

Gavin Wiggins <https://gavinw.me>, Srikanth Allu, and Hsin Wang

Background

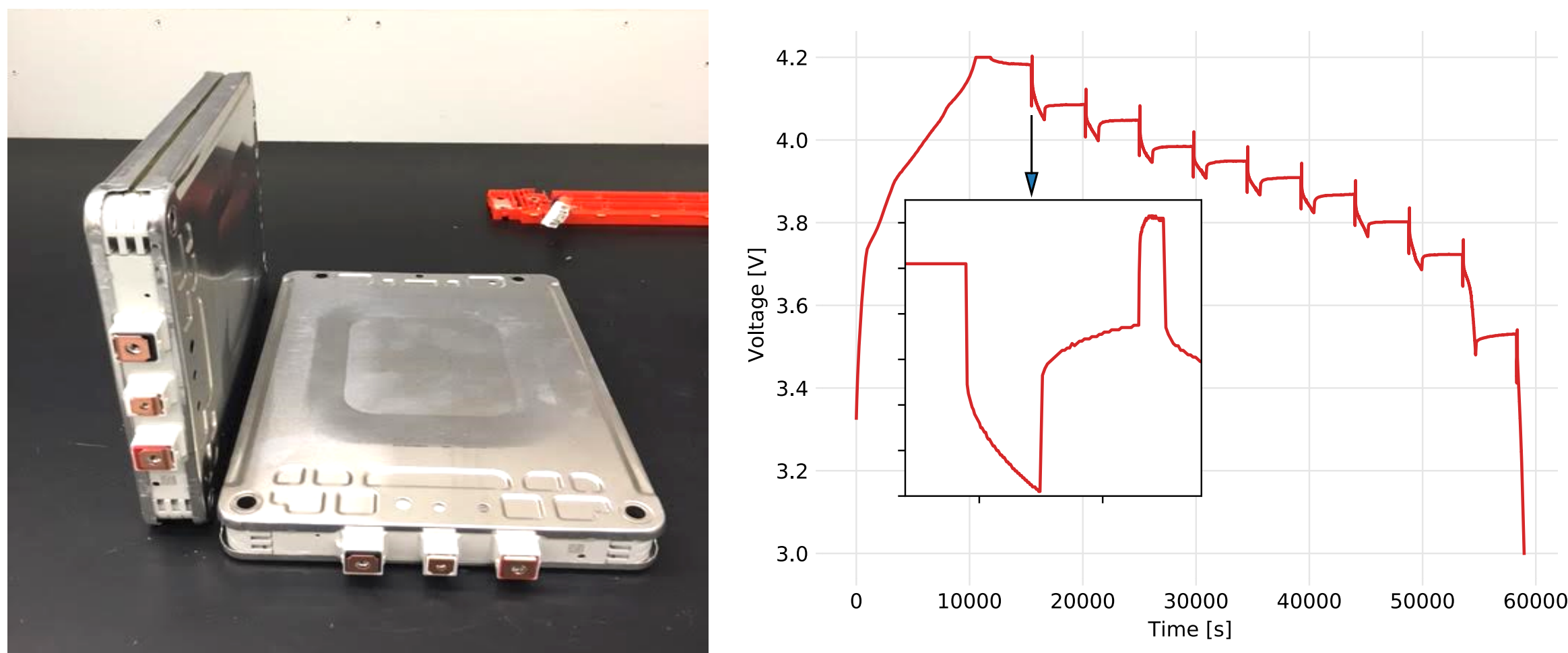
Electric vehicles are poised to reduce fuel consumption and carbon emissions around the world. To ensure efficient operation of the battery pack, an effective battery management system must be implemented.

Electrochemical models are capable of capturing many aspects of battery behavior with great accuracy by understanding chemical reactions within the battery. However, the complexity of these models limit their use in battery management systems.

Equivalent circuit models utilize a lumped battery modeling approach that relies on a small parameter space. The simplicity of these models offers near real-time results with reasonable accuracy for onboard electric vehicle applications.

