Battery Sizing and Design for Electric Vehicles

Mike Sasena

Automotive Product Manager

msasena@mathworks.com

Danielle Chu

Simscape Product Manager

dchu@mathworks.com

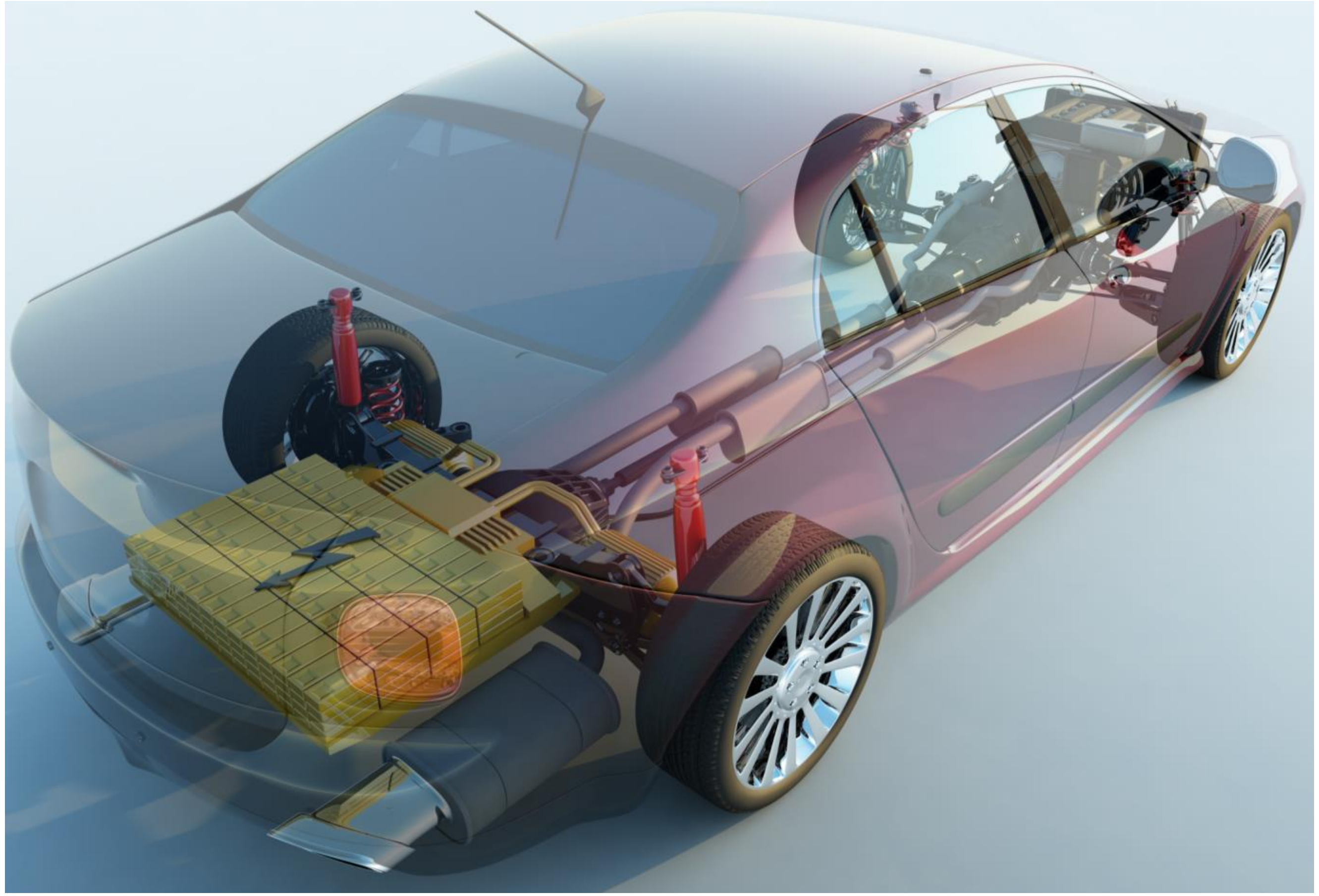
Key Takeaways

- Problem description
  – You can use an EV model to optimize battery pack size, then design the battery system and validate its performance

- Role of MathWorks tools
  – **Powertrain Blockset** offers system-level models to quantify trade-offs in battery performance, efficiency and cost
  – **Global Optimization Toolbox** and **Simulink Design Optimization** efficiently optimize the design while accounting for competing requirements
  – **Simscape Battery** can be used to perform detailed battery design studies
  – These **products are complementary** parts of the overall workflow

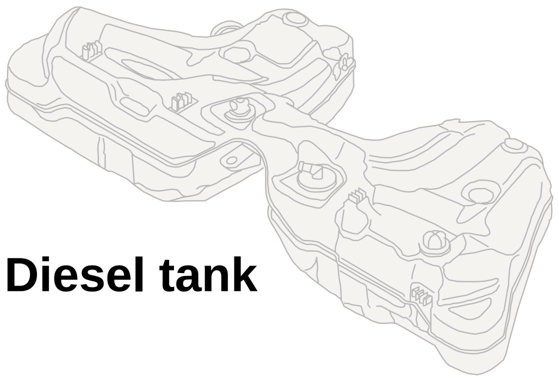
Agenda

- Context
- Vehicle model
- Battery sizing
- Battery design
- Summary



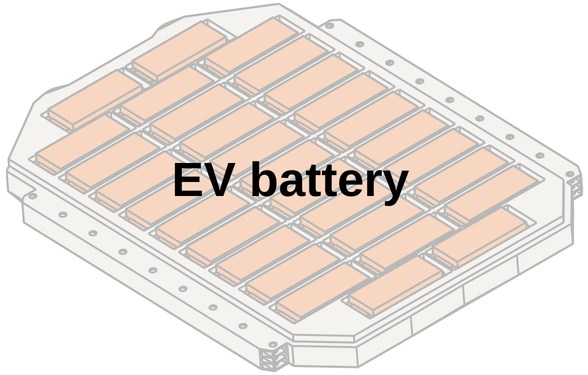
Automotive Powertrains Are Increasingly Electric

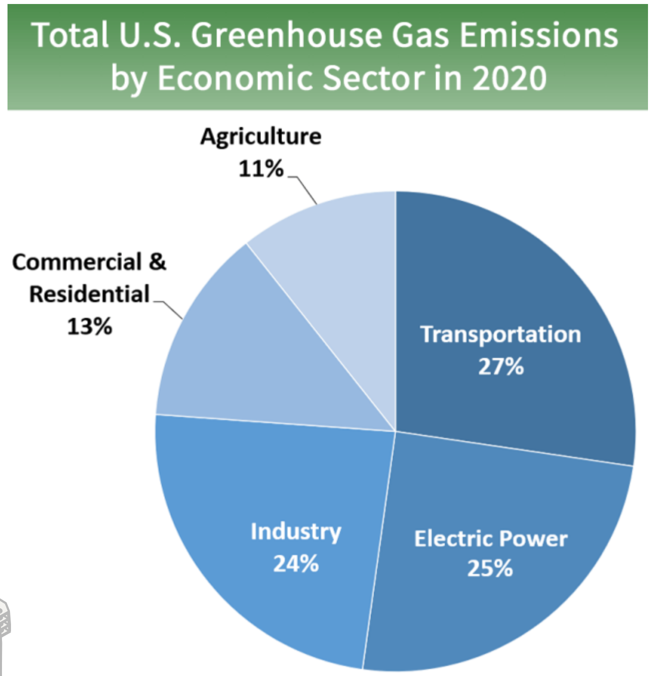
- The automotive sector is focused on reducing CO_2 emissions
- Battery Electric Vehicles (BEV’s) are a promising option
  - Localizes CO_2 emissions to energy production source
  - Can be charged from renewable energy
- But engineering challenges remain…



Diesel tank

700 kWh	95 kWh
95 kg	700 kg
85 L	430 L

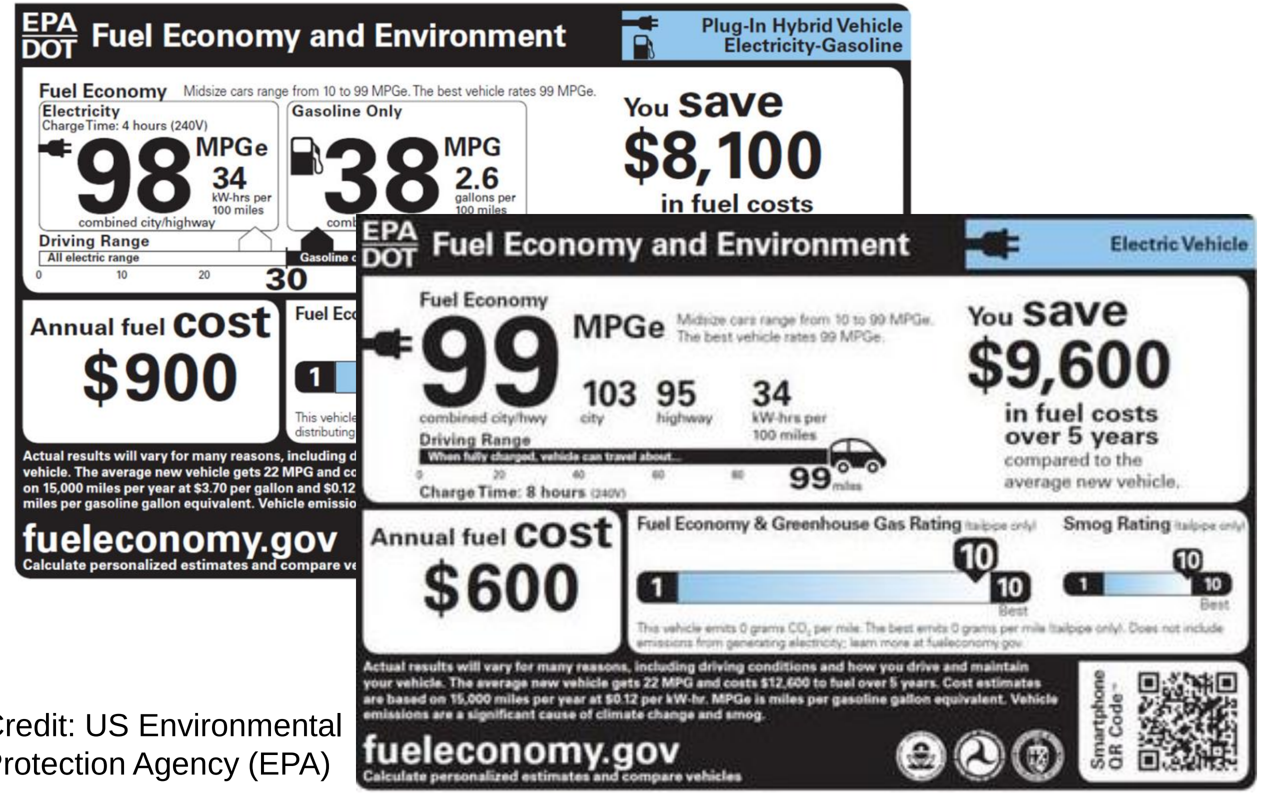




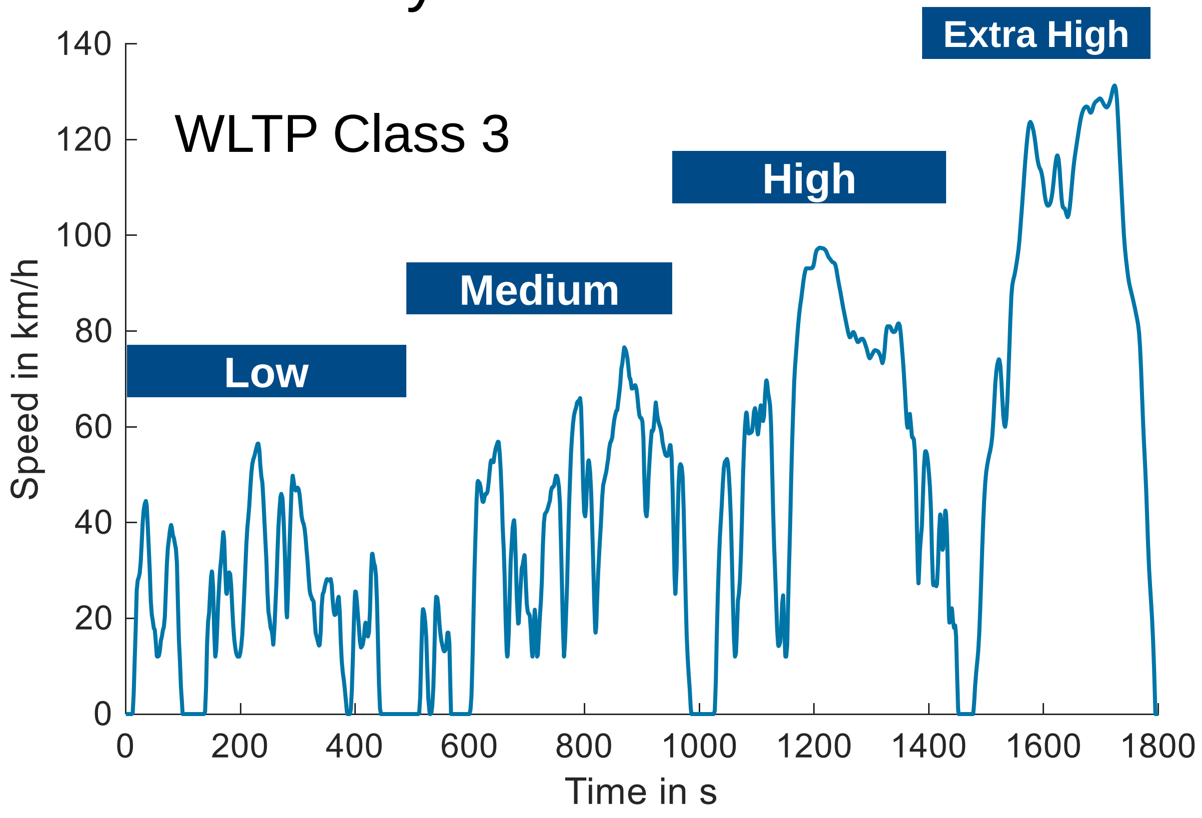
Credit: EPA.gov

Vehicle-Level Targets

- Government agencies rate conventional, HEV and EV’s using different standardized tests (US city / highway cycle, WLTP, etc.)
- Different metrics to define energy efficiency (MPGe, Wh/km, etc.)
- Vehicle program sets targets → requirements for subsystem teams



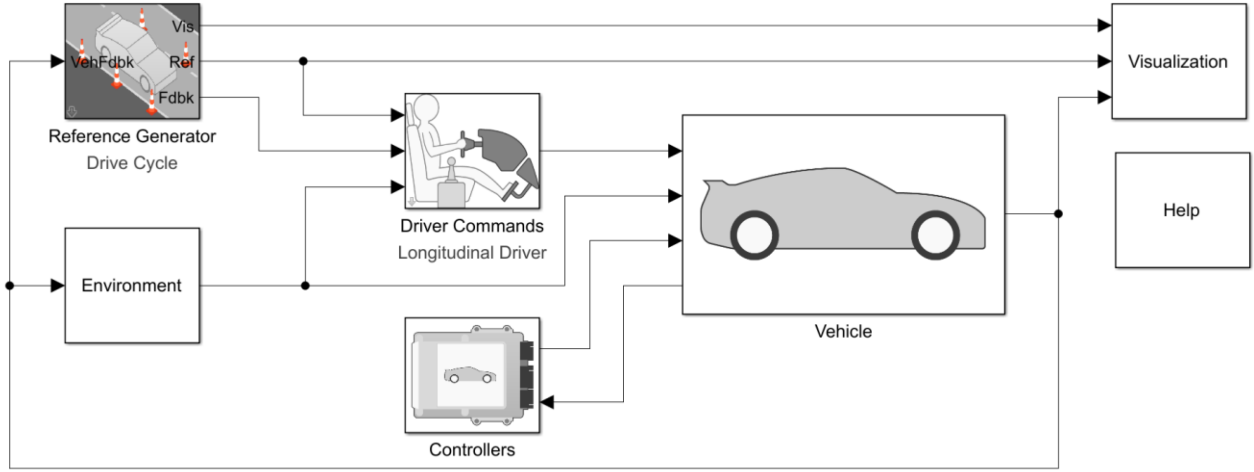
Credit: US Environmental Protection Agency (EPA)



[**W**orld harmonized **L**ight-duty vehicles **T**est **P**rocedure]

Use System-Level Models to Assess System-Level Targets

Target	How to evaluate
Fuel economy	Perform drive cycle test
Range	Perform drive cycle test
Acceleration	Perform Wide Open Throttle (WOT) test
Cost	Assume $ / kWh



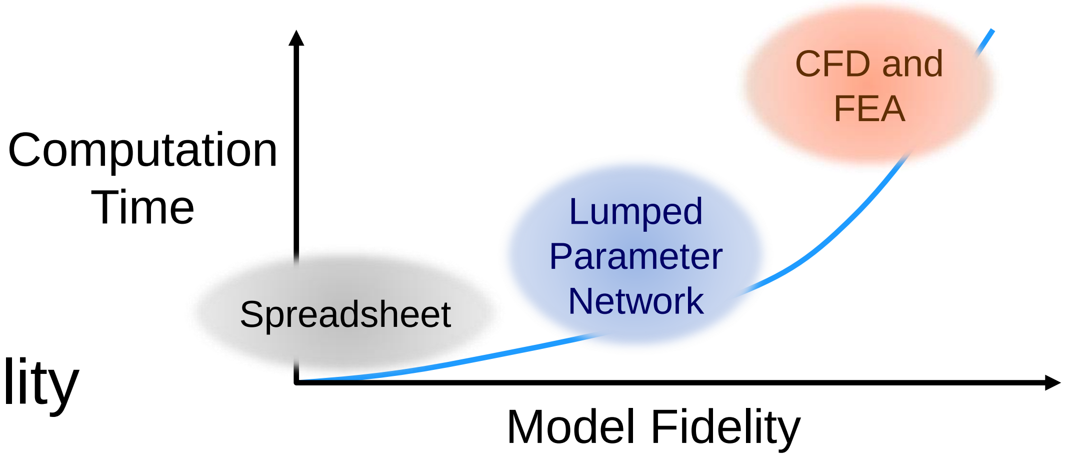
Simulations used to frontload design / save money

Credit: 4x4 Dynamometer by Adam Navrotny / CC BY-SA 3.0

Right-Level Modeling

- We can answer system-level questions using system-level models, but what level of fidelity is appropriate for the task?

