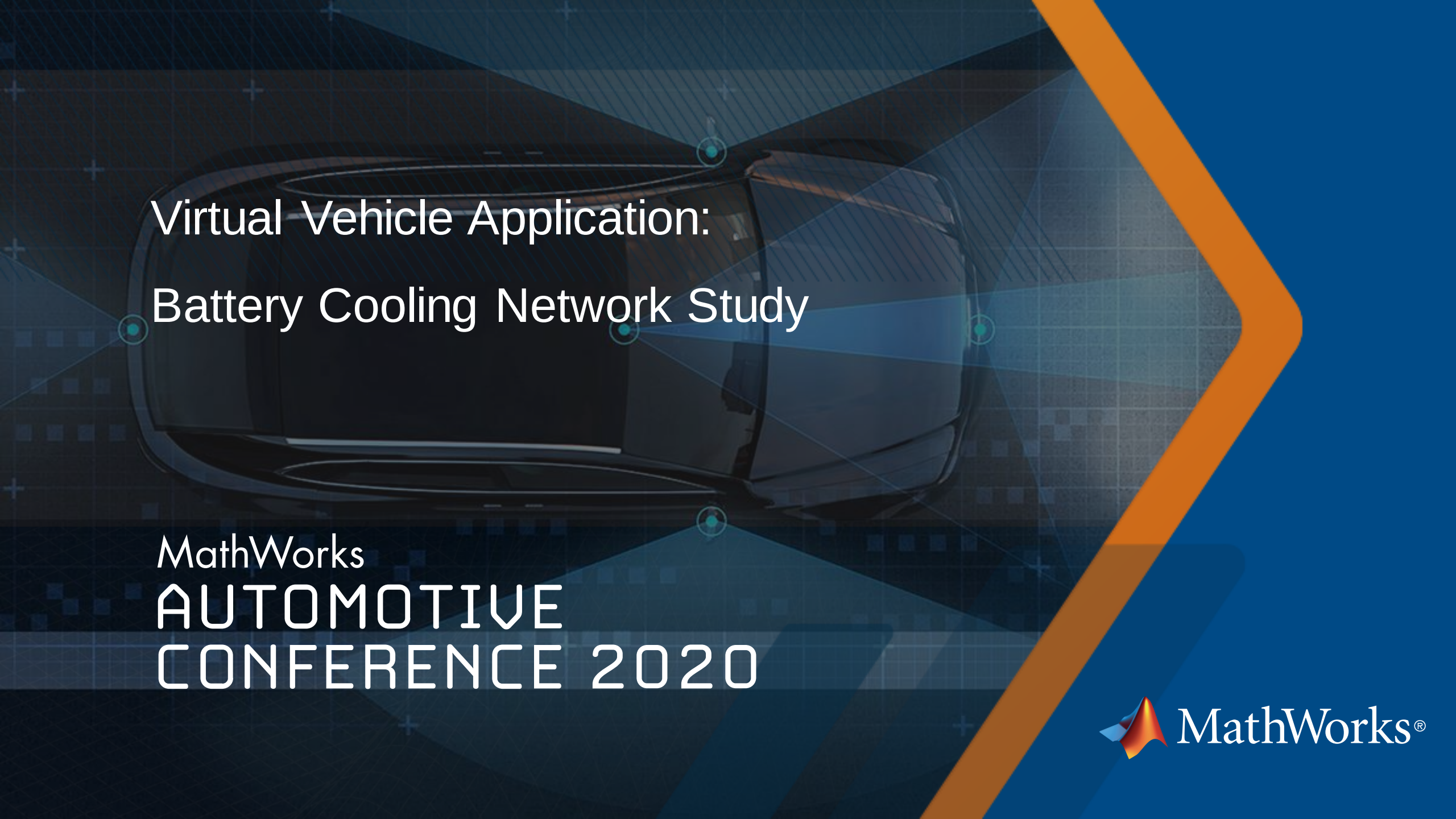

Virtual Vehicle Application:

Battery Cooling Network Study

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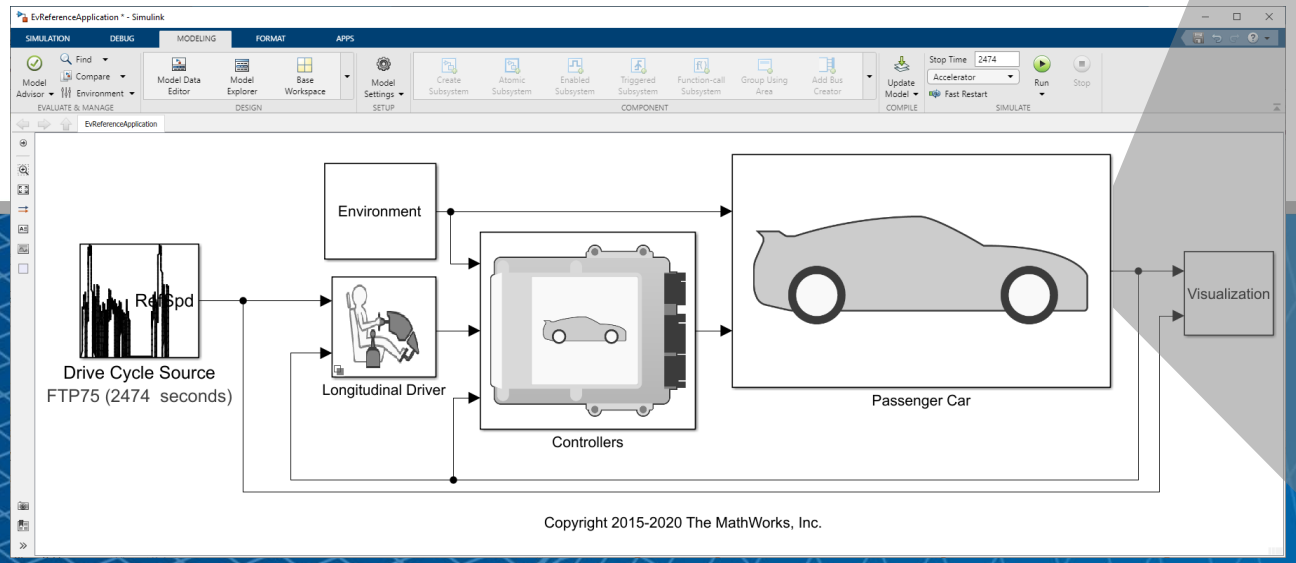
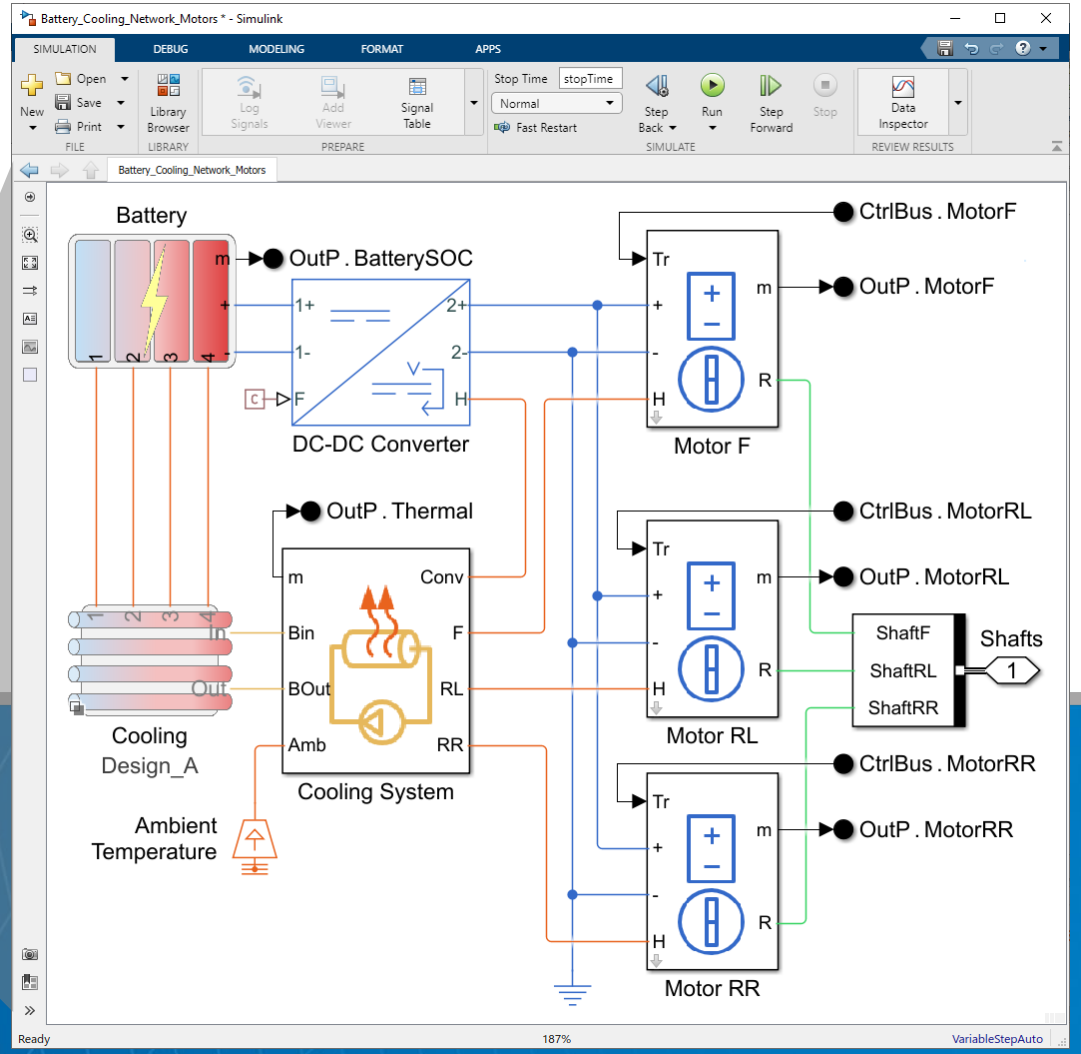
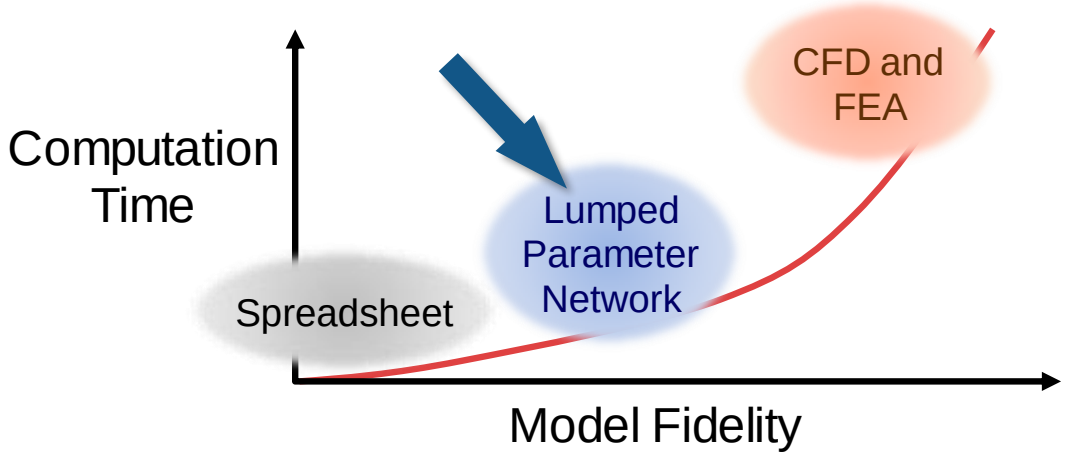
Virtual Vehicle Application: Battery Cooling Network Study

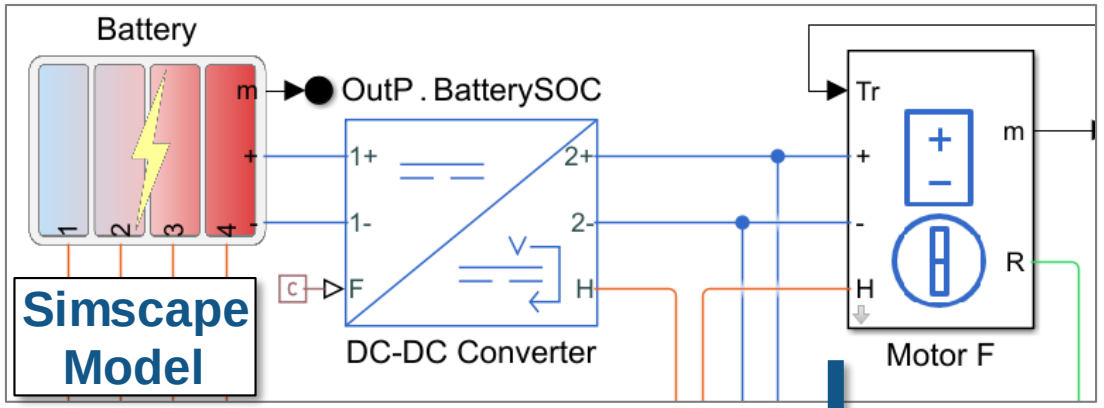


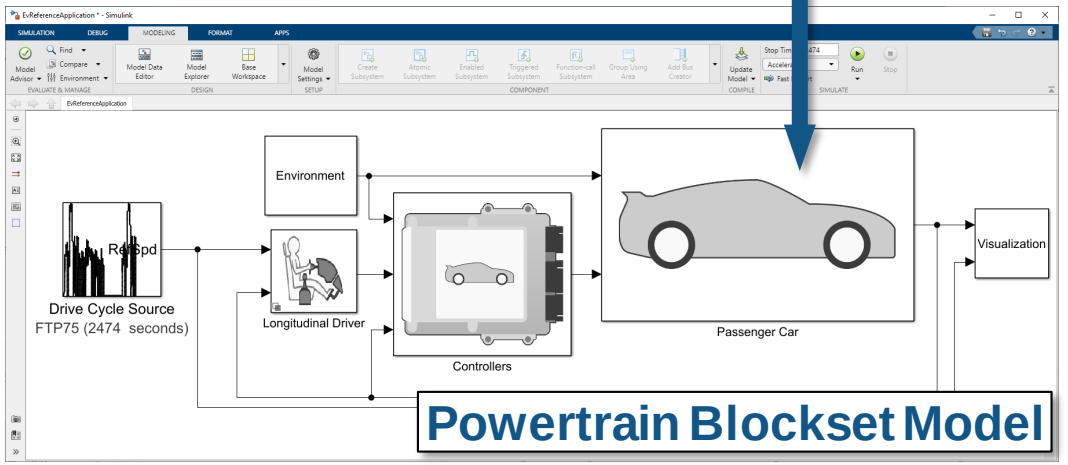


Key Takeaways

- Battery cooling network design requires component level analysis and tests within a full-vehicle simulation
- Integrating fluid, thermal, electrical, and mechanical domains is key to assessing system-level performance
- Rapid simulations covering a wide range of drive cycles and ambient conditions are needed to evaluate design criteria







Agenda

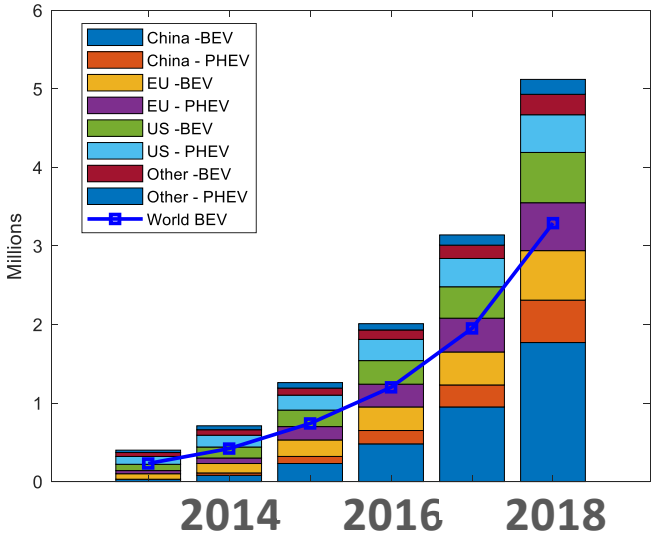
- Importance of Battery Cooling
- Exploring Battery Cooling Network Designs
- Integration in Vehicle Model
- Evaluation of Design in Full Vehicle Tests

Why Explore Battery Cooling?

