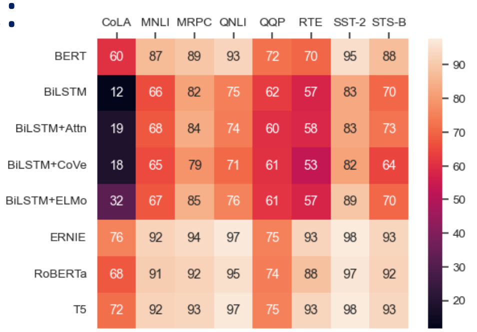
- Different possibilities: E.g. Minitab®, Python™, R

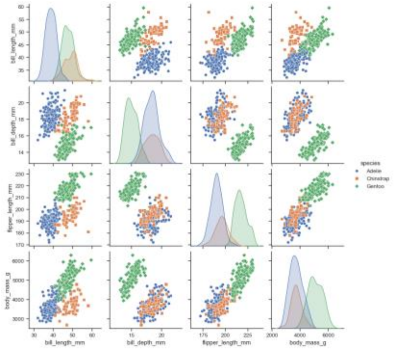
→ **Python™** was chosen by PENOX as the main data evaluation tool for this study

```python
import datetime as dt
import matplotlib.dates as mdates
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd
import scipy as sp
import seaborn as sns
import statsmodels.api as sm
from statsmodels.formula.api import ols
from statsmodels.api import qqplot
```

Advantages include:

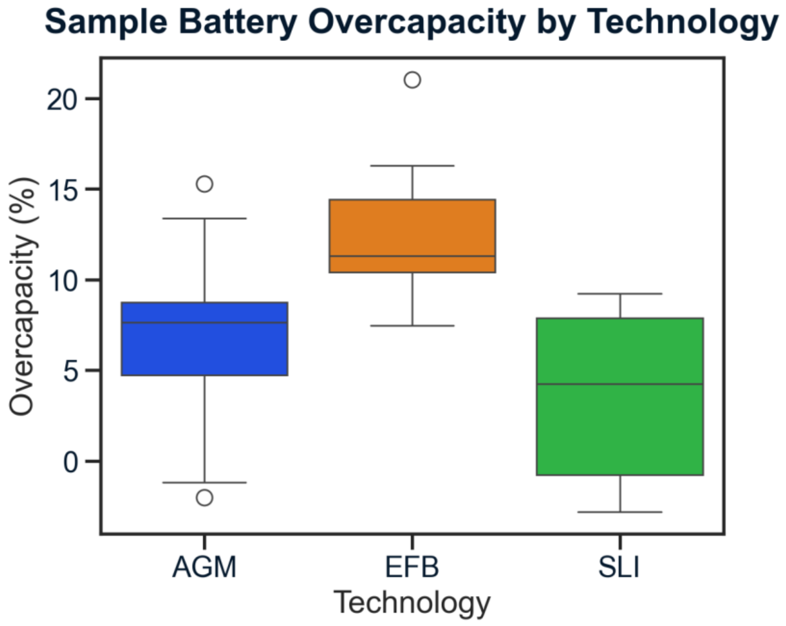
- Working efficiently with multiple categorical variables
- Creating advanced visualisations, e.g.:
    - Heatmap
    - Pairplot

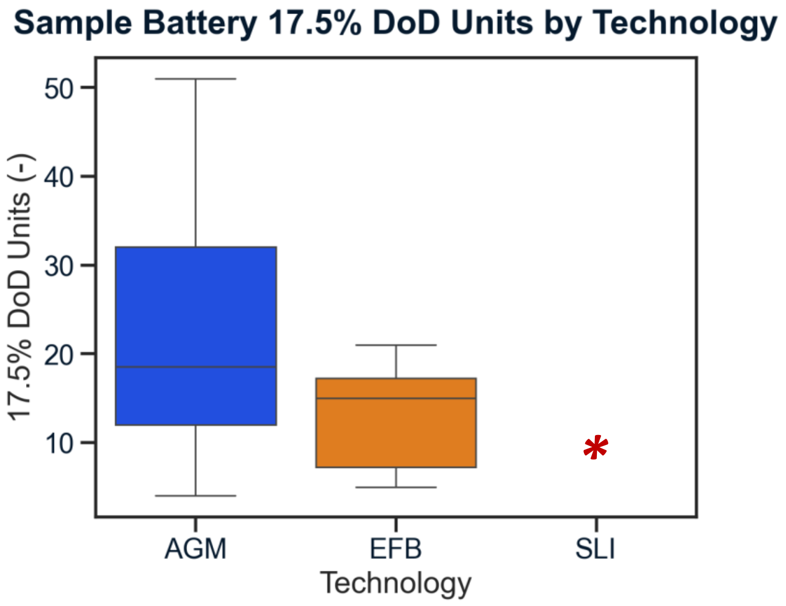


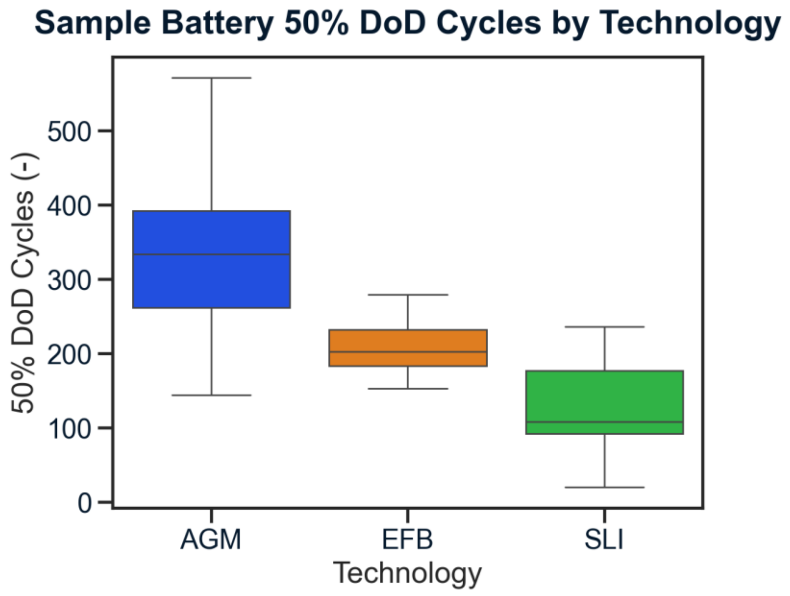


PENOX Overcapacity & Cycle Test Performance by Technology

Austrian Battery Research Laboratory GesmbH.