- Initial estimates use simplifying assumptions
  – Fast running 1D models
  – Neglect thermal / spatial effects
  – Simplified controls

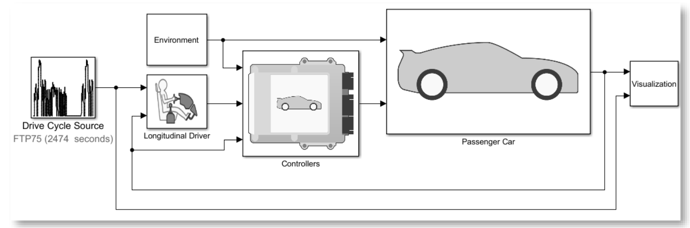


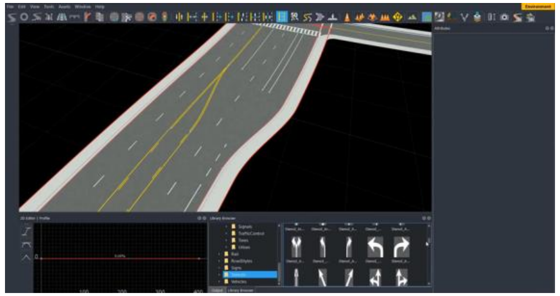
- Design-oriented tasks require higher fidelity
  – Slower running multidomain models
  – Include thermal / spatial effects
  – Production-oriented controls

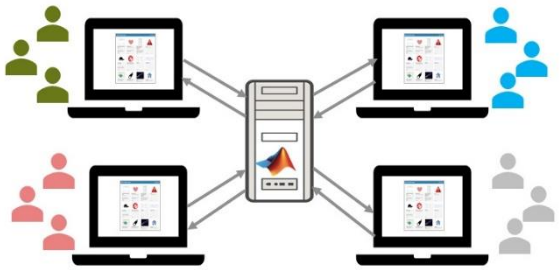
MathWorks Offering for Virtual Vehicle Simulation

Engineering Tools + Application Expertise

Create Vehicle	Integrate Software	Author Scenarios	Simulate & Analyze	Deploy Simulation
Vehicle Templates Subsystem Libraries Modeling Guidelines	C/C++ Interface Reduced Order Models FMU Integration	Scene & Scenarios Open Standards Drive Cycles	Visualization Data Analysis Report Generation	Cloud Integration Datalake Integration HIL Deployment







Value proposition:

- Proven tools for modeling of physics and software
- Reference applications for reduced time-to-simulation
- Common platform for model reuse
- Solutions for large-scale modeling and simulation
- Flexible platform for growth / new use cases

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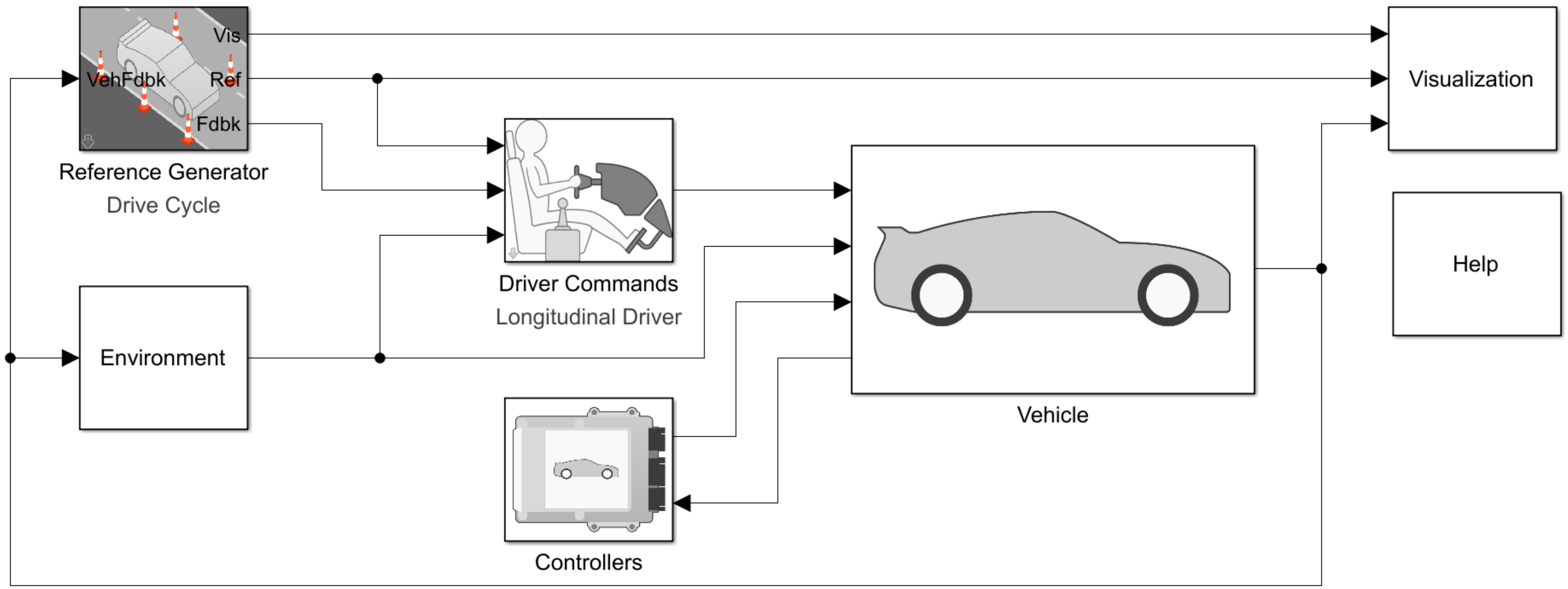
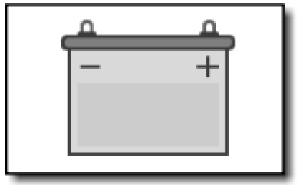
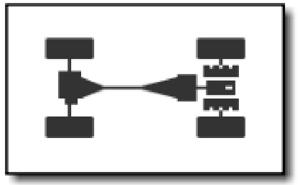
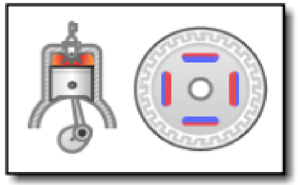


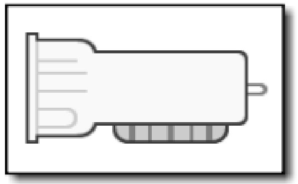
Powertrain Blockset

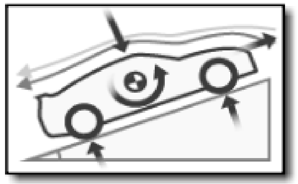
Library of blocks

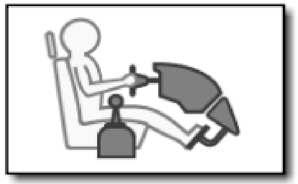

Energy Storage and Auxiliary Drive


Drivetrain

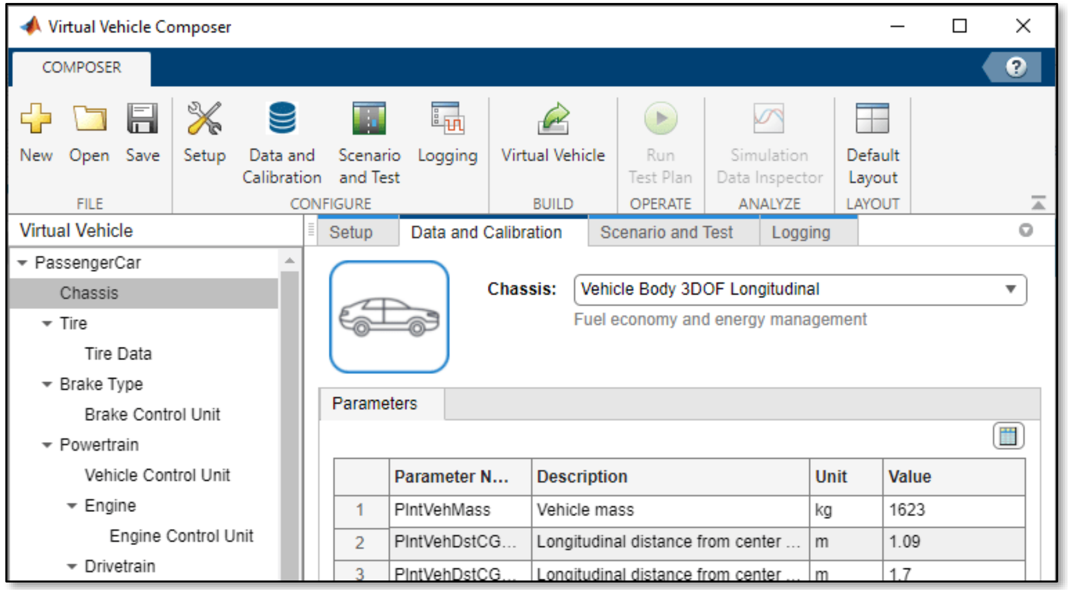

Propulsion


Transmission

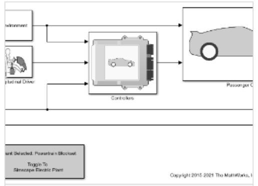

Vehicle Dynamics


Vehicle Scenario Builder

Virtual Vehicle Composer app

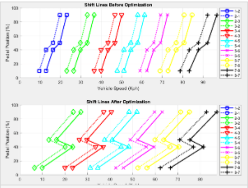


Pre-built reference applications



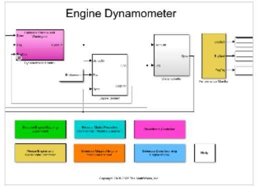
EV Reference Application

Simulate an EV model with a motor-generator, battery, direct-drive transmission, and associated powertrain control algorithms.



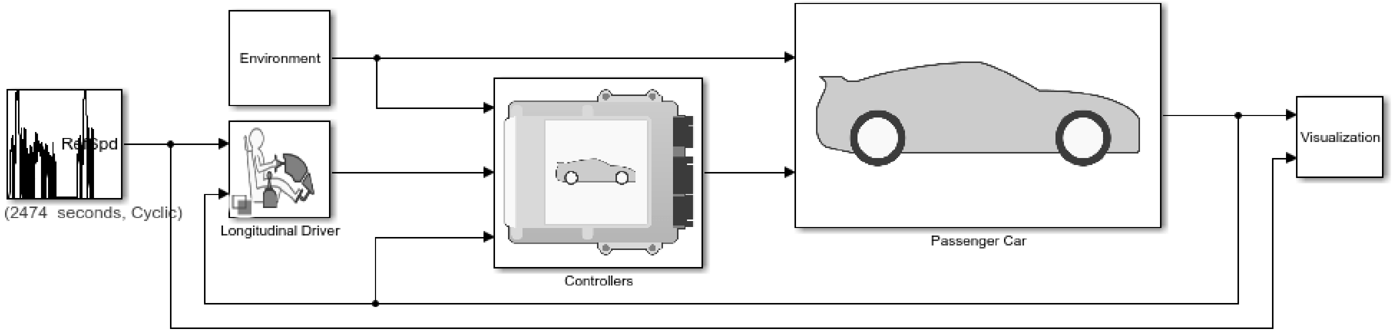
Optimize Transmission Control Module Shift Schedules

Use the conventional vehicle reference application to optimize the transmission control module (TCM) shift schedules.



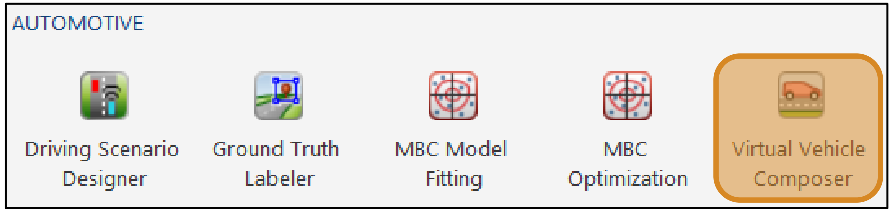
SI Engine Dynamometer Reference Application

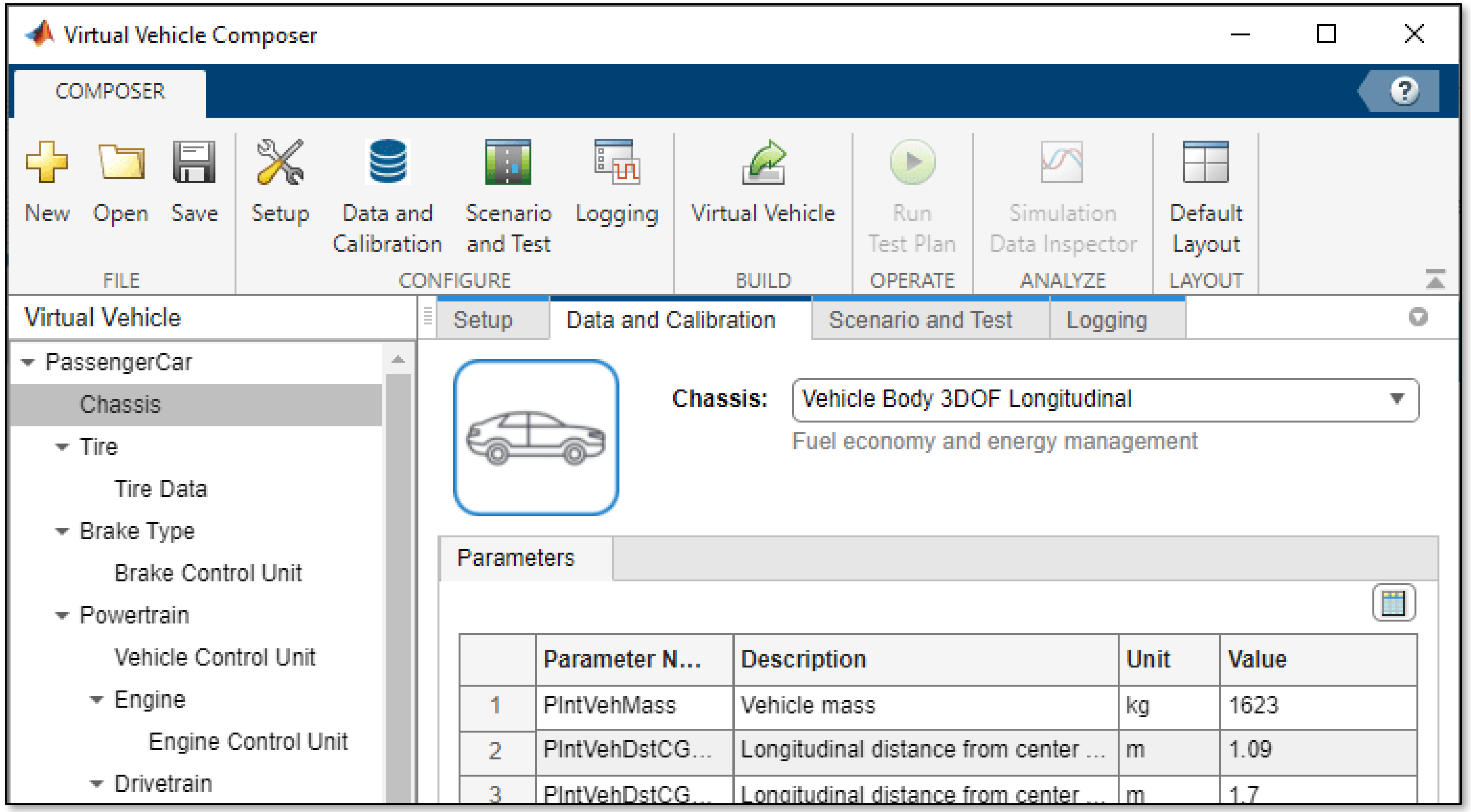
Simulate a SI engine plant and controller connected to a dynamometer with a tailpipe emission analyzer.



Virtual Vehicle Composer App

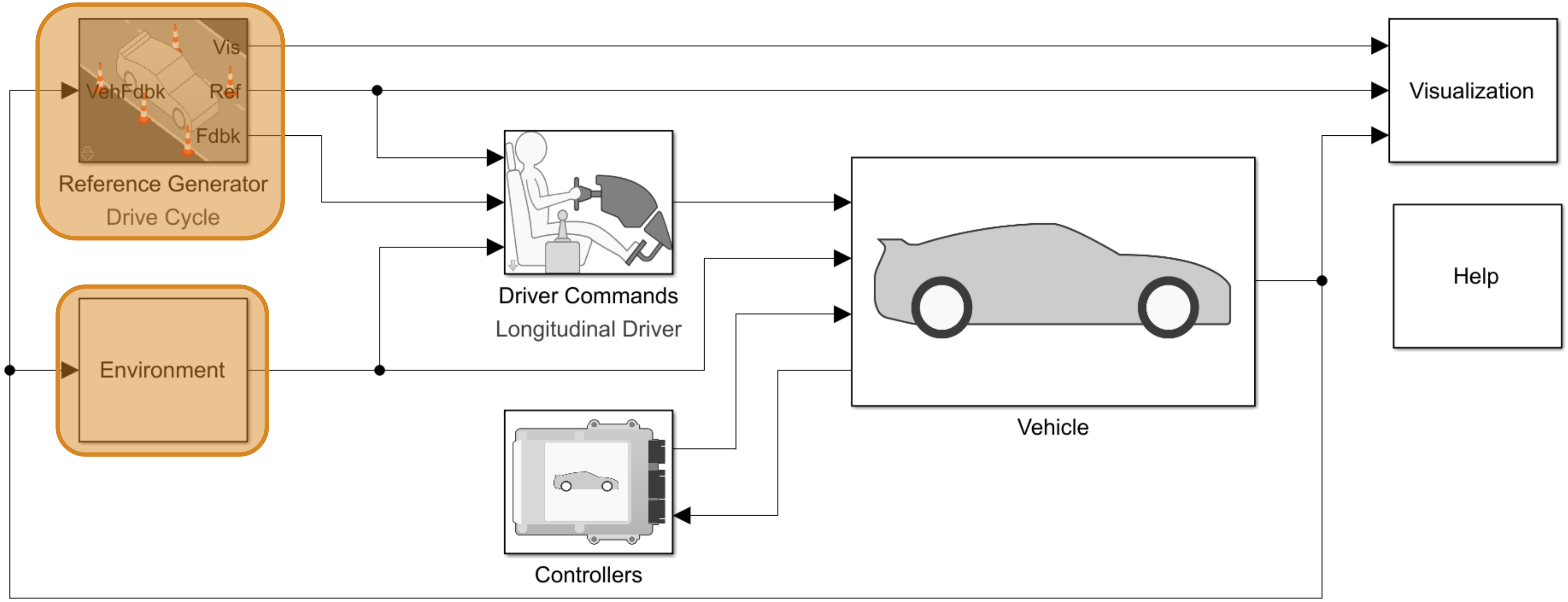
- Unified interface to quickly configure a virtual vehicle, select test cases, and review results
- Available with **Powertrain Blockset** and / or **Vehicle Dynamics Blockset**
- Includes options for detailed powertrain models, vehicle dynamics and controls
- Generated models are customizable





