1D thermal simulation of electric vehicle - Virtual operating strategy development for transient drive cycles

Poehl
MAGNA

3D CFD Simulation and/or 1D Simulation?

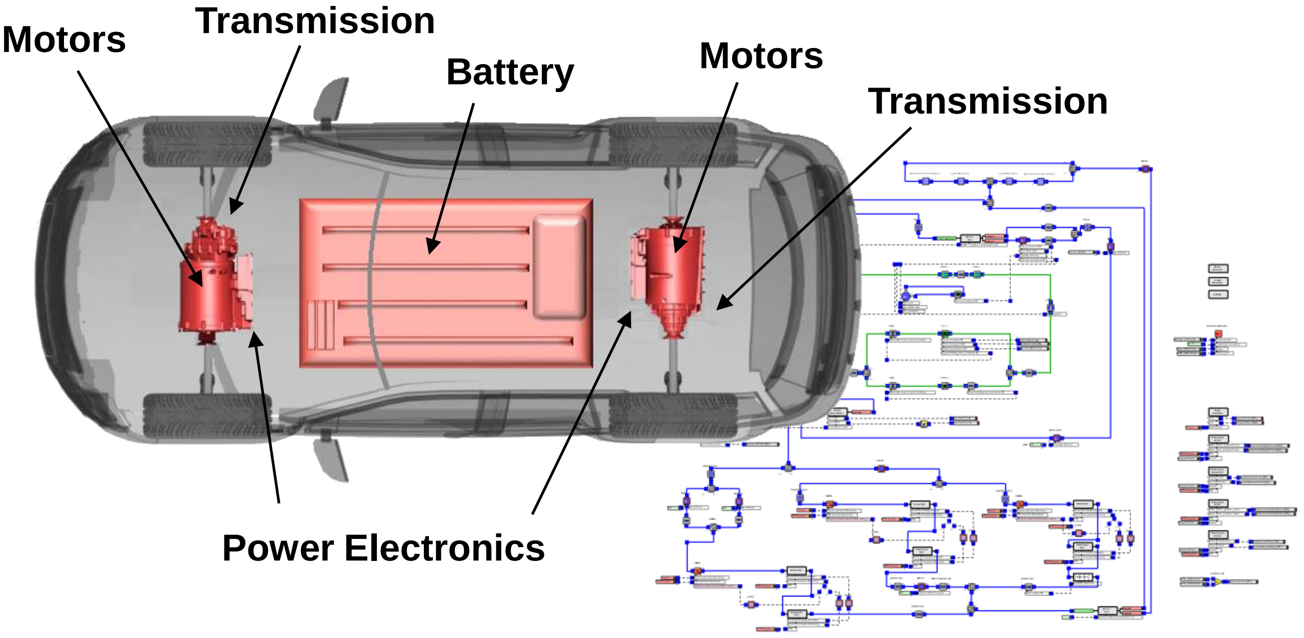
- Reasons for 3D CFD Simulation…
  - High level of detail
  - High fidelity of results
  - Can handle complex geometries
  - Established workflows and the theory
- Reasons for 1D simulation…
  - Very fast
  - Little modelling effort
  - No CAD geometry required
  - Can work with few data

→ Simulating electric vehicles often requires “the best of both worlds”

- Transient simulation of drive cycles for
- Complete cooling systems with
- Cell level battery pack simulation models and
- Detailed temperature results for e-motor components

