



Leveraging MATLAB-Simulink in Building Battery State-of-Health Estimation Pipelines for Electric Vehicles

Nilesh Kulkarni, Director, Artificial Intelligence
Matthew Daigle, Principal Scientist, Artificial Intelligence

NIO USA

Artificial Intelligence Team Overview

Team

- About 25 full-time employees
- Average experience 12 years

Projects

- Autonomous Driving: Trajectory Planning, Decision Making
- Vehicle AI: Smart Controls, Diagnostics & Prognostics



Motivation

- In electric vehicles, understanding battery State-of-Health (SOH) is critical
 - Powertrain performance
 - Range estimation
 - Fleet management
 - Service operations

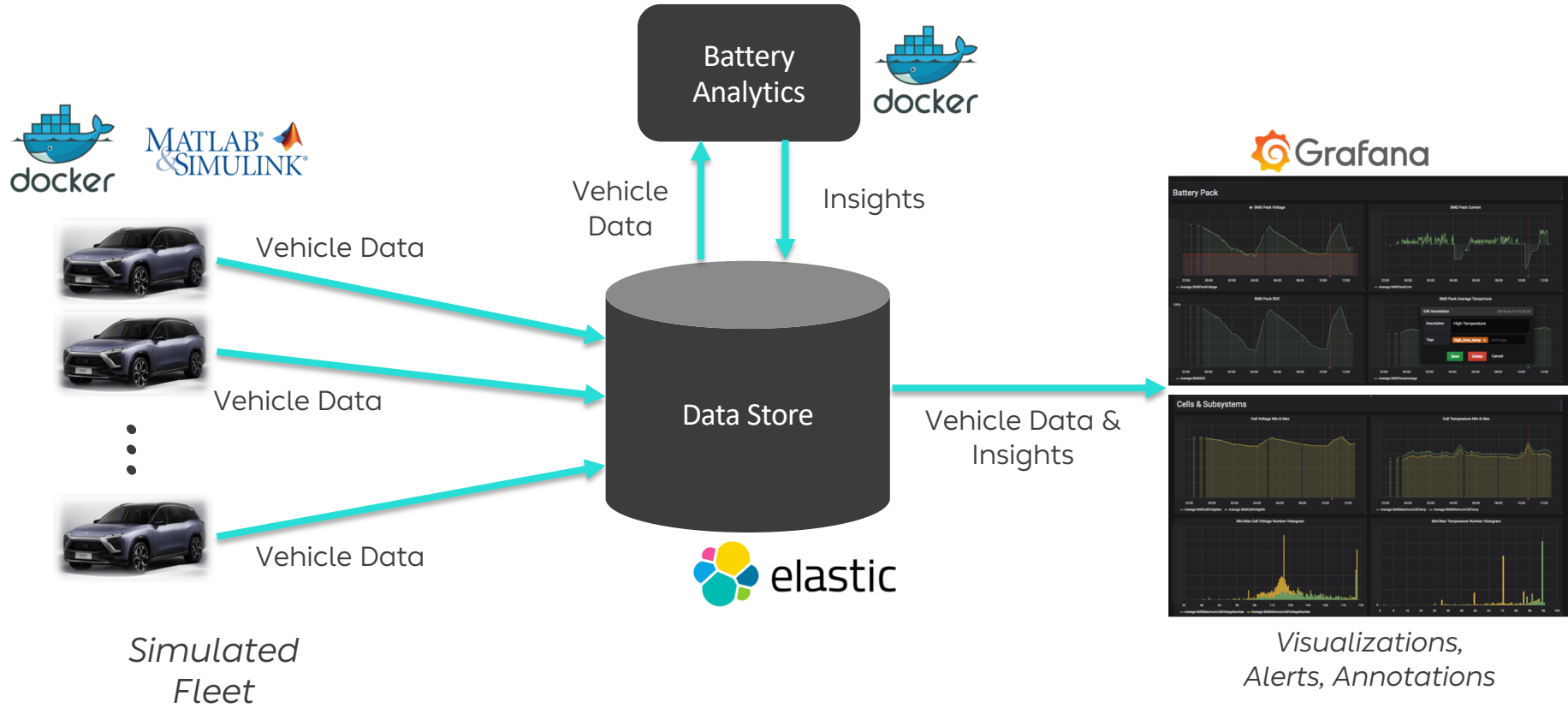


Challenges

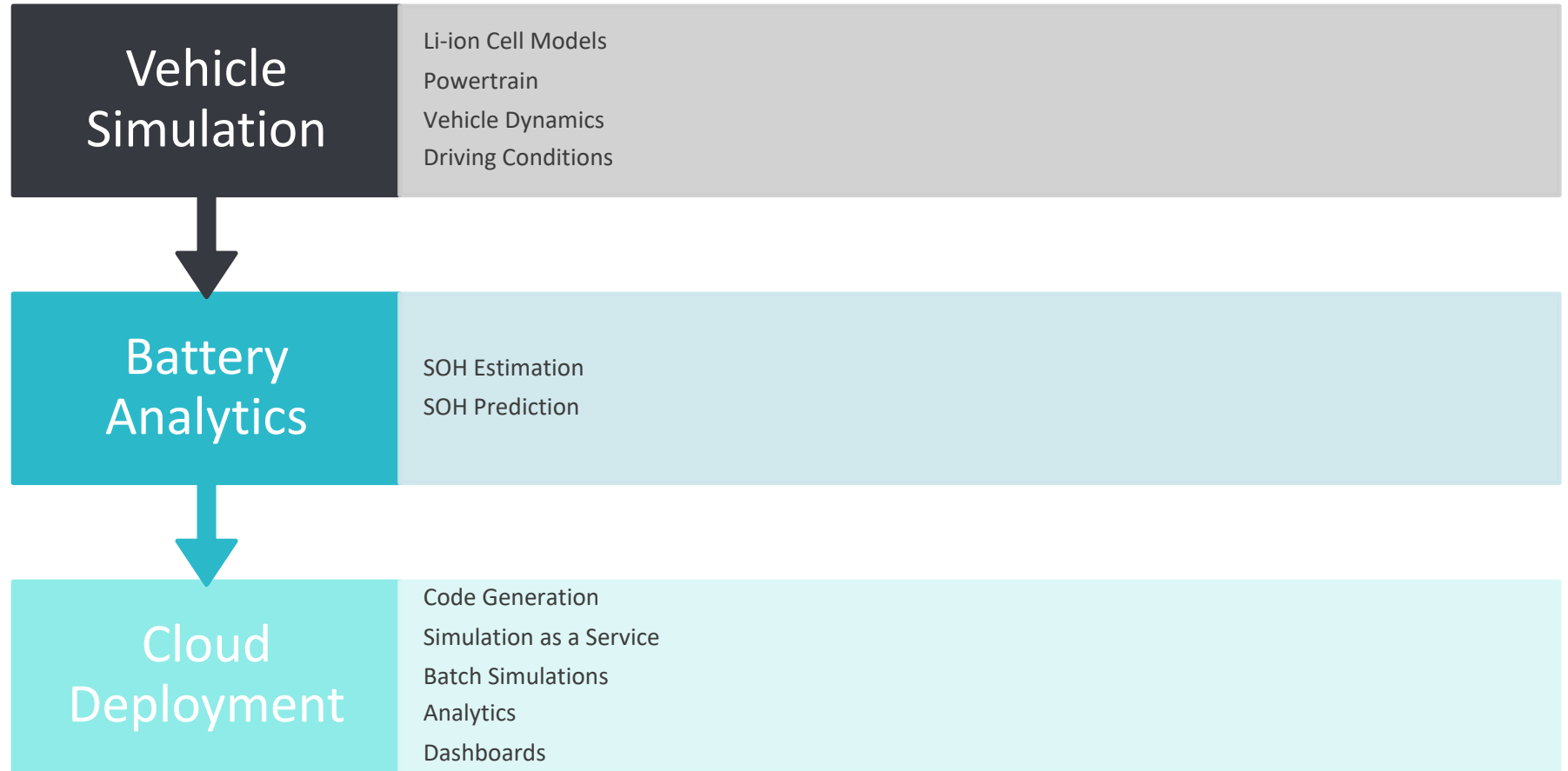
- In the product design phase, battery data is available only under laboratory and limited driving conditions
 - No existing fleet
 - Limited in-vehicle data collection
 - Data for only specific driving conditions
- However, to build an analytics stack focused on monitoring battery SOH and predicting battery life, we need lots of data

