EV Modeling Capabilities of TAITherm

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THERMO ANALYTICS

Agenda

- Introduction
- Case Study 1: Cabin Comfort Cool-down
- Case Study 2: Cabin Comfort Warm-up
- Case Study 3: Battery Thermal Management
- Case Study 4: Joule Heating
- Case Study 5: Electric Motor
- System Level Modeling with 3D Thermal Integration
- Conclusions

Introduction

The Electric Vehicle Tipping Point

Revised market forecast (as of January 2020) –

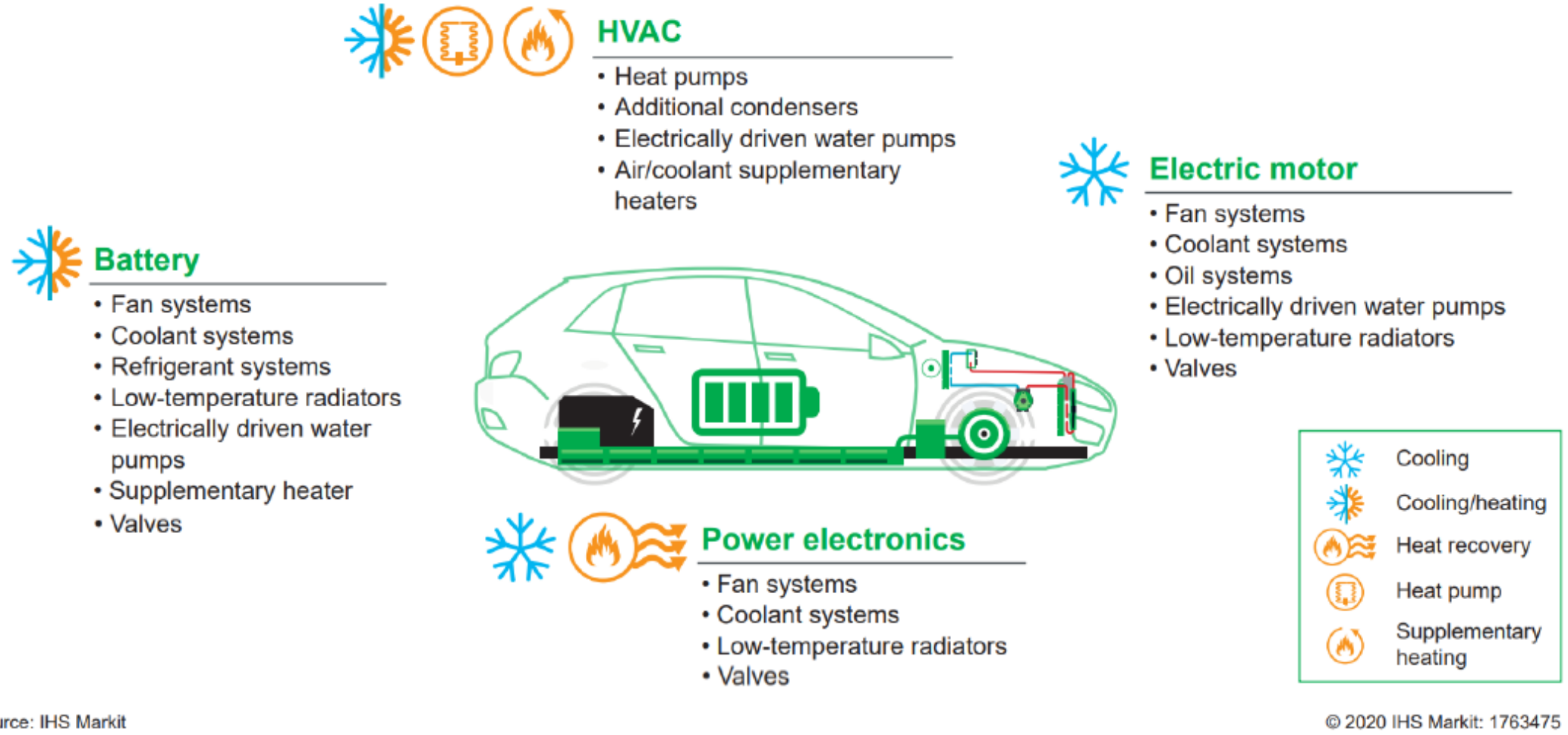
- Sales of xEVs are expected to overtake sales of traditional ICEs by 2030. PHEV and BEV sales will grow especially quickly in the second half of the coming decade, with BEV sales representing almost 20% of the global market.

- The favorable economics of xEVs for ridesharing (taxis and ride-hailing services) will contribute to additional growth—hybrids already account for a significant share of the taxi business—but the impact will be lower than we expected two years ago.

- BEV sales from 2025 to 2030 should rise more than 30% a year.

Source: BCG.com, January 2020

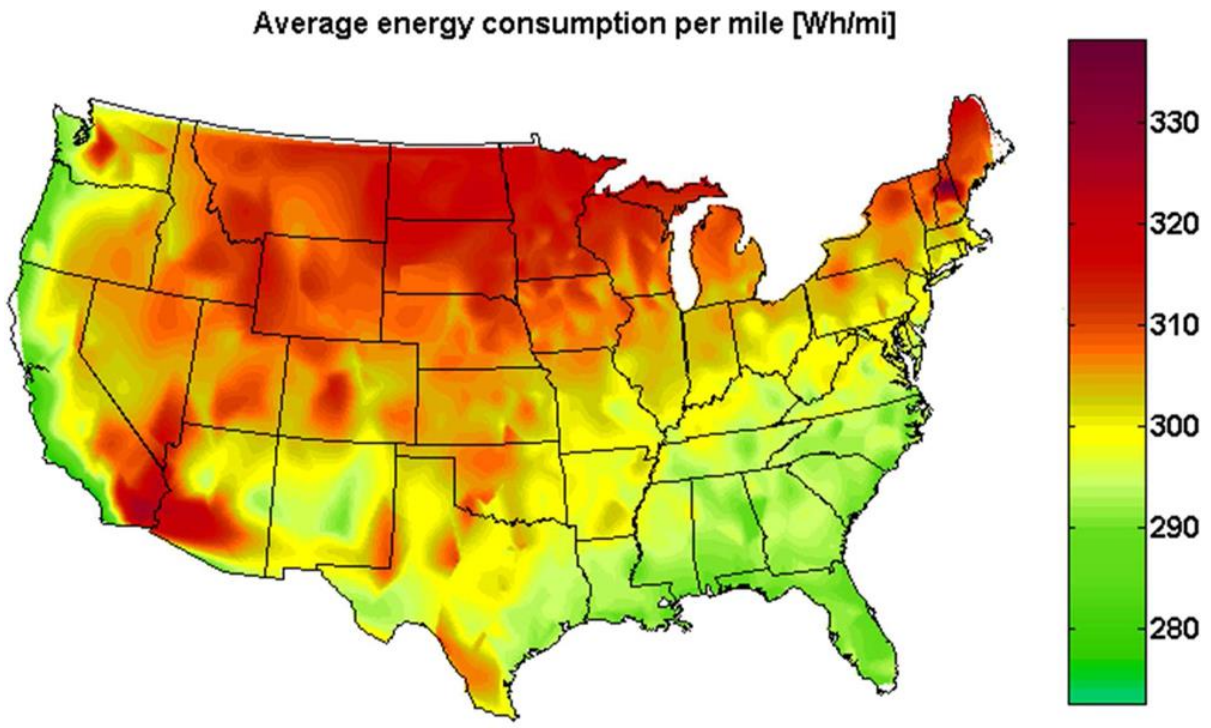
Electrification Impact on Thermal Management



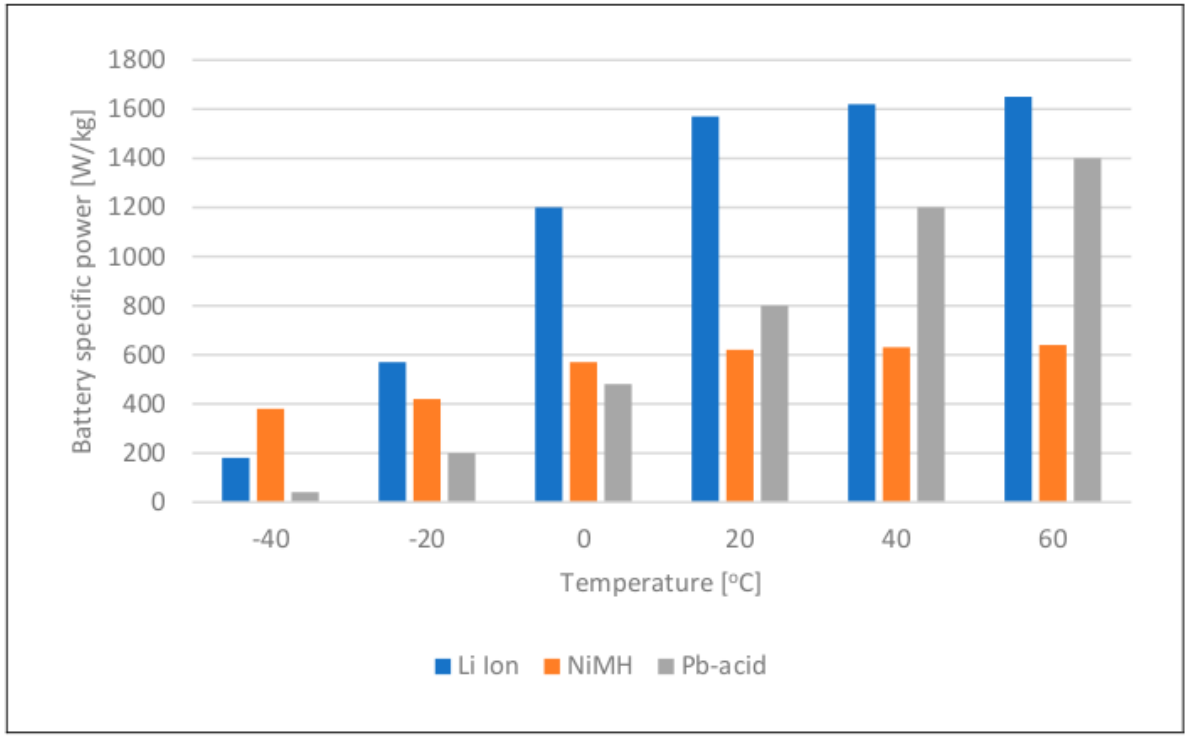
Source: IHS Markit

- All these systems influence energy budget and range

EV range is strongly influenced by temperature



Energy consumption per mile averaged across a fleet of Nissan Leaf EVs over a full year. (Environ. Sci. Technol. 49, 2015.)

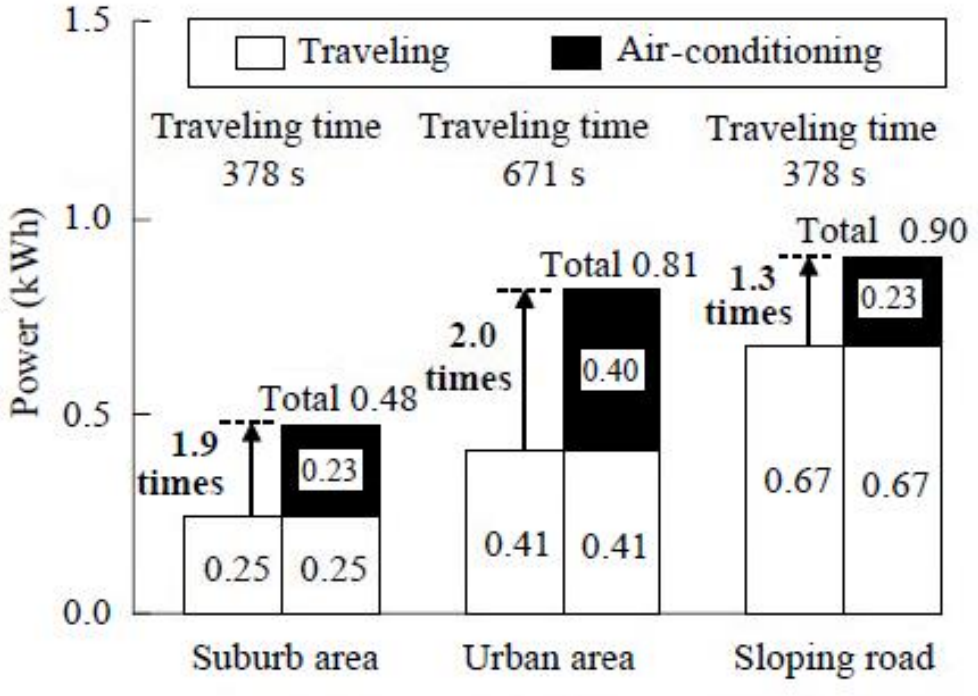


Influence of temperature on energy performance of different battery types (Energies 2019, 12, 946)

Case Study 1: Cool-down Cabin Comfort

HVAC Energy Budget

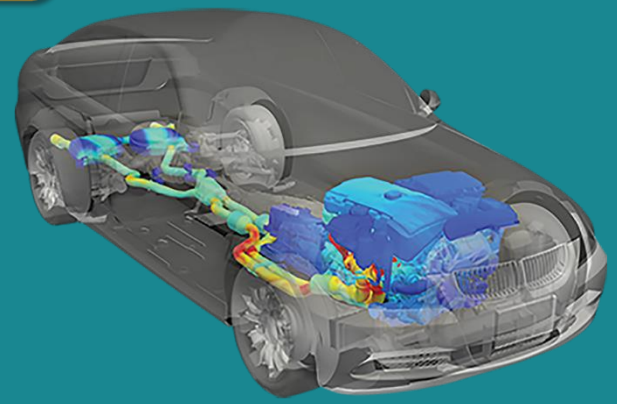
- Climate control loads cause significant range reduction
  - 17-37% in summer
  - 17-54% in winter
- Energy management is critical for meeting a budget
- Predicting the energy required to regulate the cabin helps develop and evaluate HVAC control strategies



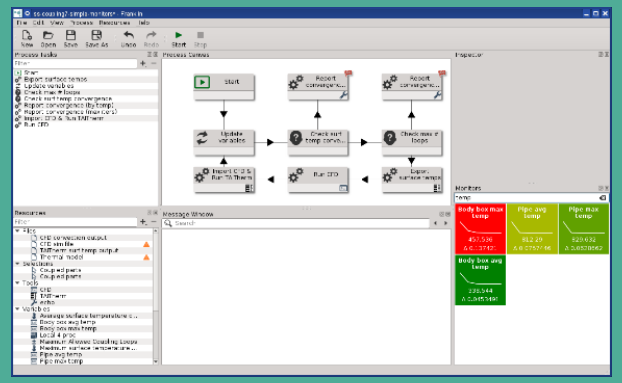
EV Power consumption with operating the air-conditioner in different environments. Shibata et. al. JEPE 9 (2015)

