



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

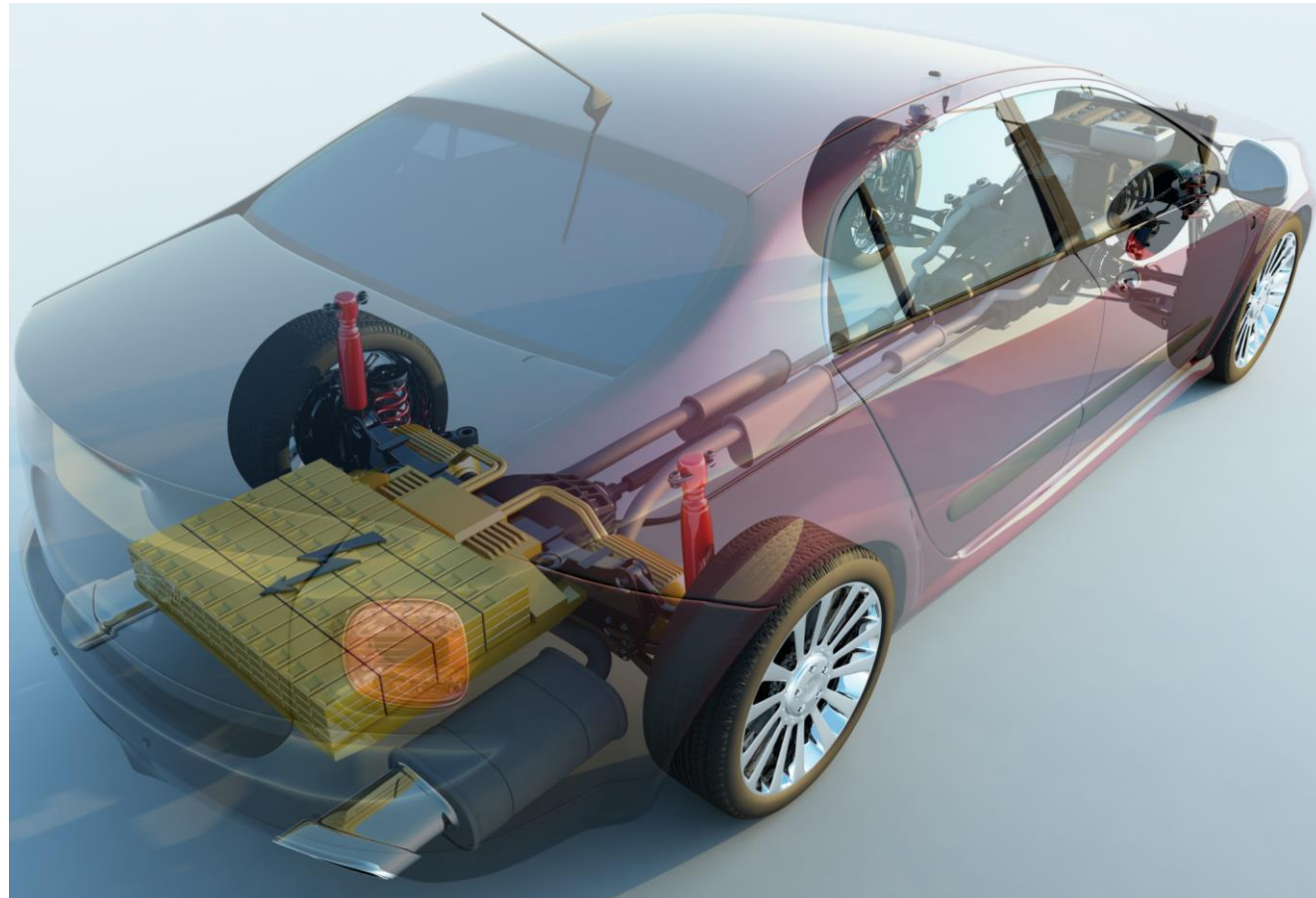


- Role of MathWorks tools

- **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

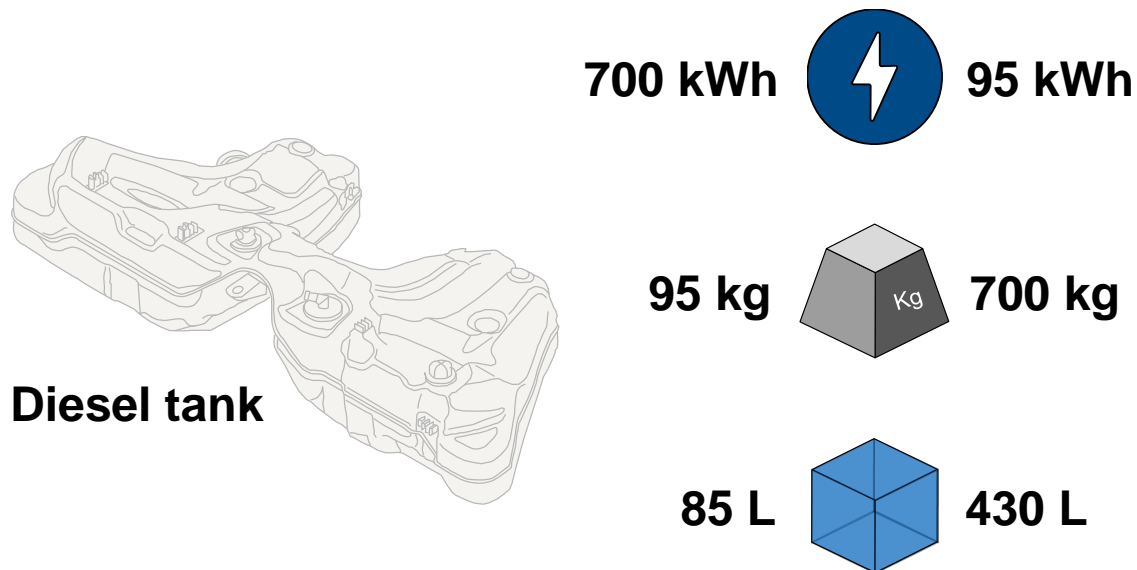
Agenda

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

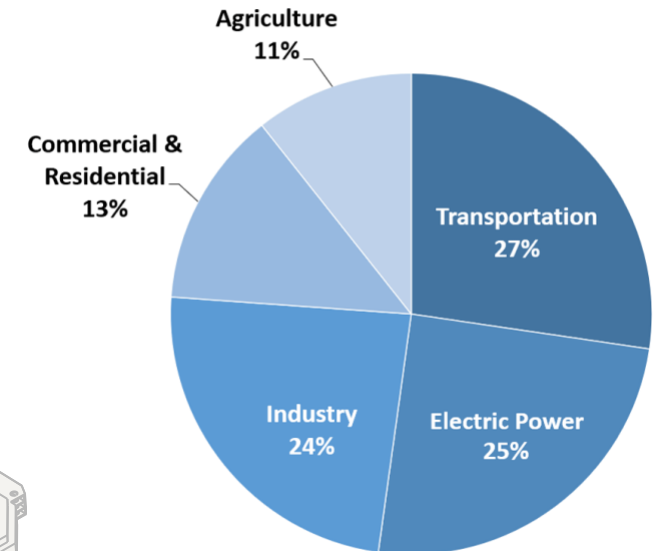


Automotive Powertrains Are Increasingly Electric

- The automotive sector is focused on reducing CO₂ emissions
- Battery Electric Vehicles (BEV's) are a promising option
 - Localizes CO₂ emissions to energy production source
 - Can be charged from renewable energy
- But engineering challenges remain...



Total U.S. Greenhouse Gas Emissions by Economic Sector in 2020



Credit: [EPA.gov](https://www.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

EPA DOT Fuel Economy and Environment Plug-In Hybrid Vehicle Electricity-Gasoline

Fuel Economy Midsize cars range from 10 to 99 MPGe. The best vehicle rates 99 MPGe.

Electricity Charge Time: 4 hours (240V) **98 MPGe** 34 kWhrs per 100 miles

Gasoline Only **38 MPG** 2.6 gallons per 100 miles

You save \$8,100 in fuel costs

EPA DOT Fuel Economy and Environment Electric Vehicle

Fuel Economy Midsize cars range from 10 to 99 MPGe. The best vehicle rates 99 MPGe.

99 MPGe 103 city 95 highway 34 kWhrs per 100 miles

You save \$9,600 in fuel costs over 5 years compared to the average new vehicle.

Annual fuel cost \$900

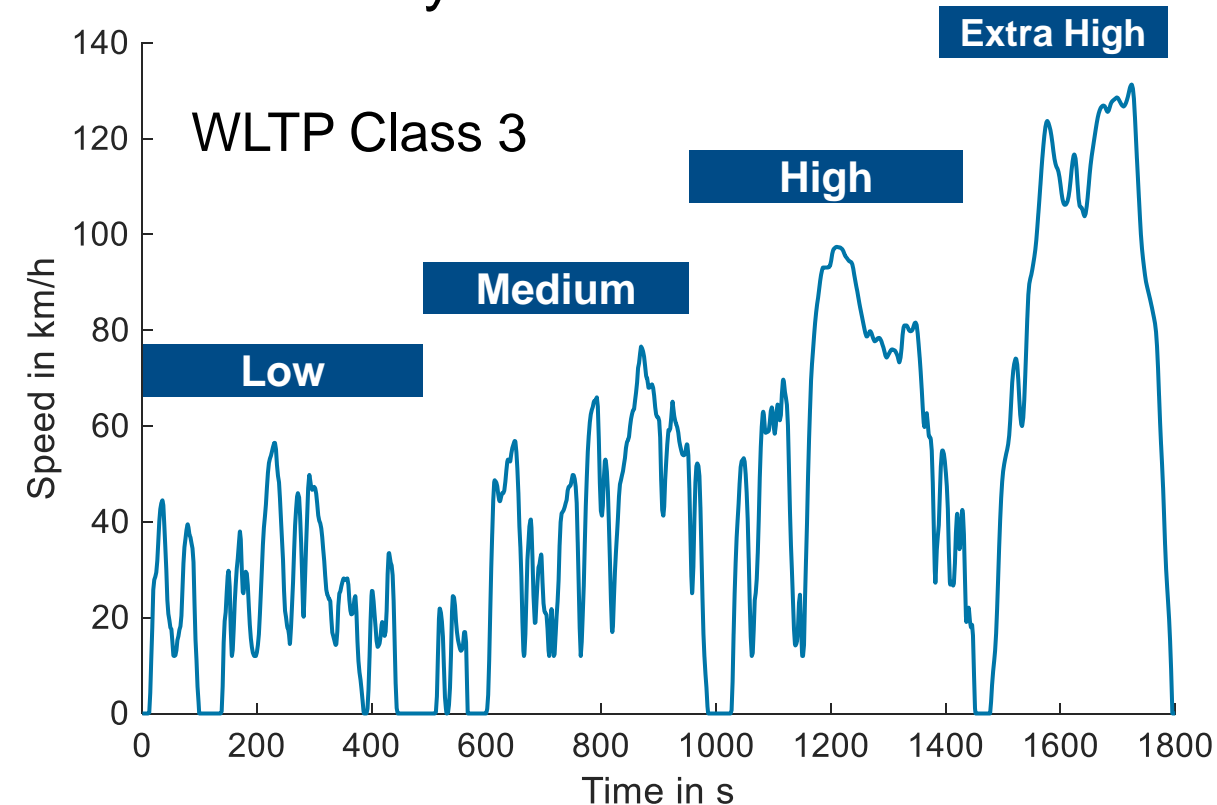
Annual fuel cost \$600

Smog Rating 10 Best

Smog Rating 10 Best

Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. The average new vehicle gets 22 MPG and costs \$12,600 to fuel over 5 years. Cost estimates are based on 15,000 miles per year at \$0.12 per kW-hr. MPGe is miles per gasoline gallon equivalent. Vehicle emissions are a significant cause of climate change and smog.

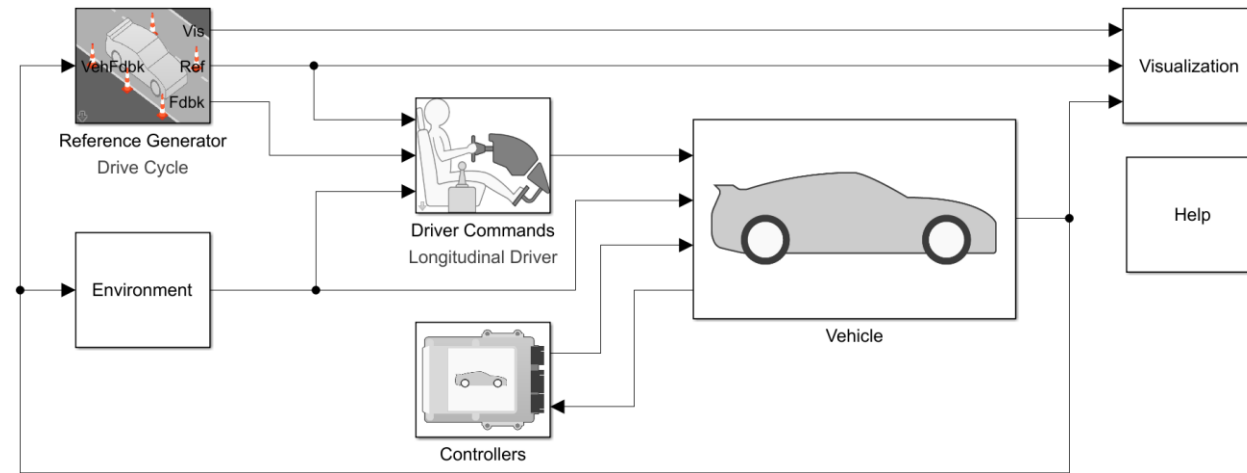
fueleconomy.gov Calculate personalized estimates and compare vehicles



Credit: US Environmental Protection Agency (EPA)

Use System-Level Models to Assess System-Level Targets

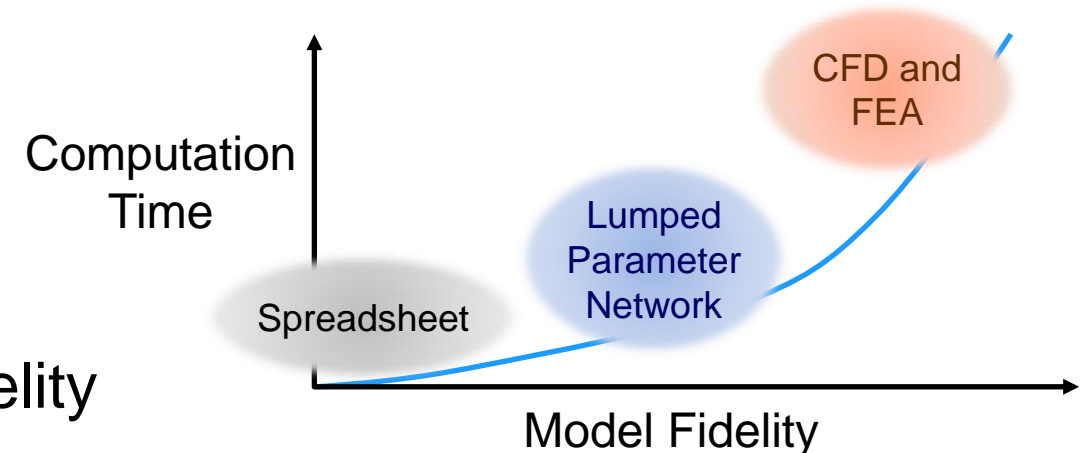
Target	How to evaluate
Fuel economy	Perform drive cycle test
Range	Perform drive cycle test
Acceleration	Perform Wide Open Throttle (WOT) test
Cost	Assume \$ / kWh



Simulations used to frontload design / save money

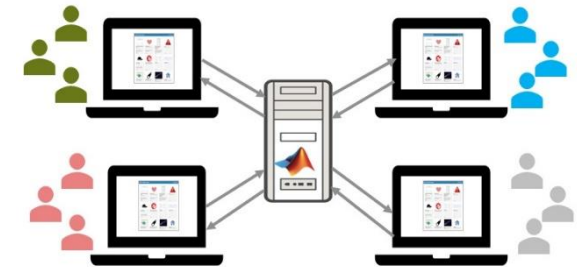
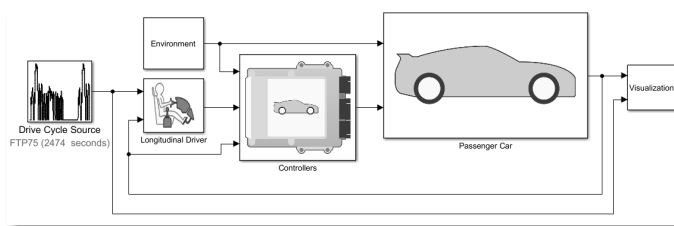
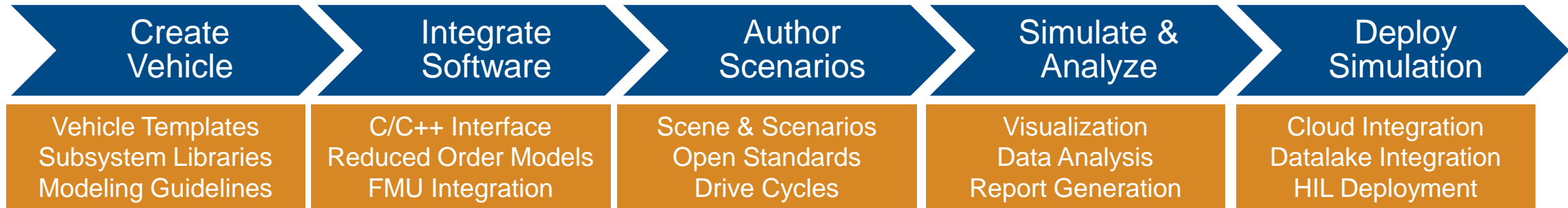
Right-Level Modeling