Agenda Overview…

Thermal Management Simulation of…

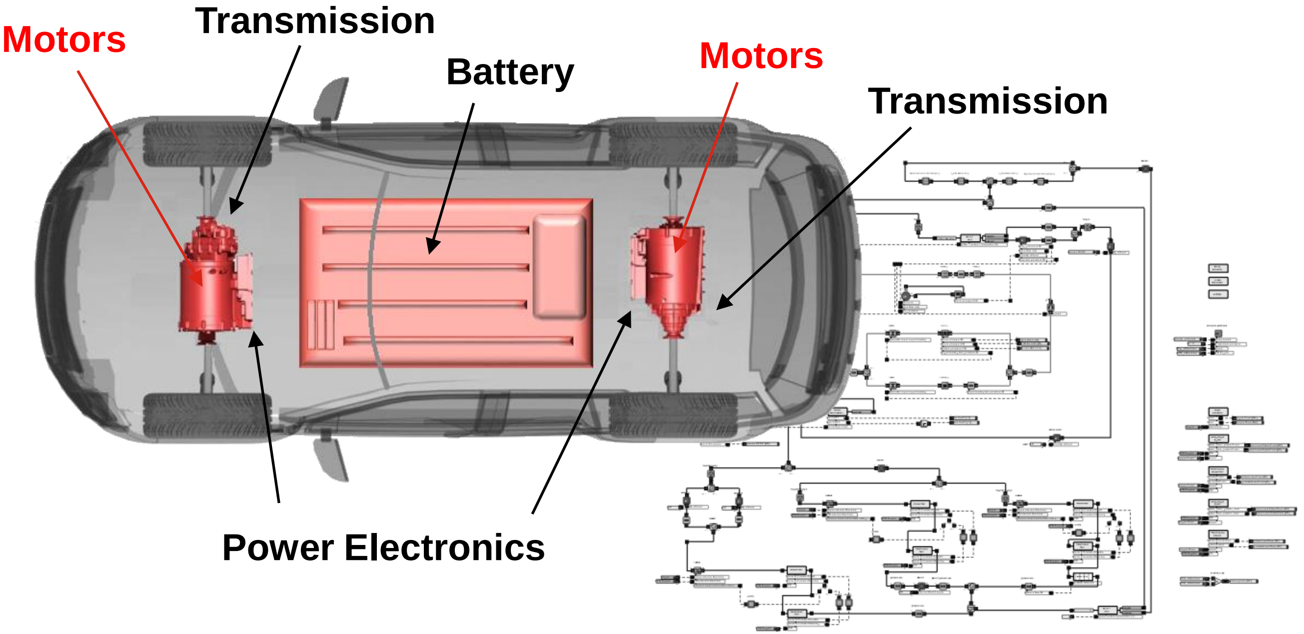


… and of the complete vehicle model.

- Motor/Inverter
  - E1 Motors
- Battery
  - Air Cooled i-MiEV
  - Coolant Cooled Tesla S
  - Handling of big amount of cells
- Vehicle Model
  - E1 Democar

Agenda
Battery Simulation

Thermal Management Simulation of…



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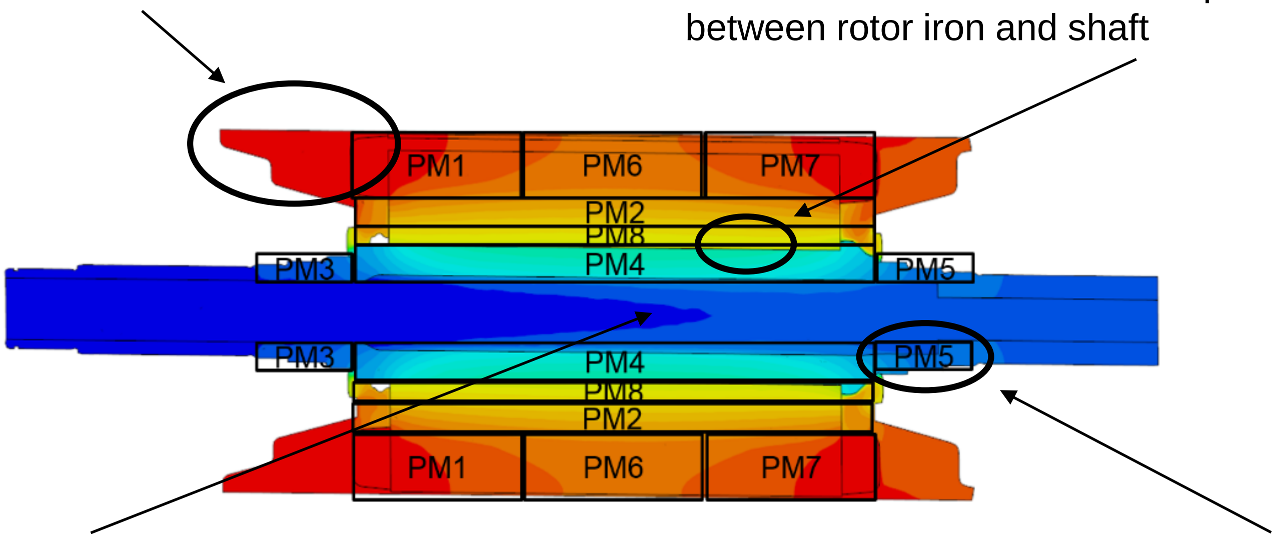
3D Simulation Results of an E-Motor Rotor…
… and 1D discretization