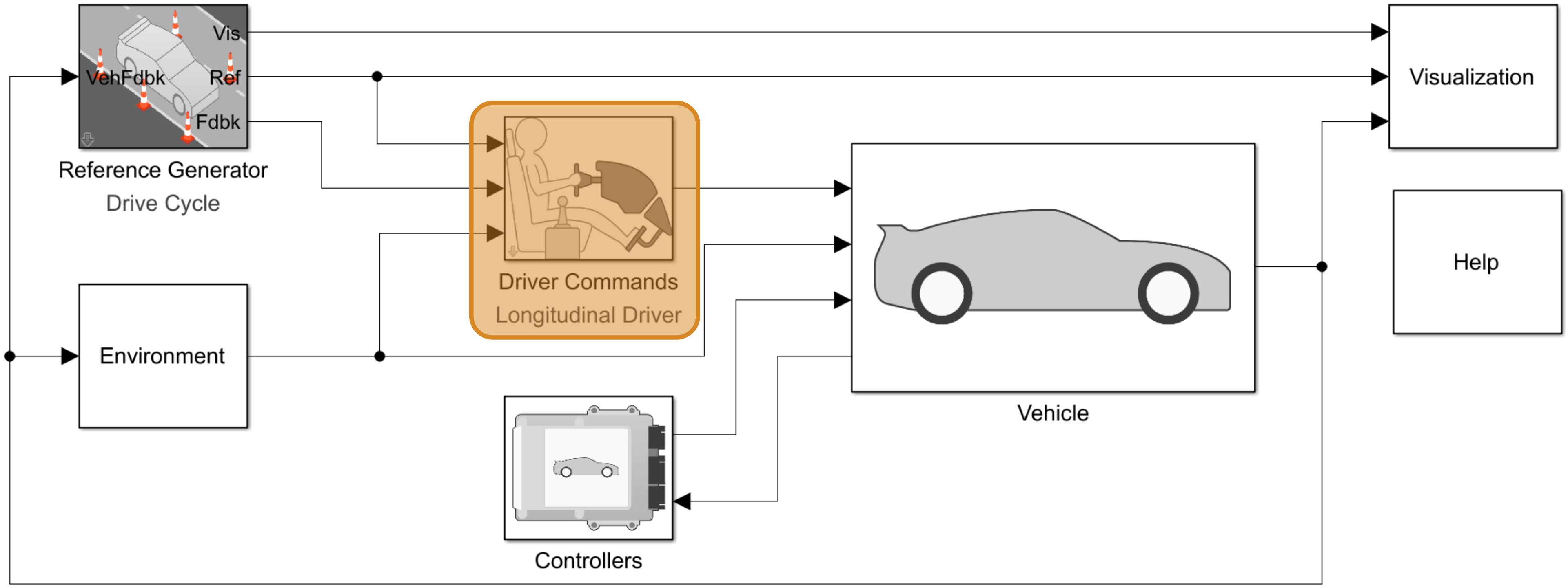
EV Model

1. Set target speed and ambient conditions



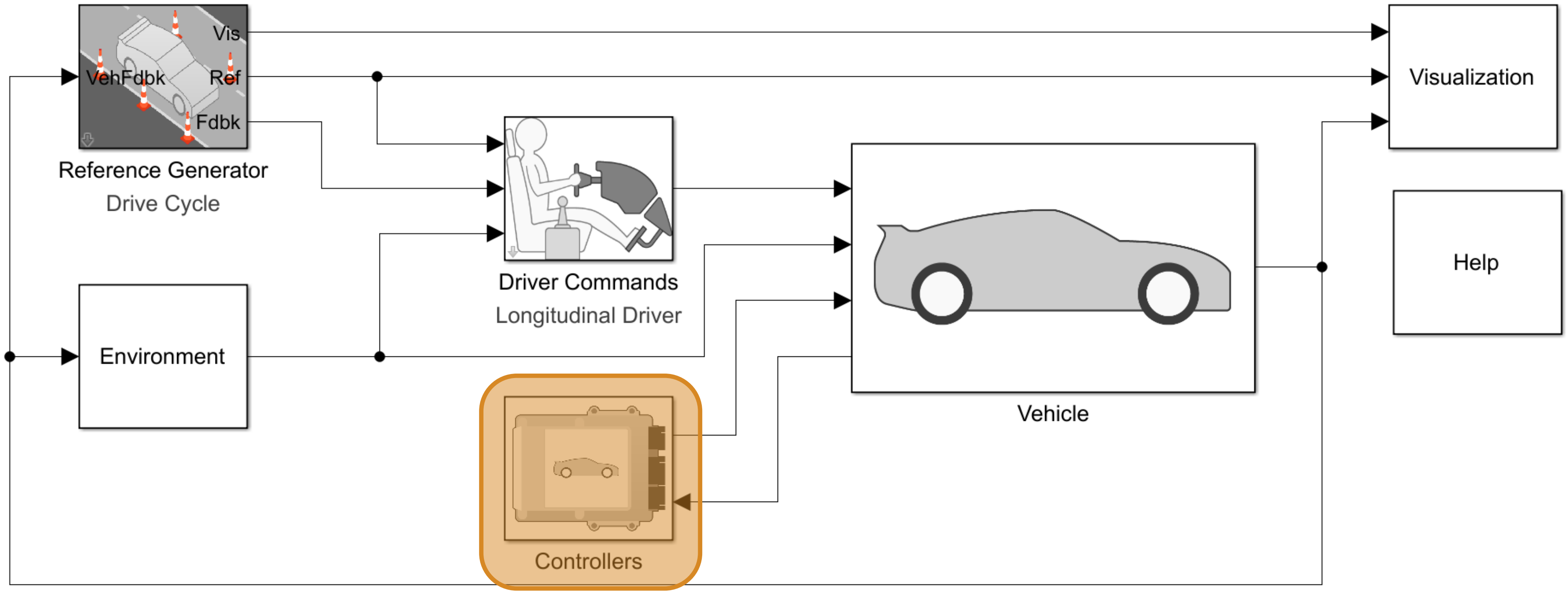
EV Model

1. Set target speed and ambient conditions
2. Set brake, accel, shift commands to achieve target speed



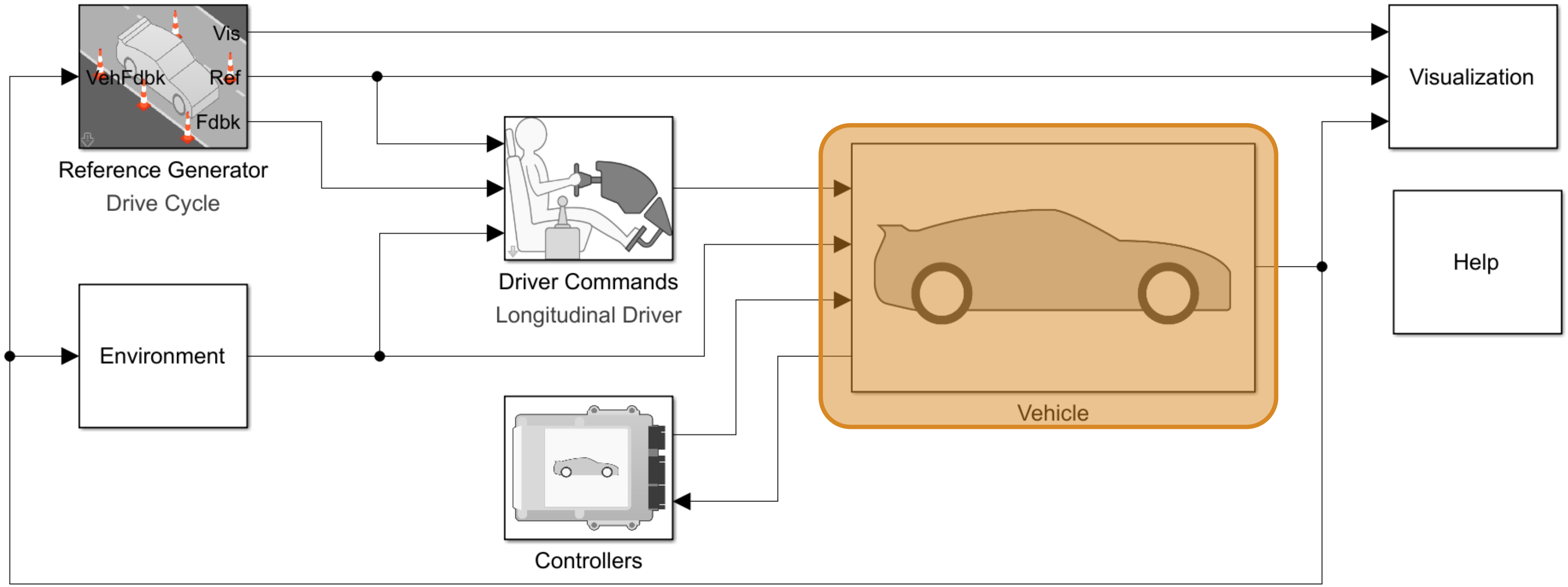
EV Model

1. Set target speed and ambient conditions
2. Set brake, accel, shift commands to achieve target speed
3. Set lower-level control commands (e.g., motor torque)



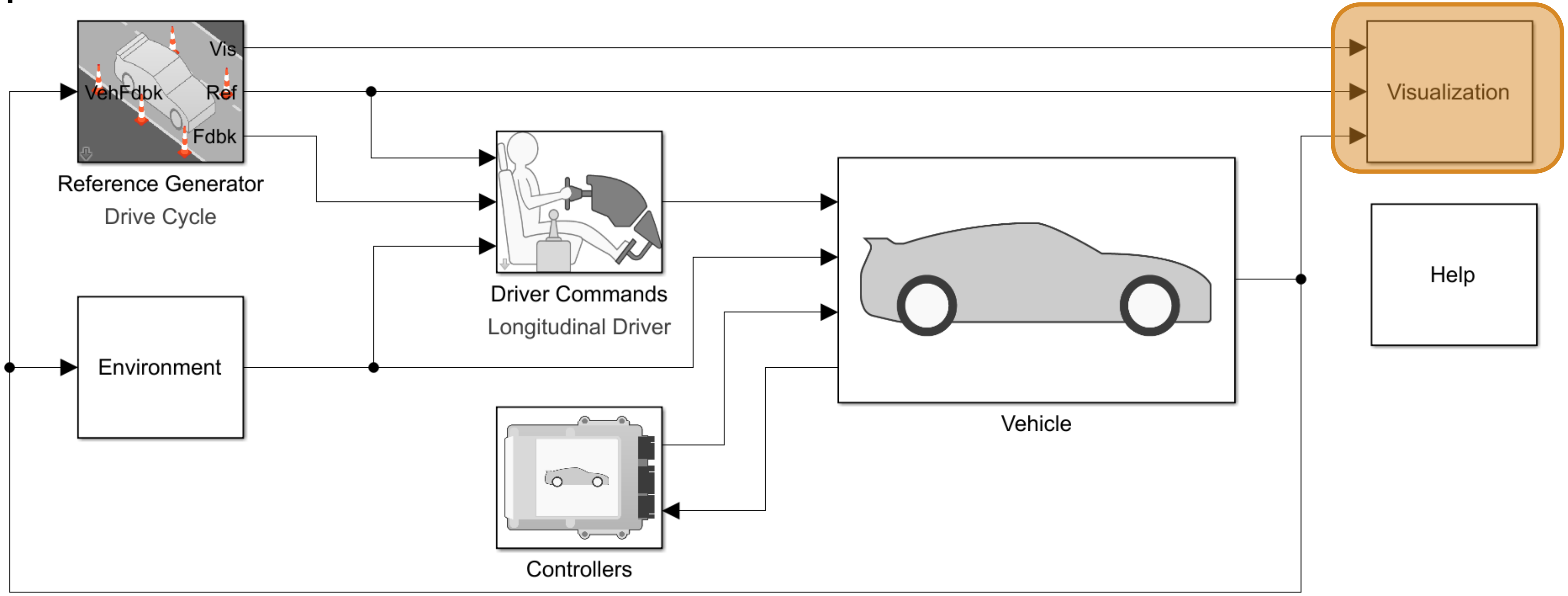
EV Model

1. Set target speed and ambient conditions
2. Set brake, accel, shift commands to achieve target speed
3. Set lower-level control commands (e.g., motor torque)
4. Calculate vehicle response



EV Model

1. Set target speed and ambient conditions
2. Set brake, accel, shift commands to achieve target speed
3. Set lower-level control commands (e.g., motor torque)
4. Calculate vehicle response
5. Report results



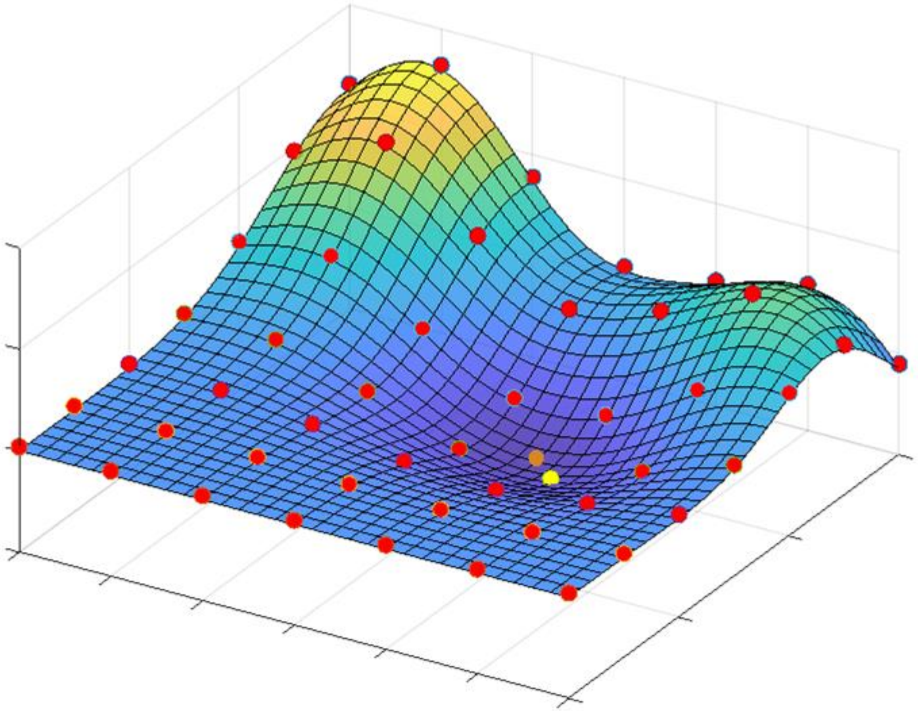
Summary: Vehicle Model

- Key takeaways
  - Virtual Vehicle Composer app can quickly configure a closed-loop EV model
  - Generated model can be customized for your application
- Next step
  - Perform optimization study to identify battery size that meets requirements

Agenda

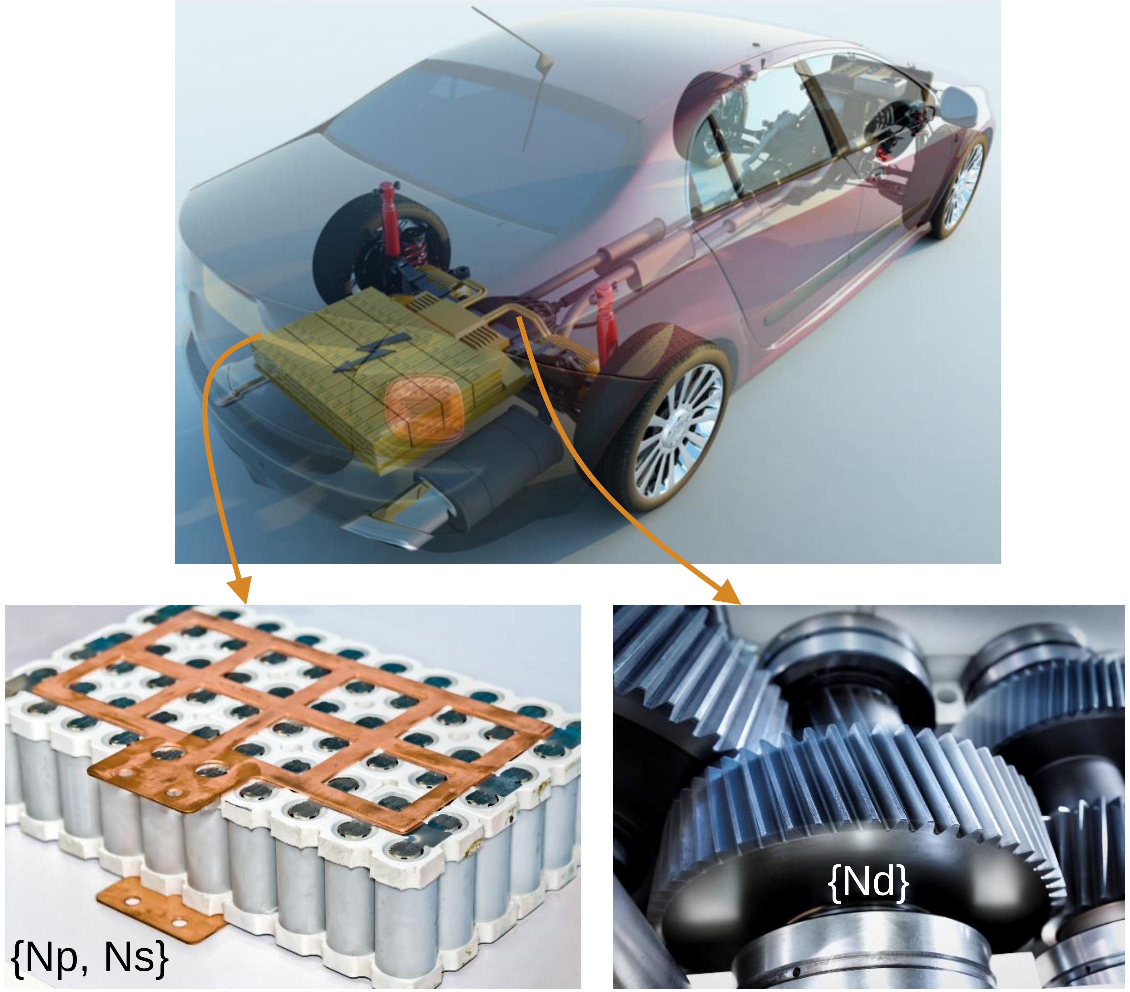
- Context
- Vehicle model
- Battery sizing
- Battery design
- Summary

Assess → Optimize → Design → Validate



Component Sizing Problem Statement

- Objective:
  - Design a BEV that provides a good range at a reasonable price
- Constraints:
  - Meets typical driving demands
  - Reasonable electric range
  - Reasonable acceleration
- Design Variables:
  - Number of battery cells in parallel (Np)
  - Number of battery cells in series (Ns)
  - Gearbox ratio (Nd)



Component Sizing Problem Statement

- Objective:

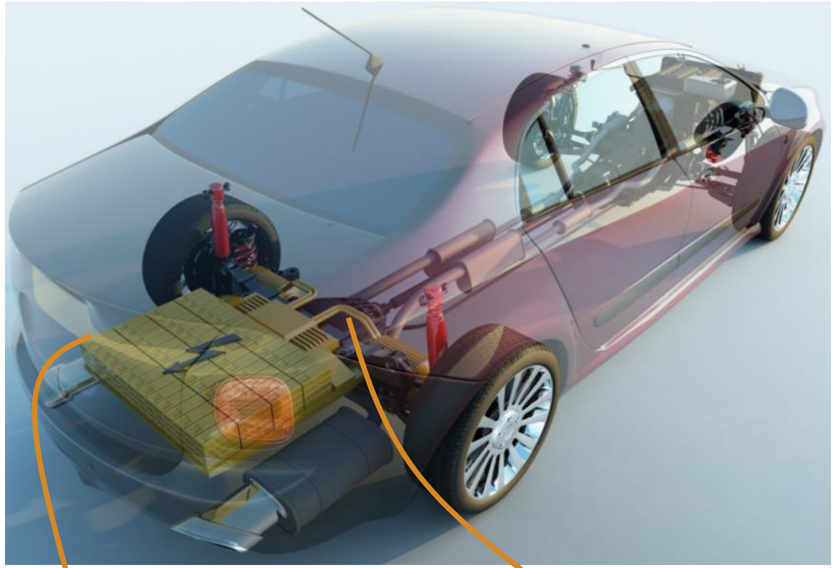
  min f(**x**) = w_1*Cost - w_2*Range

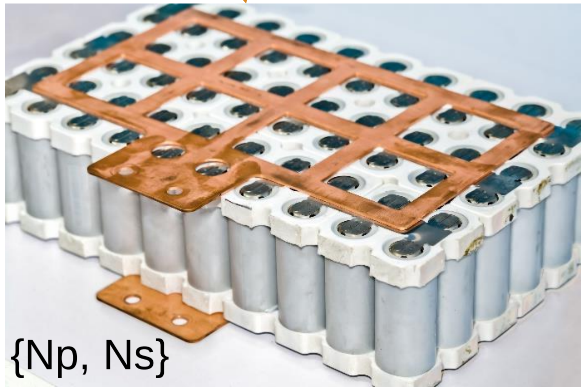
- Constraints:

  g_1: DriveCycleFault $\leq$ 0
  g_2: Range $\geq$ 400 km
  g_3: $t_{0\text{-}100\ kph} \leq 7$ s