Experiment data for model development

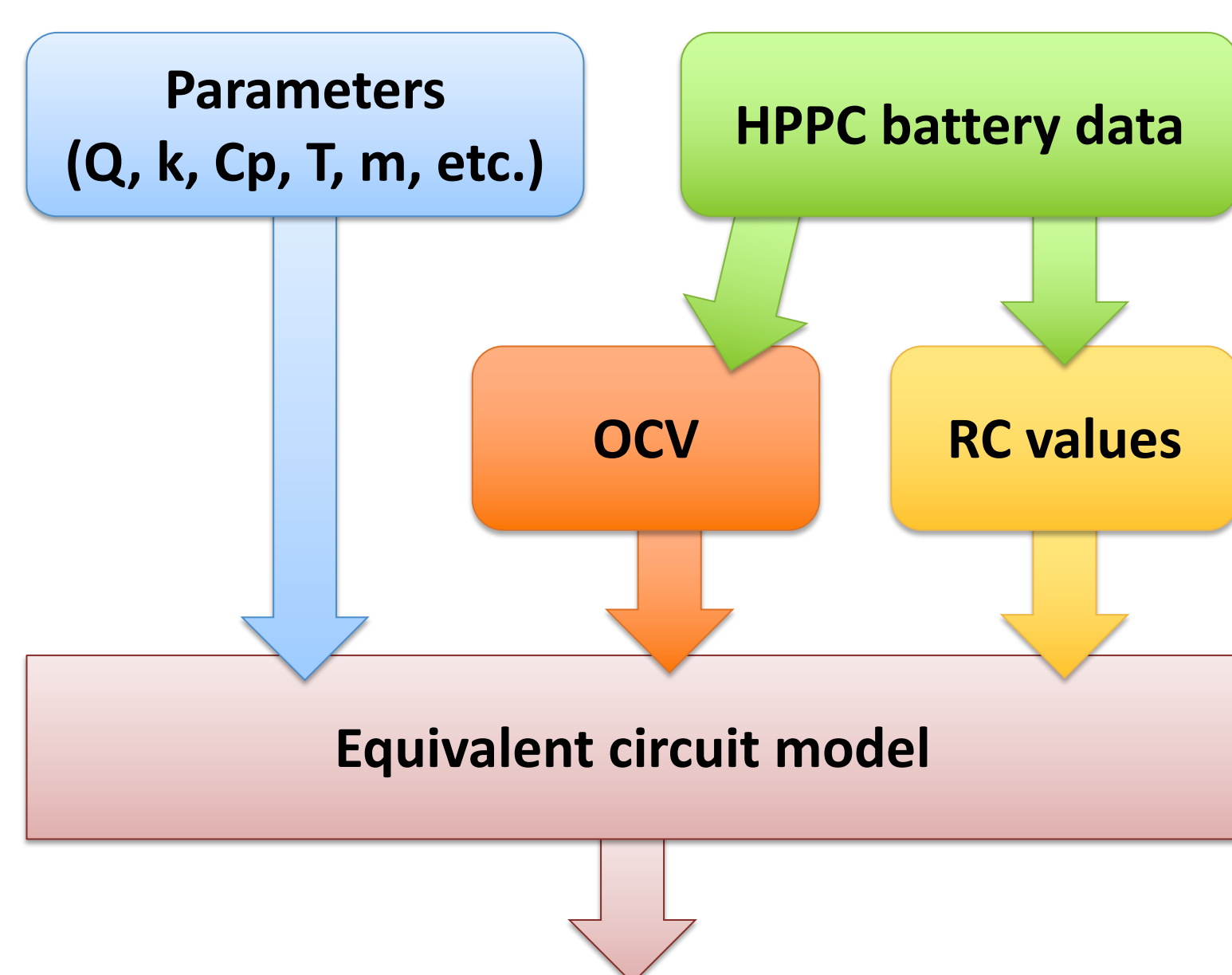
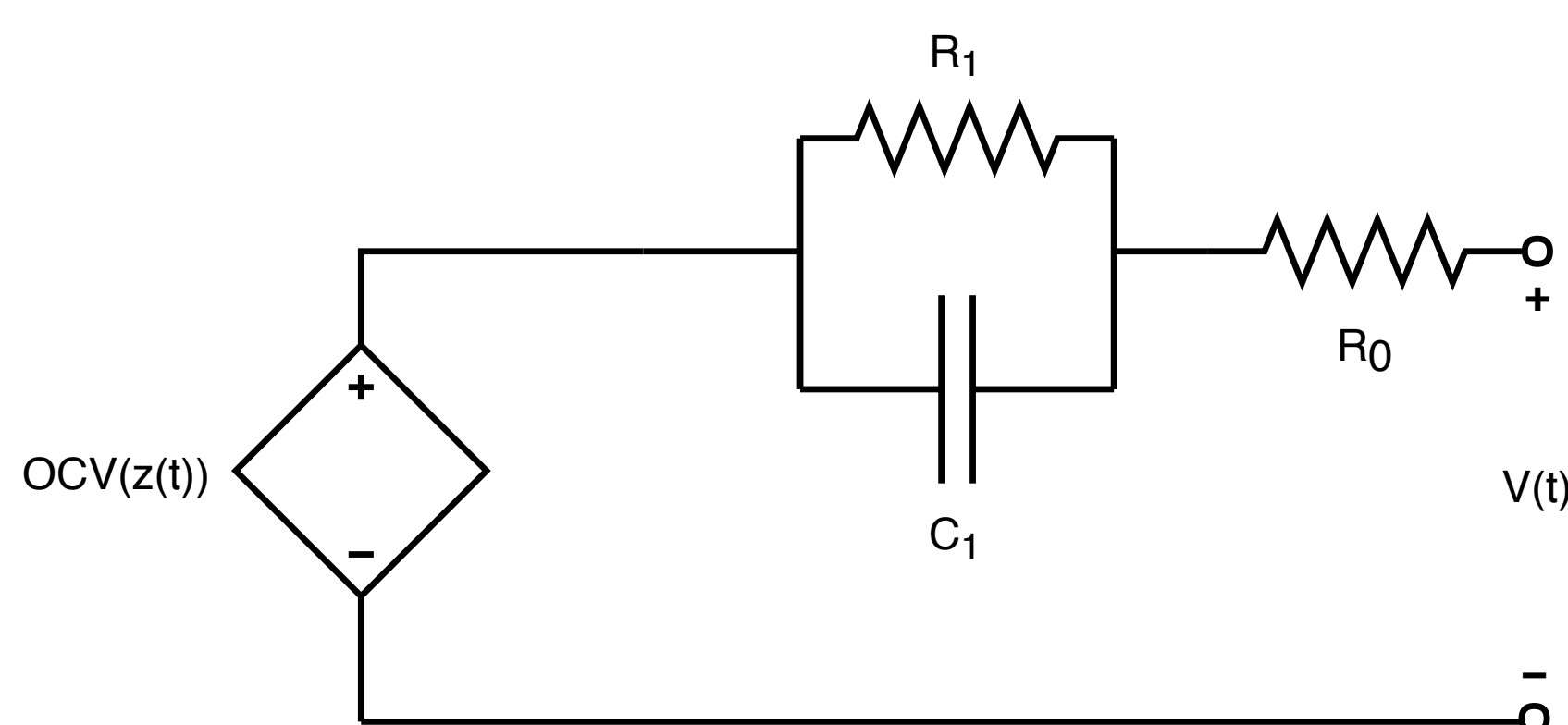
Hybrid Performance Pulse Characterization (HPPC) tests were conducted on a Nissan Leaf battery cell at 10°C, 25°C, and 40°C. The experiment data is stored as CSV files and parsed with **Numpy** or **Pandas**. Data visualization and plotting of model results is handled with the **Matplotlib** library.