- **EFB** with highest average overcapacity
- **SLI** with lowest average overcapacity
- Strong overcapacity variation for **SLI** and especially **AGM**

- Strong 17.5% DoD cycle test performance variation for **AGM**
- Overlap of **EFB** performance with **low-level AGM**
- **Best-in-class AGM** performs far better than all other types

- Strong 50% DoD cycle test performance variation for **AGM**
- Overlap between **low-level AGM** and **EFB** & **SLI**, and also between **low-level EFB** and **SLI**
- **Best-in-class AGM** performs far better than all other types

* *Not tested with **SLI** batteries*

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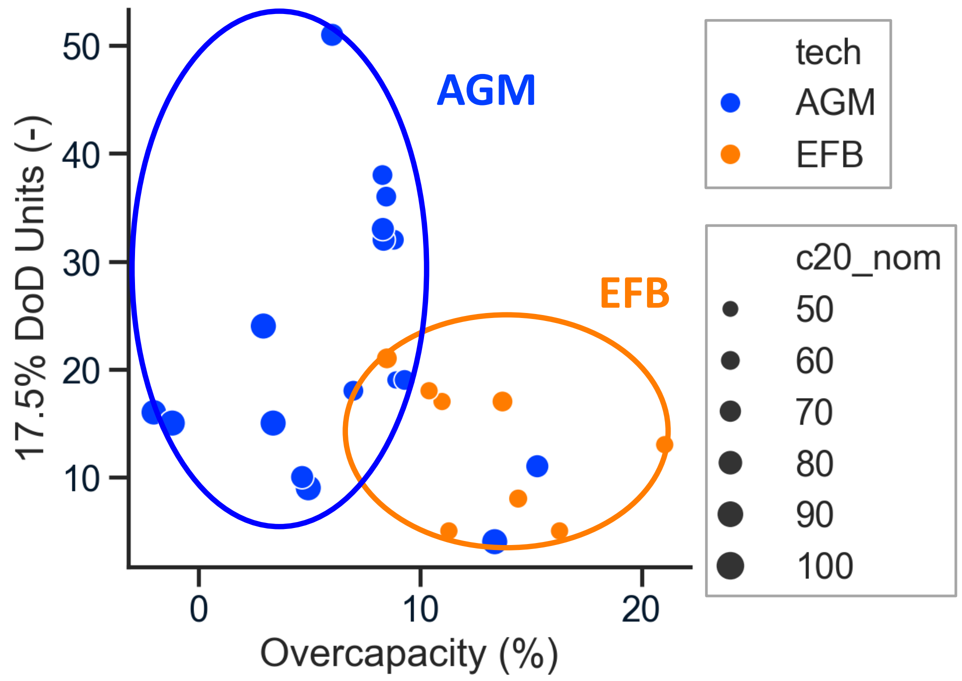
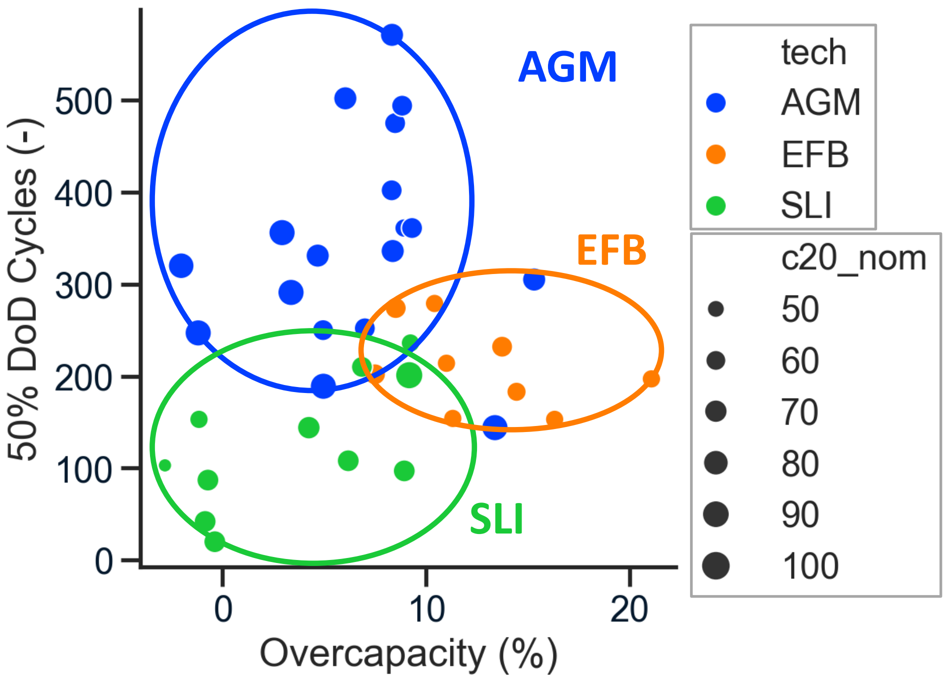
Cycle Test Performance vs Overcapacity