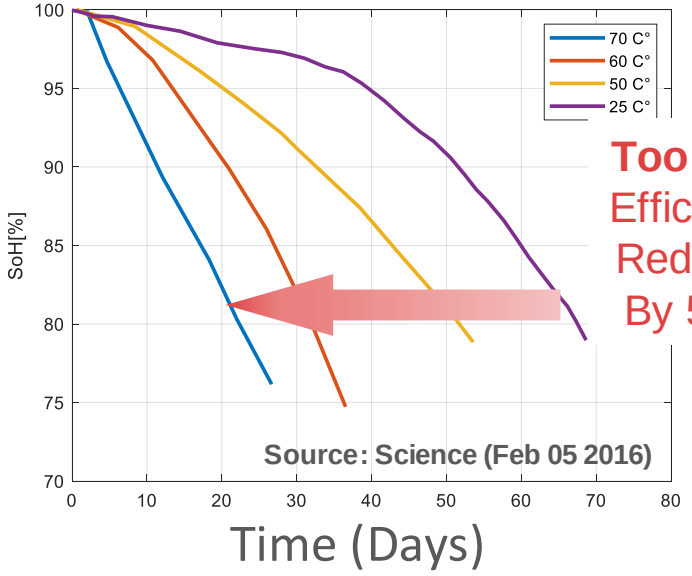
- Electrification is a cross-industry market driver
  - Power, heating, transportation
  - Shift to electric and hybrid powertrains
- Key to success: efficiency and safety

EV Sales and Market Share

Data Source: International Energy Agency (2018)

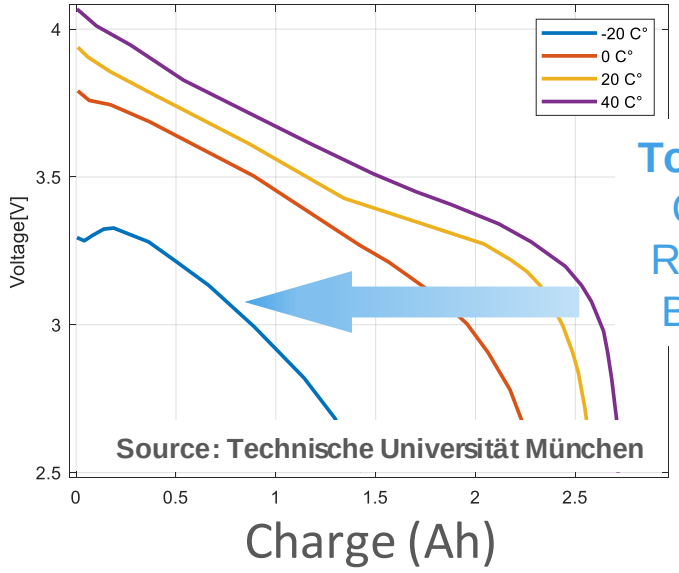


Battery State of Health



Too Hot: Efficiency Reduced By 50%

Voltage vs. Charge



Too Cold: Output Reduced By 80%

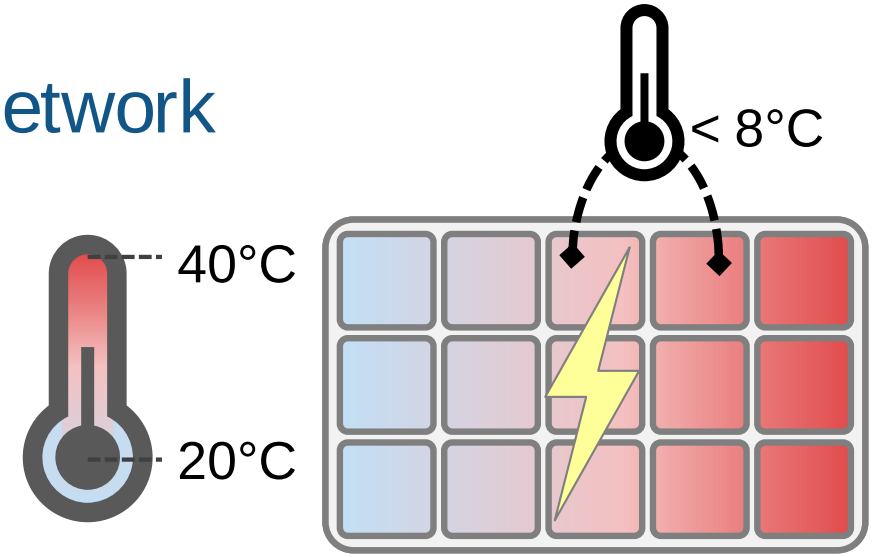
Safety Concerns Thermal Runaway Leads to Explosion

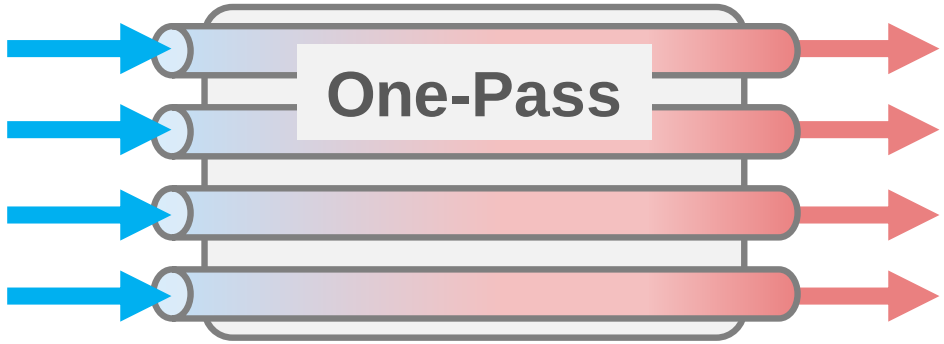
Agenda

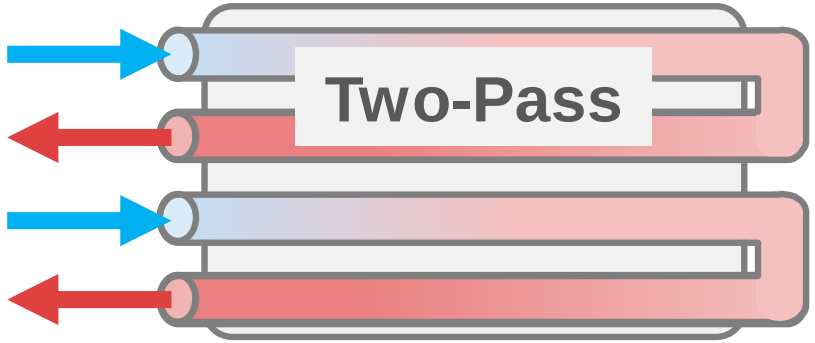
- Importance of Battery Cooling
- Exploring Battery Cooling Network Designs
- Integration in Vehicle Model
- Evaluation of Design in Full Vehicle Tests

Design Challenge: Battery Cooling Network

- Requirements
  - Cell temperature range: 20-40 °C
  - Cell temperature max delta: 8 °C
- Evaluation
  - Hot and cold environments
  - Driving conditions (FTP75, US06, WOT, etc.)
  - Charge cycle
- Two options considered
  - One-pass
  - Two-pass

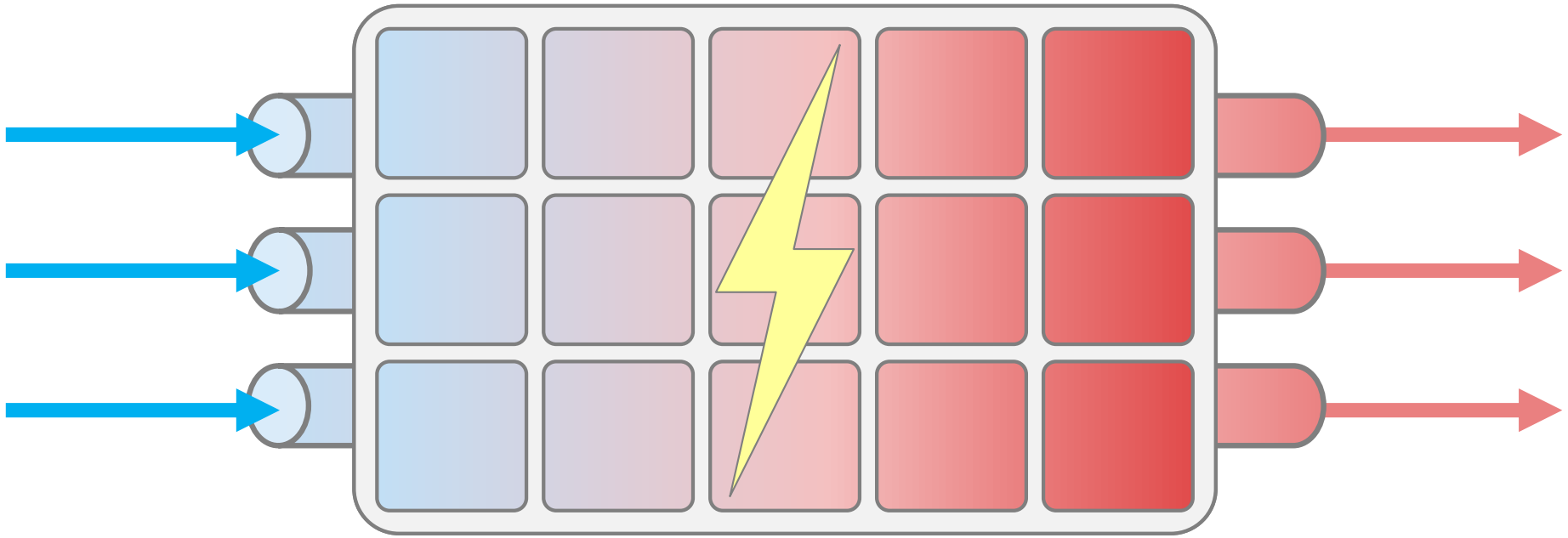






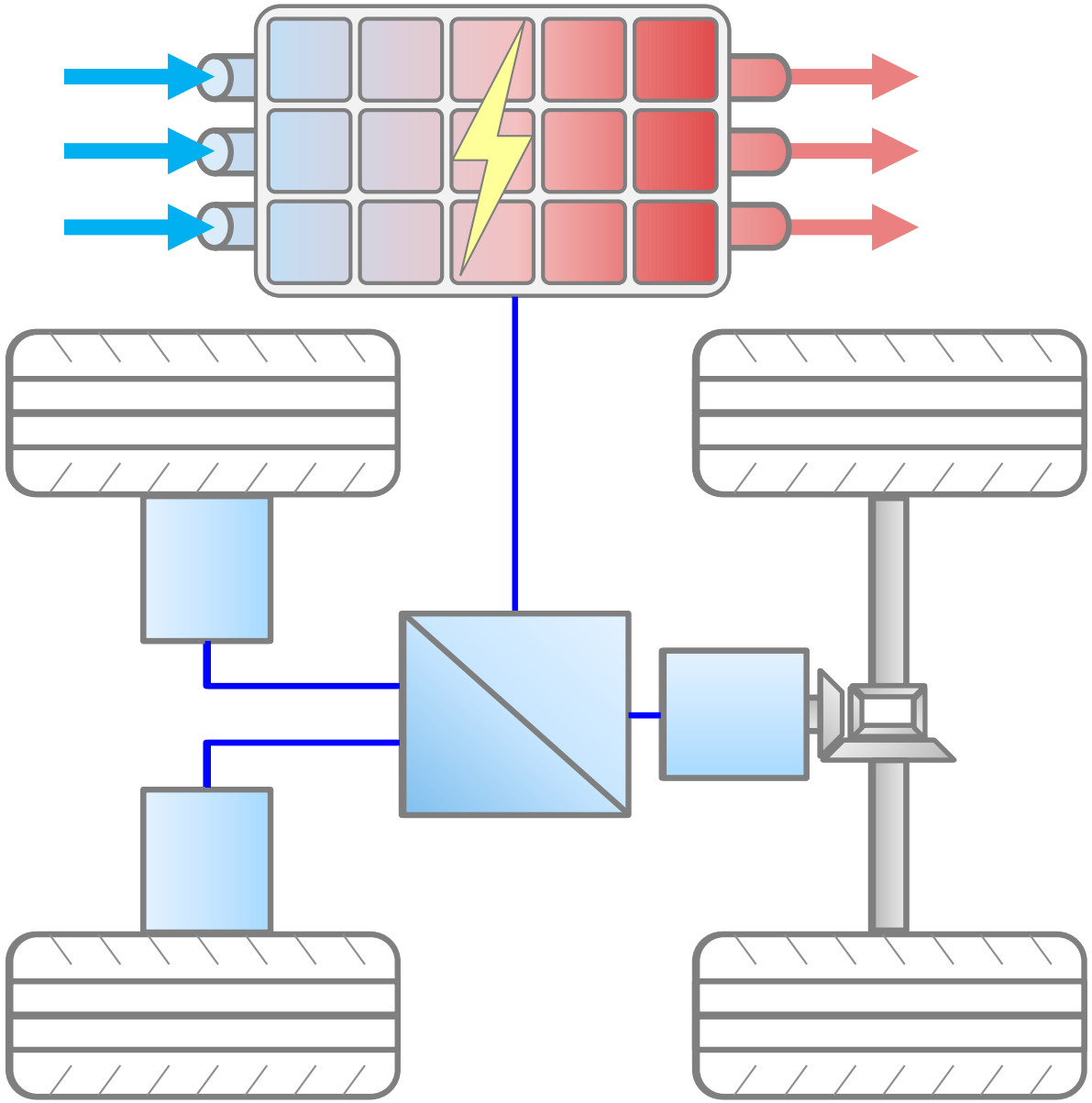
Design Process for Battery Cooling Network

1. Explore designs



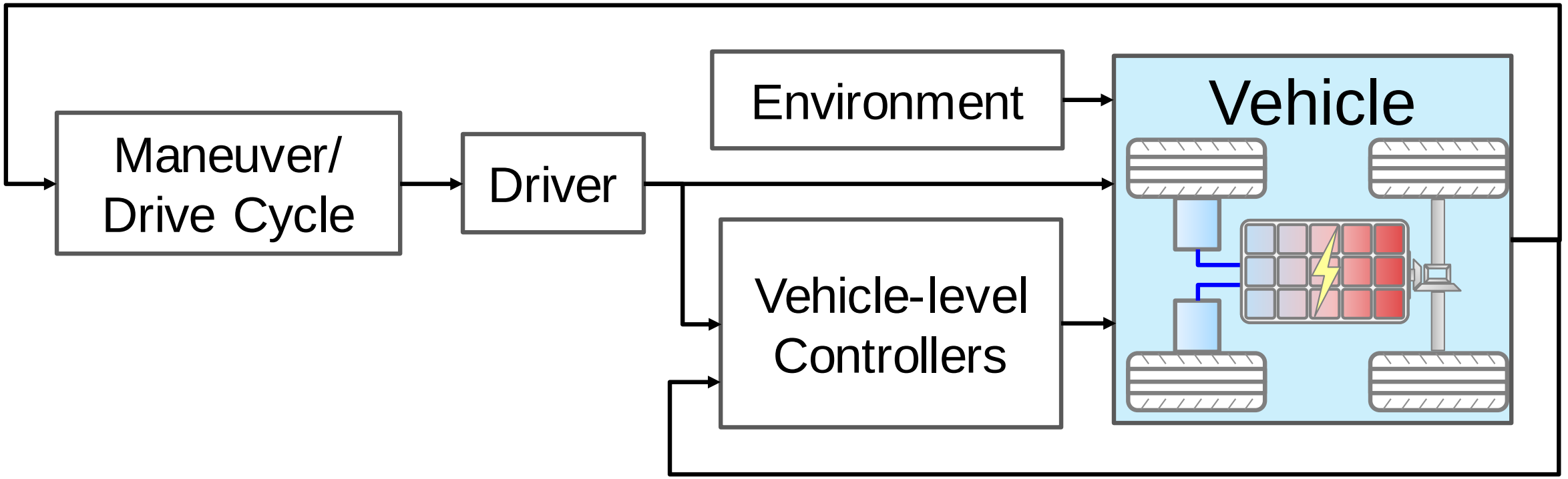
Design Process for Battery Cooling Network