Left – Nissan Leaf battery module from NREL. The module contains 4 cells wired in a 2P-2S configuration. Right – Voltage profile from a HPPC battery cell test. Inset represents 10% SOC.

Equivalent circuit model (ECM)

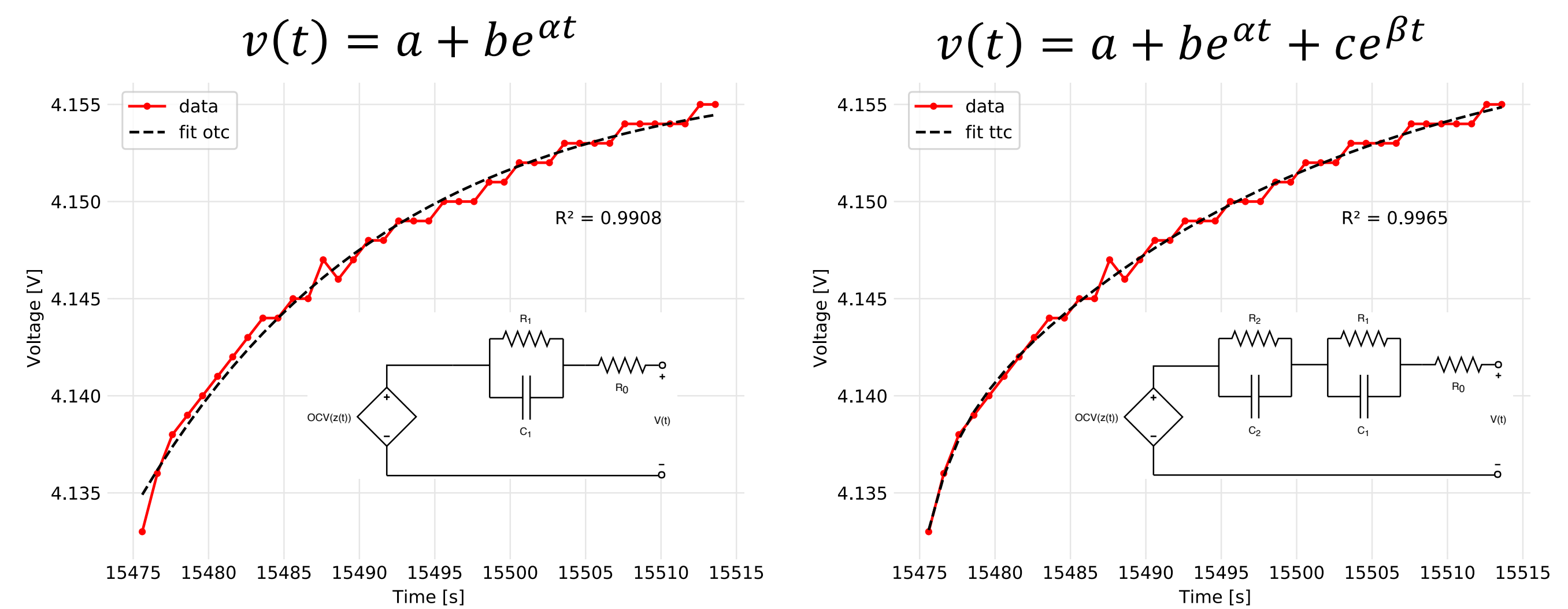
An equivalent circuit represents the behavior of a battery cell. Components of the equivalent circuit model are developed from the RC circuit and data collected from HPPC tests.



