MATLAB EXPO

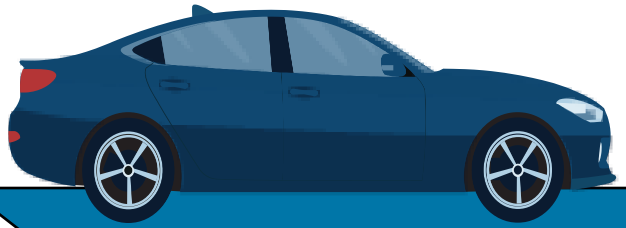
시스템 모델링을 이용한 EV용 배터리 팩 성능 최적화

강효석 부장/Ph.D, 매스웍스코리아

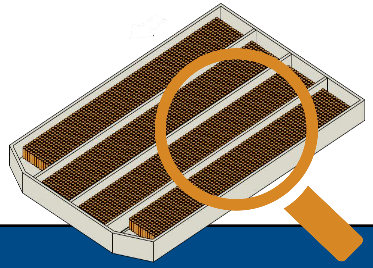
MathWorks®

Key takeaways

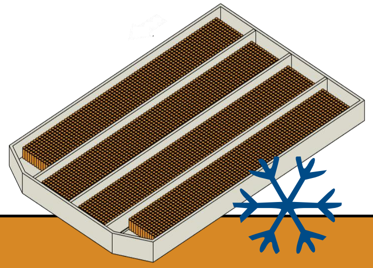
Optimize EV battery performance using simulation



Assess system performance



Find optimal pack size



Design battery pack

Powertrain Blockset

System-level models to quantify vehicle range, battery performance, and costs

Global Optimization Toolbox
Simulink Design Optimization

Efficiently optimize the design while accounting for competing requirements

Simscape Battery

Perform detailed battery design studies

Agenda

Optimize EV battery performance using simulation

- **Problem statement**
- Assess system performance
- Find optimal pack size
- Design battery pack
- Conclusions

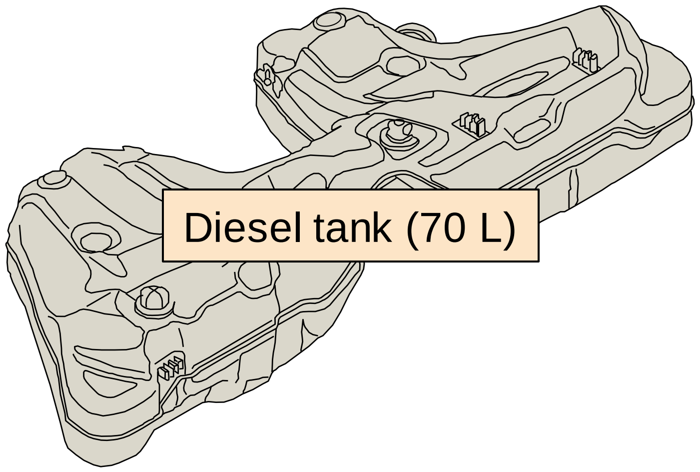
Problem statement: the electrification of the powertrain

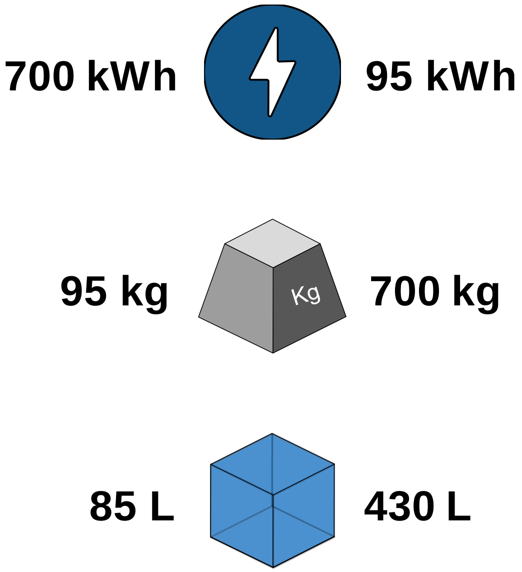
Current challenges

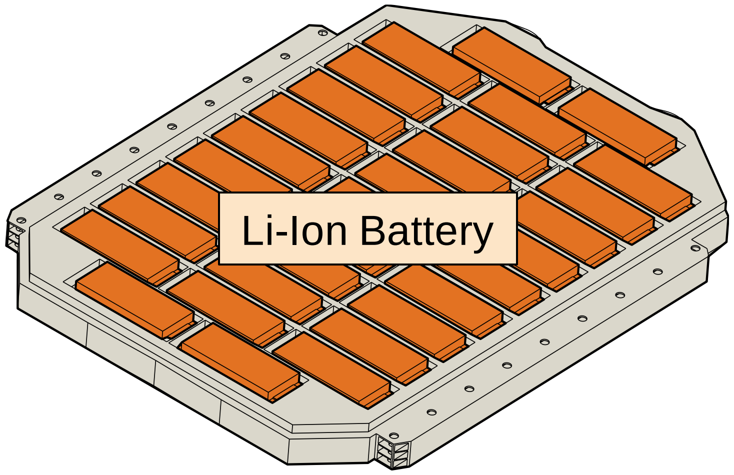
The automotive sector is focusing on reducing CO_2 emissions.
For this scope, Battery Electric Vehicles (BEVs) are a promising solution:

- Localize emissions to energy production source
- Can be charged with renewable energy

However, **engineering challenges remain** …



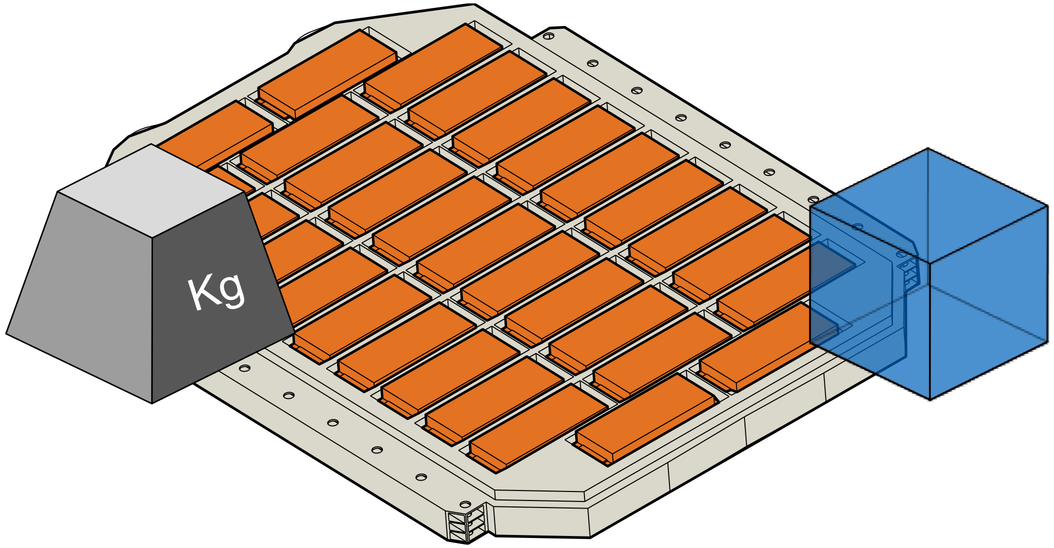




Problem statement: the electrification of the powertrain

Current challenges

- The battery impacts the **vehicle mass** and on other crucial system-level specifications
  - **Energy consumption**
  - **Acceleration**
  - **Range**
- The battery's integration represents a major challenge
- Today's goal is to show how you can use MathWorks products to:
  1. Create a BEV model (and assess vehicle performance)
  2. Optimize the battery pack size
  3. Detail the battery pack



Agenda

Optimize EV battery performance using simulation

- Problem statement
- **Assess system performance**
- Find optimal pack size
- Design battery pack
- Conclusions

Create a BEV model

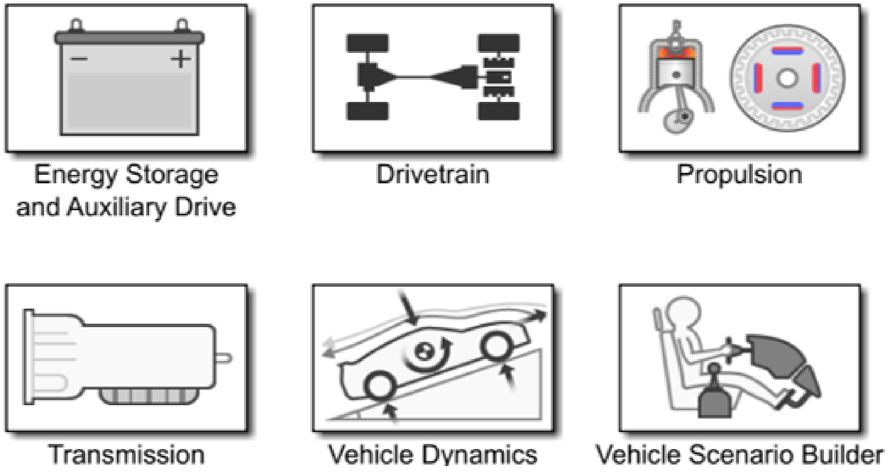
Powertrain Blockset™

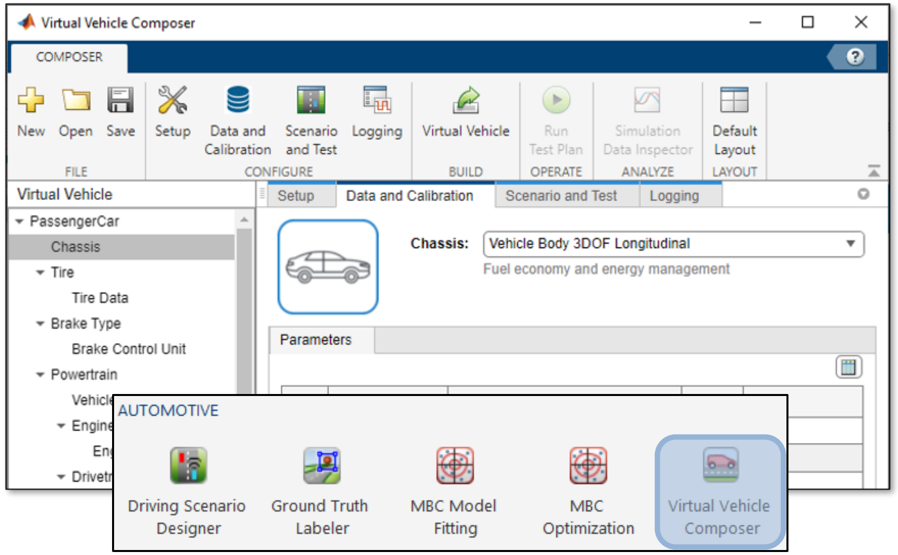
Create a vehicle model with Powertrain Blockset

- Blocks for gasoline, diesel, hybrid, and electric systems
- Provides a standard model architecture that can be reused throughout the development process
- Ideal for trade-off analysis, component sizing, and optimization

Generate a vehicle model with Virtual Vehicle Composer

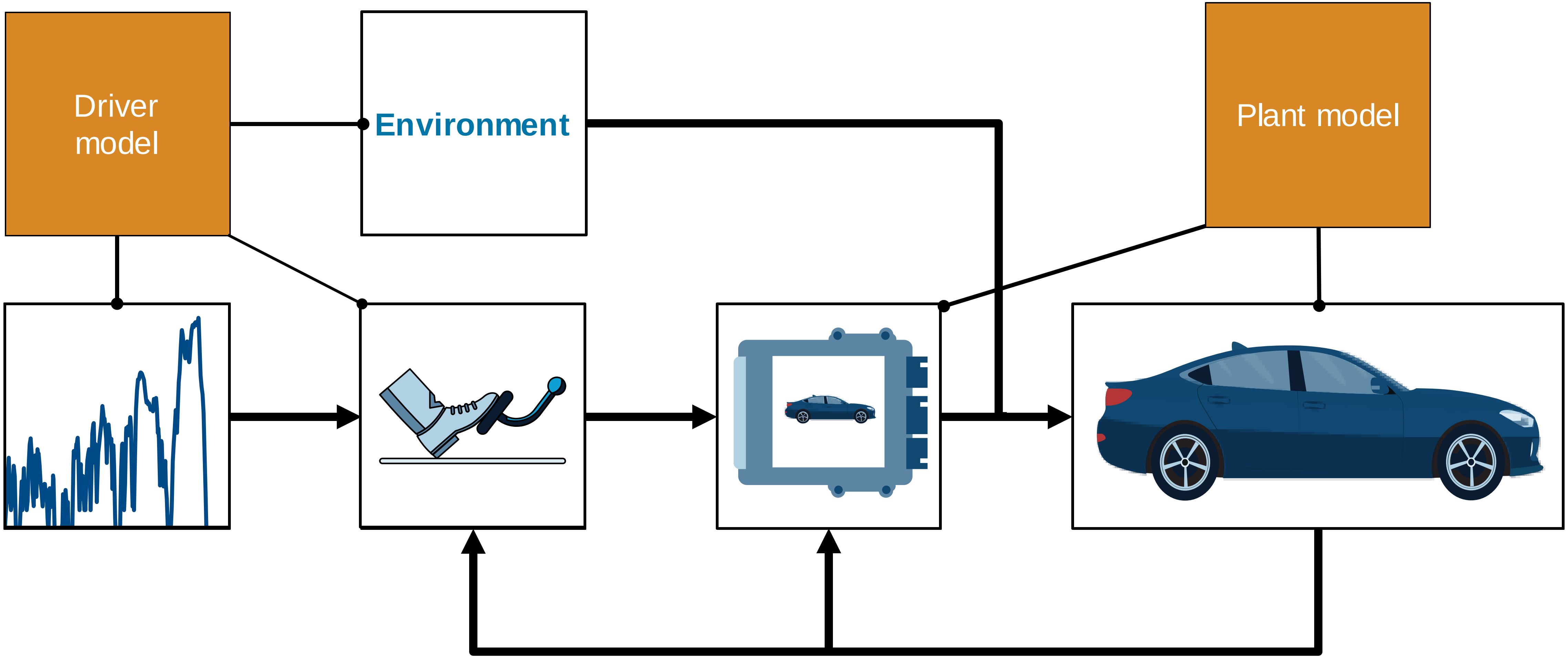
- Interactive app
- Several pre-built vehicle templates
- Easy component parametrization
- Generates a full vehicle model