Temperature peaks at rotor end windings

Problematic heat transfer / steep temperature gradient between rotor iron and shaft

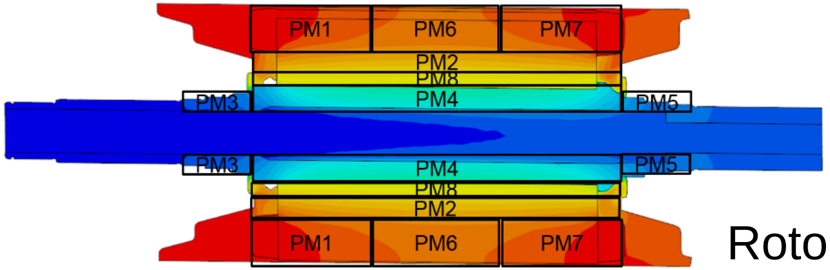


Coolant warmup in shaft

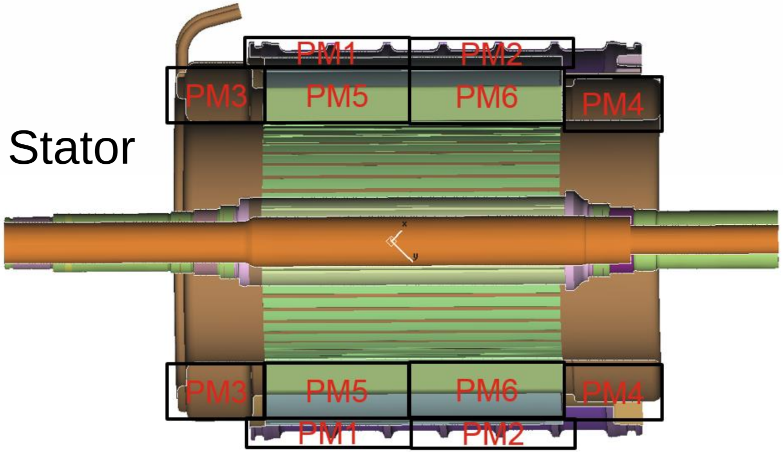
Losses in bearings (RPM dependent)

These details need to be available in the 1D simulation model as well!
(other details can be neglected)

Rotor and Stator Discretization



Rotor



Stator

Discretization Rotor:

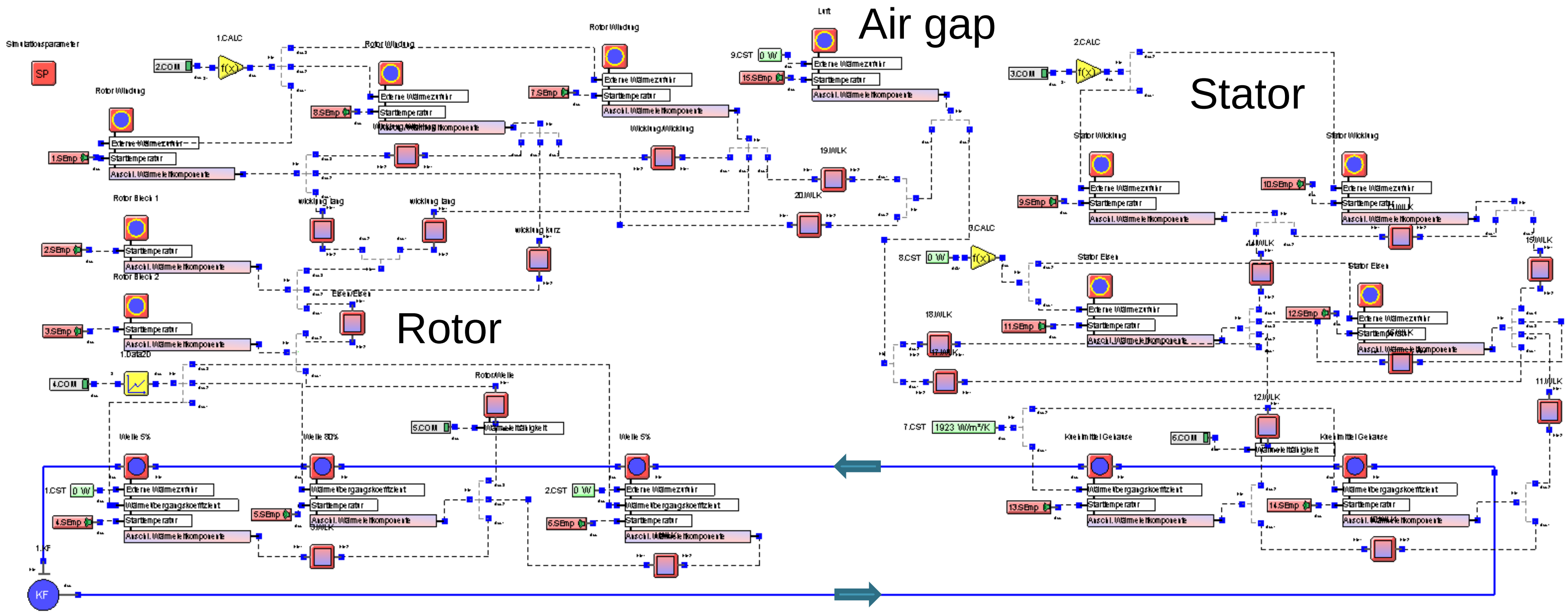
PM1, 6, 7: rotor winding; PM2, 8: rotor iron sheet; PM3, 4, 5: shaft

Discretization Stator:

PM1, 2: cooling jacket; PM3, 4: stator winding; PM5, 6: stator iron sheet

Discretization of one component into several point masses → temperature distribution

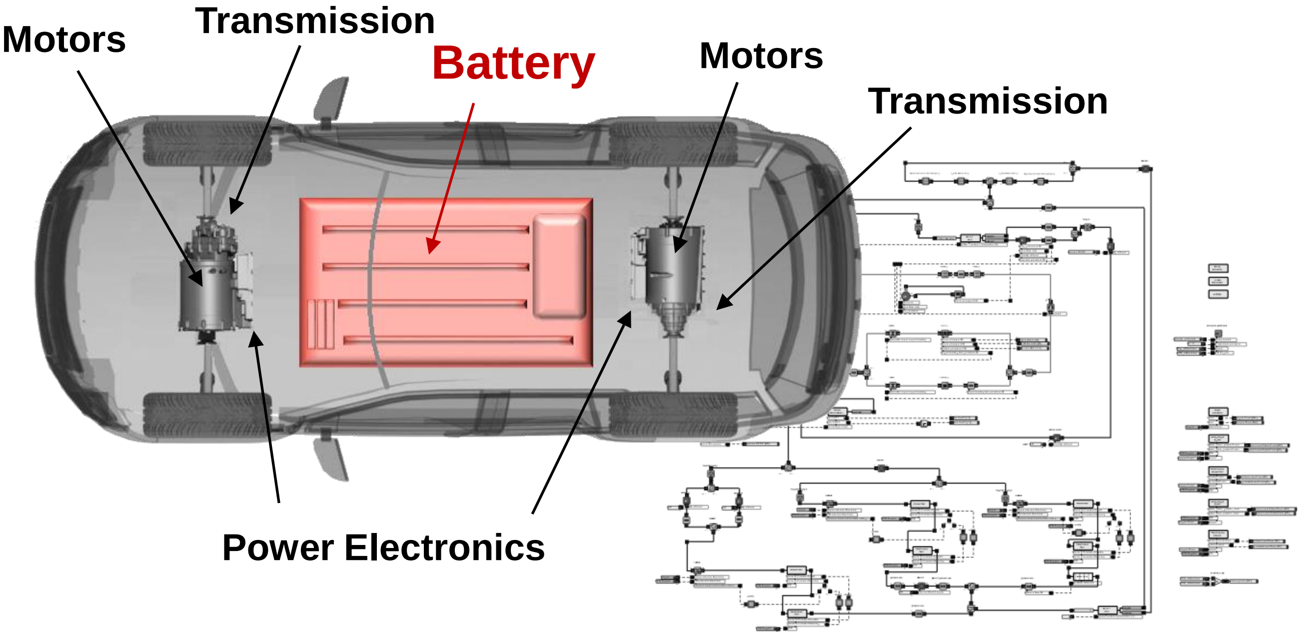
1D Thermal Network for an Electric Motor