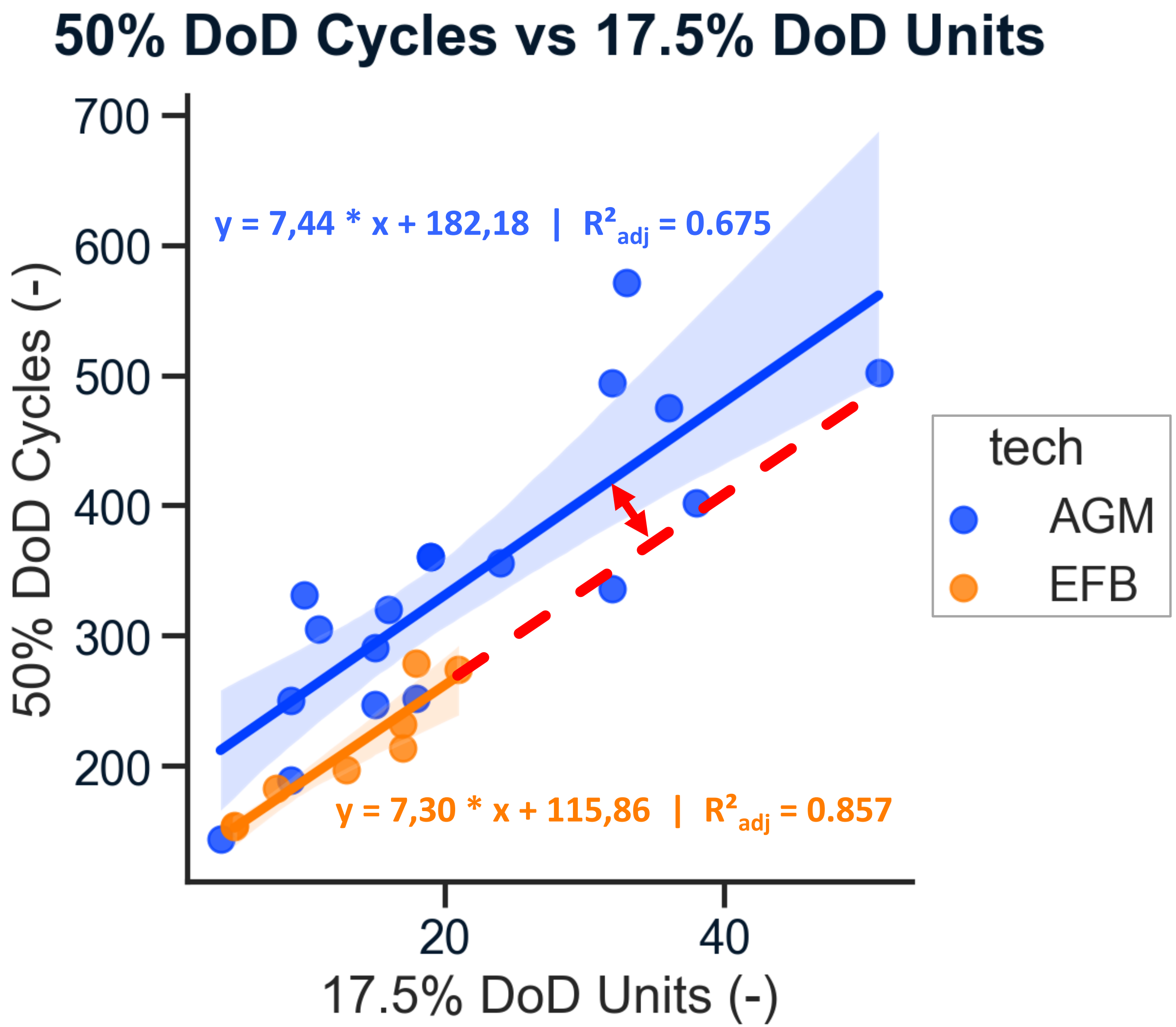


- Strong variation in **AGM** battery performance
- Overlap of **low-level AGM** with **high-level EFB**
- **Best-in-class AGM** performs far better than **EFB**

- Strong variation in **AGM** battery performance
- Overlap of **low-level AGM** with **high-level EFB**
- Overlap of low-level **EFB** with high-level **SLI**
- **Best-in-class AGM** far better than all other types

➢ Highest number of units not achieved with largest battery types → **Limitations** *(e.g., box size)*

50% DoD vs 17.5% DoD Cycle Test Performance



- 17.5% DoD Test performance is strongly correlated with 50% DoD Test performance for both **AGM** and **EFB**
- Linear regression results in a very similar slope for **AGM** and **EFB** → **parallel-shifted**
- Potential reason for this parallel shift: different average **plate group compression level** (**AGM >> EFB**)
- *Lighter colored areas represent 95% confidence intervals*

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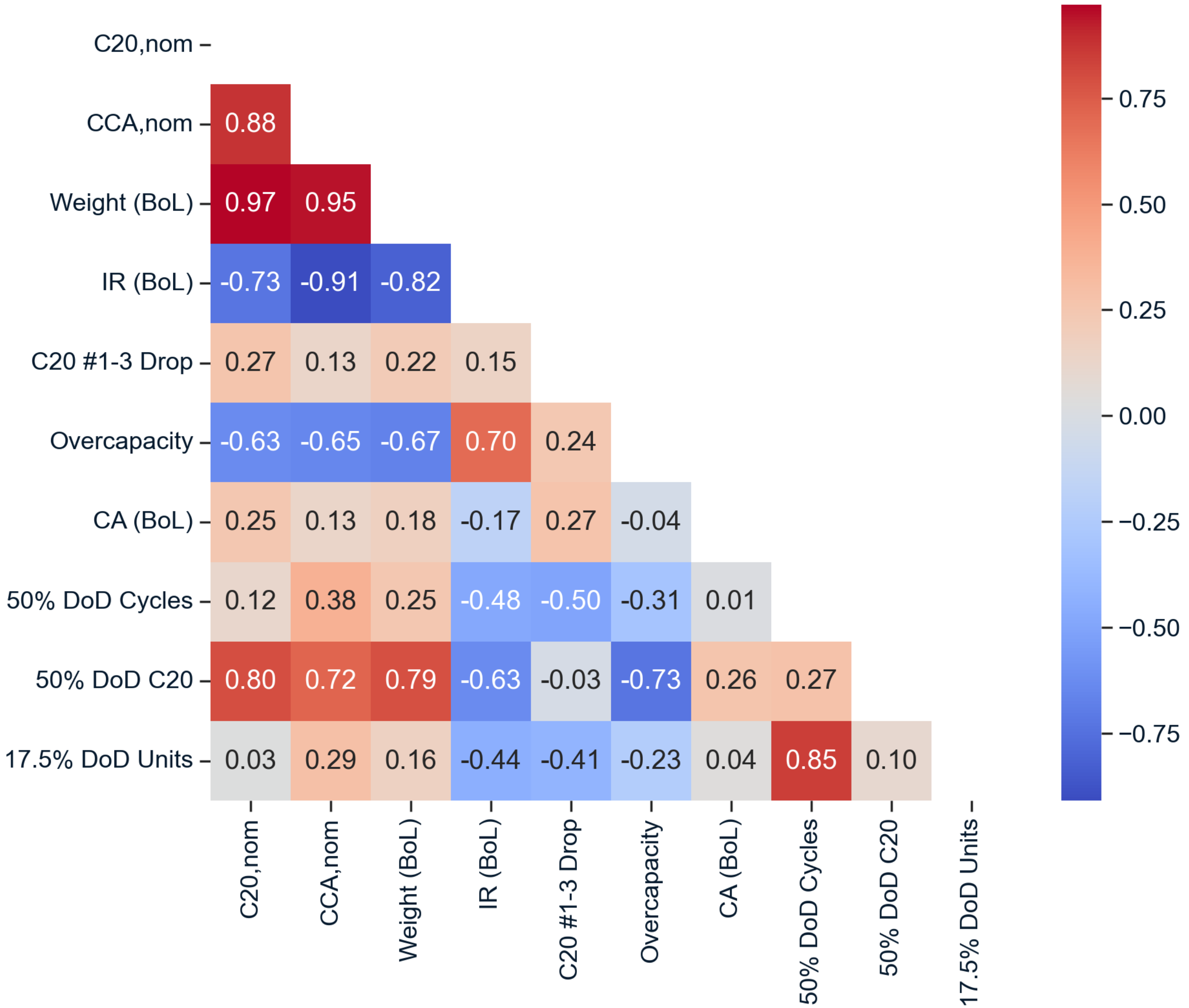
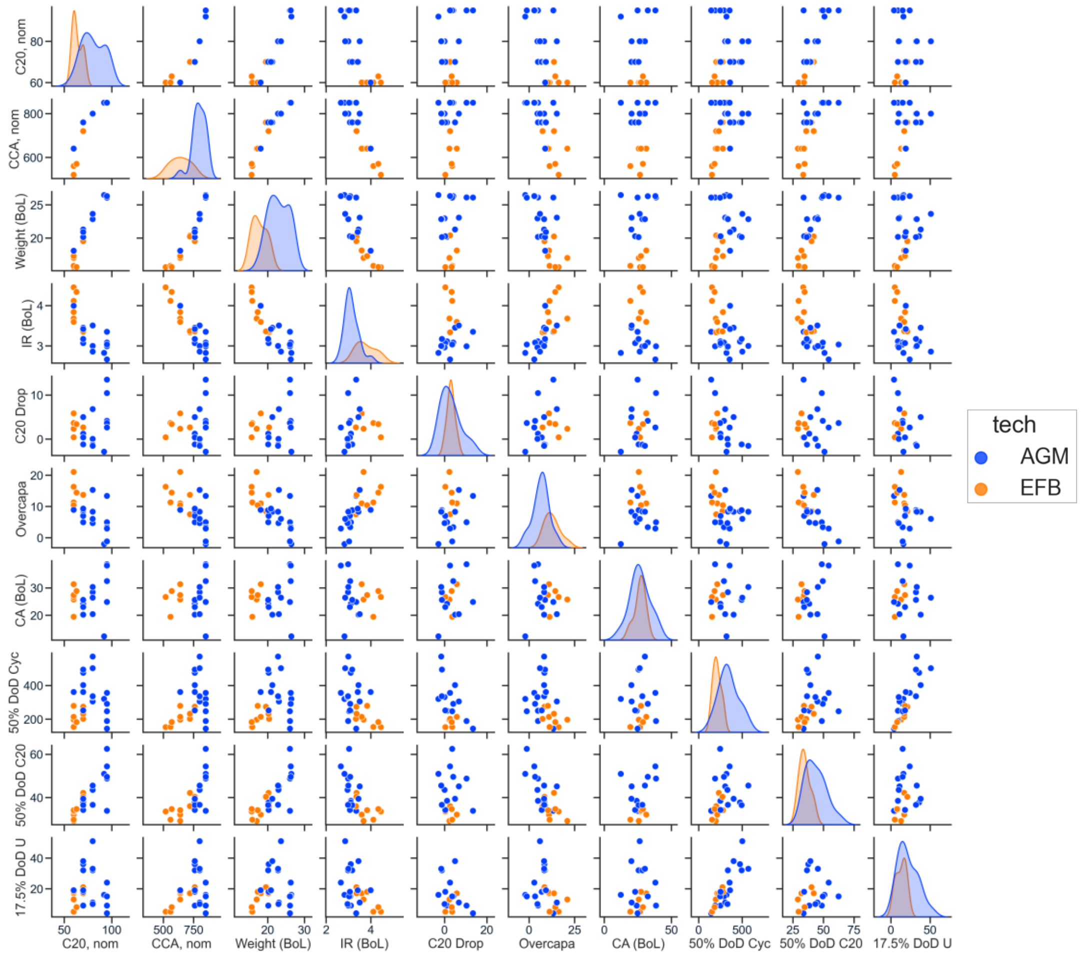
Linear Correlations: AGM & EFB