CAE Toolbox

TAITherm



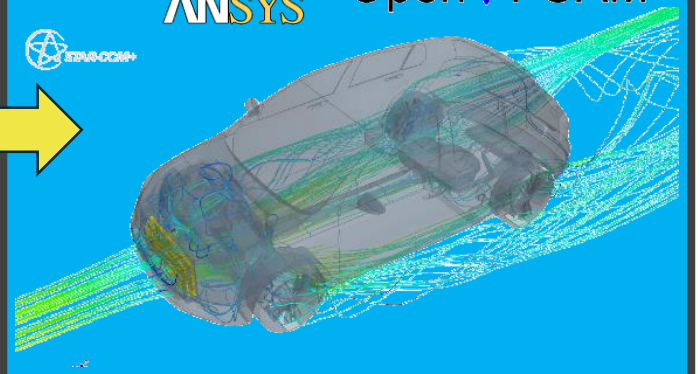
CoTherm



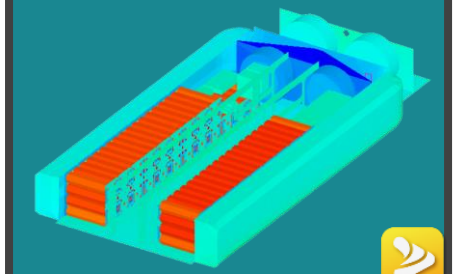
3D CFD

ANSYS

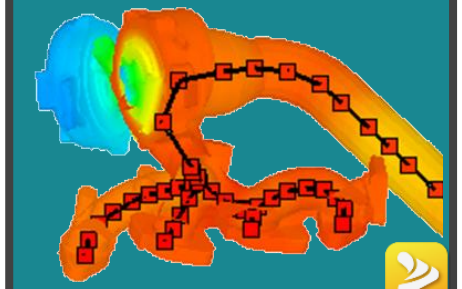
OpenFOAM



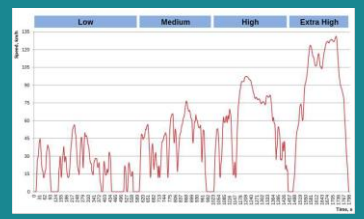
Battery Extension



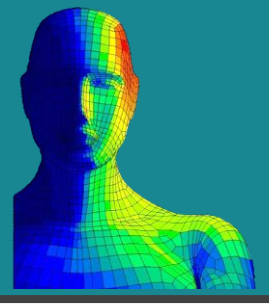
Exhaust Extension



Drive Cycle Extension



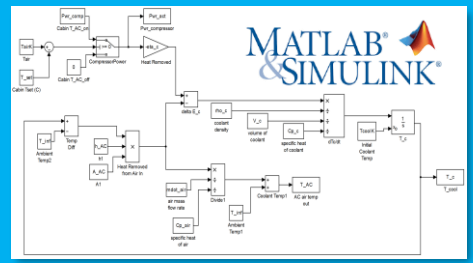
Human Comfort Extension



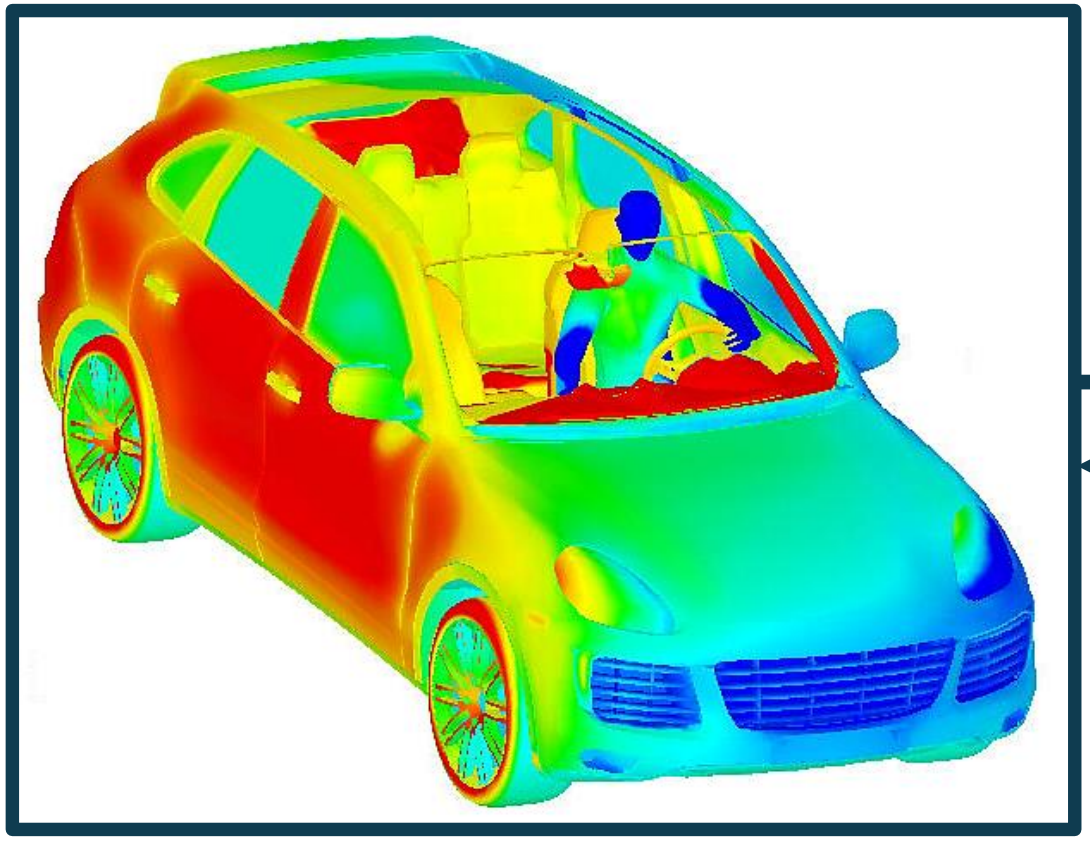
1D System Tools

GT

LMS ENGINEERING INNOVATION

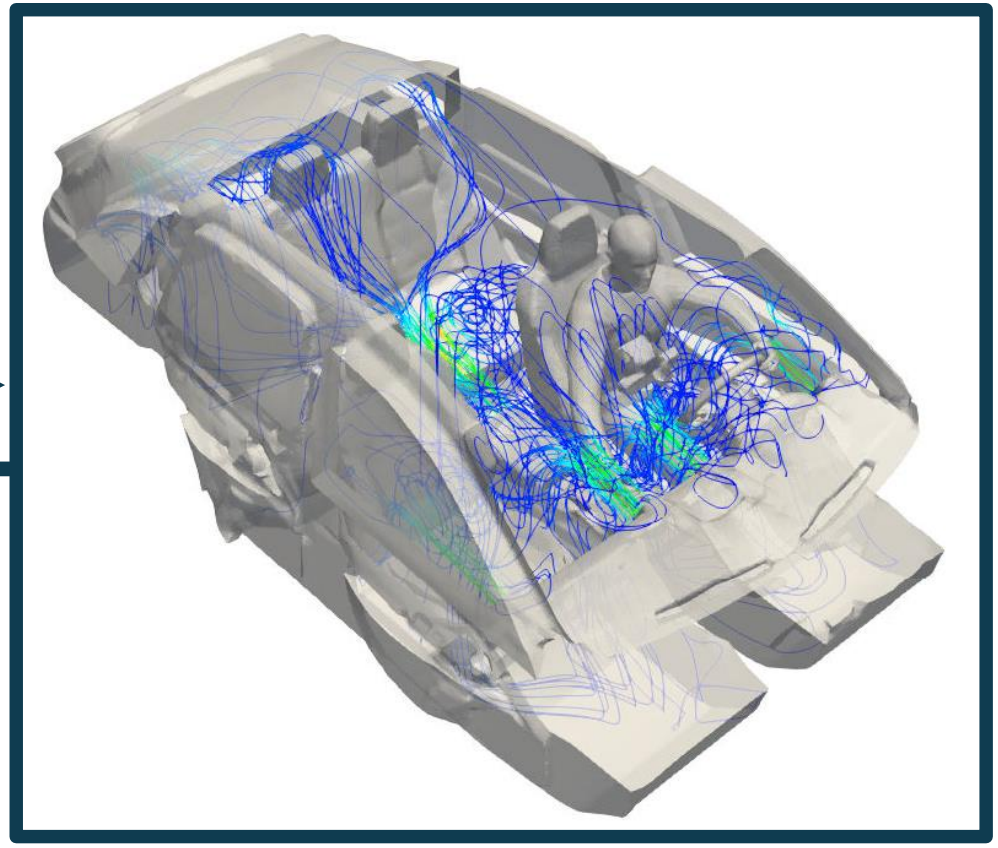


Thermal-CFD Coupling



Surface Temperatures (T_w)

Convection coefficients and fluid temperatures (h & T_{fluid})



TAITherm

OpenFOAM

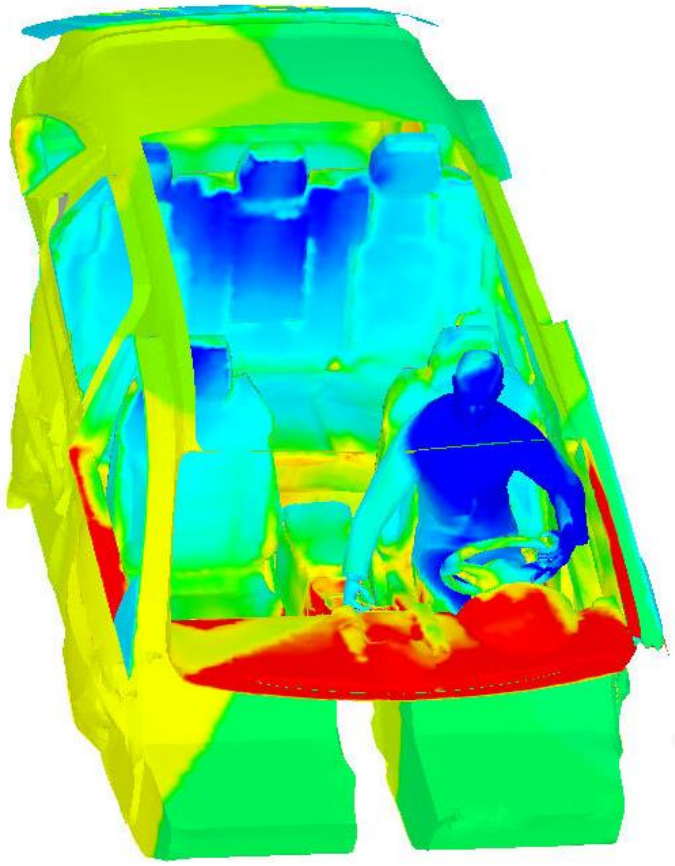
AC-Cooldown Base Case Scenario

- Vehicle preconditioning – Hot Soak
  - Natural weather: Phoenix, Arizona (8/16)
- Human preconditioning - Office
  - 2 hours transient in office setting (25 ºC)
- 30 minute AC cooldown (10:30-11:00 AM)
  - Constant vehicle speed = 50 mph
  - Vehicle heading: 0º North
  - Max AC cooldown
    - Air inlet temperature = 7 ºC
    - Total mass flow = .25 kg/s
      - 4 dash vents
      - 2 rear console vents

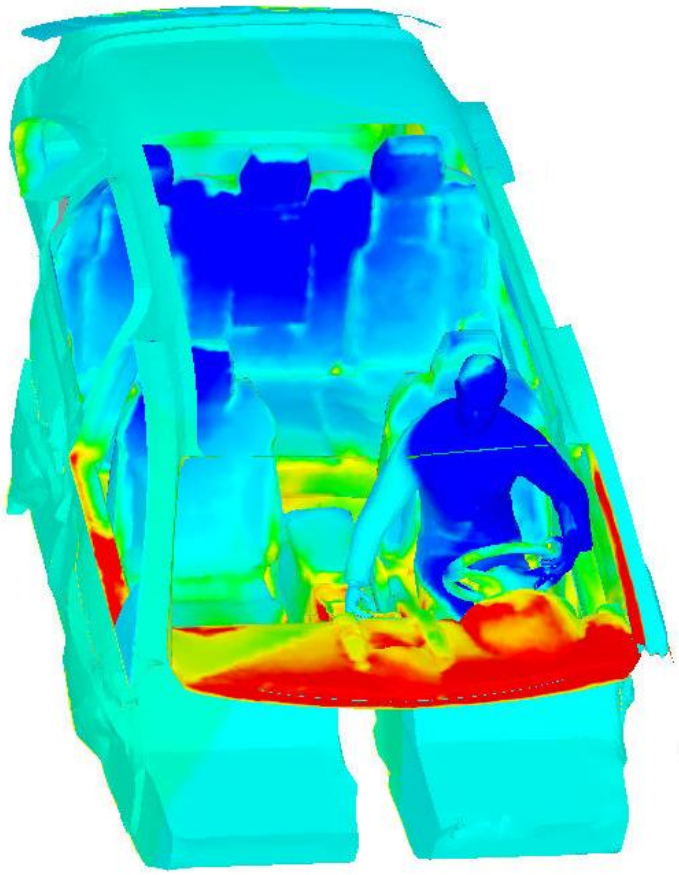
Thermal Model Boundary Conditions

Near-Wall Air Temperatures

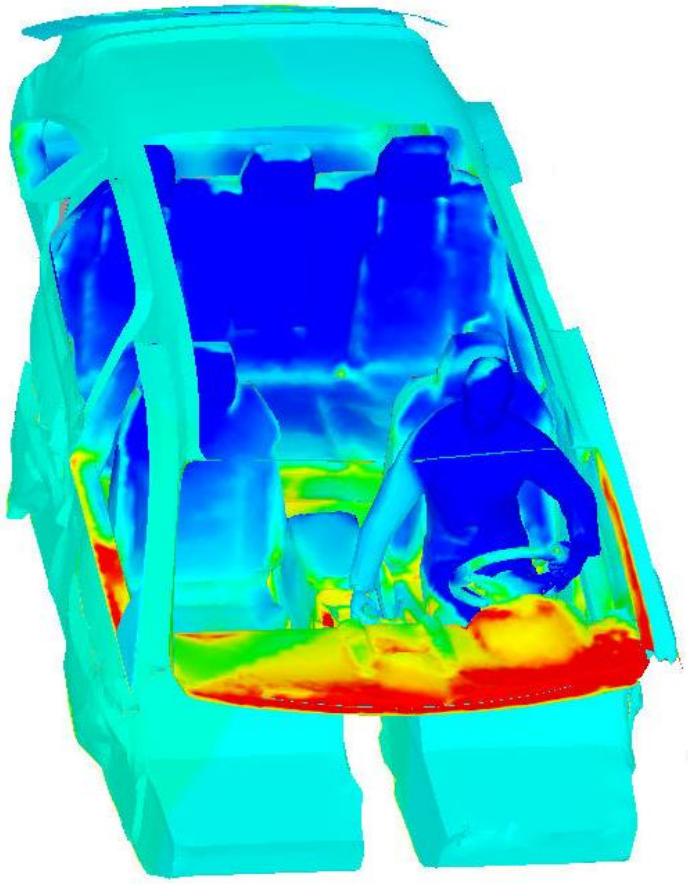
10:31 AM – 1 minute



10:45 AM – 15 minutes



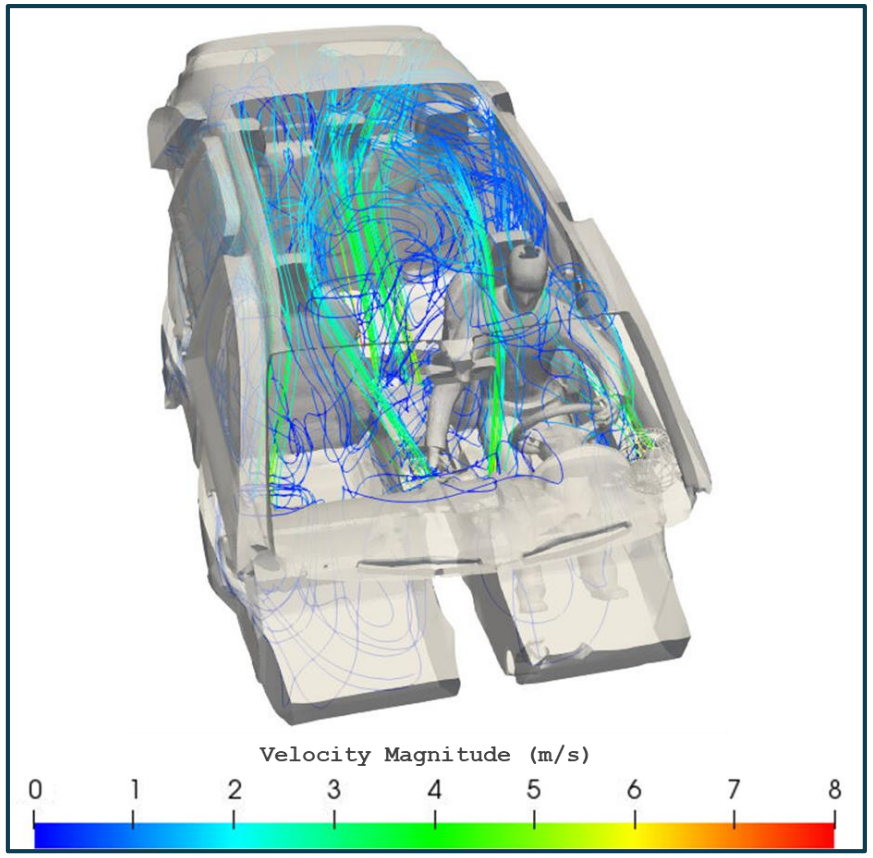
11:00 AM – 30 minutes

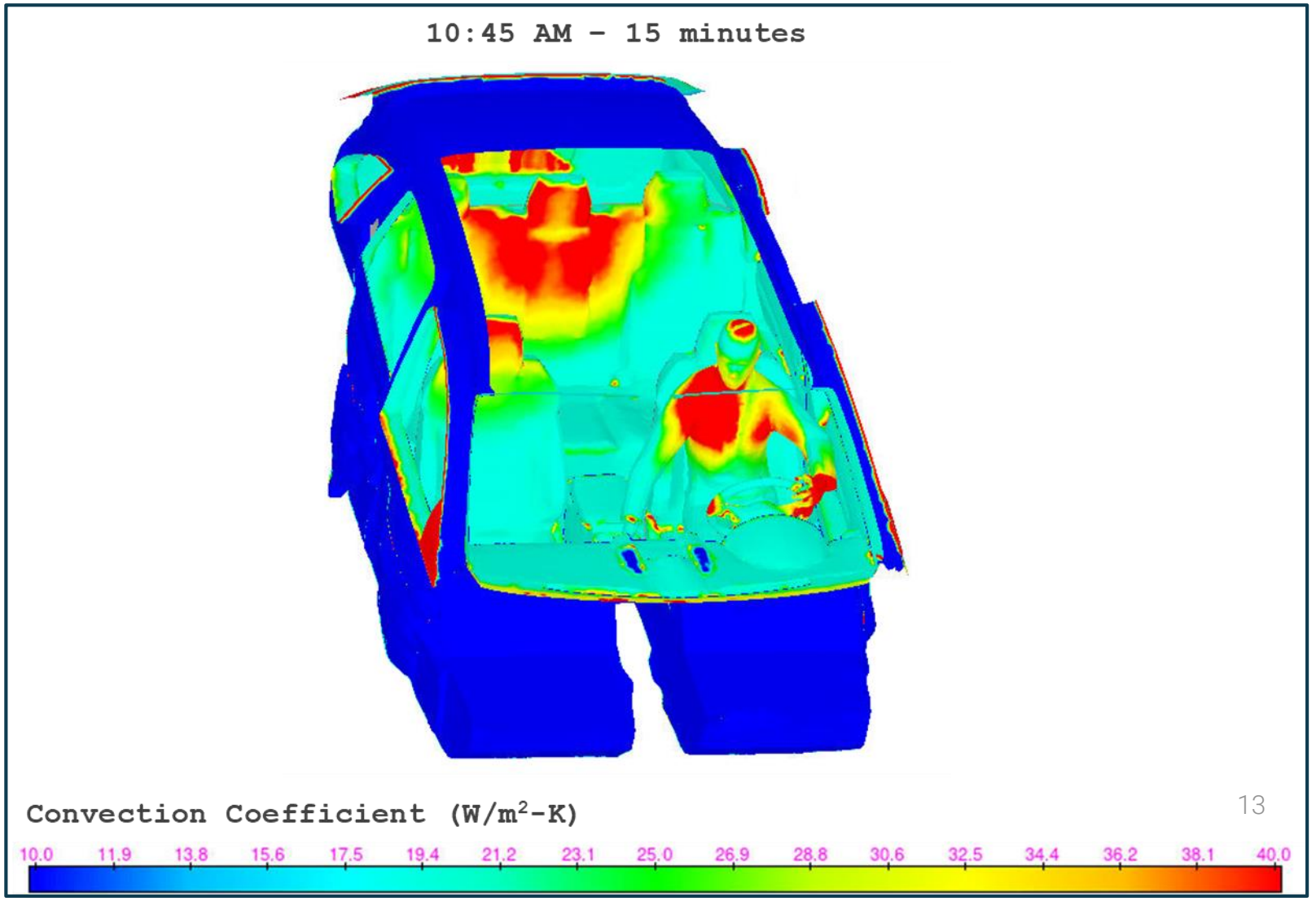


Temperature (°C)