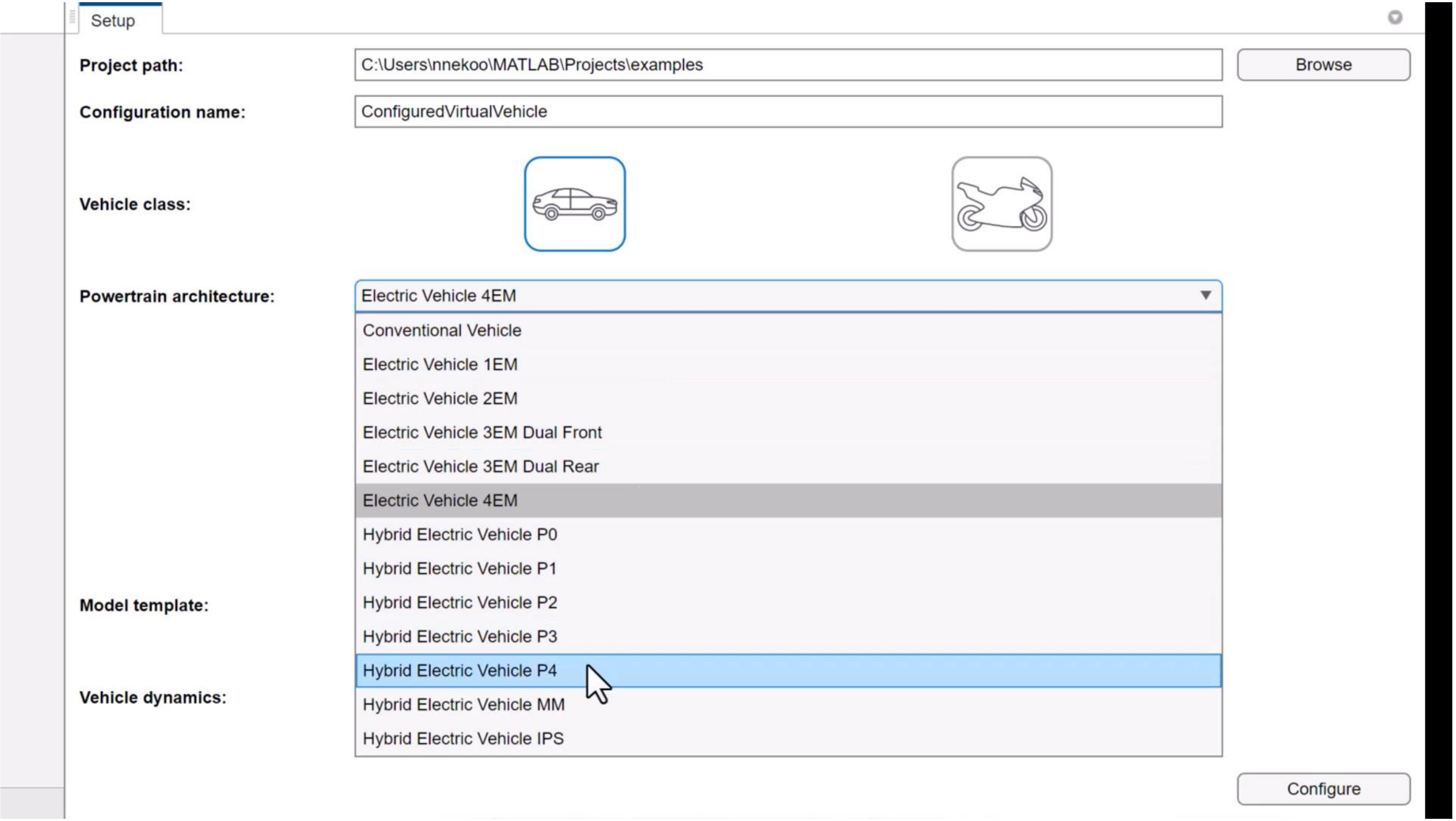


Overview vehicle model

Generated with Virtual Vehicle Composer

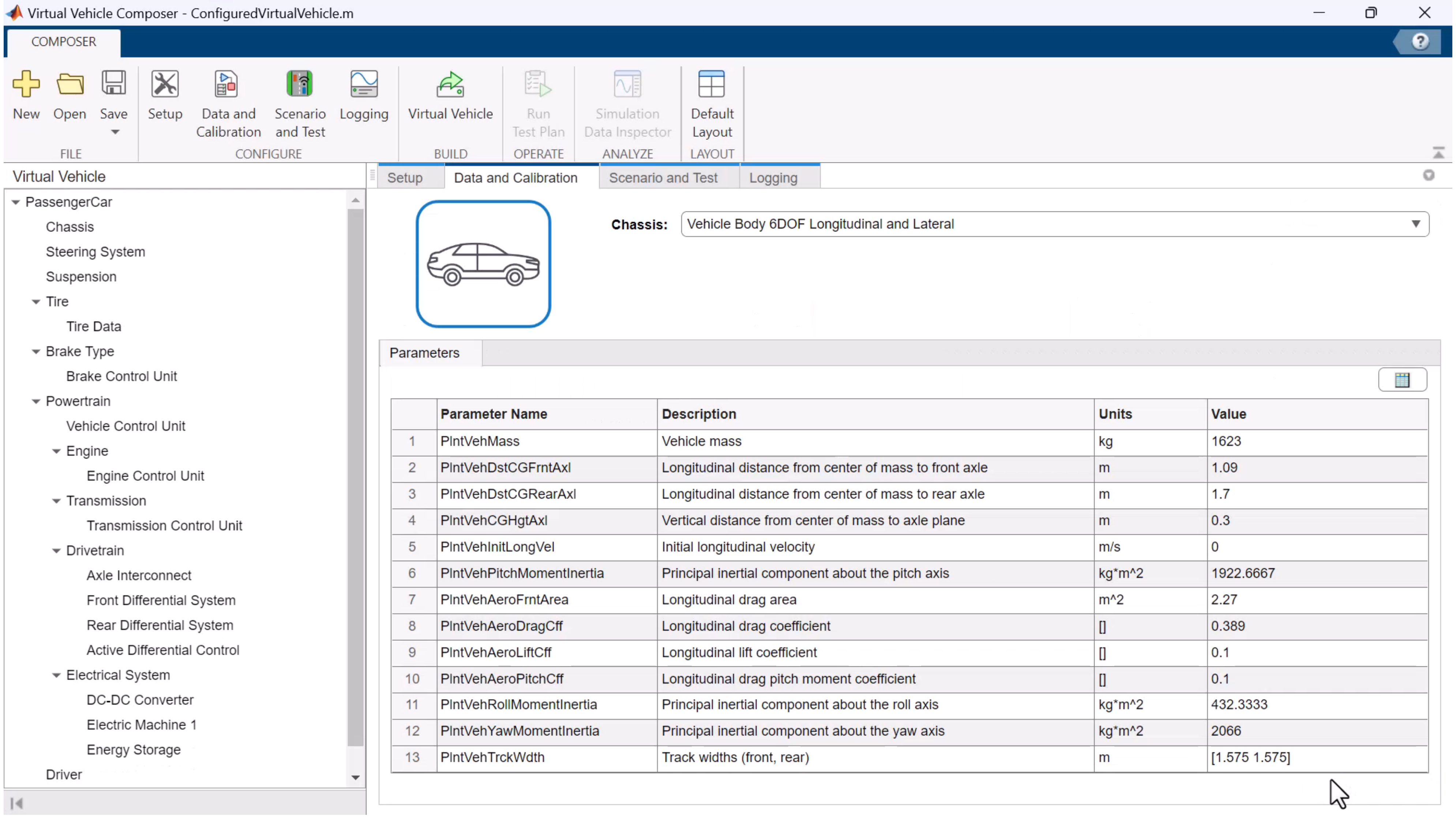


Virtual Vehicle Composer App offers uniquely flexible solution



1. Specify model type
2. Parameterize subsystems
3. Select test scenarios
4. Generate model
5. Customize as needed

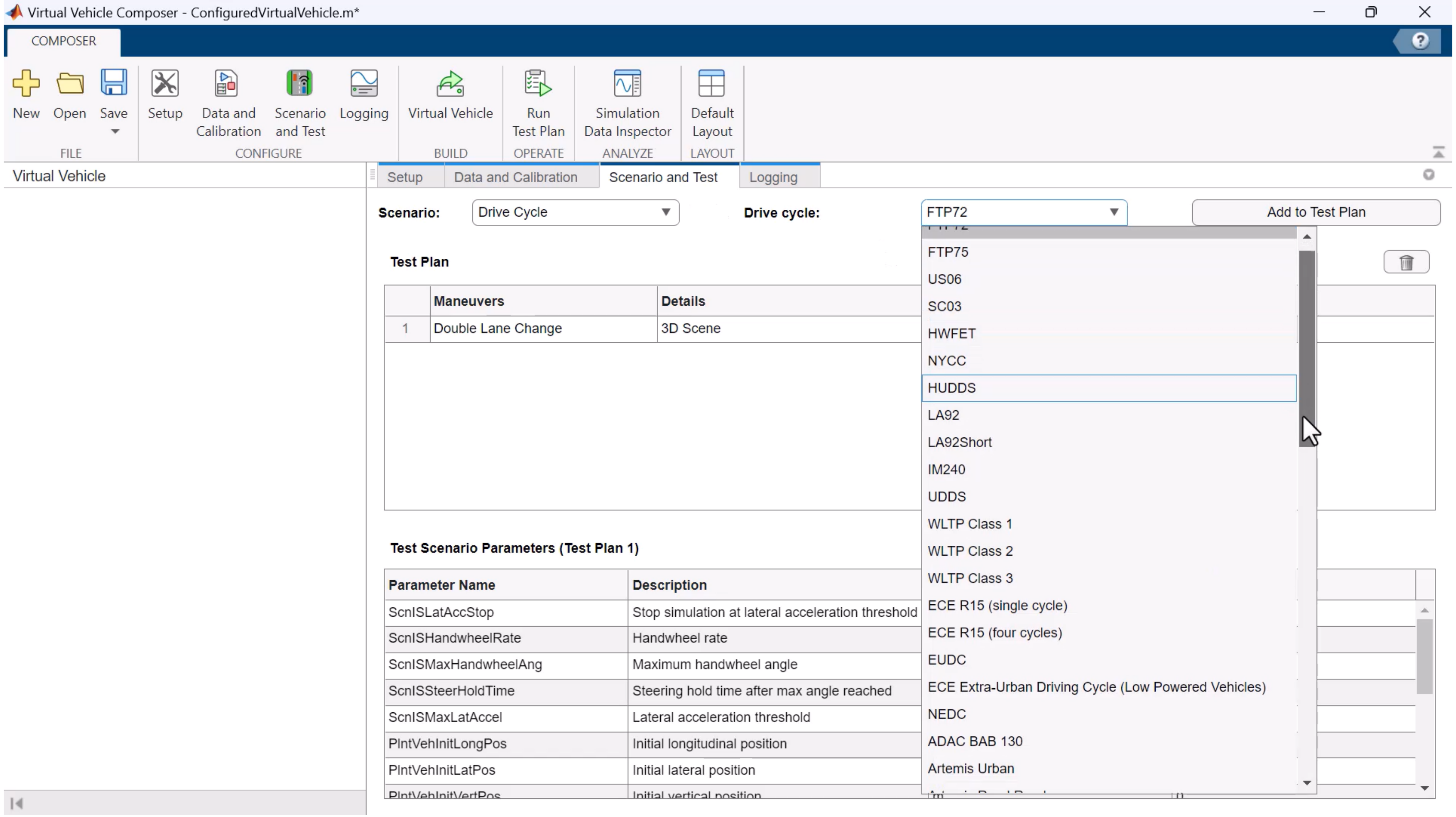
Virtual Vehicle Composer App offers uniquely flexible solution



	Parameter Name	Description	Units	Value
1	PlntVehMass	Vehicle mass	kg	1623
2	PlntVehDstCGFrntAxl	Longitudinal distance from center of mass to front axle	m	1.09
3	PlntVehDstCGRearAxl	Longitudinal distance from center of mass to rear axle	m	1.7
4	PlntVehCGHgtAxl	Vertical distance from center of mass to axle plane	m	0.3
5	PlntVehInitLongVel	Initial longitudinal velocity	m/s	0
6	PlntVehPitchMomentInertia	Principal inertial component about the pitch axis	kg*m^2	1922.6667
7	PlntVehAeroFrntArea	Longitudinal drag area	m^2	2.27
8	PlntVehAeroDragCff	Longitudinal drag coefficient	[]	0.389
9	PlntVehAeroLiftCff	Longitudinal lift coefficient	[]	0.1
10	PlntVehAeroPitchCff	Longitudinal drag pitch moment coefficient	[]	0.1
11	PlntVehRollMomentInertia	Principal inertial component about the roll axis	kg*m^2	432.3333
12	PlntVehYawMomentInertia	Principal inertial component about the yaw axis	kg*m^2	2066
13	PlntVehTrckWdth	Track widths (front, rear)	m	[1.575 1.575]

1. Specify model type
2. **Parameterize subsystems**
3. Select test scenarios
4. Generate model
5. Customize as needed

Virtual Vehicle Composer App offers uniquely flexible solution



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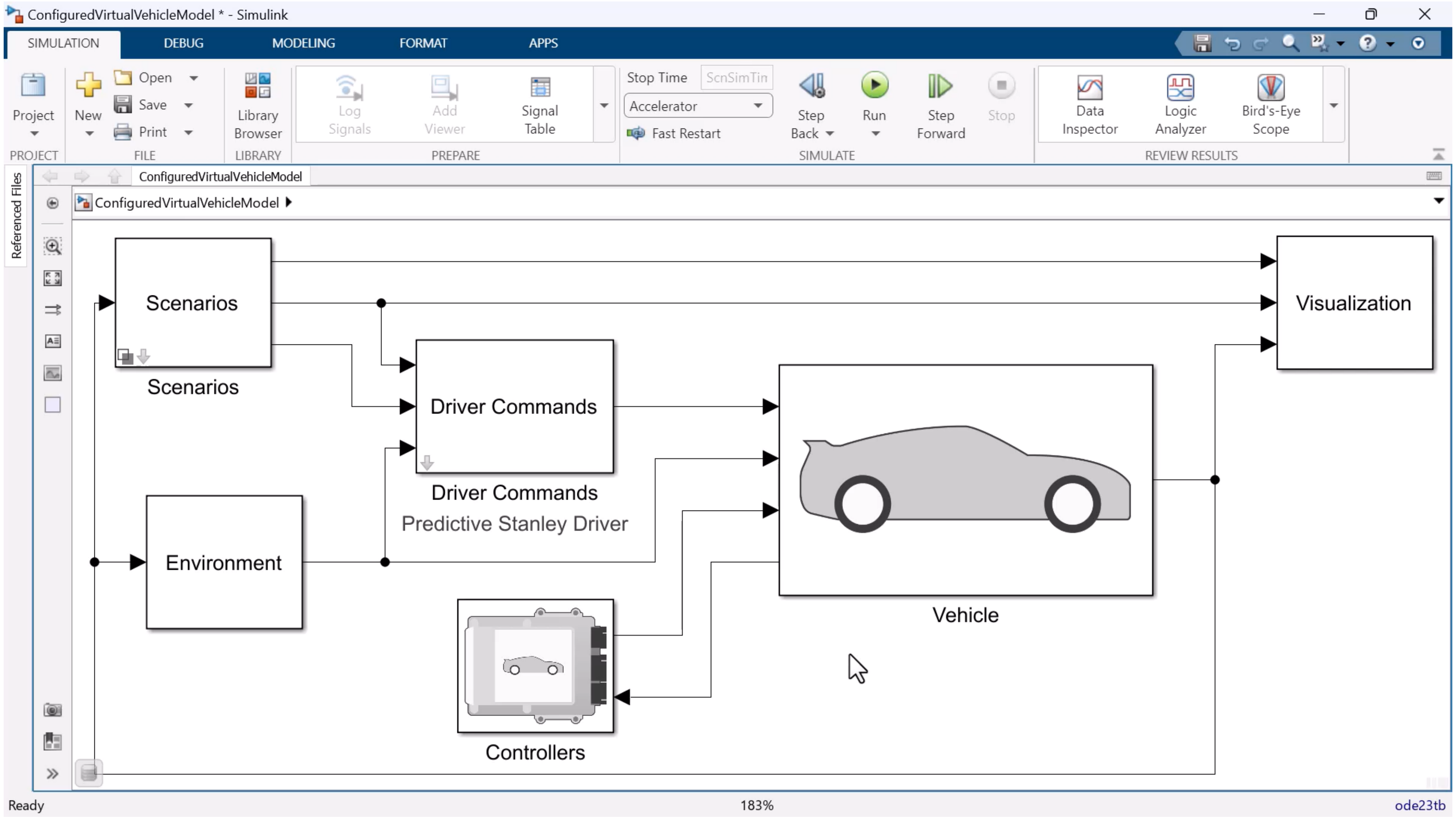
Virtual Vehicle Composer App offers uniquely flexible solution



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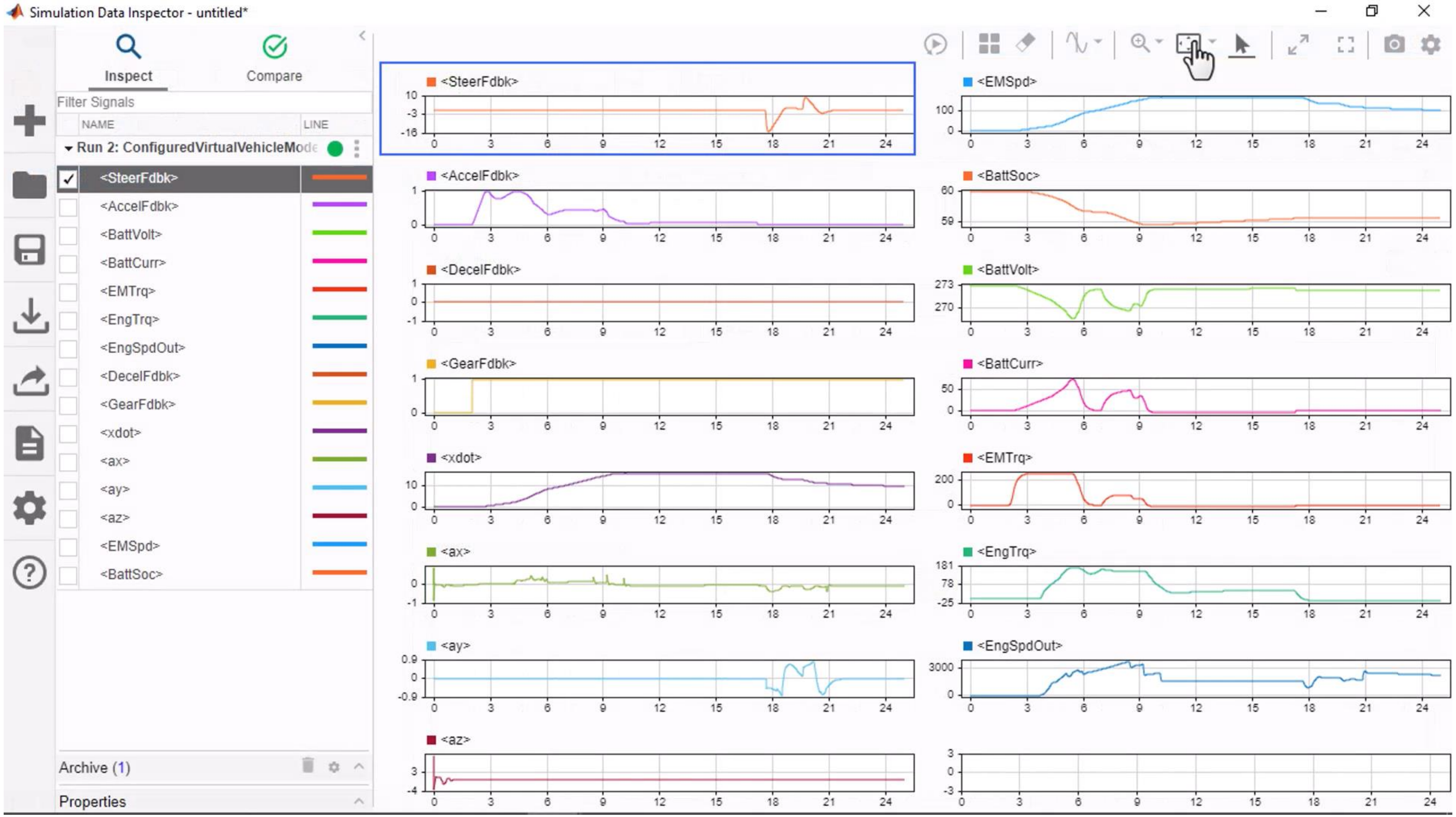
Virtual Vehicle Composer App offers uniquely flexible solution