Austrian Battery Research Laboratory GesmbH.

AGM & EFB



AGM & EFB

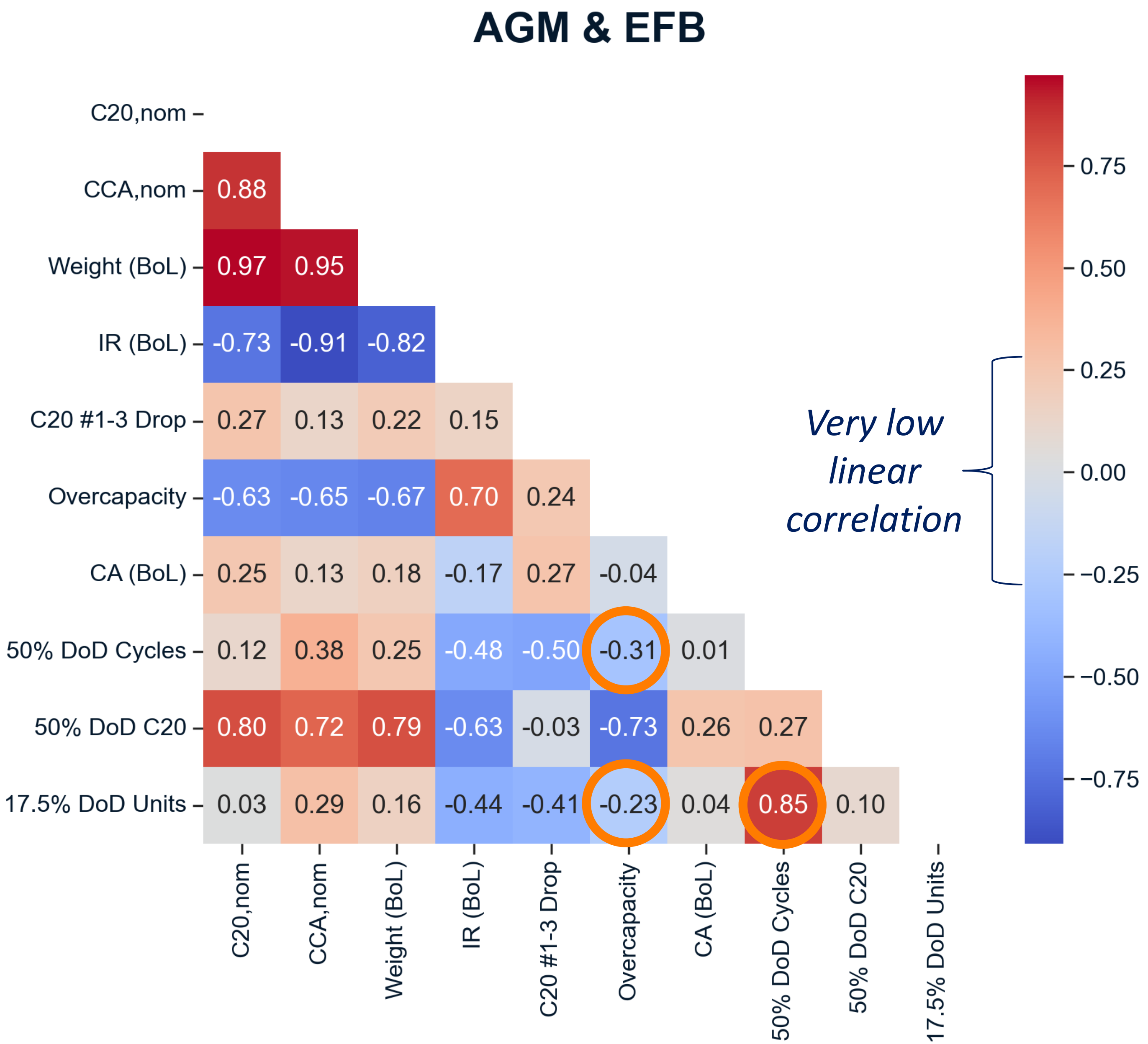


BoL = Beginning of Life

CA = Charge Acceptance

IR = Internal Resistance

Linear Correlations: AGM & EFB



- Checking for **linear *(i.e., Pearson)* correlation**:
  - **Red** = Positive correlation
  - **Blue** = Negative correlation
- **SLI** is excluded from this graph, as **AGM** is technologically better comparable to **EFB,** and also, no 17.5% DoD data is available for **SLI**
- **Examples of how to interpret these values:**
  - **17.5% DoD** and **50% DoD** cycle test performance are strongly correlated
  - **17.5% DoD** units and **50% DoD** cycles are not strongly correlated with **overcapacity**
- *Data for this mix of **AGM** & **EFB** batteries is interesting to evaluate, but effects may get masked if these battery types strongly differ regarding these linear relationships*

→ **Thus, AGM and EFB have also been evaluated separately side by side**

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Linear Correlations: AGM vs EFB