Solution: Scalable simulation-based data generation deployed in the cloud

Cloud-based Architecture

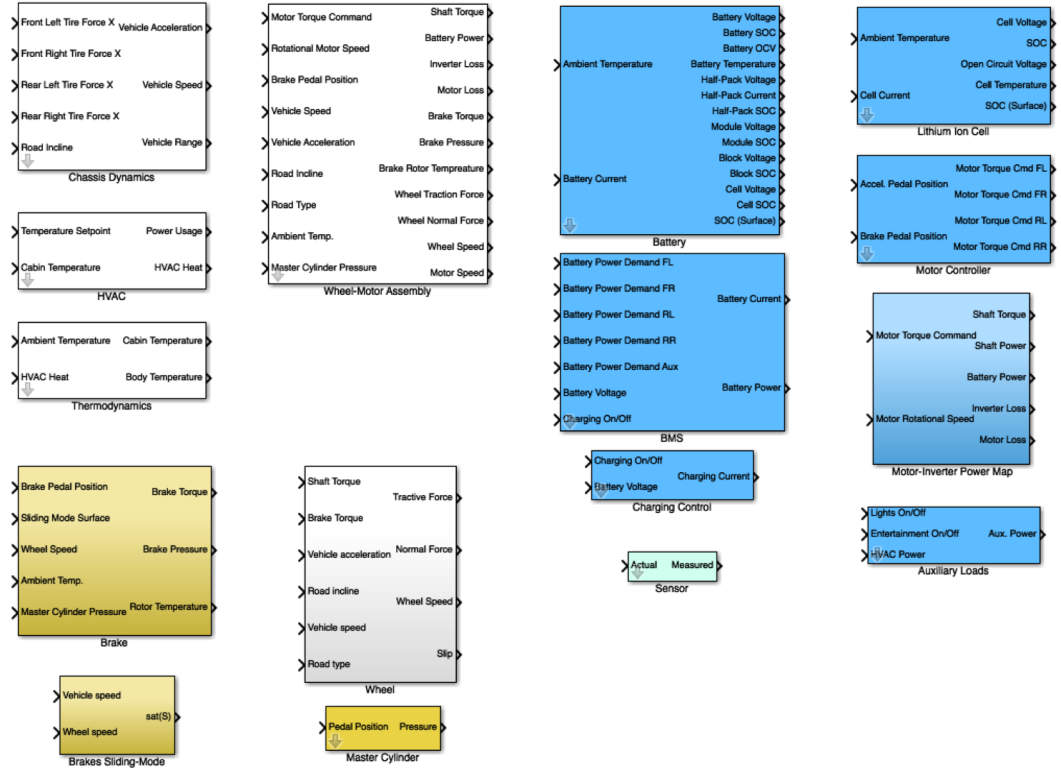


Outline

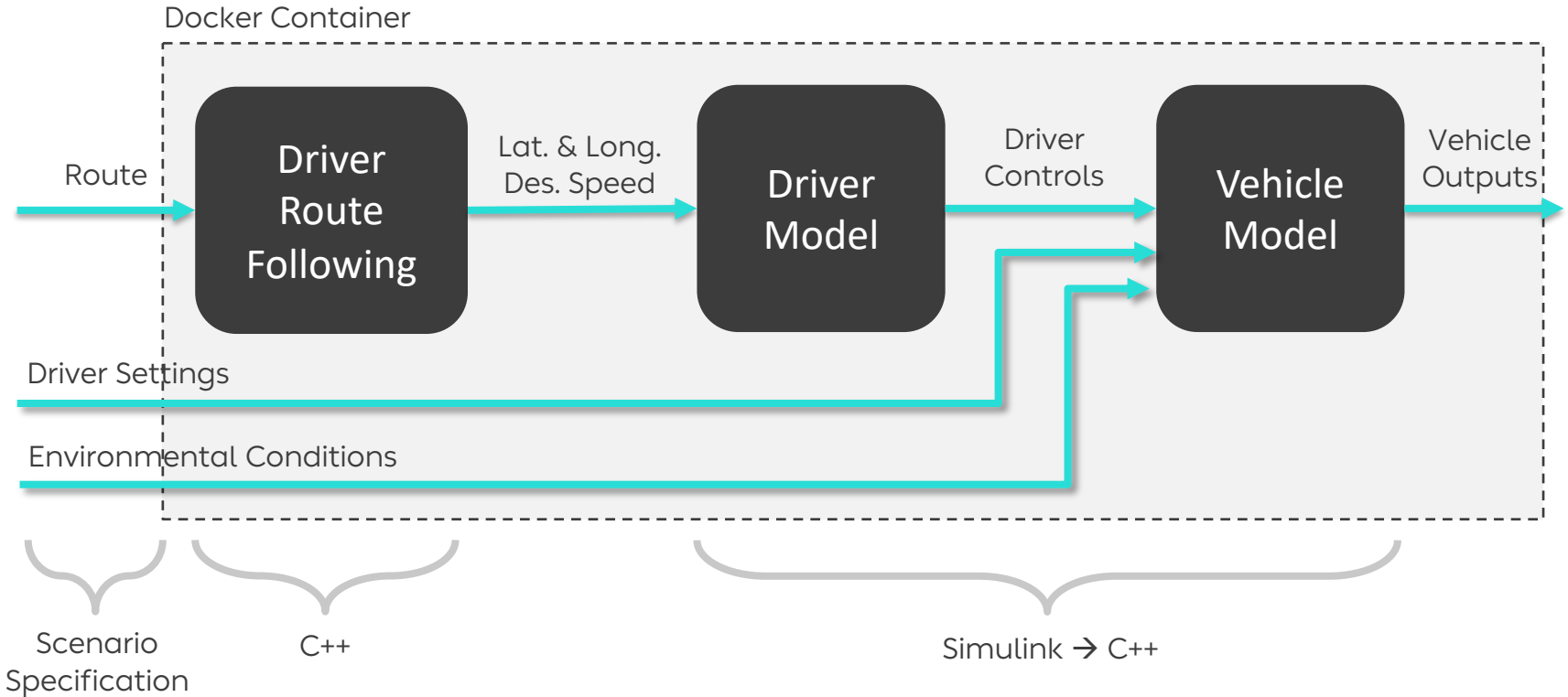


Vehicle Simulation Summary

- Electrical
 - Cell models and battery configuration
 - Cell/battery health degradation
 - Motor and inverter efficiency and losses
 - Torque/current limits
 - Regenerative braking
 - Charging
 - HVAC
 - Thermal management
- Mechanical
 - Drag
 - Road type
 - Brakes
 - Driver model
- Sensors
 - Speed, brake pressures, voltages, currents, etc.
- Fault injection via parameter changes