1. Specify model type
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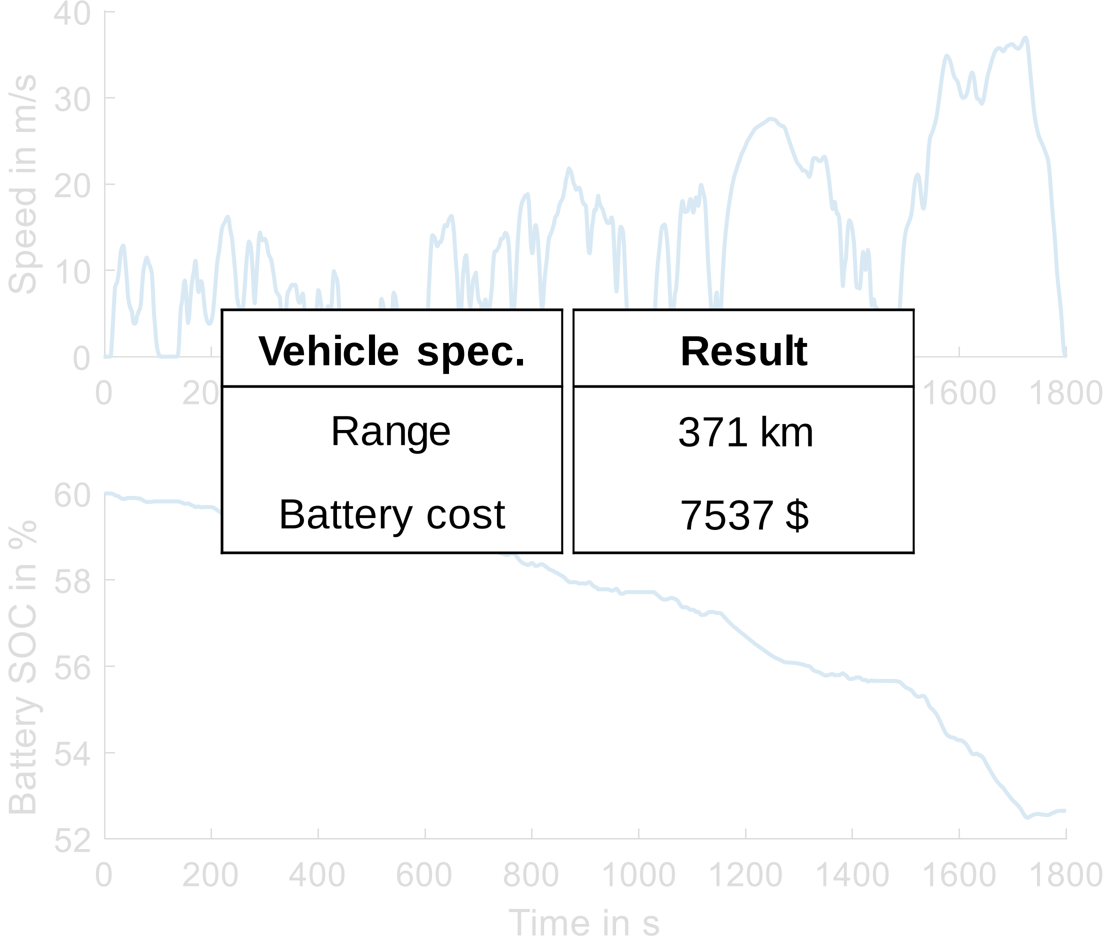
Overview vehicle model

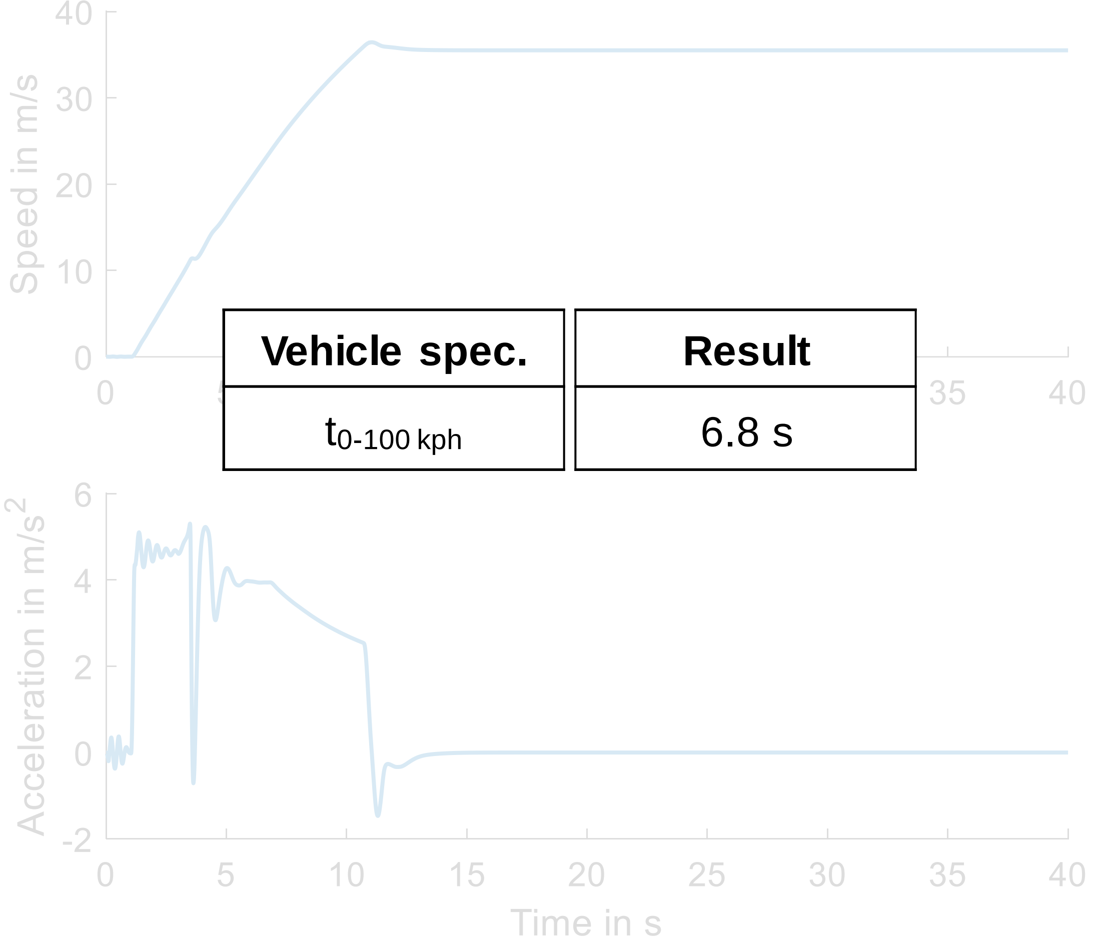
Initial assessment, mid-size electric passenger car

Drive cycle simulation (WLTP)



Vehicle spec.	Result
Range	371 km
Battery cost	7537 $

Acceleration simulation (WOT)



Vehicle spec.	Result
$t_{0\text{-}100\ \text{kph}}$	6.8 s

Summary: Assess system performance

- 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

Optimize EV battery performance using simulation

- Problem statement
- Assess system performance
- **Find optimal pack size**
- Design battery pack
- Conclusions

Problem statement

Objectives, constraints, and design variables

Given the vehicle model, define the optimization problem:

- Objective:

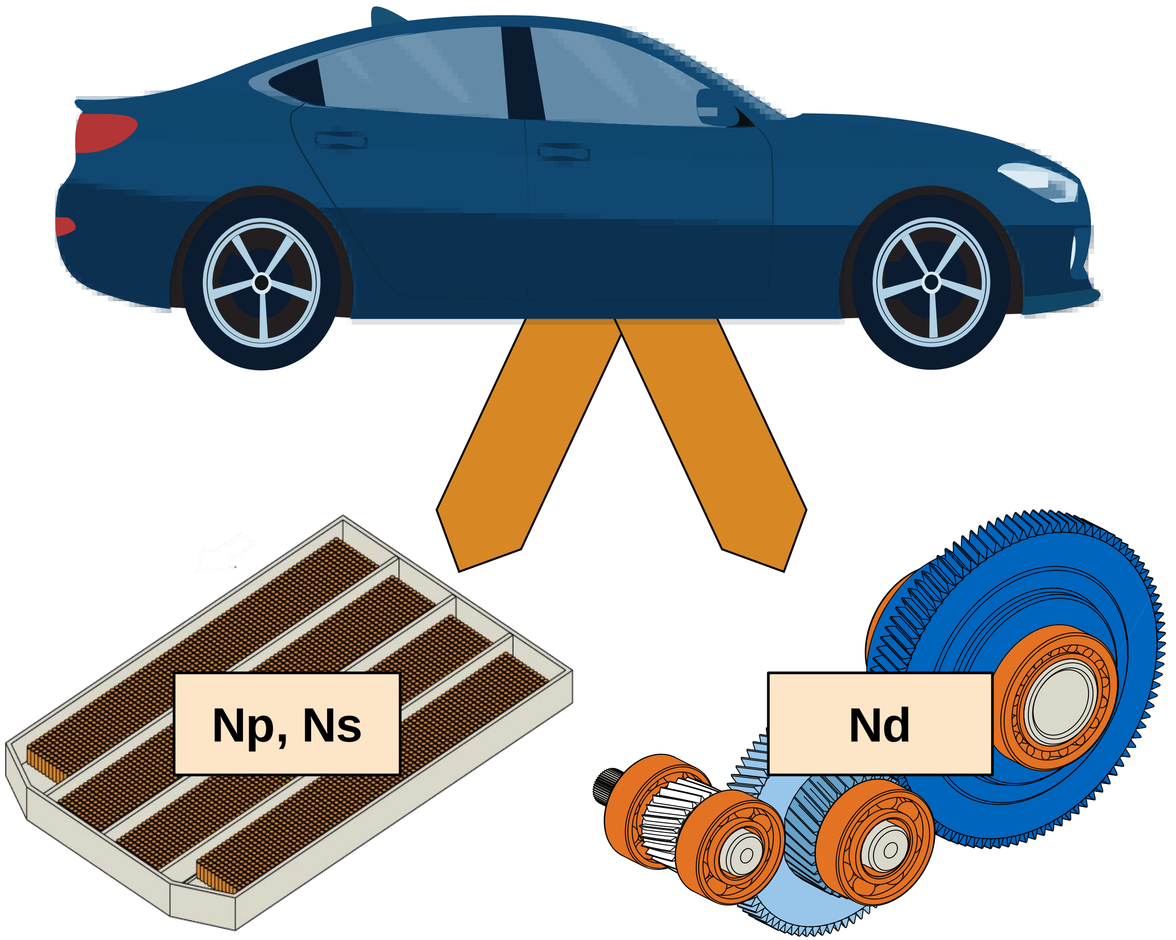
  minimize $f(x) = w_1*Cost - w_2*Range$

- Constraints:

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

- Design variables

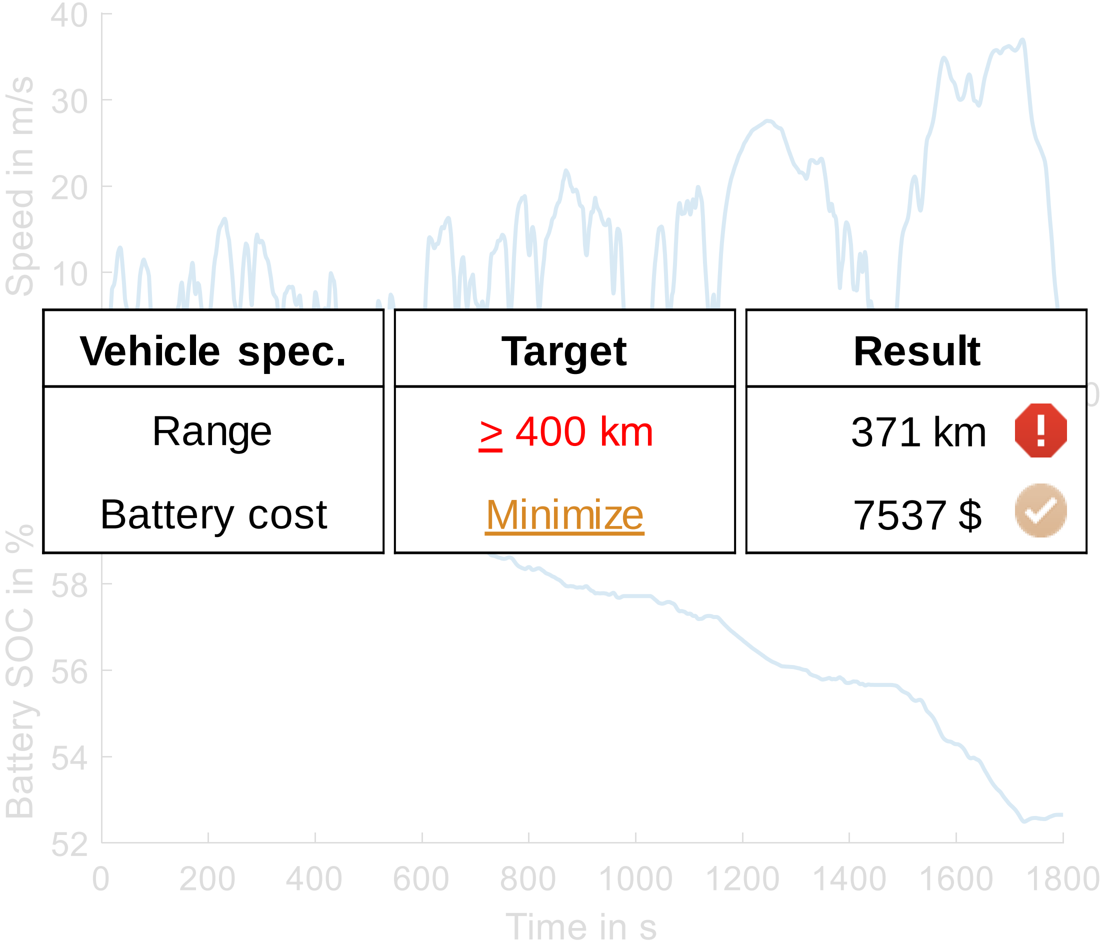
  x_1: $10 \leq Np \leq 50$ (Integer)
  x_2: $80 \leq Ns \leq 140$ (Integer)
  x_3: $7 \leq Nd \leq 10$ (Continuous)



Comparison with initial assessment

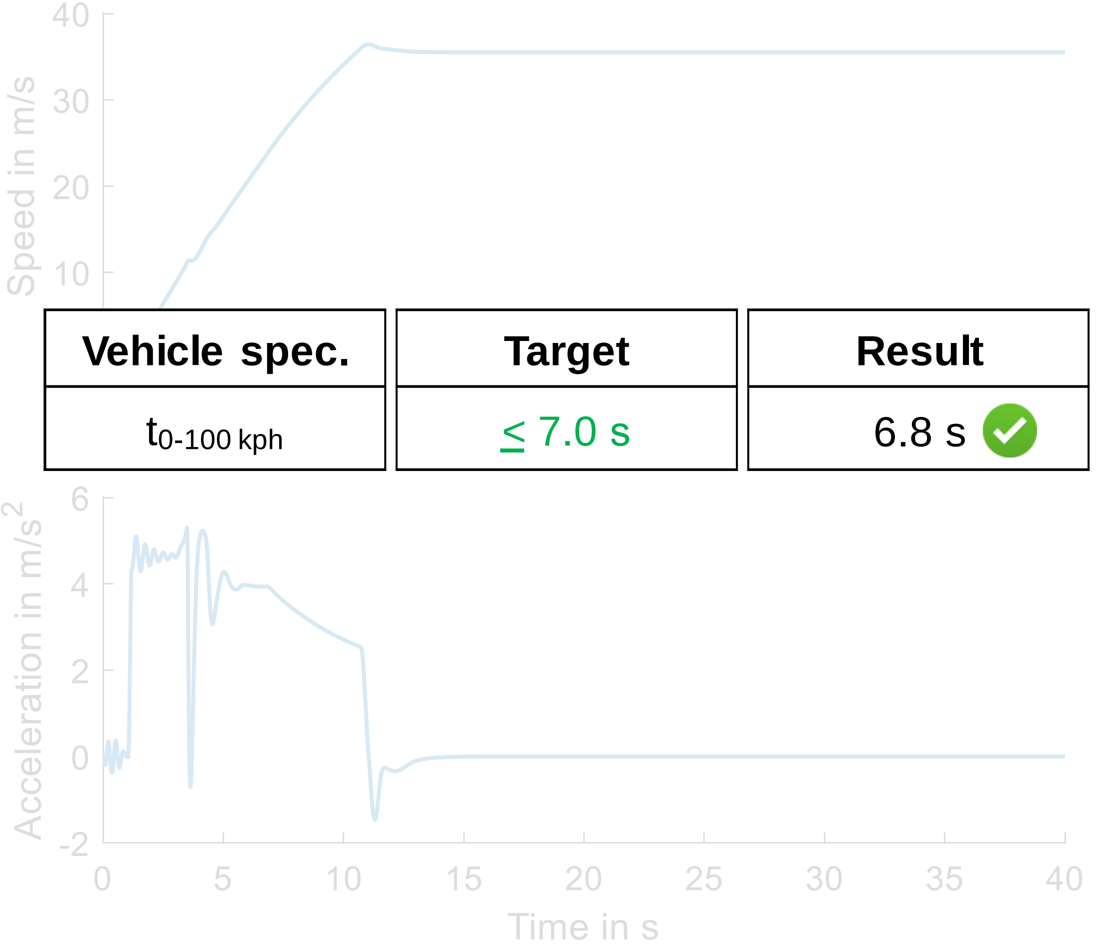
Range constraint is not fulfilled

Drive cycle simulation (WLTP)



Vehicle spec.	Target	Result
Range	≥ 400 km	371 km ❗
Battery cost	Minimize	7537 $ ✔

Acceleration simulation (WOT)



Vehicle spec.	Target	Result
$t_{0\text{-}100\ kph}$	≤ 7.0 s	6.8 s ✔

Optimization algorithm

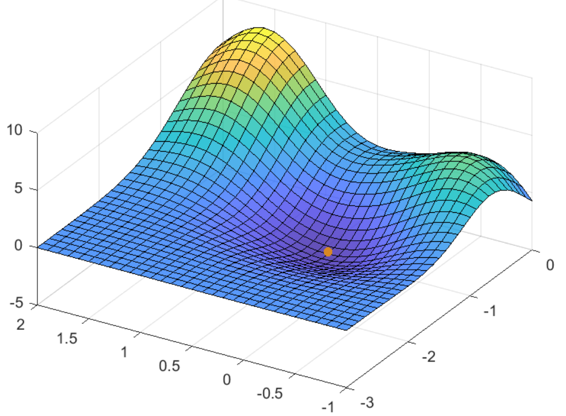
Selecting the appropriate optimizer

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

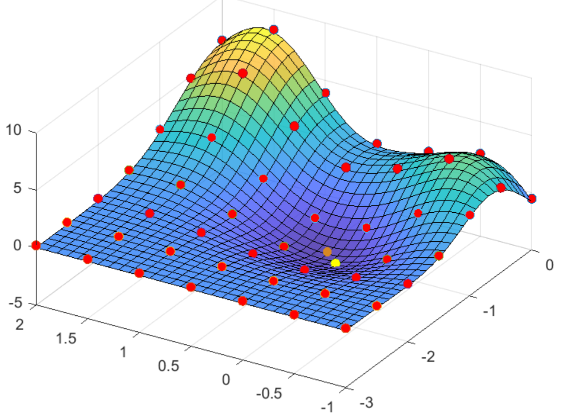
The choice of a suitable optimization algorithm must take into account different requirements