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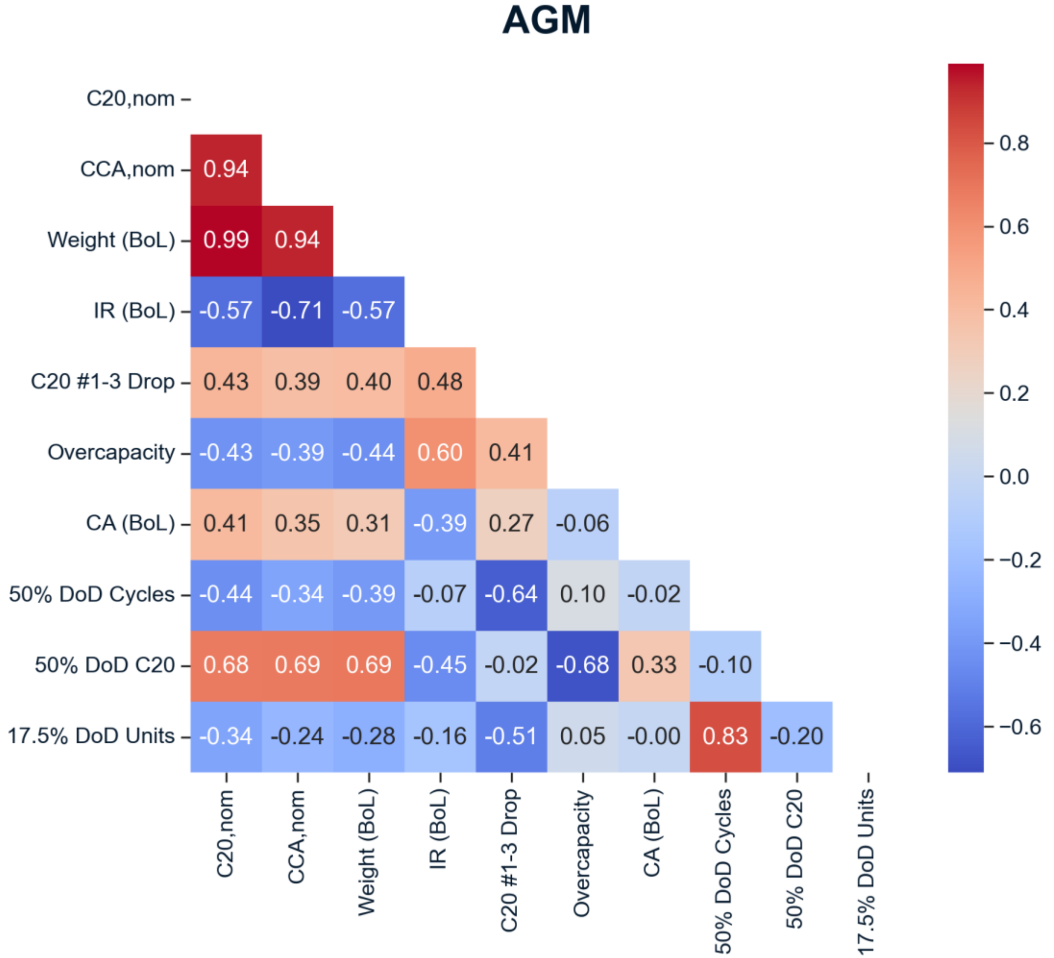

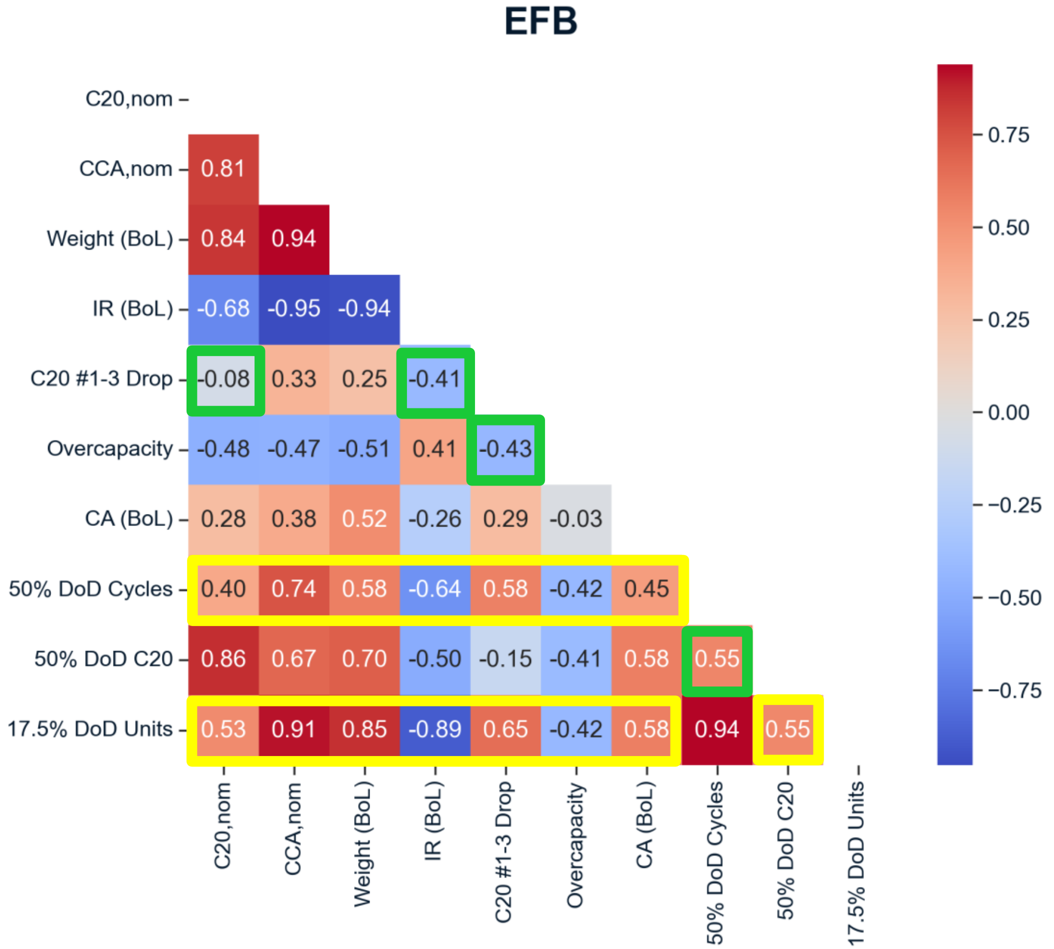

- While many of these linear correlations are comparable between AGM and EFB, **there are also big differences, especially concerning 50% DoD cycles and 17.5% DoD units *(marked in yellow)***
- Other main differences are marked in green