Calibration for steady state operating points and load steps based on CFD results…

Agenda
Battery Simulation

Thermal Management Simulation of…



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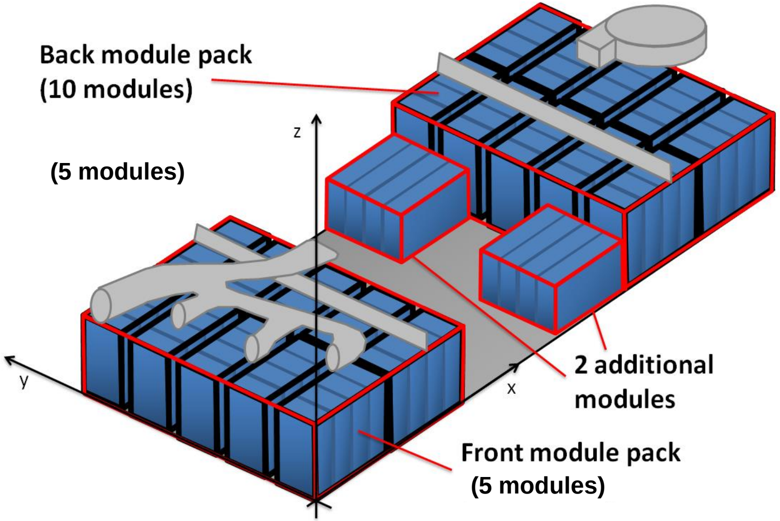
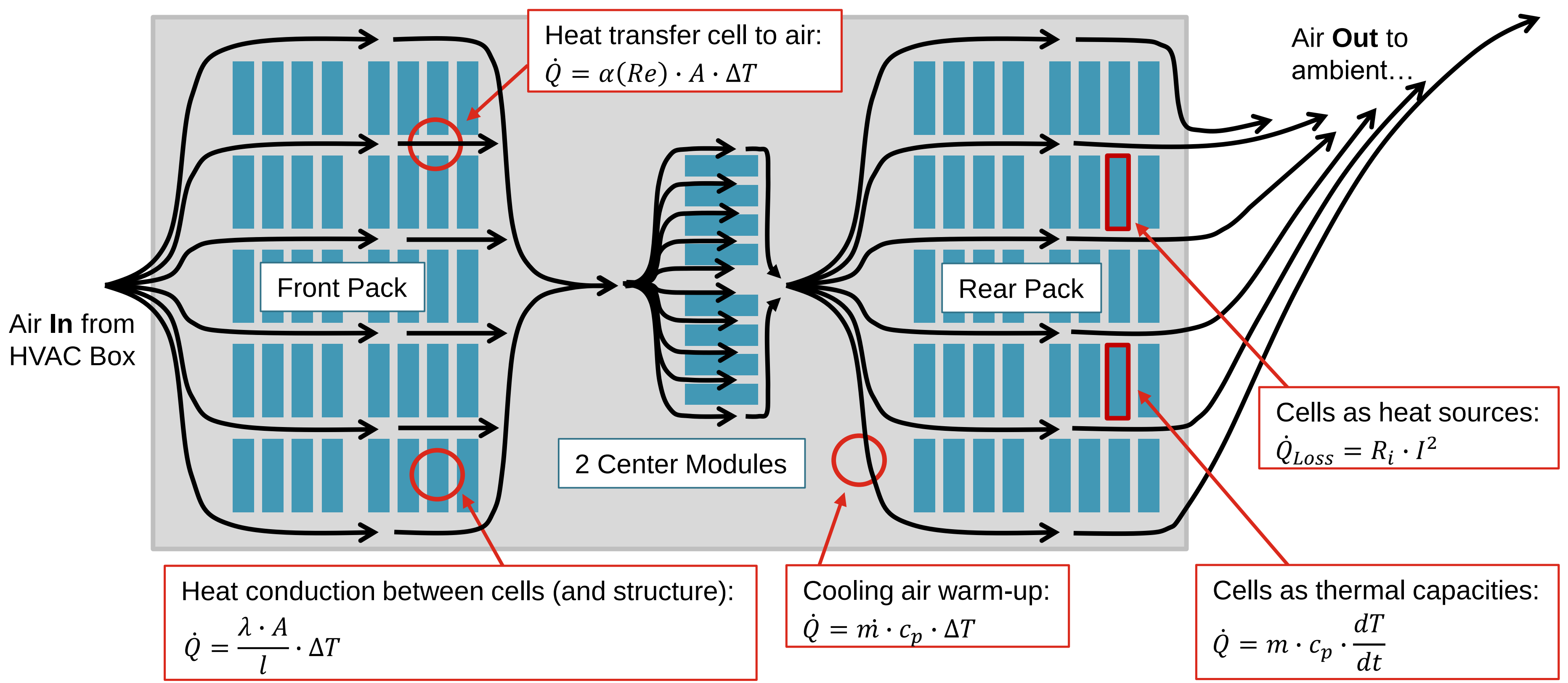
1) Mitsubishi i-MiEV Battery Pack