- Design variable space
  - Continuous
  - Integer (discrete)
  - Mixed Integer
- Local / global search space
  - Optimization Toolbox (local)
  - Global Optimization Toolbox

Continuous



Discrete

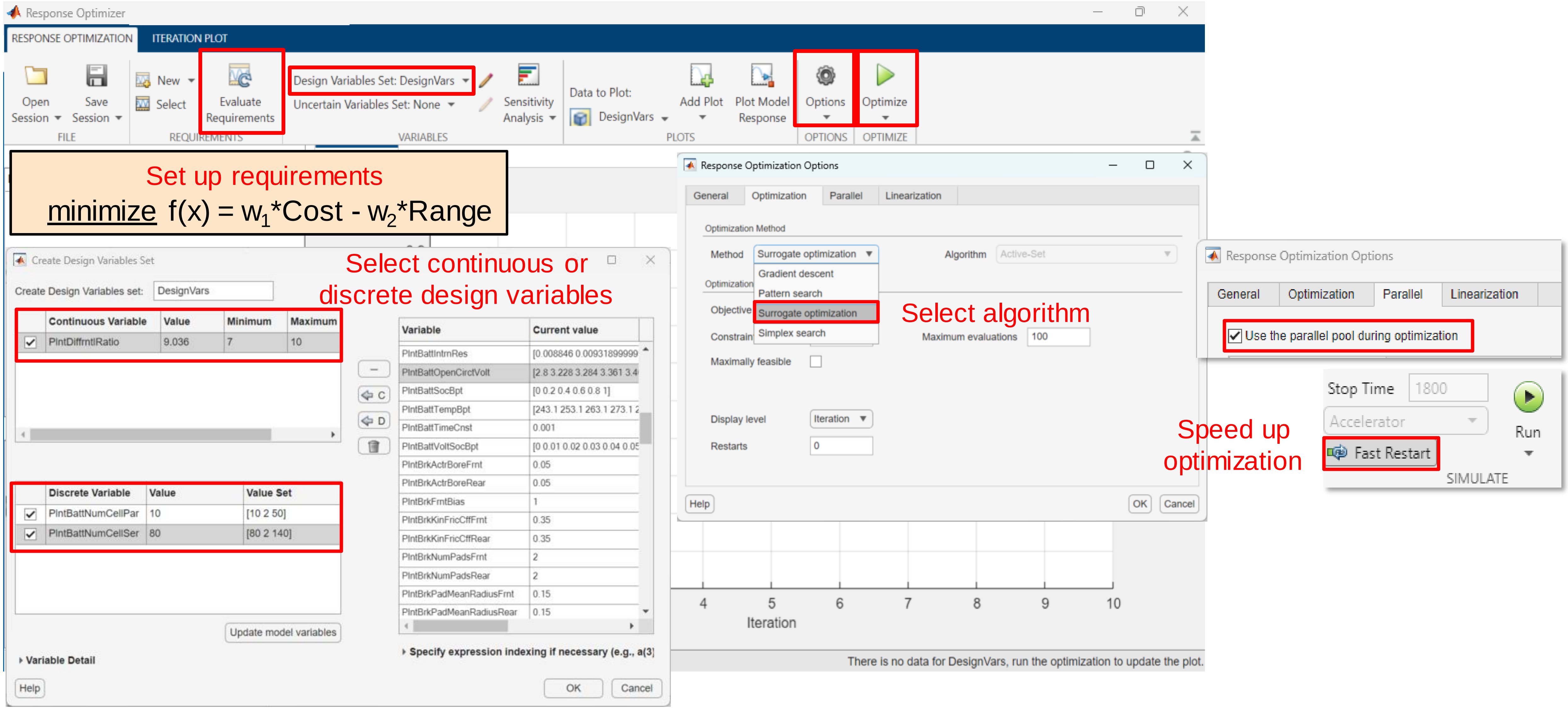


For this problem, the surrogate optimization (surrogateopt) algorithm was selected

- Uses fewer function calls than other global optimization solvers
- Automatically builds up cheap to evaluate surrogate models
- Searches for global solution
- Can work with continuous and integer variables

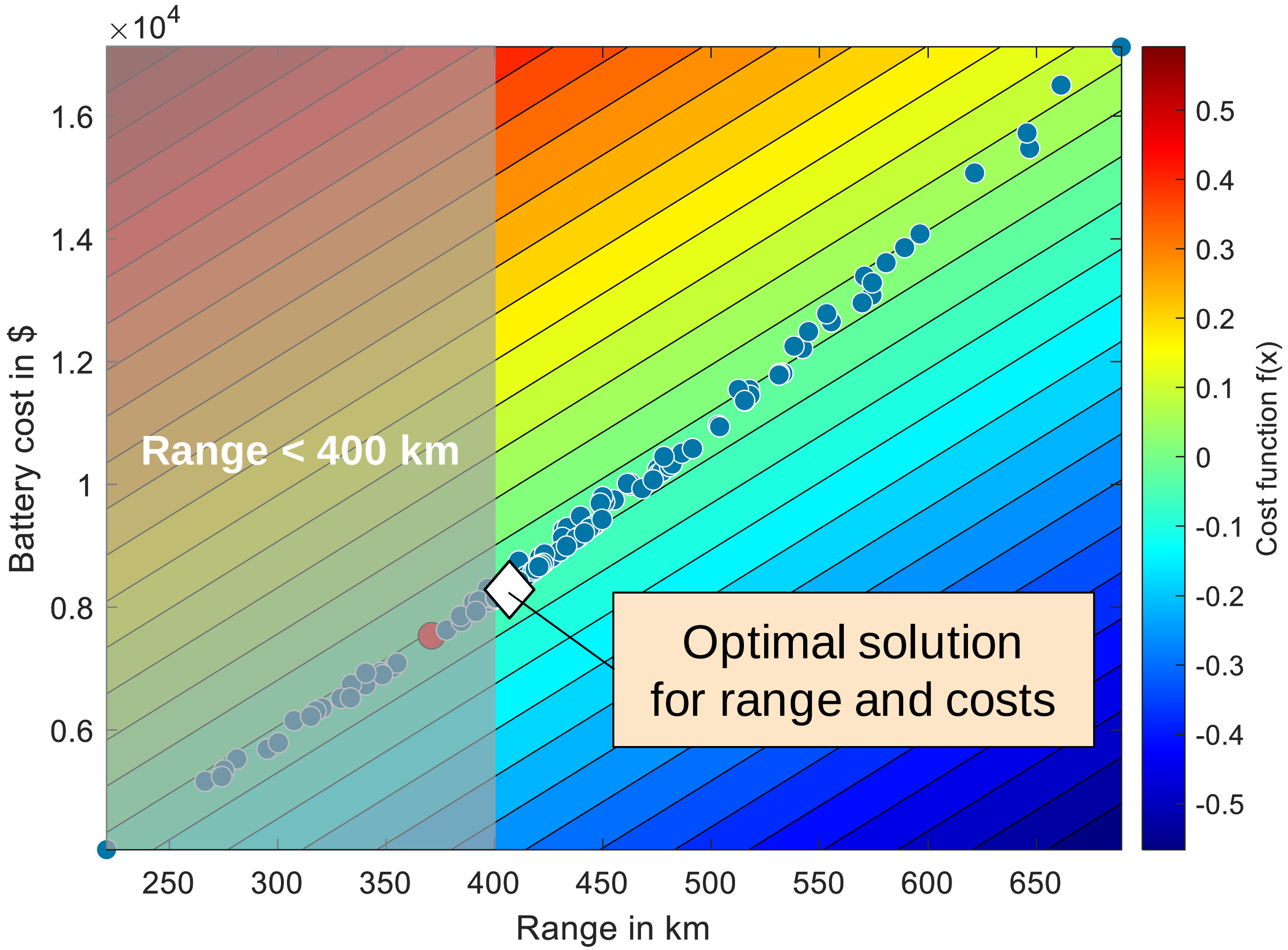
$$\min f(x) \text{ such that } \begin{cases} LB \leq x \leq UB \\ Ax \leq b \\ Ax_{eq} = b_{eq} \\ c(x) \leq 0 \end{cases}$$

Simulink Design Optimization makes problem setup easy



Optimization results

Compare initial assessment and optimal solution



Variable	Initial assessment	Optimal solution
Range	371 km	406 km ✔
Battery cost	7537 $	8279 $ *(+10%)*
$t_{0\text{-}100\ kph}$	6.8 s	6.8 s ✔
Nd	9	7
Ns, Np	96s31p	91s36p
Bus voltage	357.8 V	339.2 V
Capacity	60.3 kWh	66.3 kWh

The algorithm performed 300 function calls
and converged within 2.5 hours
(no Parallel Computing)

Summary: Find optimal pack size

- 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

Optimize EV battery performance using simulation

- Problem statement
- Assess system performance
- Find optimal pack size
- **Design battery pack**
- Conclusions

Battery design study workflow

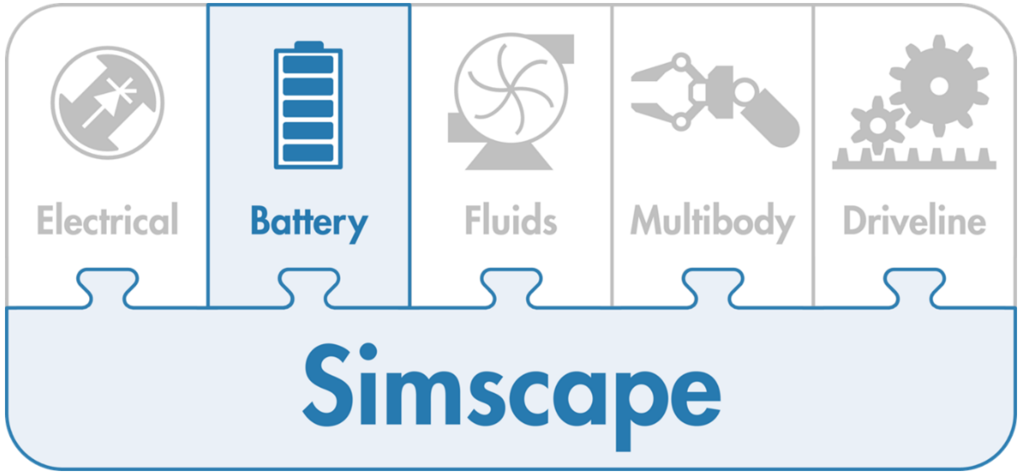
Simscape Battery

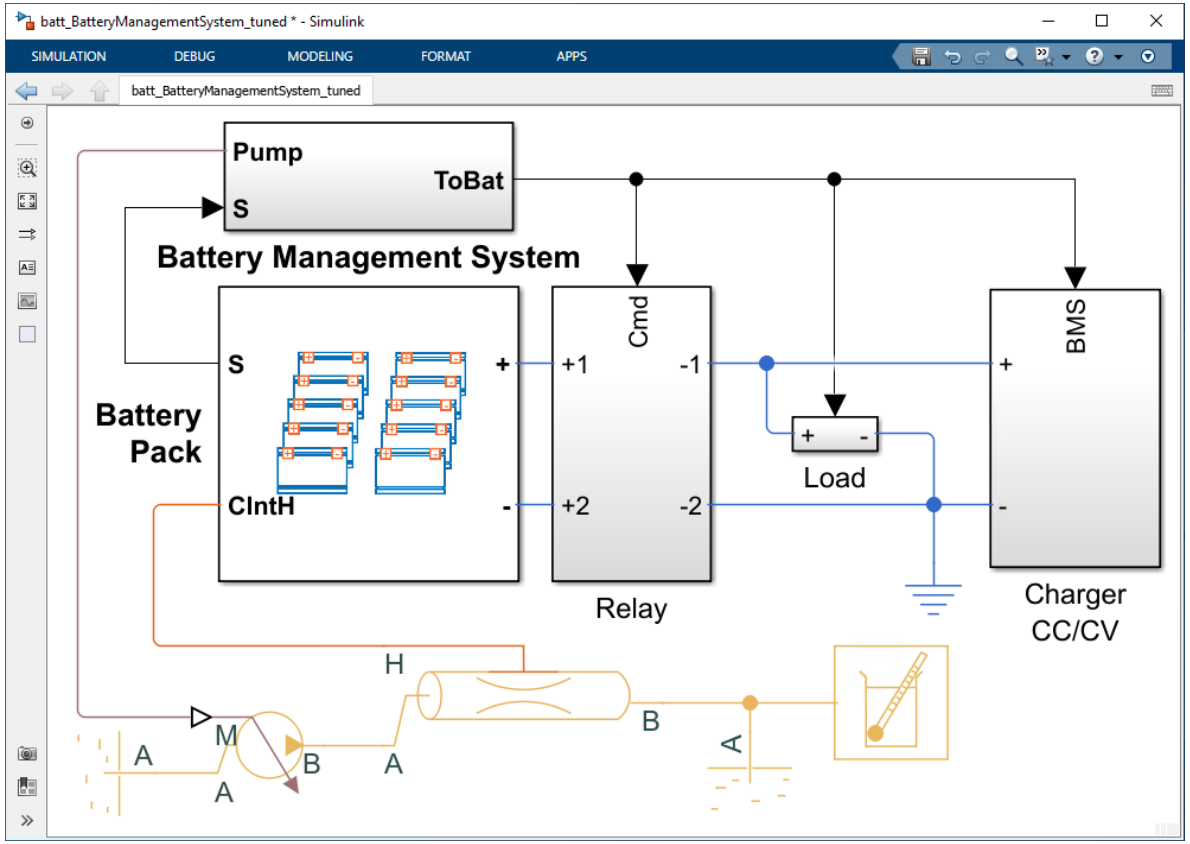
1. Size battery pack within context of full system operation
2. Create lumped battery pack model and demonstrate equivalence
3. Design battery system in Simscape Battery
4. Select appropriate model fidelity for full system evaluation
5. Evaluate battery design in full system

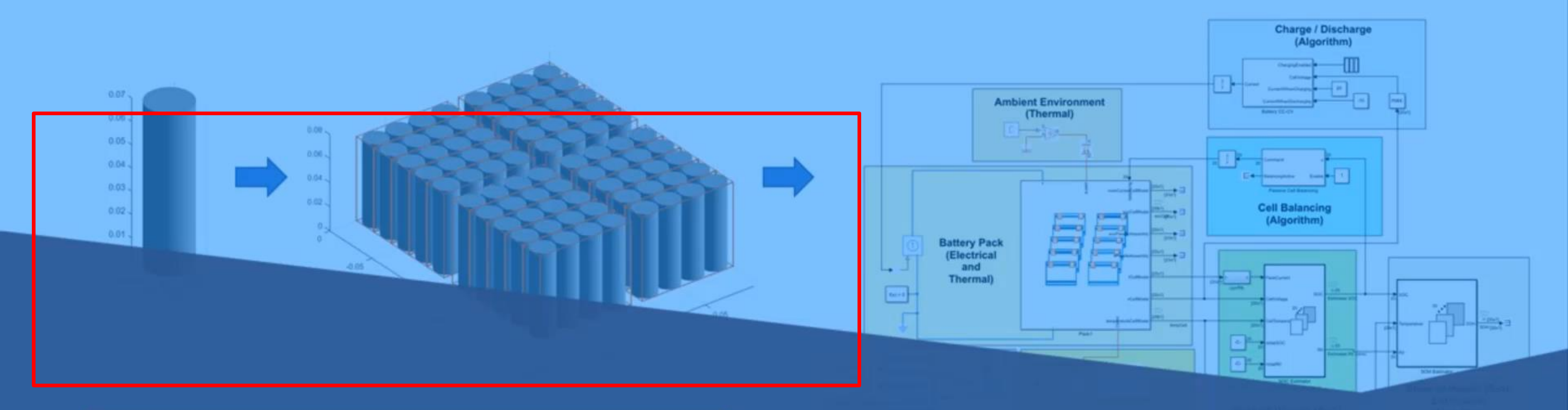
Simscape Battery

- 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







SIMSCAPE BATTERY

A THREE MINUTE TOUR FROM CELL TO SYSTEM

C:\Users\gdudgeon\OneDrive - MathWorks\Simscape Battery\From_Cell_To_System\createPack.mlx *

Create cell object

```
batteryCell = Cell(Geometry = cylindricalGeometry);
```

Visualize cell

```
BatteryChart(Parent = f, Battery = batteryCell);
```

Define cell thermal properties

```
batteryCell.CellModelOptions.BlockParameters.thermal_port = "model";
batteryCell.CellModelOptions.BlockParameters.T_dependence = "yes";
```

Define parallel assembly (4 cells connected in parallel)

```
batteryParallelAssembly = ParallelAssembly(Cell = batteryCell, numParallelCells = 4);
batteryParallelAssembly.StackingAxis = "X";
```

Visualize parallel assembly

```
BatteryChart(Parent = f, Battery = batteryParallelAssembly);
```

Define module (5 parallel assemblies connected in series)

```
batteryModule = Module(ParallelAssembly = batteryParallelAssembly, numSeriesAssemblies = 5);
```