- **AGM**: More „technology-driven“
- **EFB**: More „tweaking“

✓ ***Much insight can be gained from detailed evaluation of this data***

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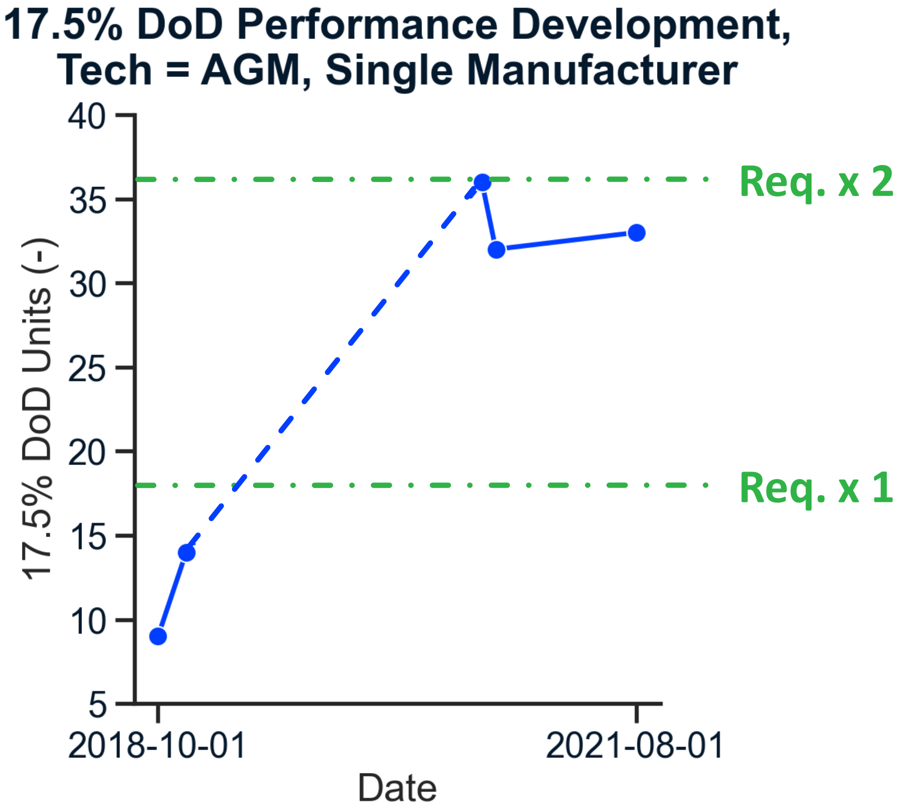
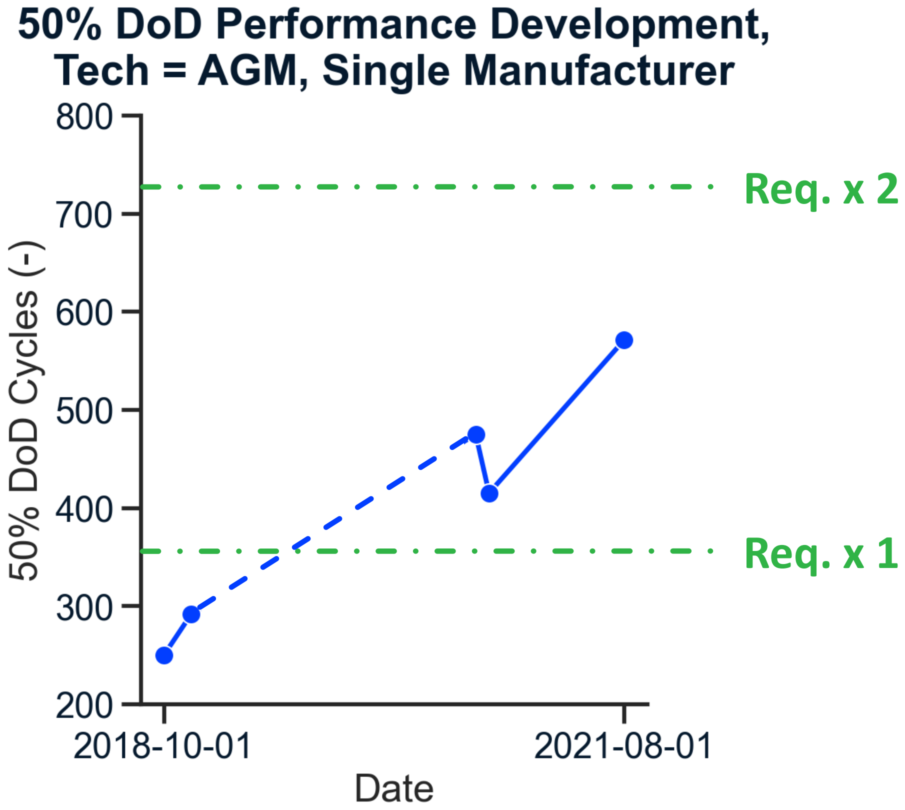
Cycle Test Performance Development over Time





- Significant improvements achievable, depending on current battery performance, process control, and technical competence levels of the manufacturer
- Good example for the strong correlation between 17.5% and 50% DoD cycle test performance, as shown in the linear correlation heatmaps

→ How does data from the field compare to this lab test data?