- 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

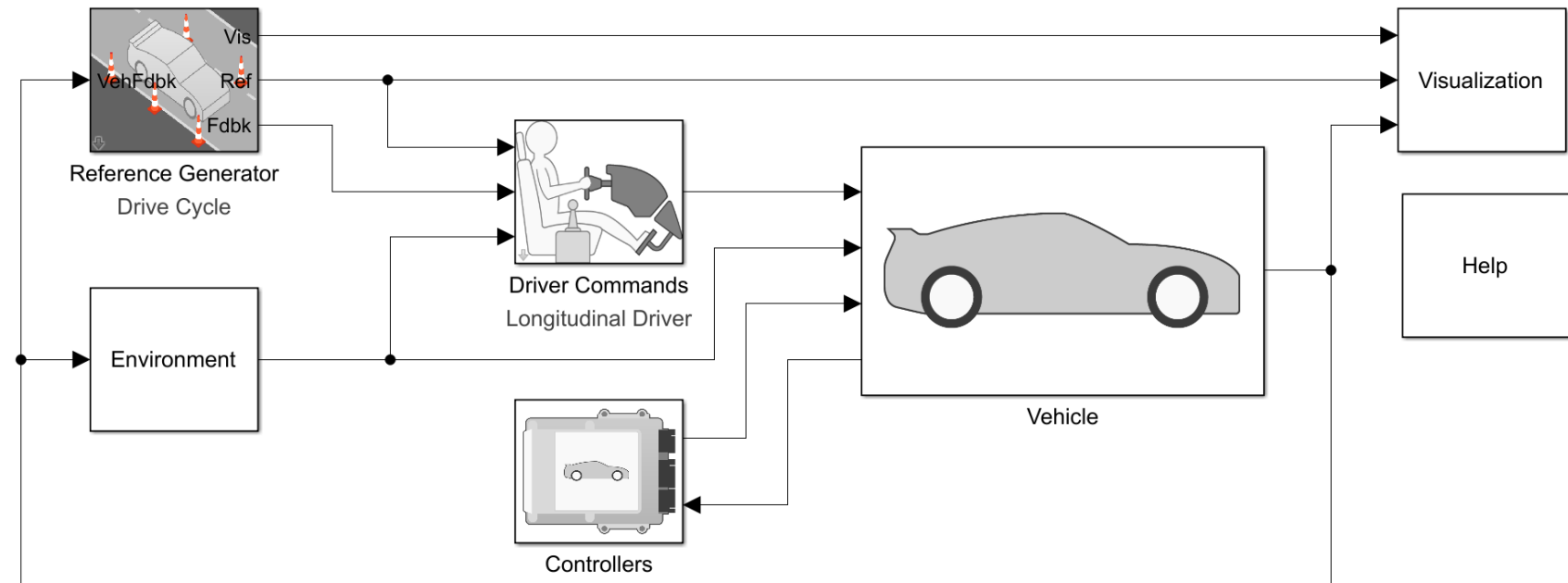


Value proposition:

- 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

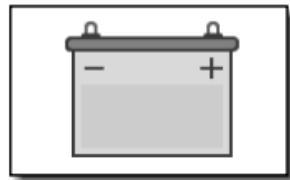
Agenda

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

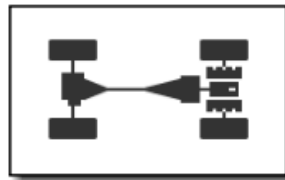


Powertrain Blockset

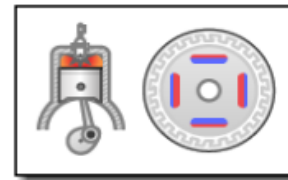
Library of blocks



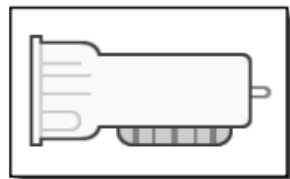
Energy Storage and Auxiliary Drive



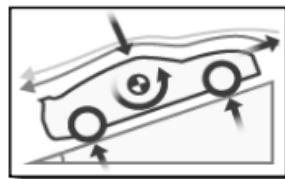
Drivetrain



Propulsion



Transmission

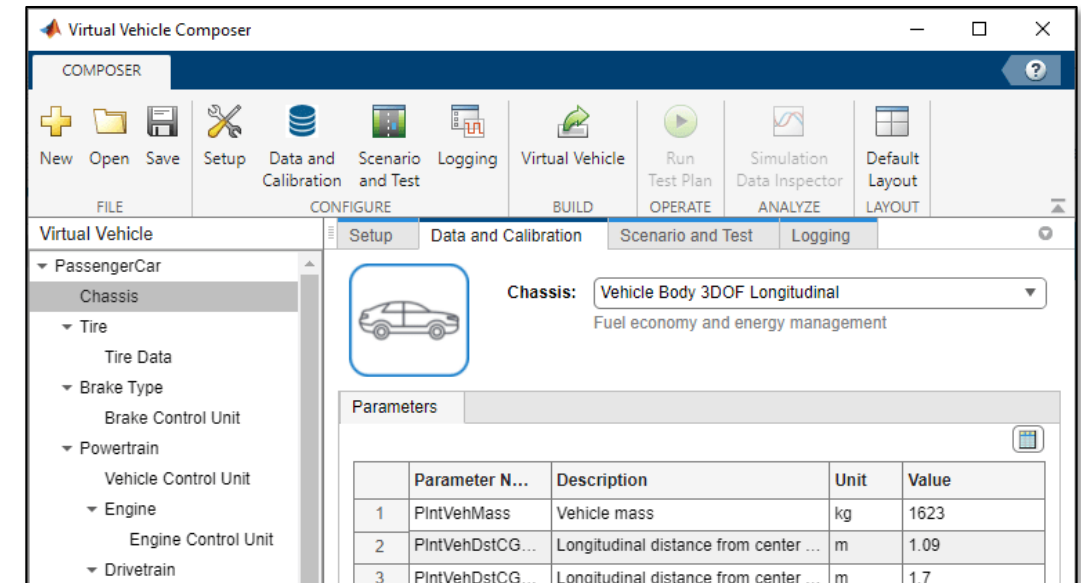


Vehicle Dynamics



Vehicle Scenario Builder

Virtual Vehicle Composer app



Pre-built reference applications

EV Reference Application

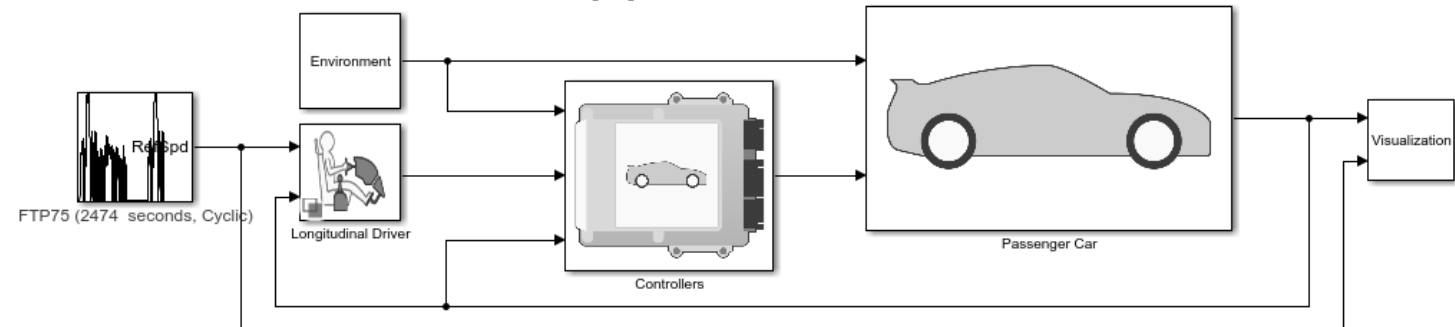
Simulate an EV model with a motor-generator, battery, direct-drive transmission, and associated powertrain control algorithms.

Optimize Transmission Control Module Shift Schedules

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

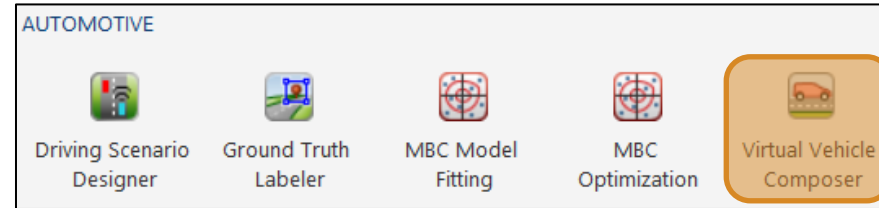
SI Engine Dynamometer Reference Application

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



Virtual Vehicle Composer App

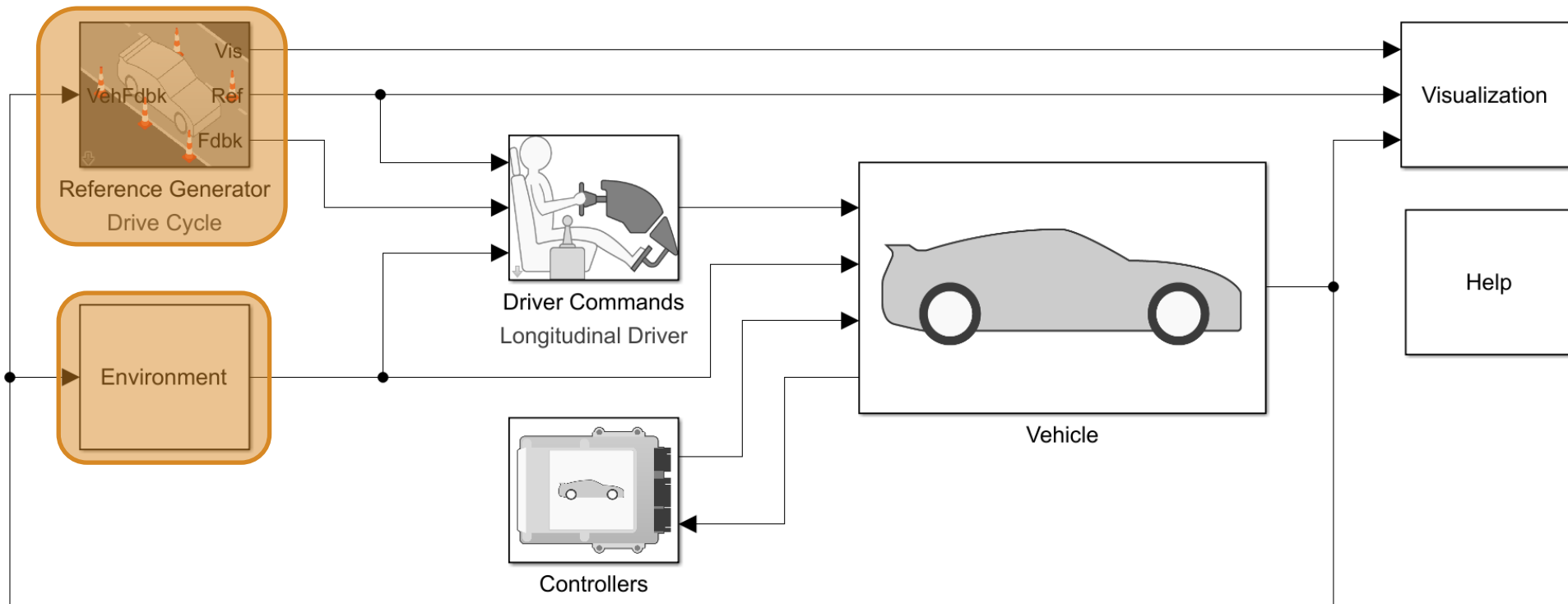
- Unified interface to quickly configure a virtual vehicle, select test cases, and review results
- Available with **Powertrain Blockset** and / or **Vehicle Dynamics Blockset**
- Includes options for detailed powertrain models, vehicle dynamics and controls
- Generated models are customizable



	Parameter N...	Description	Unit	Value
1	PIntVehMass	Vehicle mass	kg	1623
2	PIntVehDstCG...	Longitudinal distance from center ...	m	1.09
3	PIntVehDstCG...	Longitudinal distance from center ...	m	1.7