Define simulation strategy

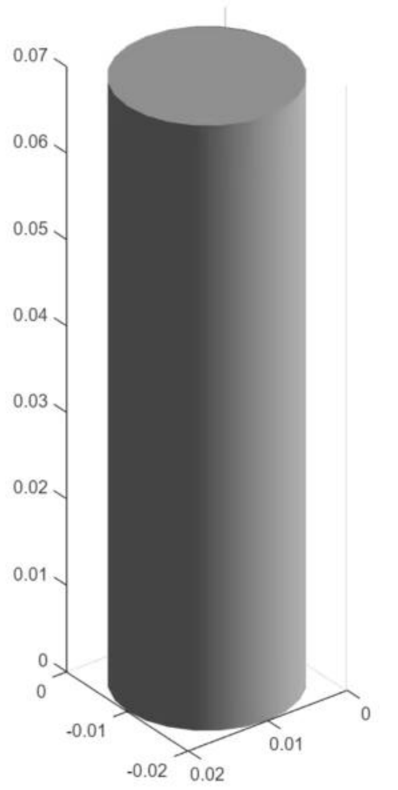
```
batteryModule.ModelResolution = "Grouped";
batteryModule.SeriesGrouping = ones(1,5);
```

Visualize module

```
BatteryChart(Parent = f, Battery = batteryModule, SimulationStrategyVisible = "on");
```

Define module thermal properties

Zoom: 125% UTF-8 LF script



Define Individual Cell

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Define parallel assembly (4 cells connected in parallel)

```
batteryParallelAssembly = ParallelAssembly(Cell = batteryCell, numParallelCells = 4);
batteryParallelAssembly.StackingAxis = "X";
```

Visualize parallel assembly

```
BatteryChart(Parent = f, Battery = batteryParallelAssembly);
```

Define module (5 parallel assemblies connected in series)

```
batteryModule = Module(ParallelAssembly = batteryParallelAssembly, numSeriesAssemblies = 5);
```

Define simulation strategy

```
batteryModule.ModelResolution = "Grouped";
batteryModule.SeriesGrouping = ones(1,5);
```

Visualize module

```
BatteryChart(Parent = f, Battery = batteryModule, SimulationStrategyVisible = "on");
```

Define module thermal properties

```
batteryModule.AmbientThermalPath = "CellBasedThermalResistance";
batteryModule.CoolantThermalPath = "CellBasedThermalResistance";
```

Define module assembly (2 modules connected in series)

```
batteryModuleAssembly = ModuleAssembly(Module = repmat(batteryModule,1,2));
batteryModuleAssembly.InterModuleGap = simscape.Value(0.01,"m");
```

Visualize module assembly

```
BatteryChart(Parent = f, Battery = batteryModuleAssembly, SimulationStrategyVisible = "on");
```

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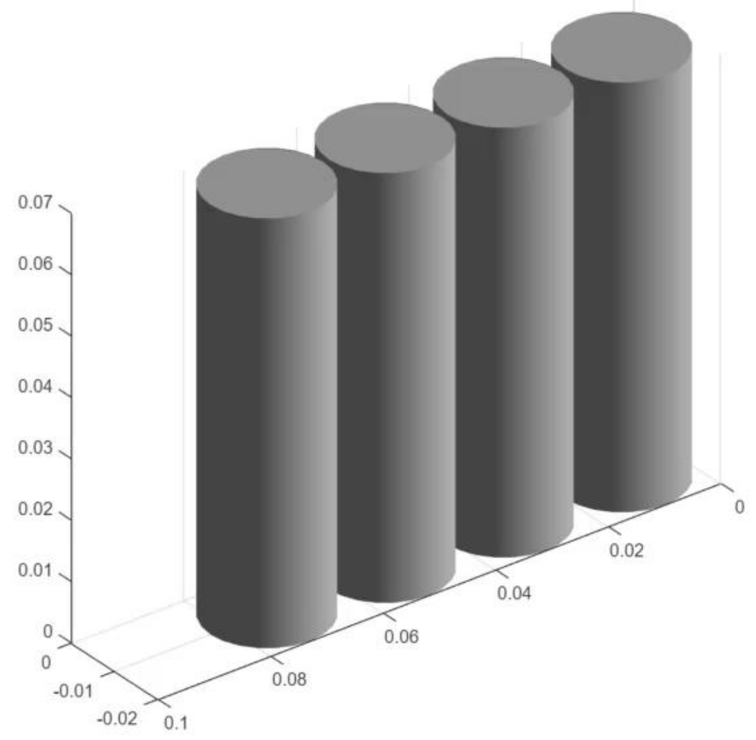


Define Parallel Assembly

Define Model Resolution

Orange boundaries indicate mapping of cell assembly to cell models.

In this example, 4 cells will be represented as a single cell model, suitably scaled.

Define balancing strategy

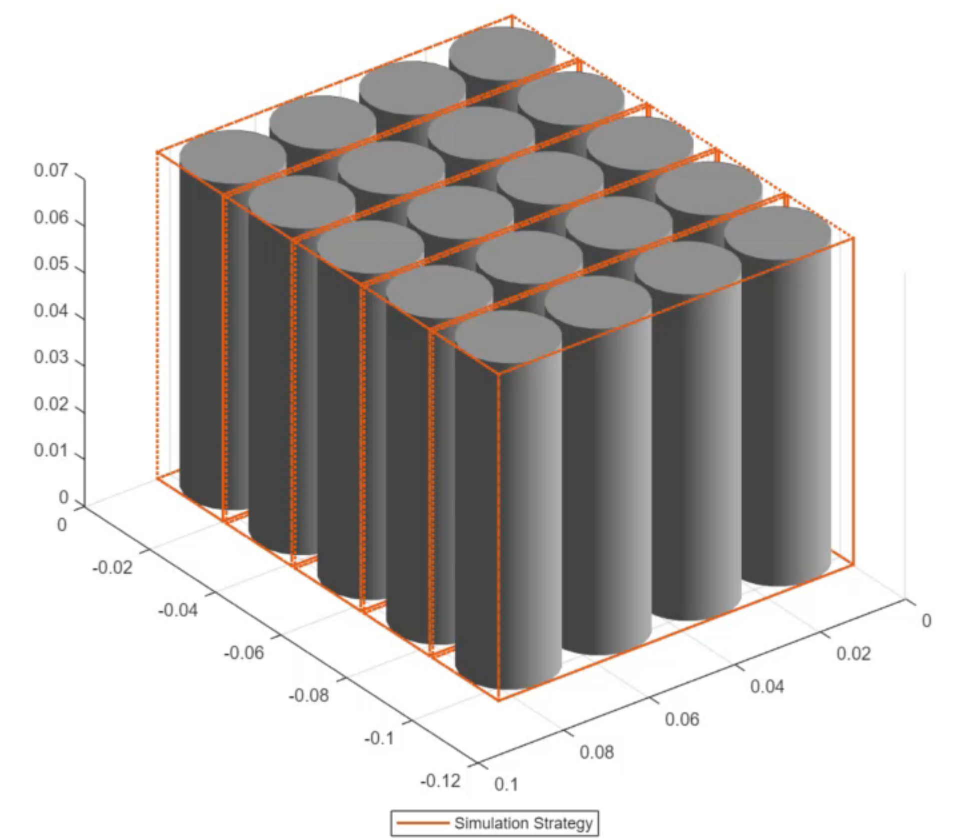
```
batteryPack.BalancingStrategy = "Passive";
```

Define thermal properties

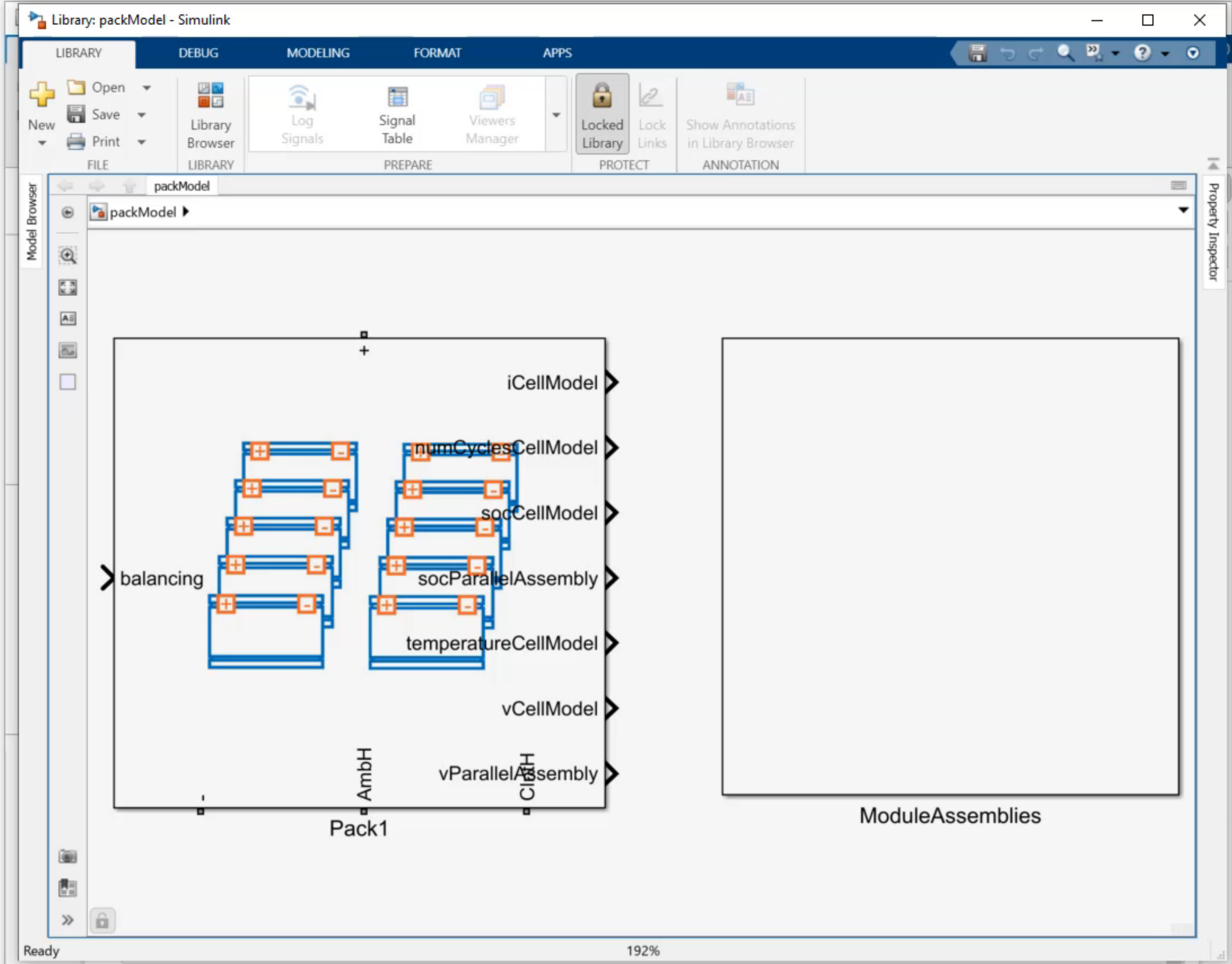
```
batteryPack.AmbientThermalPath = "CellBasedThermalResistance";
batteryPack.CoolantThermalPath = "CellBasedThermalResistance";
```

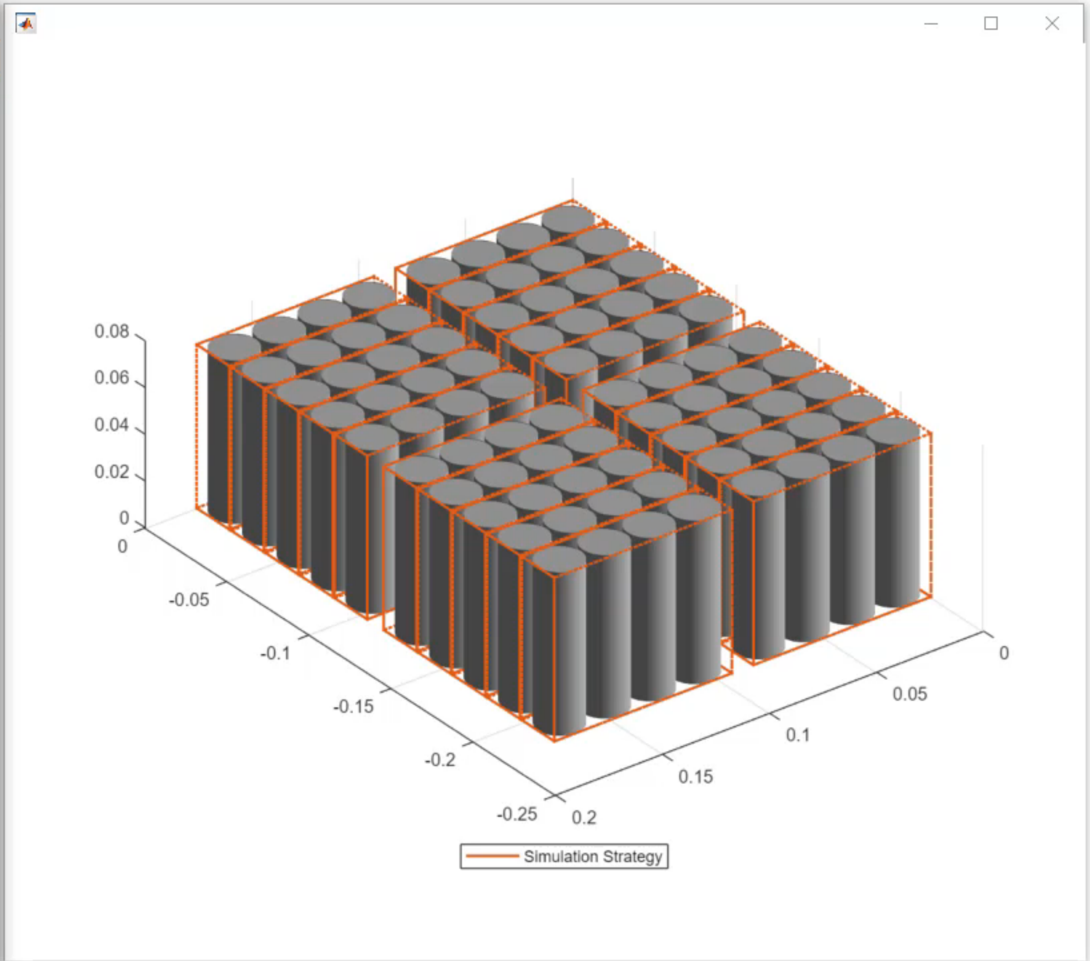
Build Simscape model of battery pack

```
buildBattery(batteryPack,"LibraryName","packModel",...
    "MaskInitialTargets","VariableNames",...
    "MaskParameters","VariableNames")
```



Define Module





Build Simscape model of battery pack

```
buildBattery(batteryPack,"LibraryName","packModel",...
    "MaskInitialTargets","VariableNames",...
    "MaskParameters","VariableNames")
```