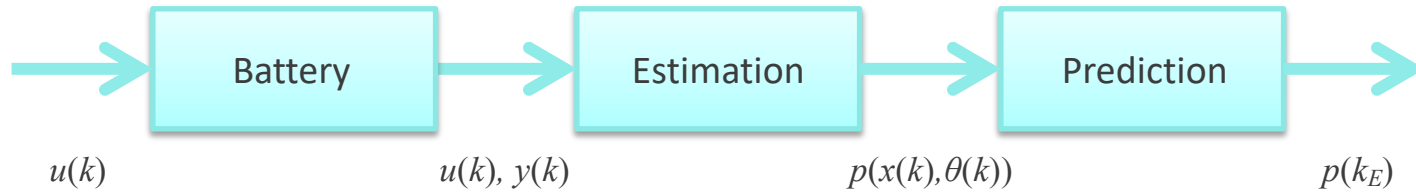


Simulation Architecture



Battery Analytics

Prognostics Architecture



System gets input and produces output

Estimation module estimates the states and parameters, given system inputs and outputs

- Must handle sensor noise
- Must handle process noise

For some event E, e.g., end-of-discharge or end-of-life, prediction module predicts k_E

- Must handle state-parameter uncertainty at time of prediction
- Must handle future process noise trajectories
- Must handle future input trajectories (battery loads)

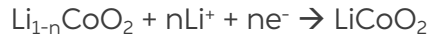
In model-based approaches, require a dynamic model of the battery

Lithium Ion Chemistry

Discharge

Positive electrode is cathode, negative electrode is anode

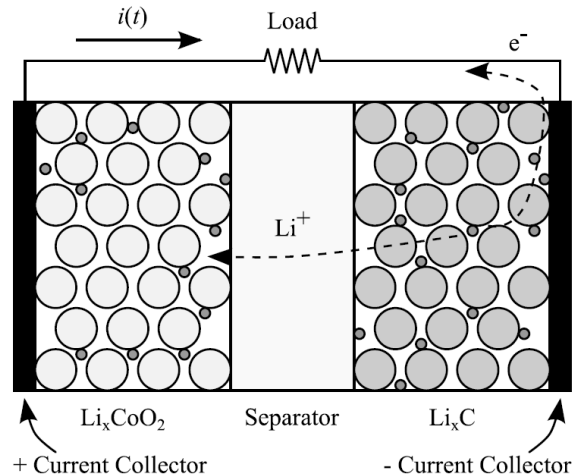
Reduction at pos. electrode:



Oxidation at neg. electrode:



Current flows + to -, electrons flow - to +, lithium ions flow - to +



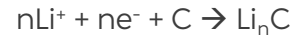
Charge

Positive electrode is anode, negative electrode is cathode

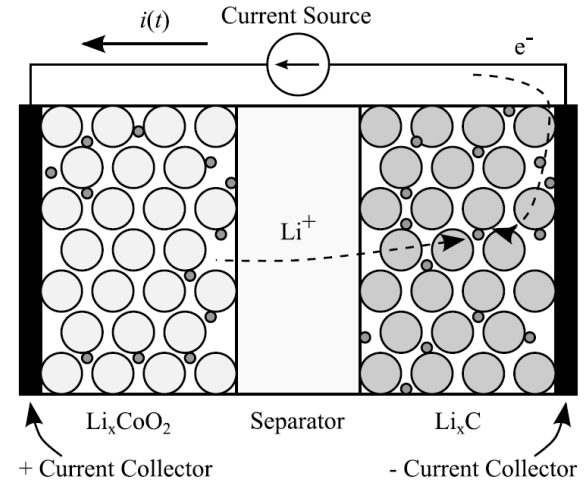
Oxidation at pos. electrode:



Reduction at neg. electrode:

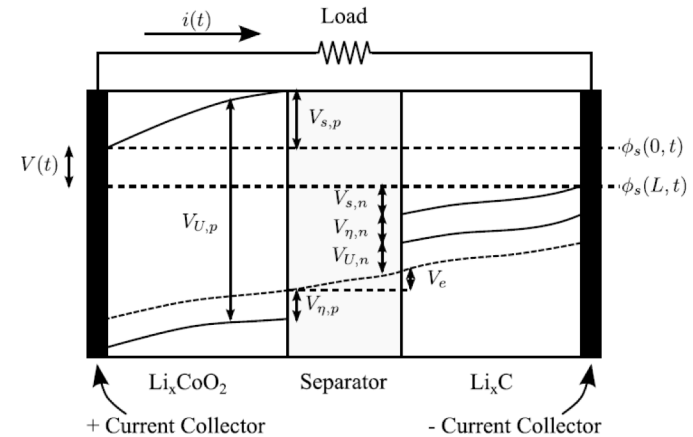


Current flows - to +, electrons flow + to -, lithium ions flow + to -



Cell Discharge Modeling

- Lumped-parameter, ordinary differential equations
- Capture voltage contributions from different sources
 - Equilibrium potential \rightarrow Nernst equation with Redlich-Kister expansion
 - Concentration overpotential \rightarrow split electrodes into surface and bulk control volumes
 - Surface overpotential \rightarrow Butler-Volmer equation applied at surface layers
 - Ohmic overpotential \rightarrow Constant lumped resistance accounting for current collector resistances, electrolyte resistance, solid-phase ohmic resistances



Battery Aging Modeling

Aging results in two major qualitative effects on dynamics:

- Loss of capacity (due to diffusion stress, irreversible parasitic side reactions)
- Increase in internal resistance (due to solid electrolyte interface layer growth)

Capture with changes in three age-related parameters:

- q_{\max} (max available charge)
- R_o (Ohmic resistance)
- D (diffusion rate parameter)

Given a discharge cycle, can estimate age-related parameters and determine how they change over time

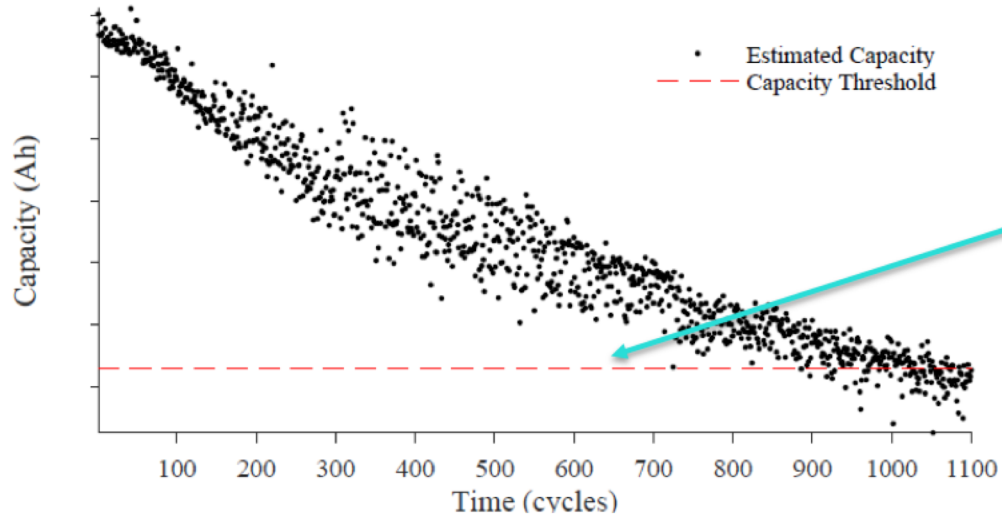
- Assume rate of change of age parameters is of form $w \cdot |i_{\text{applied}}|$
- w is aging rate parameter, i_{applied} is applied current

Models developed and validated in MATLAB

Defining EOL

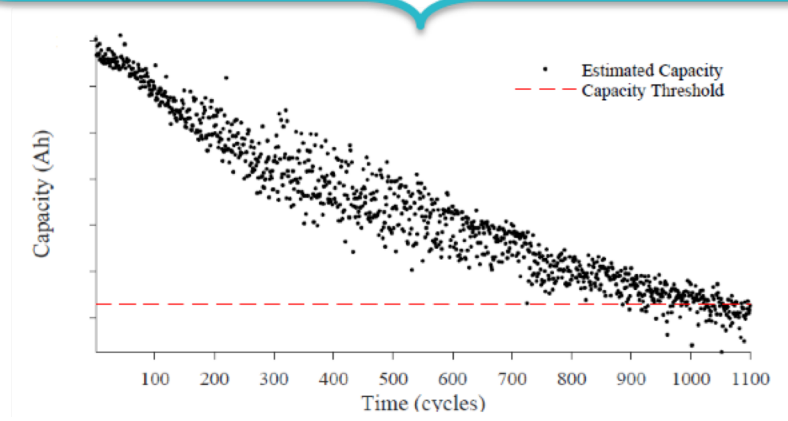
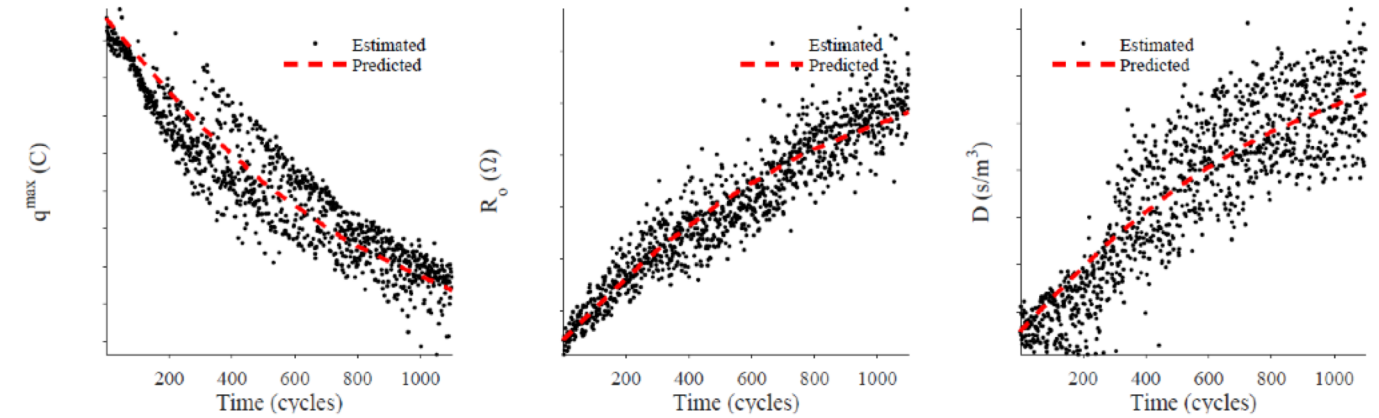
Capacity is measured in Ah for a given discharge cycle