Thermal Model Boundary Conditions

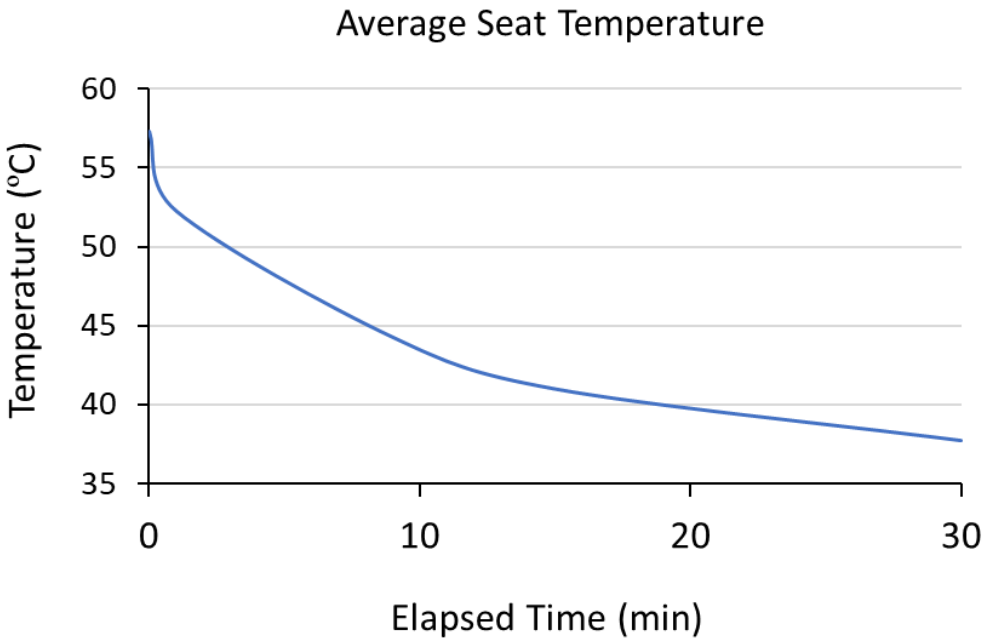
Heat Transfer Coefficients

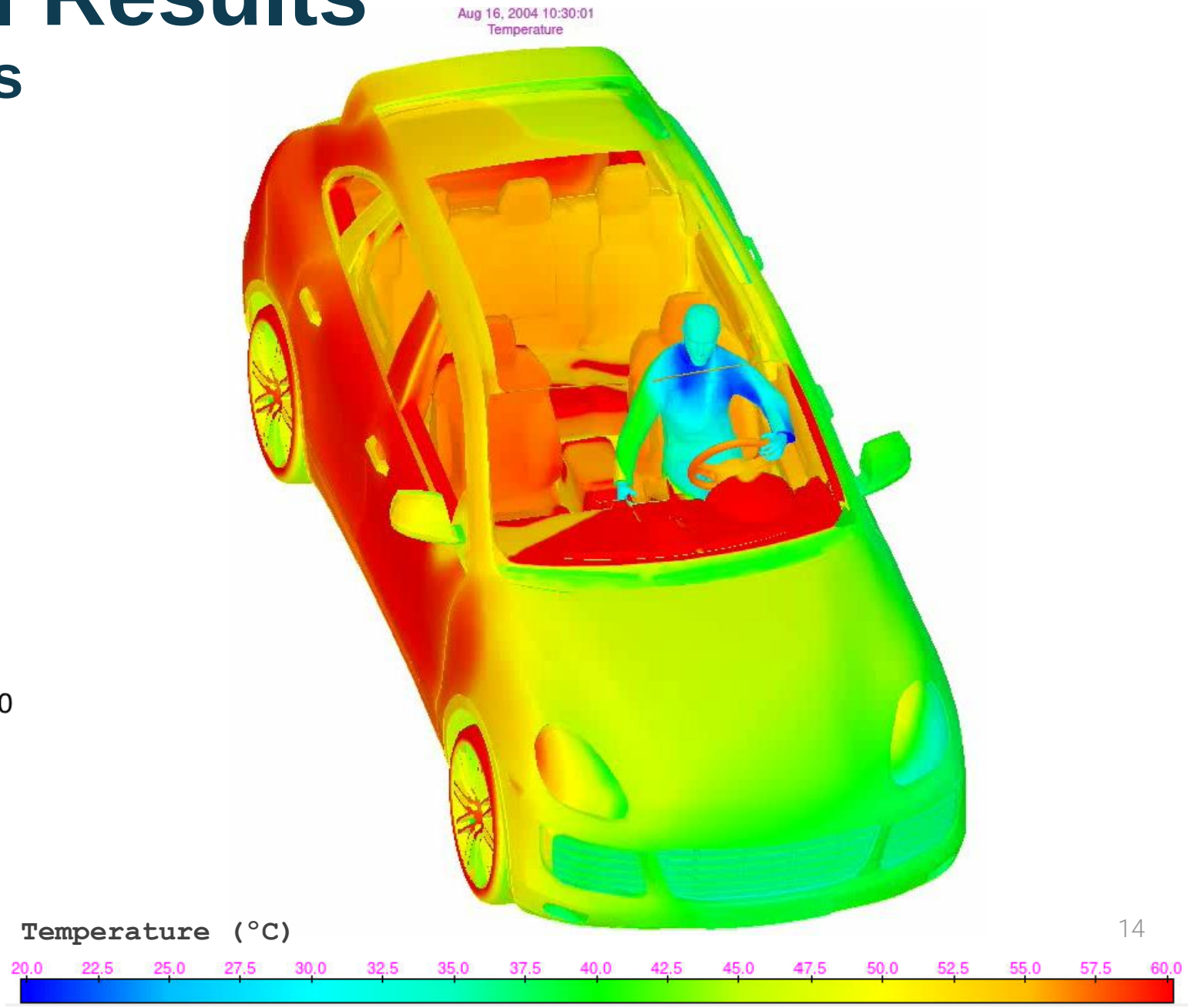




Thermal Model Results

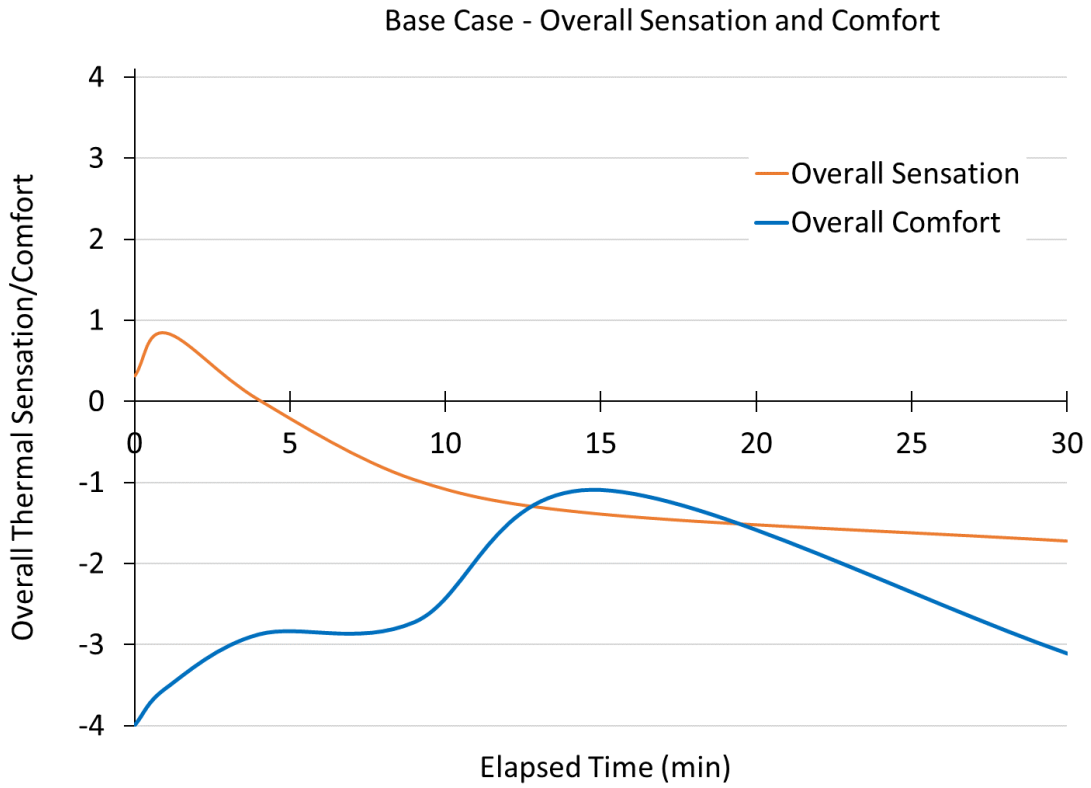
Surface Temperatures



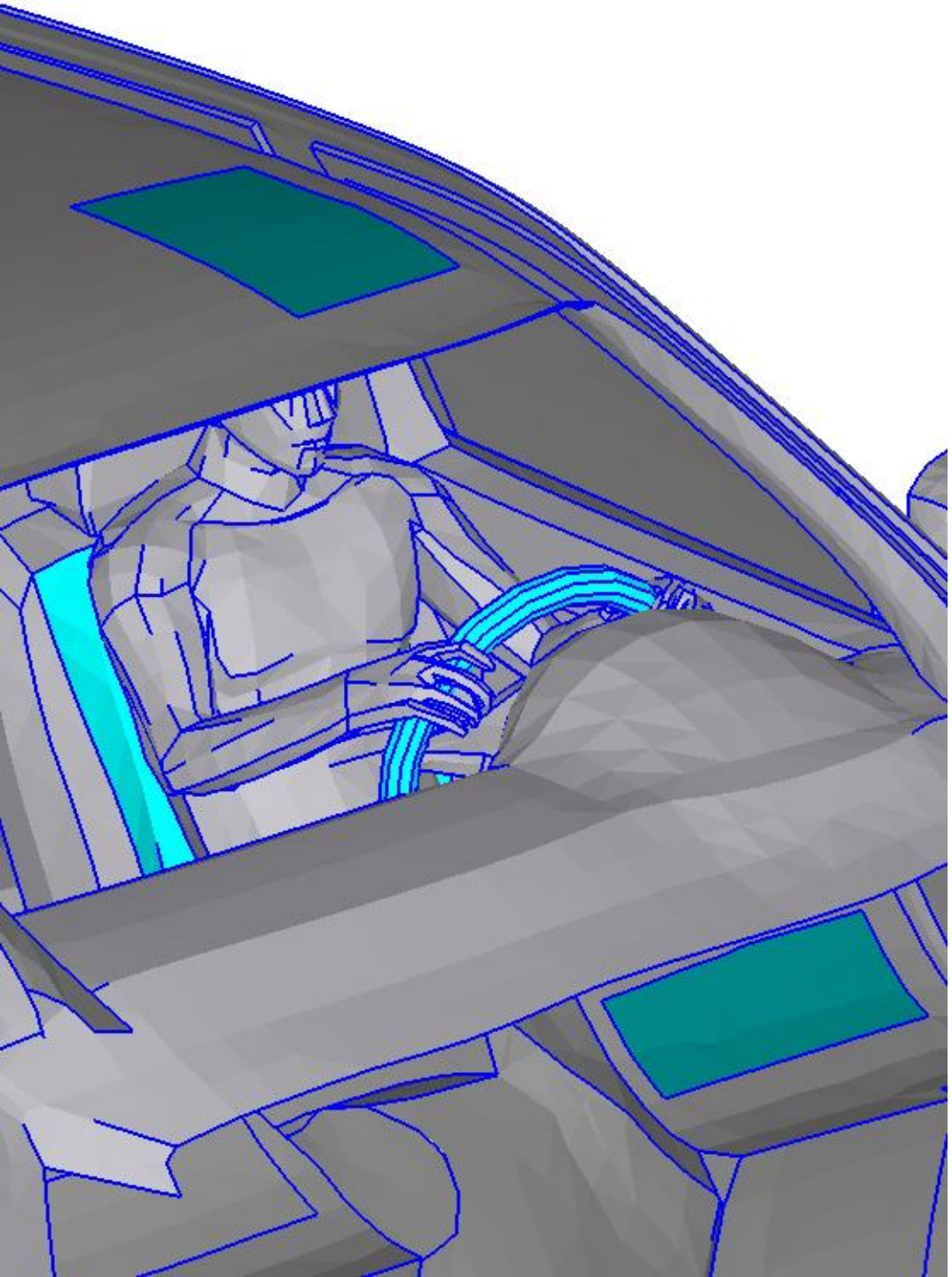


Human Thermal Comfort & Sensation

Berkeley Comfort & Sensation Scales [1]-[5]



Case Study 2: Warm-up Cabin Comfort



TAITherm Setup – Heated Surfaces

- Energy use optimization using CoTherm CAE process automation software
- Three cases considered with variable power to heating sources
  - HVAC only, foot heaters
  - HVAC only, panel heaters
  - HVAC + localized heating
    - Radiant panels
    - Seat heater
    - Steering wheel heater

CoTherm Optimization Process

Inputs

Variables with bounds

Cost Function

Optimization Method

Stopping Criteria

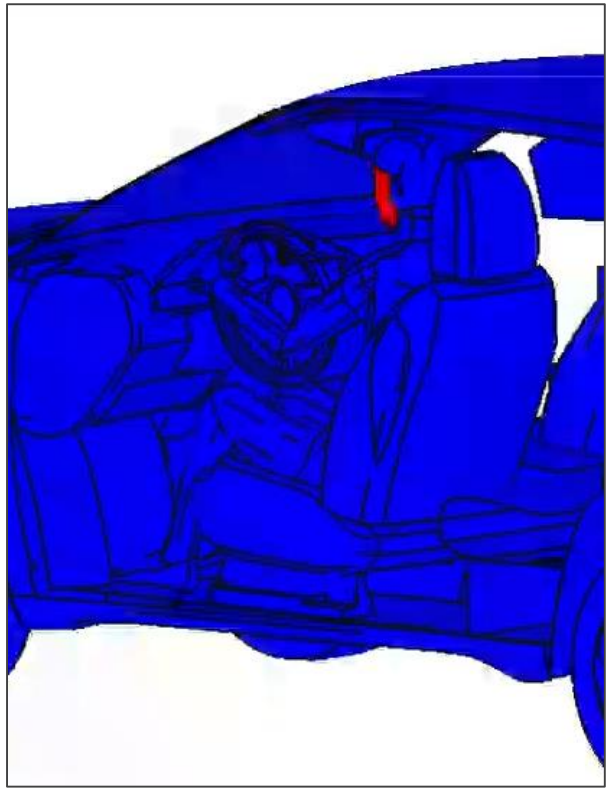
Runs optimization to determine best variable values

Output

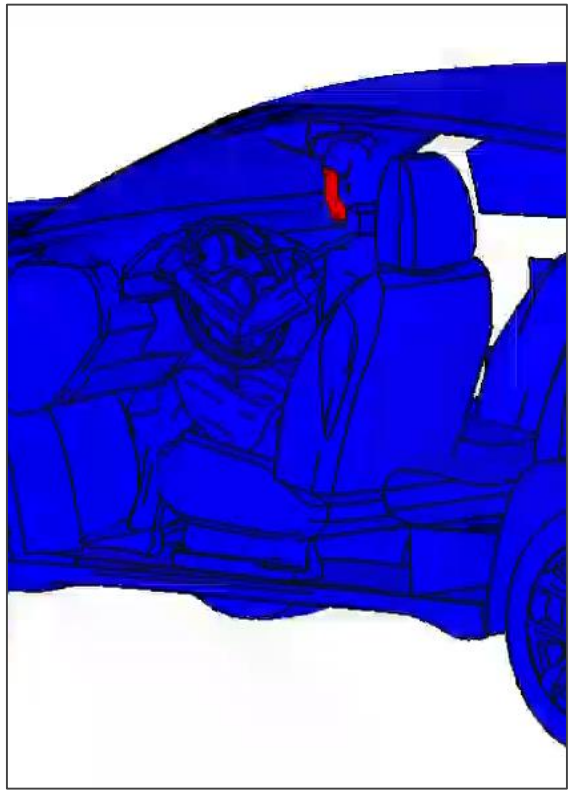
Optimized variables that minimize cost function based on user requirements

Thermal Results

HVAC Floor Mode



HVAC Panel Mode

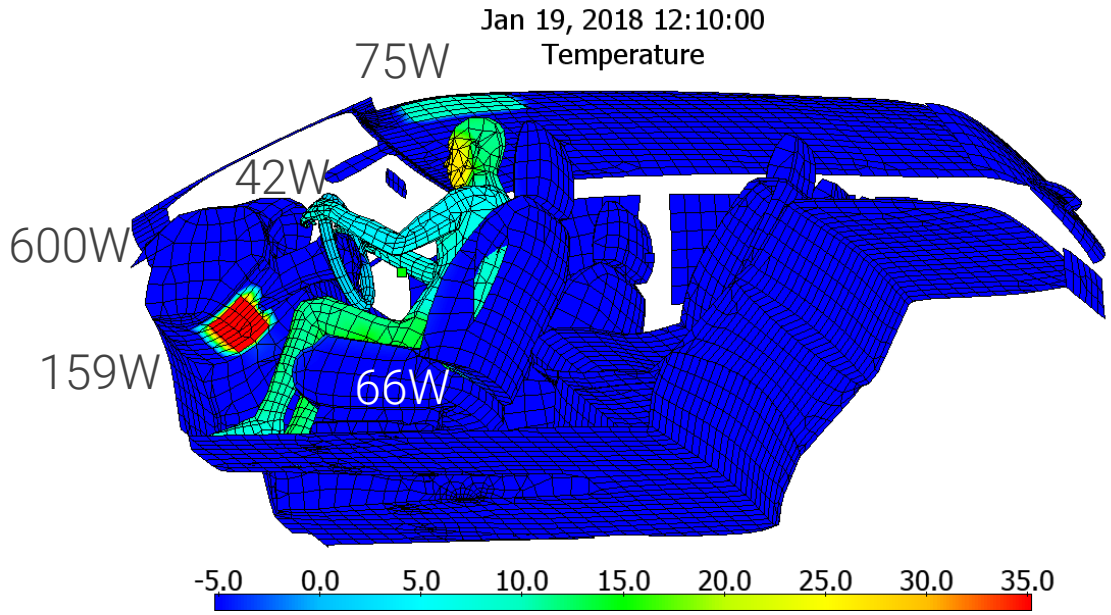


Heated Surfaces Mode

Energy Comparison

- HVAC directed at upper body: **3376W**
- HVAC directed at upper body and Legs: **3334W**
- HVAC + Heating panels
  - HVAC: 600W
  - Seat: 66W
  - Overhead panel: 75W
  - Feet panel: 159W
  - Steering wheel: 42W