- Design Variables:

  x_1: 10 < Np < 50 (Integer)
  x_2: 80 < Ns < 140 (Integer)
  x_3: 7 < Nd < 10 (Continuous)

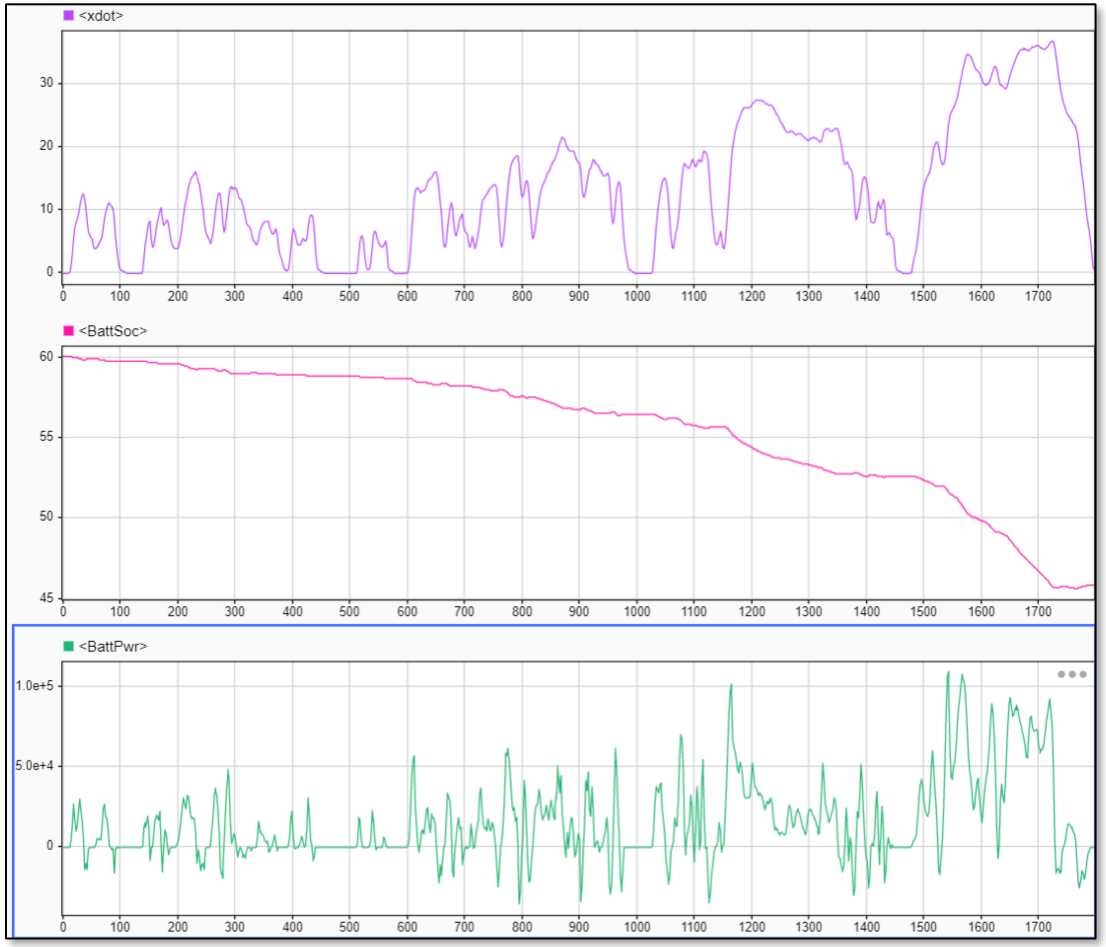




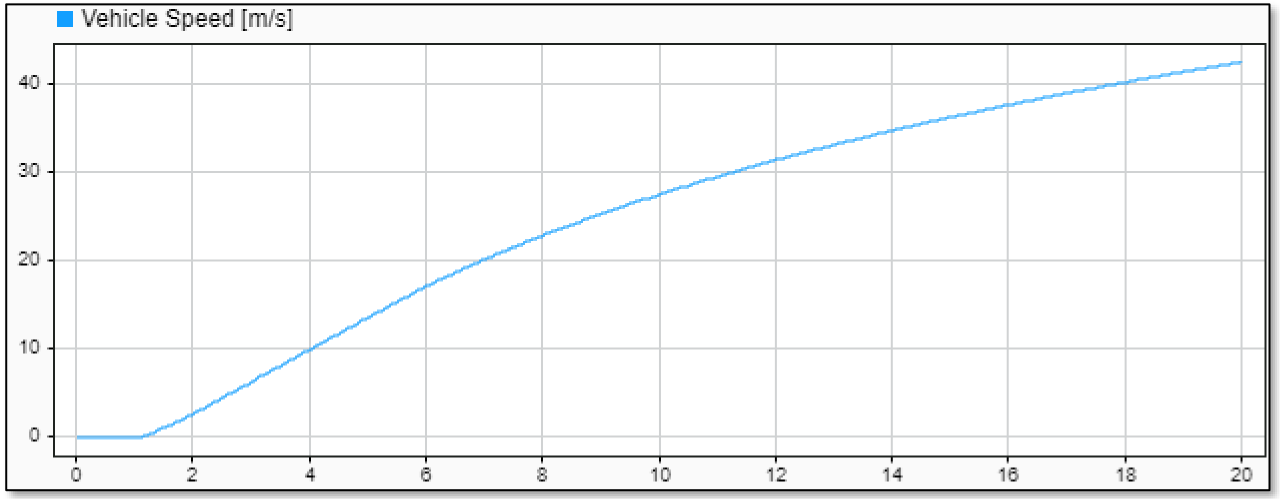
Initial Assessment

Default component sizes don't achieve system-level requirements. Time for a redesign!

Metric	Target	Results
Battery cost [$]	*min*	7537
Range [km]	≥ 400	371
$t_{0\text{-}100}$ [s]	≤ 7.0	6.8



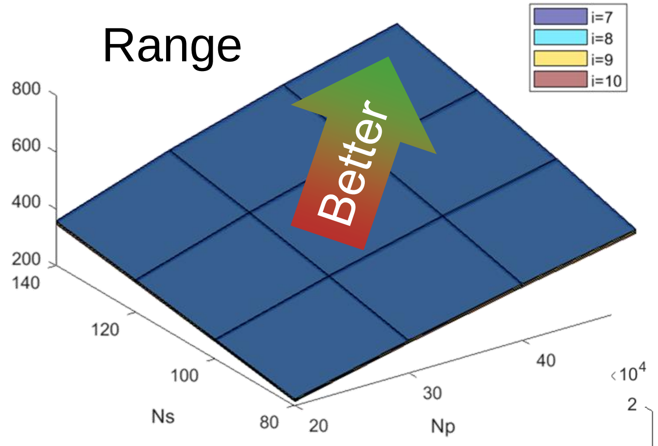
WLTP test

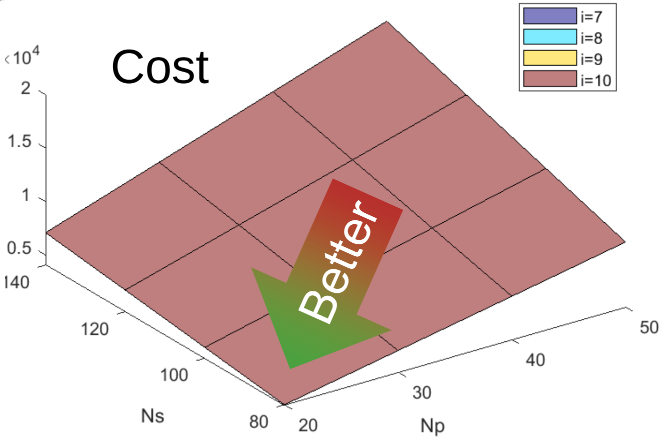


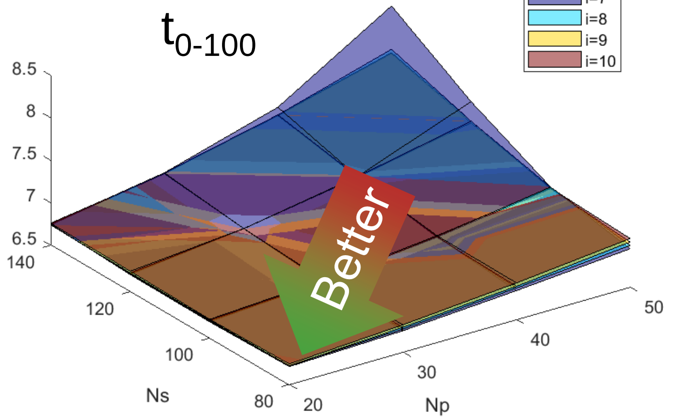
WOT test

Initial Assessment

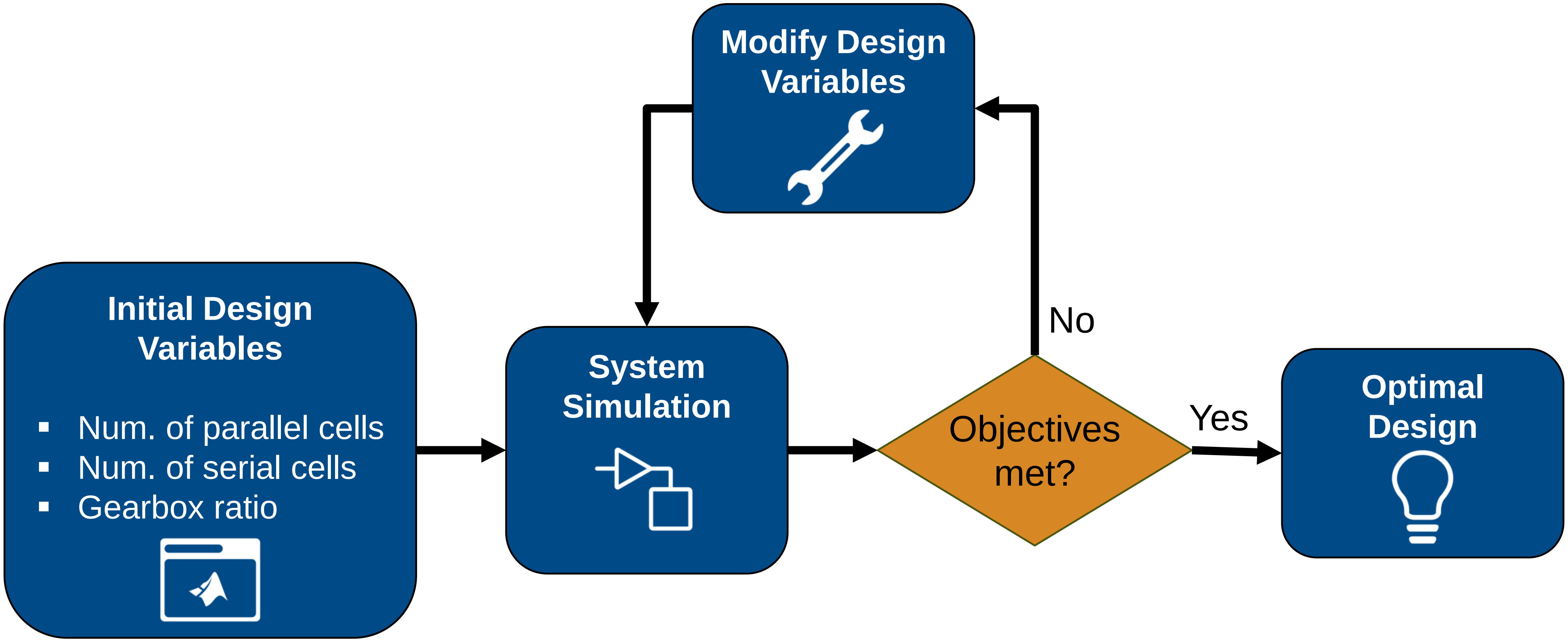
- Performed initial parametric study
  - Sweep of Np, Ns, and Nd
  - Study problem statement before launching long optimization study
- Lessons learned
  - Range helped by large pack with higher voltage (Ns) / lower losses (Np)
  - Cost scales linearly (as expected)
  - Battery pack size has nonlinear impact on performance







Optimization Workflow

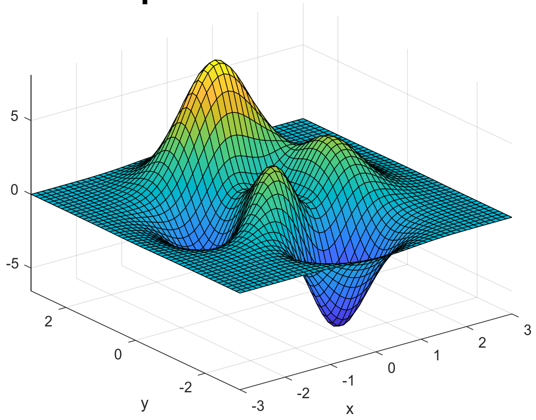


Selecting the Appropriate Optimization Solver

- MATLAB can indicate applicable optimization solvers
- Design variable space
  - Continuous
  - Integer (discrete)
  - Mixed Integer
- Local / global search space
  - Optimization Toolbox (local)
  - Global Optimization Toolbox

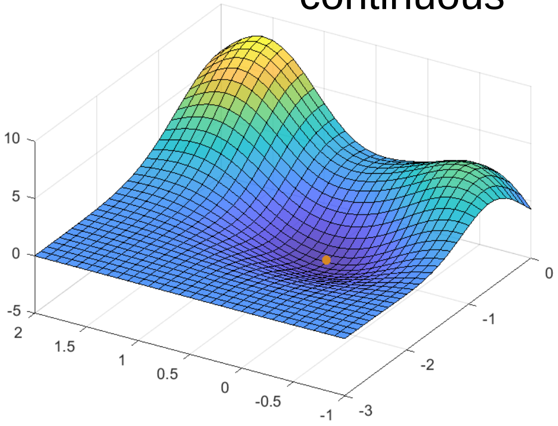
```
[autoSolver,allSolvers] = solvers(elecProb)

autoSolver = "fmincon"
 allSolvers = 1×6 string
    "fmincon"   "ga"        "patternse…  "surrogat…  "
```

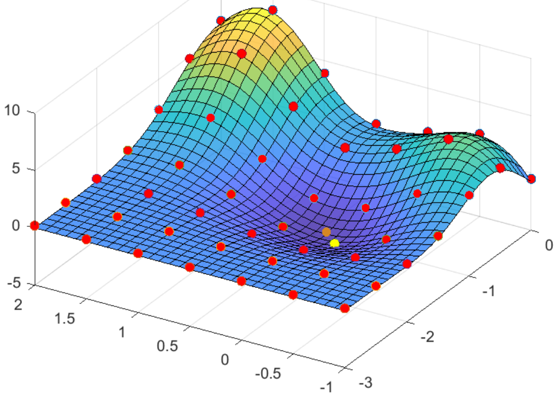


Objective with multiple minima

continuous



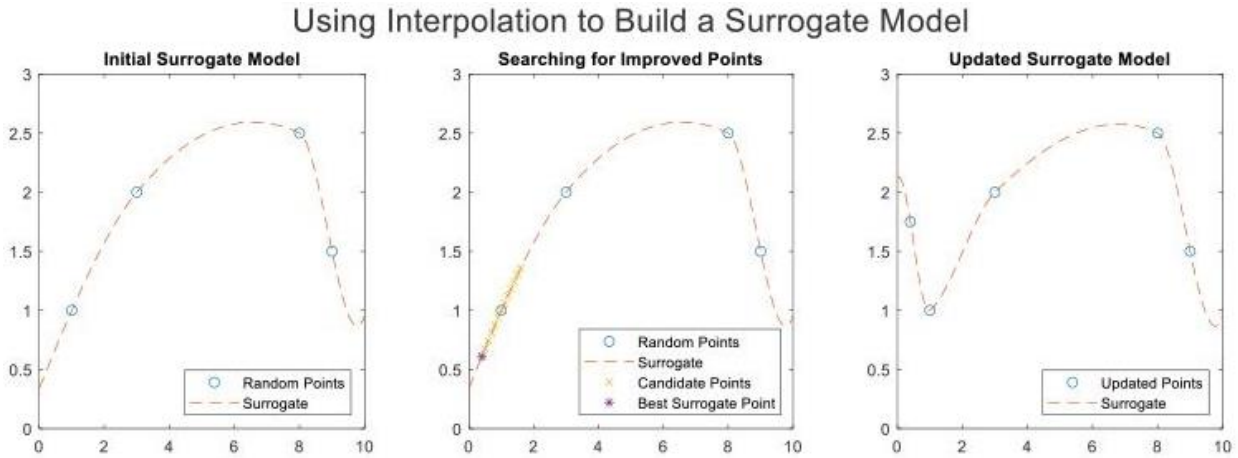
discrete



Objective with single minimum

Solve Expensive Nonlinear Problems with `surrogateopt`

- Concept
  - Create a surrogate model of the objective / constraints
  - Find the best point on the surrogate model, then sample new points
    - near the best point found so far (refine solution)
    - far from any sample (improve model accuracy)
- Benefits
  - Automatically builds a cheap-to-evaluate surrogate model
  - Searches for global solution
  - Uses fewer function evaluations than other global solvers
  - Works with continuous and integer variables
  - Accepts nonlinear and linear constraints



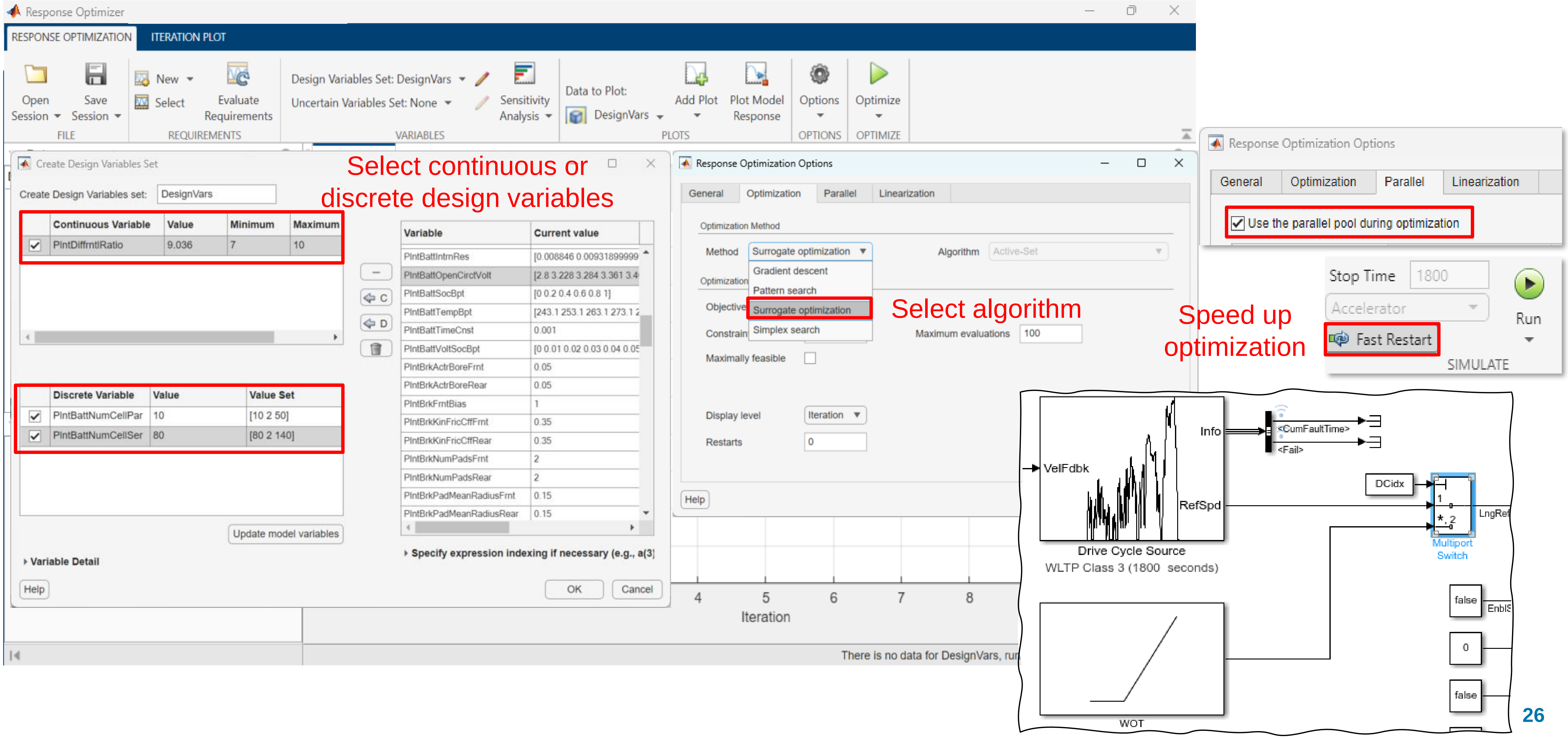
Description

`surrogateopt` is a global solver for time-consuming objective functions.