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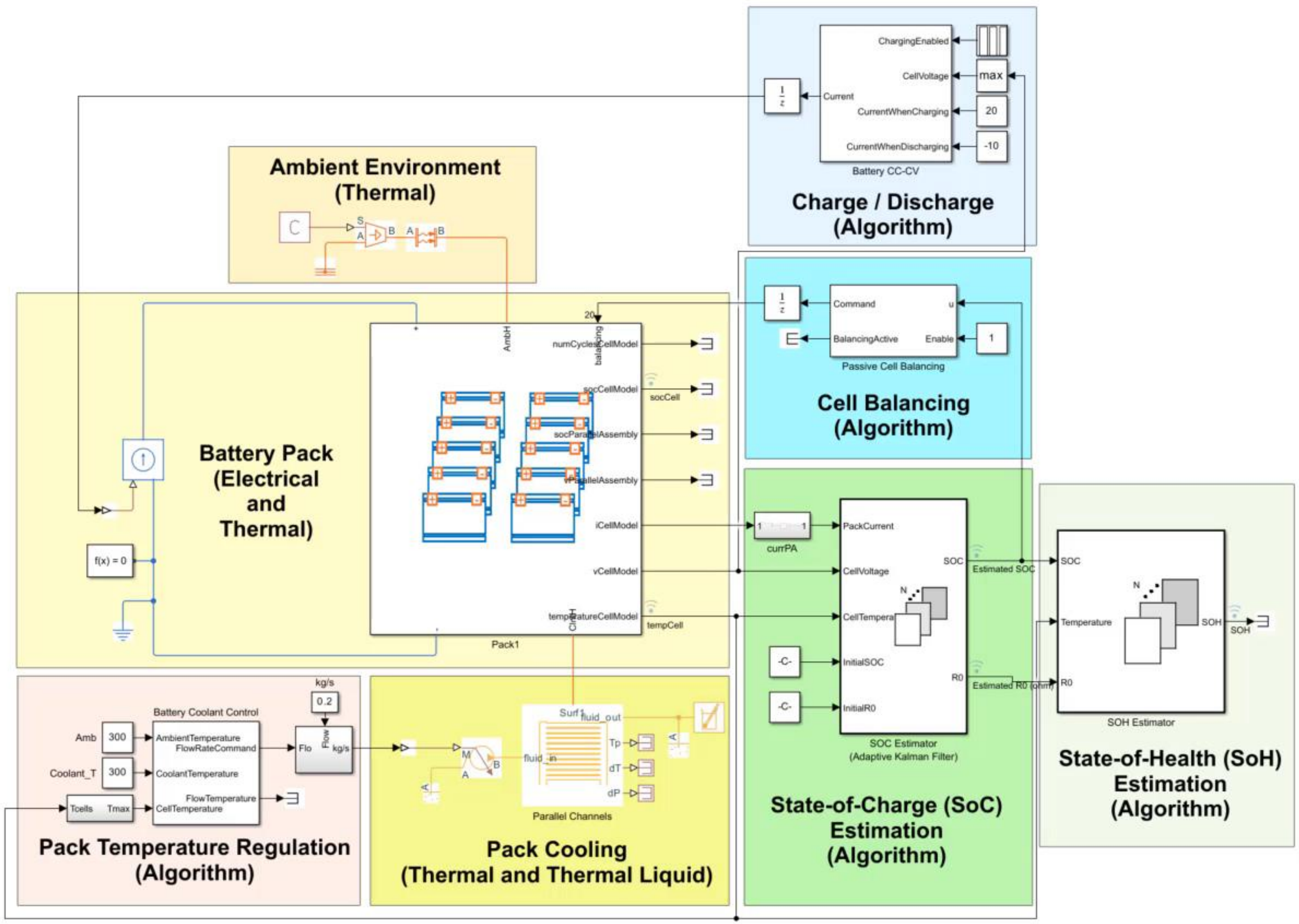
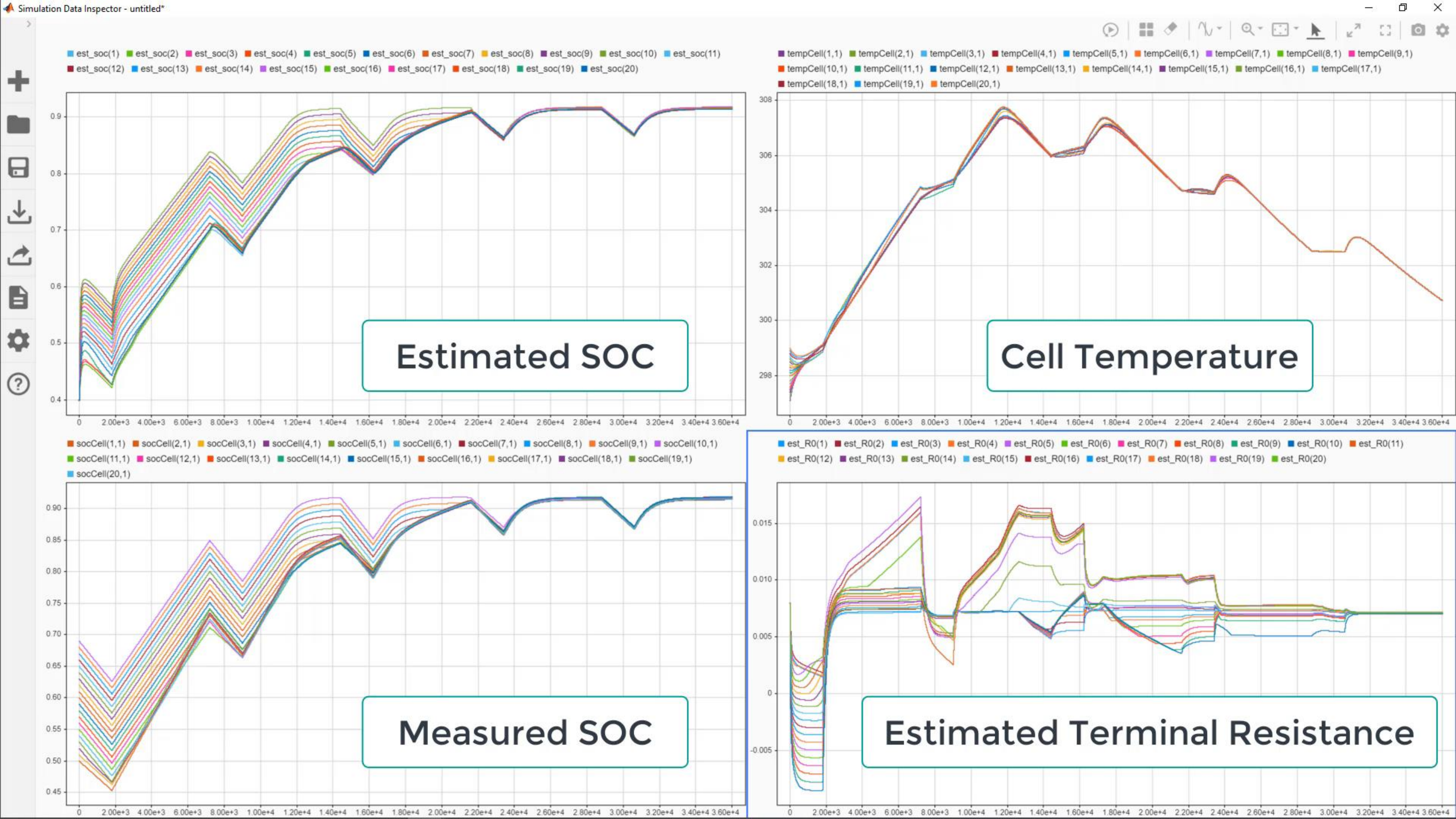
Build Pack Model

Voila!

We now have a functional battery system.

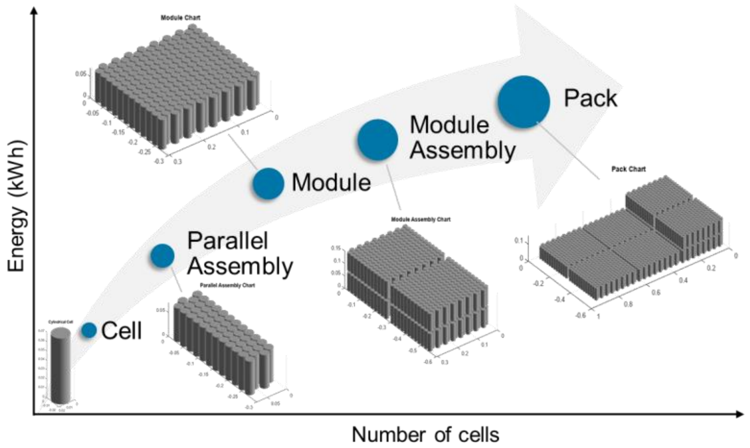
Time to simulate and analyze.



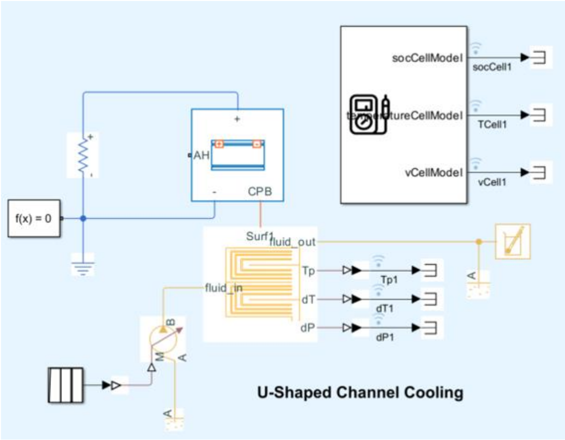

Simulation Data Inspector - untitled*
est_soc(1) est_soc(2) est_soc(3) est_soc(4) est_soc(5) est_soc(6) est_soc(7) est_soc(8) est_soc(9) est_soc(10) est_soc(11) est_soc(12) est_soc(13) est_soc(14) est_soc(15) est_soc(16) est_soc(17) est_soc(18) est_soc(19) est_soc(20)
Estimated SOC
tempCell(1,1) tempCell(2,1) tempCell(3,1) tempCell(4,1) tempCell(5,1) tempCell(6,1) tempCell(7,1) tempCell(8,1) tempCell(9,1) tempCell(10,1) tempCell(11,1) tempCell(12,1) tempCell(13,1) tempCell(14,1) tempCell(15,1) tempCell(16,1) tempCell(17,1) tempCell(18,1) tempCell(19,1) tempCell(20,1)
Cell Temperature
socCell(1,1) socCell(2,1) socCell(3,1) socCell(4,1) socCell(5,1) socCell(6,1) socCell(7,1) socCell(8,1) socCell(9,1) socCell(10,1) socCell(11,1) socCell(12,1) socCell(13,1) socCell(14,1) socCell(15,1) socCell(16,1) socCell(17,1) socCell(18,1) socCell(19,1) socCell(20,1)
Measured SOC
est_R0(1) est_R0(2) est_R0(3) est_R0(4) est_R0(5) est_R0(6) est_R0(7) est_R0(8) est_R0(9) est_R0(10) est_R0(11) est_R0(12) est_R0(13) est_R0(14) est_R0(15) est_R0(16) est_R0(17) est_R0(18) est_R0(19) est_R0(20)
Estimated Terminal Resistance

Simscape Battery – Main workflow themes

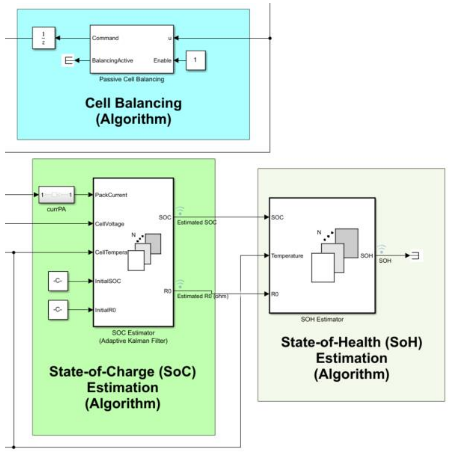
1. Battery Pack Design



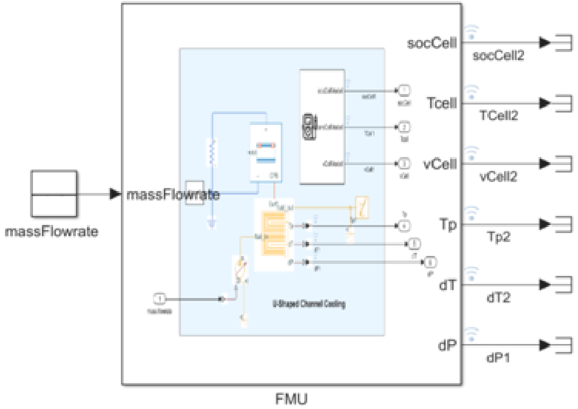
2. Thermal Management System Design



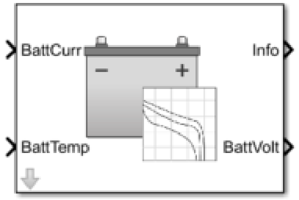
3. Battery Management System Design

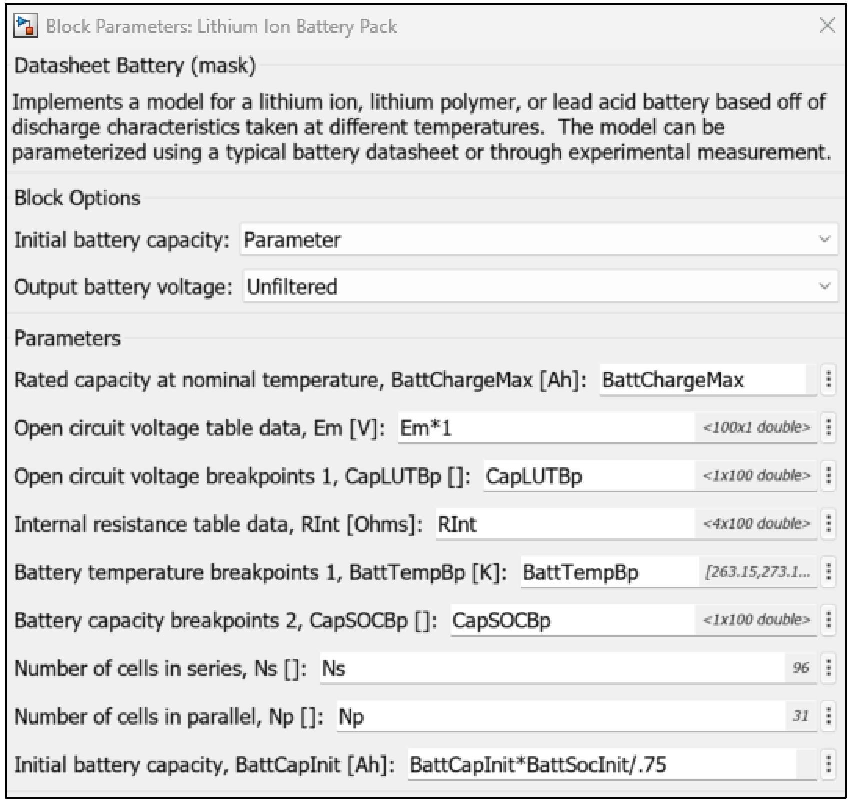


4. Support for Deployment and HIL



Create lumped battery pack model in Simscape Battery




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.

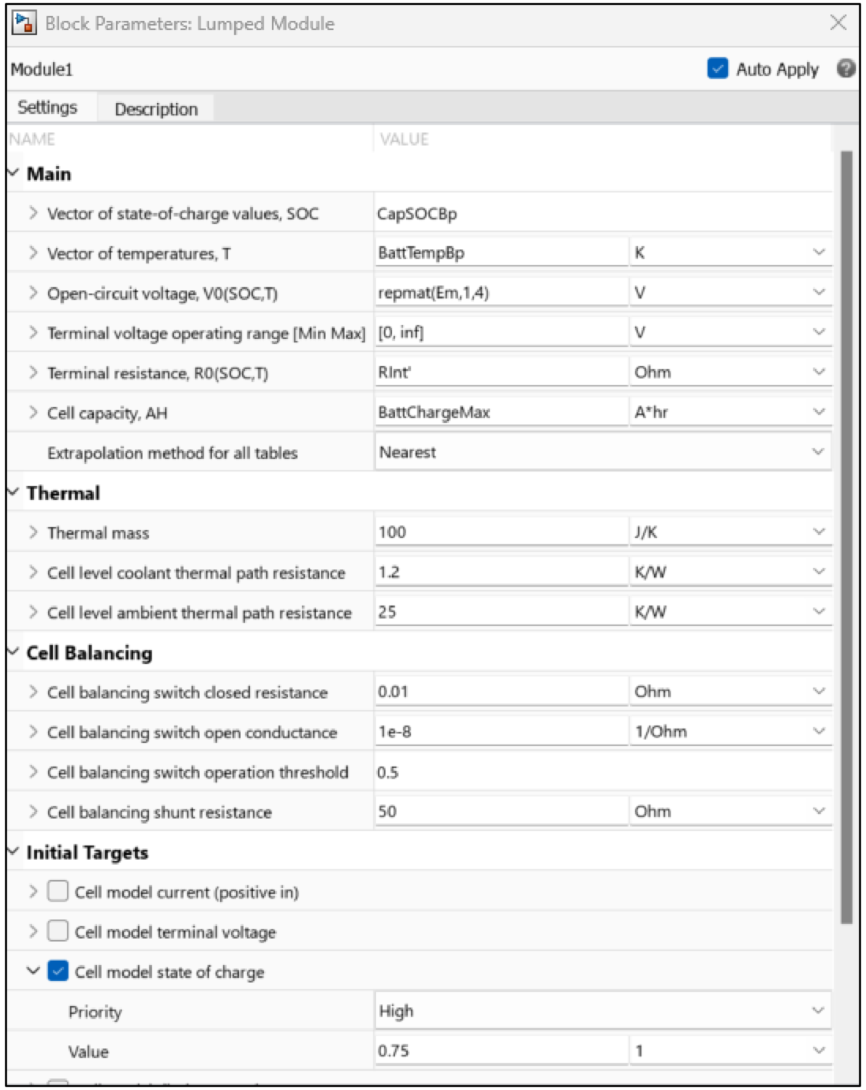
Block Options

Initial battery capacity: Parameter

Output battery voltage: Unfiltered

Parameters

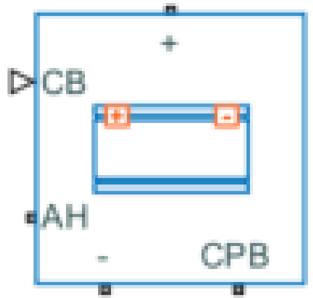
Rated capacity at nominal temperature, BattChargeMax [Ah]:	BattChargeMax	
Open circuit voltage table data, Em [V]:	Em*1	<100x1 double>
Open circuit voltage breakpoints 1, CapLUTBp []:	CapLUTBp	<1x100 double>
Internal resistance table data, RInt [Ohms]:	RInt	<4x100 double>
Battery temperature breakpoints 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

