Integrated Data Analysis for Battery Degradation

Implementing and Comparing DVA, ICA, dP/dE, and the LEAN Method

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1 Motivation

Lithium-ion batteries are crucial for electric vehicles and energy storage systems, but their performance degrades over time. Efficient, **non-invasive diagnostic methods** are essential for monitoring degradation and predicting battery lifetime.

Common diagnostic techniques, such as **Incremental Capacity Analysis (dQ/dV, ICA)** and **Differential Voltage Analysis (dV/dQ, DVA)**, convert plateaus in charge/discharge (V-Q) curves into clear peaks, aiding in battery assessment (*Figure 1*). Recently**, Level Evaluation Analysis (LEAN)** has emerged as a refined method [1], alongside new approaches like **Differential Power-Energy (dP/dE)**.

This project compares these four methods across multiple cycles in the **Borealis dataset [2]**, which contains aging data from **Samsung INR21700-30T** lithium-ion cells, aiming to provide comparative insights into their advantages and limitations. Key evaluation criteria **include preconditions, algorithmic and mathematical stability, computational efficiency,** and **visual interpretability**.

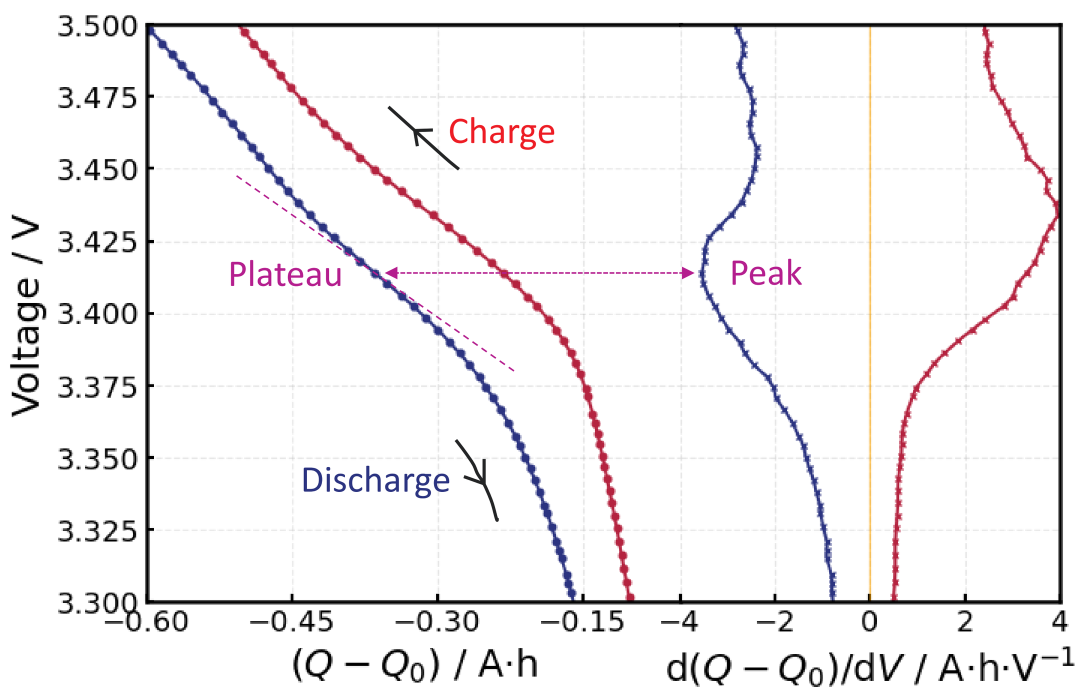

Figure 1. *Cycle 520: $(Q - Q_0)$–V and $d(Q - Q_0)$ /dV – V (3.28–3.54 V), with Q_0 = maximum capacity.*

2 Method

Data Acquisition
- Proper sampling frequency
- Constant current I_0
- Low rate

Data Cleaning
- Handle missing data
- Remove NaNs/∞

Pre-processing

Cycle Segmentation
- Cycle separation
- Separate charge/discharge

Monotonic Windowing
Retain only strictly monotonic segments

Implementation

Differential Techniques — *Constant potential*

Resampling

Filtering
- Applied when enough data points are available.
- Retains one point every set interval in the independent variable (*Figure 2*).
- **Rule of thumb**: maintain ≥ 5 points across each peak half-width to trust peak position and intensity [3].