  Total: 942W



Case Study 3: Battery Thermal Management

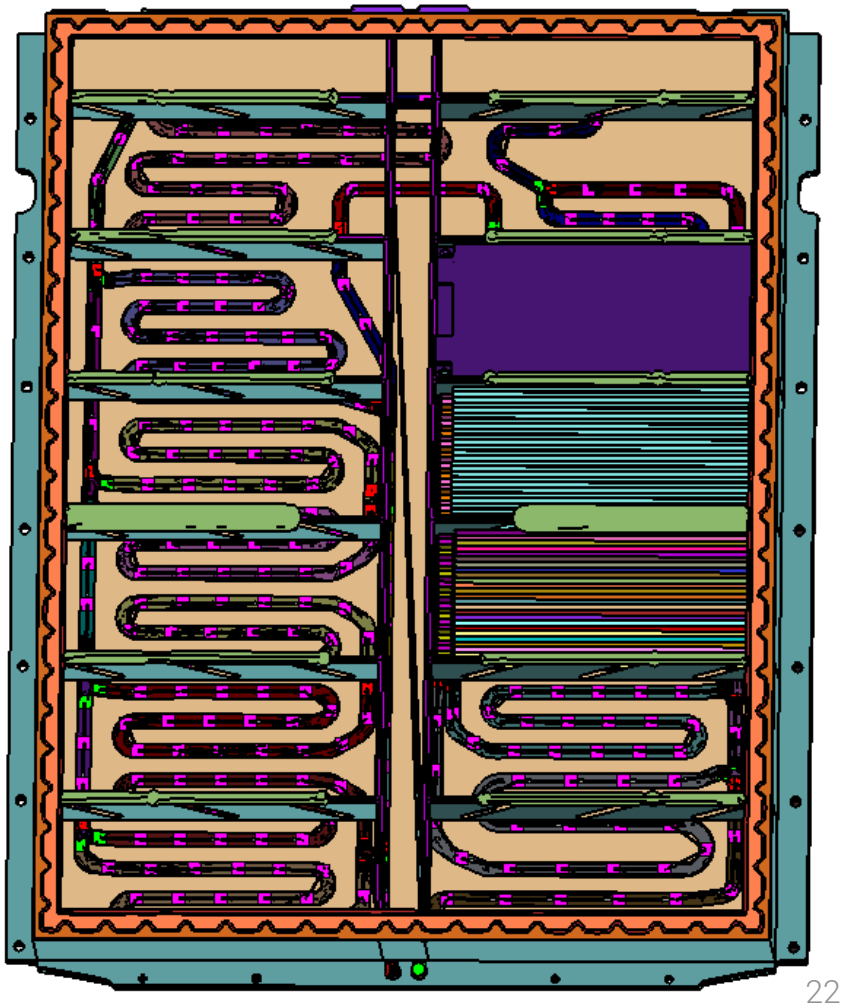
Battery Pack Geometry

- Pack model uses modular design
- 256 cells
- 2 parallel, 128 series connections
- Fluid streams represent flow in cooling plate
- Model requires improved convergence battery model

Model Size (mm):
X = 1147.15
Y = 166.569
Z = 1430.28

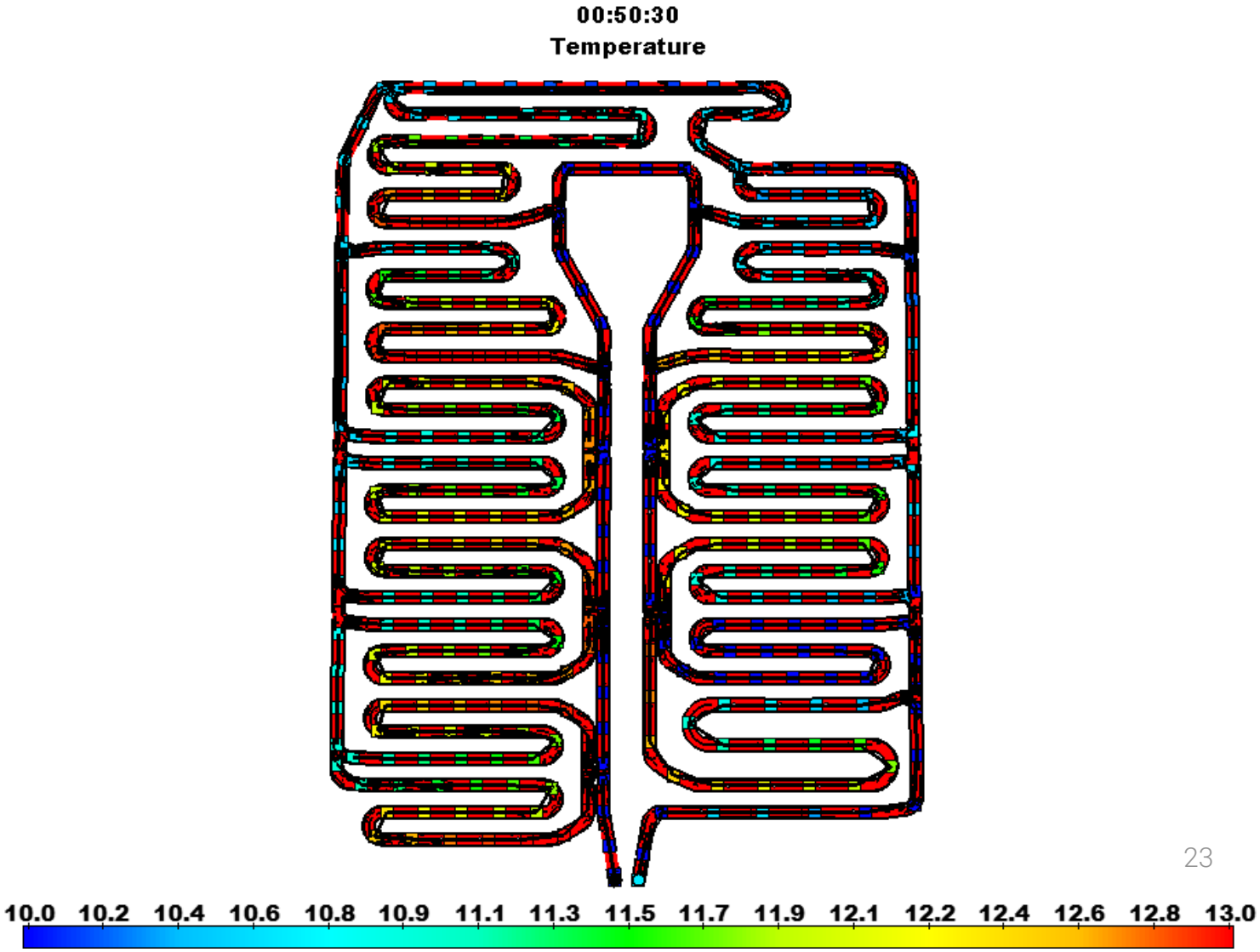
Visible Size (mm):
X = 1147.15
Y = 166.569
Z = 1430.28

Visible Counts:
Parts = 161
Elements = 172660



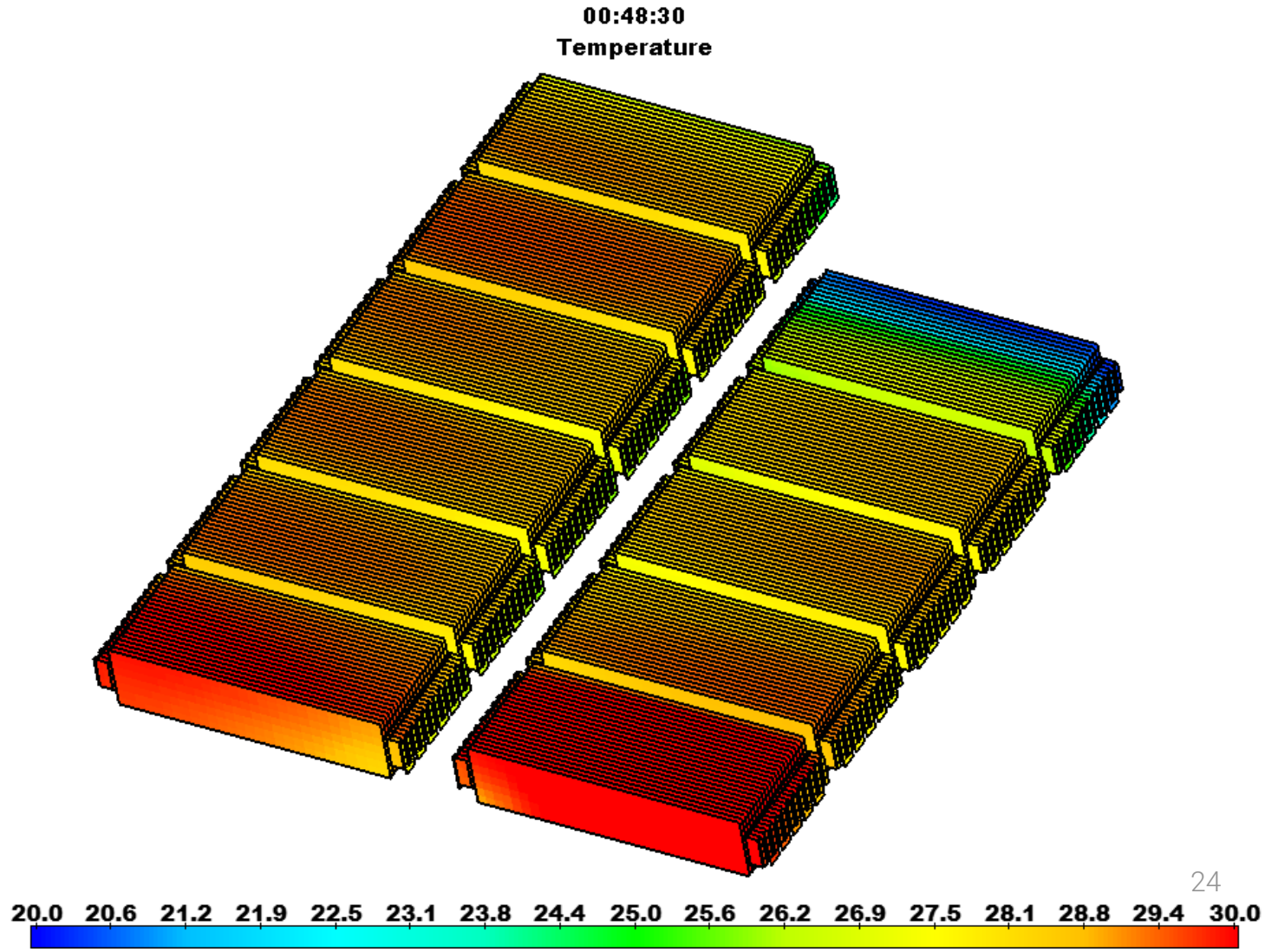
Fluid Stream Temperatures

- Fluid streams are set up to distribute flow evenly across pack
- Channel locations are not optimized for pack cooling
- Fluid stream temperature difference is 3°C



Cell Temperature Distribution

- Temperature dependent heat rates predicted for each cell
- Temperature difference across cells is 10°C
- Temperature difference within cell is 3°C
- This design is not best case scenario and requires improvements



Case Study 4: Joule Heating

Introduction

- Joule heating, also known as resistive or Ohmic heating, is heat that is produced when electric current is passed through an electrical conductor

- xEV Examples
  - Battery cell tabs
  - Bus bars
  - Wiring harnesses
  - Fast charger connections and wiring
  - Electronic circuits (inverters)
  - PTC Heaters in HVAC
  - Catalyst heater for exhaust
  - Heated seats

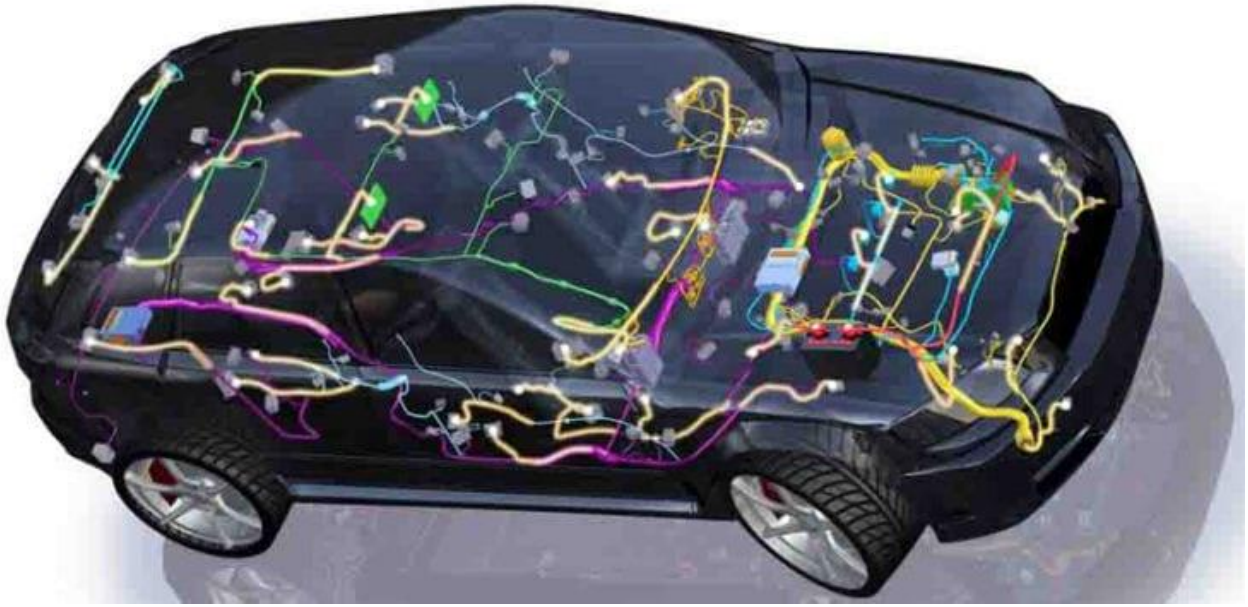
$$\rho = \rho_0\left(1 + \alpha(T - T_0)\right)$$

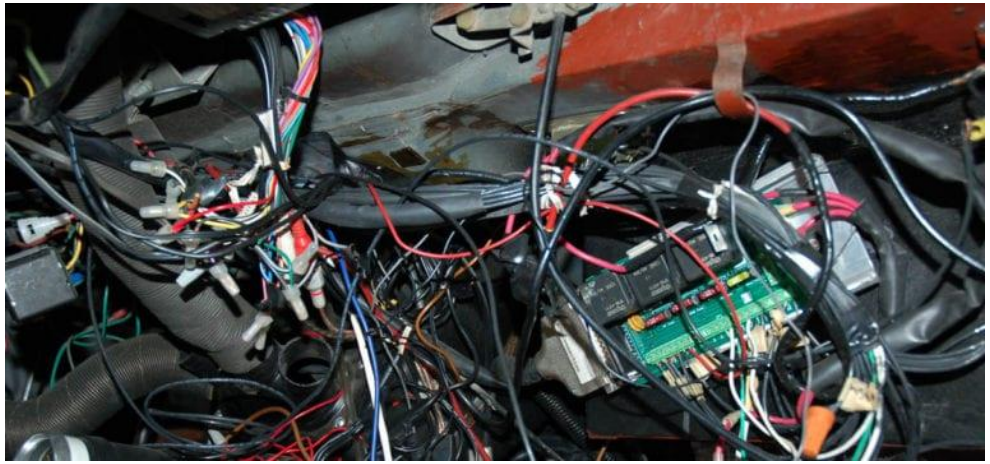
$$R = \rho\frac{L}{A}$$

$$Q = IV = I^2R = \frac{V^2}{R}$$

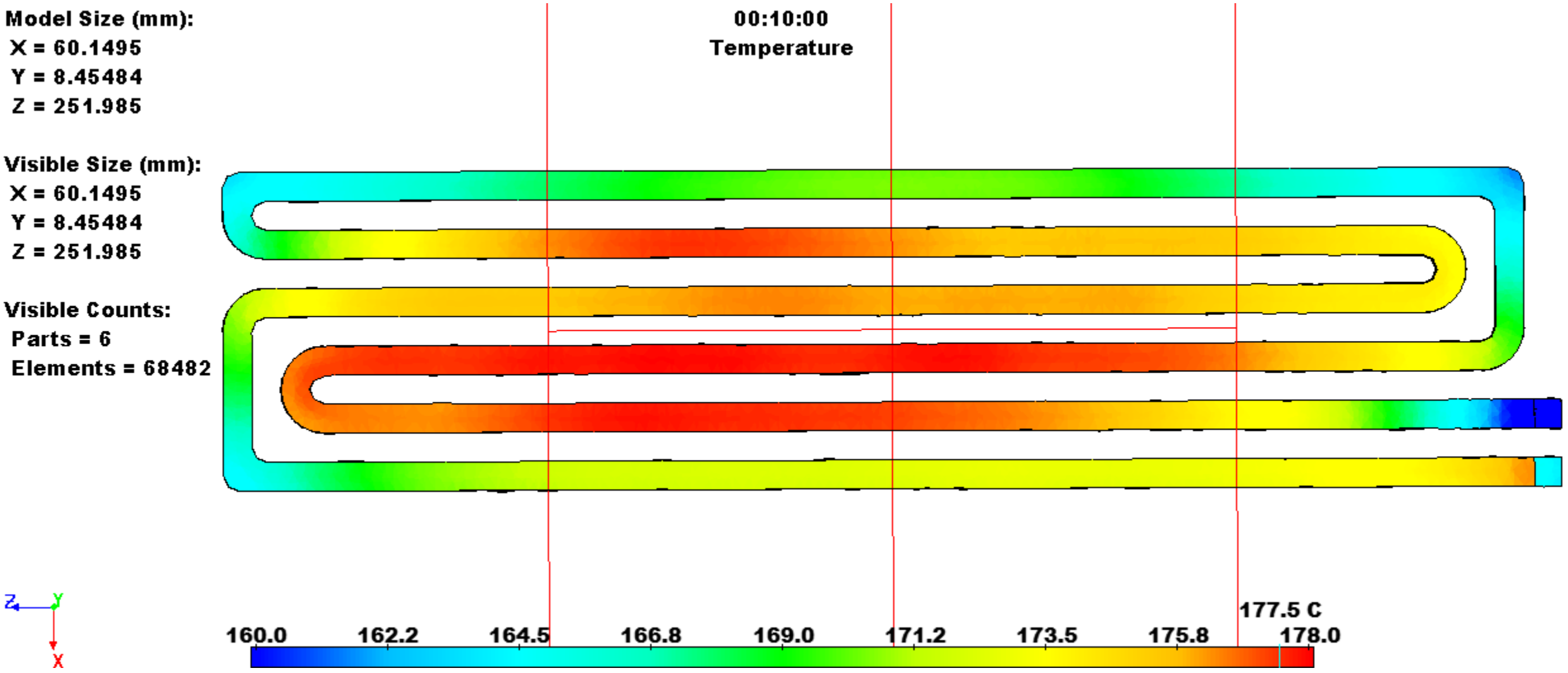
Electric Vehicle Wiring Harnesses

- Electric vehicles have over 150 pounds (68 kg) of wiring in a single vehicle
- There are two main categories of automotive wire
- PVC: rated 80 to 105°C
- Cross-linked: rated 125°C
- Wiring must not only be protected from surrounding heat sources, but undergoes self-heating due to resistance