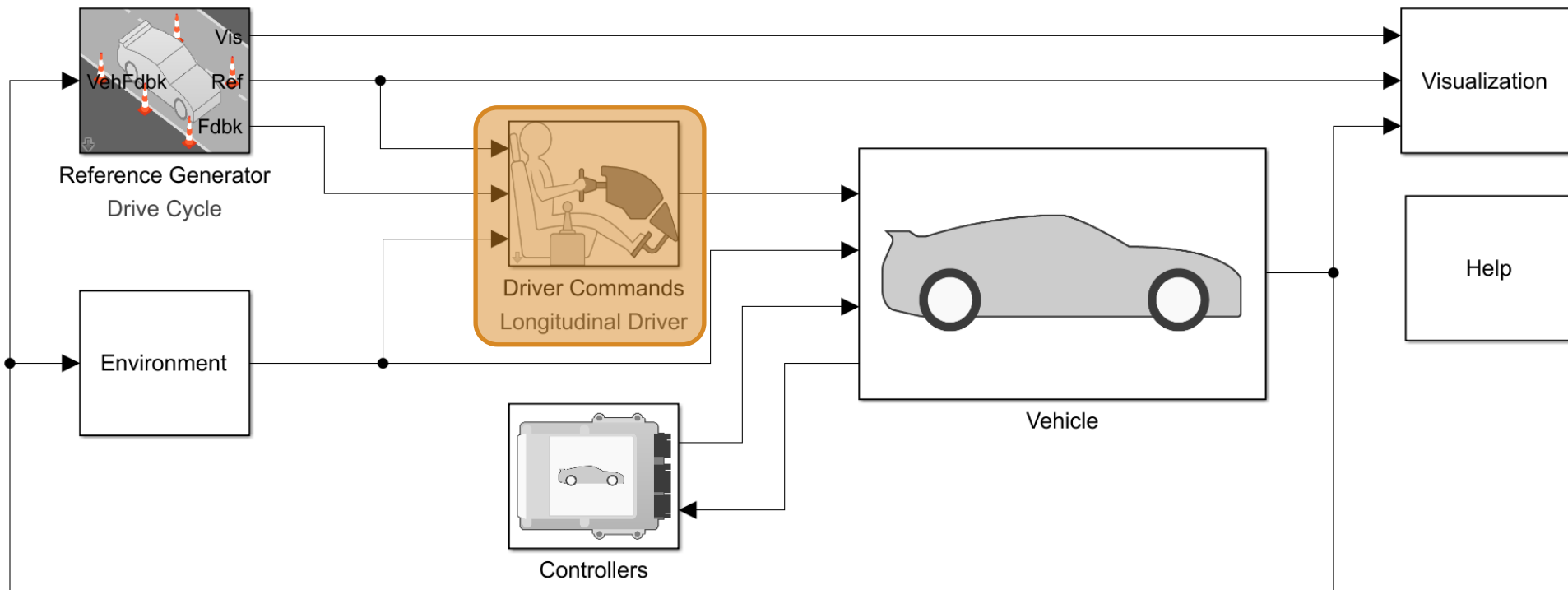
EV Model

1. Set target speed and ambient conditions



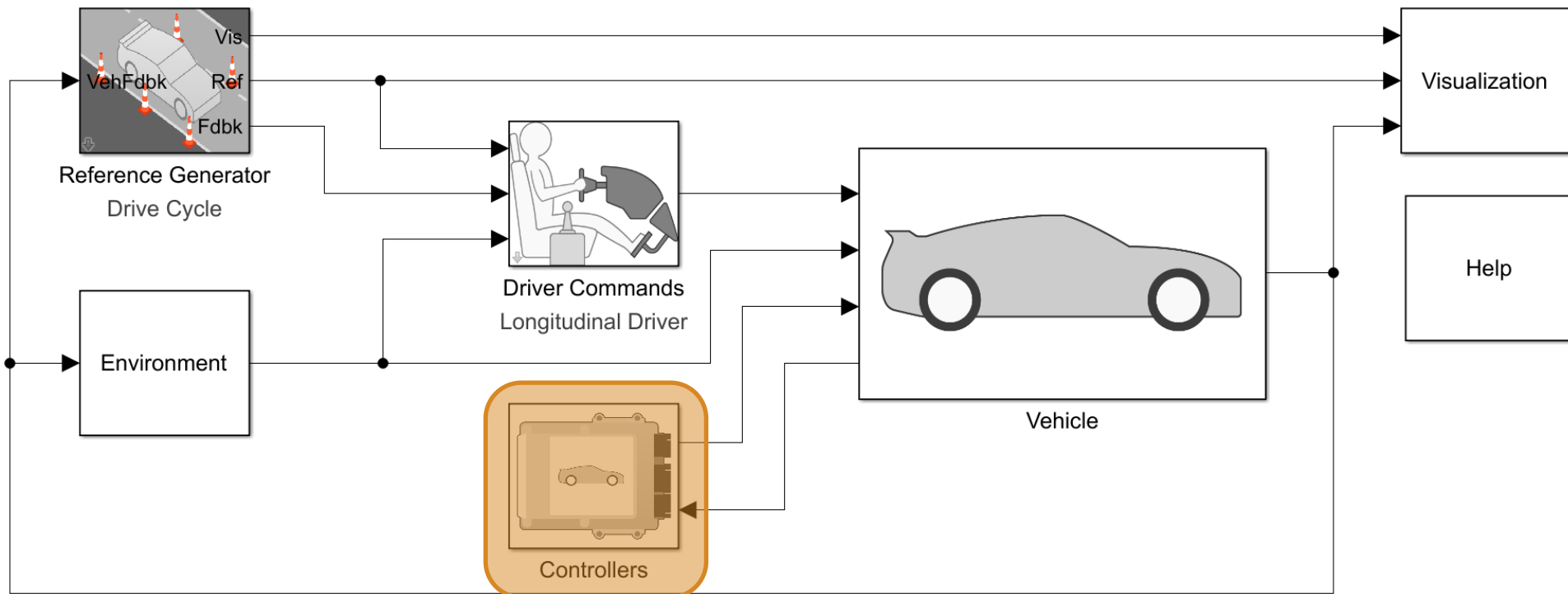
EV Model

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



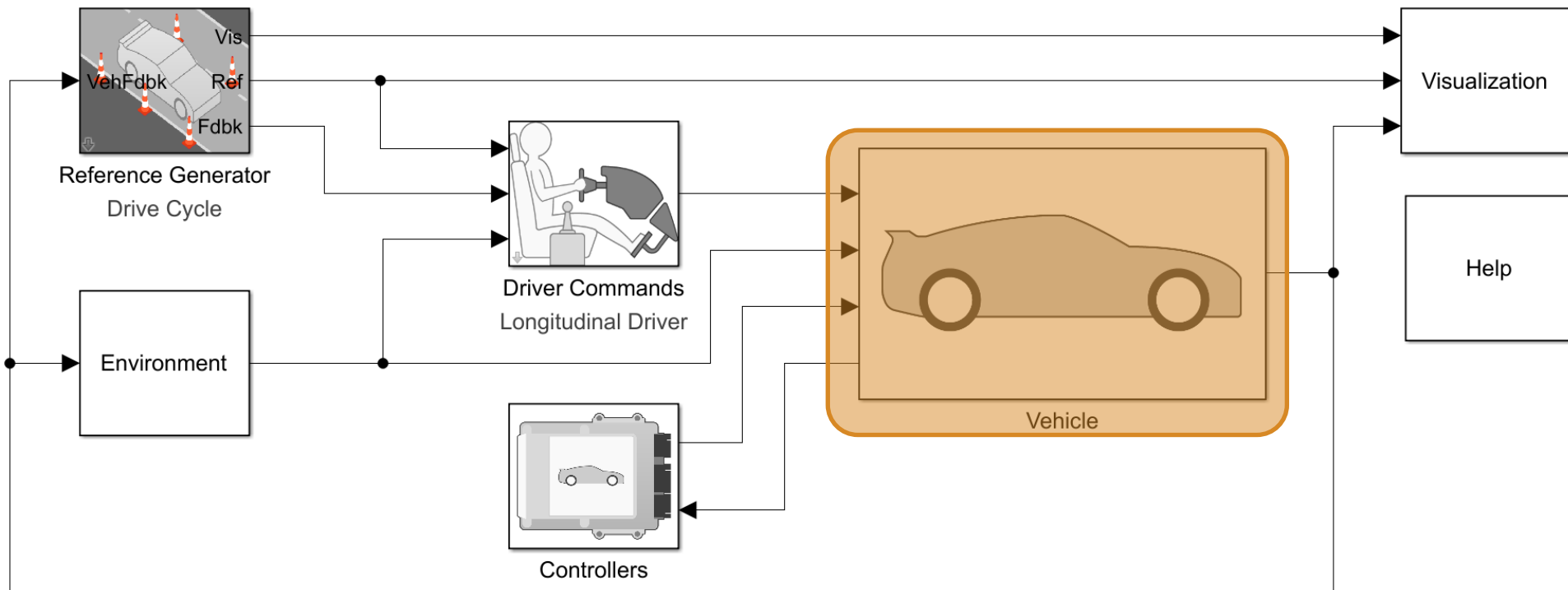
EV Model

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)



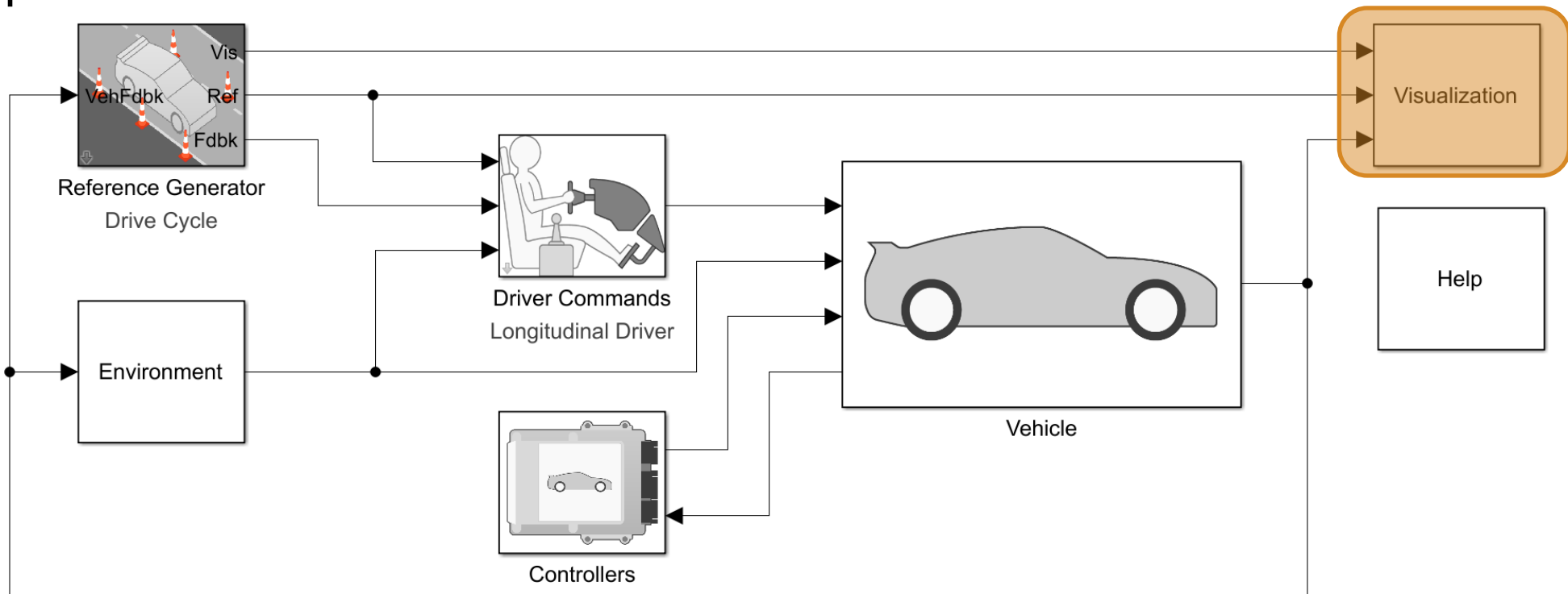
EV Model

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



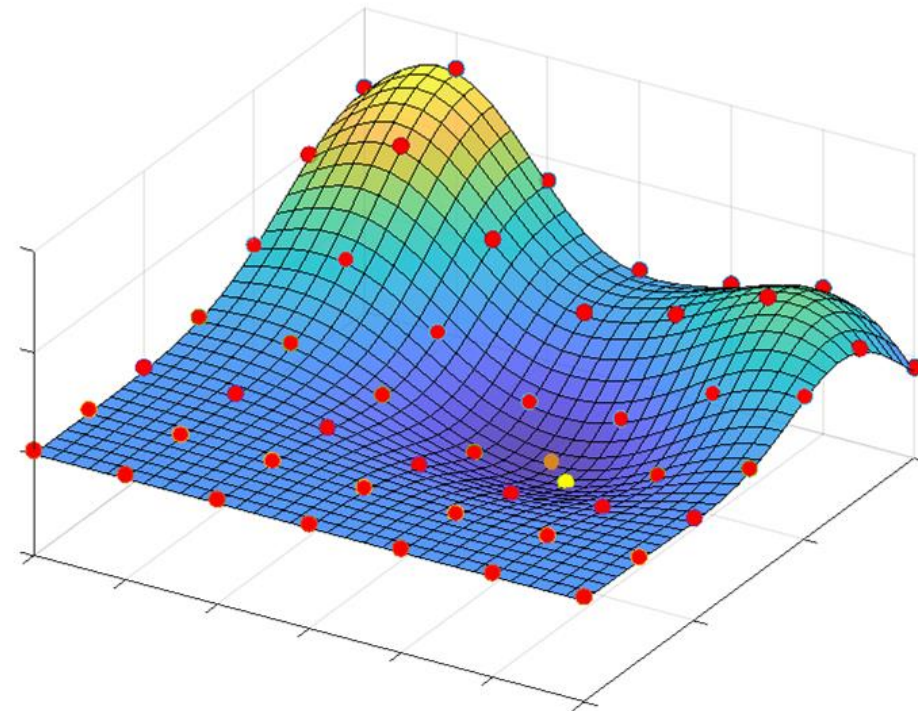
Summary: Vehicle Model

- 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

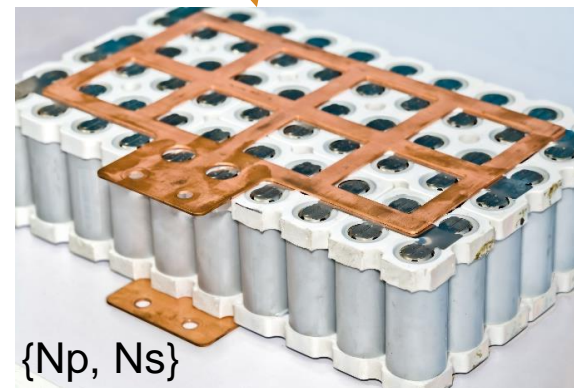
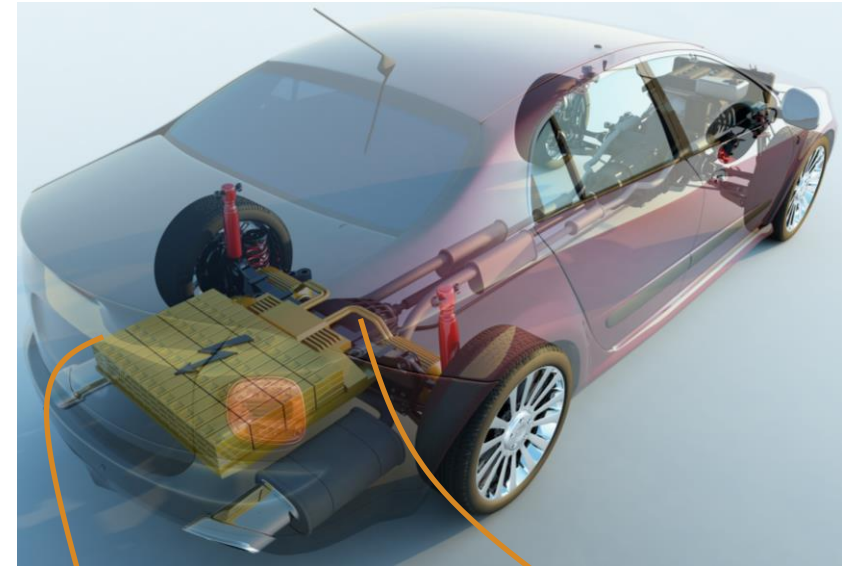
Agenda

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



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 (N_p)
 - Number of battery cells in series (N_s)
 - Gearbox ratio (N_d)



Component Sizing Problem Statement

- Objective:

$$\min f(\mathbf{x}) = w_1 * \text{Cost} - w_2 * \text{Range}$$

- Constraints:

$$g_1: \text{DriveCycleFault} \leq 0$$

$$g_2: \text{Range} \geq 400 \text{ km}$$

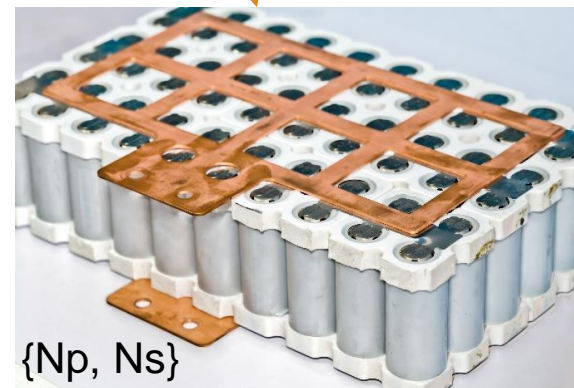
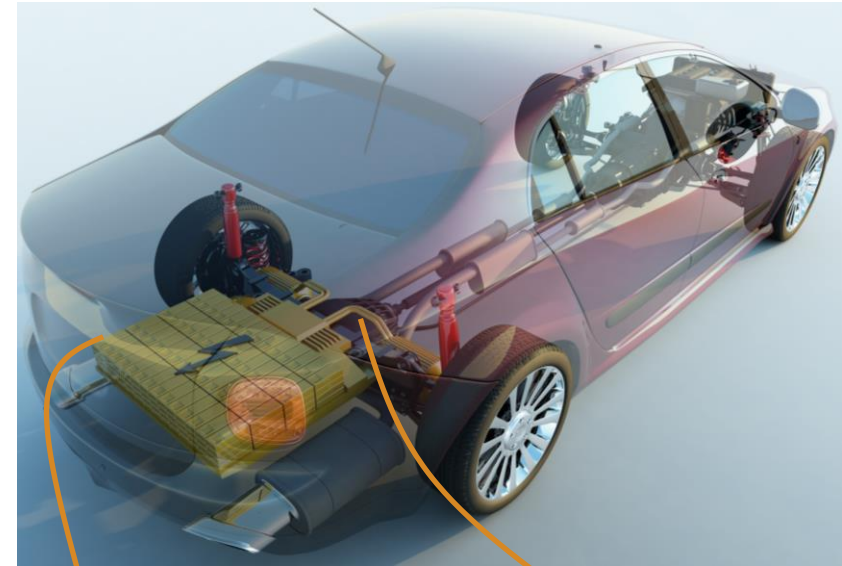
$$g_3: t_{0-100 \text{ kph}} \leq 7 \text{ s}$$