- Air cooled battery
- 88 LiIon battery cells
  - Cell type: Yuasa-Mitsubishi LEV 50
  - Cell capacity: 50Ah
  - Nominal voltage: 3.7V
  - Cell weight: 1.7kg

- 22 modules á 4 cells
- All cells electrically in series yields pack voltage 325.6V

Mitsubishi i-MiEV
Battery Pack Schematics and Main Physical Effects



Mitsubishi i-MiEV
Battery Pack Simulation Model

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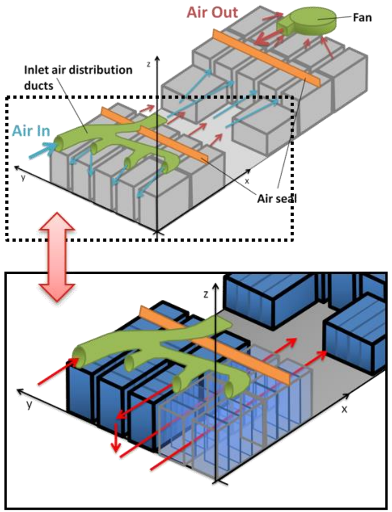
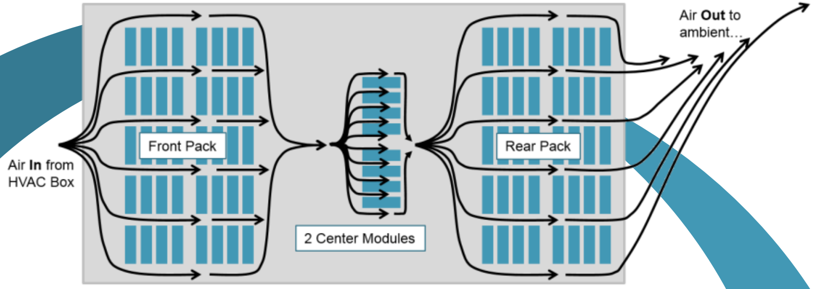
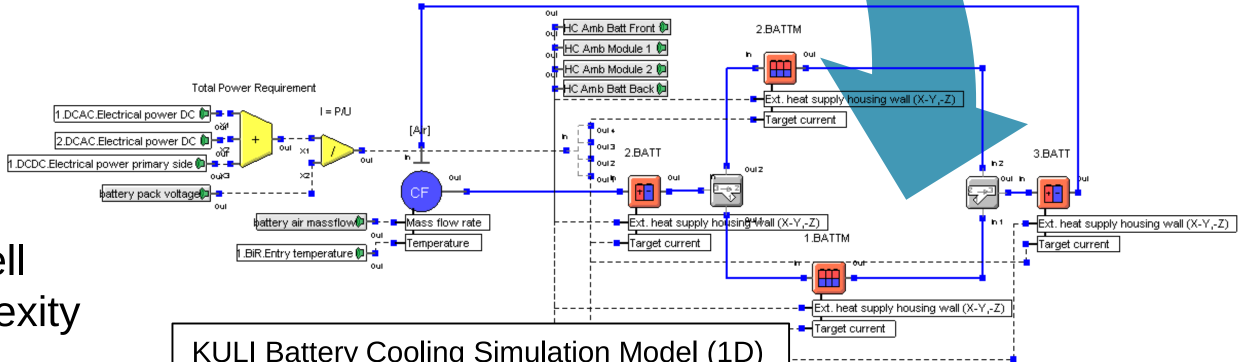