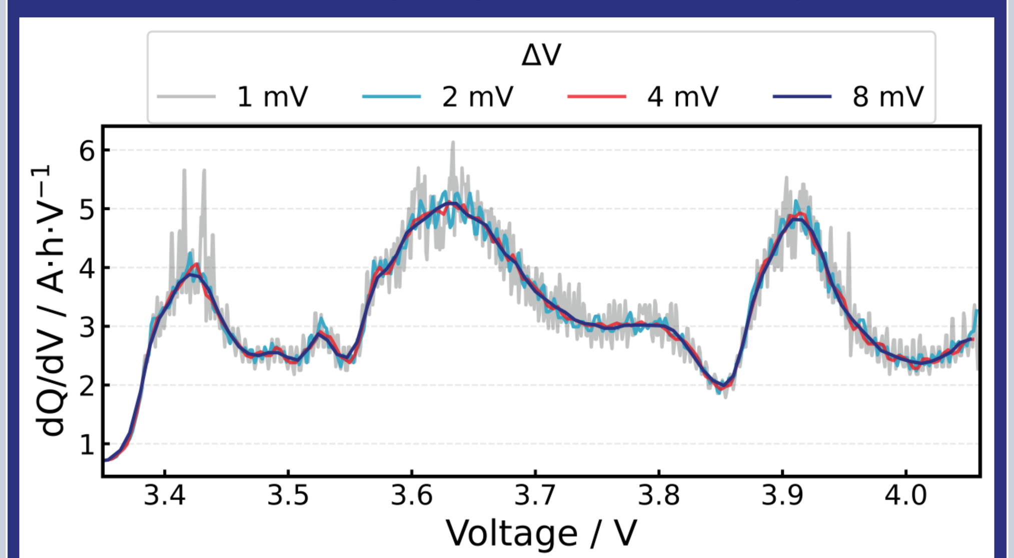

Figure 2. *Impact of fixed voltage step size (ΔV) on dQ/dV in filtering.*

Interpolation
- Common in earlier literature and when data are sparse or step sizes are uneven.
- Result depends on the method (e.g., linear, cubic).

Smoothing

Optional Smoothing
- Most often via Savitzky–Golay smoothing.
- Parameters (window length, polynomial order) strongly affect peak sharpness and noise suppression.
- Over-smoothing can shift or erase peaks (*Figure 3*).

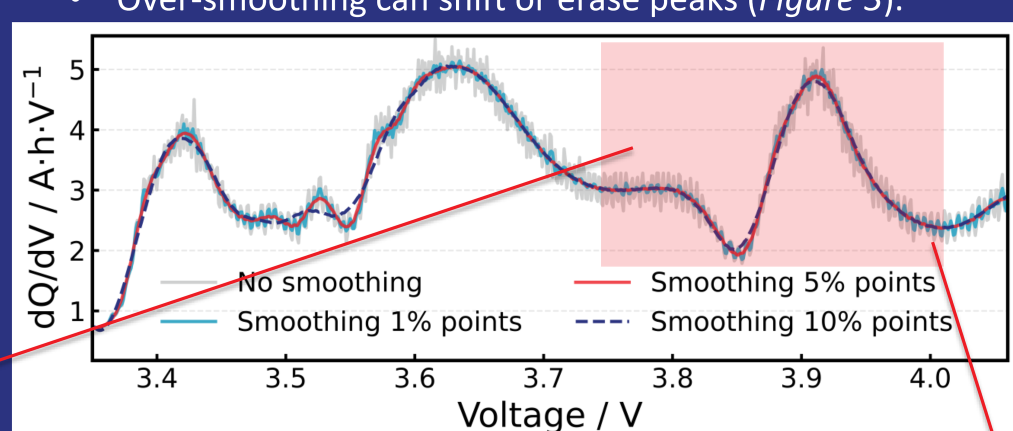

Figure 3. *Impact of smoothing on dQ/dV with ΔV = 1 mV filter applied.*

Smoothing

Verified: *filtering*/smoothing does not alter peak shape or position

Differentiate

LEAN

Precondition
Uniform sampling interval dt

Obtain Digital Resolution, dR

Histogram

Choose Bin Width $\Delta V = K \cdot dR$
Where K is an integer chosen so that $\Delta V \geq s_V$ (*voltage noise scale*).