1. Explore designs
2. Integrate in vehicle model



Design Process for Battery Cooling Network

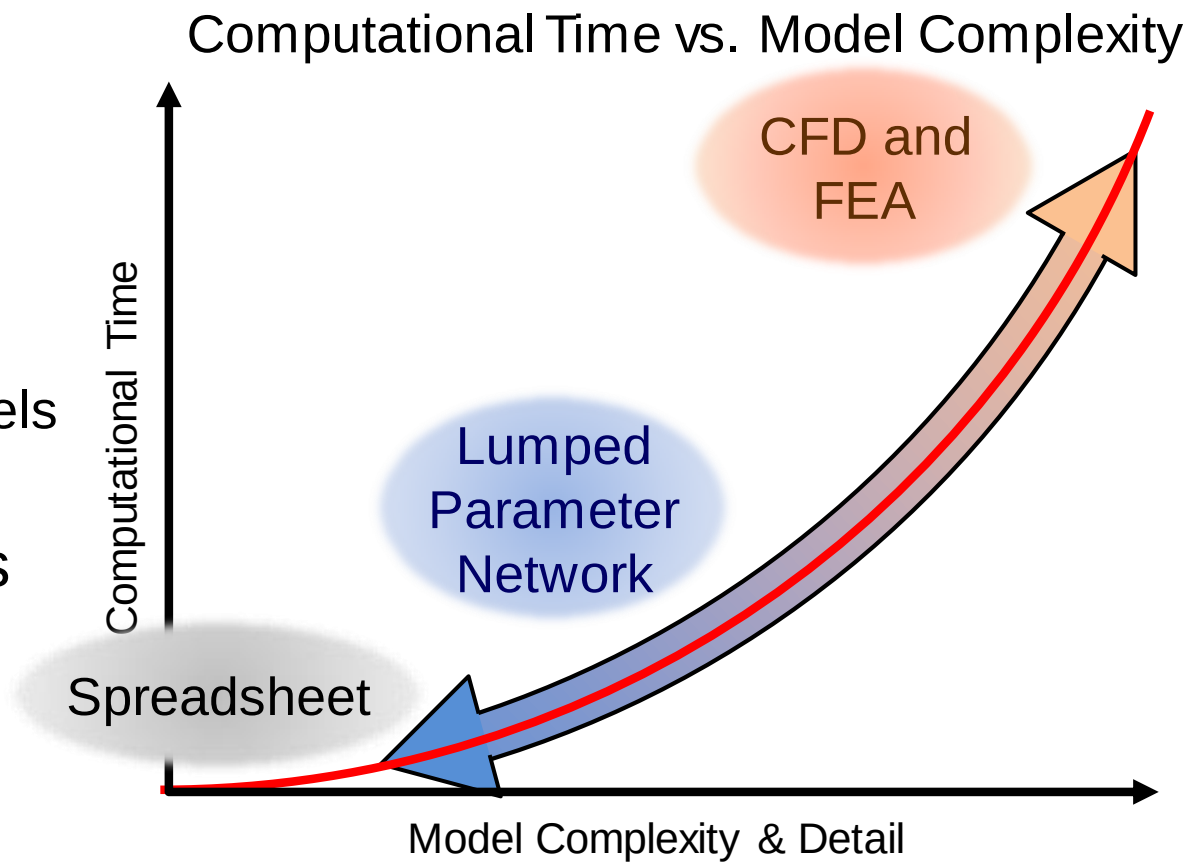
1. Explore designs
2. Integrate in vehicle model
3. Perform full vehicle tests



Design Challenge: Battery Cooling Network

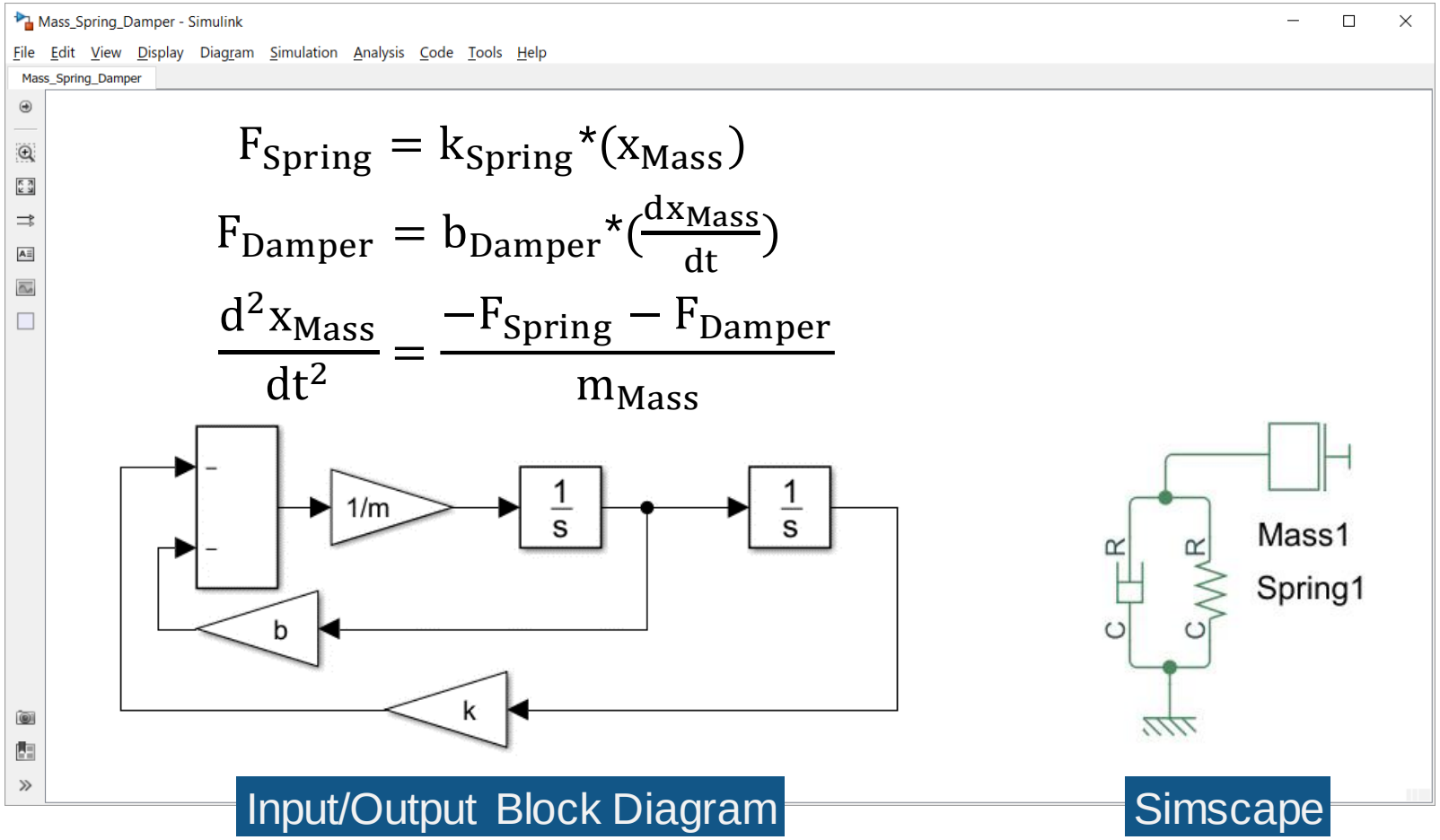
Modeling and Simulation Options

- **CFD and FEA**
  - Accurate, but computation intensive
- **Spreadsheet**
  - Accessible, but limited scalability
  - Limited options for integrating other models
- **Lumped parameter physical networks**
  - Less accurate than CFD, but scalable
  - Appropriate for system-level analysis
  - Integrates well with other domains including control algorithms



Simscape: Build Accurate Models Quickly

- Simply connect the components you need
- The more complex the system, the more value you get from Simscape
- Resulting model is intuitive, easy to modify, and easy for others to understand

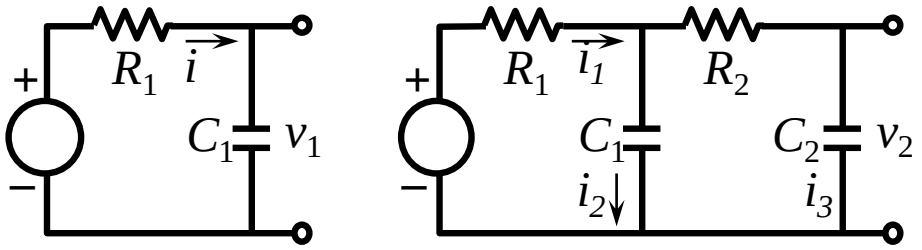


Input/Output Block Diagram

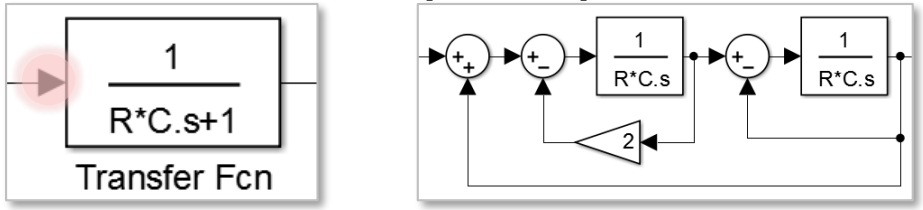
Simscape

Physical Modeling Within Simulink

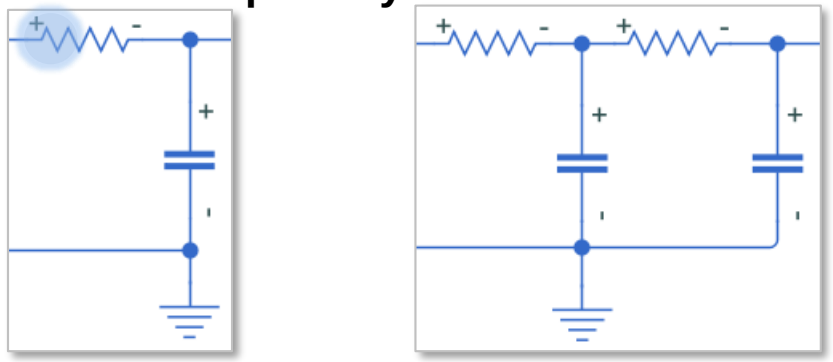
- Simulink is best known for signal-based modeling
  - Causal, or input/output
- Simscape enables bidirectional flow of energy between components
- System level equations:
  - Formulated automatically
  - Solved simultaneously
  - Cover multiple domains

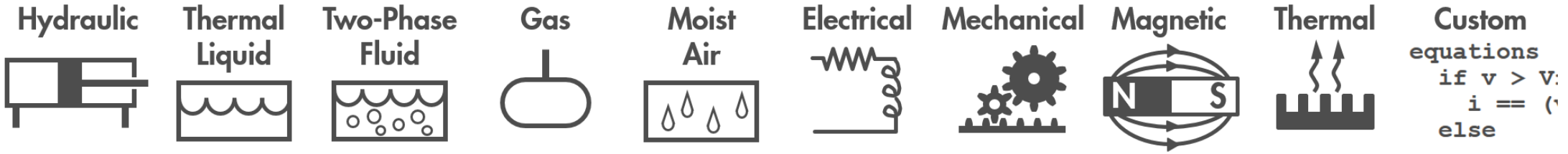


Simulink: Input/Output



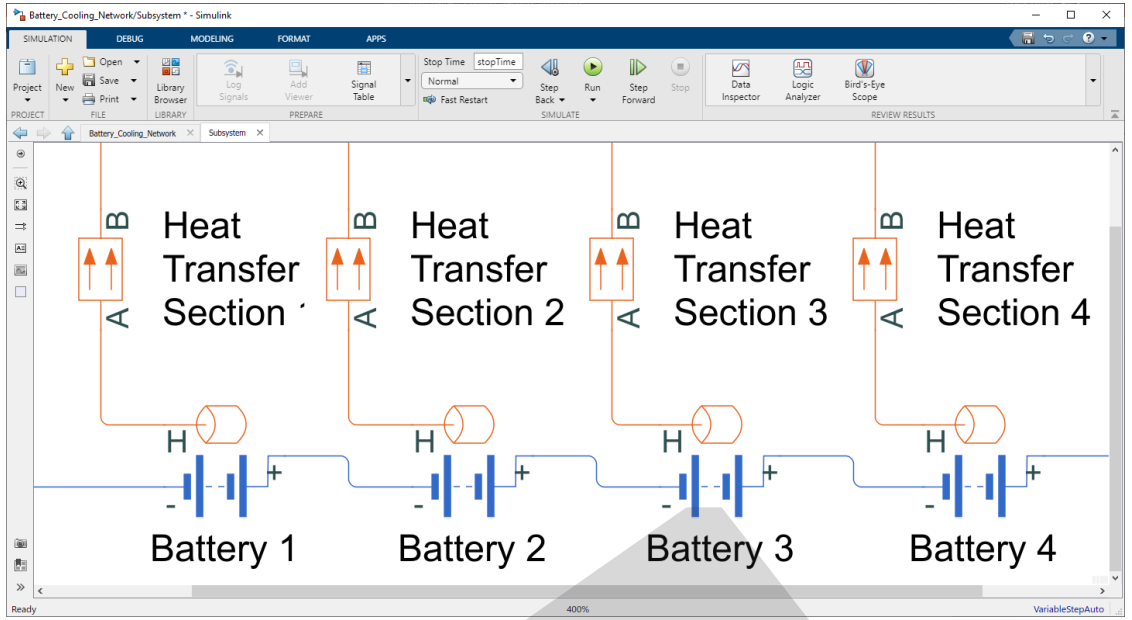
Simscape: Physical Networks

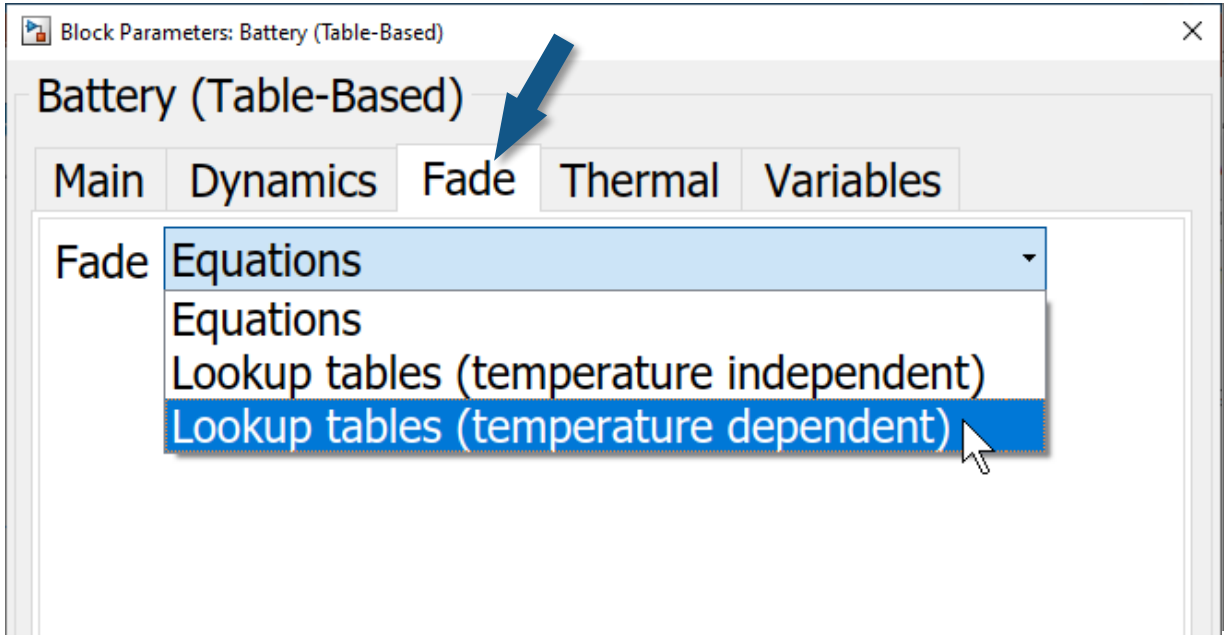


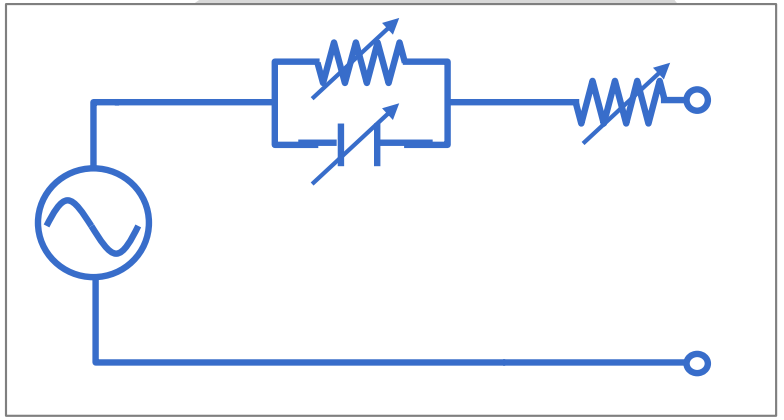


Battery Model

- Modeled using Simscape
  - 60kWh total capacity (4 sections)
  - Equivalent circuit captures transient dynamics
  - Lookup tables: nonlinear and thermal effects
  - Battery aging can be included