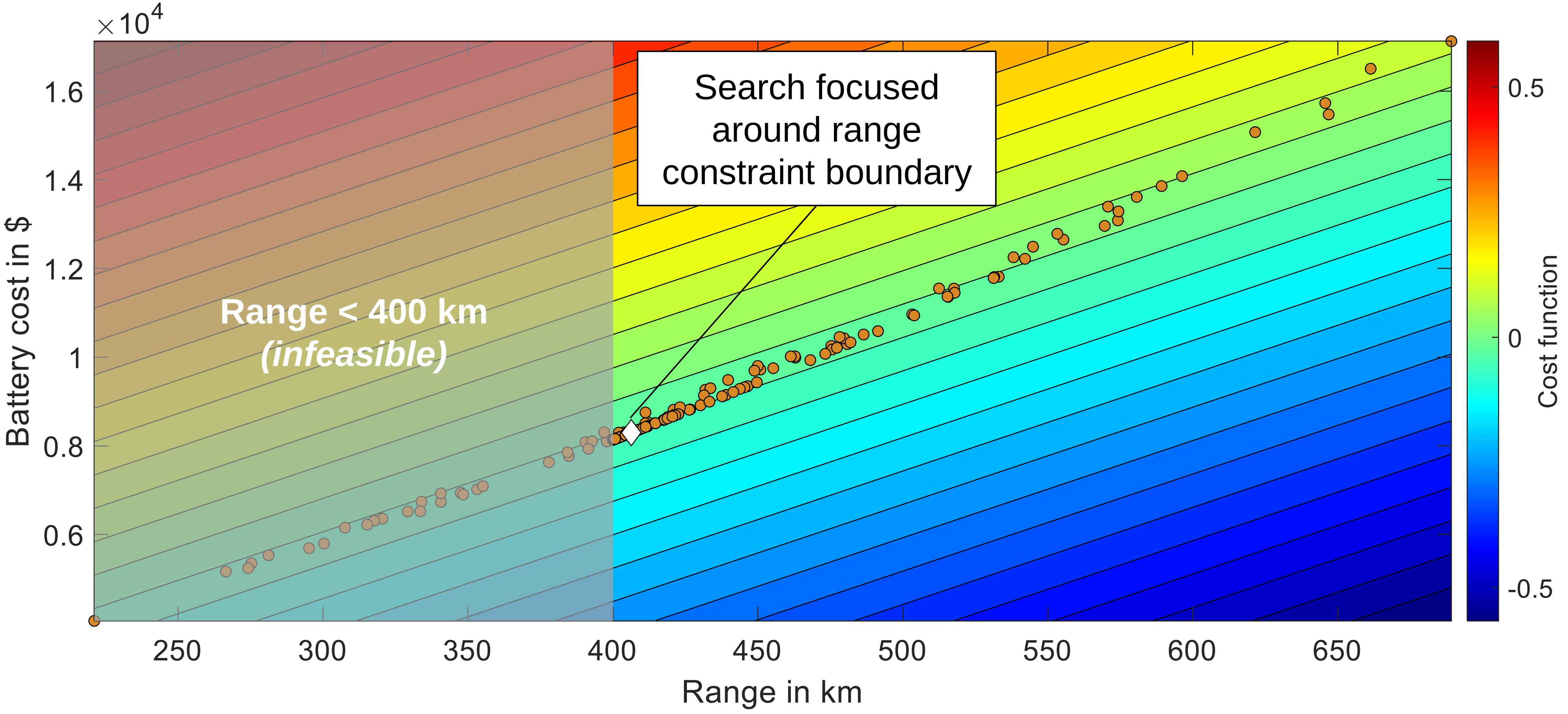
`surrogateopt` attempts to solve problems of the form

$$\min_x f(x) \text{ such that } \begin{cases} \text{lb} \le x \le \text{ub} \\ A \cdot x \le b \\ \text{Aeq} \cdot x = \text{beq} \\ c(x) \le 0 \\ x_i \text{ integer, } i \in \text{intcon.} \end{cases}$$

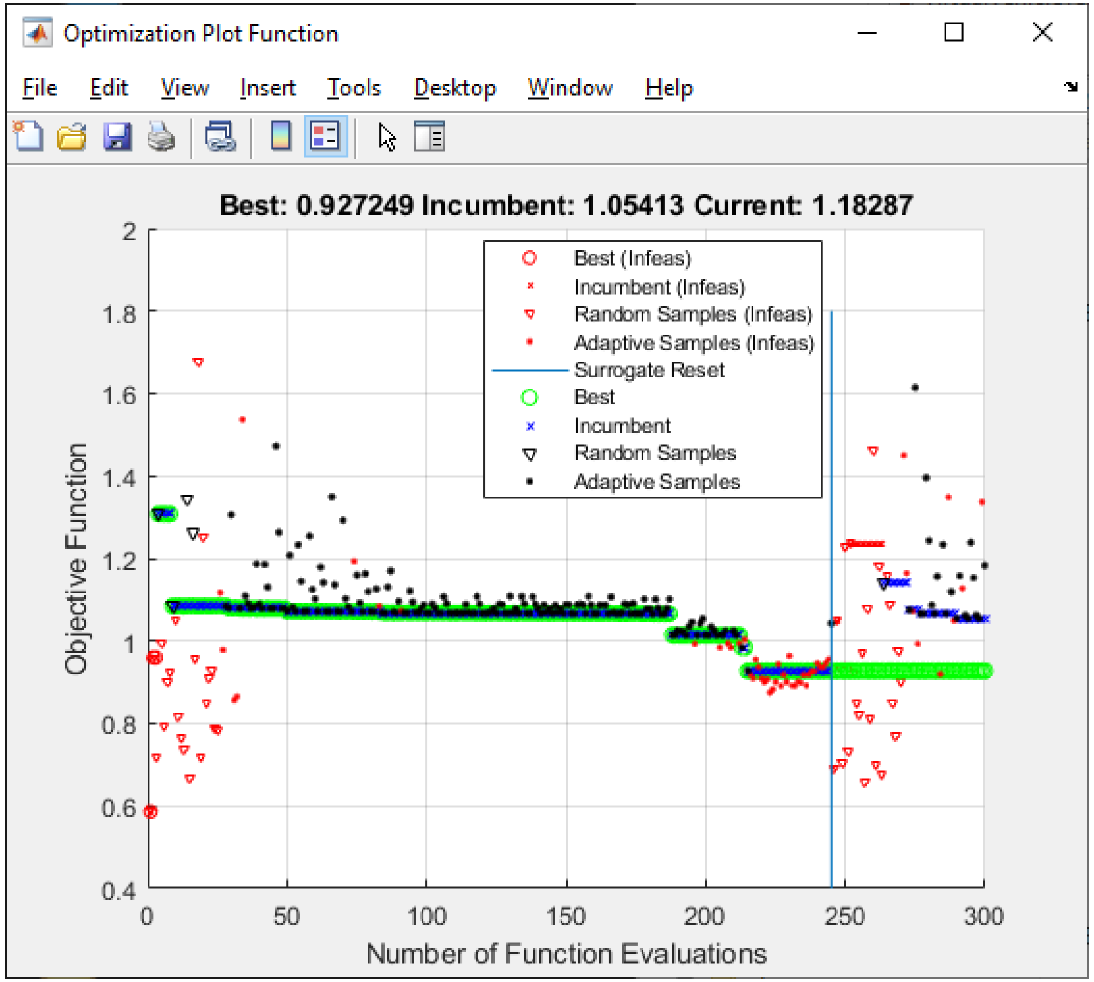
Simulink Design Optimization Makes Problem Setup Easy



Optimization Results



Optimization Results



Performed 300 function calls

Metric	Baseline	Optimized (% change)
Cost [$]	7537	8297 *(+10%)*
Range [km]	371	406 *(+9.4%)*
$t_{0\text{-}100}$ [s]	6.77	6.83 *(+0.9%)*
Nd	9	7
Battery cells	96s31p	91s36p
Bus voltage [V]	357.8	339.2
Capacity [kWh]	60.3	66.3

Summary: Battery Sizing

- Key takeaways
  - Formal optimization tools can iterate on model parameters to meet conflicting requirements and optimize design performance
  - Set up and automate the process easily using Simulink Design Optimization or MATLAB scripts

- Next step
  - Use the information from optimization study to perform more detailed design-oriented analysis on the battery system

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- **Battery design**
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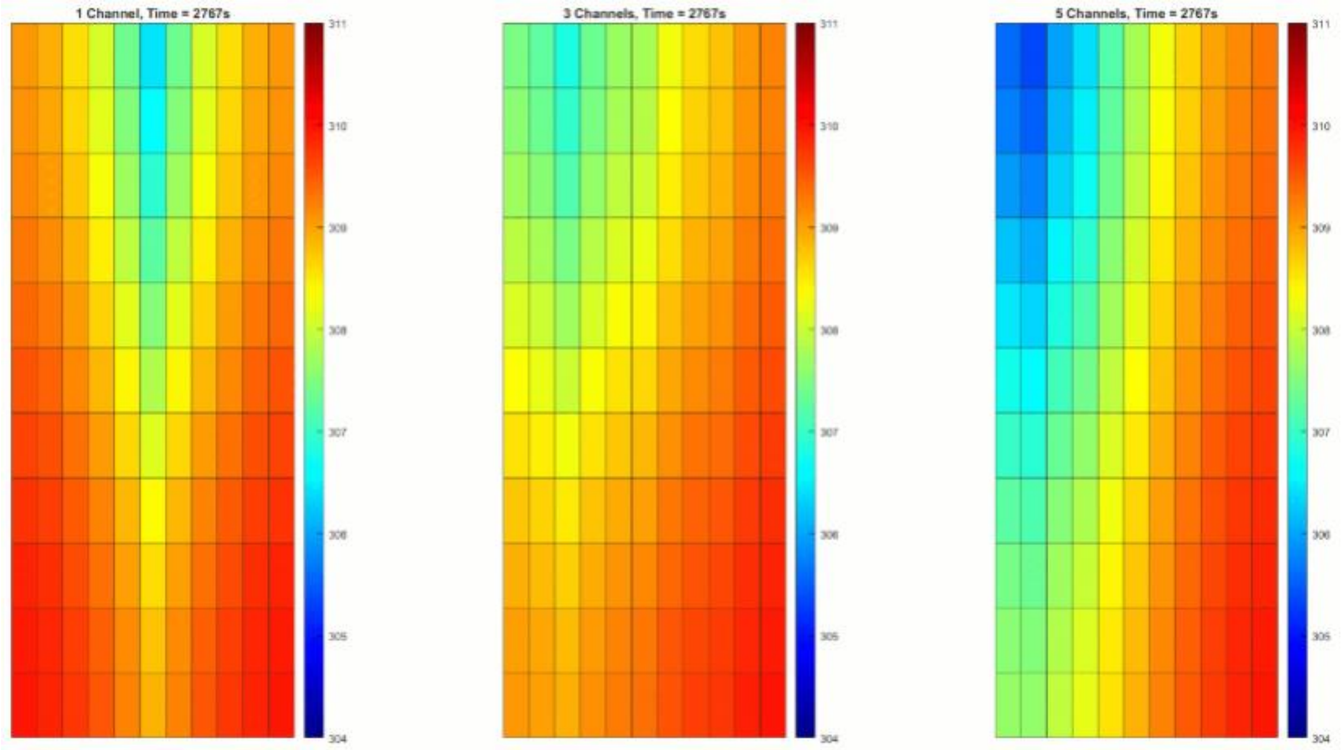
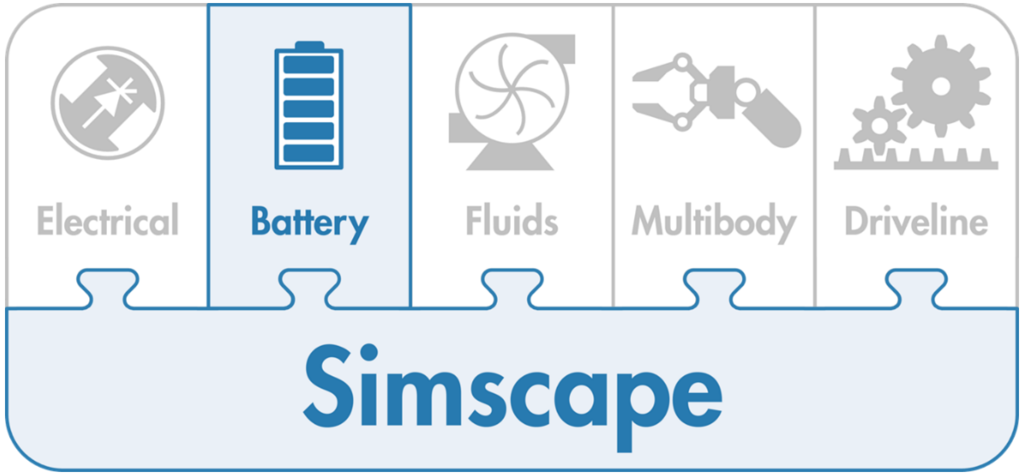
Assess → Optimize → Design → Validate



Design Study Workflow

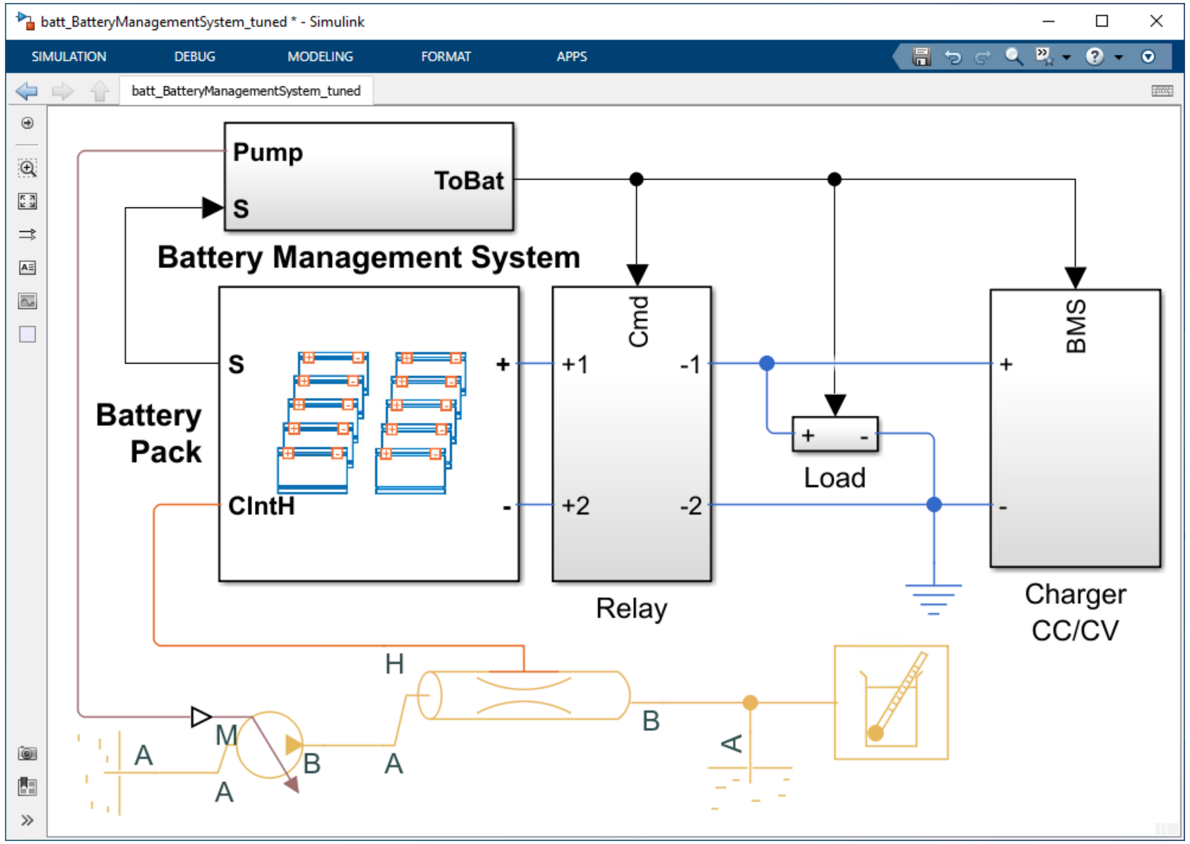
1. Size battery pack within context of full system operation
2. Create lumped battery pack model in Simscape Battery and demonstrate equivalence
3. Design battery system in Simscape Battery
4. Select appropriate model fidelity for full system evaluation
5. Evaluate battery design in full system