Thermal Results: Temperature

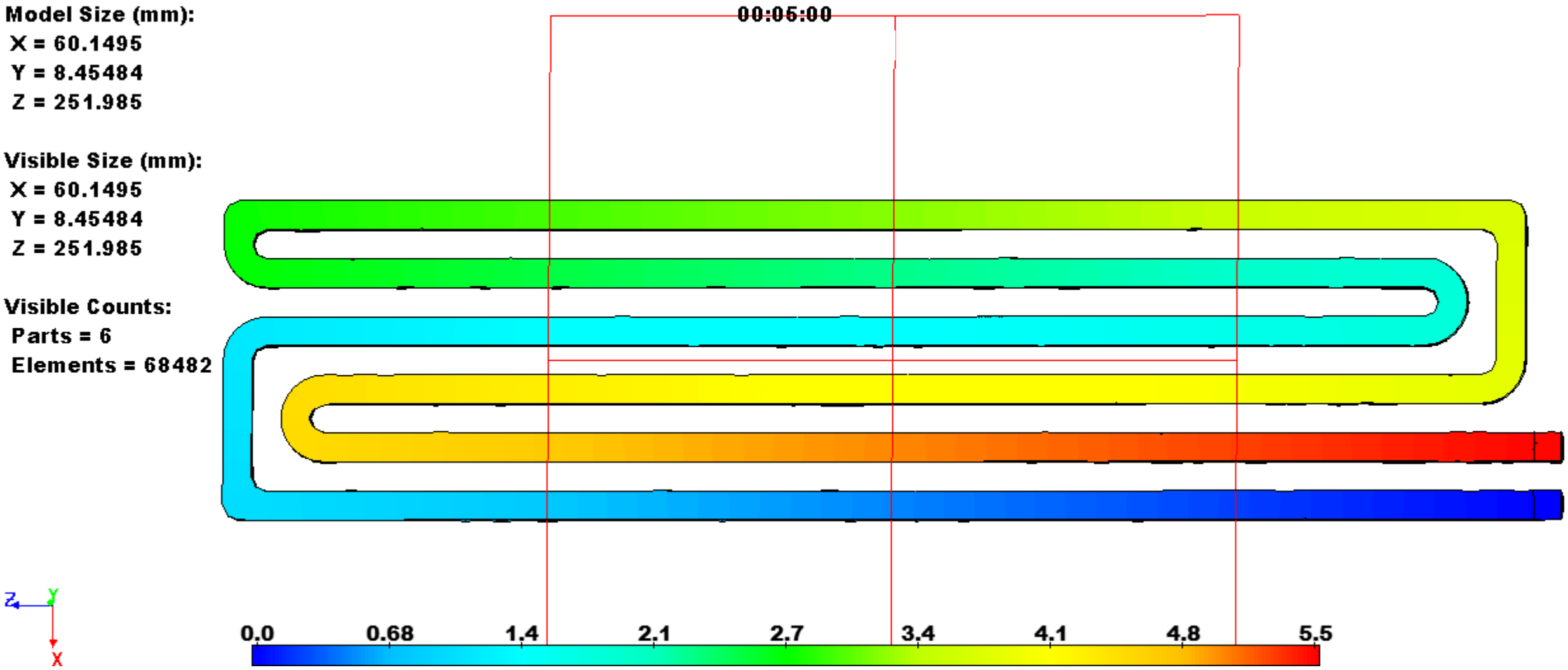


Electrical Results: Voltage

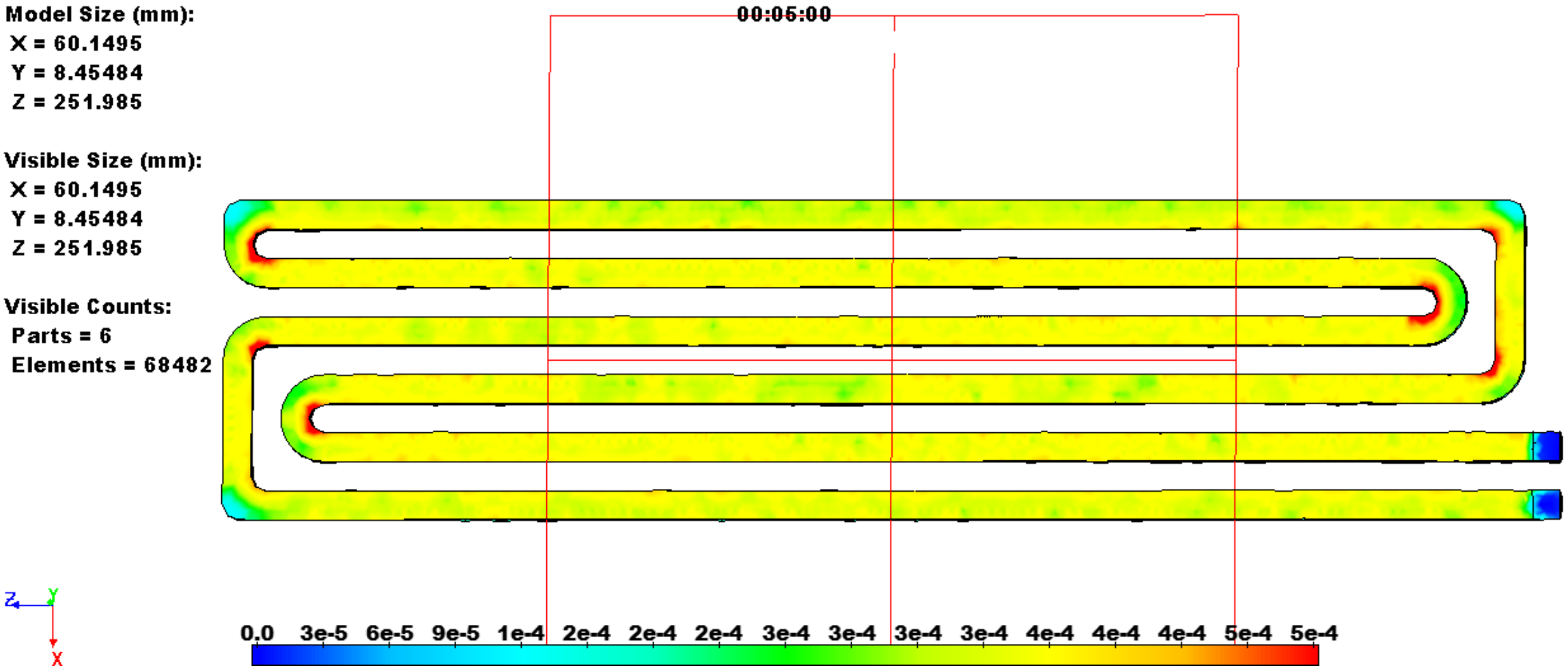
Model Size (mm):
X = 60.1495
Y = 8.45484
Z = 251.985

Visible Size (mm):
X = 60.1495
Y = 8.45484
Z = 251.985

Visible Counts:
Parts = 6
Elements = 68482



Electrical Results: Current (50 Amps)



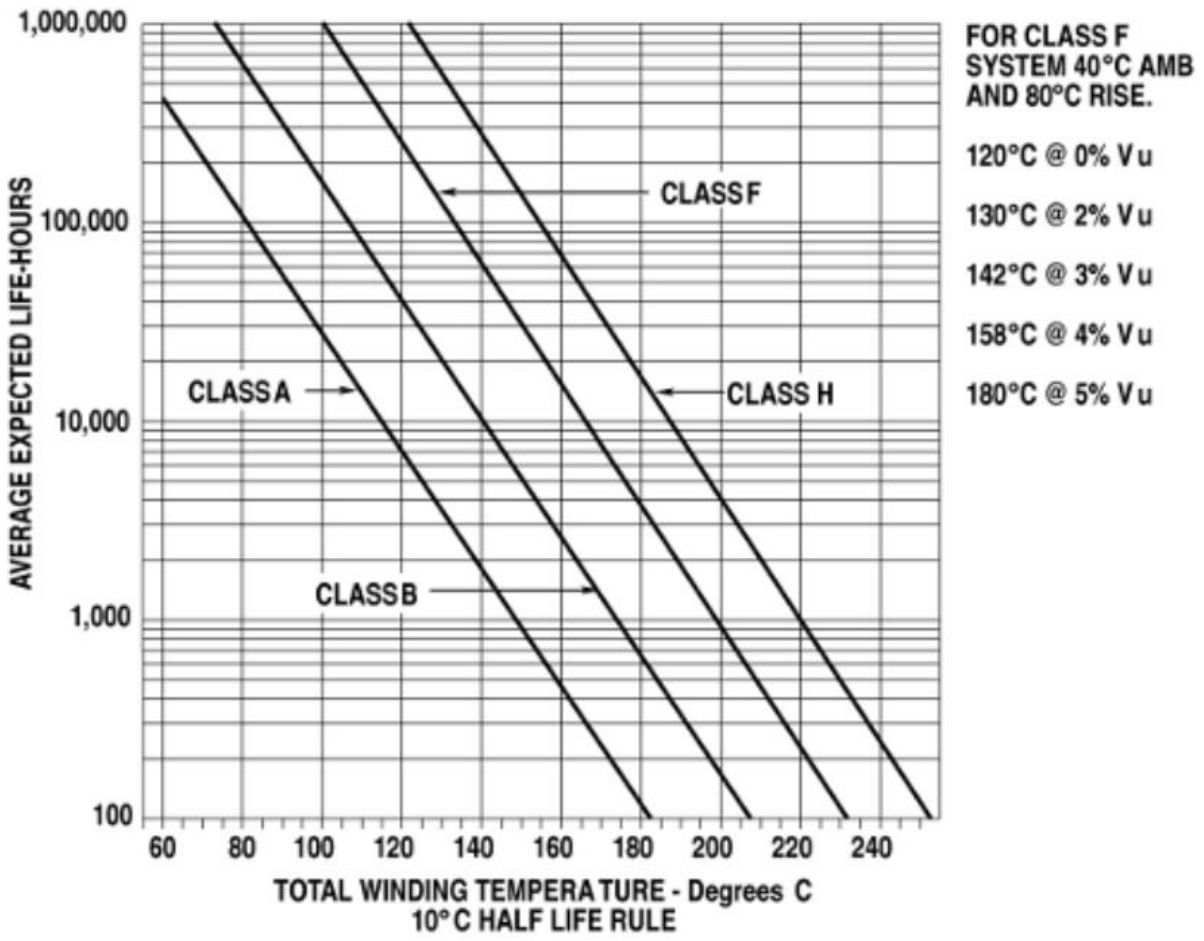
- Current is per element, flux not available

Case Study 5: Electric Motor

Internal Temperature Limits

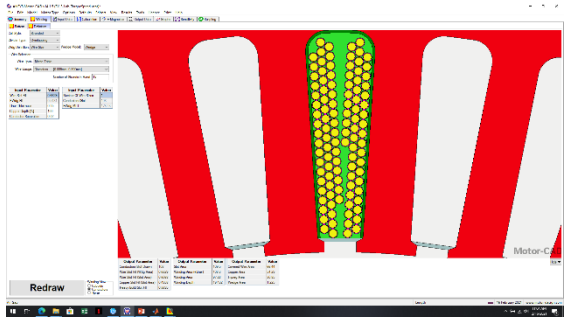
- There are two components in the motor that are temperature-sensitive
- Insulating material: 90 to >240°C
- Magnets (PMSM only): 150 to 180°C
- Continuous power is typically limited to ~50% of peak power due to thermal limits

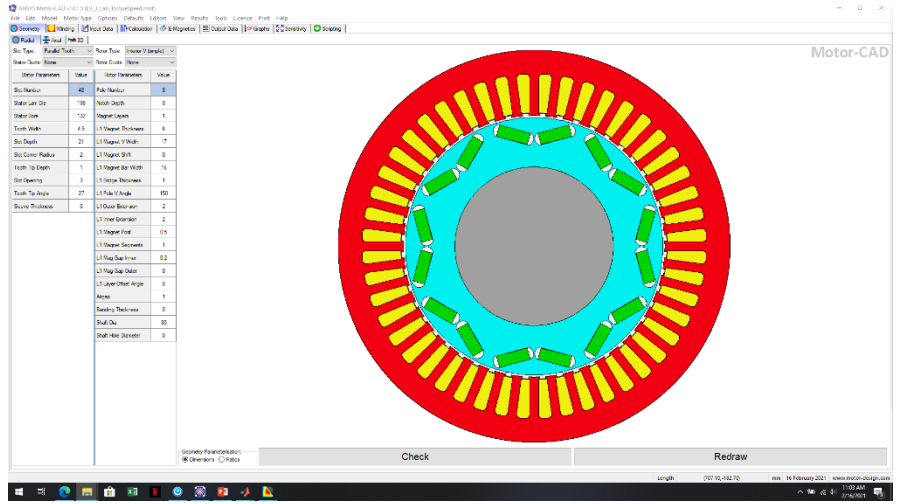
Insulation Class	Temperature Rating
A	105°C
B	130°C
F	155°C
H	180°C

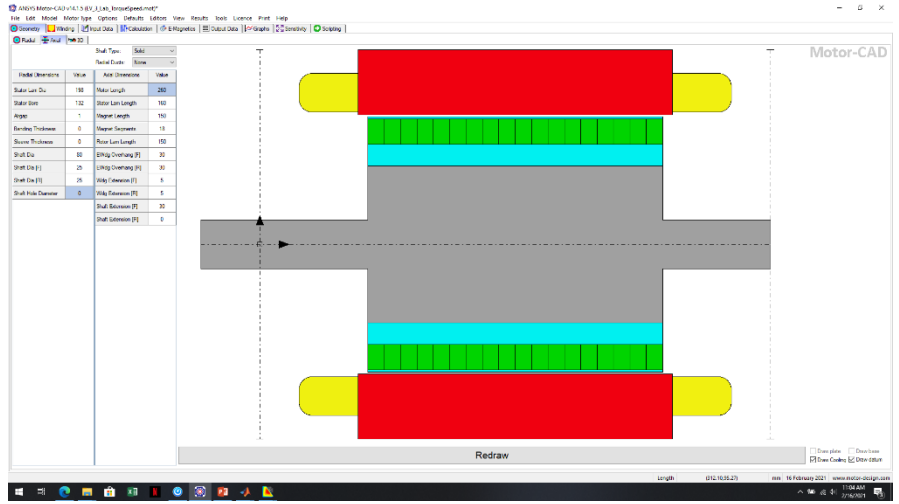


Electromagnetic Model

- An electromagnetic model was used to calculate inputs to the TAITherm thermal model
  - Loss maps for the motor
  - Drive cycle motor speed and torque