Battery Layout (3D)



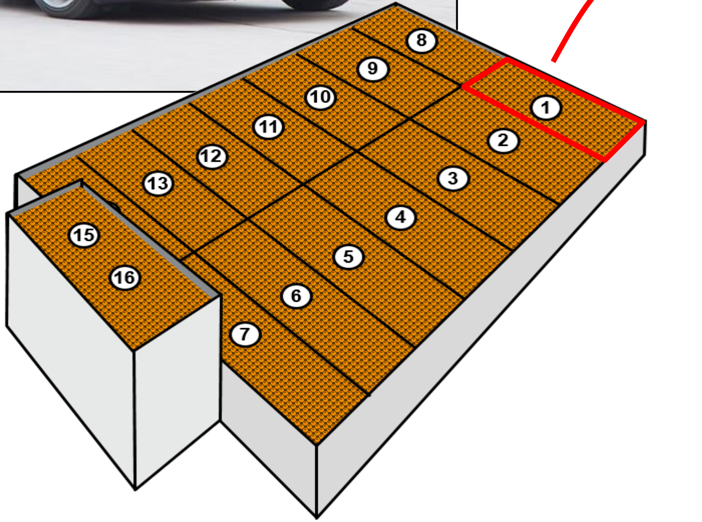
Battery Schematics

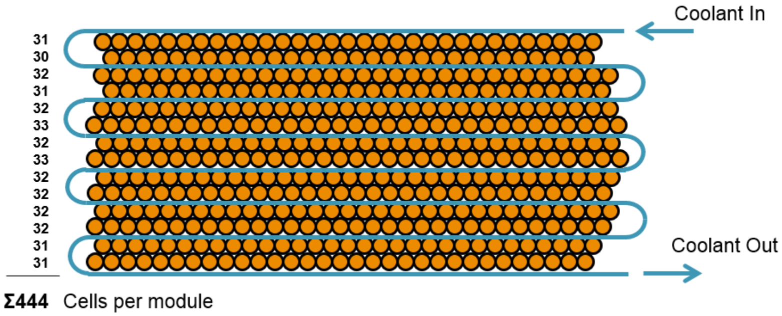


KULI Battery Cooling Simulation Model (1D)

Simulation model supports cell level details, but hides complexity behind easy to use interface…

2) Magna E1 Battery Pack (Tesla 85kWh)