Simscape Battery

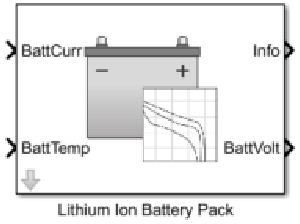


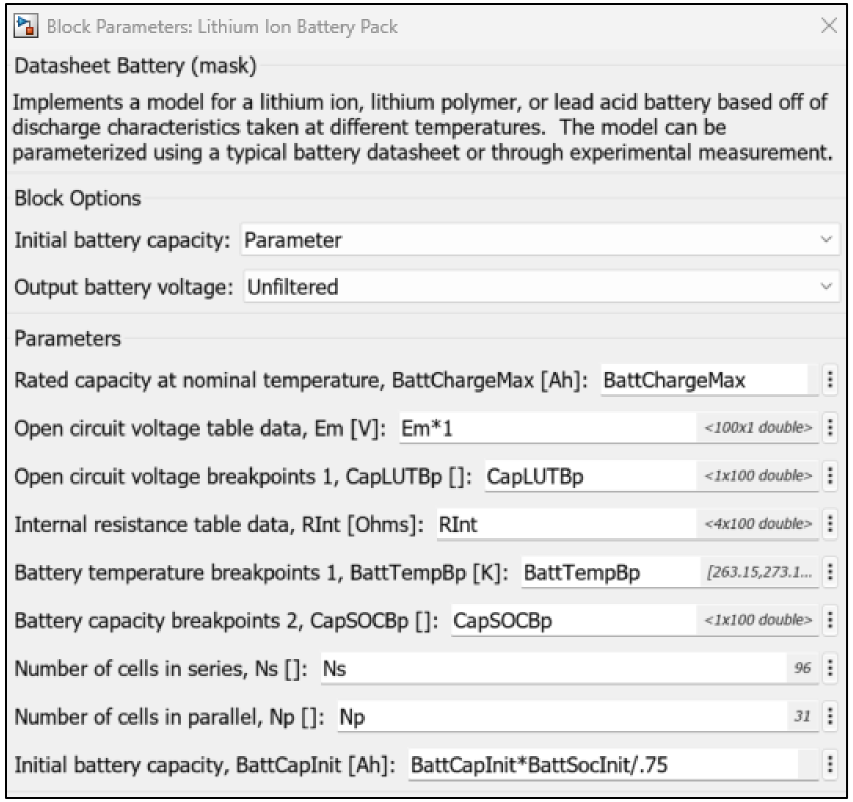
- Design and simulate battery and energy storage systems
  - Electrothermal cell behavior
  - Battery pack design
  - Battery management systems (BMS)

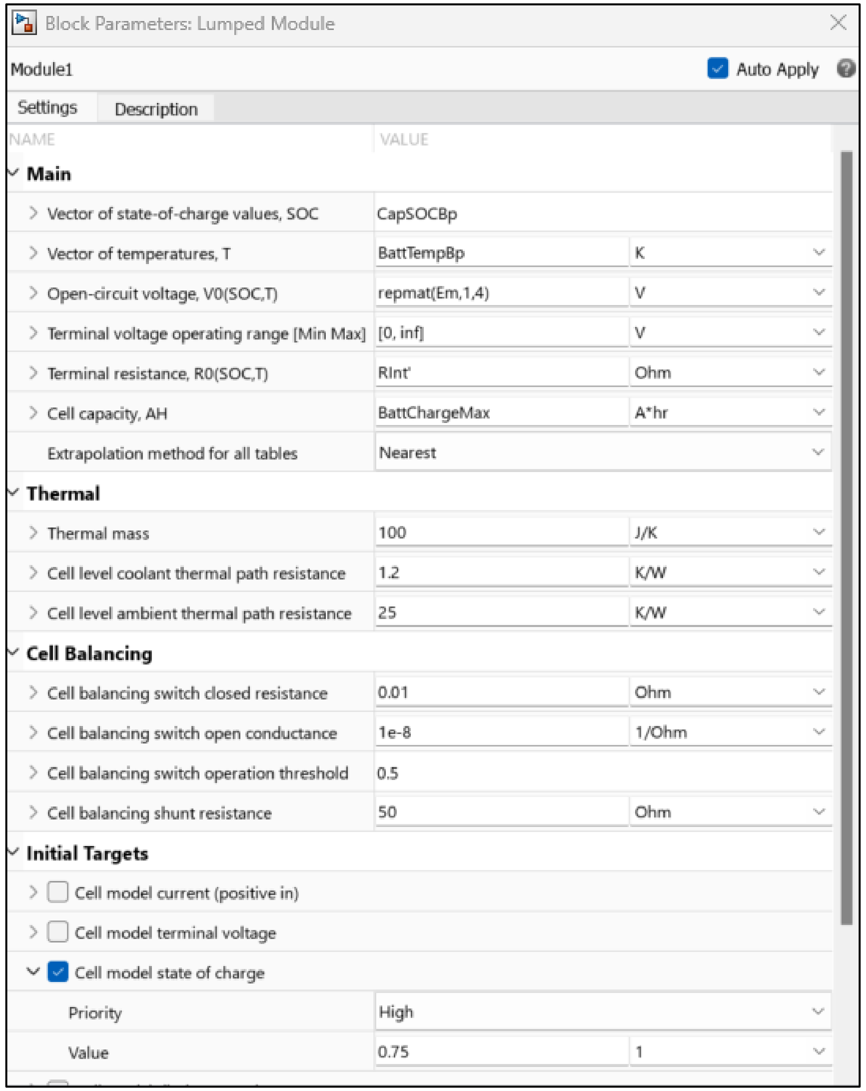
- With Simscape Battery you can
  - Evaluate pack architectures for electrical and thermal requirements
  - Verify robustness of discharge, charge and thermal management algorithms
  - Validate algorithms using HIL testing

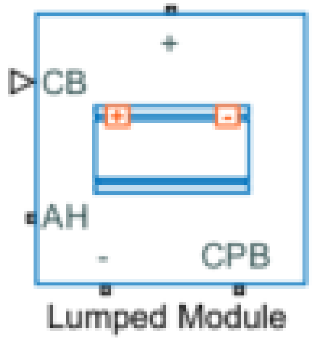


Create Lumped Battery Pack Model in Simscape Battery and Demonstrate Equivalence

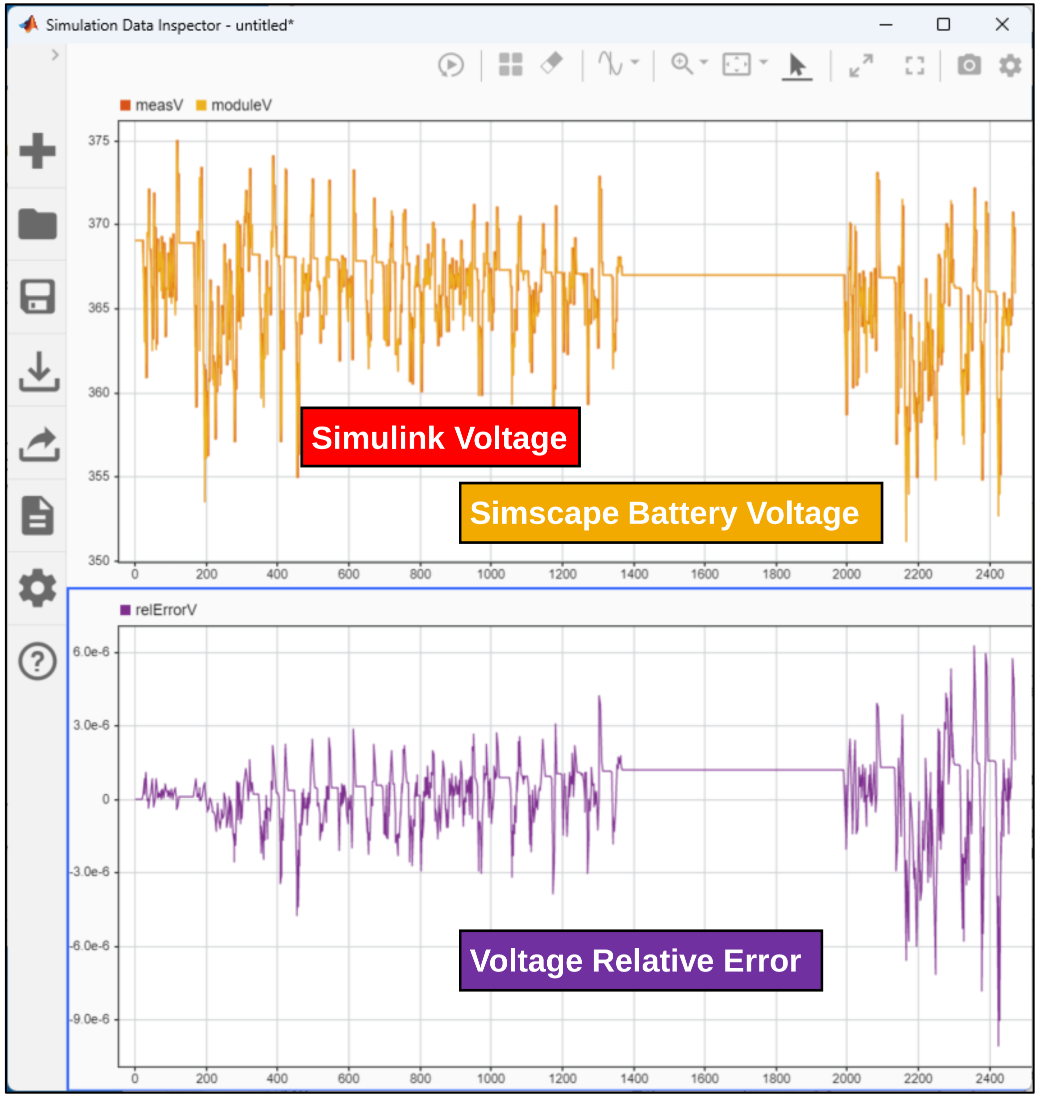




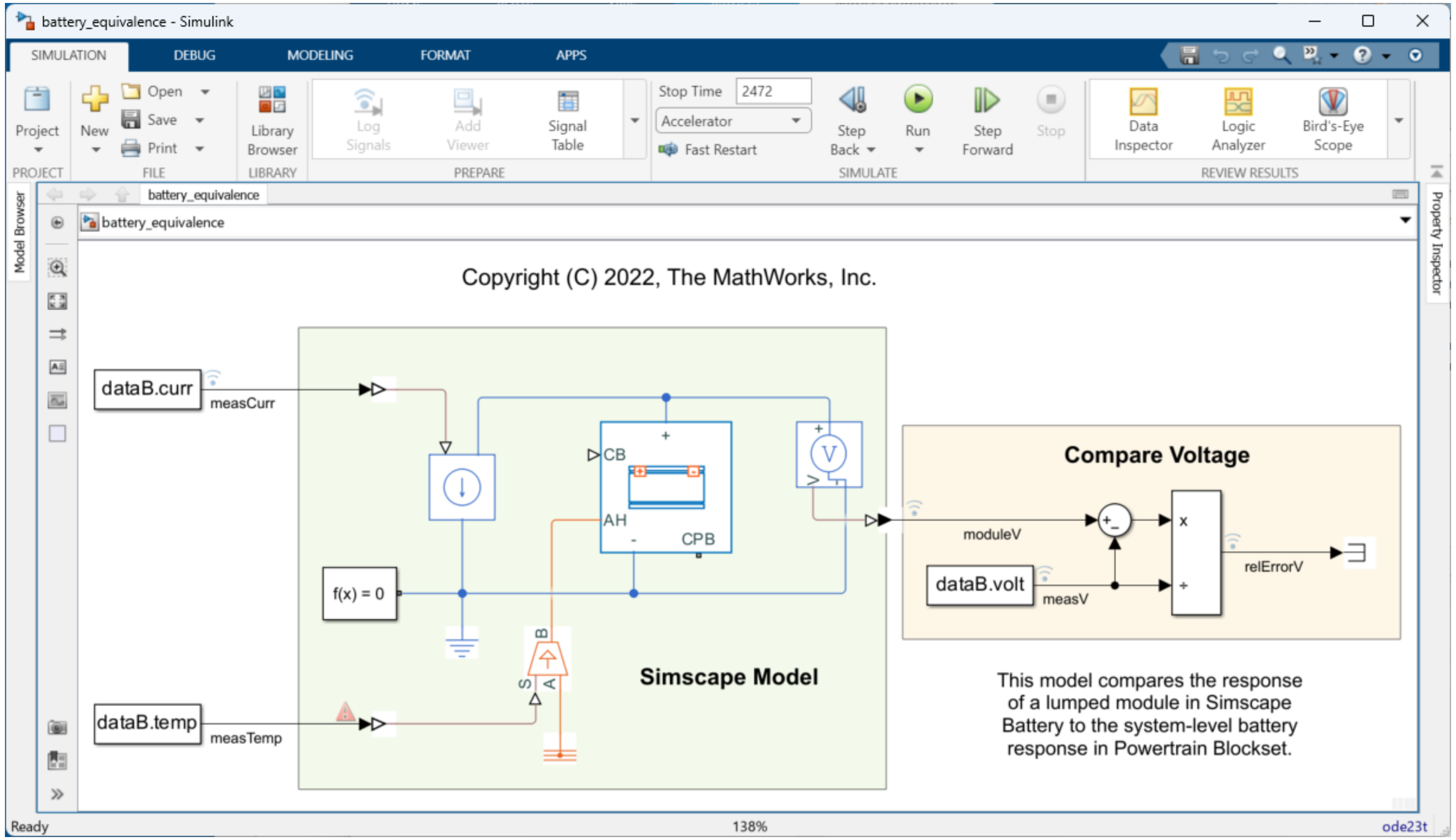




Create Lumped Battery Pack Model in Simscape Battery and Demonstrate Equivalence

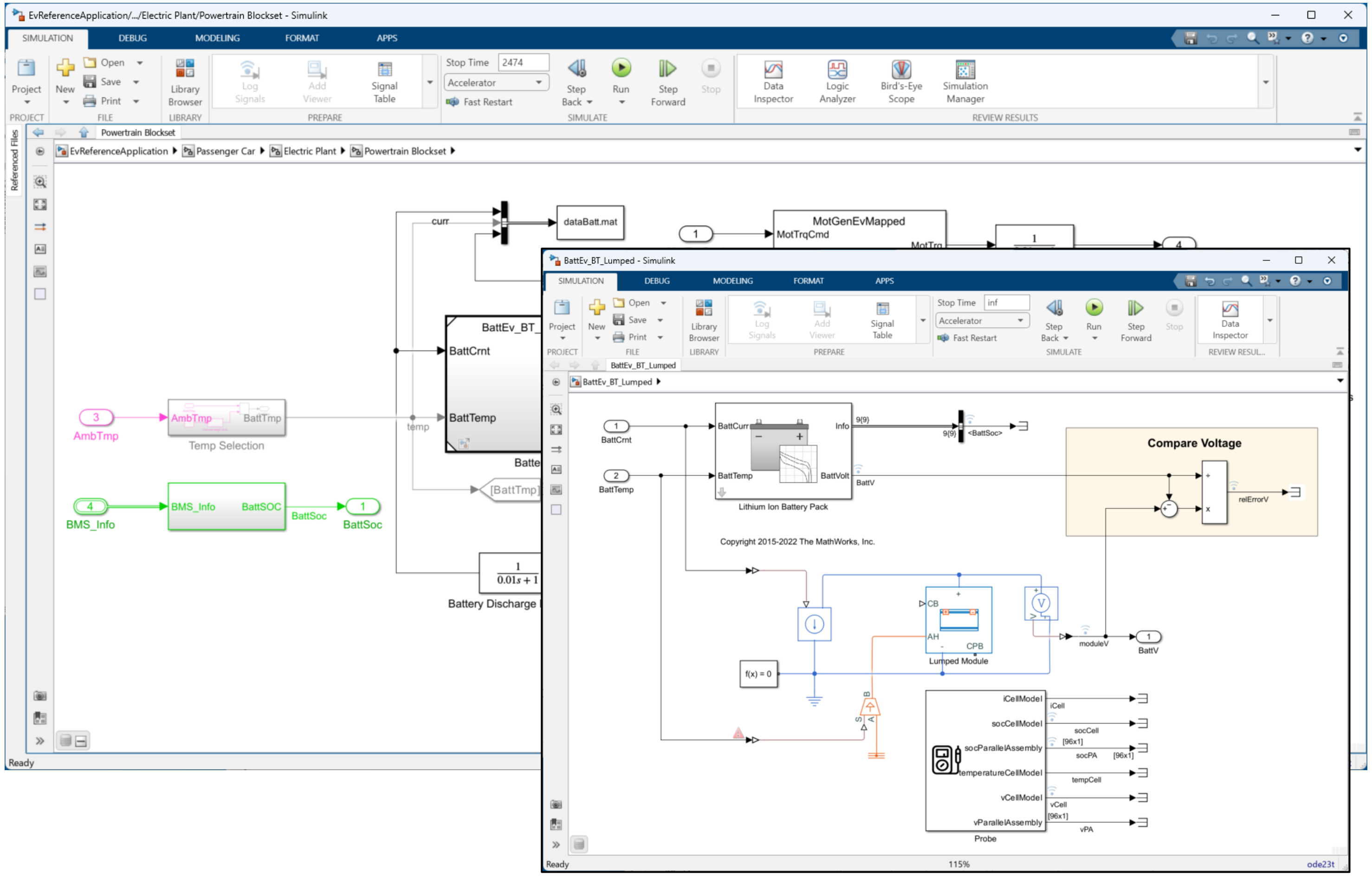


Unit Test



Create Lumped Battery Pack Model in Simscape Battery and Demonstrate Equivalence

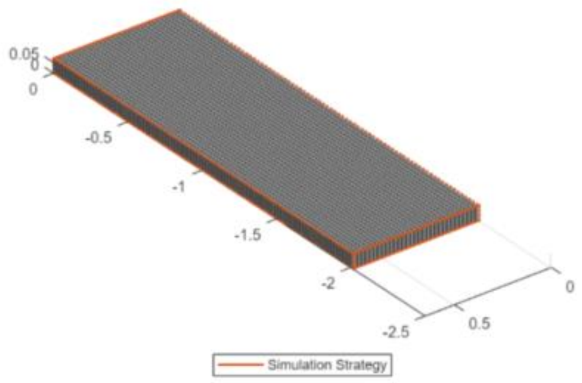
System Test



Design Battery Systems in Simscape Battery

- Create battery pack with higher resolution

Lumped (1 cell model for entire pack)



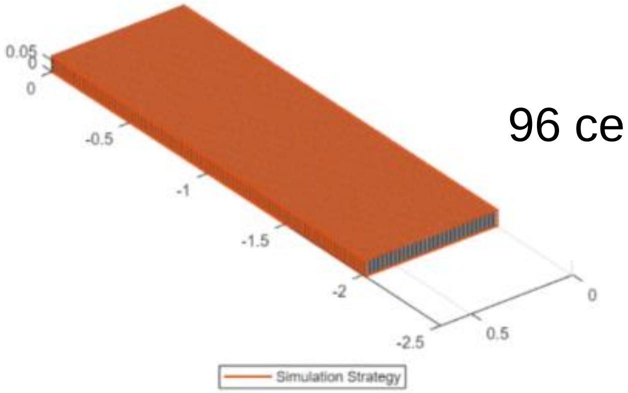
Define module

```
Ns = 96; % number of parallel assemblies in series
batteryModule = Module(ParallelAssembly = batteryParallelAssembly, numSeriesAssemblies = Ns);
```

Define simulation strategy

```
batteryModule.ModelResolution = "Lumped";
```

Grouped (1 cell model for each parallel assembly)