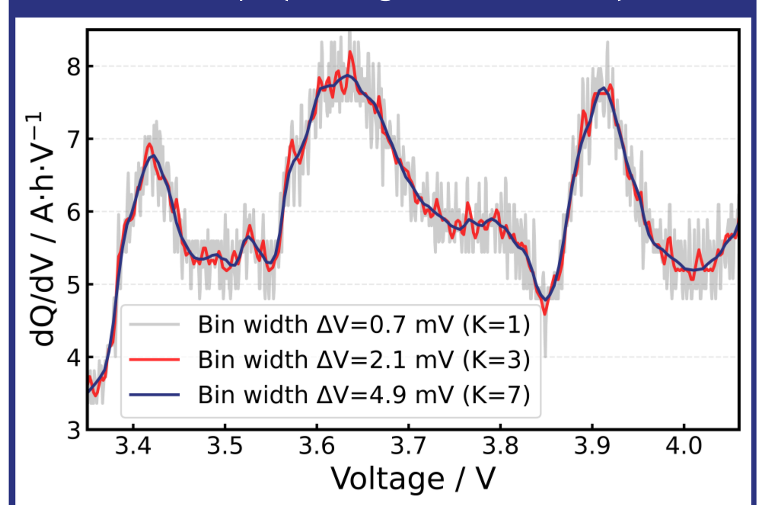

Figure 4. *LEAN outputs with increasing bin width.*

Build dR-aligned Edges
- Spaced by ΔV
- Centred at `v_centres`

Count Samples Per Bin, N_i

Compute Differential Curves

$$\frac{dQ}{dV_i} = I_0 \cdot \frac{dt}{\Delta V_i} \cdot N_i$$

Outputs – `v_centres`, dQ/dV
Can be attached back to original columns for direct comparison with differential methods

Optional Reversible Smoothing
Symmetric kernels, strictly invertible

Interpretation

3 Interpretation

Degradation mechanisms can be investigated through the study of:

- Evolution of the shape
- The height and position of peaks

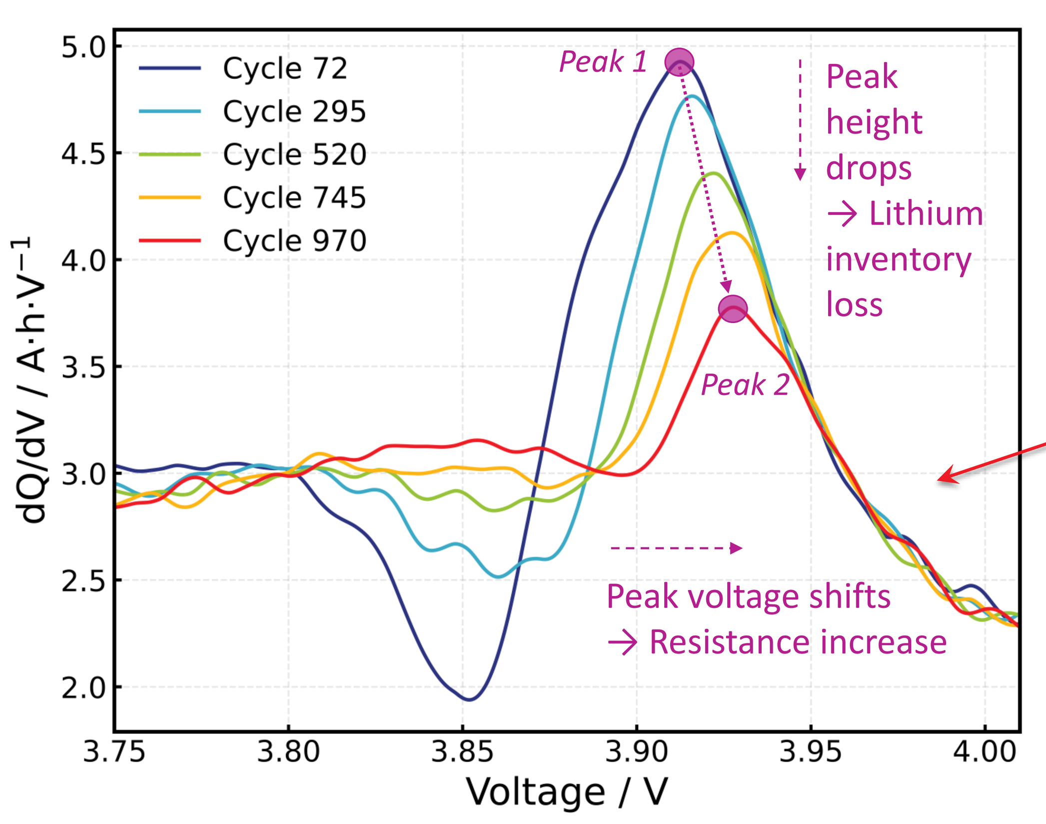

Figure 5. *Part of differential capacity (dQ/dV) curves across selected cycles, annotated with characteristic peak changes linked to degradation modes.*

4 Comparison

As shown in *Figure 6*, all four methods reveal consistent patterns (within the scope of this project), validating their implementation. Under similar levels of resampling and/or smoothing, **dP/dE exhibits stronger fluctuations**, making interpretation more challenging. The table below highlights **differences** between the **differential techniques** and **LEAN** (shared traits omitted).

Method	Differential Techniques	LEAN
Advantages	• **DVA and ICA Widely used**: well-established in literature, easy to compare with prior work • **Useful for electrode balancing**: more direct insight into anode/cathode alignment	• **Mathematically stable**: each sample is a fixed charge increment ($I_0 \cdot dt$) so bin counts scale with charge; dividing by ΔV directly yields dQ/dV, requiring no transformations and few parameters → reliable peak capture • **Computationally efficient**: much faster due to linear complexity [1] • **Broad applicability**: works well with discrete sampled-data [1] • **Versatile**: compatible with multiple experimental techniques [1]
Limitations	• **Noise amplification**: differentiation amplifies experimental noise • **Strict monotonicity required**: duplicated or flat data can cause 0/∞ errors • **Extreme values**: can yield unstable ratios when denominator is very small	• **Constant sampling interval (dt) required** • **Discrete outputs**: may need post-processing for clarity