- Design Variables:

$$x_1: 10 < N_p < 50 \text{ (Integer)}$$

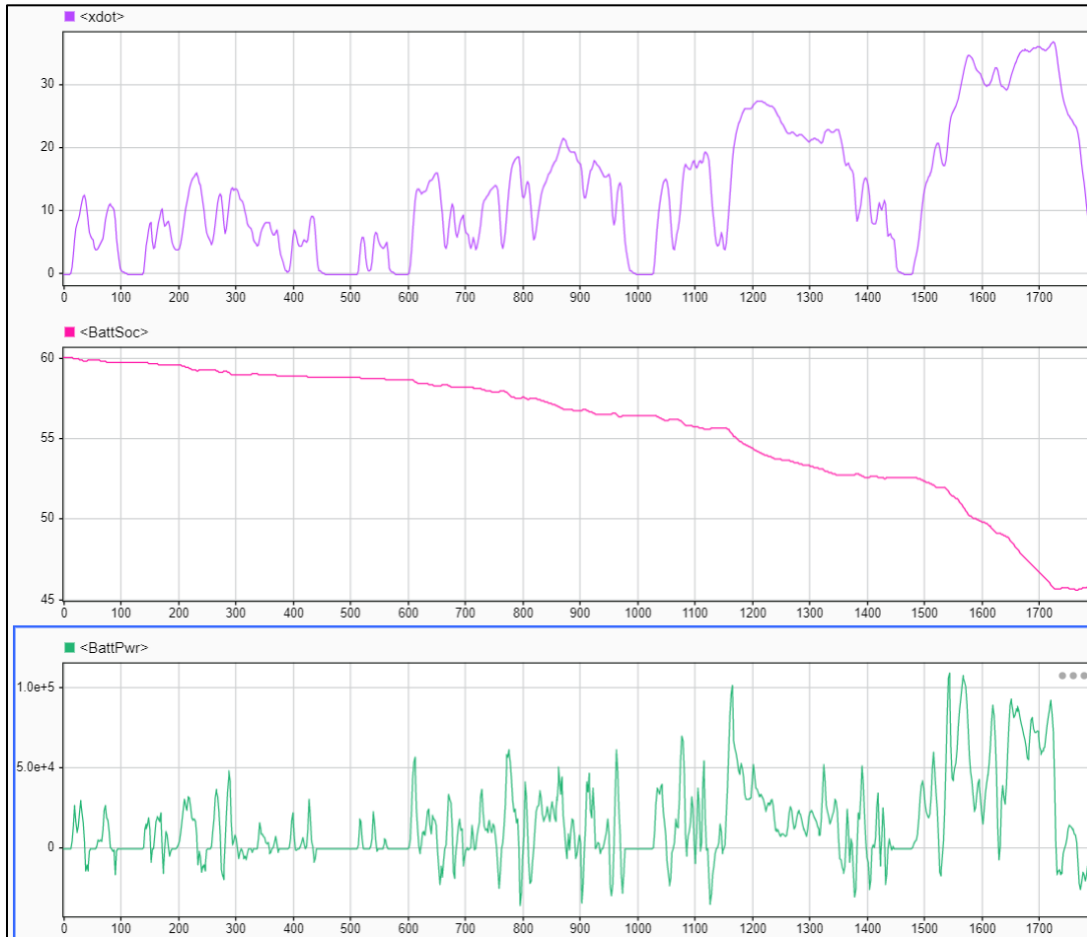
$$x_2: 80 < N_s < 140 \text{ (Integer)}$$

$$x_3: 7 < N_d < 10 \text{ (Continuous)}$$



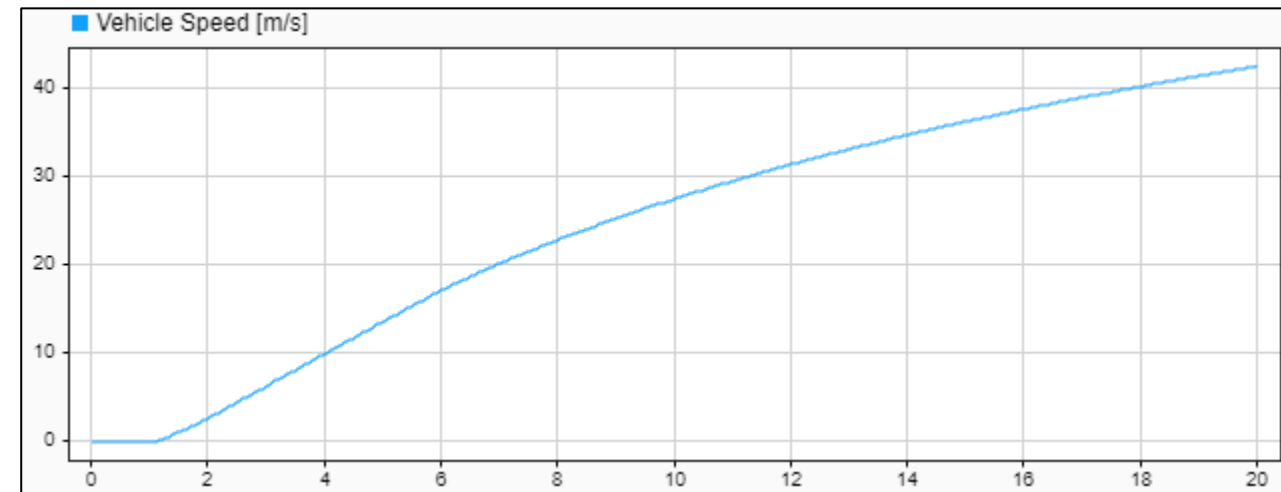
Initial Assessment

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



WLTP test

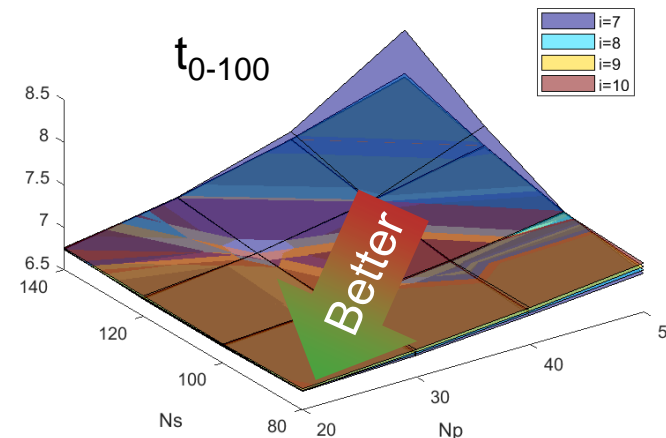
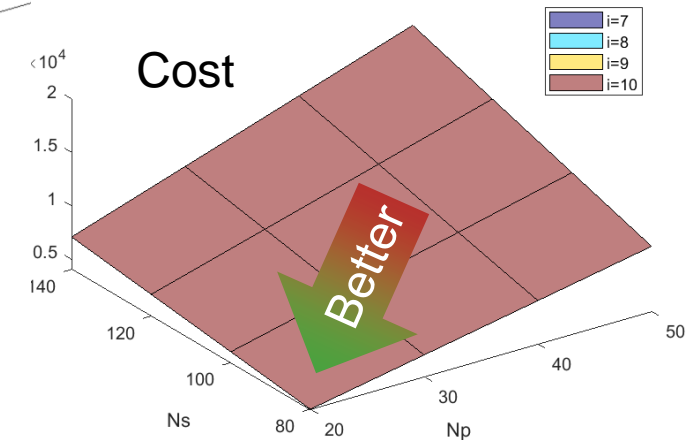
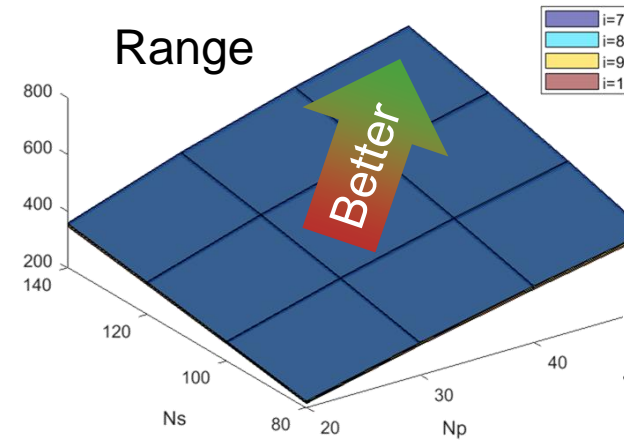
Metric	Target	Results
Battery cost [\$]	<i>min</i>	7537
Range [km]	≥ 400	371
t_{0-100} [s]	≤ 7.0	6.8



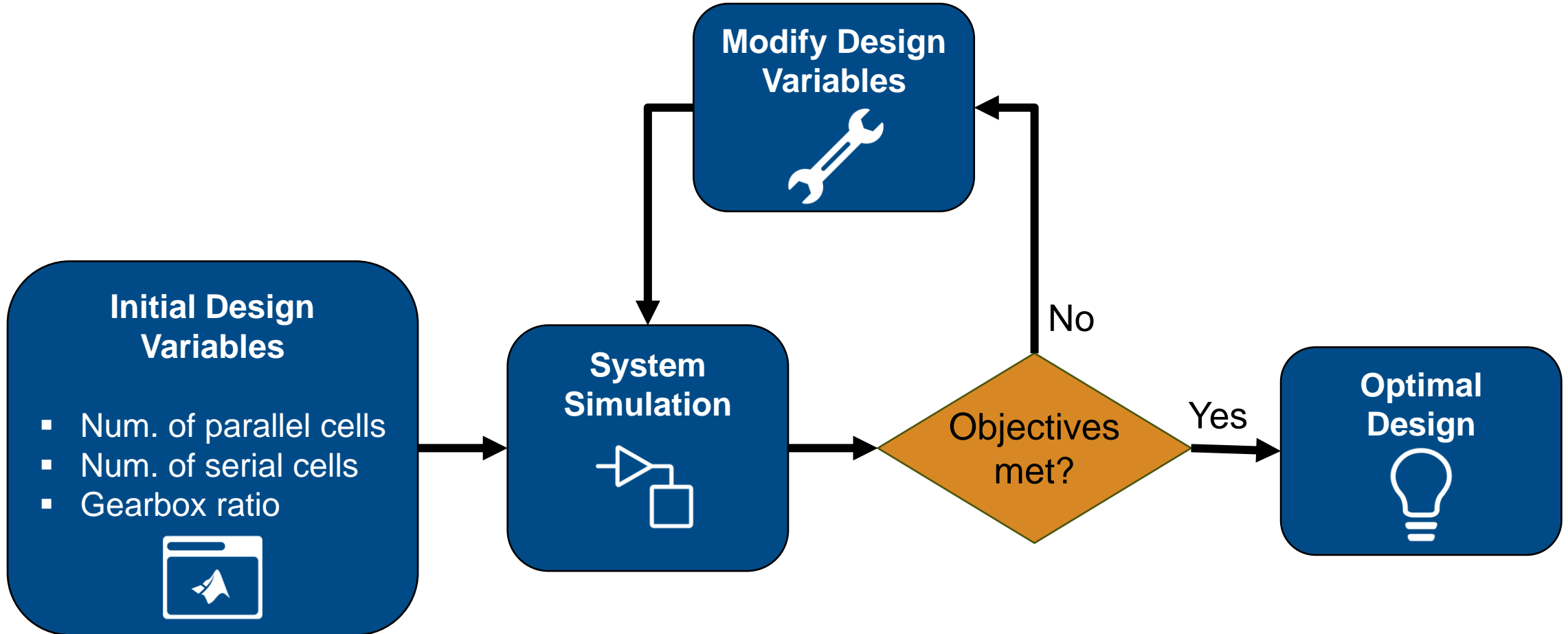
WOT test

Initial Assessment

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



Optimization Workflow

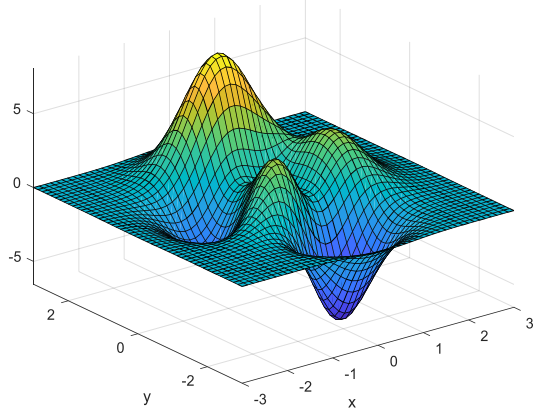


Selecting the Appropriate Optimization Solver

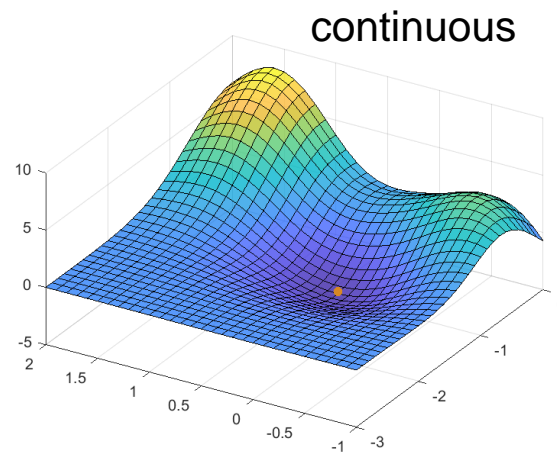
- MATLAB can indicate applicable optimization solvers
- Design variable space
 - Continuous
 - Integer (discrete)
 - Mixed Integer
- Local / global search space
 - Optimization Toolbox (local)
 - Global Optimization Toolbox

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

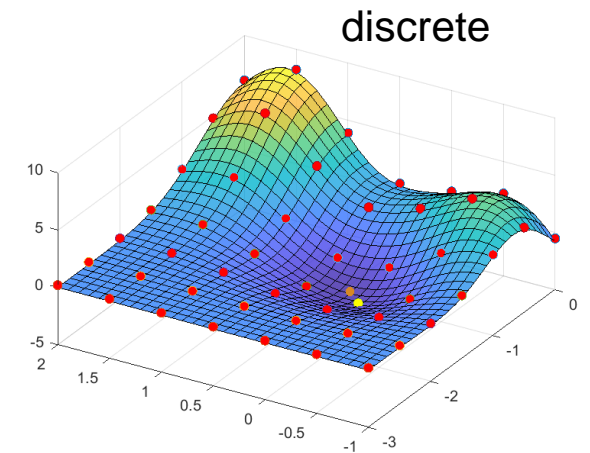
```
autoSolver = "fmincon"
allSolvers = 1x6 string
             "fmincon" "ga"           "patternse... "surrogat... "
```



Objective with multiple minima



Objective with single minimum



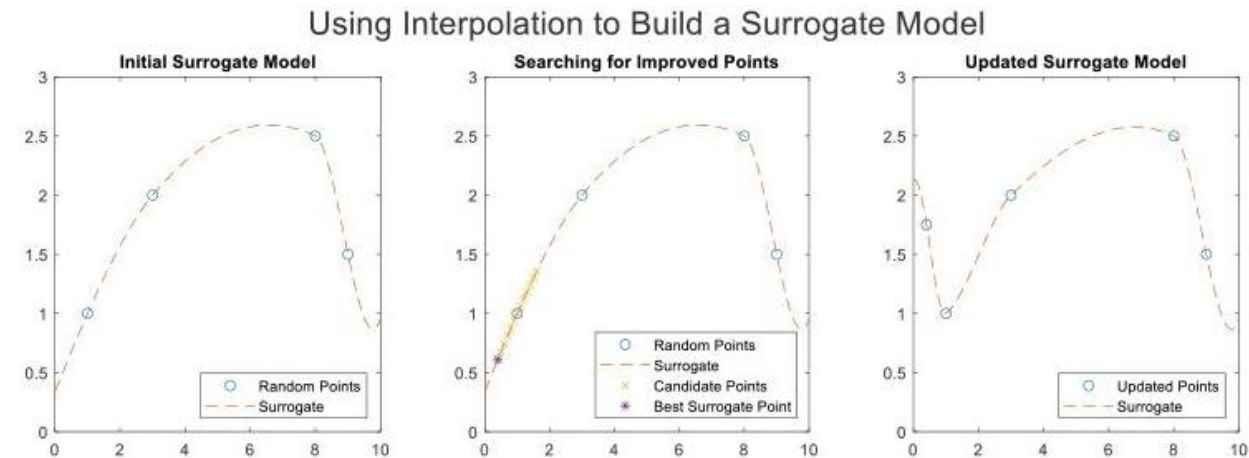
Solve Expensive Nonlinear Problems with `surrogateopt`

■ 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

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

Simulink Design Optimization Makes Problem Setup Easy

RESPONSE OPTIMIZATION | ITERATION PLOT

Design Variables Set: DesignVars

Uncertain Variables Set: None

Data to Plot: DesignVars

Optimize

Create Design Variables Set

Create Design Variables set: DesignVars

Continuous Variable	Value	Minimum	Maximum
<input checked="" type="checkbox"/> PintDiffmtlRatio	9.036	7	10

Discrete Variable	Value	Value Set
<input checked="" type="checkbox"/> PintBattNumCellPar	10	[10 2 50]
<input checked="" type="checkbox"/> PintBattNumCellSer	80	[80 2 140]

Response Optimization Options

Optimization Method: Surrogate optimization (Algorithm: Active-Set)

Method: Surrogate optimization

Optimization: Gradient descent, Pattern search

Objective: Surrogate optimization

Constraint: Simplex search

Maximum evaluations: 100

Maximally feasible:

Display level: Iteration

Restarts: 0

Iteration: 4, 5, 6, 7, 8

There is no data for DesignVars, run

Select continuous or discrete design variables

Select algorithm

Speed up optimization

Response Optimization Options

General | Optimization | Parallel | Linearization

Use the parallel pool during optimization

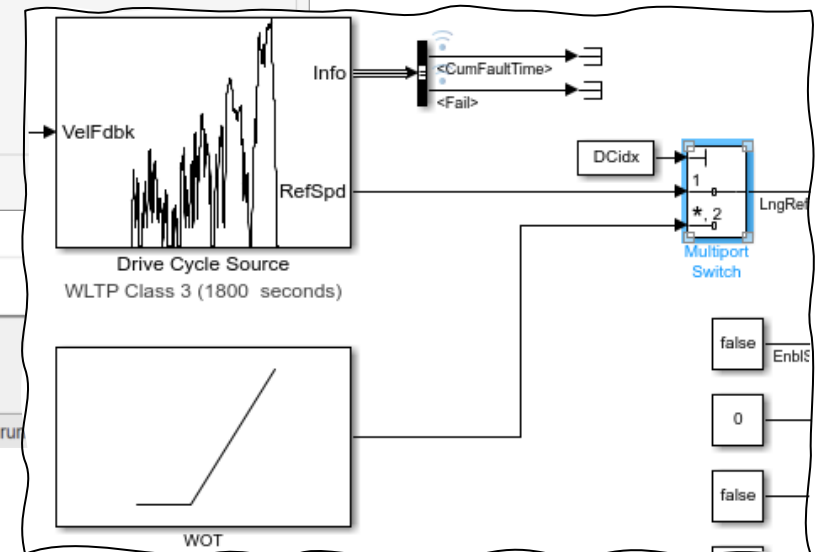
Stop Time: 1800

Accelerator: [dropdown]

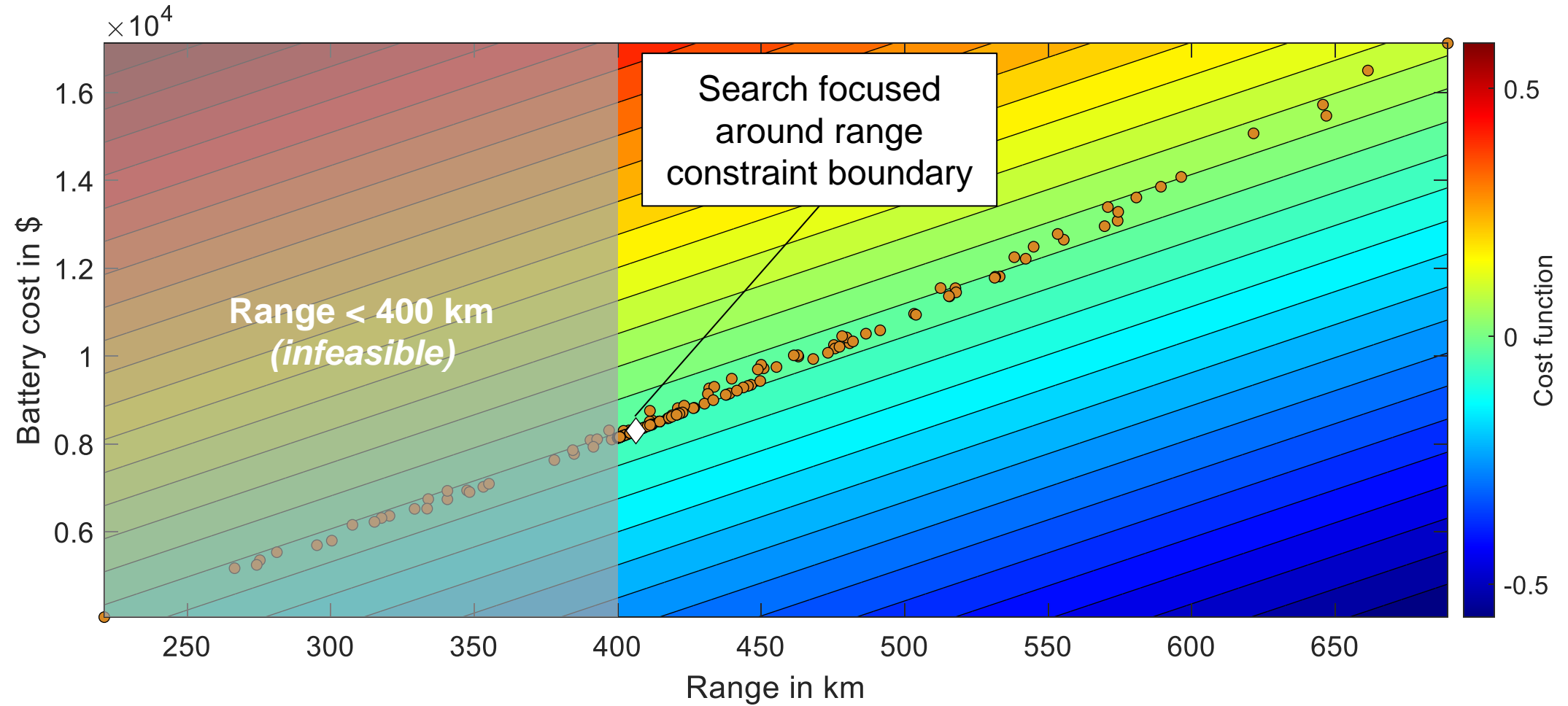
Fast Restart

Run

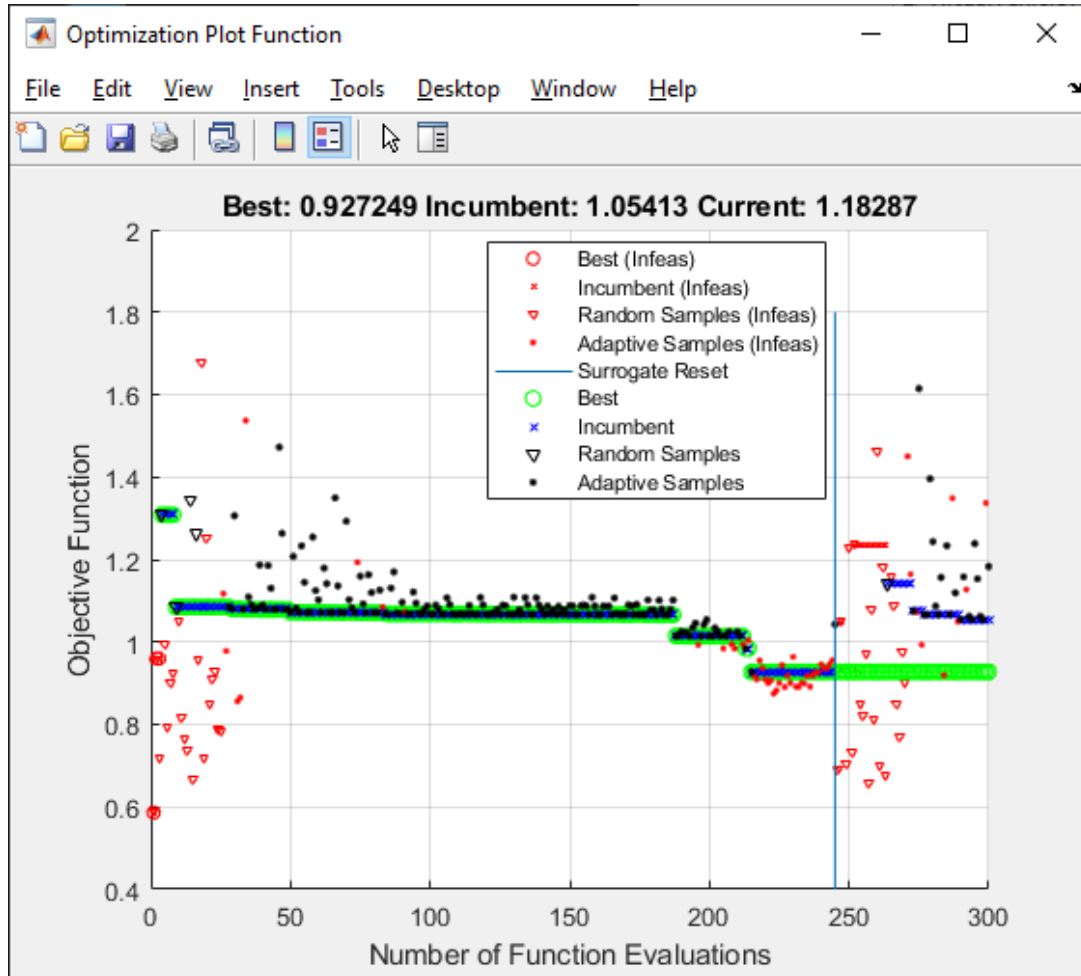
SIMULATE



Optimization Results



Optimization Results



Performed 300 function calls

Metric	Baseline	Optimized (% change)
Cost [\$]	7537	8297 (+10%)
Range [km]	371	406 (+9.4%) ✓
t_{0-100} [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

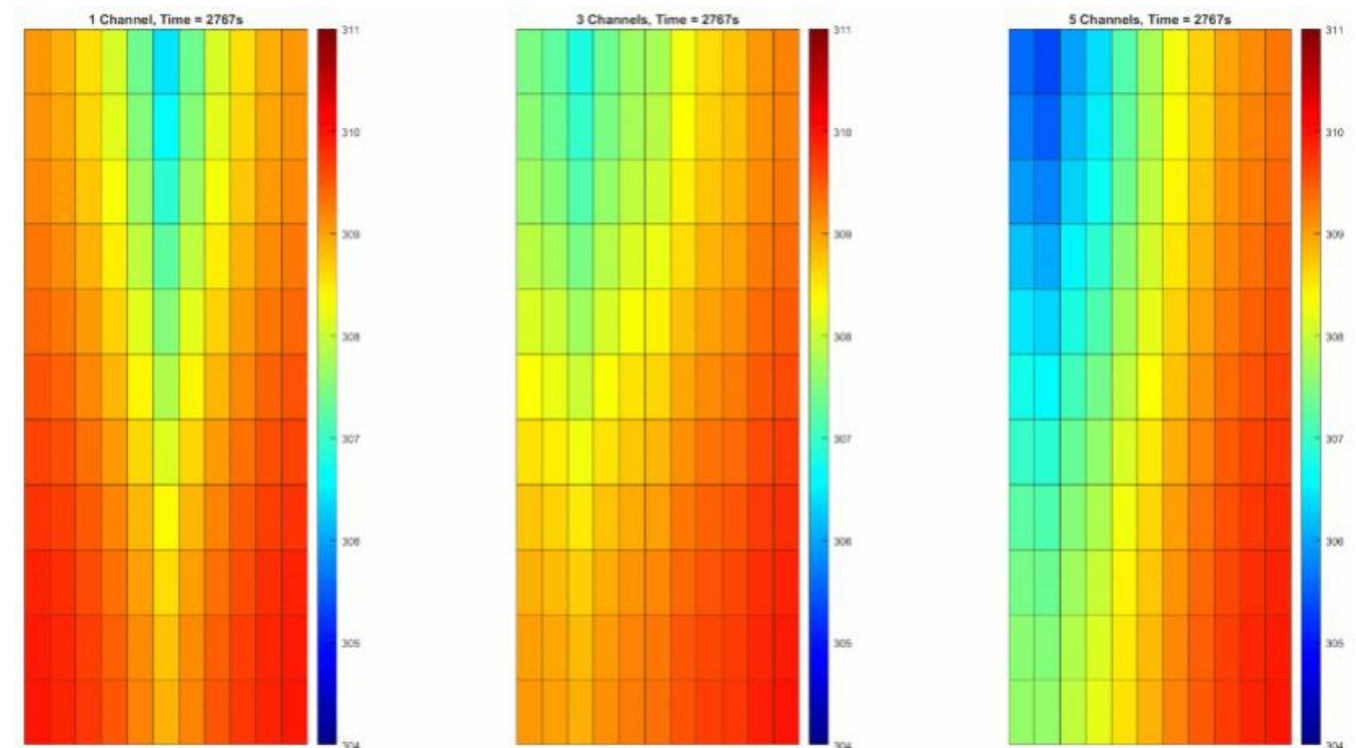
Summary: Battery Sizing

- 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

Agenda

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



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

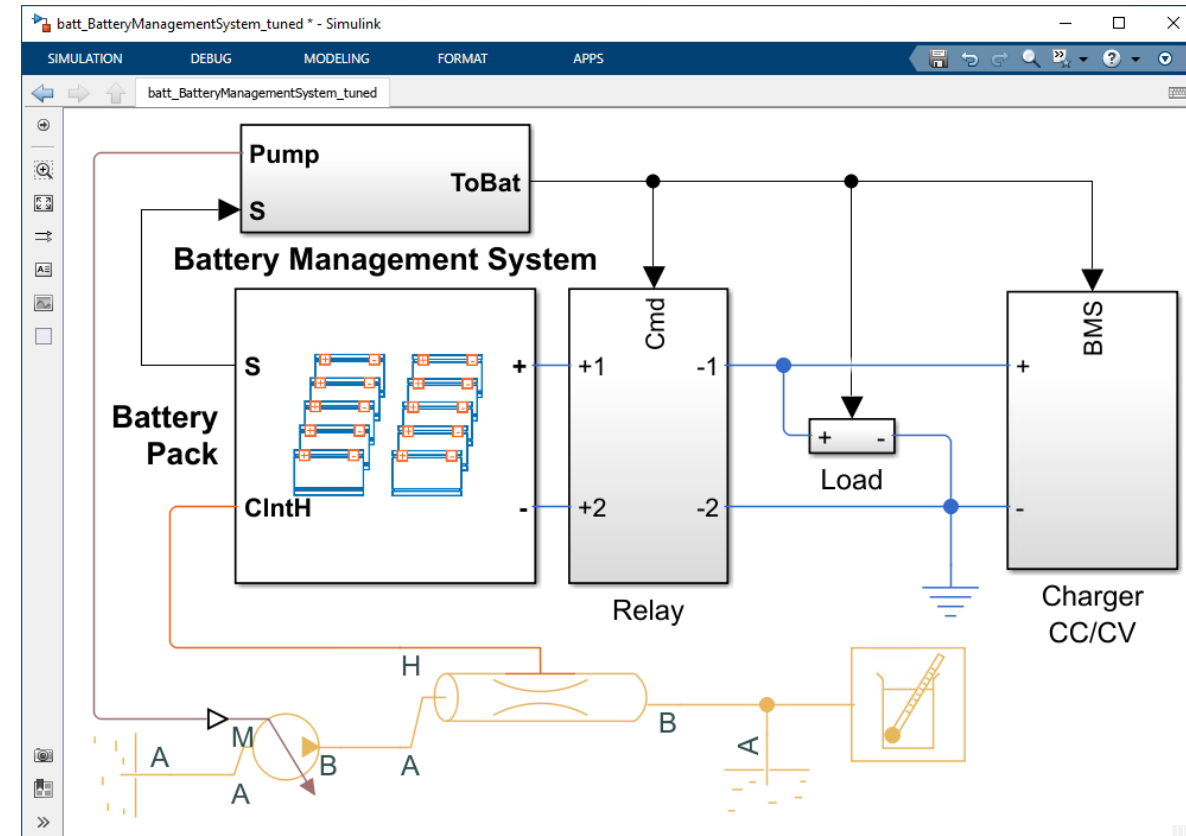
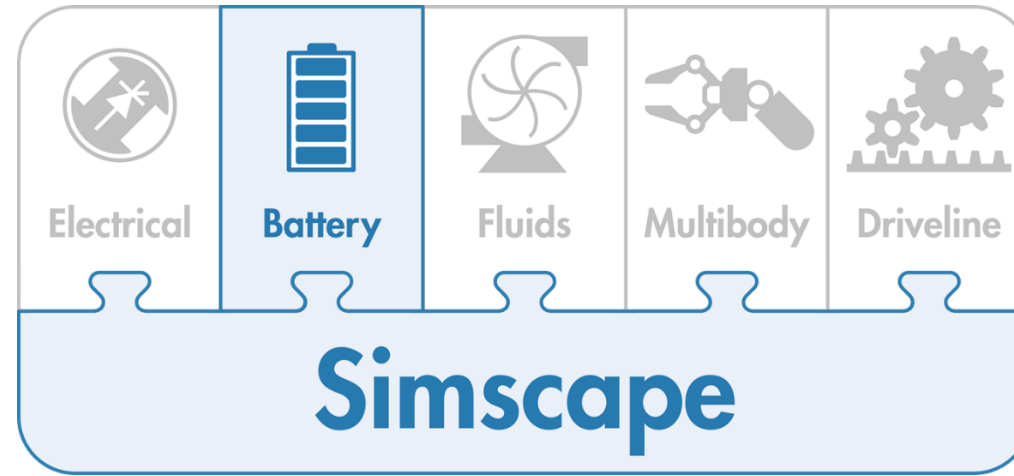
Select appropriate model fidelity for full system evaluation

5

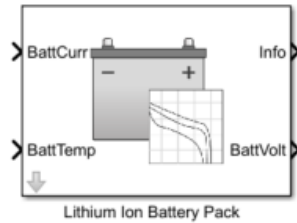
Evaluate battery design in full system

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



Block Parameters: Lithium Ion Battery Pack

Datasheet Battery (mask)

Implements a model for a lithium ion, lithium polymer, or lead acid battery based off of discharge characteristics taken at different temperatures. The model can be parameterized using a typical battery datasheet or through experimental measurement.