$$v_{ecm}(t) = v_{ocv}(z(t)) - v_1(t) - i(t)R_0$$

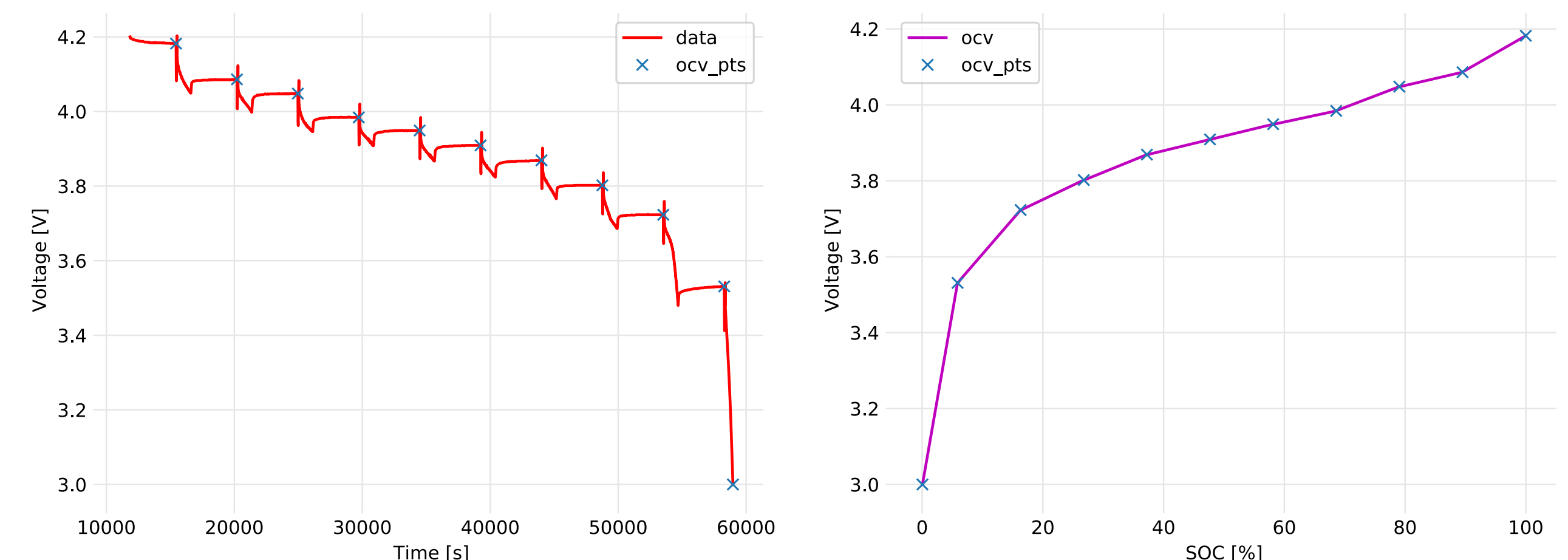
Results

Number of RC pairs and the associated RC parameters are determined from a curve fit with the HPPC voltage profile. For the Nissan Leaf cell, two RC pairs provided a good fit with data.

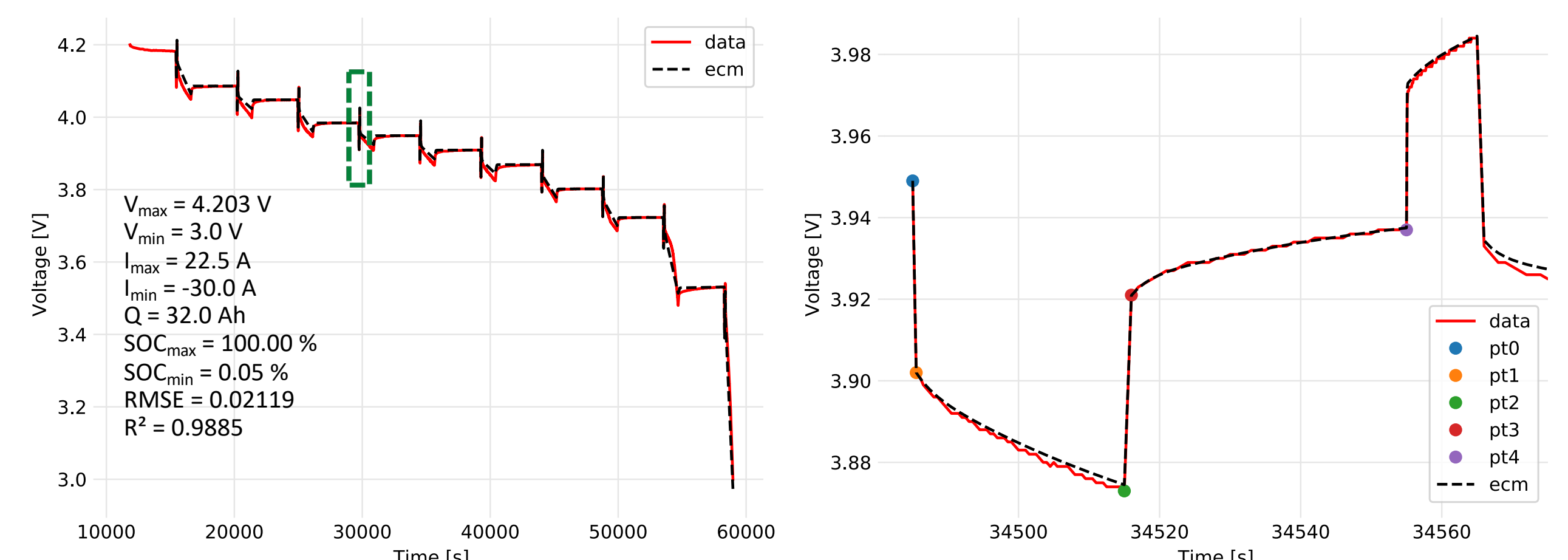


Left – Curve fit using one RC time constant. Right – curve fit using two RC time constants.

Onset of each discharge pulse defines OCV at that SOC. Intermediate values between OCV points are determined via linear interpolation using the **Numpy interp** function. Once the OCV and RC values are determined for each SOC, the voltage in each RC pair can be calculated.



Left – OCV points for each 10% SOC. Right – Linearly interpolated OCV from 0% to 100% state of charge.



HPPC voltage profile from Nissan Leaf battery cell compared to the ECM at 25°C. Left – HPPC and ECM results for entire pulse test. Right – Zoomed in view of a pulse discharge section.

Open source code

Python code for the equivalent circuit model is available on BatterySim GitHub. See the **ecm-python** repository for more information <https://github.com/batterysim>

Acknowledgment

The authors would like to thank NHTSA for the Nissan Leaf battery modules, NREL for specific battery test data, and EERE's Vehicle Technology Office under the CAEBAT program for support of this project.