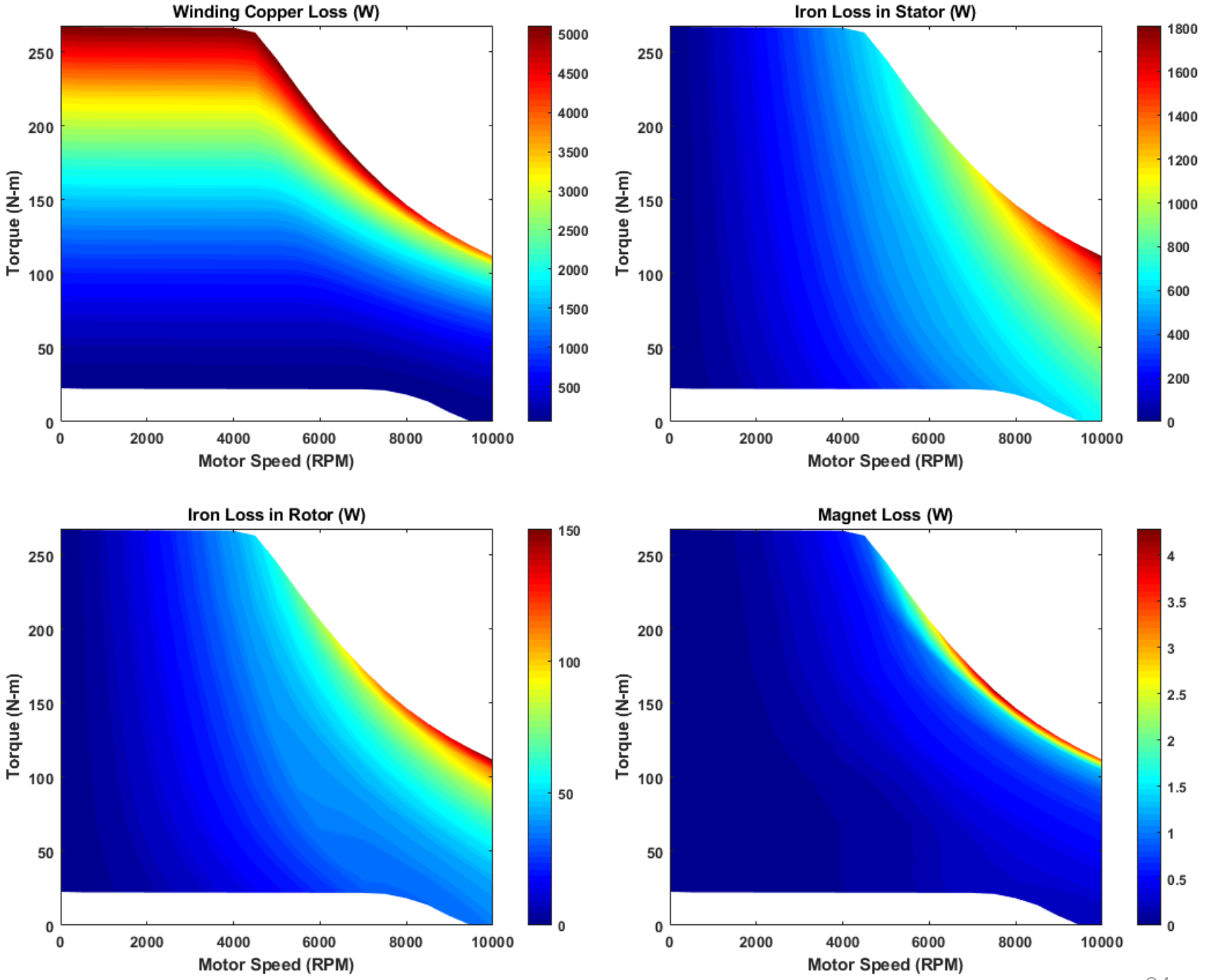




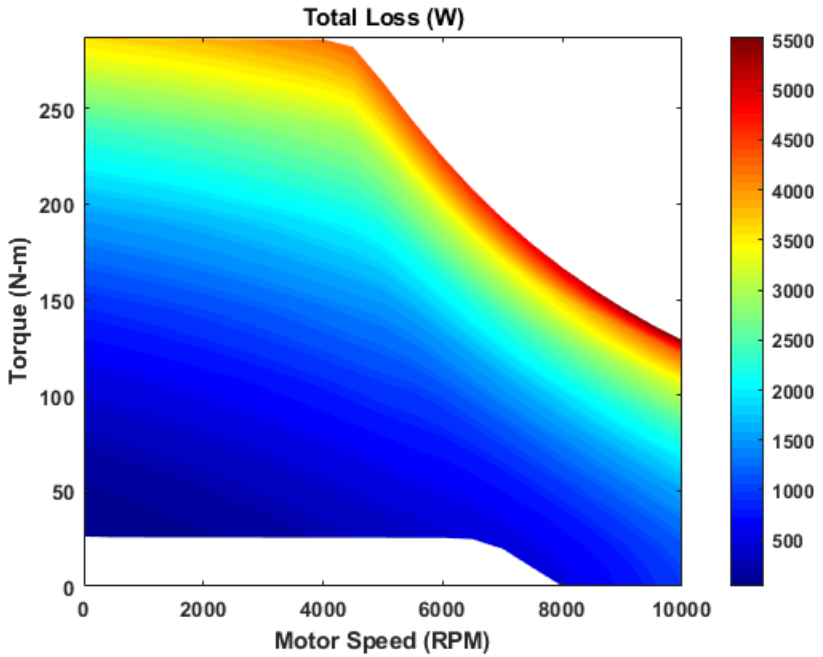


Loss Maps

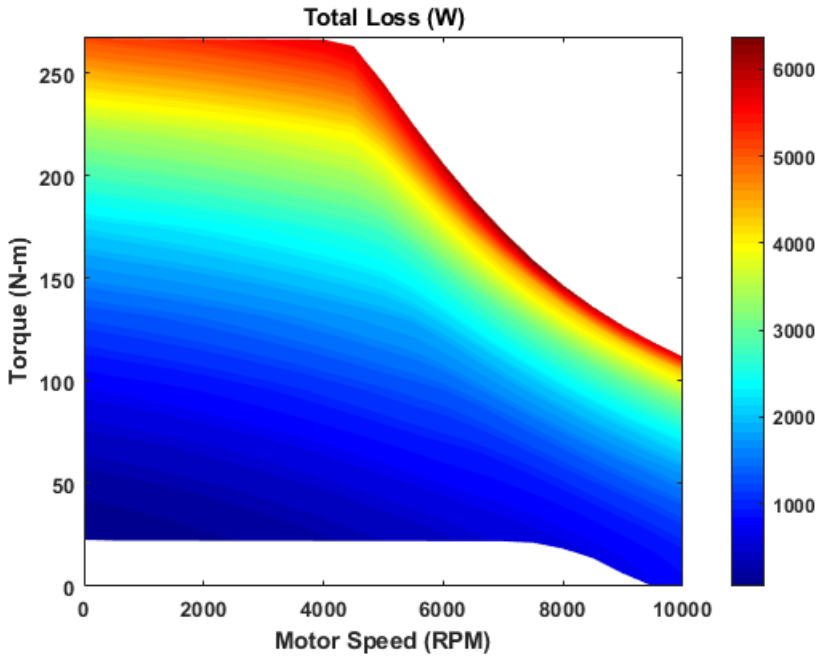
- Loss map data was exported from electromagnetic model
- Losses are interpolated in TAITherm for drive cycle profile



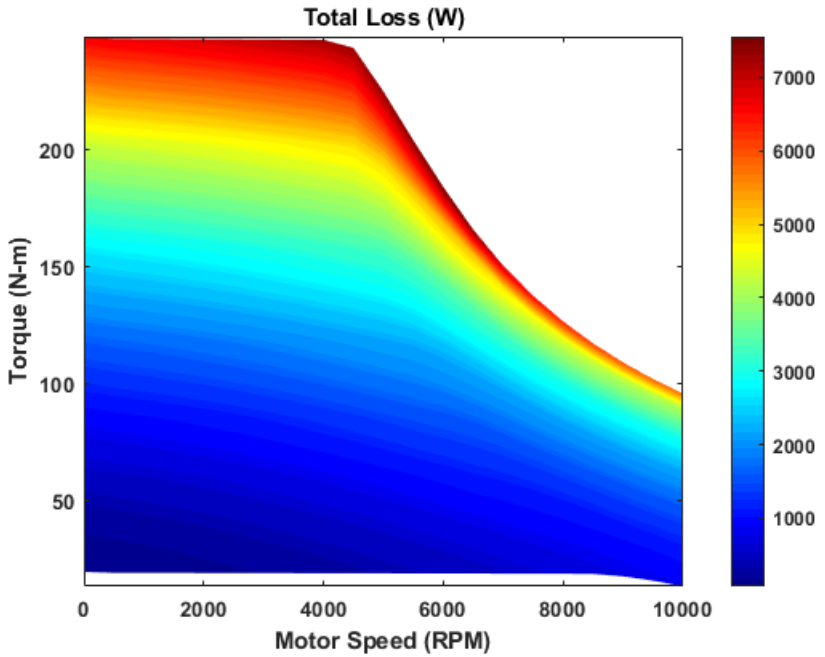
Temperature Dependence



T = 0°C



T = 100°C

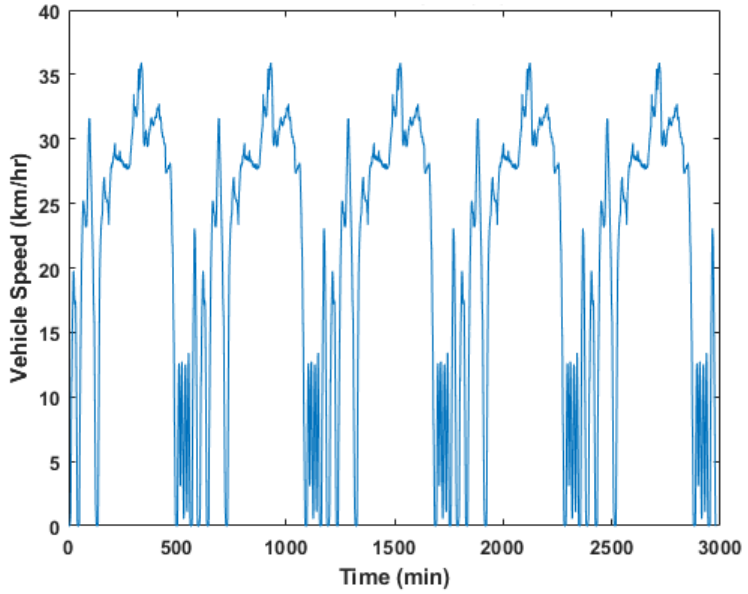


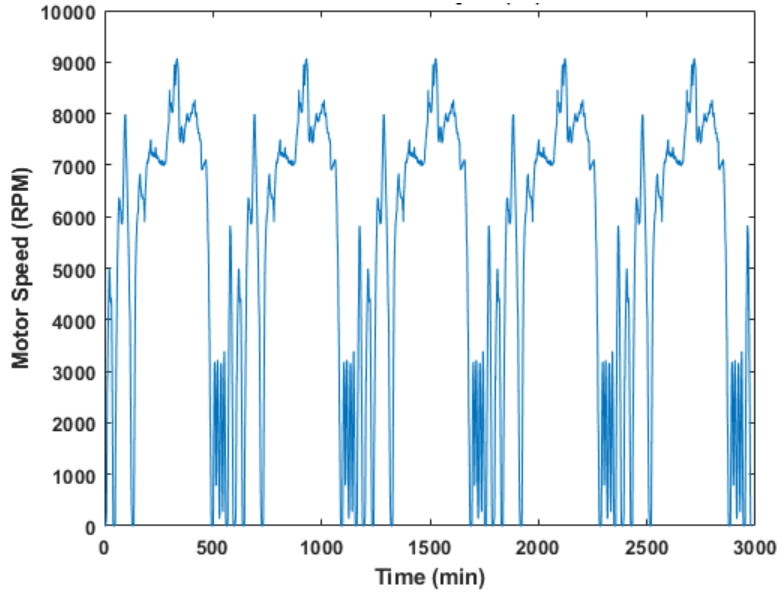
T = 200°C

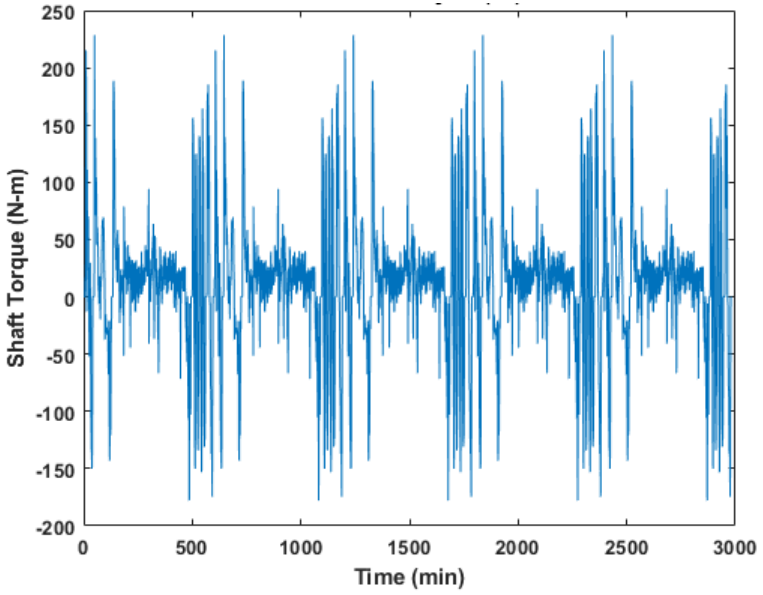
- All maps are generated for different temperatures
- Losses are interpolated with temperature during drive cycle

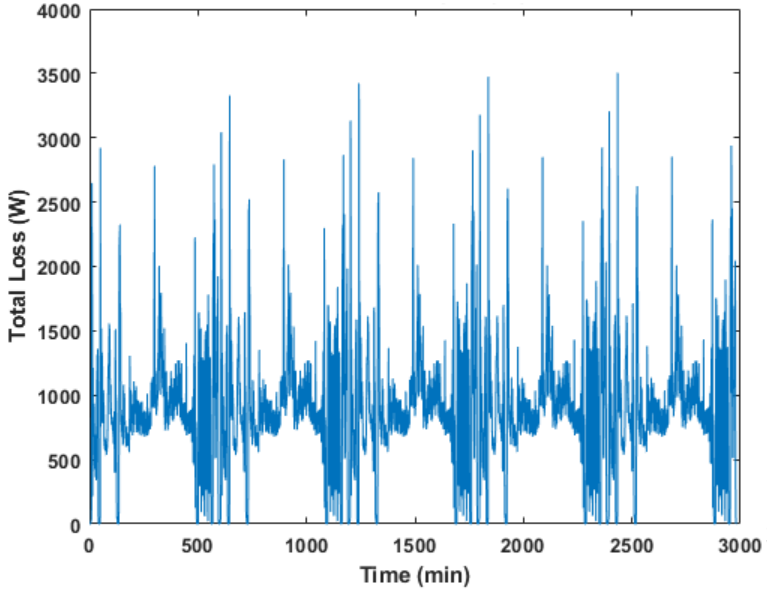
US06 Drive Cycle (x5)

- A drive cycle was run using the electromagnetic model as input to TAITherm
- TAITherm uses the drive cycle inputs with loss maps to apply heating to components