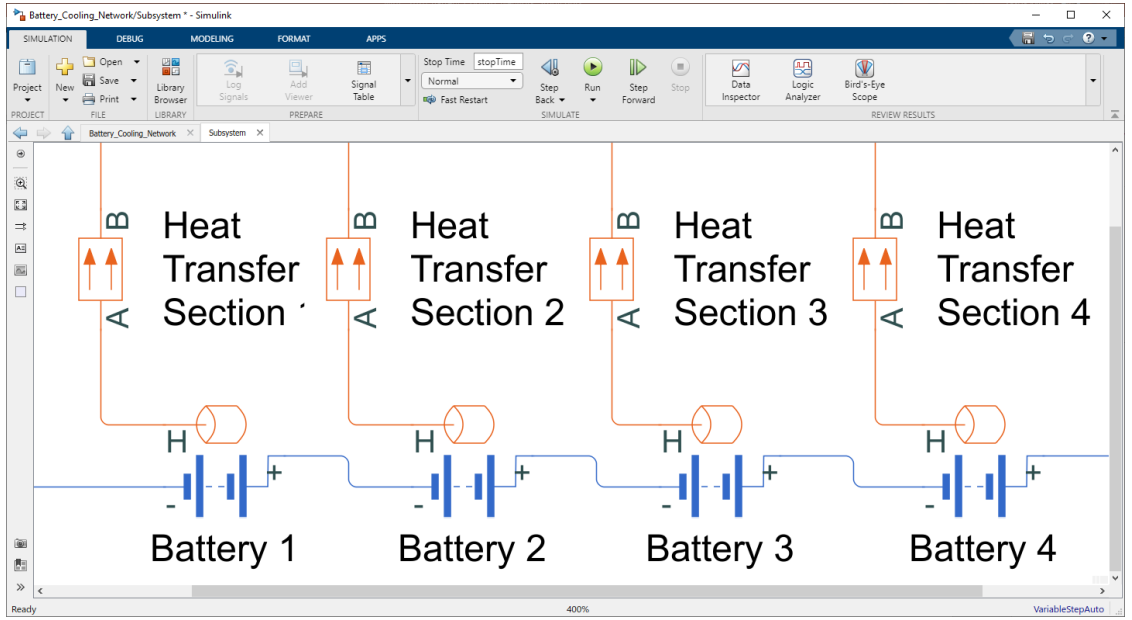


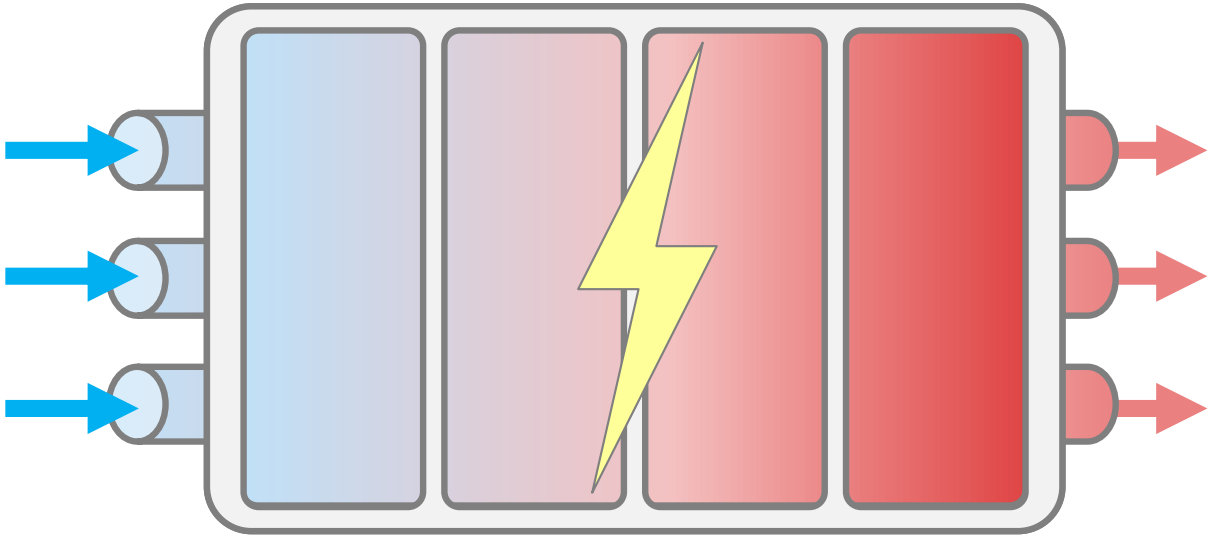


Resistors, capacitor, and voltage source depend upon SOC, DOC, and temperature

Battery Pack

- Create test to compare the cooling network designs
- Lumped thermal model
  - Divided into four sections along flow path
- Heat transferred to different portions of the cooling channel

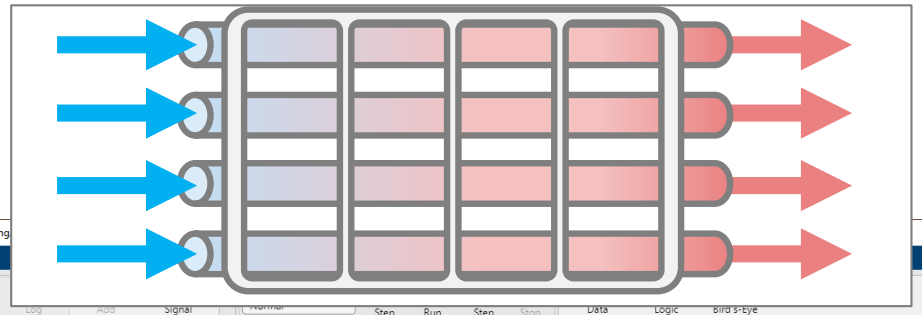


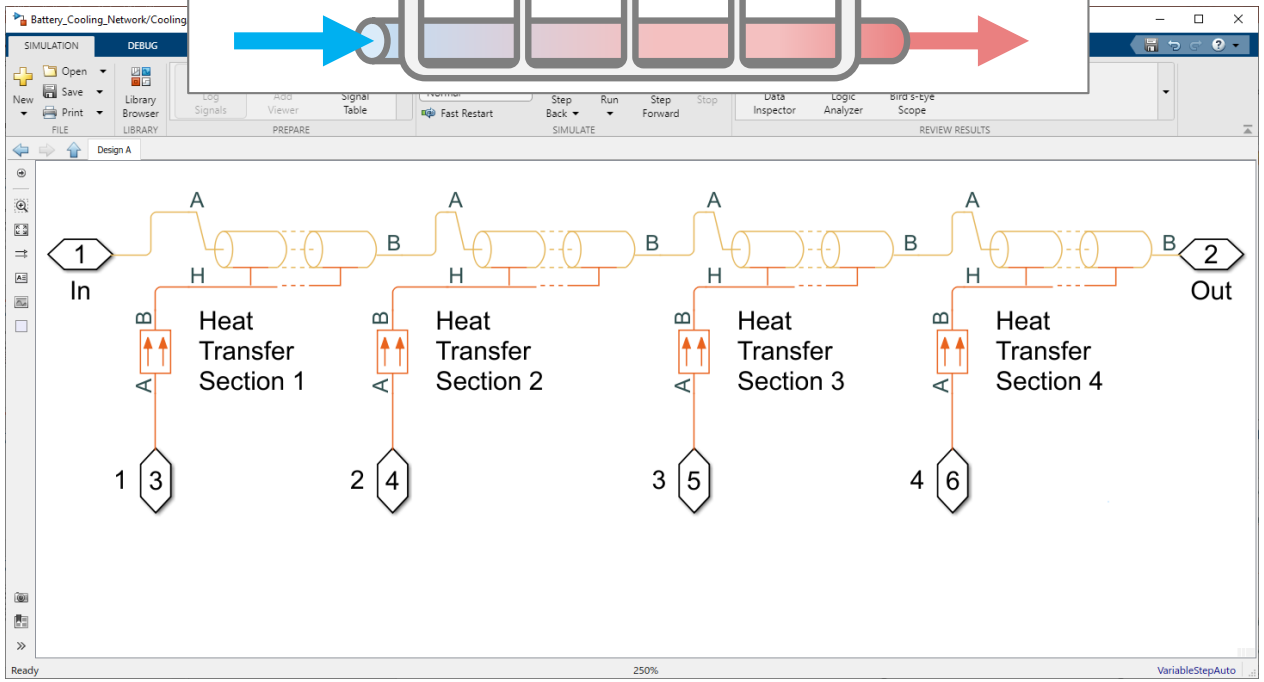


Battery Cooling Network

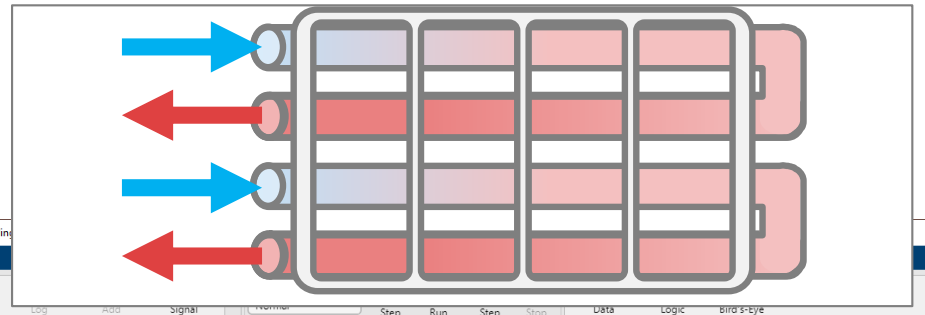
- Physical connections in the Simscape model match architecture of design

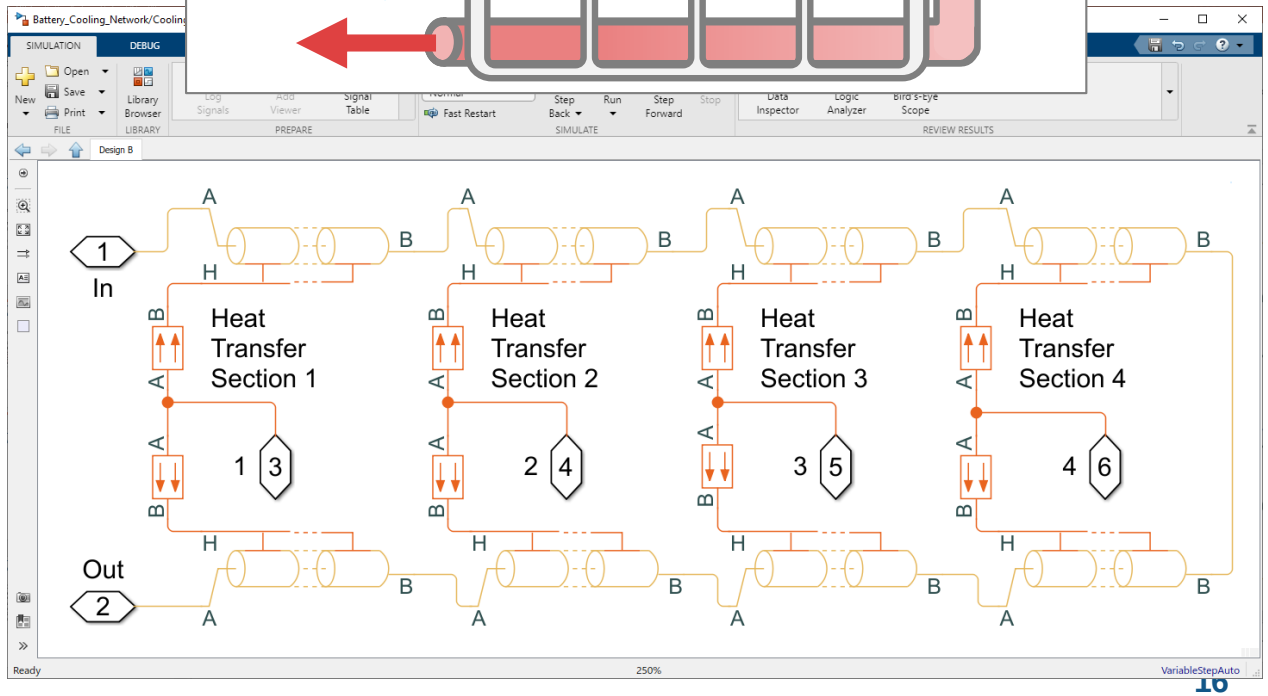
One-Pass





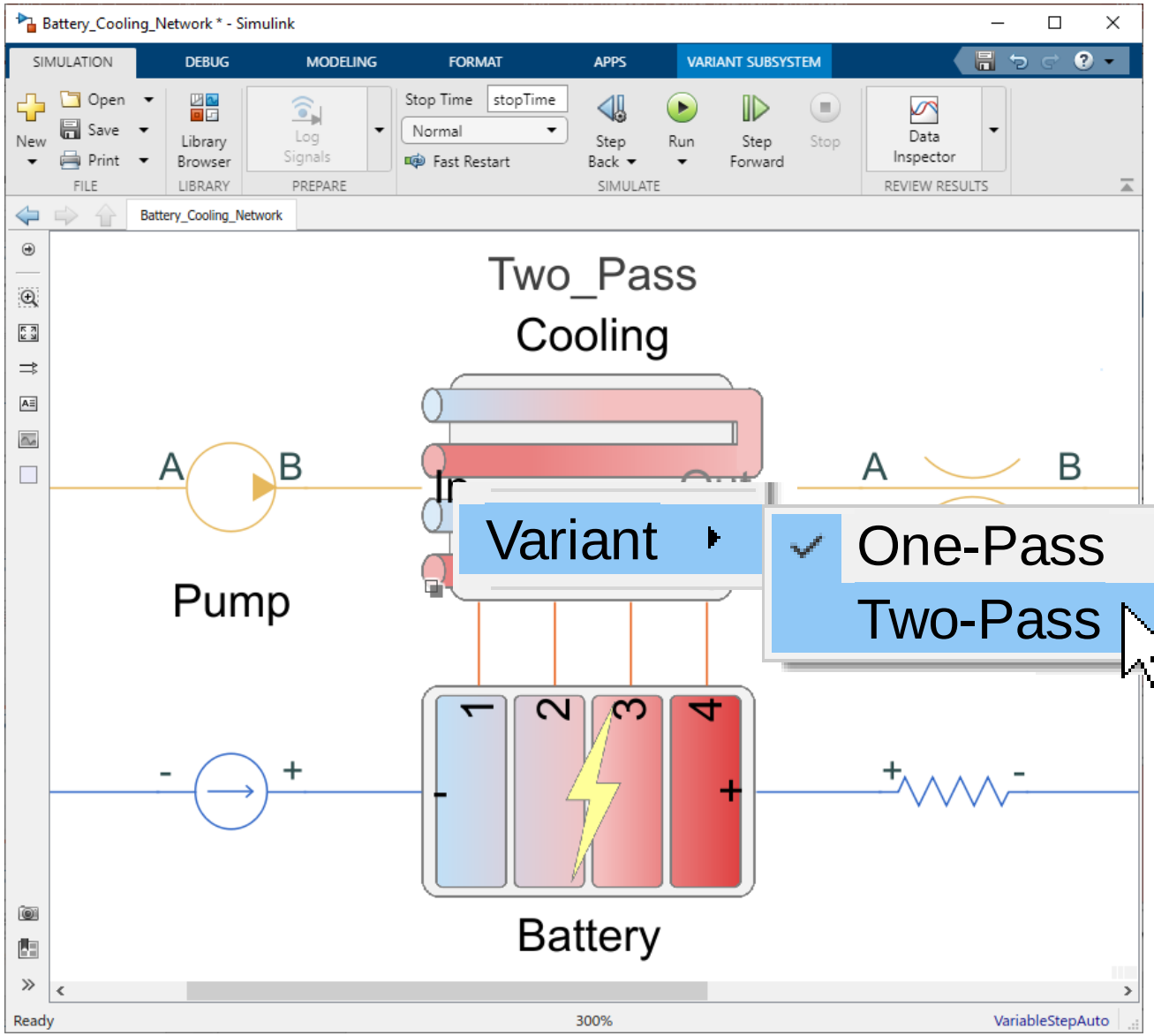
Two-Pass





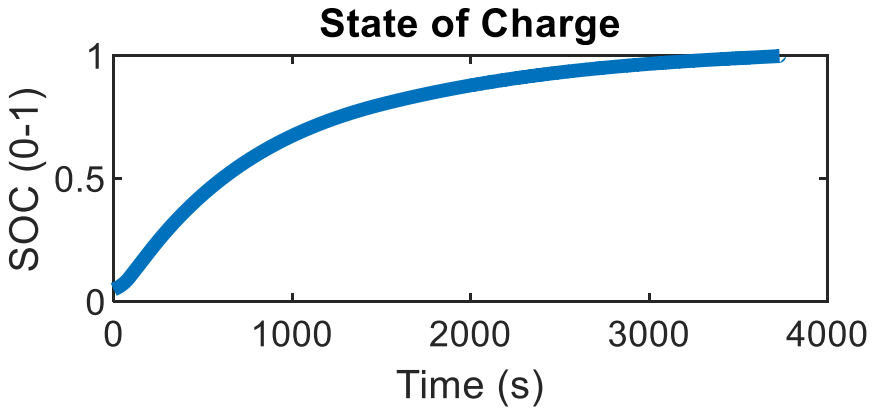
Battery Cooling Network

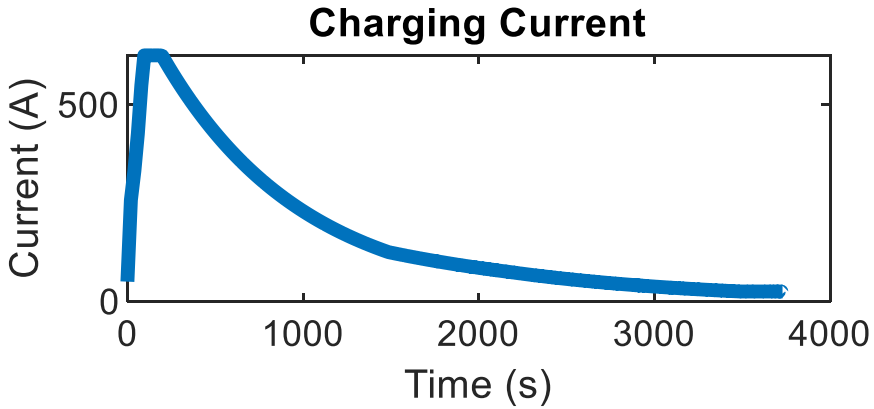
- Simplify testing using Variant Subsystems
  - Swap in different cooling designs
  - Interactive or automated using MATLAB commands
- Same model, settings, and test set up
  - Input vectors
  - Results analysis