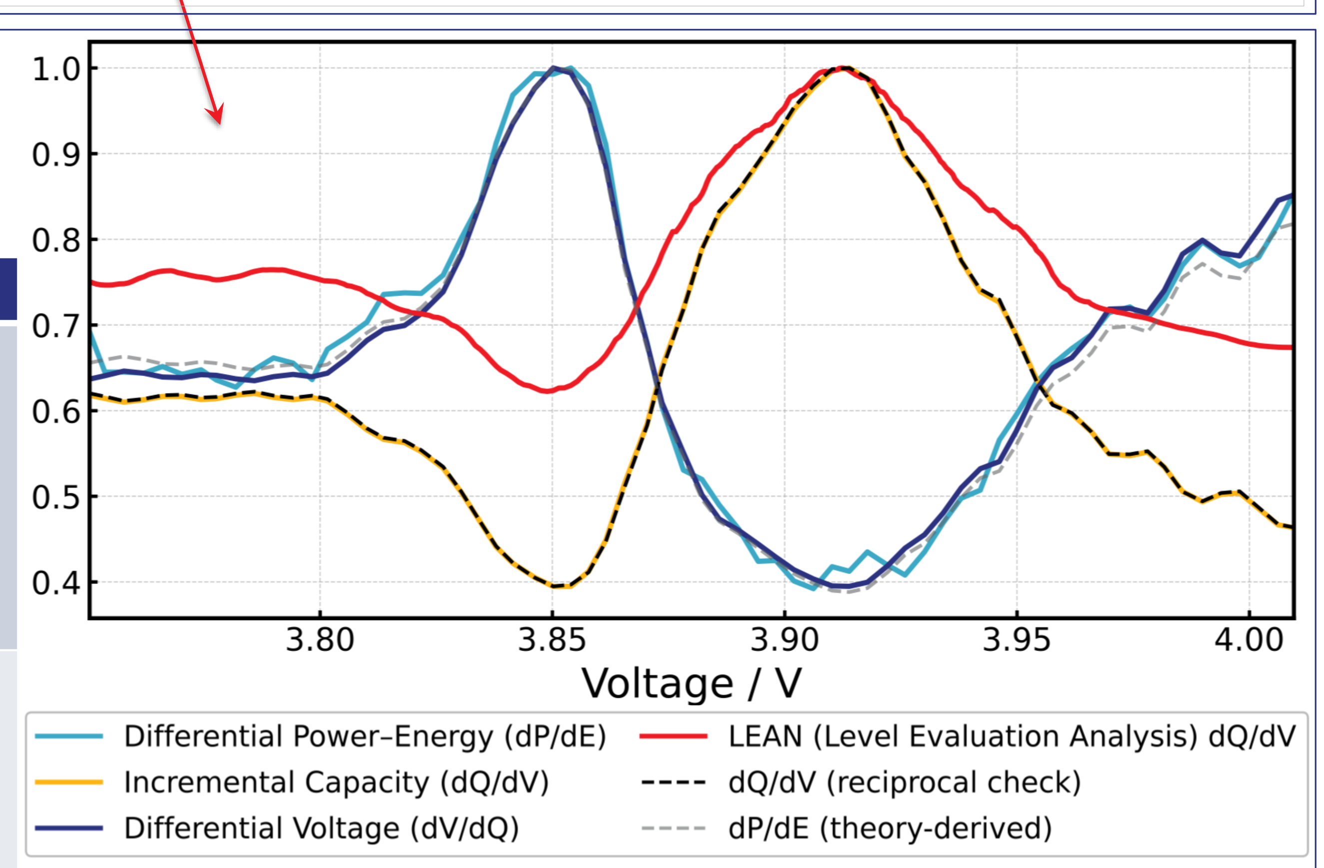

Figure 6. ***Normalised** comparison of four differential diagnostic methods: ICA (dQ/dV), DVA (dV/dQ), dP/dE, and LEAN. Dashed curves represent reciprocal and theoretical relations, confirming consistency among methods. The theory-derived **dP/dE = $V/I \cdot dQ/dV$**, is not exactly aligned with the experimental dP/dE because they are expressed against different independent variables and downsampled on different grids. All curves correspond to **charge, cycle 72**.*

5 Summary

- **dP/dE** shows stronger fluctuations under same resampling and/or smoothing.
- **DVA, ICA, LEAN** yield more stable results; **LEAN** is mathematically stable and computationally simple.
- The main challenge lies in **selecting parameters** carefully during post-processing to avoid distortion or loss of physical features.
- All methods are easy to implement, so **applying them together** provides more robust interpretation.

6 References

[1] X. Feng *et al.*, "A reliable approach of differentiating discrete sampled-data for battery diagnosis," *eTransportation*, vol. 3, 100051, 2020. doi:10.1016/j.etran.2020.100051.

[2] J. Duque, P. J. Kollmeyer, and M. Naguib, *Battery Aging Dataset for 15 Minute Fast Charging of Samsung 30T Cells*, V2. Borealis, 2023. doi:10.5683/SP3/UYPYDJ.

[3] M. Dubarry and D. Anseán, "Best practices for incremental capacity analysis," *Front. Energy Res.*, vol. 10, 2022. doi:10.3389/fenrg.2022.1023555.

7 Intern bio

Jimei (May) Cui is studying Physics at the University of Cambridge. Interested in data-driven methods for energy and technology applications, aspiring to apply quantitative analysis and modelling to solve interdisciplinary challenges.

Full project details: scan QR code or visit the GitHub Repository.

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