Block Options

Initial battery capacity: Parameter

Output battery voltage: Unfiltered

Parameters

Rated capacity at nominal temperature, BattChargeMax [Ah]: BattChargeMax

Open circuit voltage table data, Em [V]: Em*1 <100x1 double>

Open circuit voltage breakpoints 1, CapLUTBp []: CapLUTBp <1x100 double>

Internal resistance table data, RInt [Ohms]: RInt <4x100 double>

Battery temperature breakpoints 1, BattTempBp [K]: BattTempBp [263.15,273.1...]

Battery capacity breakpoints 2, CapSOCBp []: CapSOCBp <1x100 double>

Number of cells in series, Ns []: Ns 96

Number of cells in parallel, Np []: Np 31

Initial battery capacity, BattCapInit [Ah]: BattCapInit*BattSocInit/.75

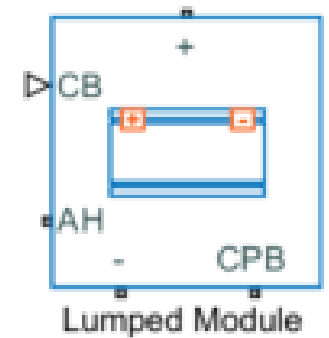


Block Parameters: Lumped Module

Module1

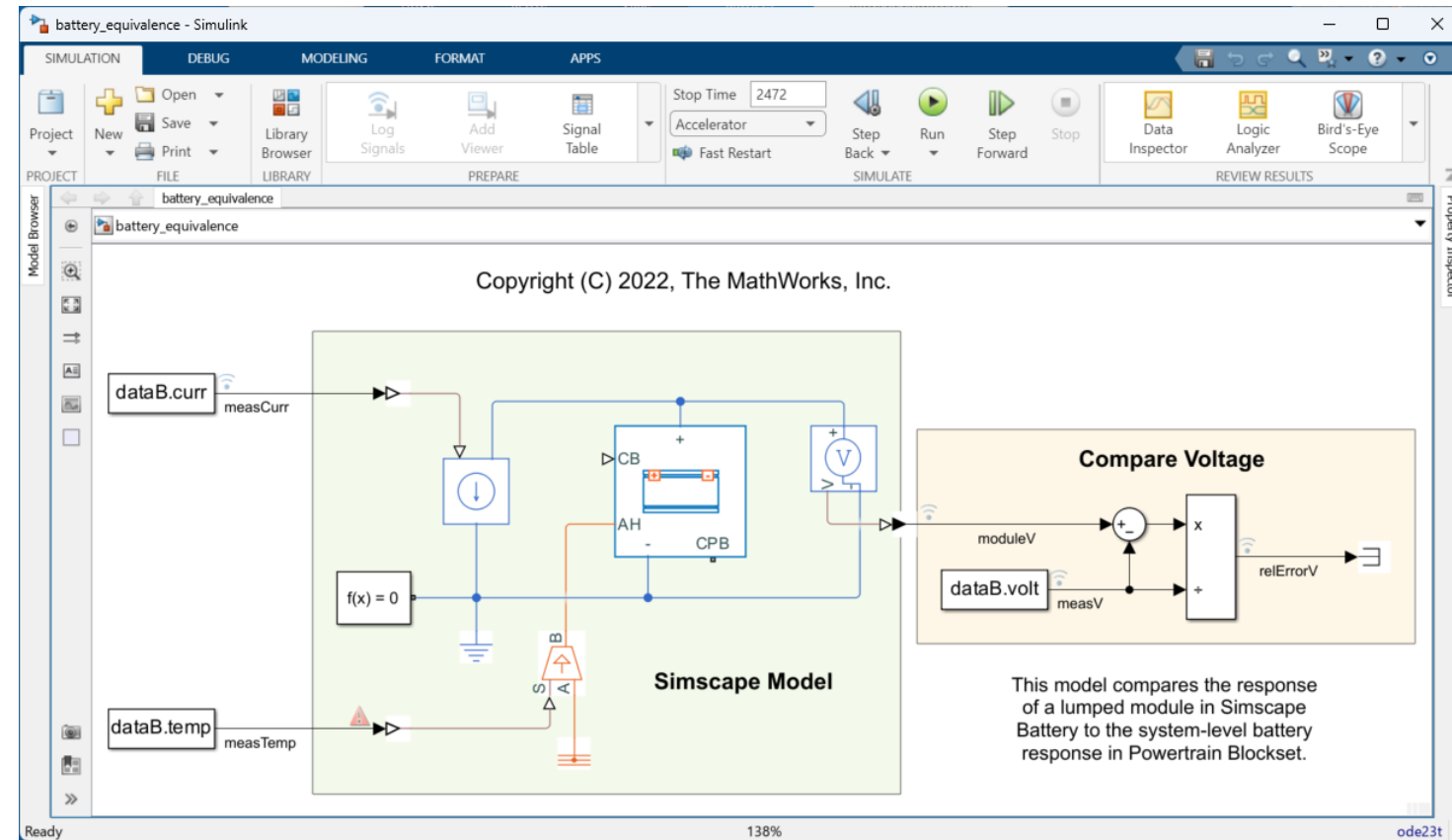
Settings Description

NAME	VALUE
Main	
> Vector of state-of-charge values, SOC	CapSOCBp
> Vector of temperatures, T	BattTempBp K
> Open-circuit voltage, V0(SOC,T)	repmat(Em,1,4) V
> Terminal voltage operating range [Min Max]	[0, inf] V
> Terminal resistance, R0(SOC,T)	RInt' Ohm
> Cell capacity, AH	BattChargeMax A*hr
Extrapolation method for all tables: Nearest	
Thermal	
> Thermal mass	100 J/K
> Cell level coolant thermal path resistance	1.2 K/W
> Cell level ambient thermal path resistance	25 K/W
Cell Balancing	
> Cell balancing switch closed resistance	0.01 Ohm
> Cell balancing switch open conductance	1e-8 1/Ohm
> Cell balancing switch operation threshold	0.5
> Cell balancing shunt resistance	50 Ohm
Initial Targets	
> <input type="checkbox"/> Cell model current (positive in)	
> <input type="checkbox"/> Cell model terminal voltage	
> <input checked="" type="checkbox"/> Cell model state of charge	
Priority	High
Value	0.75 1



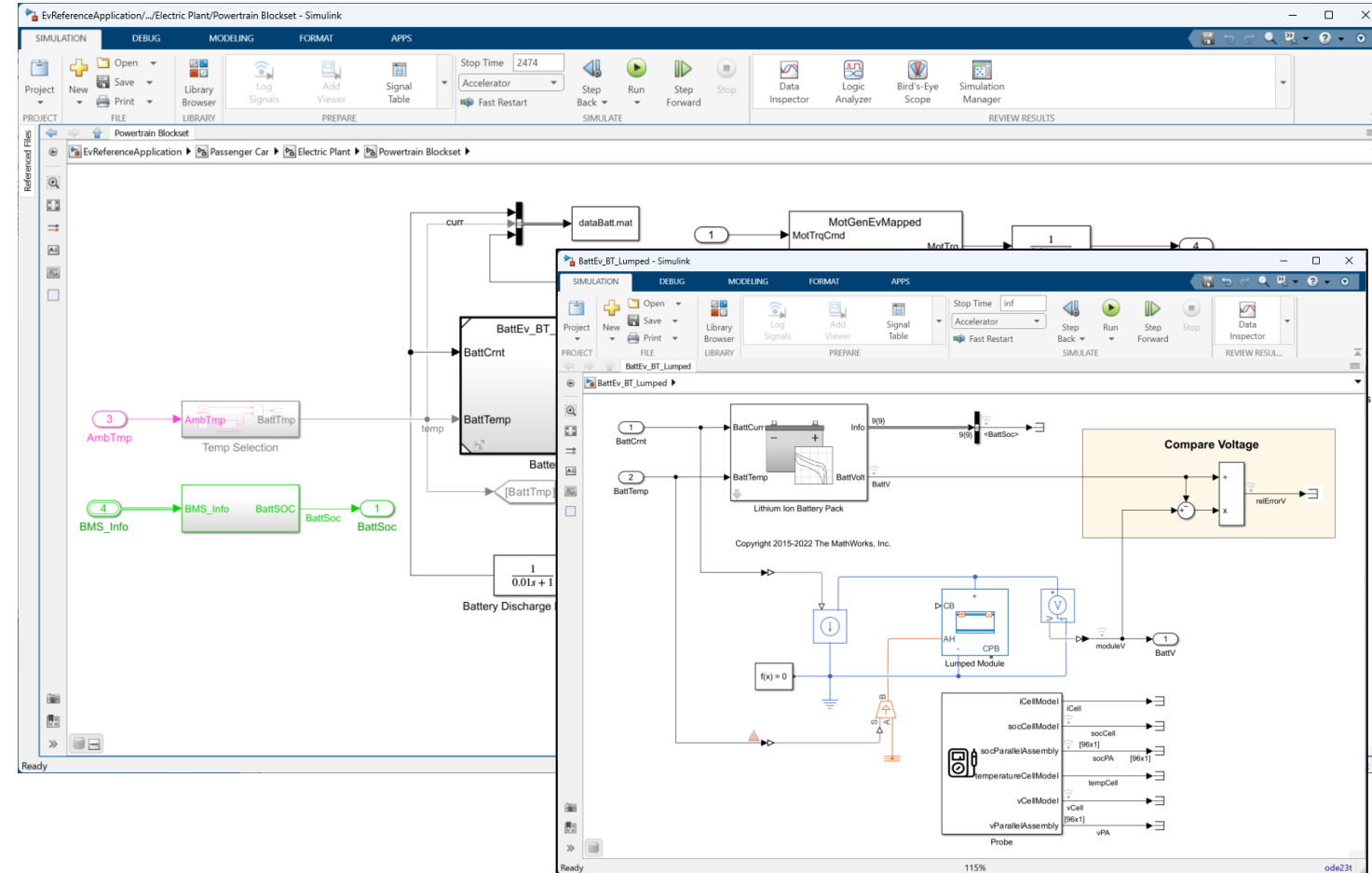
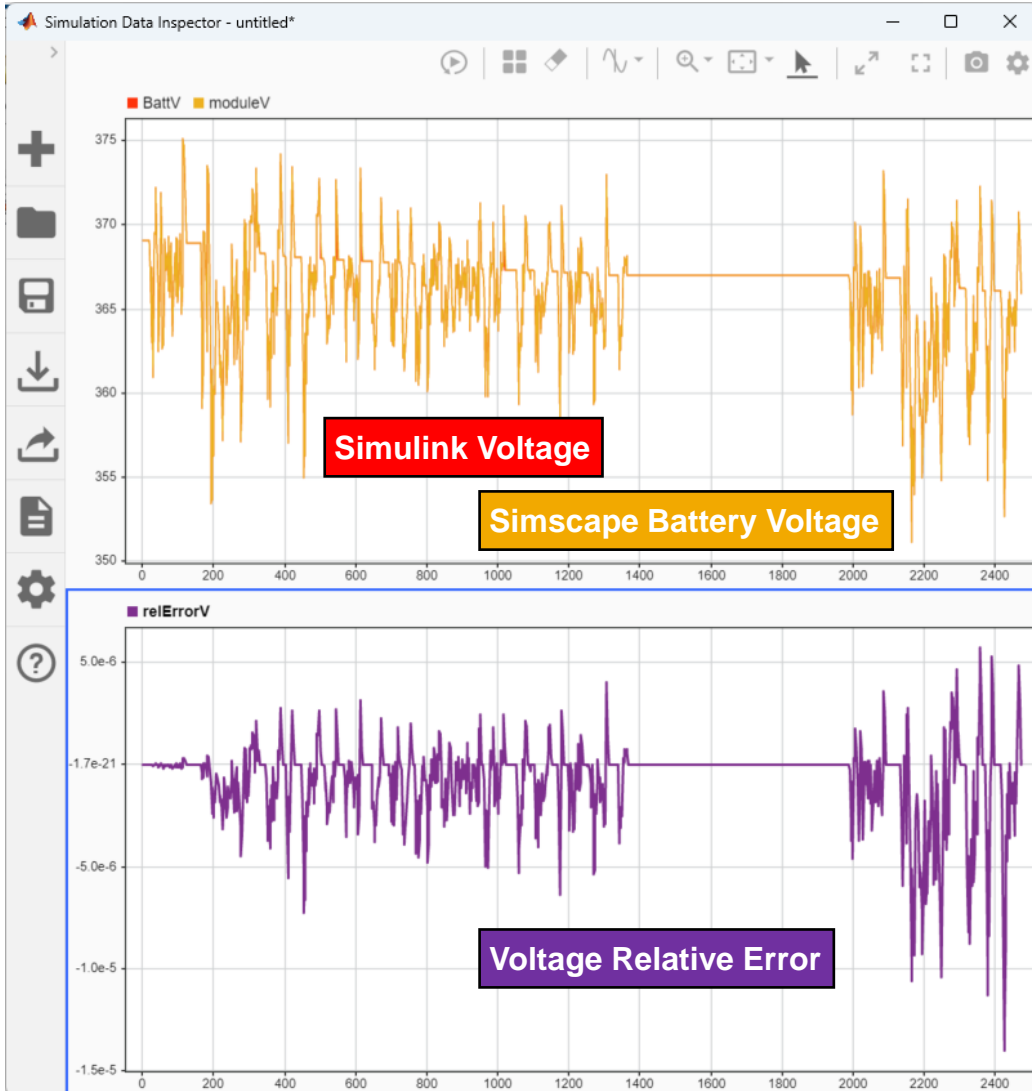
Create Lumped Battery Pack Model in Simscape Battery and Demonstrate Equivalence

Unit Test



Create Lumped Battery Pack Model in Simscape Battery and Demonstrate Equivalence

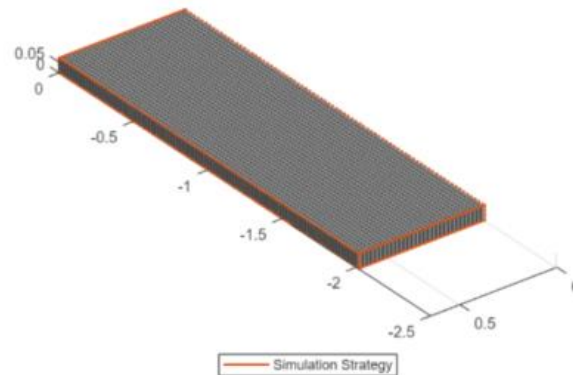
System Test



Design Battery Systems in Simscape Battery

- Create battery pack with higher resolution

Lumped (1 cell model for entire pack)