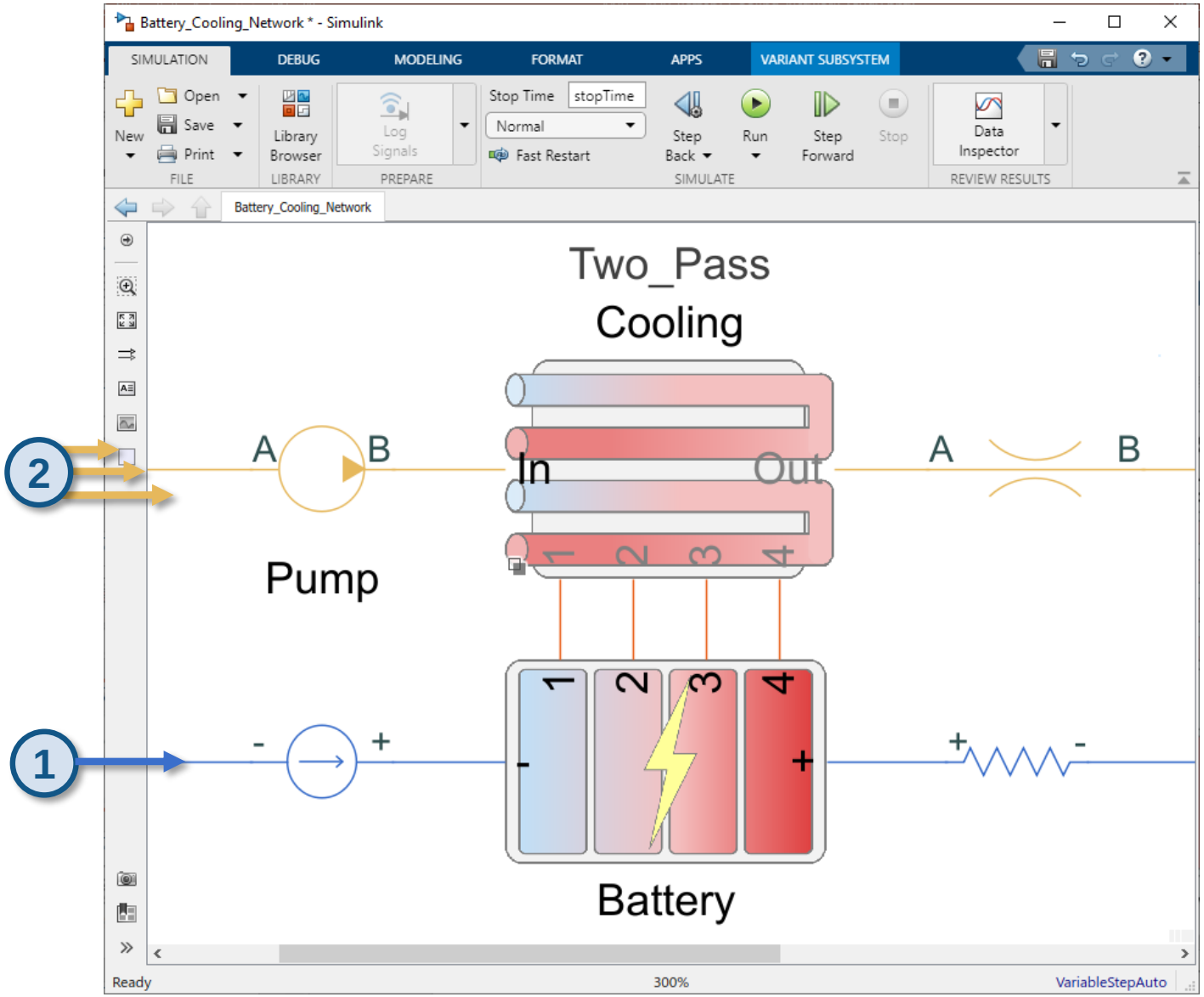


Cooling Network Test

- Fast charge (cooling critical)
  1. From 2% to 99% in 1 hour
  2. Range of coolant flow rates

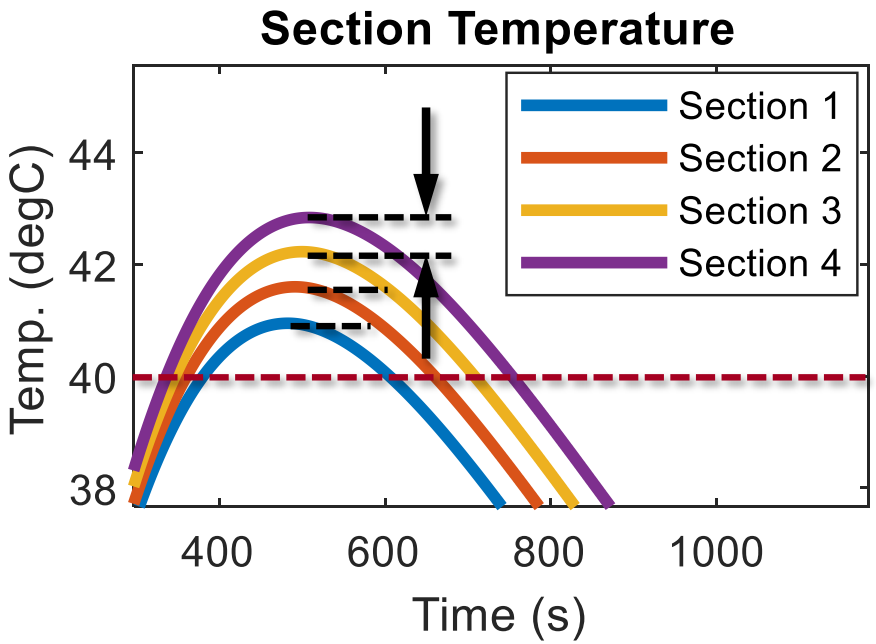


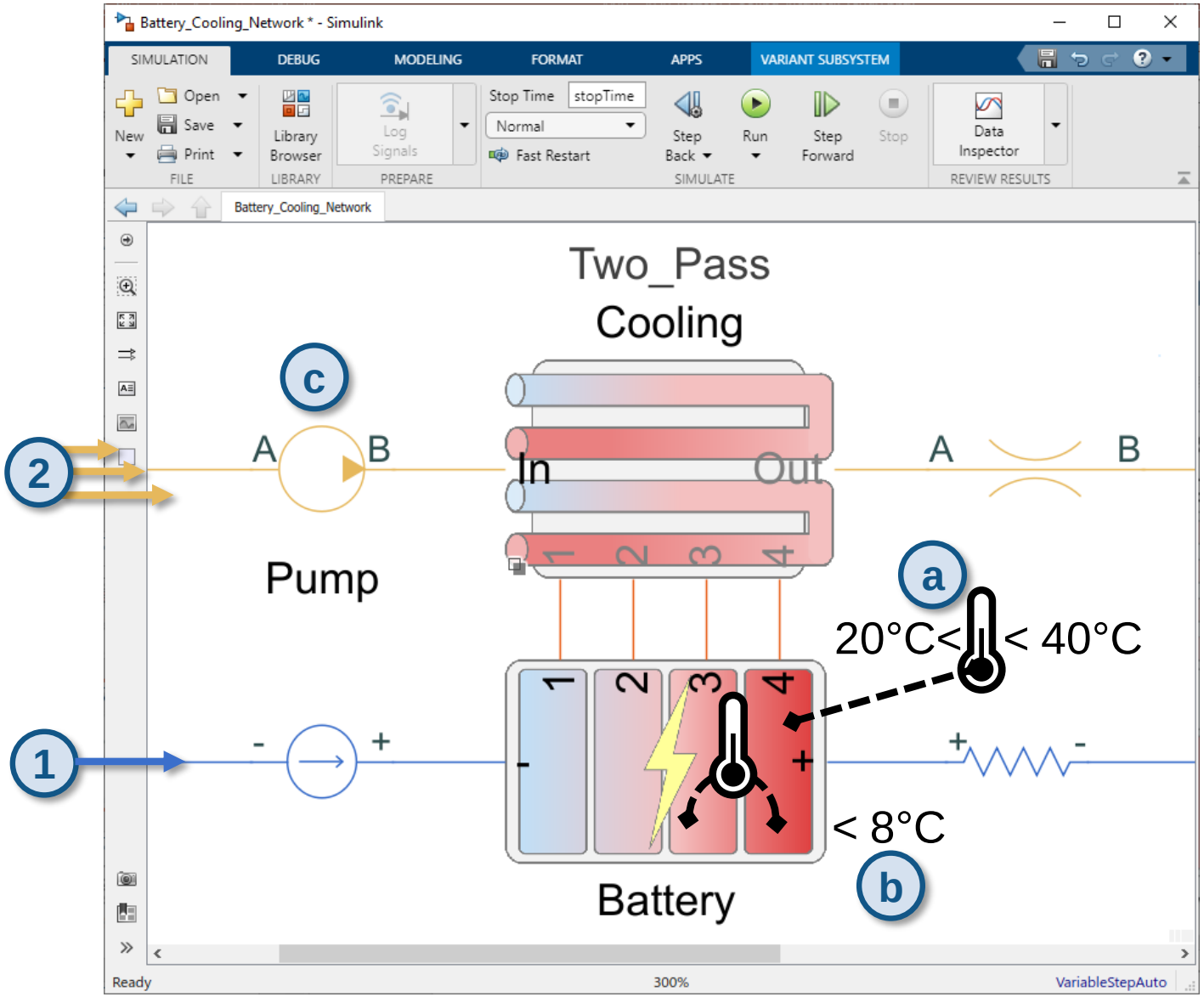




Cooling Network Test

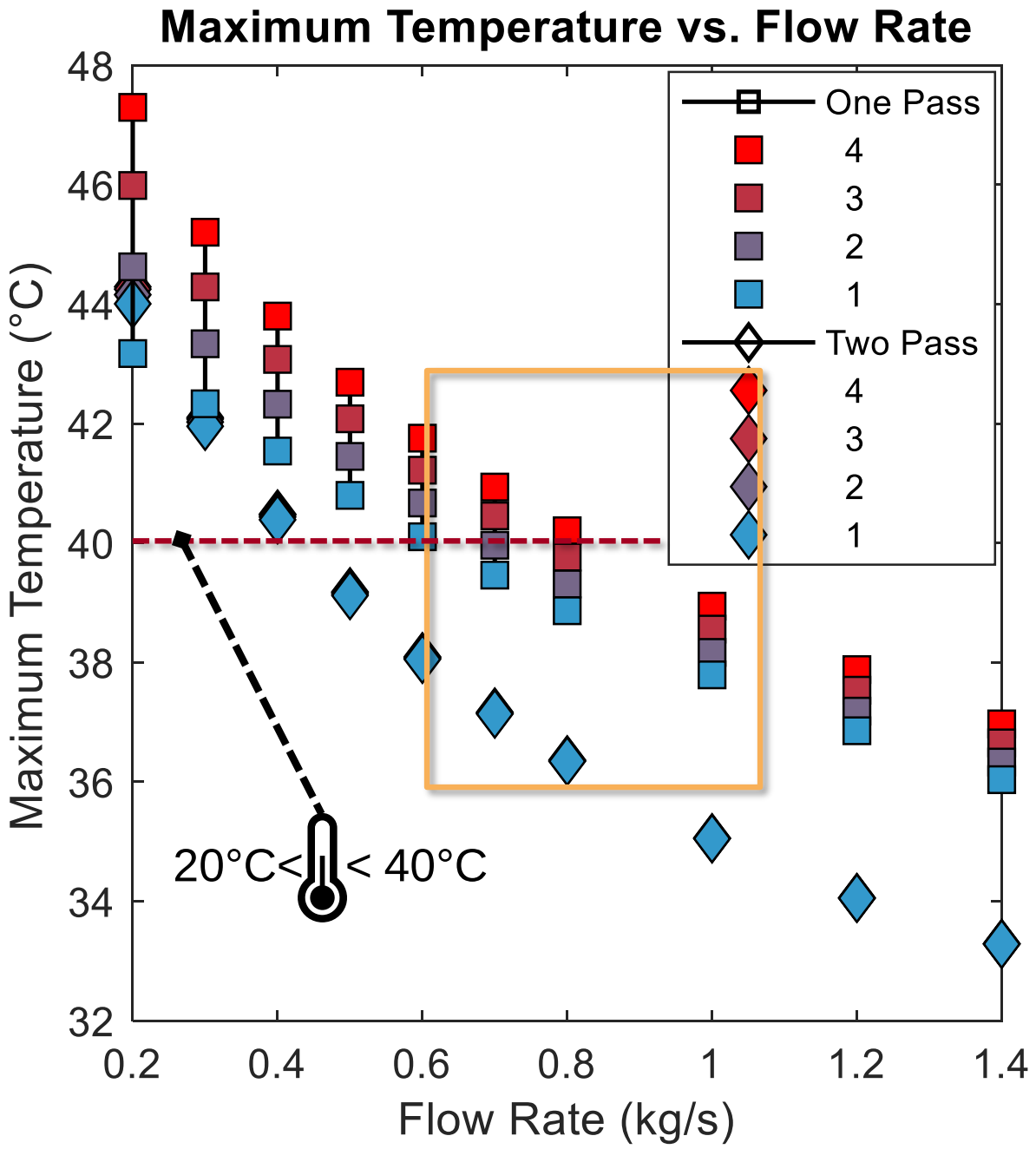
- Fast charge (cooling critical)
- Performance criteria
  a. Maximum temperature
  b. Temperature gradients
  c. Pump power consumption