96 cell models

Define module

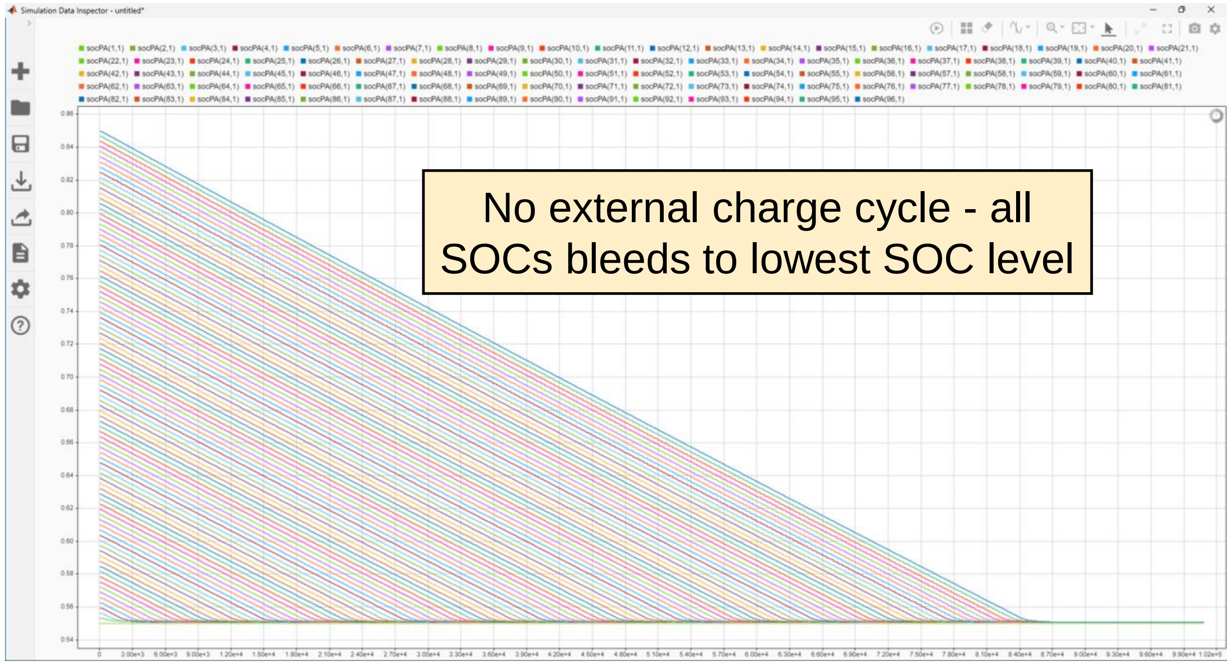
```
Ns = 96; % number of parallel assemblies in series
batteryModule = Module(ParallelAssembly = batteryParallelAssembly, numSeriesAssemblies = Ns);
```

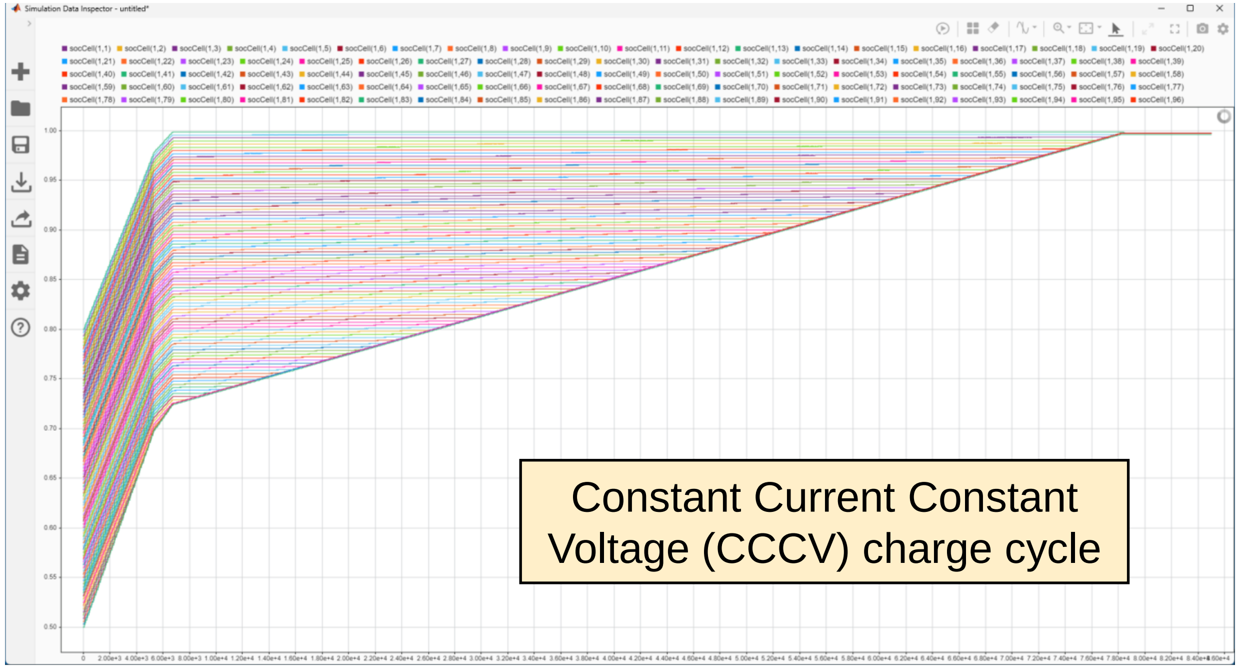
Define simulation strategy

```
batteryModule.ModelResolution = "Grouped";
batteryModule.SeriesGrouping = ones(1,Ns);
```

Passive Cell Balancing

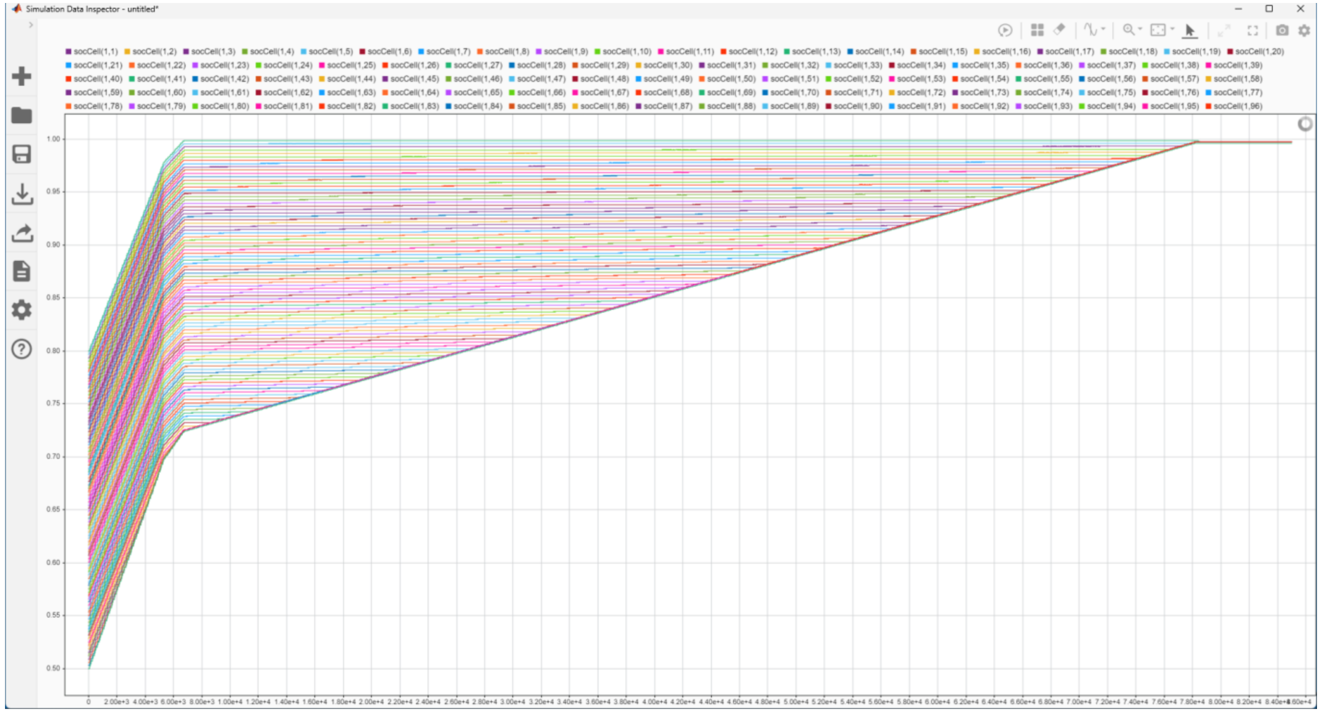
- Cells within a parallel assembly will naturally balance
- One cell balancing circuit for each series-connected parallel assembly

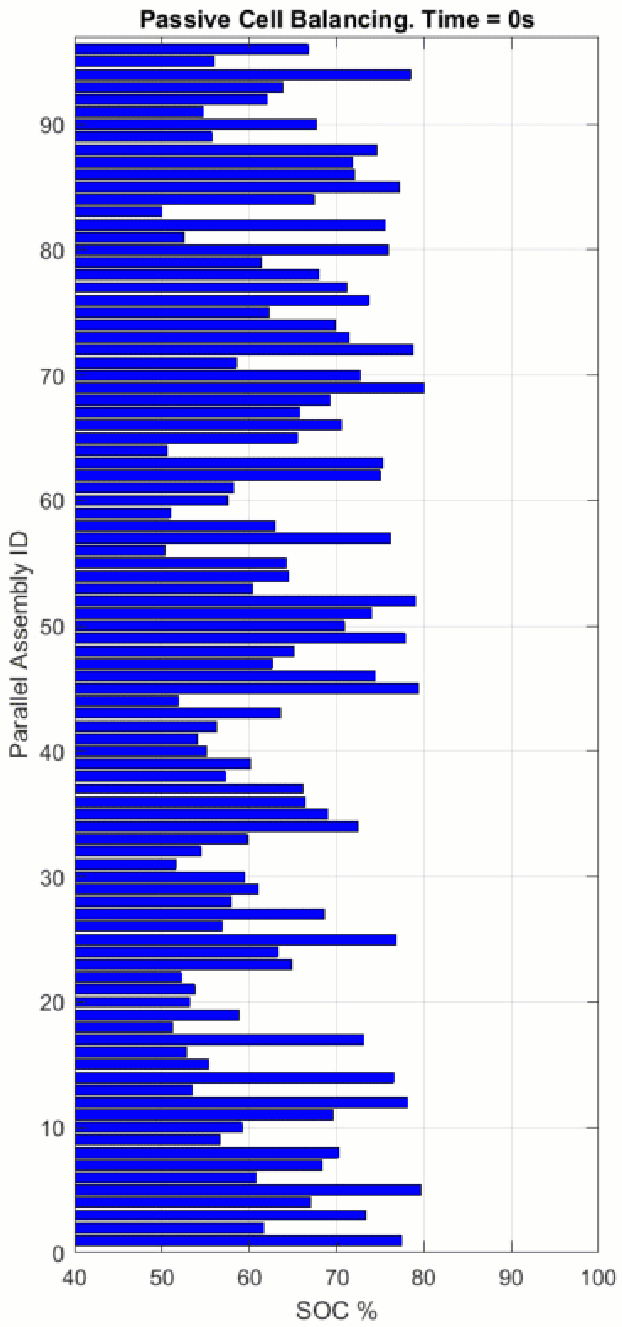




Passive Cell Balancing During CCCV

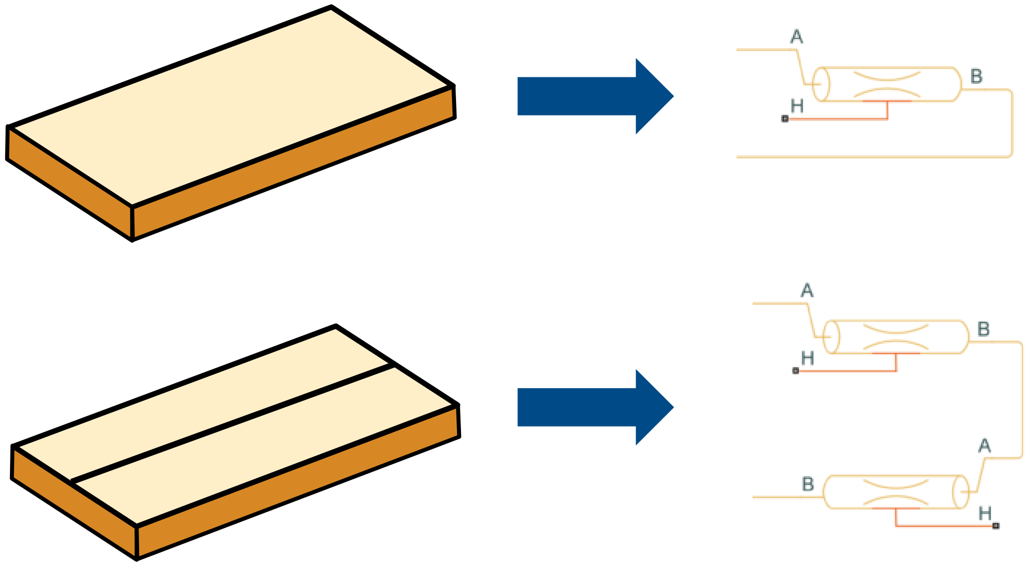
- Animation can bring further clarity to a large number of time-series responses



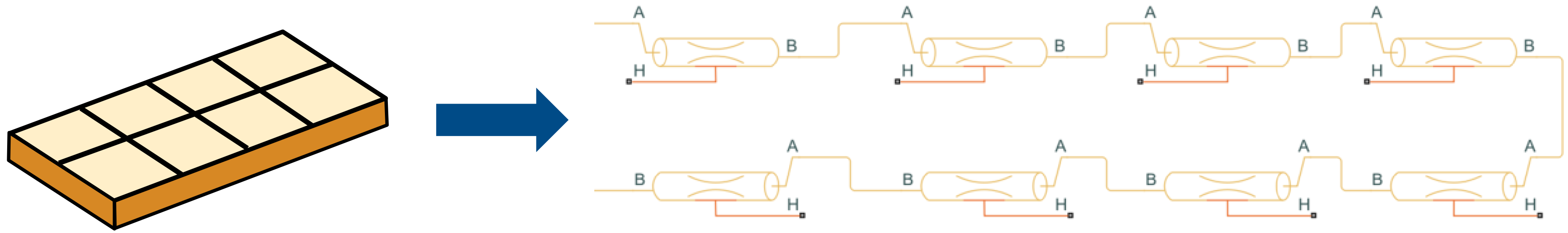


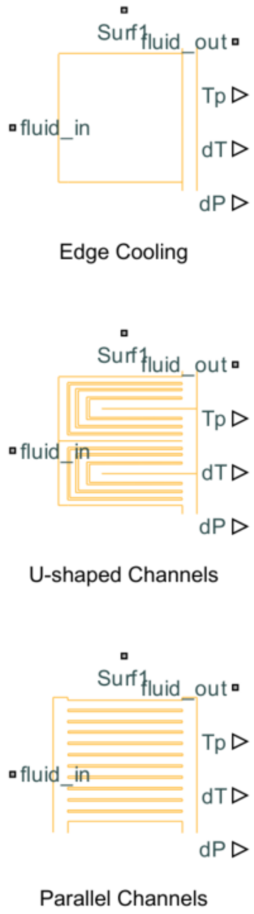
Thermal Management

- Change the simulation strategy of cooling plates to meet your model resolution needs



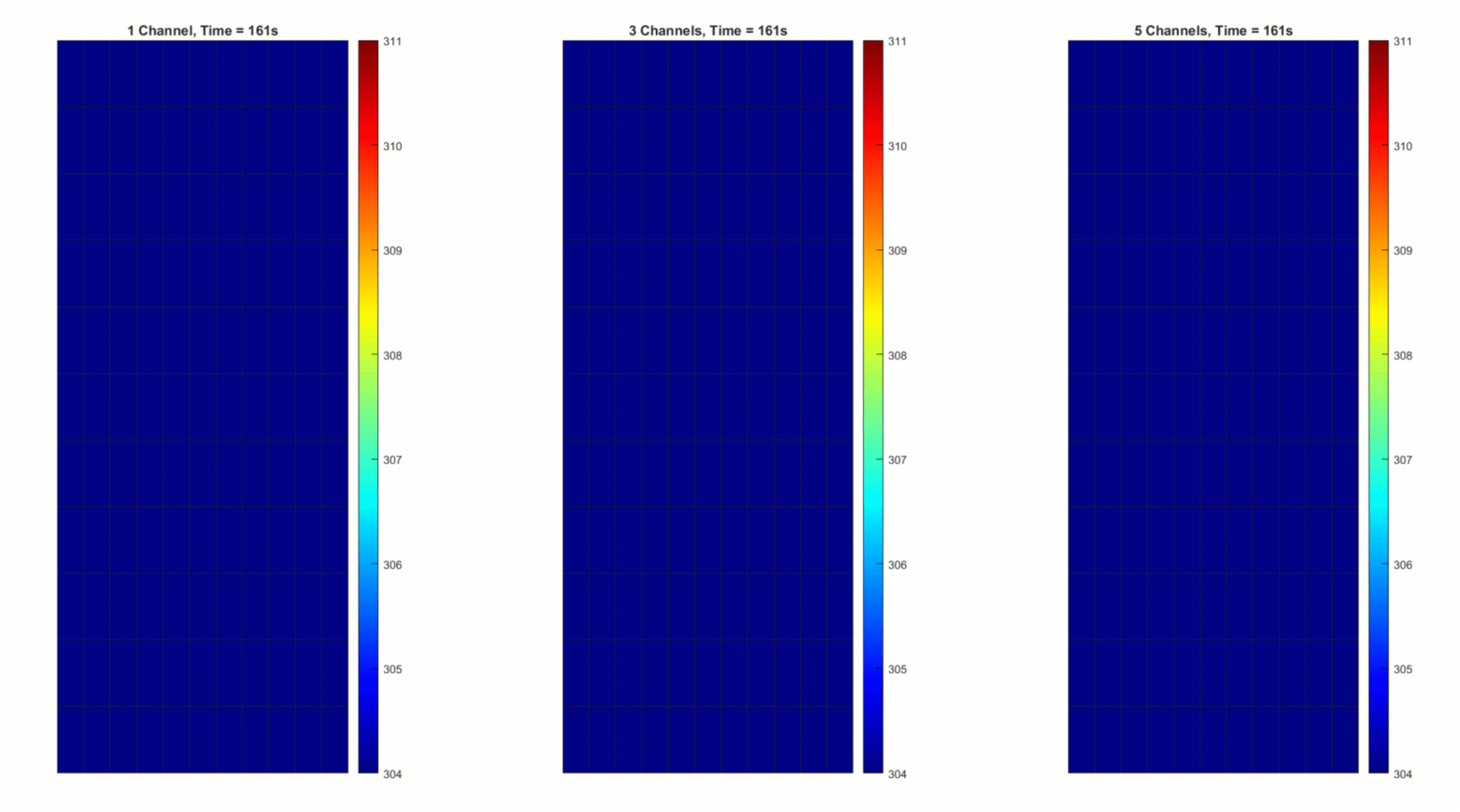
Connections dependent on cooling plate architecture