- But, EOD is dependent on the load, so capacity measurement will be different depending on how battery is used
- Only meaningful to measure capacity w/r/t reference conditions
- For given age parameters, can use model to simulate a reference discharge and compute corresponding capacity



EOL defined as 50% capacity as measured at reference conditions.

State of Health Estimation



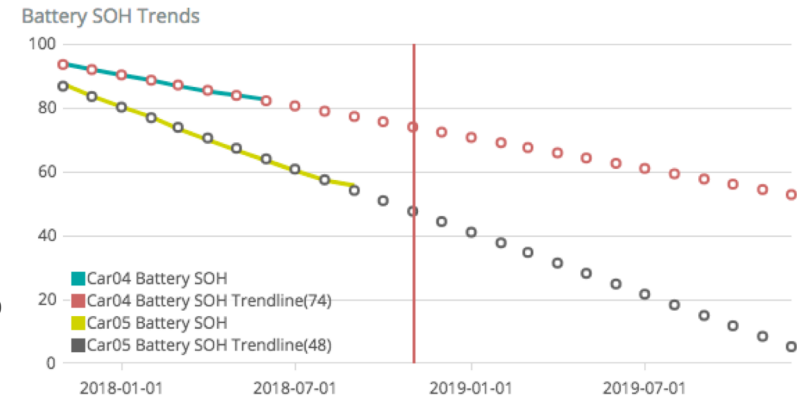
Battery Analytics

Health Estimation

- For each trip, take pack voltage, current, and temperature
- Estimate battery state of charge (SOC) using unscented Kalman filter (UKF)
- Estimate current values of aging parameters over the trip
- Map aging parameters to current battery capacity/state of health (SOH)

State of Health Prediction

- Obtain SOH estimates for all previous trips
- Determine expected future battery loads
- Fit aging model (e.g., linear regression)
- Predict time/miles at which SOH will fall below 80%