Req. = Requirement

PENOX C_{20} and CCA / U10s at End of Life vs $C_{20,nom}$: Lab vs Field

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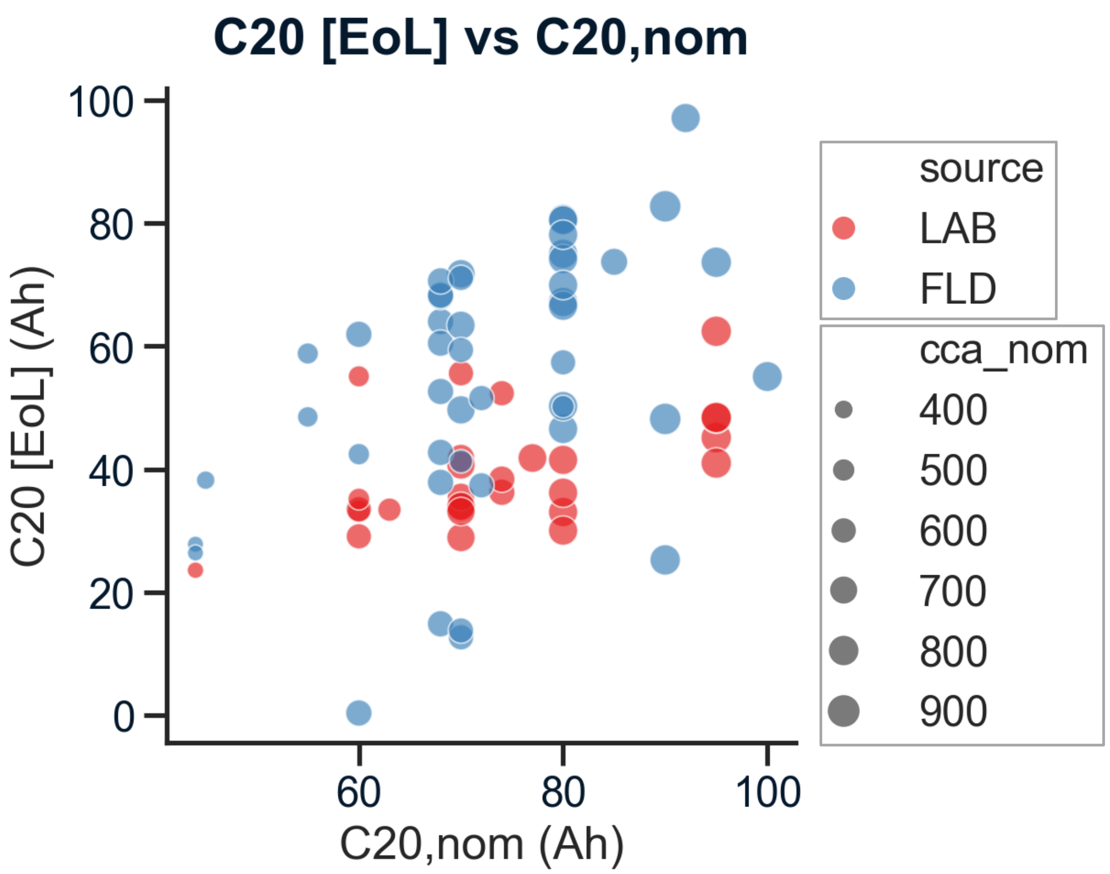
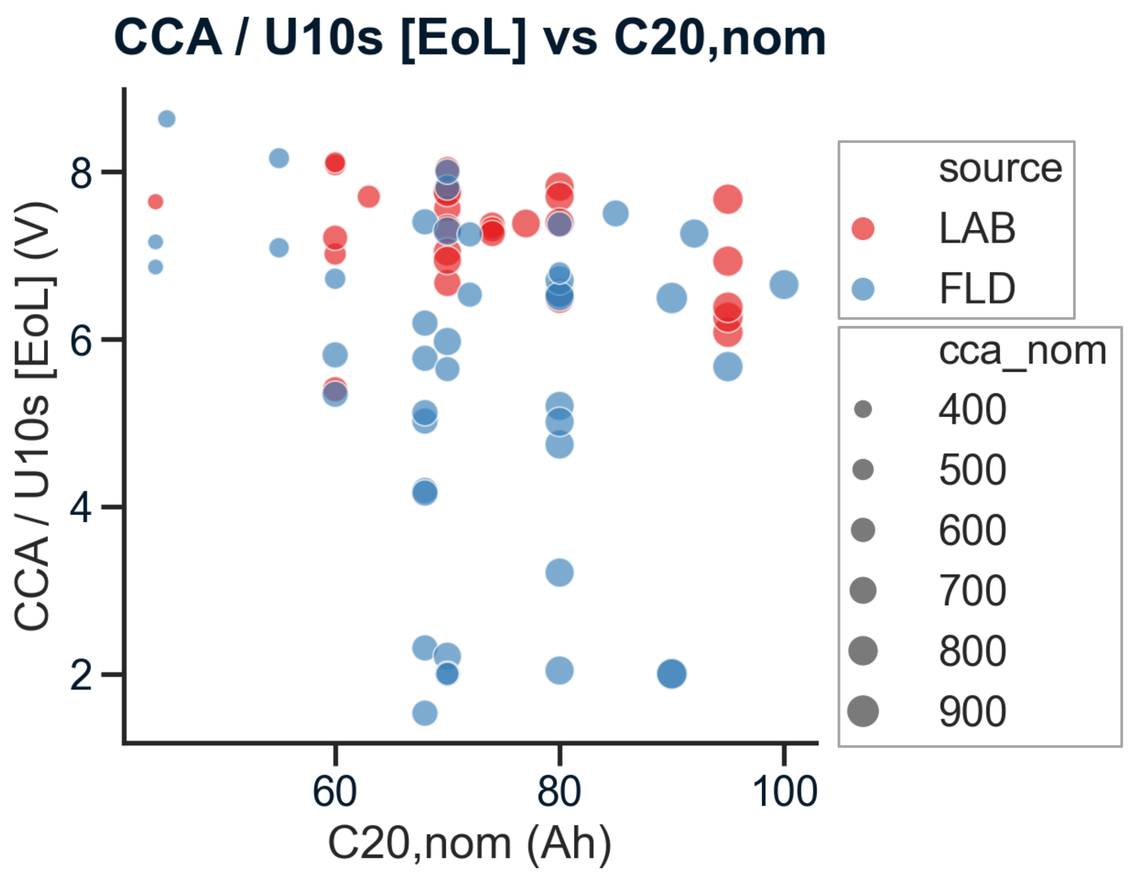