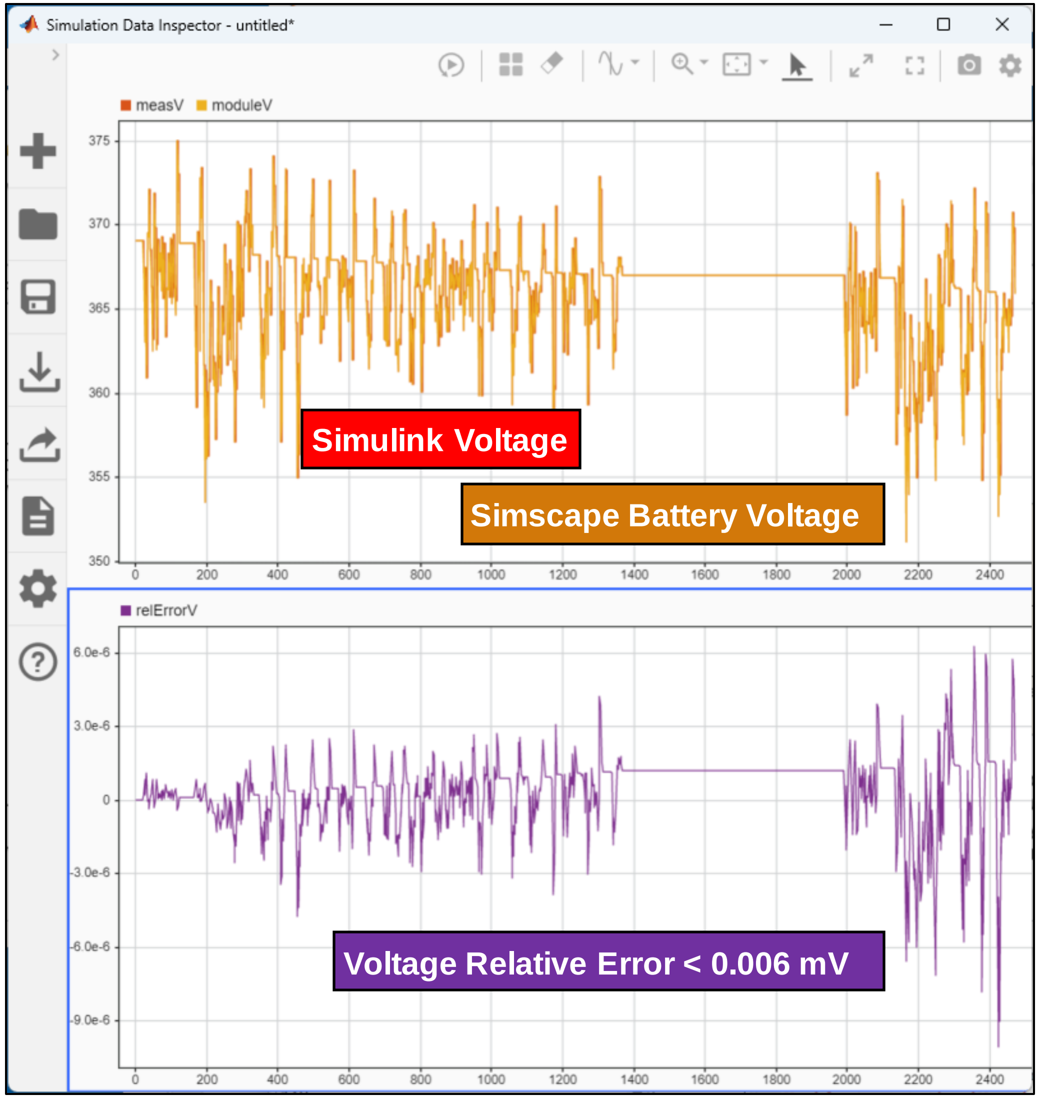
Module1 — Auto Apply

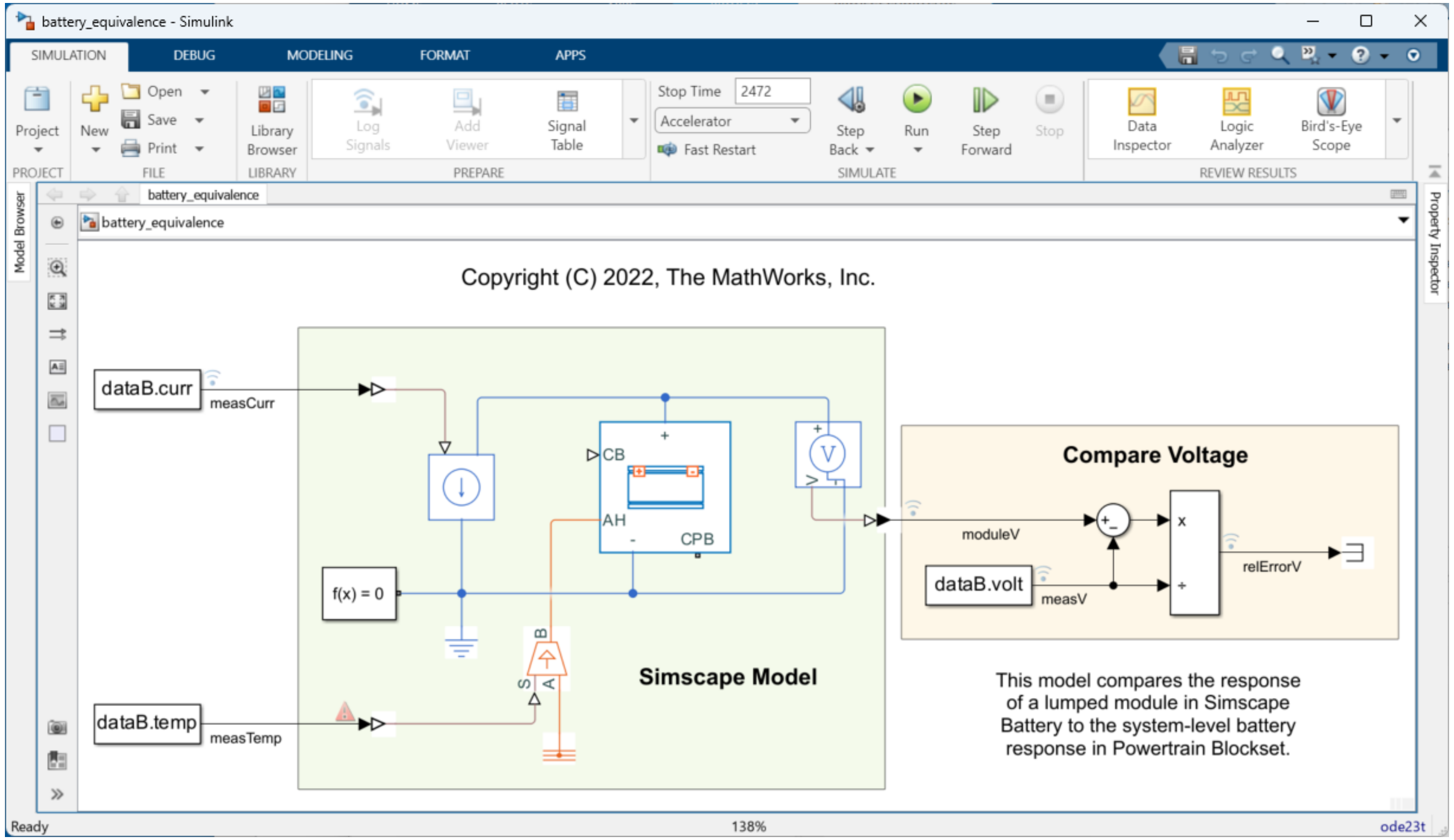
Settings | Description

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		
☐ Cell model current (positive in)		
☐ Cell model terminal voltage		
☑ Cell model state of charge		
Priority	High	
Value	0.75	1



Demonstrate equivalence with unit test

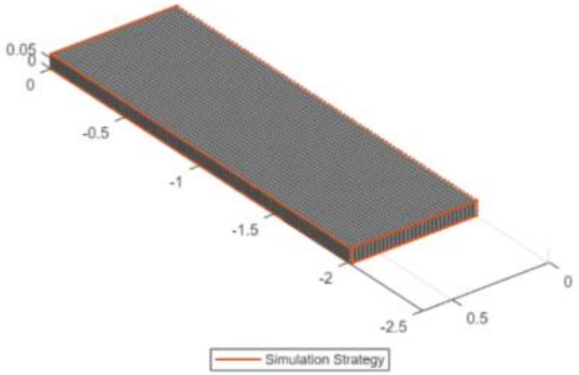




Design battery systems in Simscape Battery

- Create battery pack with higher resolution

Lumped (1 cell model for entire pack)