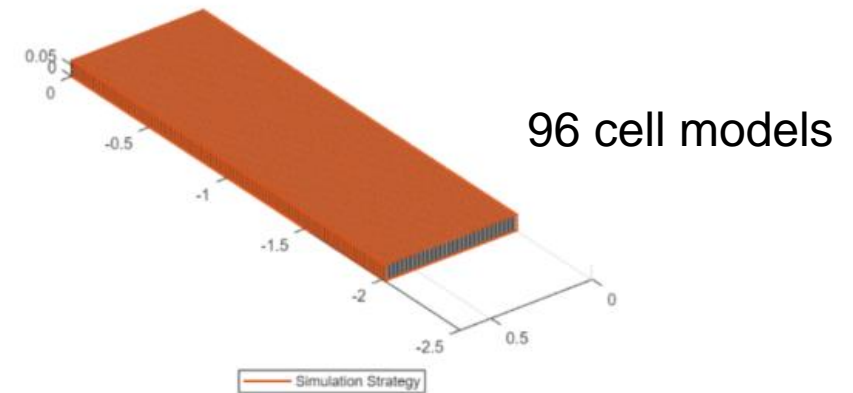
Define module

```
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)



Define module

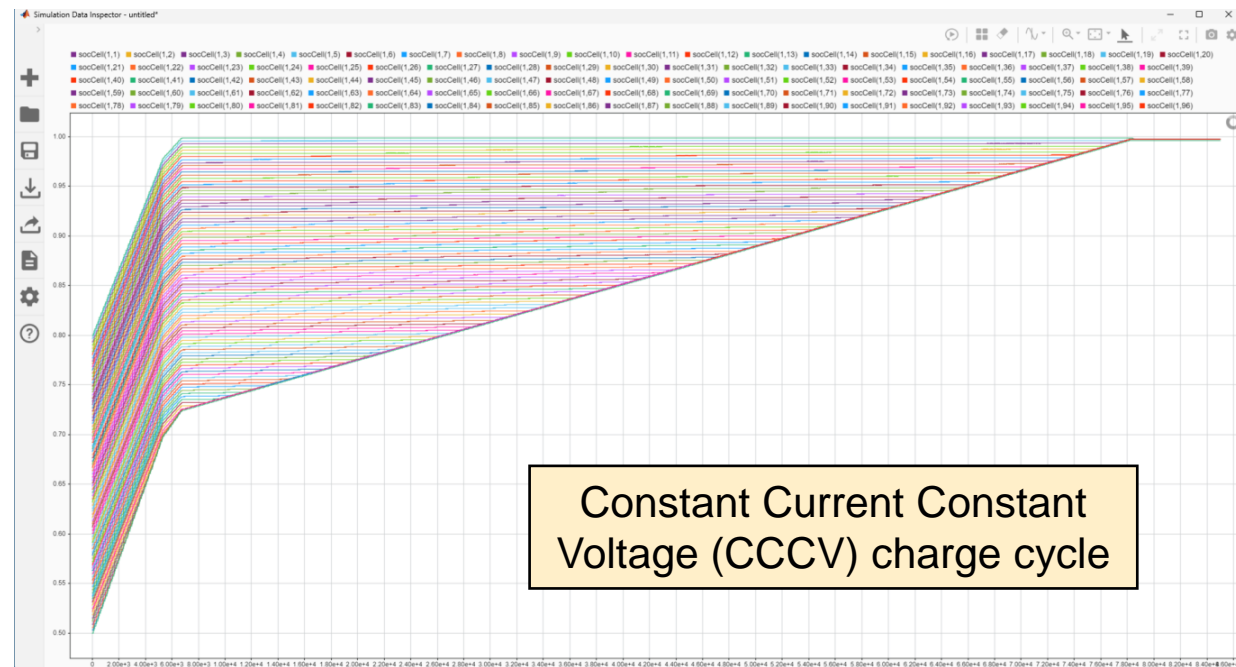
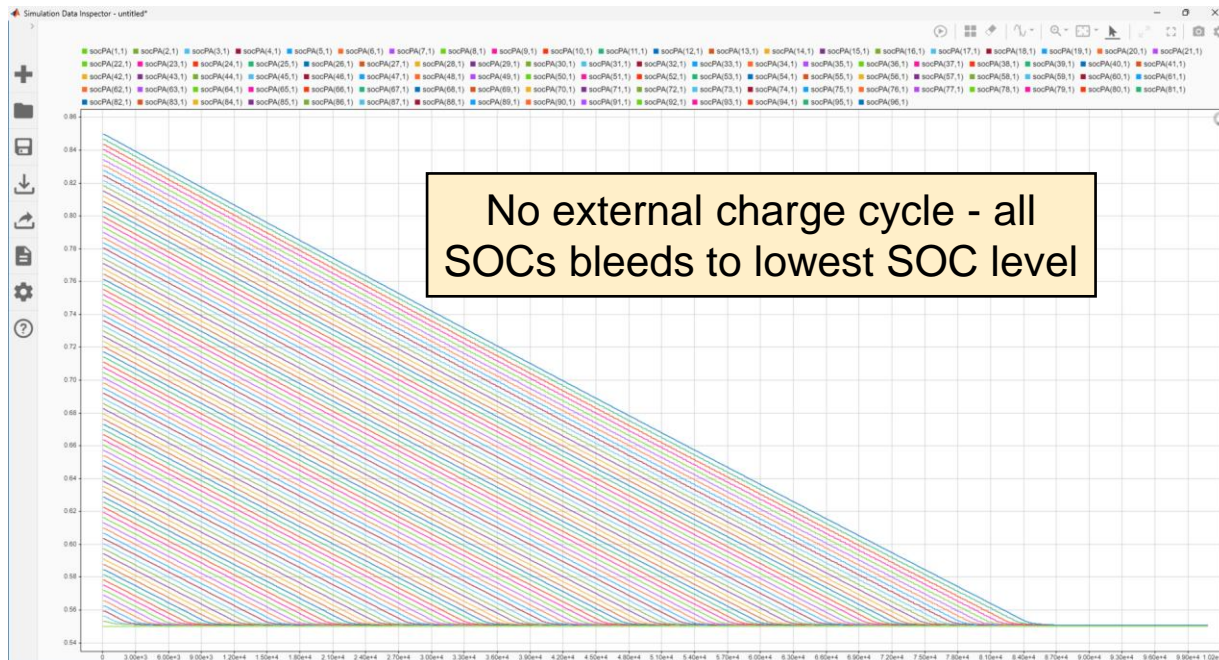
```
Ns = 96; % number of parallel assemblies in series
batteryModule = Module(ParallelAssembly = batteryParallelAssembly, numSeriesAssemblies = Ns);
```

Define simulation strategy

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

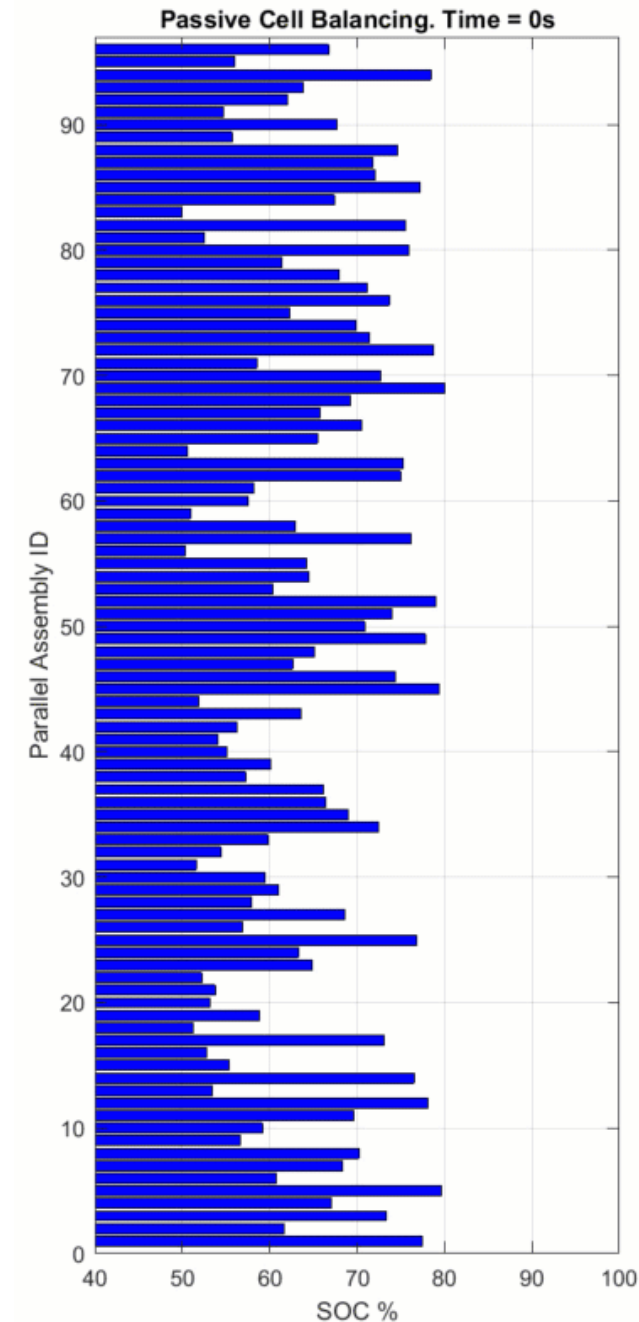
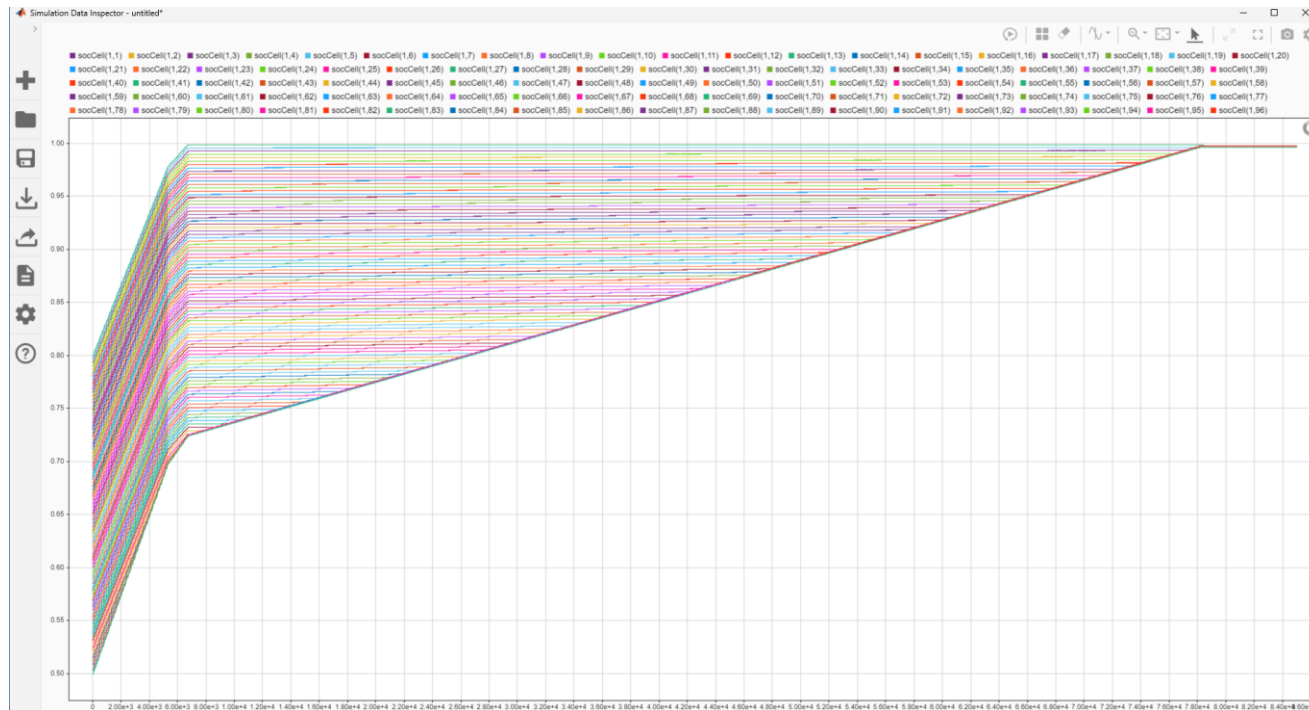
Passive Cell Balancing

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



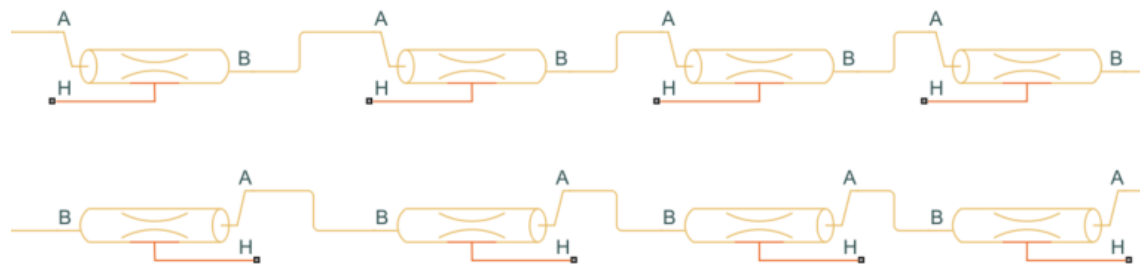
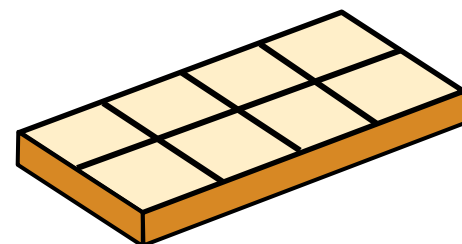
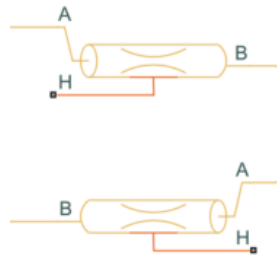
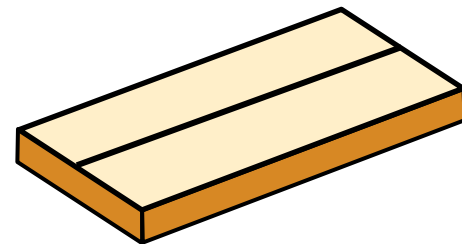
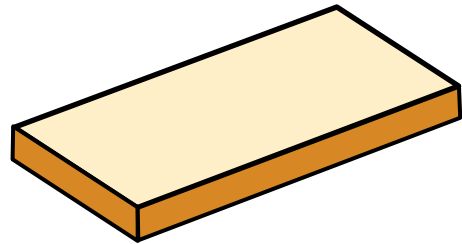
Passive Cell Balancing During CCCV

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

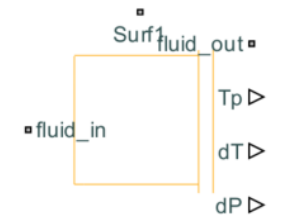


Thermal Management

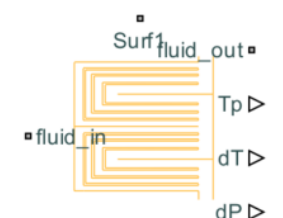
- Change the simulation strategy of cooling plates to meet your model resolution needs



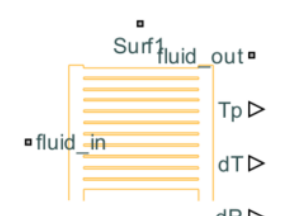
Connections dependent on cooling plate architecture



Edge Cooling



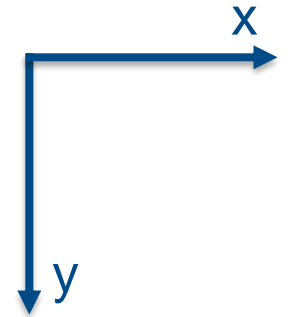
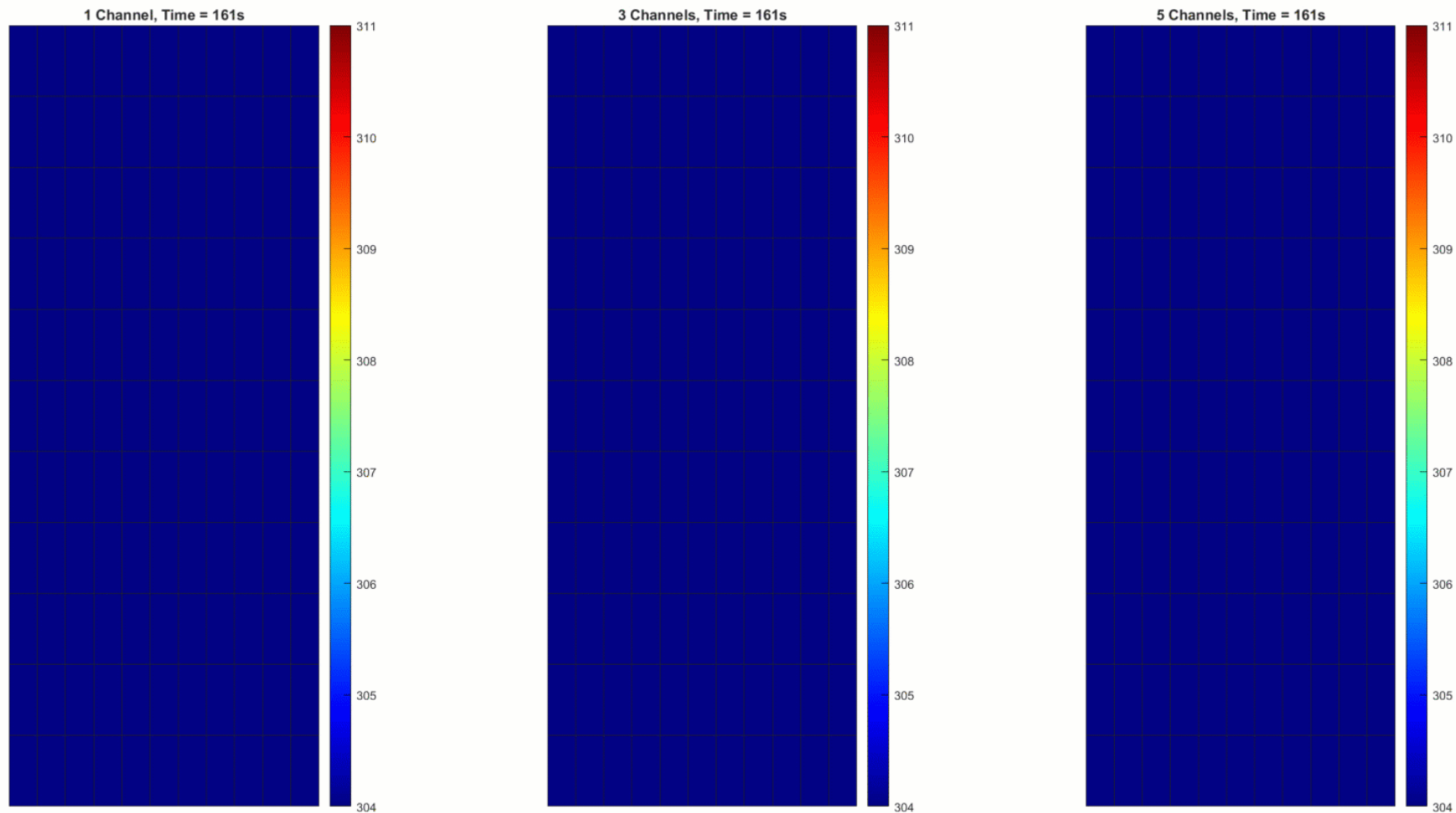
U-shaped Channels



Parallel Channels

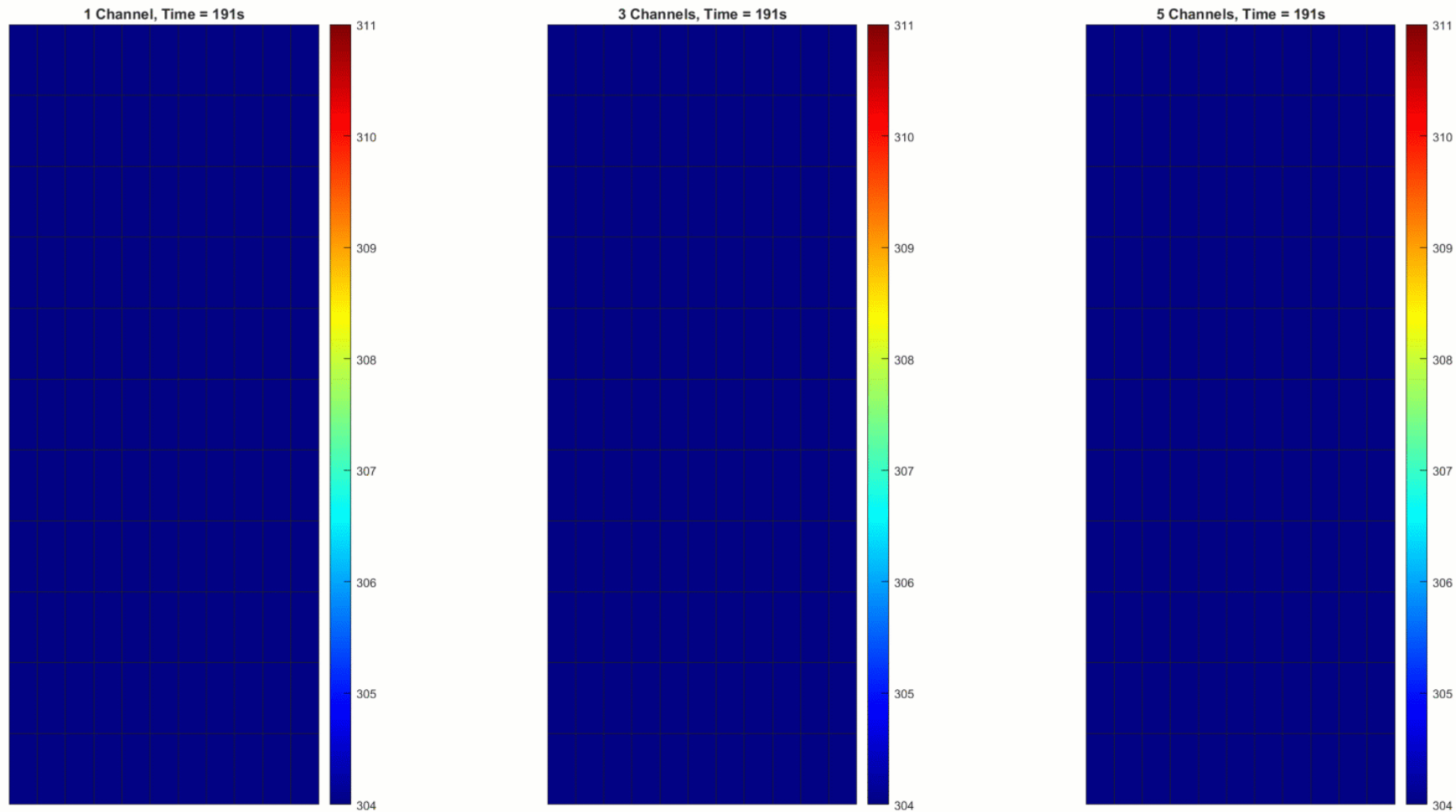
Thermal Management

- Parallel cooling channels oriented along the x-axis