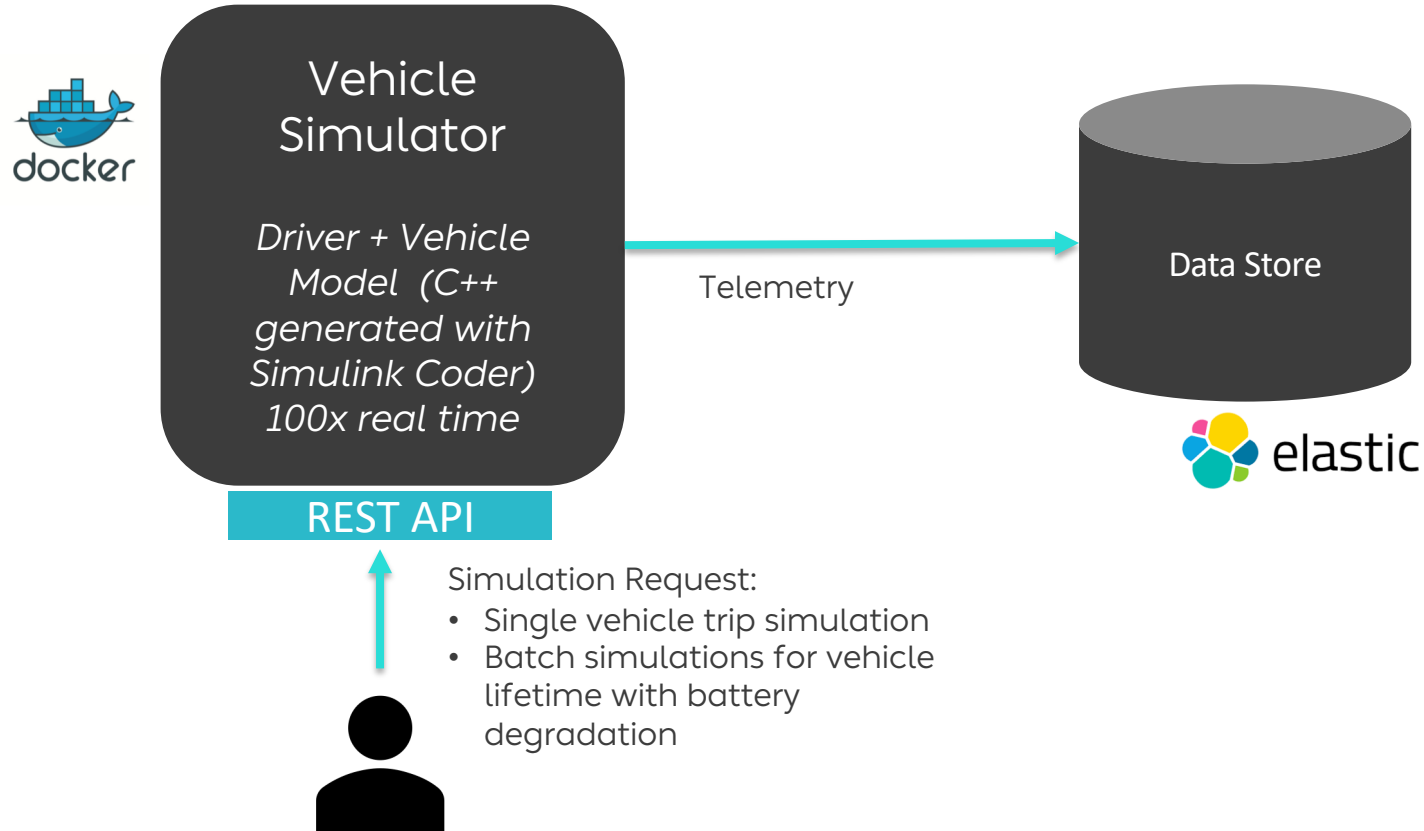


Other Metrics

- Powertrain efficiency, trip energy regenerated, etc.

Cloud Deployment

Simulation Deployment



Battery Analytics Deployment

- Algorithms are implemented in Python
 - For each vehicle
 - Queries data for a trip from Elasticsearch
 - Runs analytics algorithms on the trip data
 - Pushes results back to Elasticsearch
 - Results include time-based analytics (e.g., state-of-charge) and trip summary metrics (e.g., SOH)
- Implemented as a batch job that is Dockerized