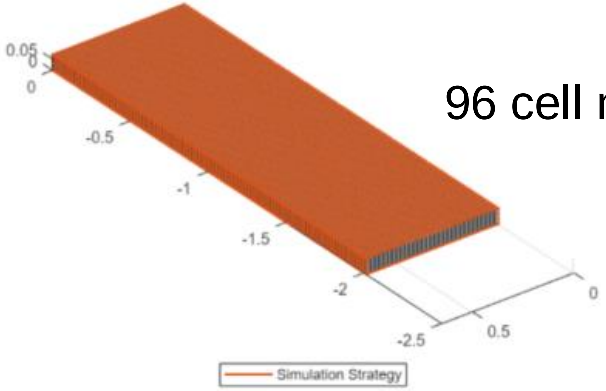
Define module

```
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

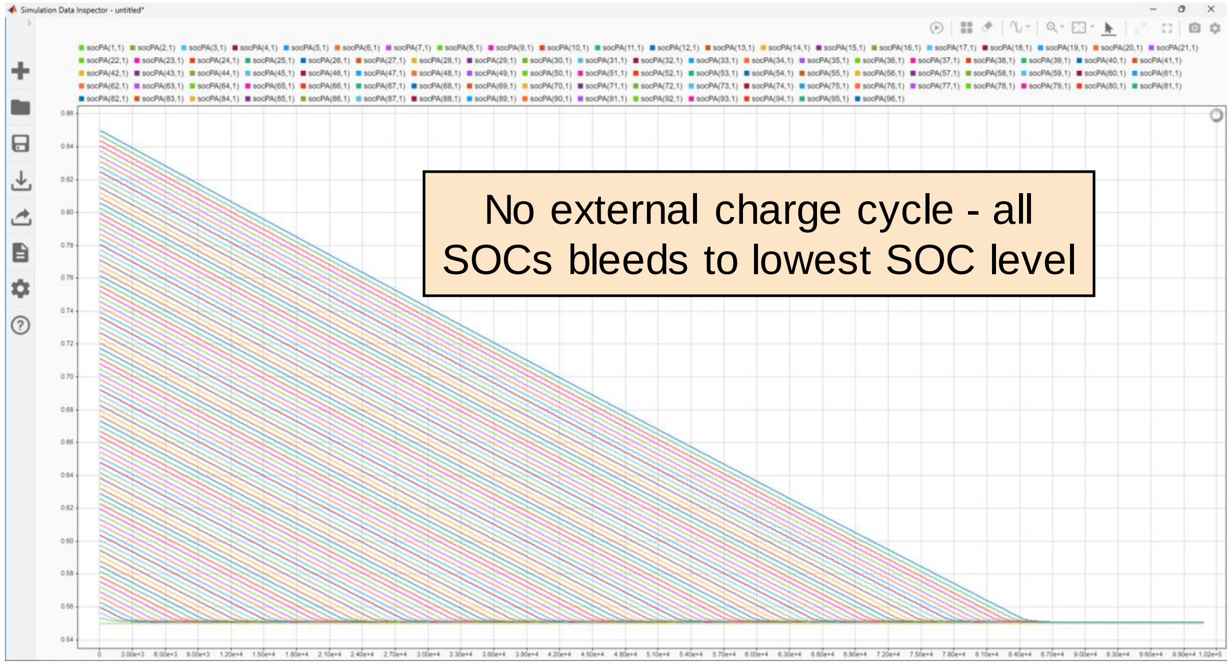
```
Ns = 96; % number of parallel assemblies in series
batteryModule = Module(ParallelAssembly = batteryParallelAssembly, numSeriesAssemblies = Ns);
```

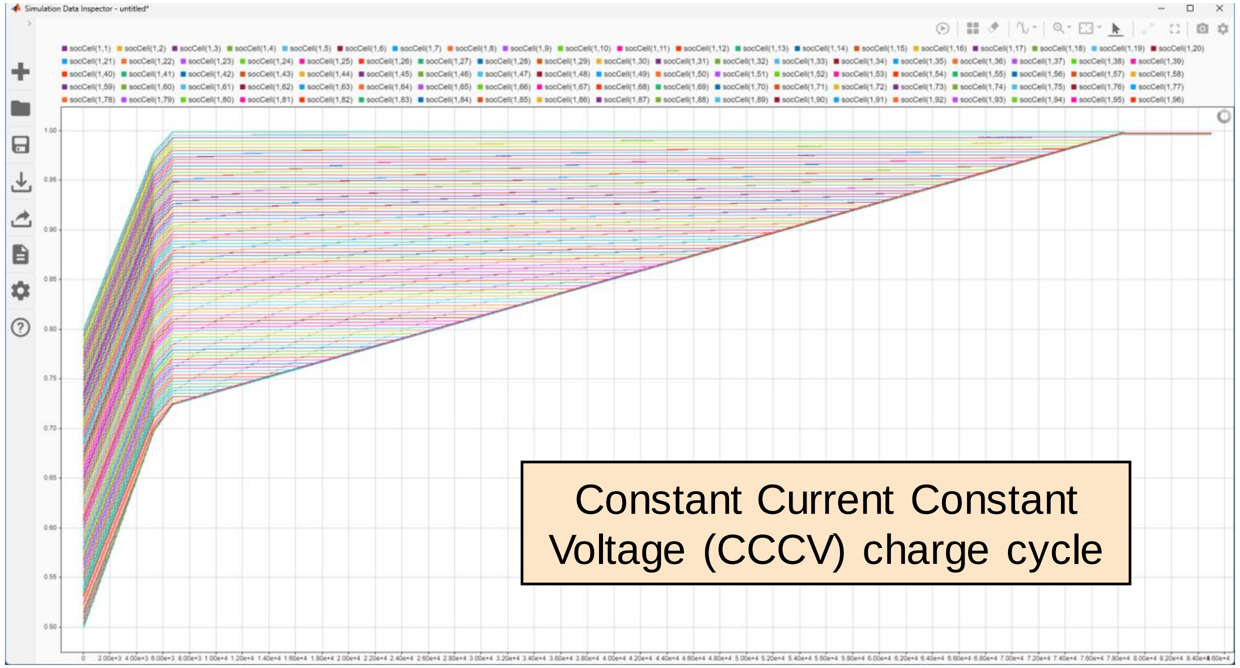
Define simulation strategy

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

Passive cell balancing

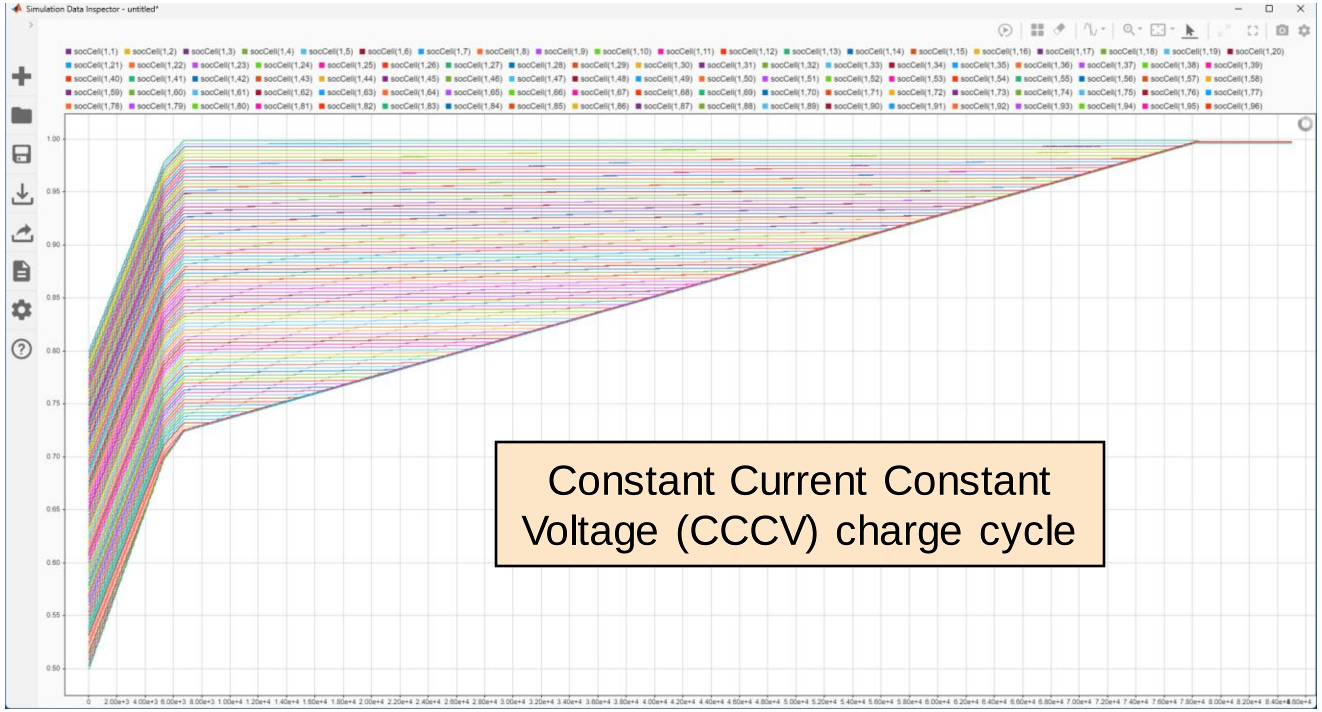
- Cells within a parallel assembly will naturally balance
- One cell balancing circuit for each series-connected parallel assembly

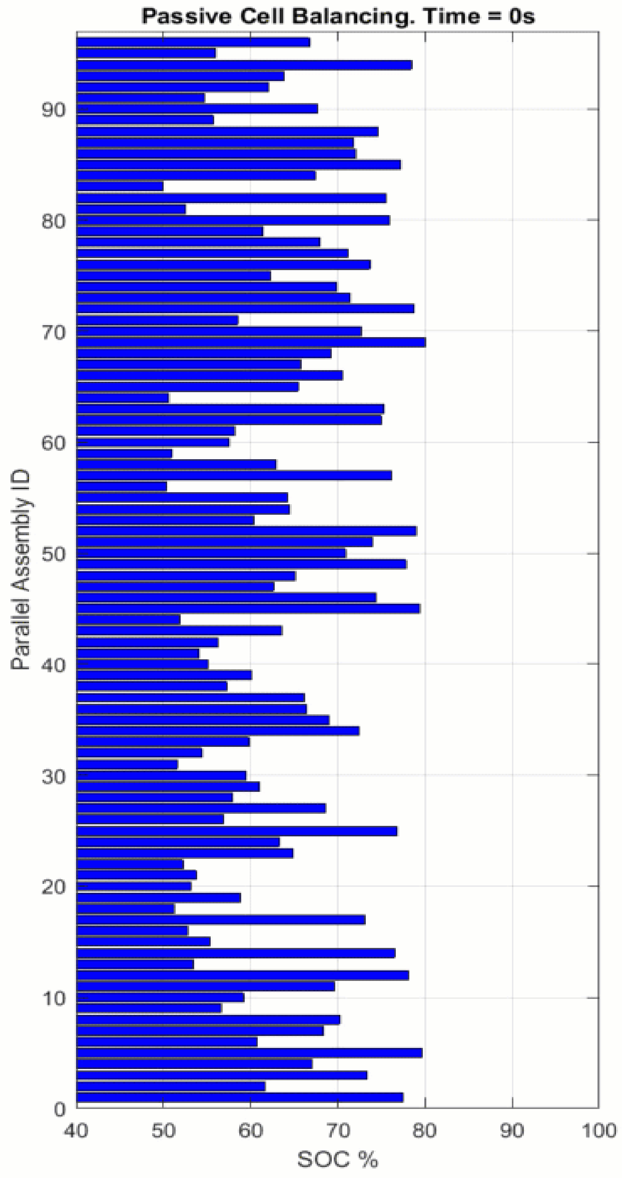




Passive cell balancing

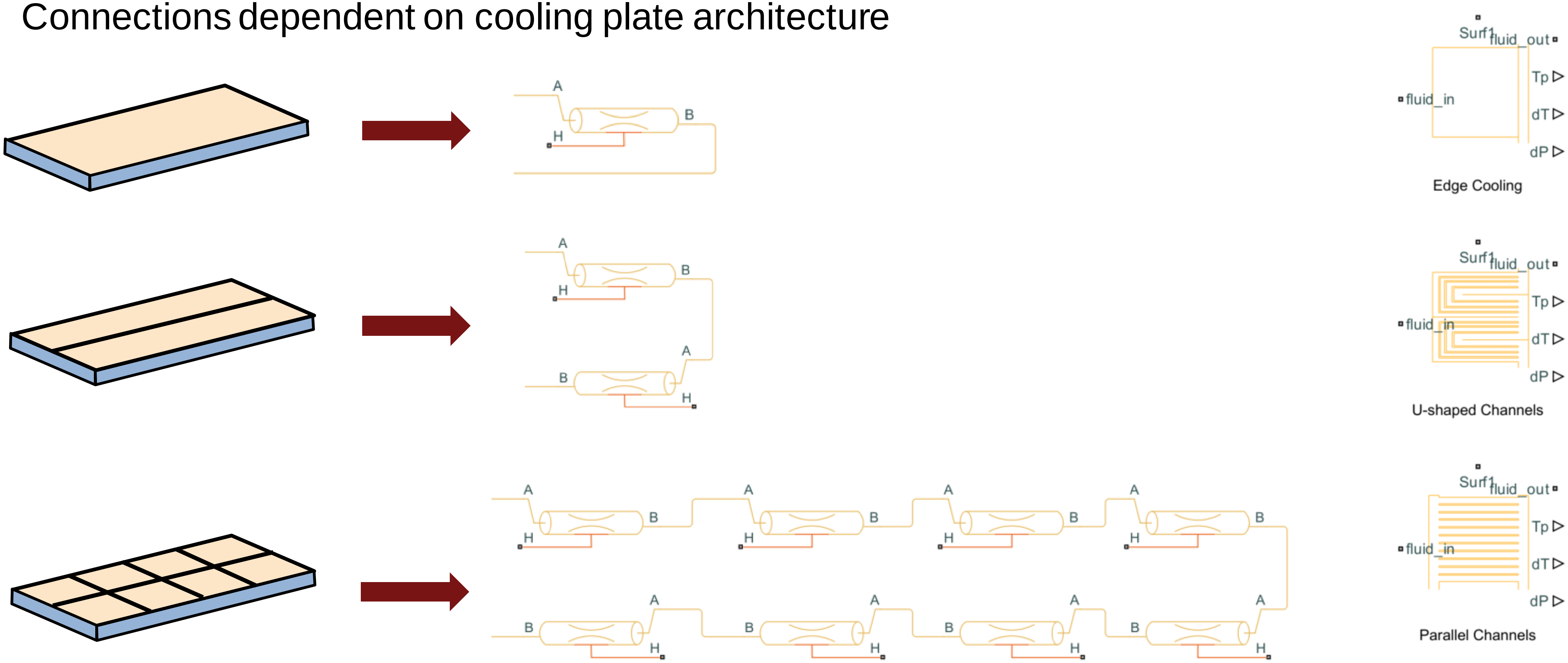
- Animation can bring further clarity to a large number of time-series responses





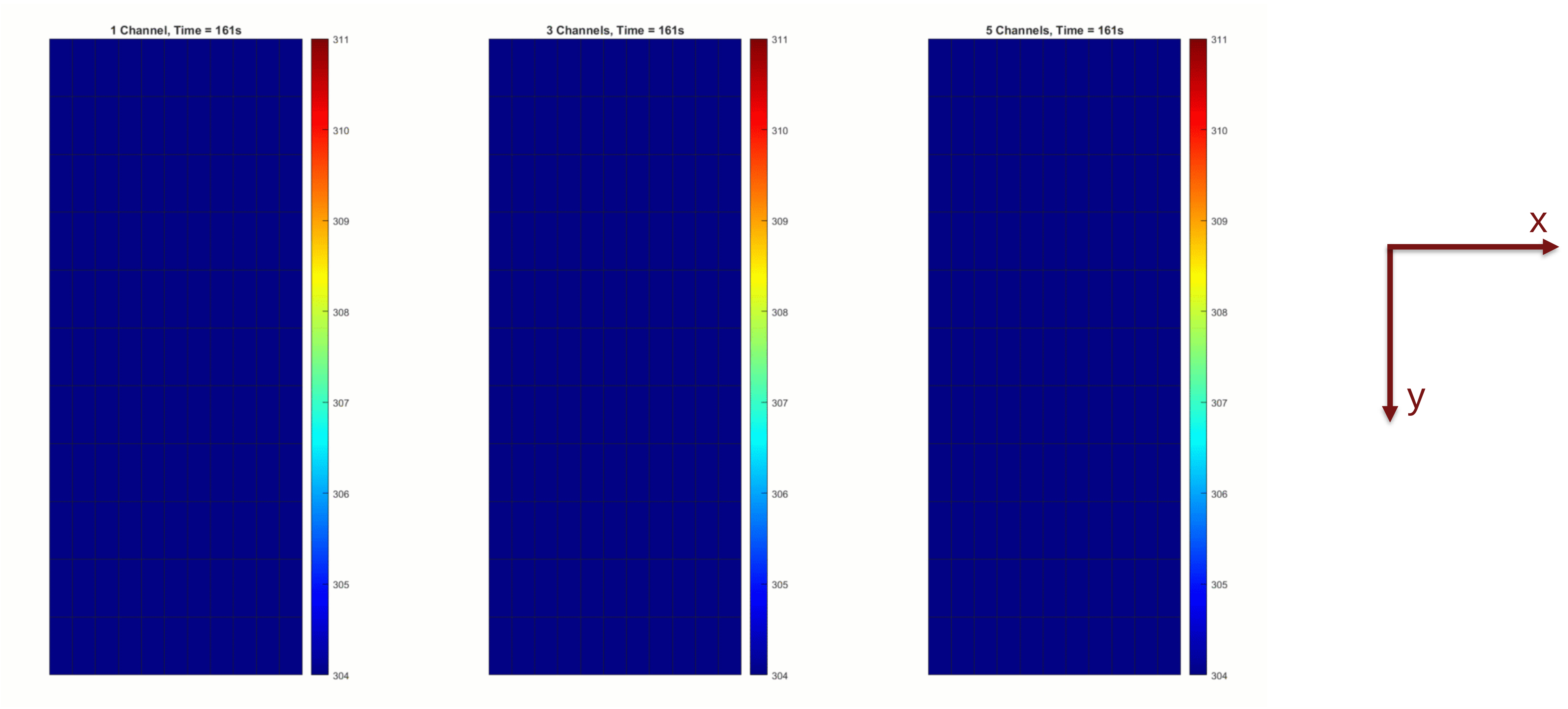
Thermal management

- Change the simulation strategy of cooling plates to meet your model resolution needs
- Connections dependent on cooling plate architecture



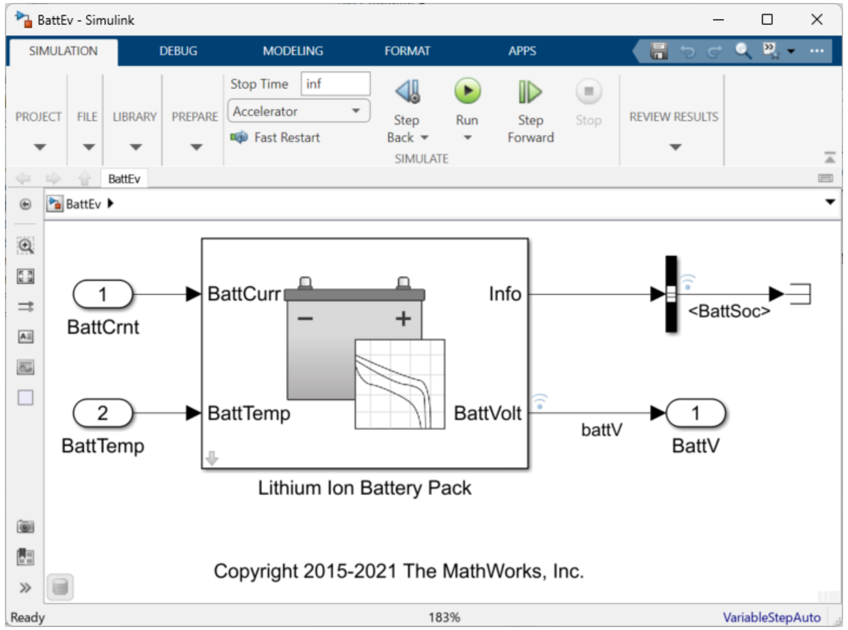
Thermal management

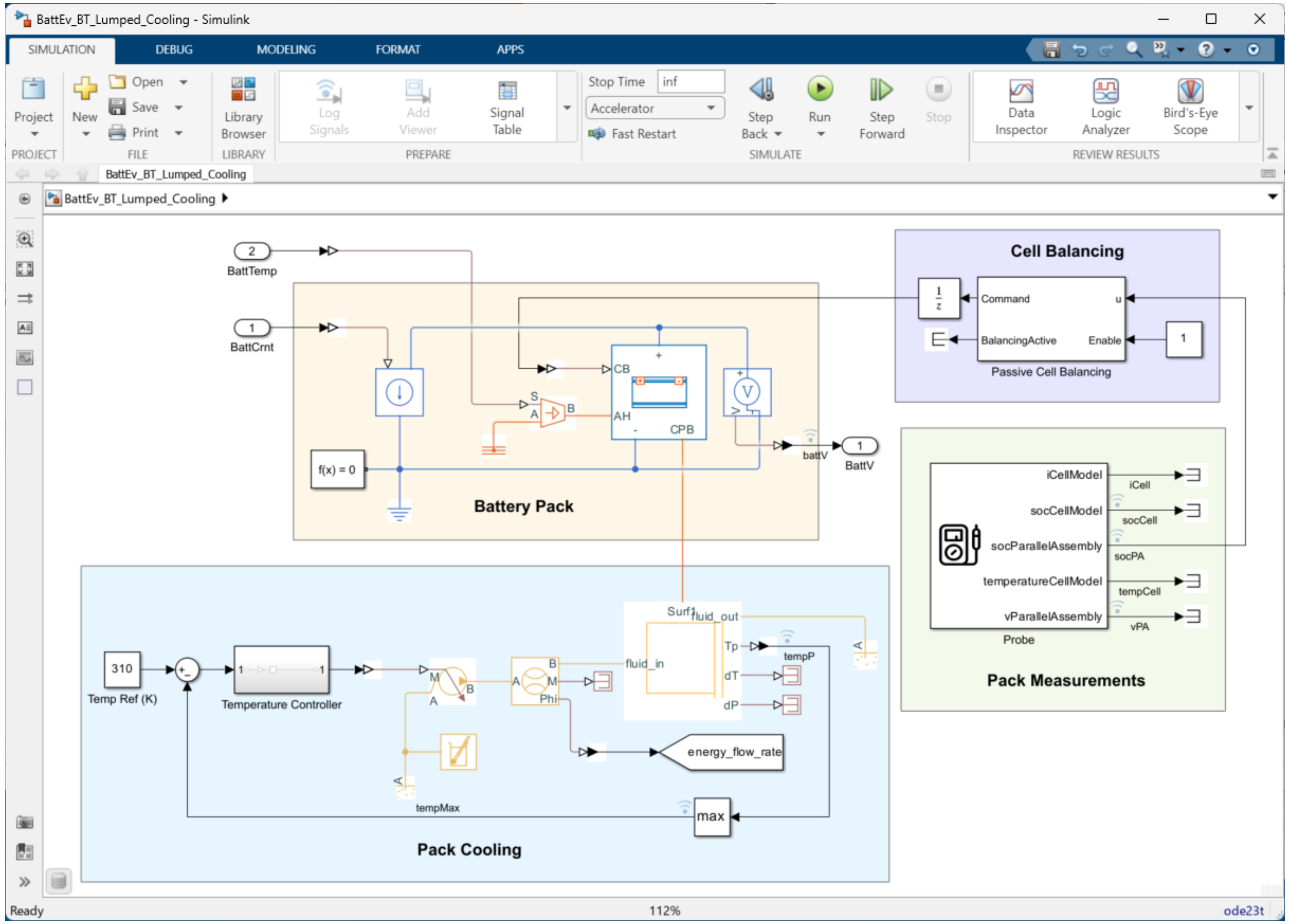
Parallel cooling channels oriented along the x-axis



Select appropriate model fidelity for full system evaluation

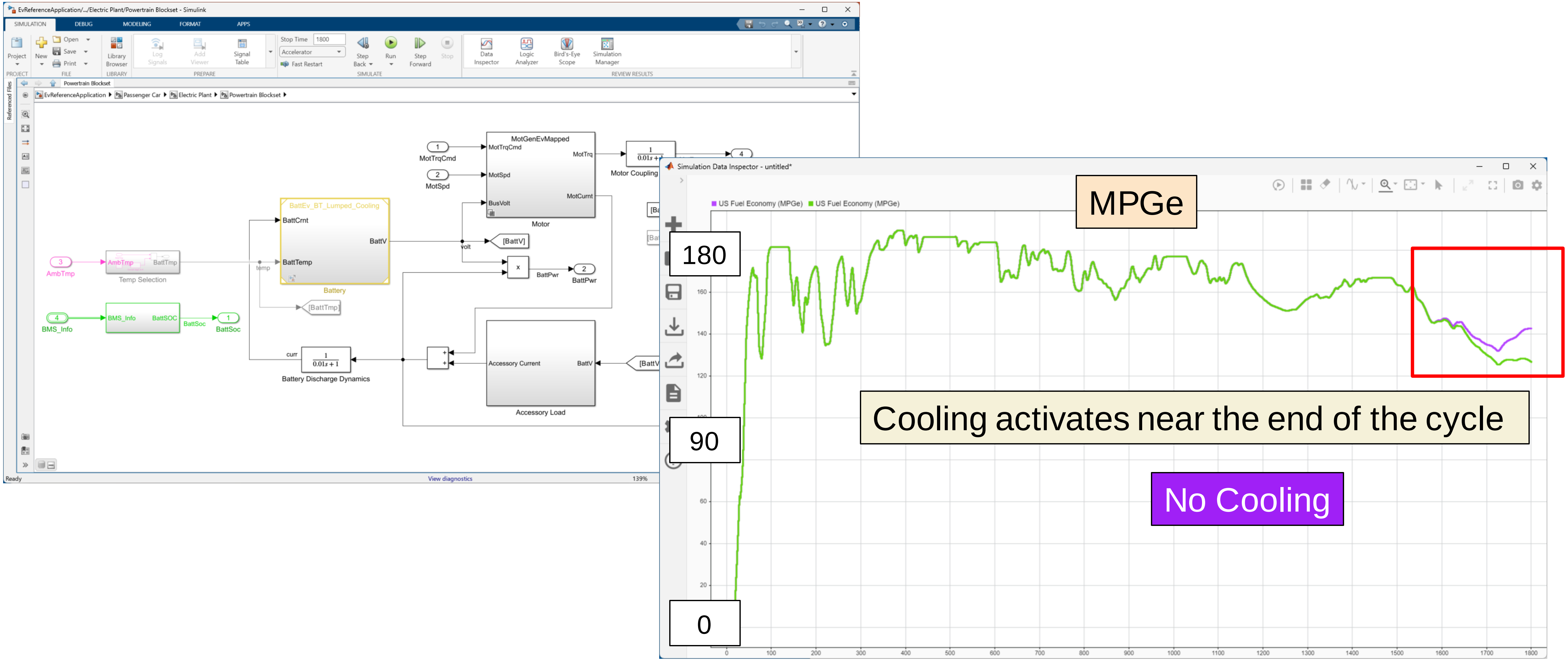
- For many scenarios, lumped battery model is sufficient for system integration
- Other fidelities can be incorporated as needed





Evaluate battery design in full system

WLTP (Class 3) drive cycle (MPGe)



Summary: Design battery pack

- 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

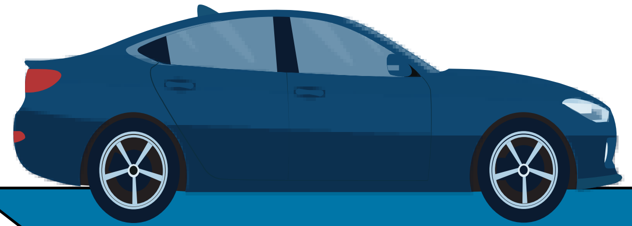
Additional Resources

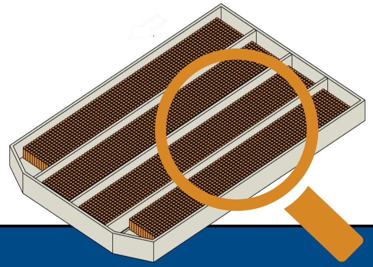
- Overview of MathWorks' automotive solutions:
  - MATLAB and Simulink for Electric Vehicle Development
  - Building Your Virtual Vehicle with Simulink
  - Upskill for the Electric Vehicle Transition

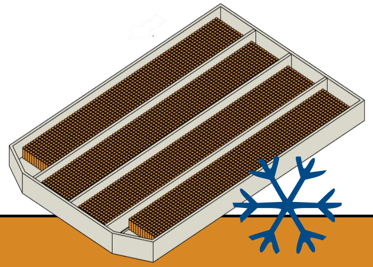
- Products highlighted in this study:
  - Powertrain Blockset
  - Simscape Battery
  - Global Optimization Toolbox
  - Simulink Design Optimization

Key takeaways

Optimize EV battery performance using simulation







Assess system performance

Find optimal pack size

Design battery pack

Powertrain Blockset

System-level models to quantify vehicle range, battery performance, and costs

Global Optimization Toolbox
Simulink Design Optimization

Efficiently optimize the design while accounting for competing requirements

Simscape Battery

Perform detailed battery design studies

MATLAB EXPO

Thank you

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