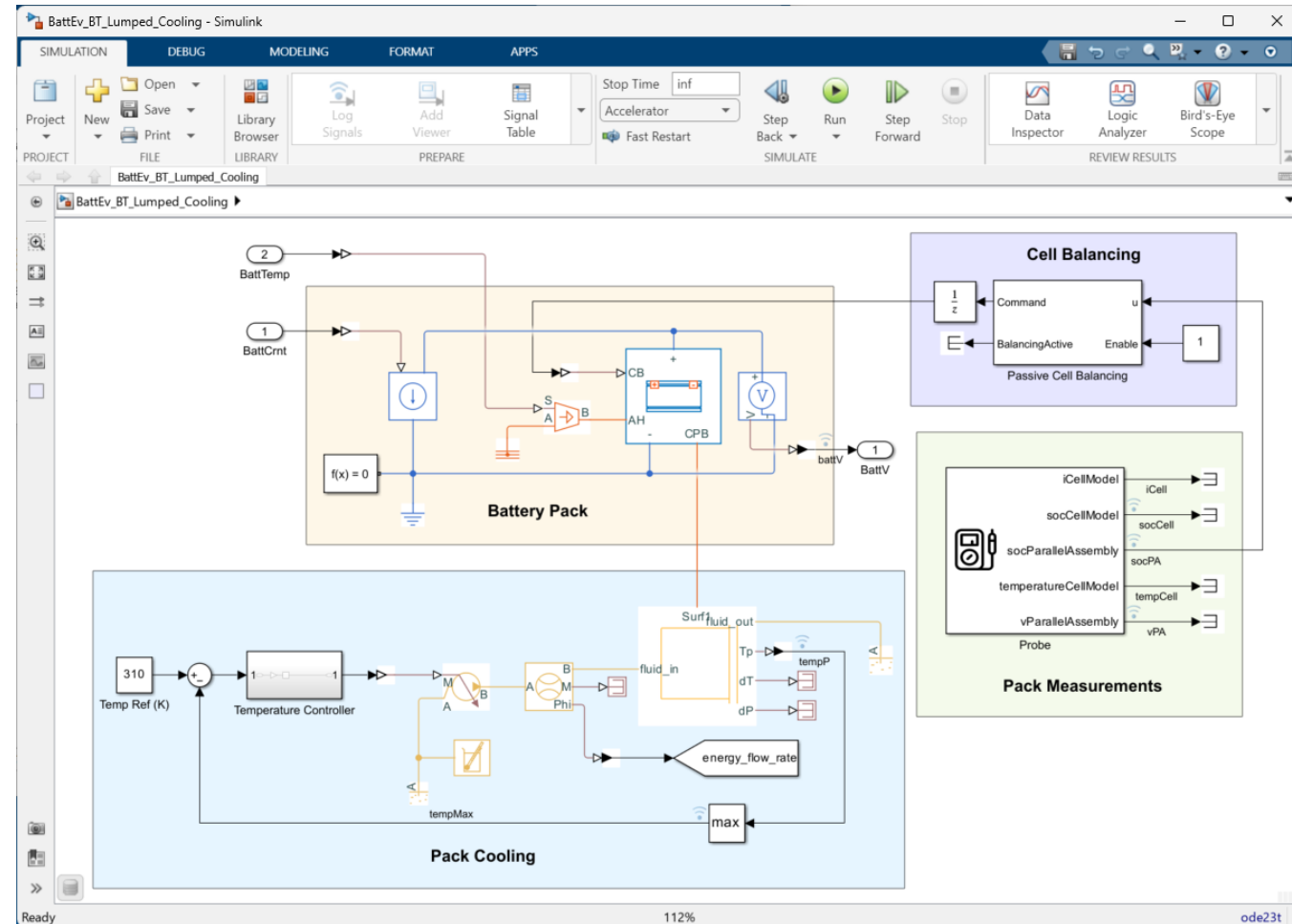
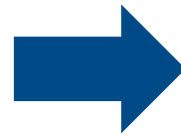
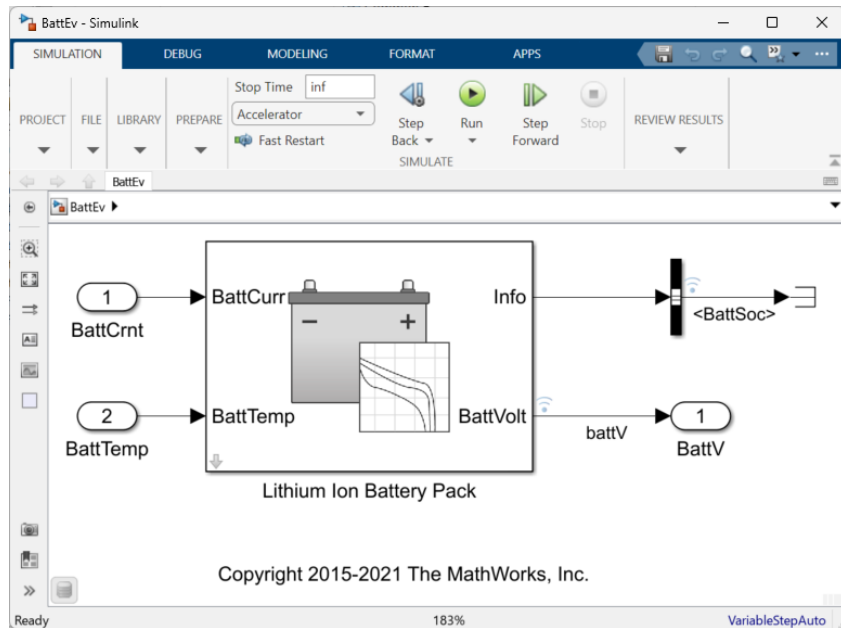
Thermal Management

- Parallel cooling channels oriented along the y-axis

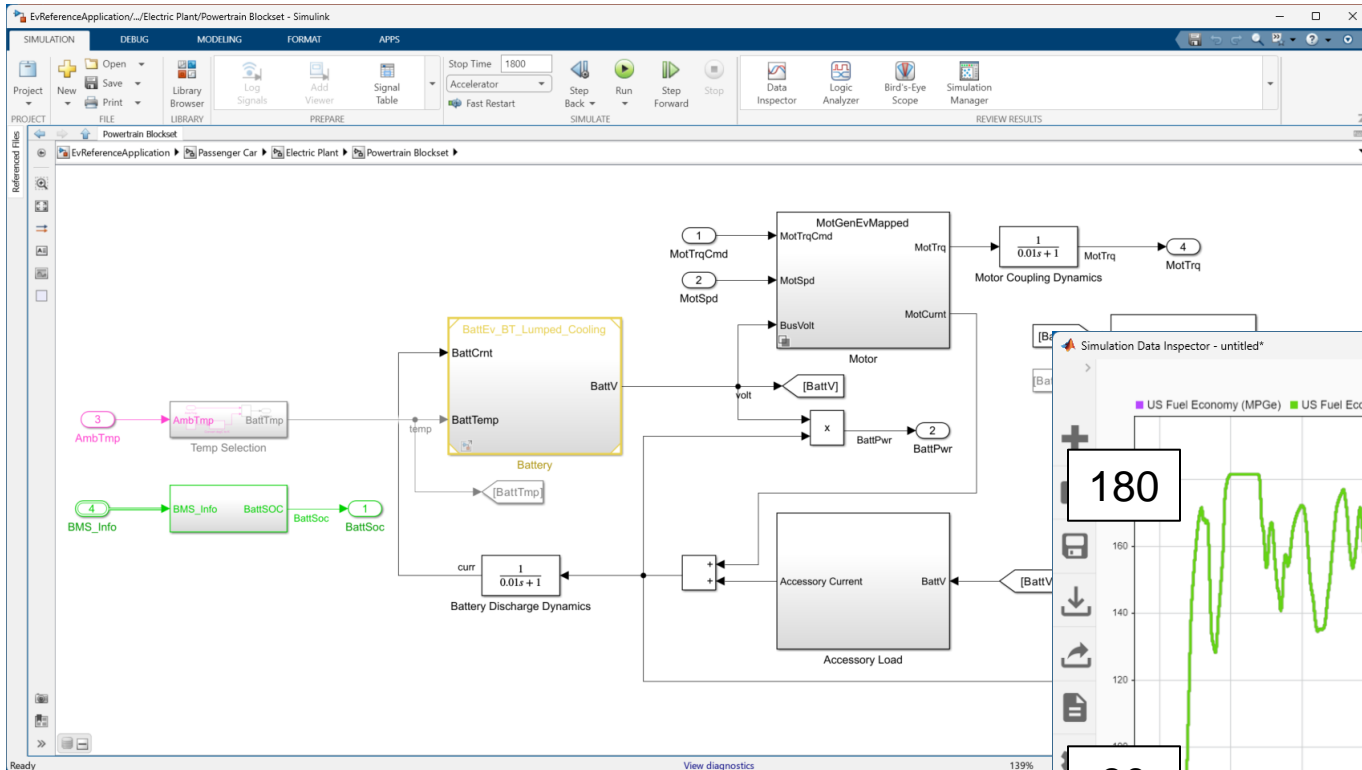


Select Appropriate Model Fidelity for Full System Evaluation

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



Evaluate Battery Design in Full System



WLTP (Class 3) Drive Cycle

Cooling activates near the end of the cycle

No Cooling

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

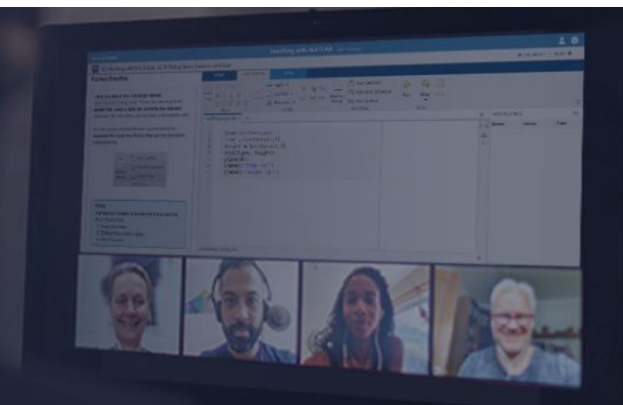
MathWorks Training Can Increase Your Productivity

- General purpose training courses
 - Optimization free [online onramp](#)
 - 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](#)

Advance Your Skills with MATLAB and Simulink Training

Virtual, in-person, and self-paced courses accommodate a variety of learning styles and organizational needs.

[Browse courses](#)



Learn more:

[MathWorks Training Services](#)

MathWorks Consulting Services Can Support You



Model Architecture

Model assessment
Simulation performance
Interface standardization
...

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



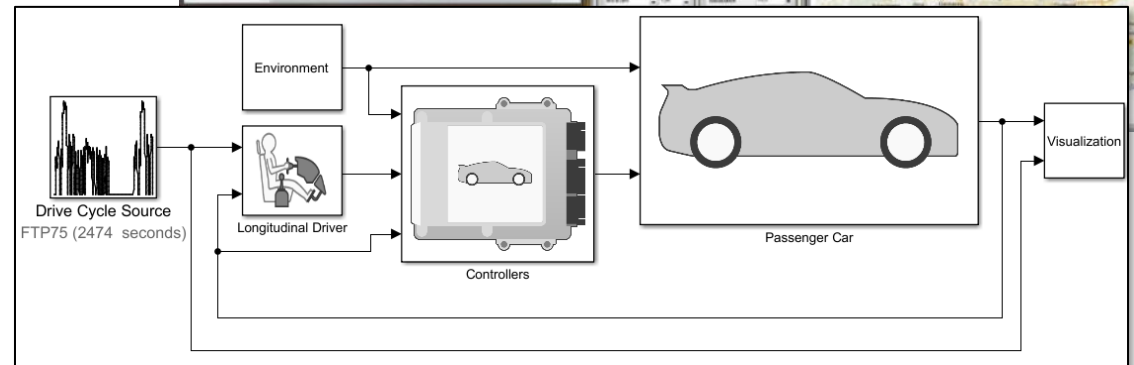
Construction

Build process automation
Database/Repo interface
Model-Building know-how
...



User Experience

GUI driven workflow
Tool compatibility support
Artifact creation
...



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