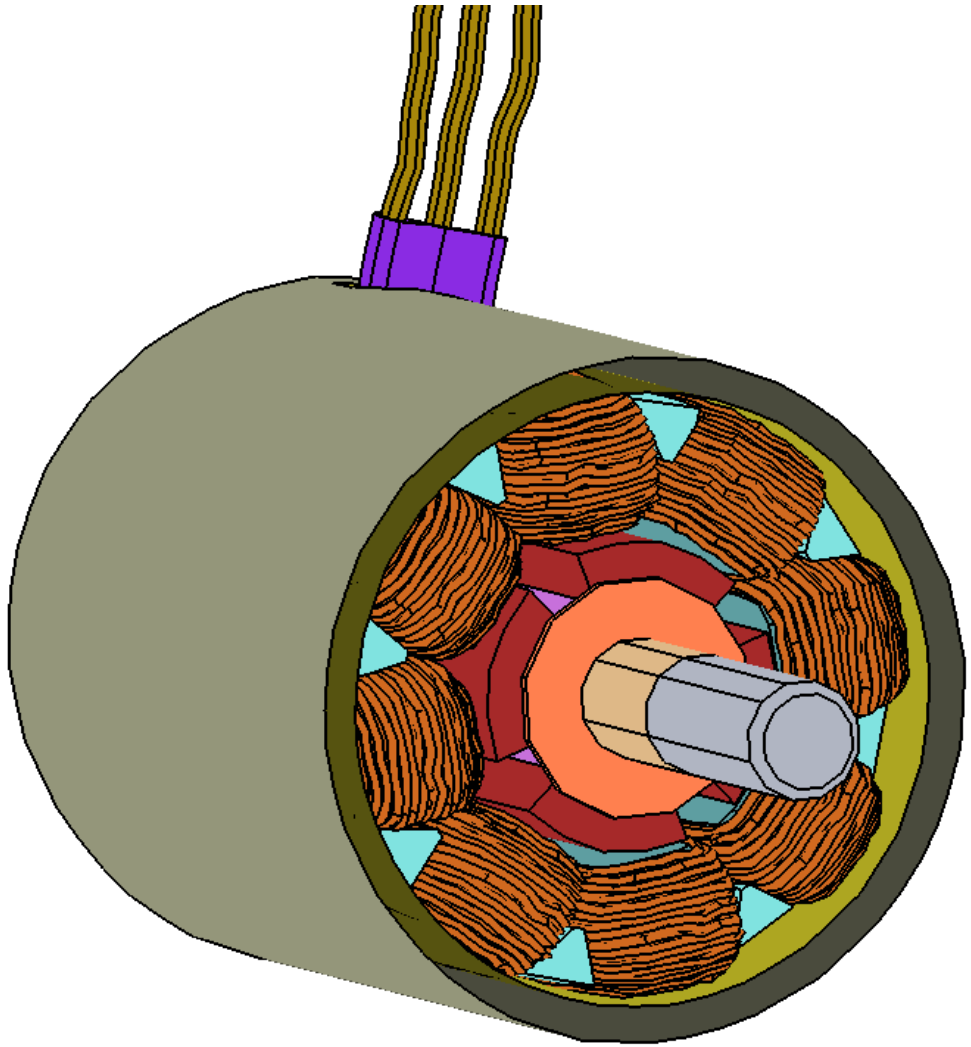


TAITherm Thermal Model

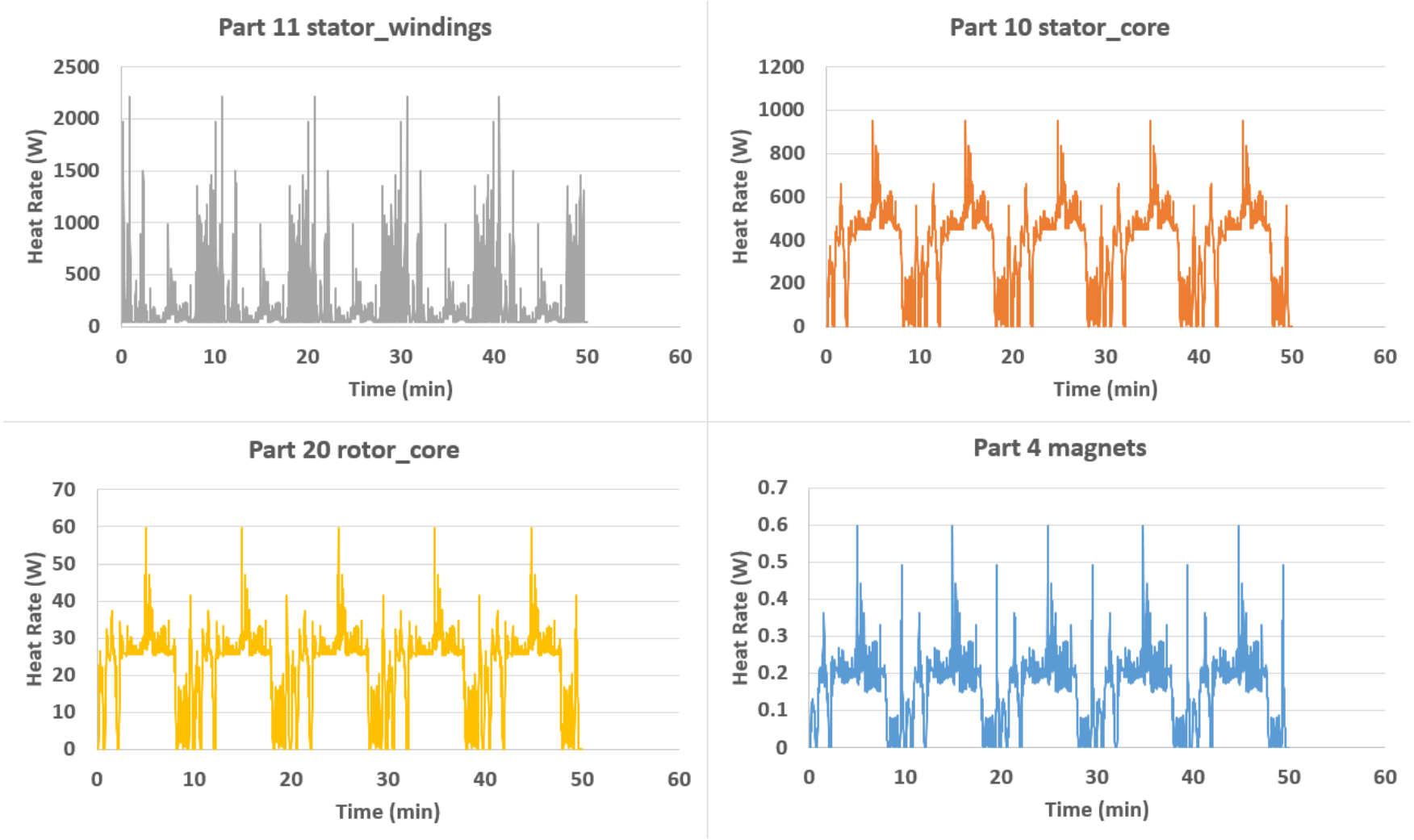
Model Size (mm):
X = 360.61
Y = 230.854
Z = 457.541

Visible Size (mm):
X = 360.61
Y = 230.854
Z = 457.541

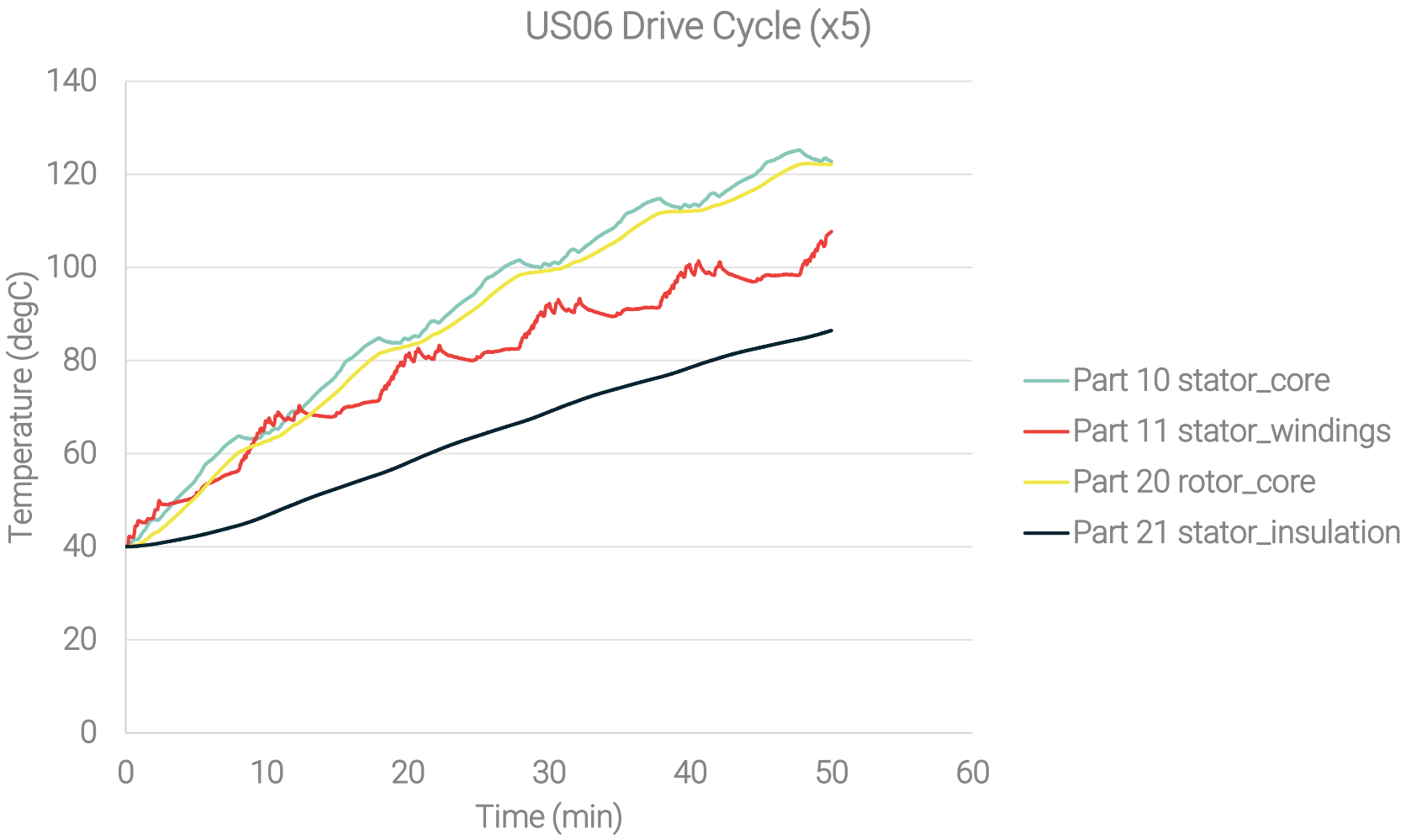
Visible Counts:
Parts = 16
Elements = 69260



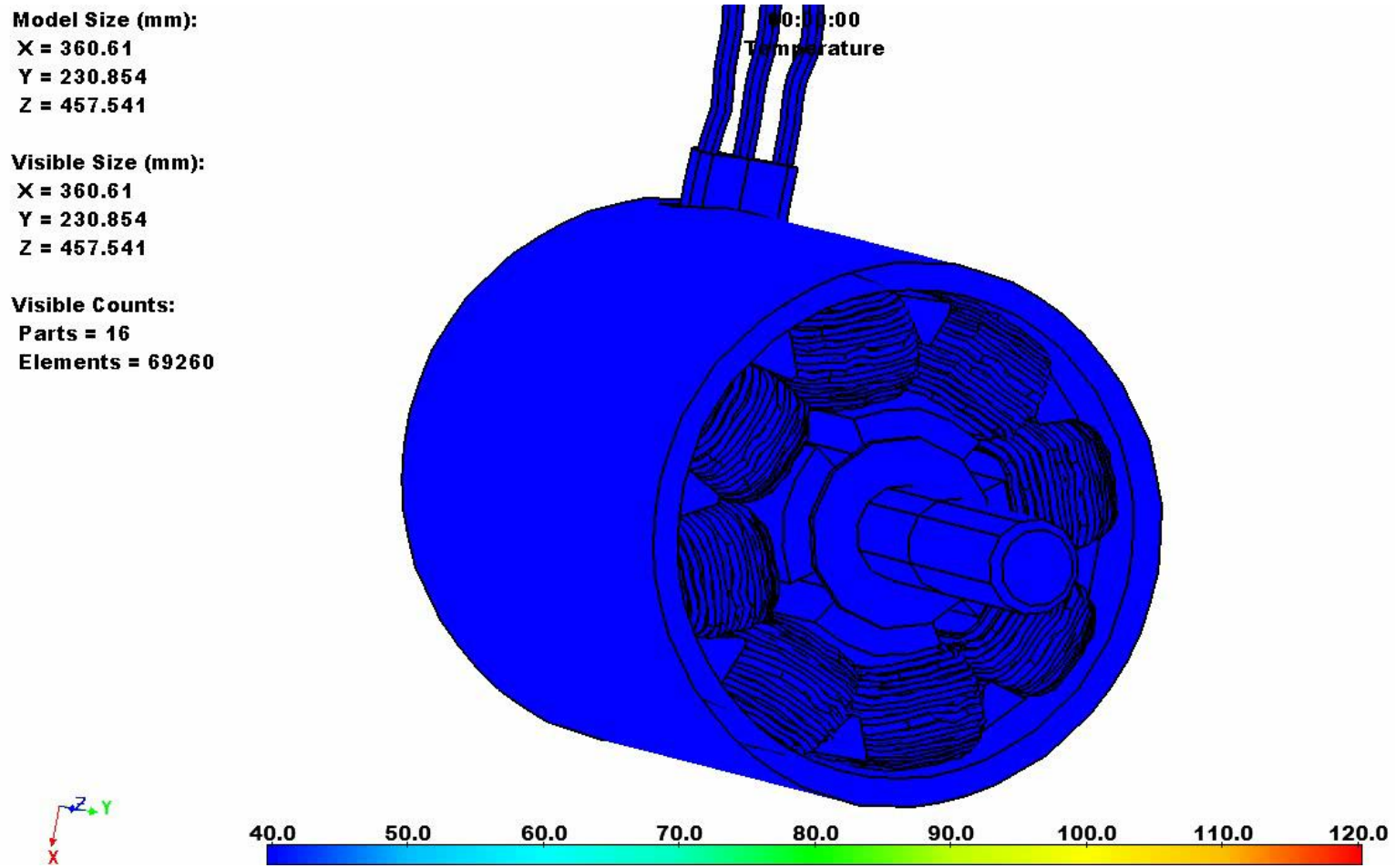
Heat Rates (Interpolated from Maps)



Temperatures



Temperatures: Animation



Advancements in System Integration with 3D Thermal Modeling

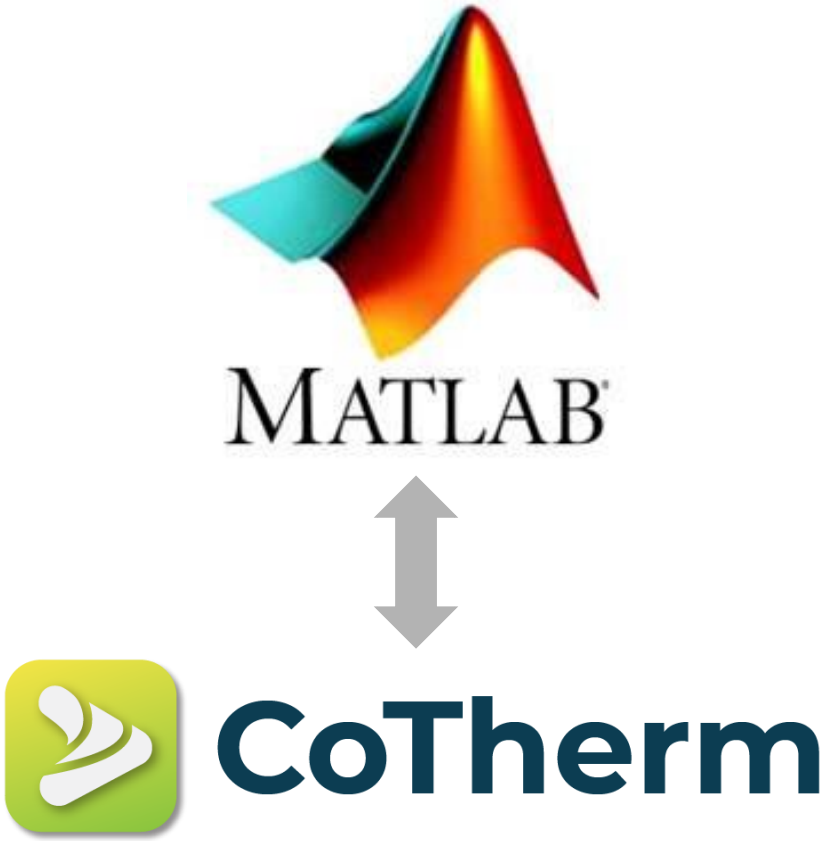
CoTherm – Excel integration

- New Excel Variable specifies sheet and range within Excel (.xlsx) document
  - Range can be read into CoTherm via Variable Update Task
  - Symbols allow accessing value, size, and indexing into range array data
  - Excel range can be written to by using Variable Assignment Task

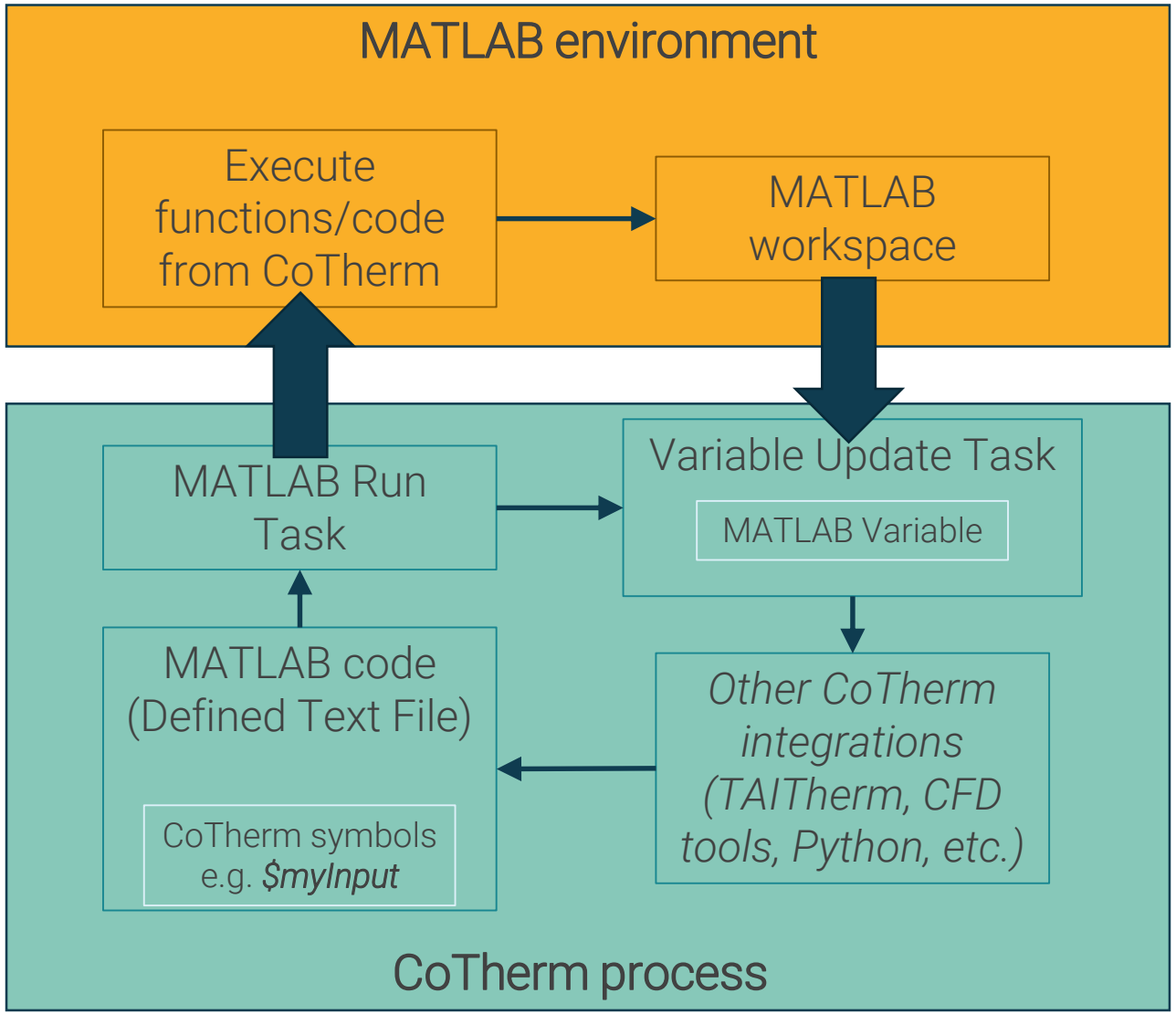
CoTherm

CoTherm – MATLAB integration

- CoTherm 2020.2 includes new MATLAB support
  - Public release available October 2020
- MATLAB is integrated using C++ API
  - Supports MATLAB v2018b through 2020a
    - Support for latest versions will be included with each future release of CoTherm