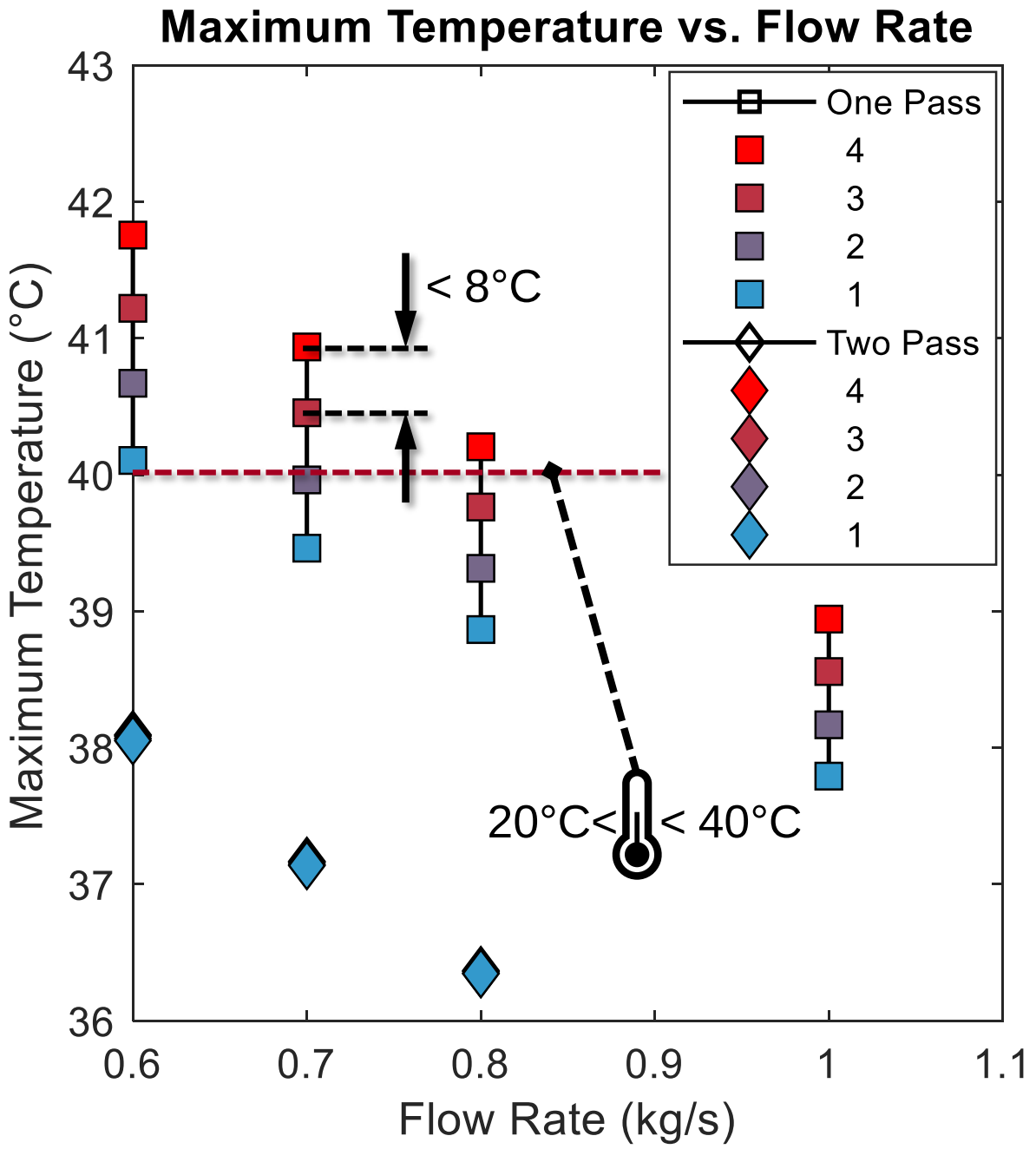
Component Level Analysis

- Criteria 1: Temperature Range
  - For same flow rate, Two-Pass has lower maximum temperature
  - Acceptable range for either design



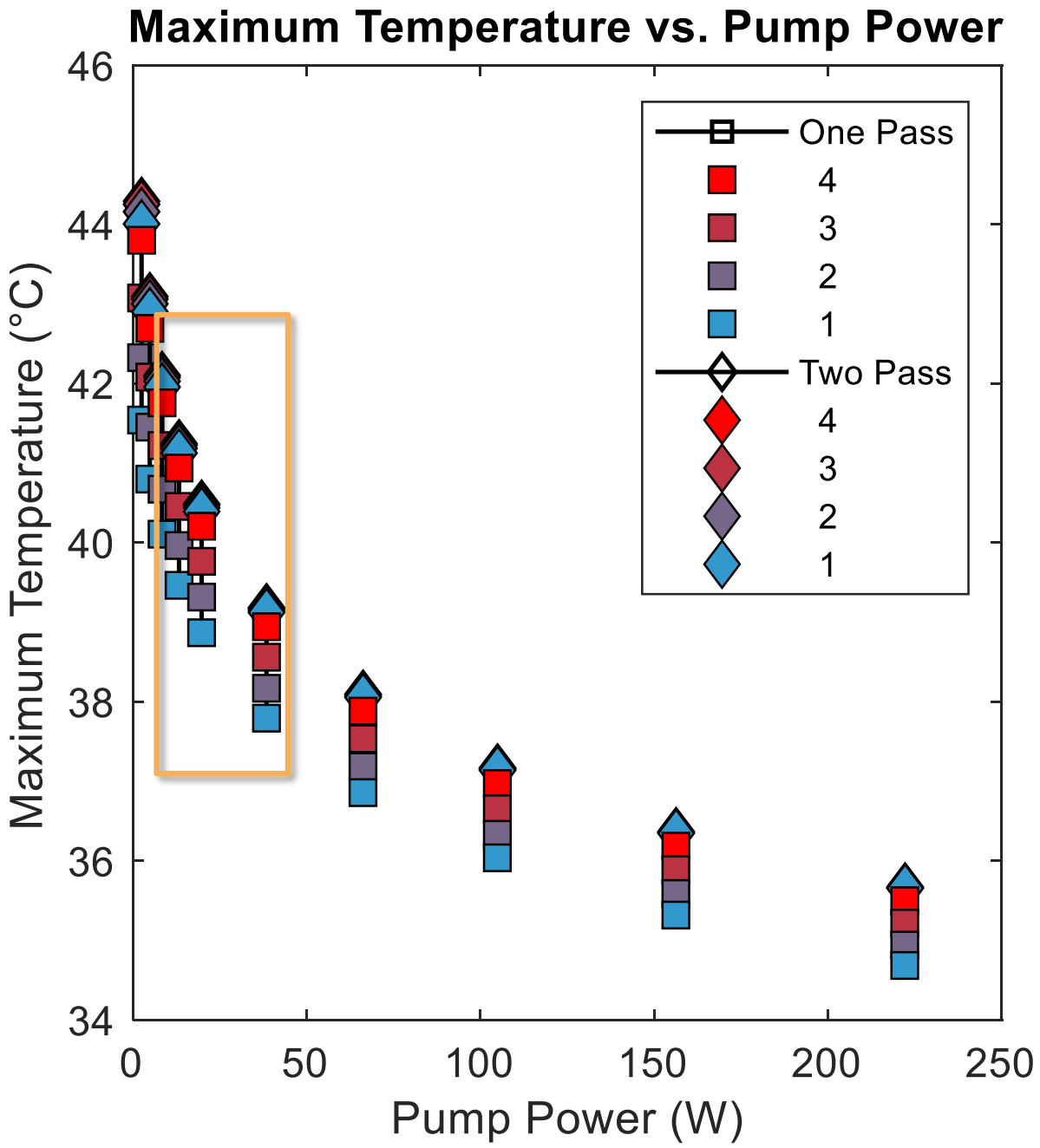
Component Level Analysis

- Criteria 1: Temperature Range
  - For same flow rate, Two-Pass has lower maximum temperature
  - Acceptable range for either design
- Criteria 2: Temperature Gradient
  - Both designs acceptable
  - Two-pass has very low temperature difference between sections



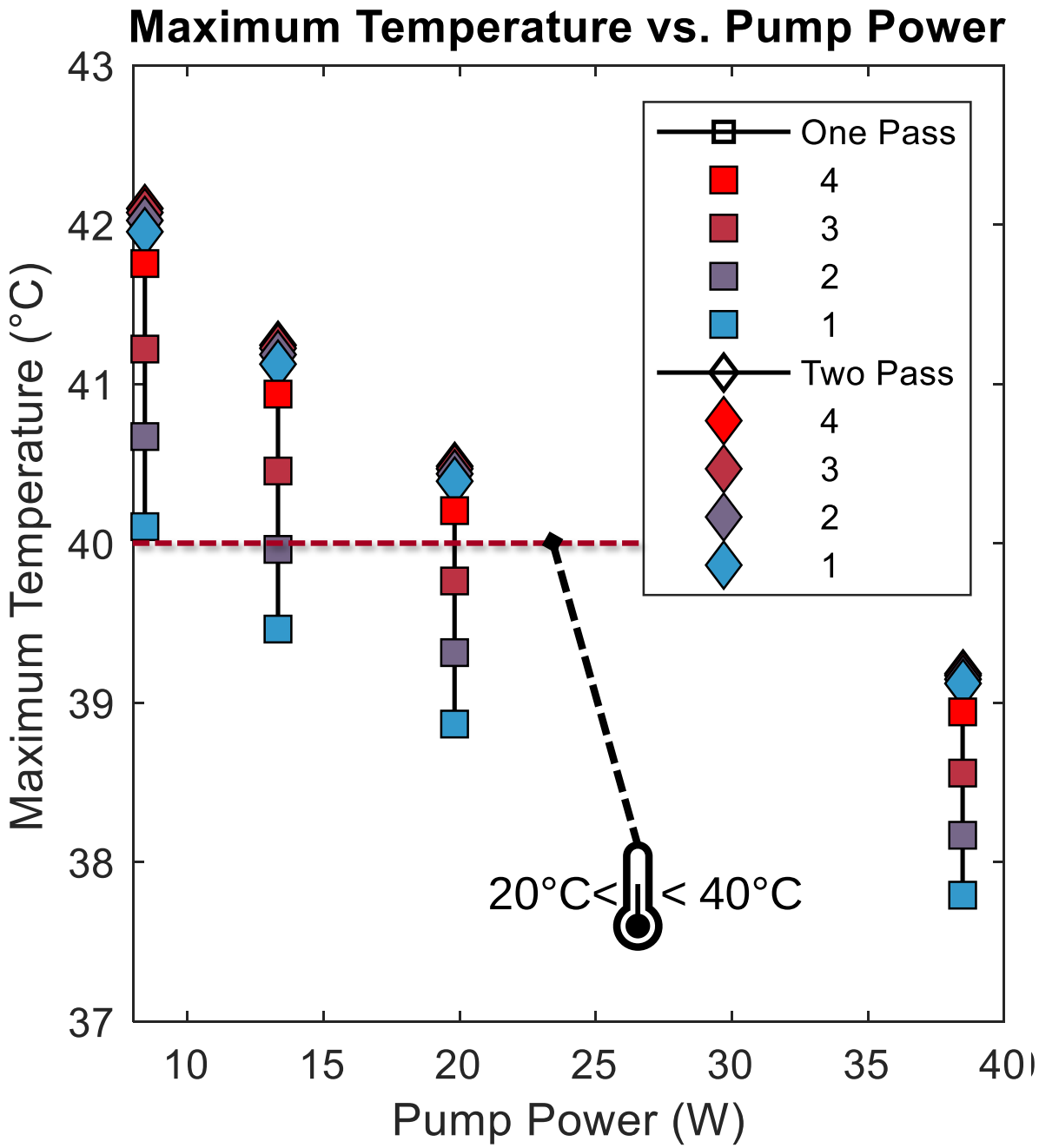
Component Level Analysis

- Criteria 3: Pump Power
  - One Pass requires less pump power than Two Pass for the same flow rate
    - Two Pass has smaller pipe diameter and longer channel



Component Level Analysis

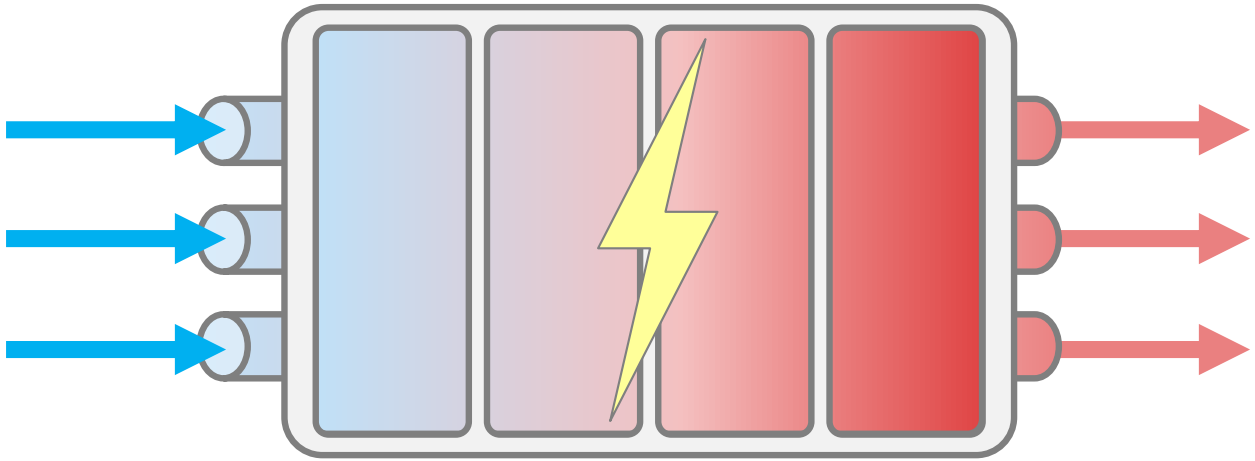
- Criteria 3: Pump Power
  - One Pass requires less pump power than Two Pass for the same flow rate
    - Two Pass has smaller pipe diameter and longer channel
- Test shows advantages of designs
- Now test system in vehicle
  - Control system, rest of physical system
  - See which criteria is most important

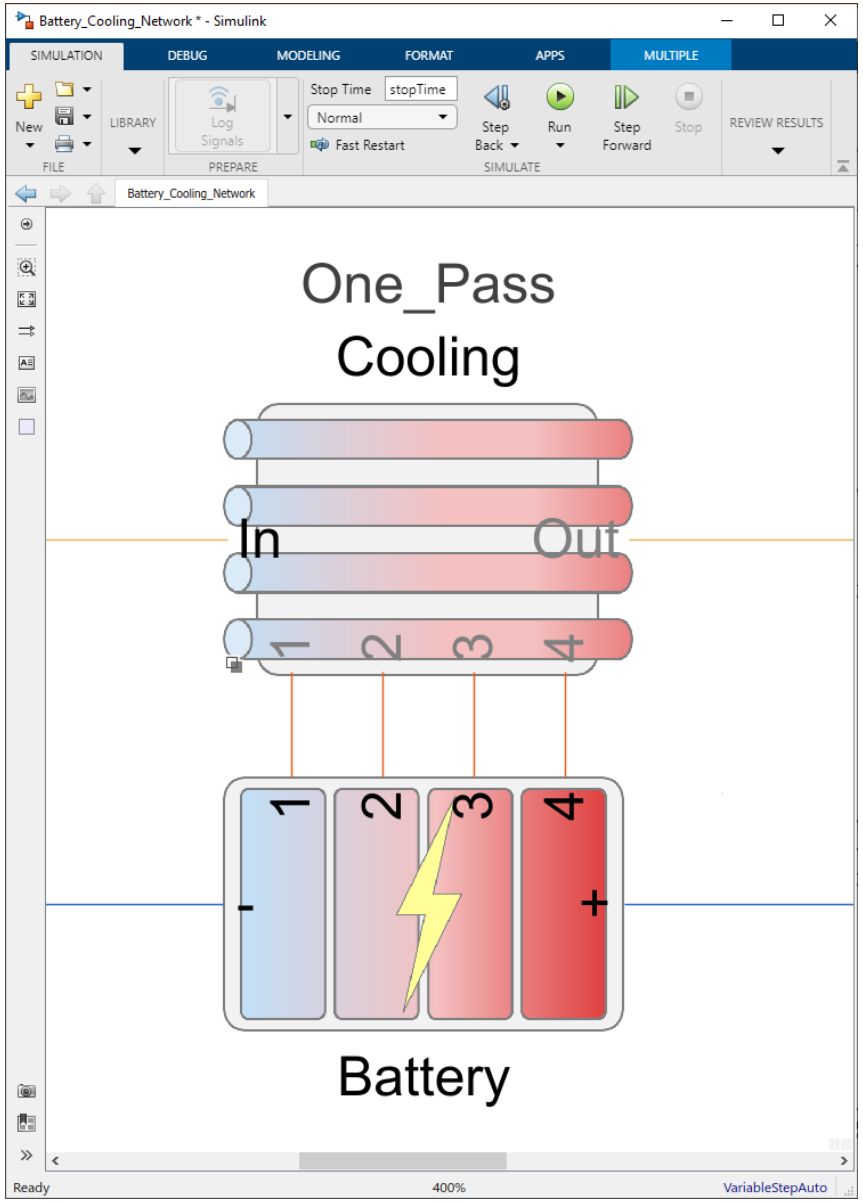


Agenda

- Importance of Battery Cooling
- Exploring Battery Cooling Network Designs
- Integration in Vehicle Model
- Evaluation of Design in Full Vehicle Tests