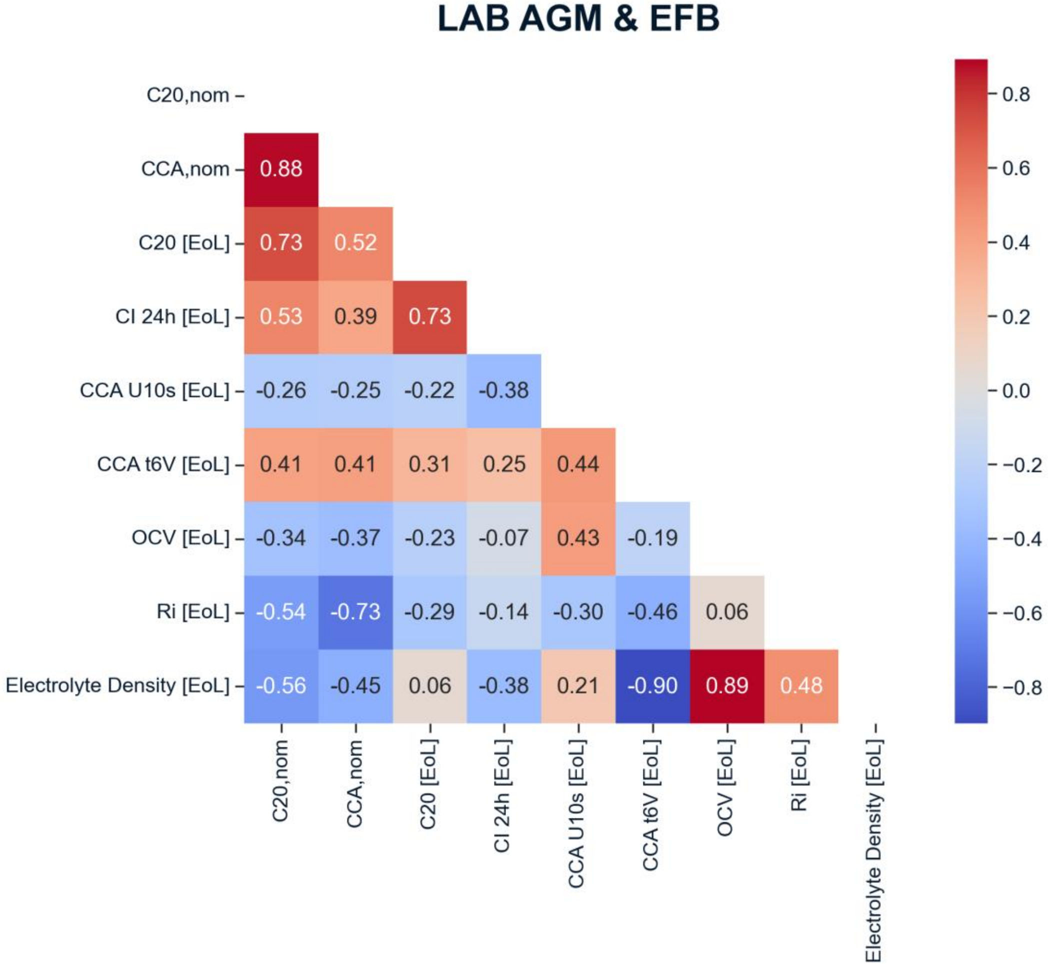


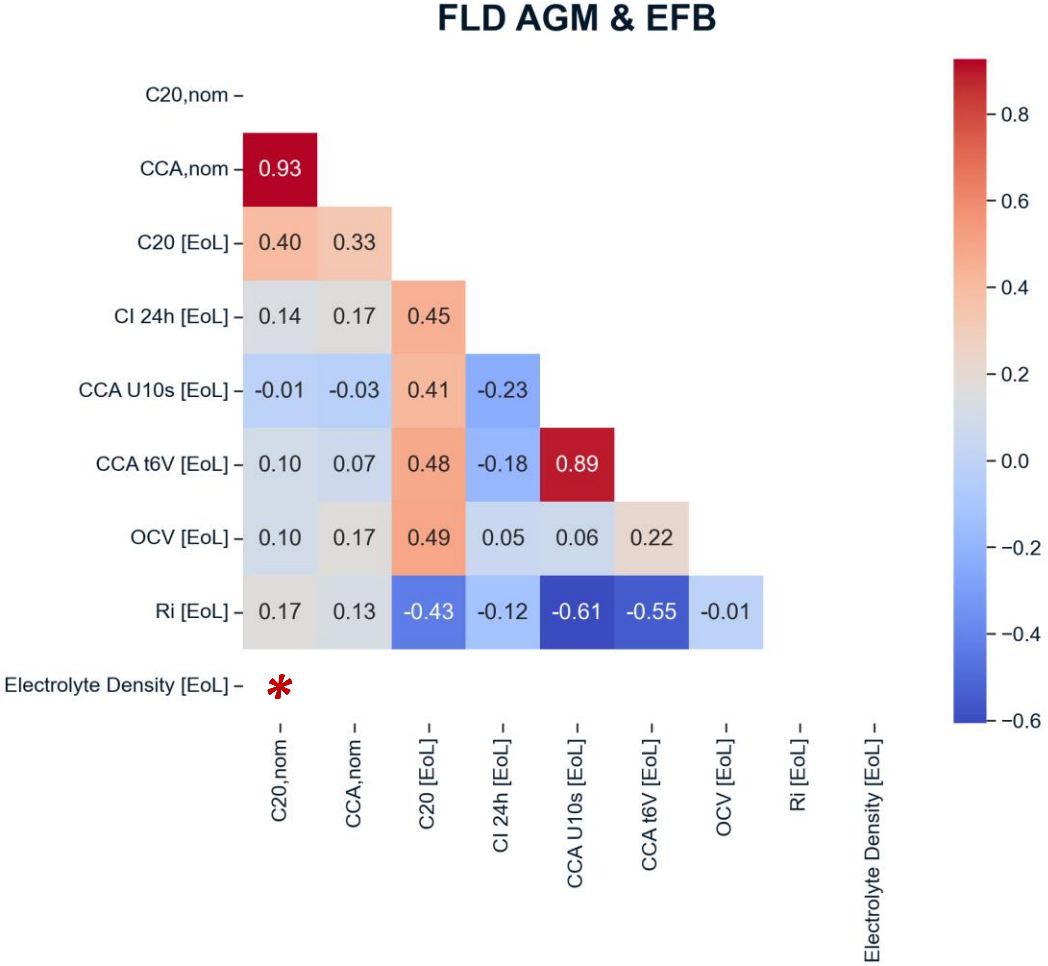
- Significant differences between the lab and field data
- Lab battery C_{20} [EoL] (after 50% DoD test) at around ~ 50% $C_{20,nom}$, while field data is significantly higher
- Also significant difference in CCA / U10s [EoL] data:

  lab data at ~ 7 V, while field data is significantly lower

EoL = End of Life

Linear Correlations: Lab vs Field





- Significant differences between the lab and field data
- To be further evaluated in detail

→ **Upcoming publication**

* *Not tested with **SLI** batteries*

EoL = End of Life

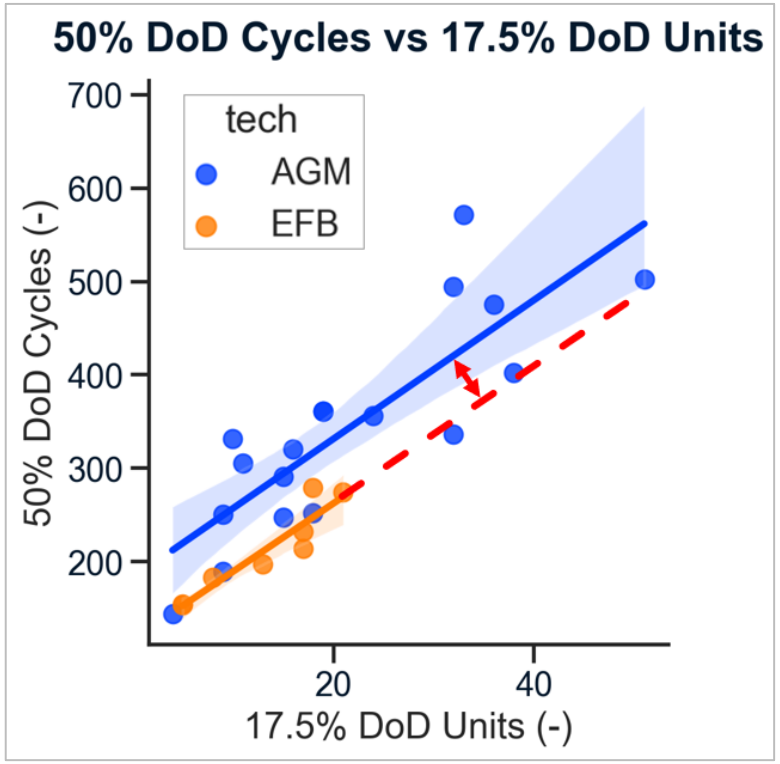
Summary and Outlook

Large performance gap between best-in-class AGM and EFB

- ➢ ***Can this gap be closed or at least significantly reduced?***

EFB: Significant potential for reducing the gap

- As seen in the "50% DoD Cycles vs 17.5% DoD Units" graph, EFB cycle test performance runs parallel to AGM, just shifted to lower values
- Potential main reason: Different average plate group compression level



→ Potential solution to minimize this gap in EFB performance:

- ✓ Increase compression
- ➢ This may require a separator material change to support sufficient porosity at higher compression rates

Upcoming:

- **Review of the Performance Patterns of Automotive Lead-Acid Batteries**
  Technical paper as a follow-up of the ELBC 2024
- **Further Data Evaluation & Publications are in Preparation**

Thank You for your Attention!

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