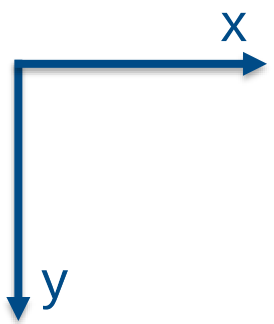




Thermal Management

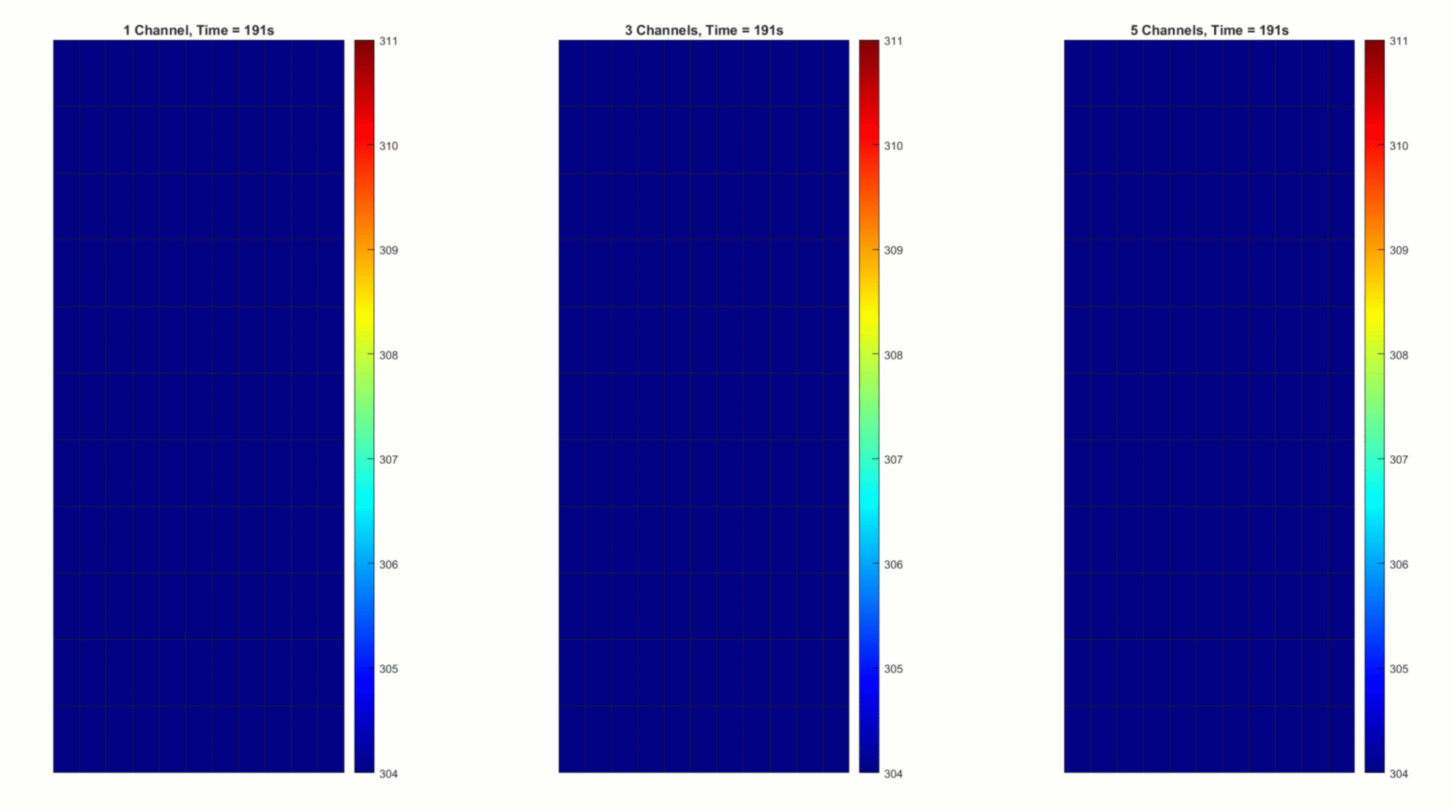
- Parallel cooling channels oriented along the x-axis

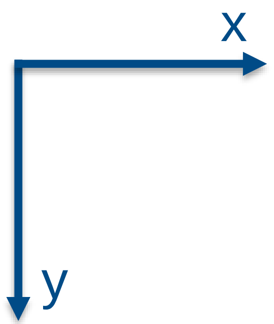




Thermal Management

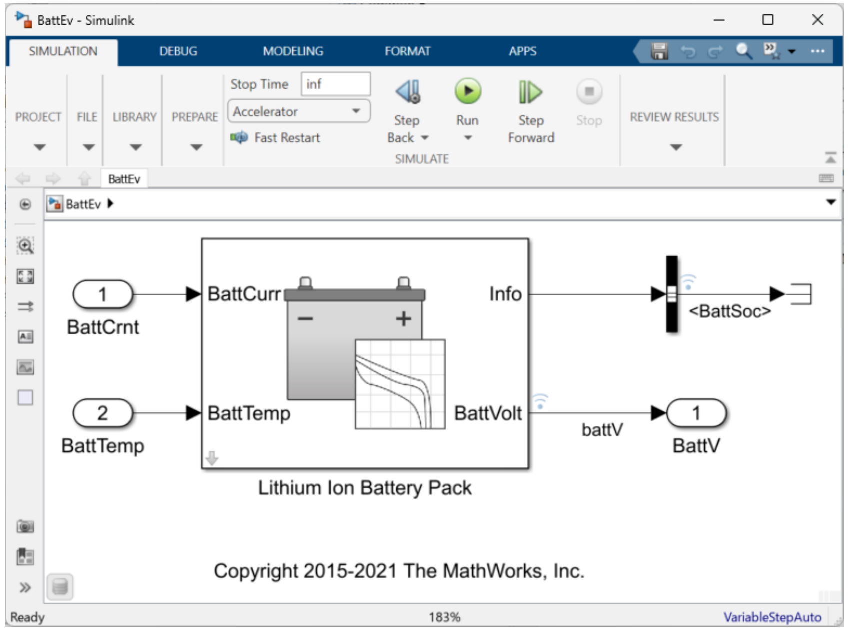
- Parallel cooling channels oriented along the y-axis

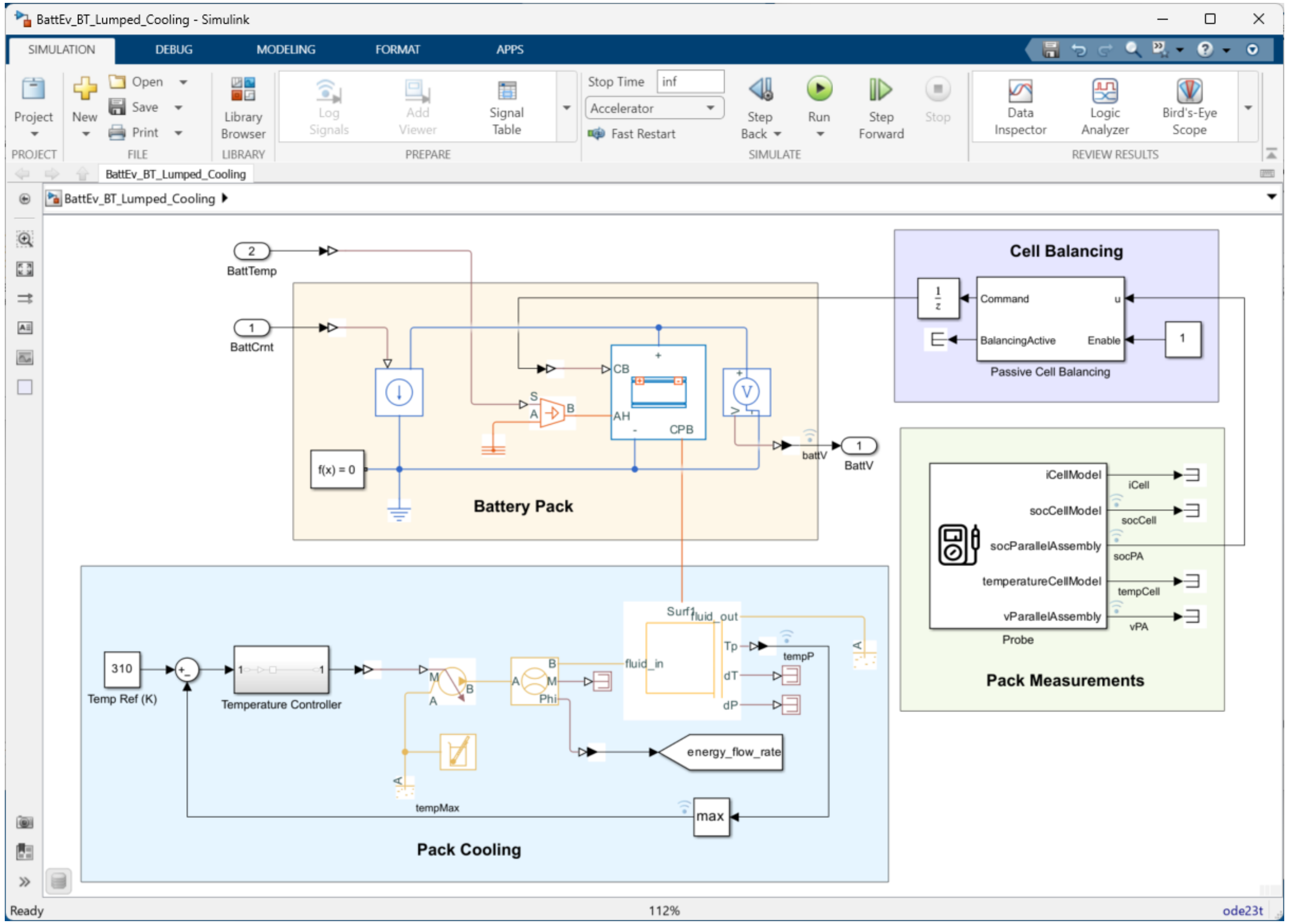




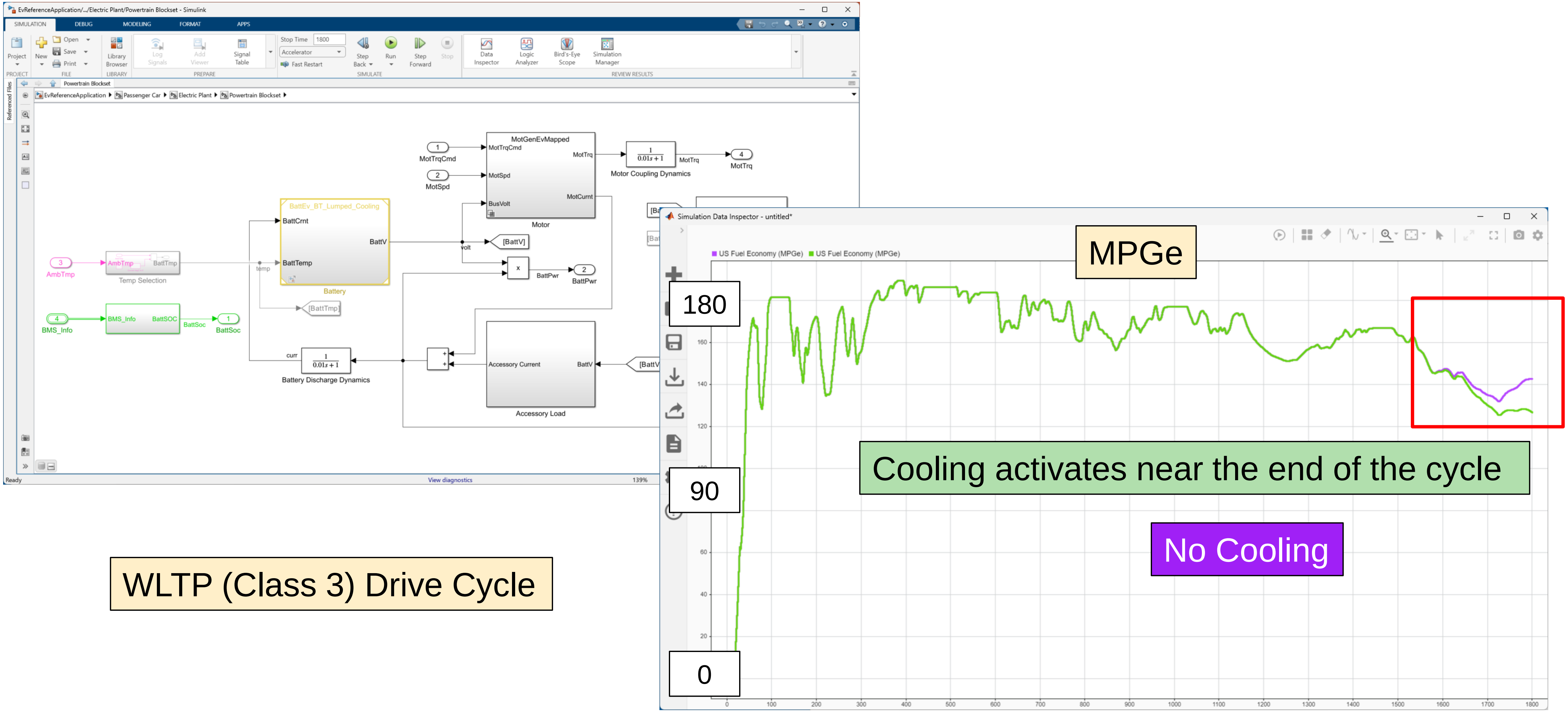
Select Appropriate Model Fidelity for Full System Evaluation

- For many scenarios, lumped battery model is sufficient for system integration
- Other fidelities can be incorporated as needed





Evaluate Battery Design in Full System



Summary: Battery Design

- Key takeaways
  - Matching model fidelity to the engineering question being asked enhances overall workflow execution
  - Design information is effectively shared across different engineering teams

- Next step
  - Where to go for more information

Agenda

- Context
- Vehicle model
- Battery sizing
- Battery design
- Summary

MathWorks Training Can Increase Your Productivity

- General purpose training courses
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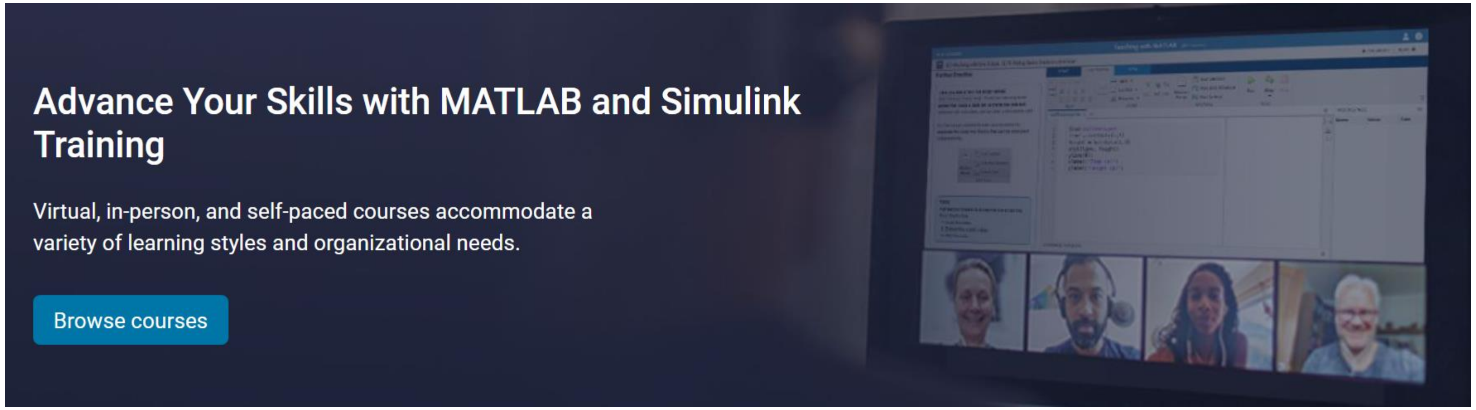
  - Optimization paid training services
  - Simscape free online onramp
  - Simscape paid training services
- Automotive-specific training
  - Simulink Fundamentals for Automotive Applications training services
  - Battery Modeling and Algorithm Development with Simulink training services
  - Powertrain Blockset jumpstart training services



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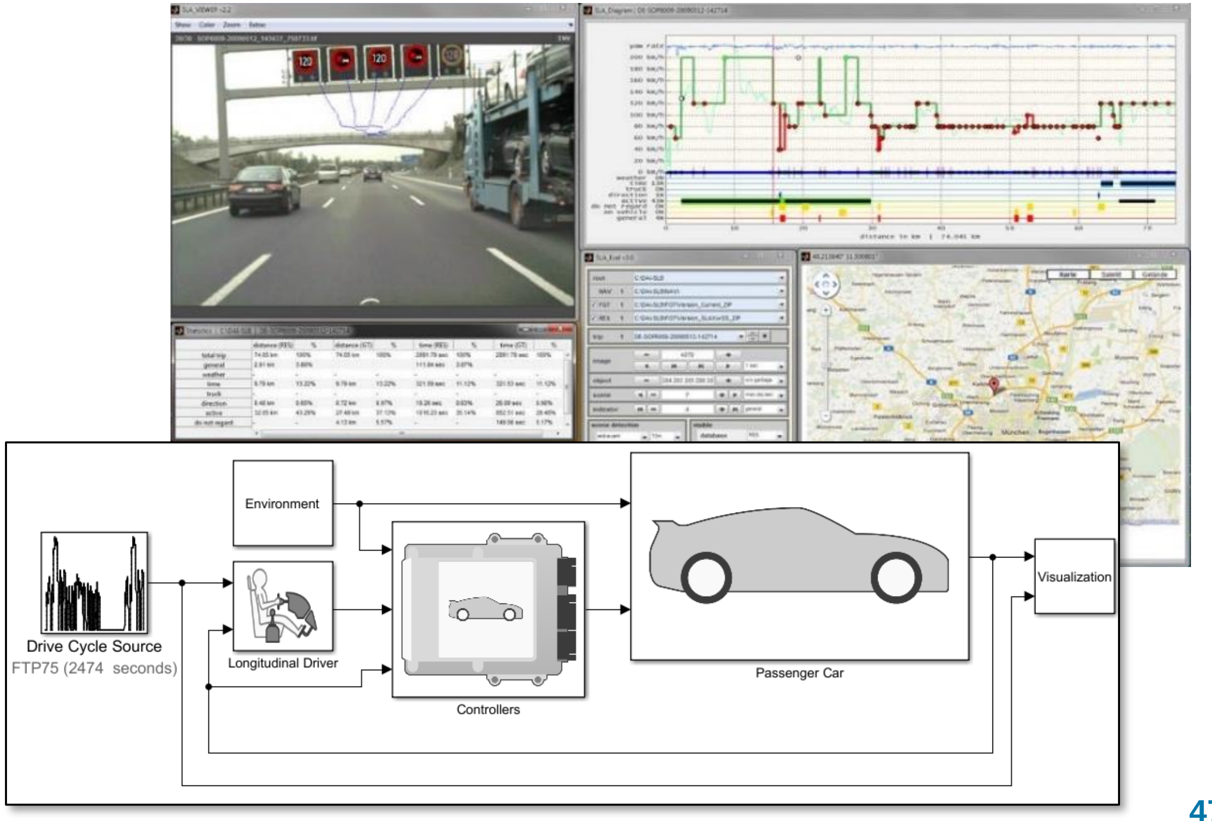
Construction	Build process automation Database/Repo interface Model-Building know-how …	
User Experience	GUI driven workflow Tool compatibility support Artifact creation …	

- Provide expert-level guidance
- Automate workflows
- Develop custom UI's



Learn more:

[MathWorks Consulting Services]

Additional Resources

- Overview of MathWorks' automotive solutions:
  - MATLAB and Simulink for Electric Vehicle Development
  - Building Your Virtual Vehicle with Simulink
  - Upskill for the Electric Vehicle Transition
- Products highlighted in this study:
  - Powertrain Blockset
  - Simscape Battery
  - Global Optimization Toolbox
  - Simulink Design Optimization

Key Takeaways

- Problem description
  - You can use an EV model to optimize battery pack size, then design the battery system and validate its performance

- Role of MathWorks tools
  - **Powertrain Blockset** offers system-level models to quantify trade-offs in battery performance, efficiency and cost
  - **Global Optimization Toolbox** and **Simulink Design Optimization** efficiently optimize the design while accounting for competing requirements
  - **Simscape Battery** can be used to perform detailed battery design studies
  - These **products are complementary** parts of the overall workflow

Thank you

Mike Sasena

Automotive Product Manager
msasena@mathworks.com

Danielle Chu

Simscape Product Manager
dchu@mathworks.com