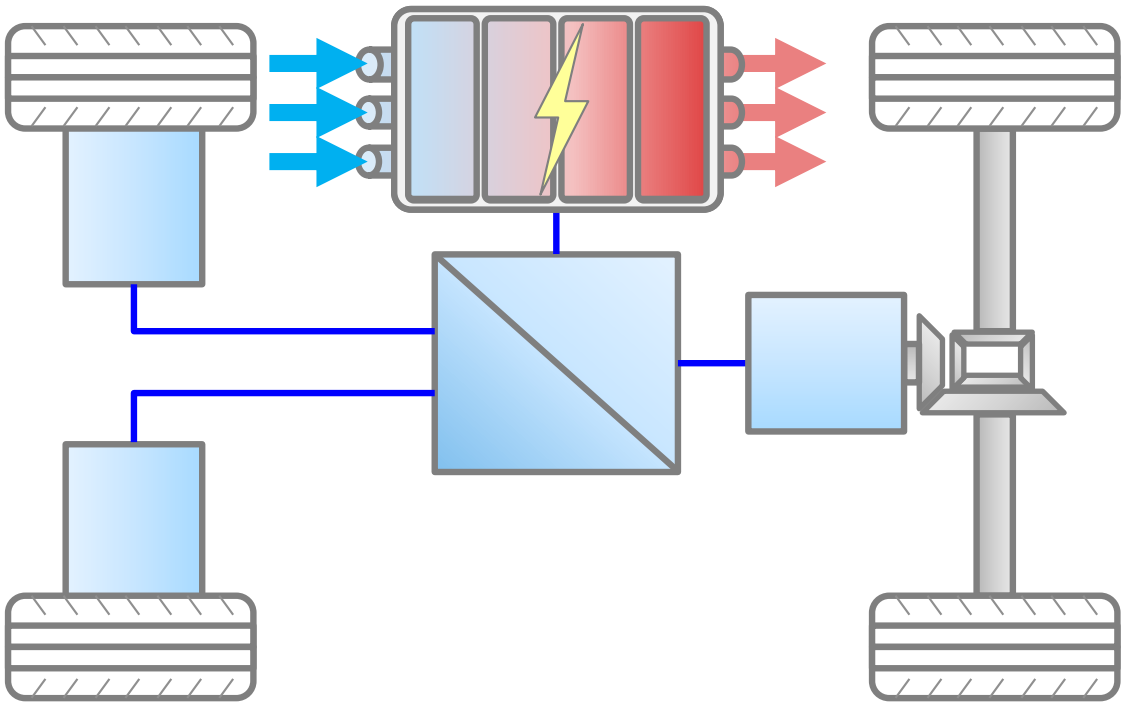
Electric Vehicle Model

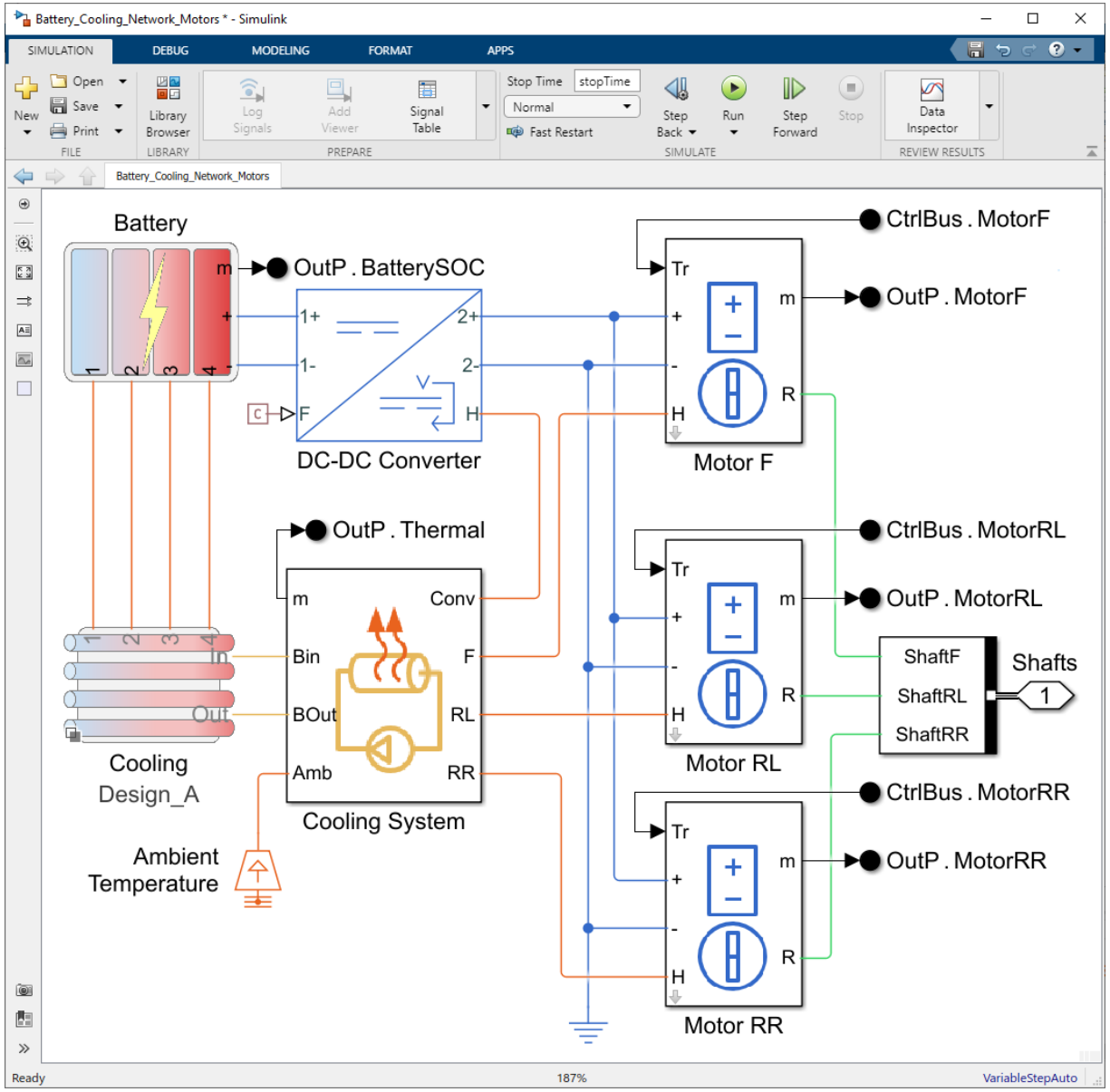




Electric Vehicle Model

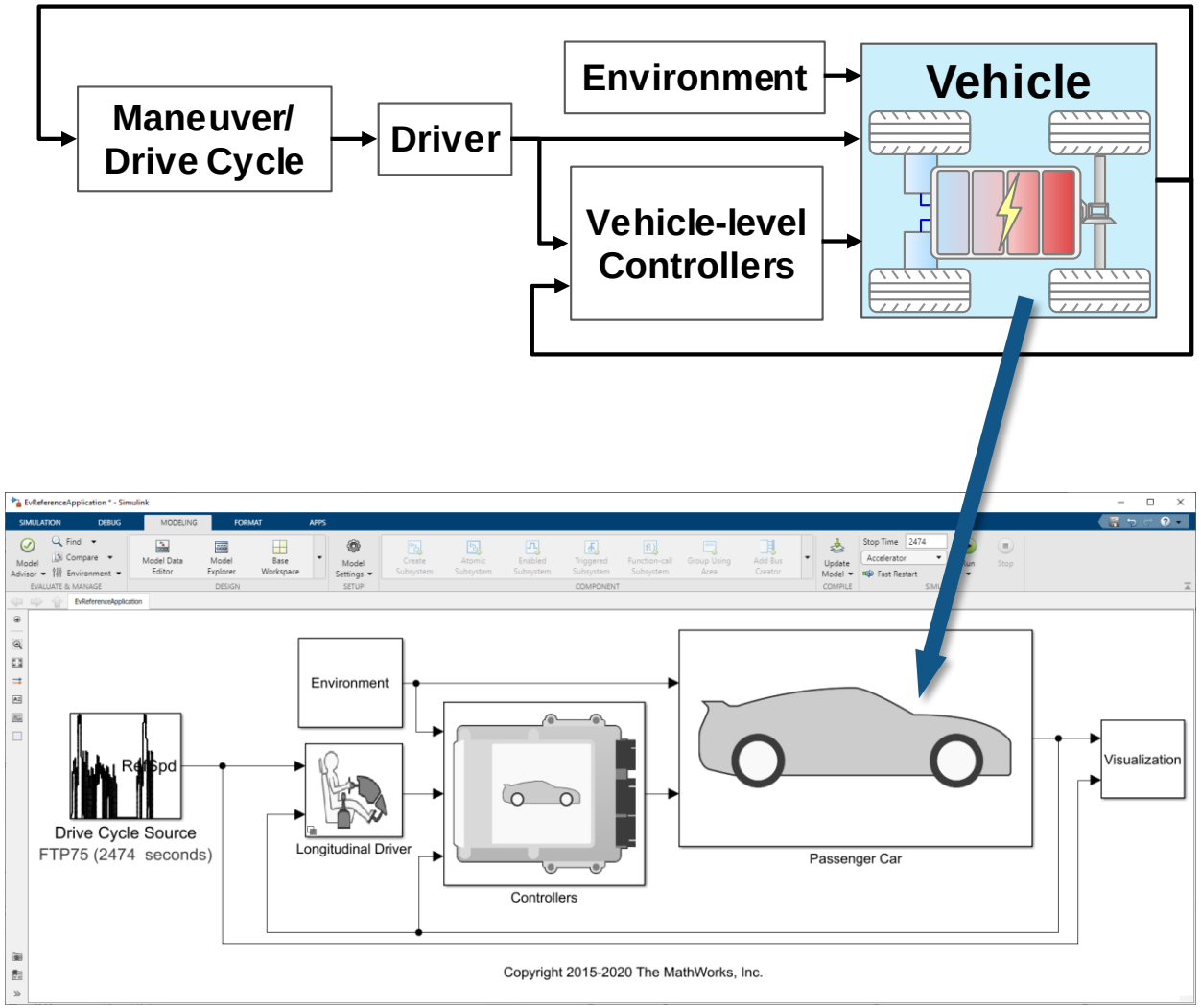
- Battery Electric vehicle
- 3-Motor Architecture
  - Rear: 40 kW Motor (2x)
  - Front: 60 kW Motor





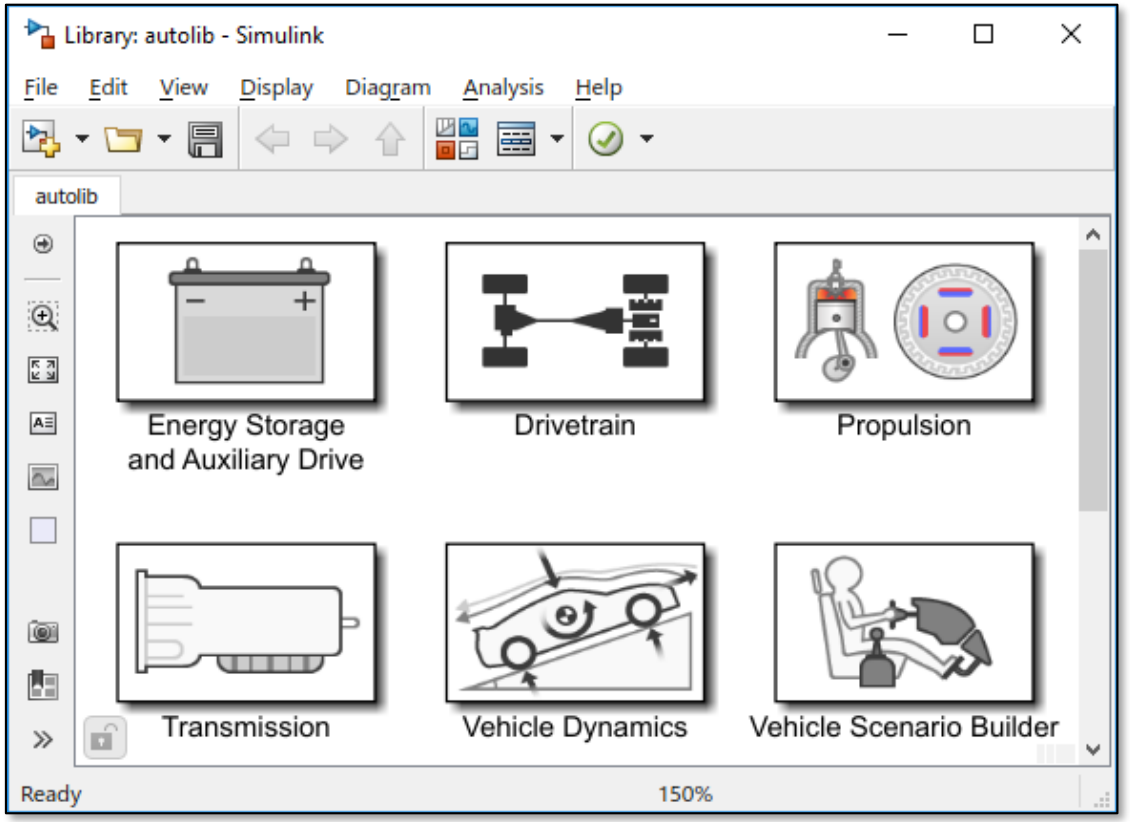
Full Vehicle Test

- Integrate into Reference Application from Powertrain Blockset
  - Baseline model provides architecture
  - Extend to 3 motor system
- Use Model-Based Design to
  - Assess performance including fuel economy and acceleration
  - Develop control algorithms
  - Deploy to hardware