Battery Pack

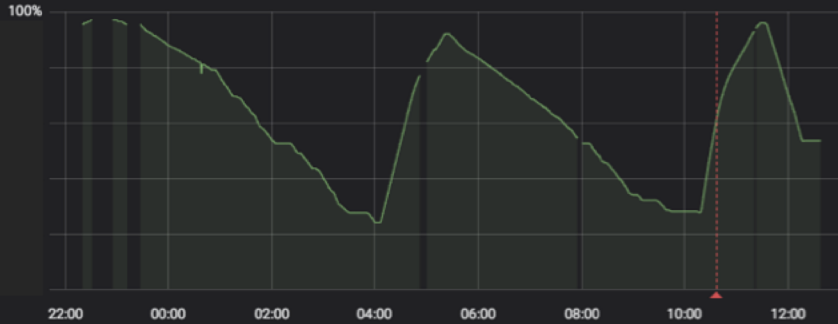
BMS Pack Voltage



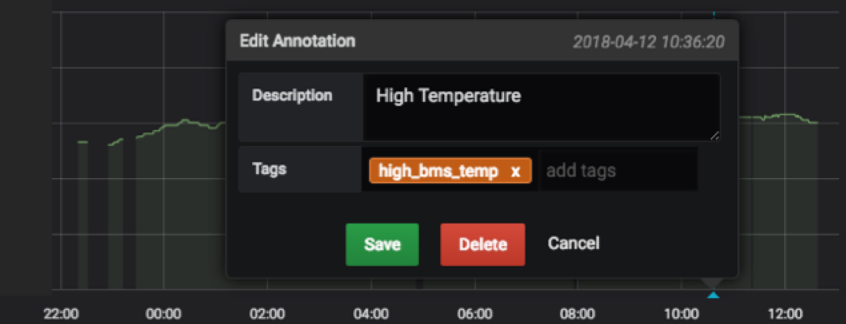
BMS Pack Current



BMS Pack SOC



BMS Pack Average Temperature



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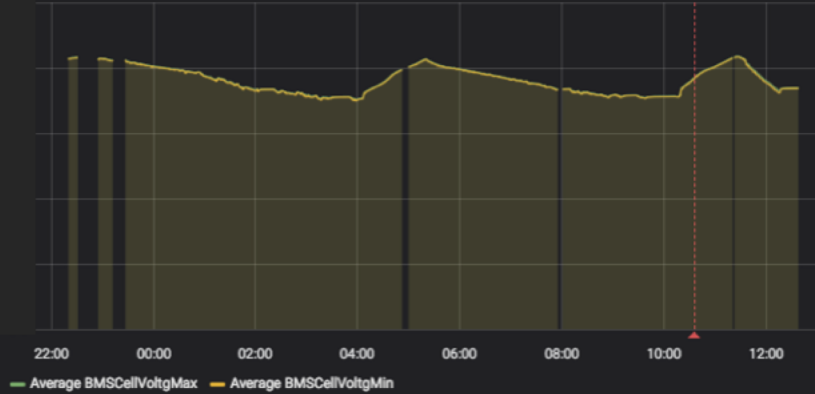
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Tags high_bms_temp x add tags

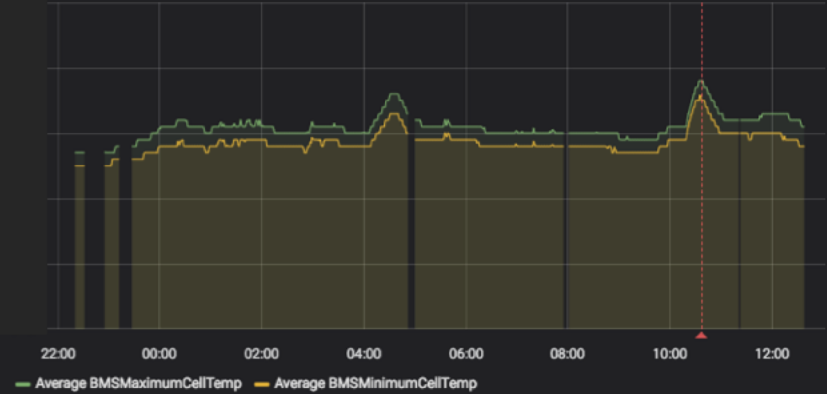
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Cells & Subsystems

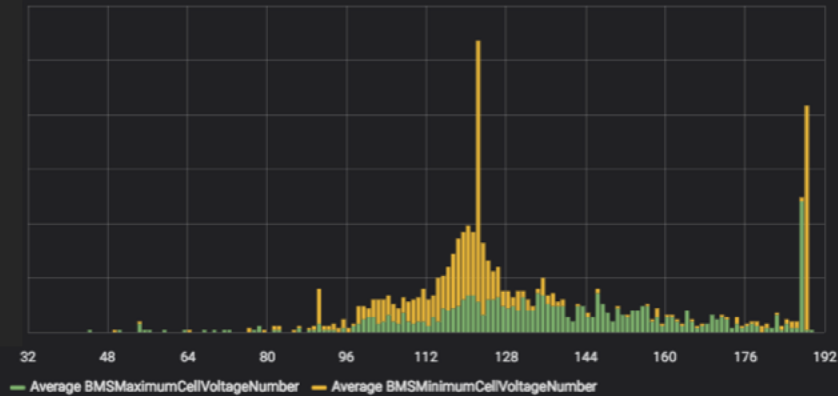
Cell Voltage Min & Max



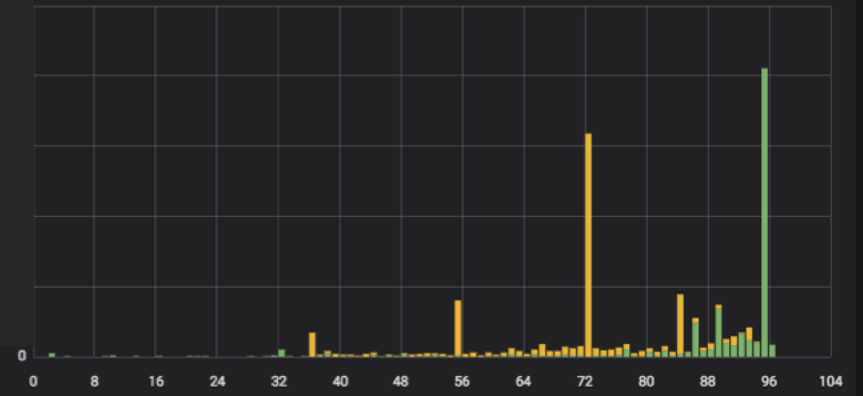
Cell Temperature Min & Max



Min/Max Cell Voltage Number Histogram



Min/Max Temperature Number Histogram



Conclusions

Summary

- Simulations executed on request basis or in batch mode
- Dashboards combining vehicle- and fleet-level metrics built from Elasticsearch data source
- Automated pipelines running on test vehicles
- Deployment to production in progress

Next Steps

- Scalability
- Validation with customer data
- Connection to service operations