CoTherm-MATLAB Roundtrip Workflow



Two-way coupling example: cabin HVAC cool-down

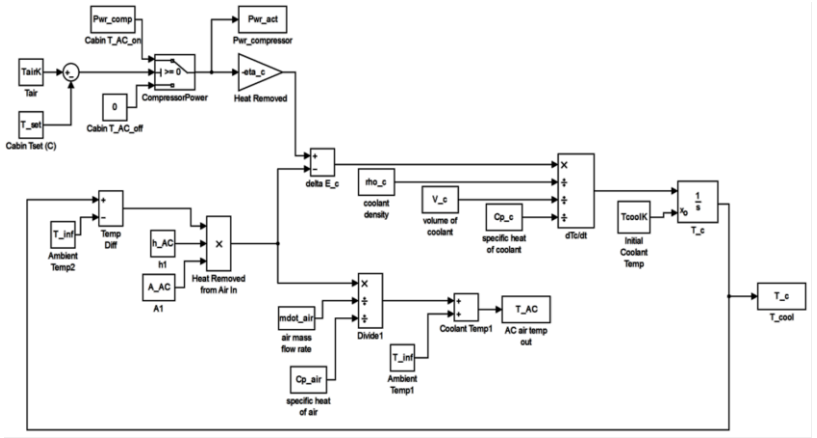
HVAC Heat Rate

Initial Temperatures

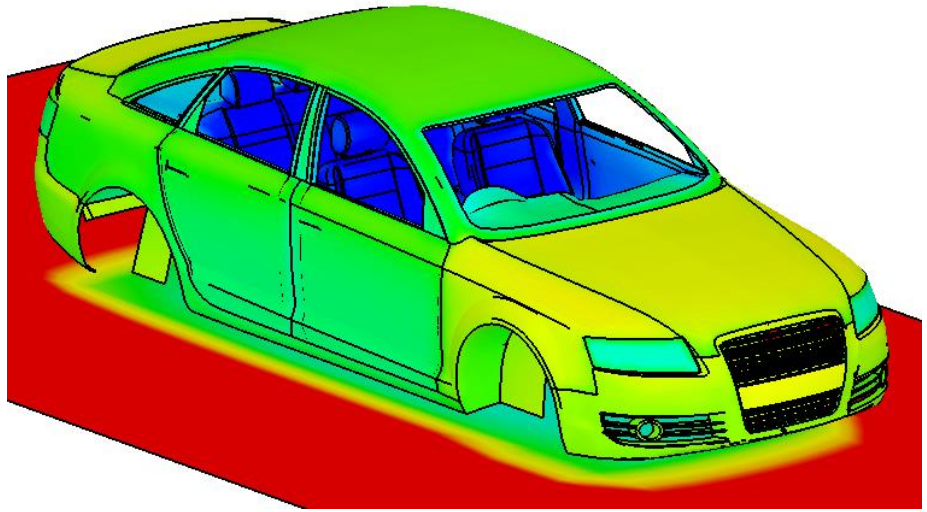
Weather File

Temperature Limits

Heat Rate Limits



MATLAB Thermostat Model



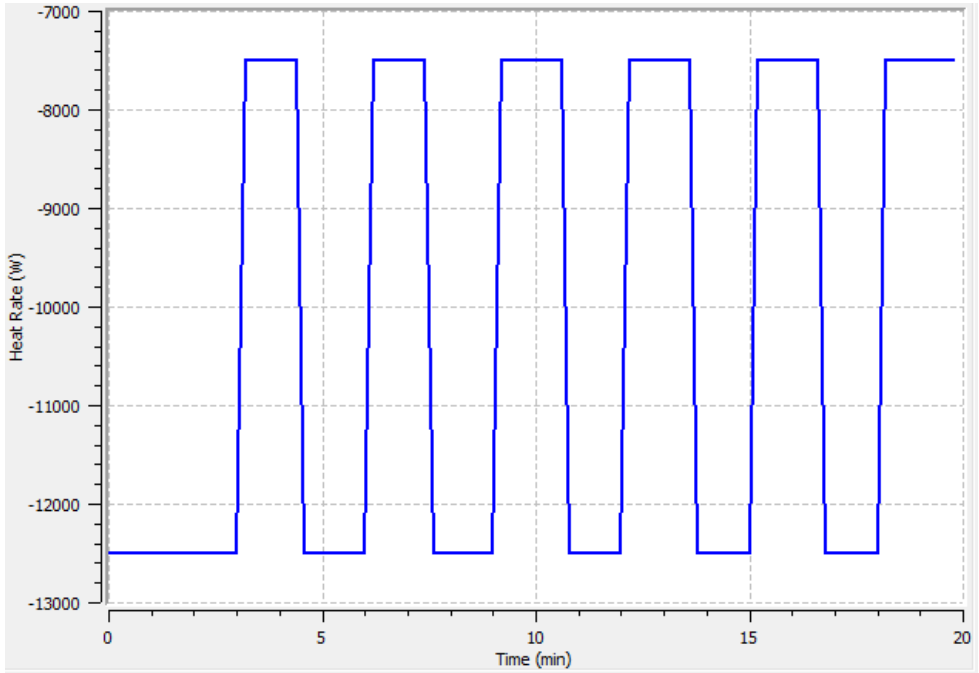
TAITherm Thermal Model

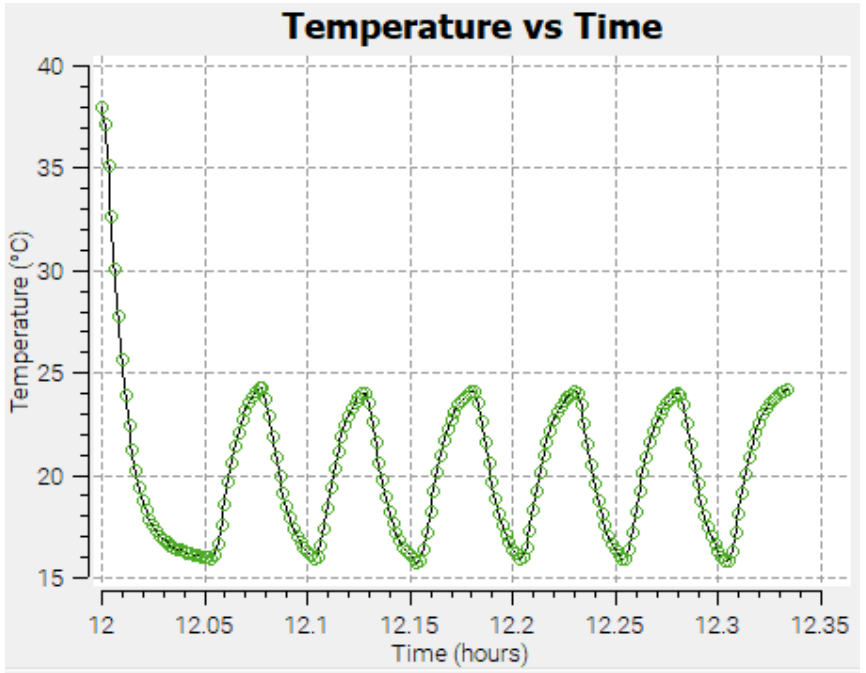
Cabin Air Temperature

- TAITherm and Matlab are coupled using CoTherm
- Matlab models thermostat
- TAITherm models heat transfer from the environment and inside the cabin

Two-way coupling example: cabin HVAC cool-down

- Cabin air temperature is monitored by MATLAB
- MATLAB sets heat rate in TAITherm by appending to the curve
- Cabin air temperature is maintained between 16°C and 24°C

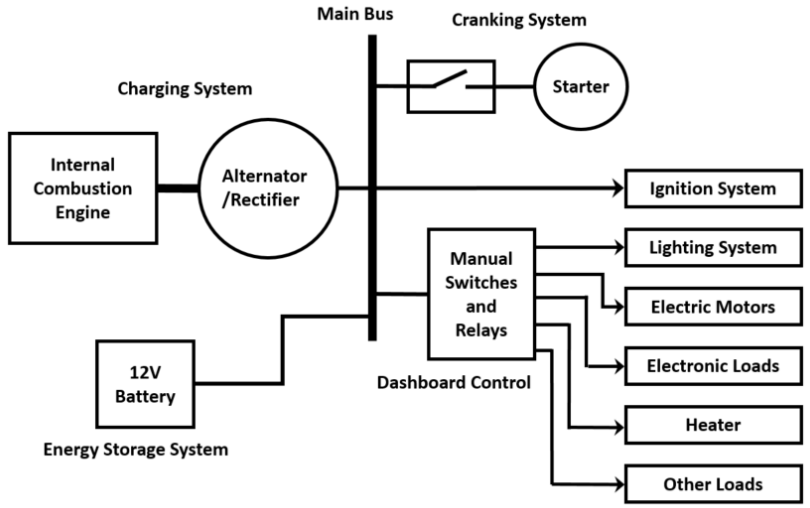


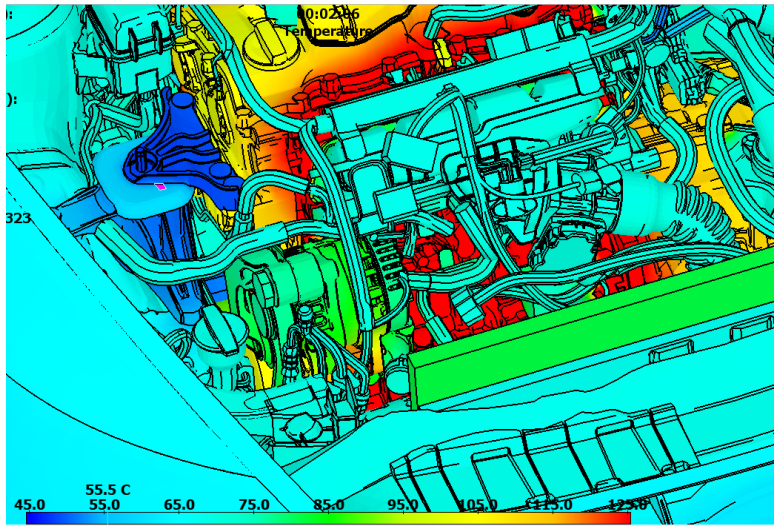


Two-way coupling example: Electro-Network Thermal/Electric Coupling

Alternator Heat Rate
Alternator HTC

Engine Speed →
Load Profile →
Target Voltage →
Initial SOC →





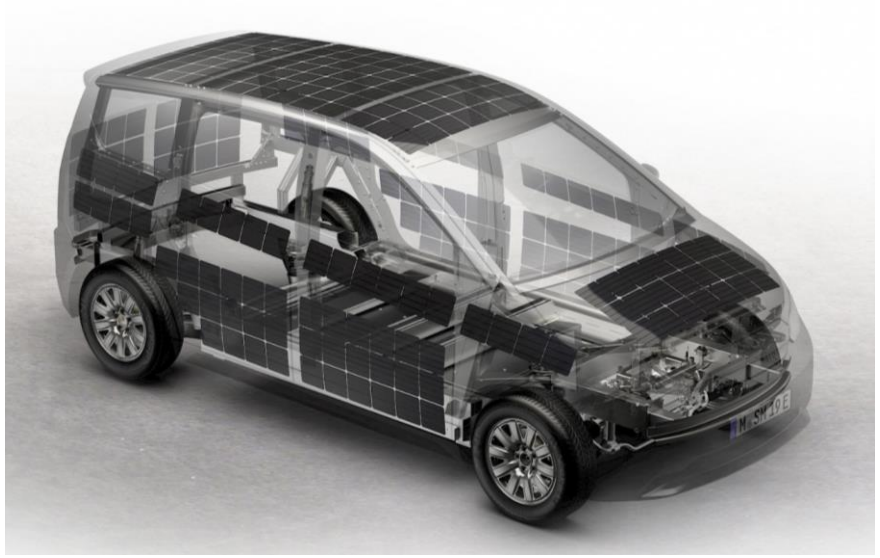
Alternator Temperature
Wire Temperature

- TAITherm and Matlab Simulink are coupled using CoTherm
- Simulink models electric network
- TAITherm models heat transfer under-hood/under-body

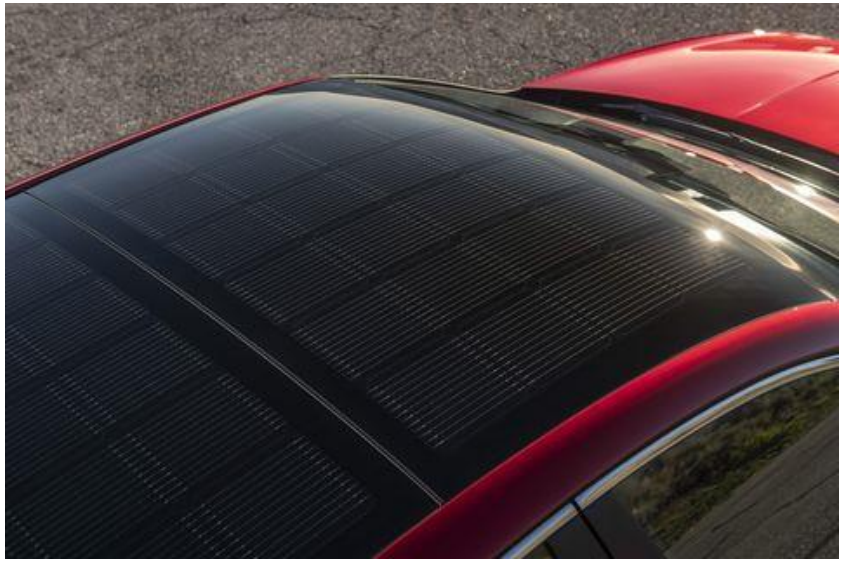
Solar Panel Relationship with Vehicle Electrification

- Vehicle-Integrated Solar Panels (VISPs)
  - Extend the range of EVs
  - Power an auxiliary battery for secondary electronics systems in both ICE vehicles and EVs

Hyundai (2018). Translucent solar roof engineering.



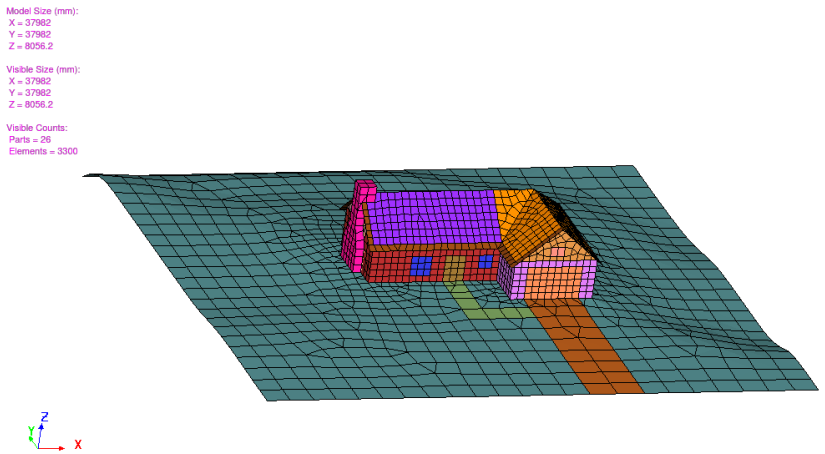
Sono Motors. Up to 34 km/day. Expected 2022. €25,500

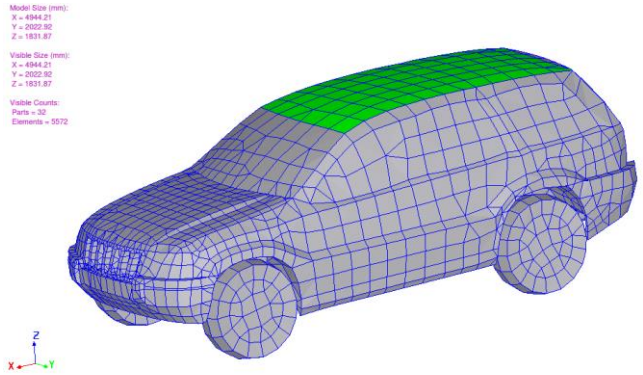


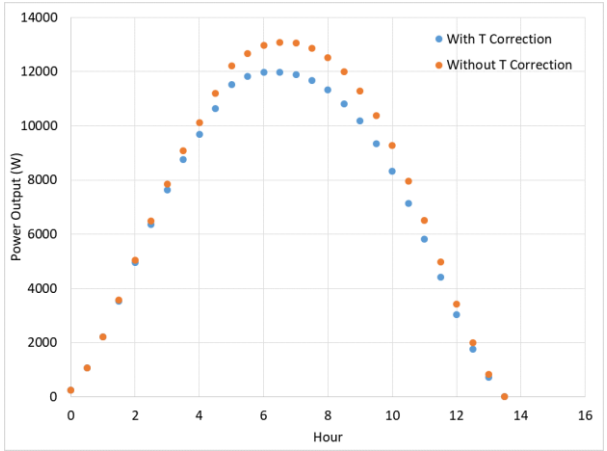
2020 Hyundai Sonata Hybrid (available). 2 miles/day, so probably best for topping off auxiliary 12V battery.

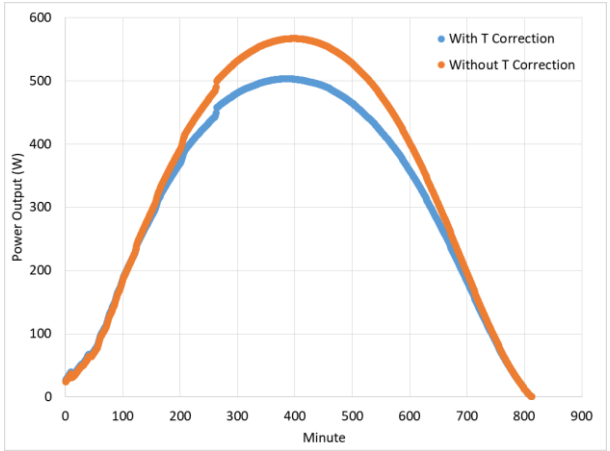
Example Thermal-Electrical PV Models

- Example models (solar roofs) demonstrate the importance of correcting for temperature when predicting PV power output
- In “Without T” correction case, ran the electrical model at 25C.
- In “With T correction” case, ran electrical model at the part temperature.









Conclusions

- Thermal management in vehicle components is becoming increasingly important as companies electrify their fleets
- HVAC design strongly influences xEV range
- Human comfort prediction is required to evaluate HVAC strategies, which must evolve to meet requirements
- New component modeling strategies have been demonstrated for xEV thermal management
- 3D thermal system integration allows full vehicle modeling
- TAI is undertaking a major initiative to meet customer requirements as xEV manufacturing is taking off

Thank you

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