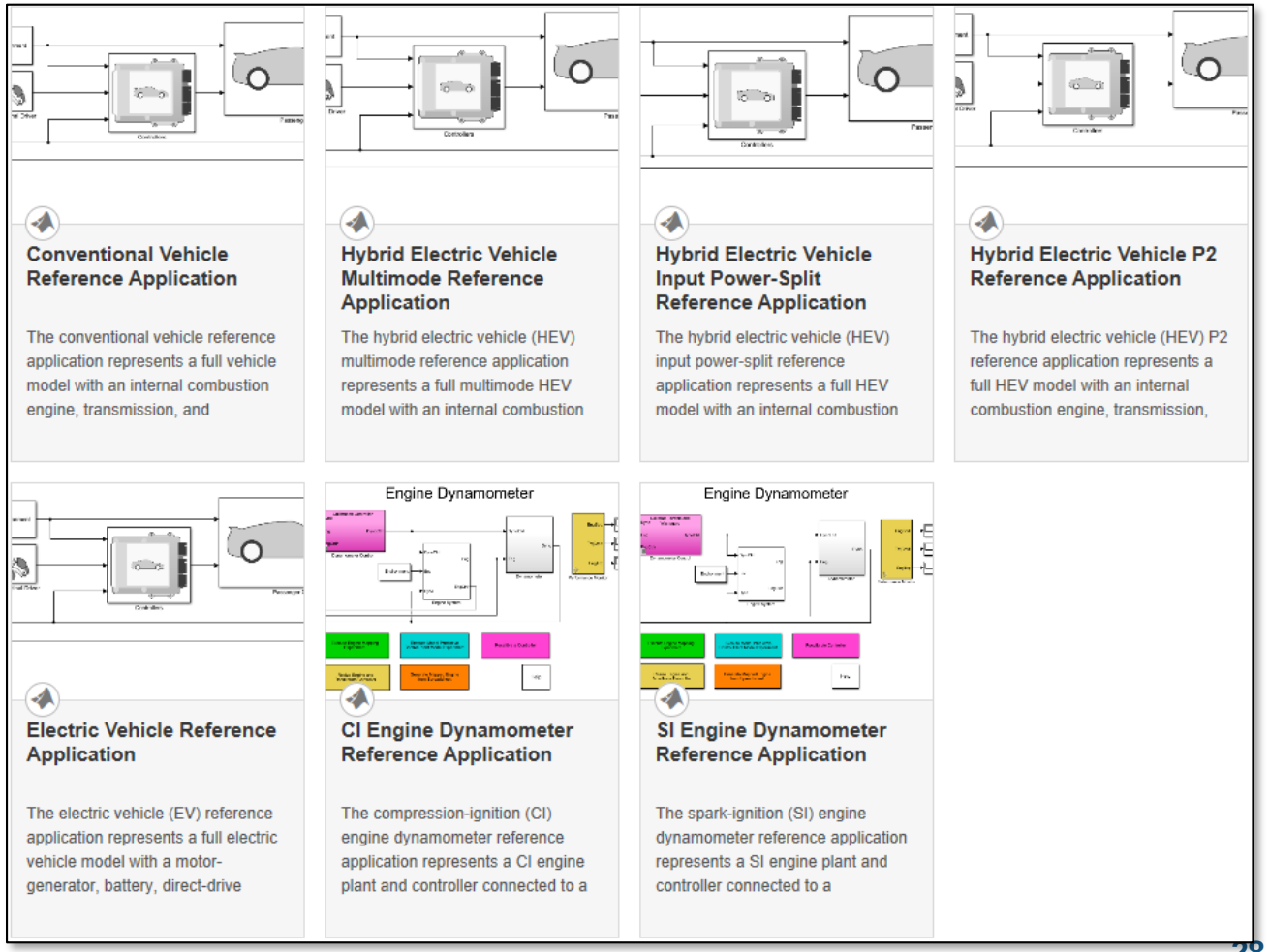


Powertrain Blockset

Library of blocks



Pre-built reference applications

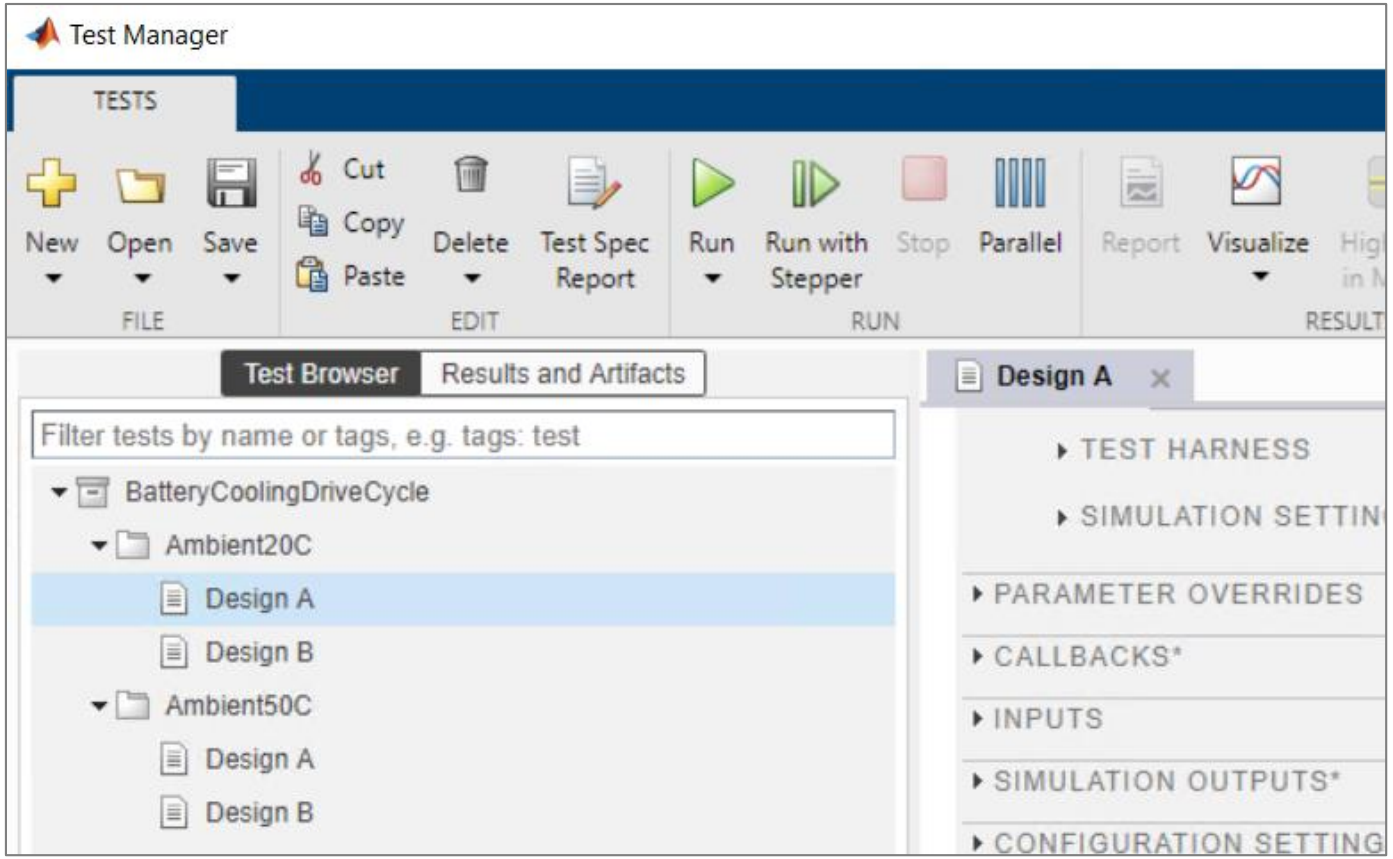


Agenda

- Importance of Battery Cooling
- Exploring Battery Cooling Network Designs
- Integration in Vehicle Model
- Evaluation of Design in Full Vehicle Tests

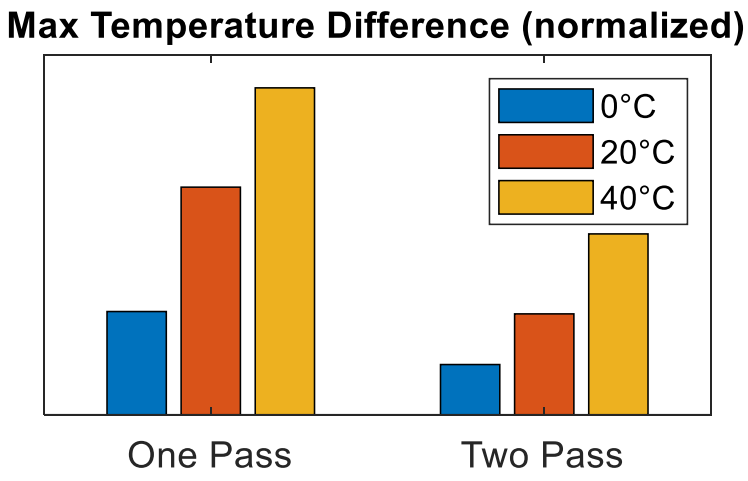
Scenario Testing

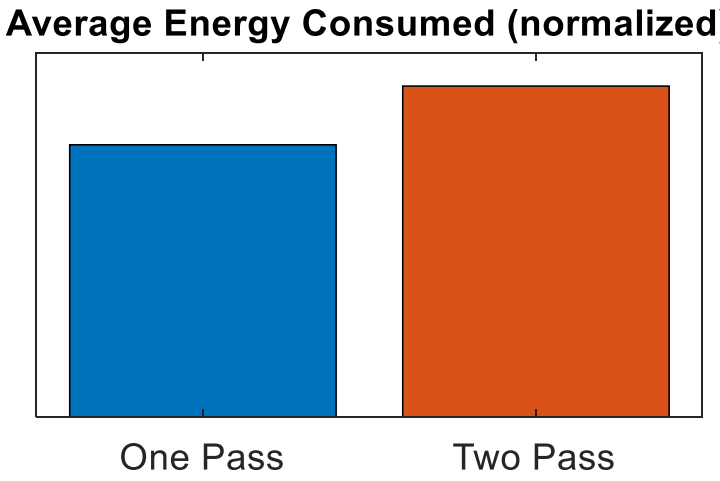
- 342 simulations:
  - 2 cooling networks
  - 57 drive cycles
  - 3 temperatures: 0/20/40 °C
- Criteria
  - Temperature range: 20-40 °C
  - Temperature gradient: <8 °C
  - Total cooling energy
- Accelerate testing
  - Parallel Computing Toolbox



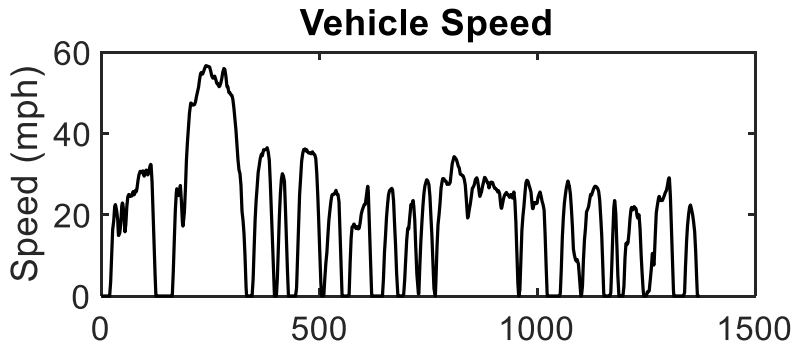
Summary of Results

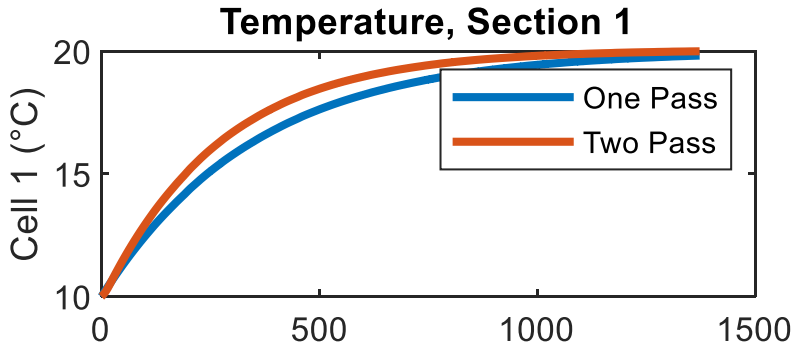
- Observations from 342 tests
  - Two Pass has lower temperature difference
    Less cell imbalance, better battery life
  - One Pass has lower energy consumption:
    Better fuel economy for same maximum temperature

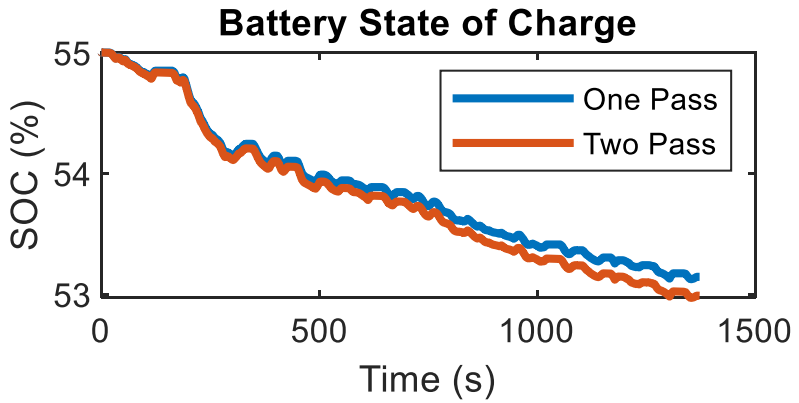




Results from One Drive Cycle

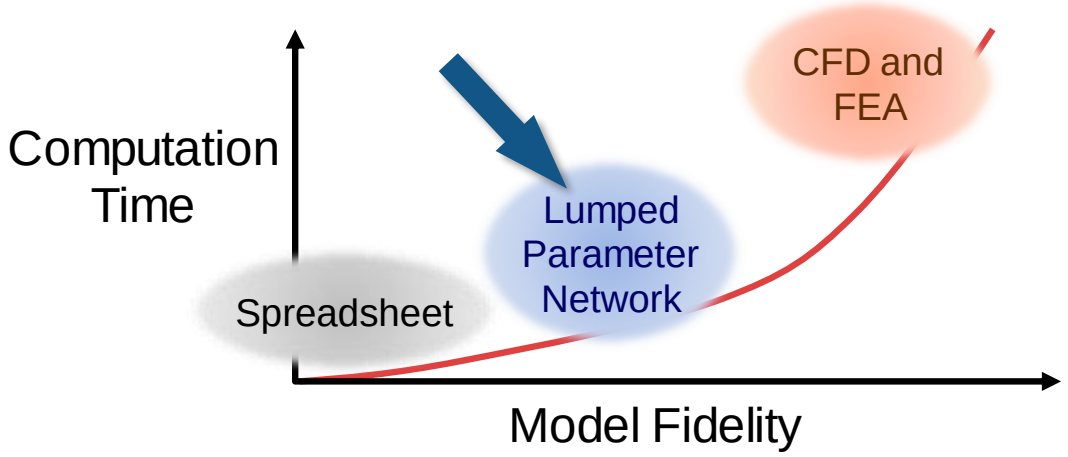


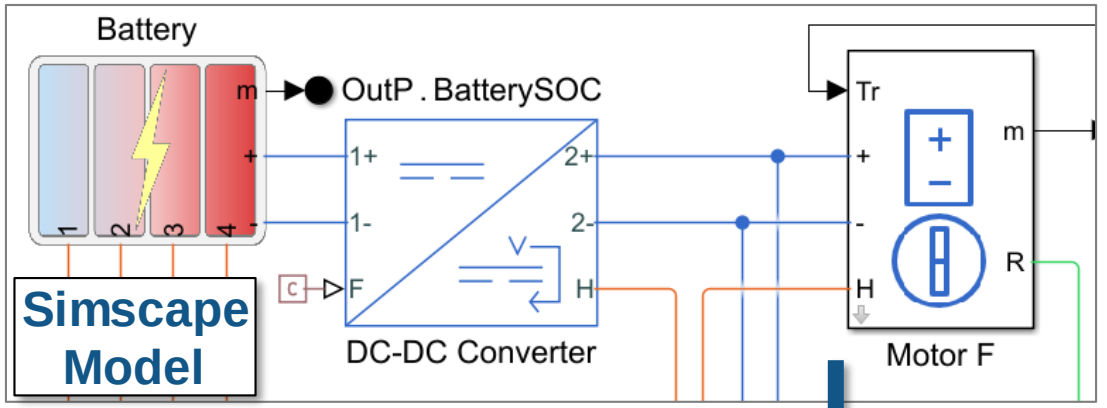


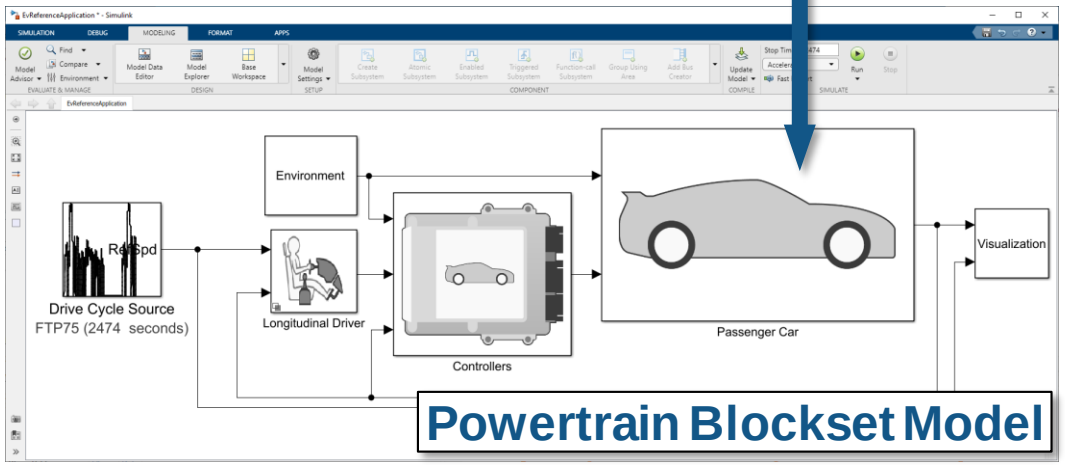


Key Takeaways

- Battery cooling network design requires component level analysis and tests within a full-vehicle simulation
- Integrating fluid, thermal, electrical, and mechanical domains is key to assessing system-level performance
- Rapid simulations covering a wide range of drive cycles and ambient conditions are needed to evaluate design criteria







Products Used

▪ Battery Cooling Network	Simscape, Simscape Fluids
▪ Electrical Network	Simscape Electrical Simscape Driveline
▪ Vehicle and Environment	Powertrain Blockset
▪ Testing	Simulink Test Parallel Computing Toolbox

Q&A

Which tasks shown in this presentation are most interesting to you?

a. Battery Modeling
b. Cooling System Modeling
c. Electrical Network Modeling
d. Full Vehicle Simulation
e. Parameter Sweeps and Results Analysis

Please contact us with questions

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