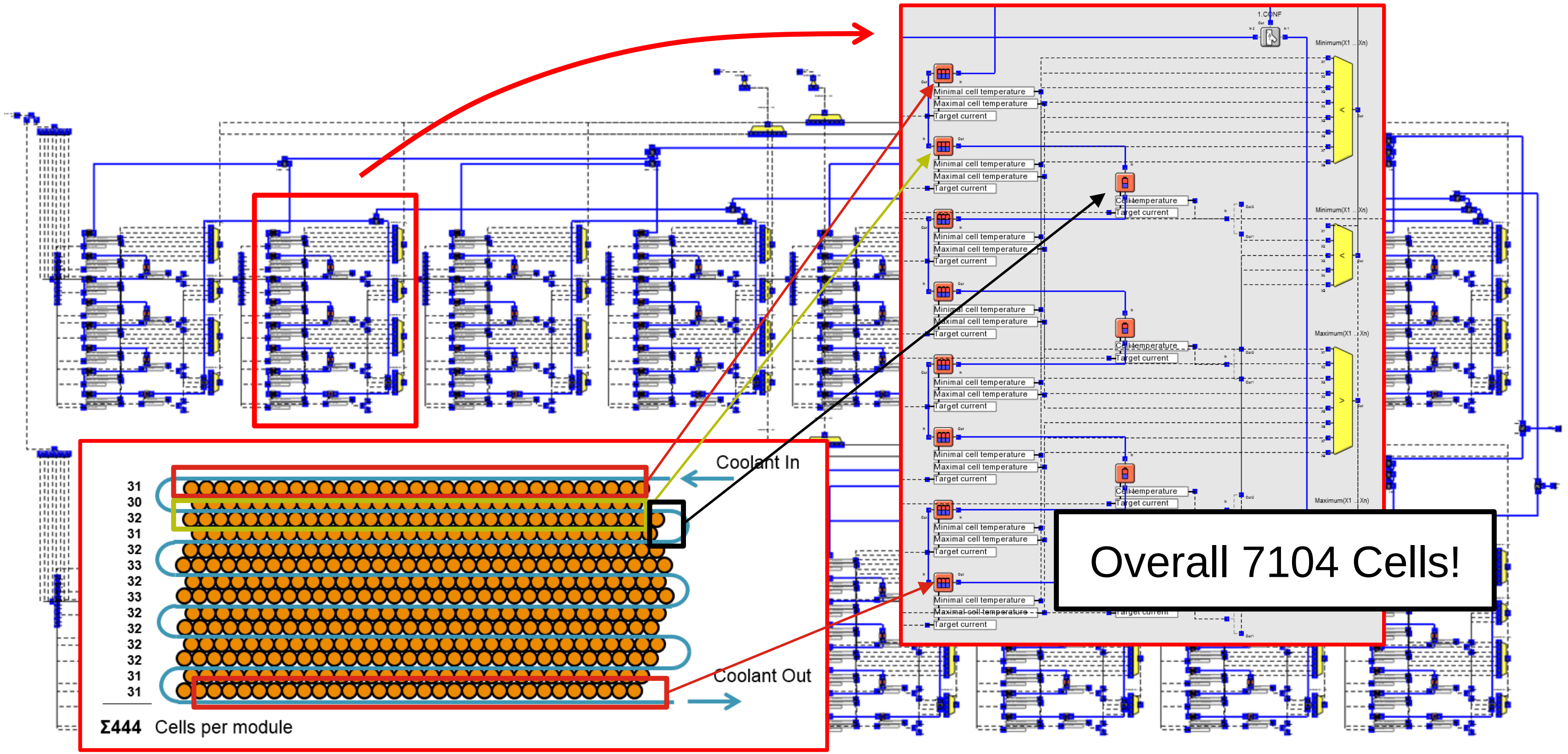


16 modules á 444 cells (Panasonic 18650)
→ 7104 cells

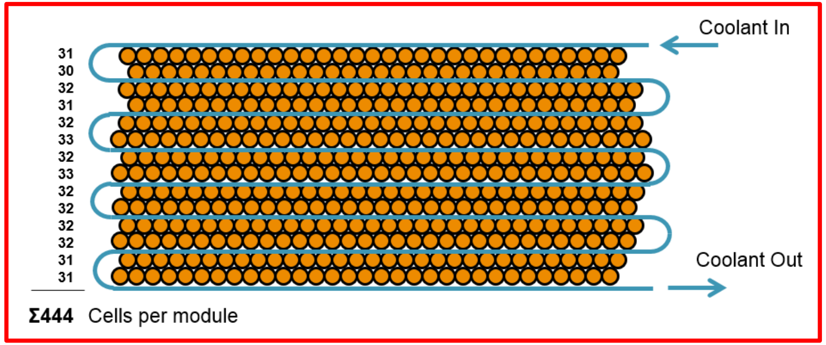
Module has 6s74p layout
→ module voltage ~25.2V
All modules electrically in series
→ pack voltage ~403.2V

Coolant flow through modules in parallel…

Magna E1
Battery Pack Simulation Model

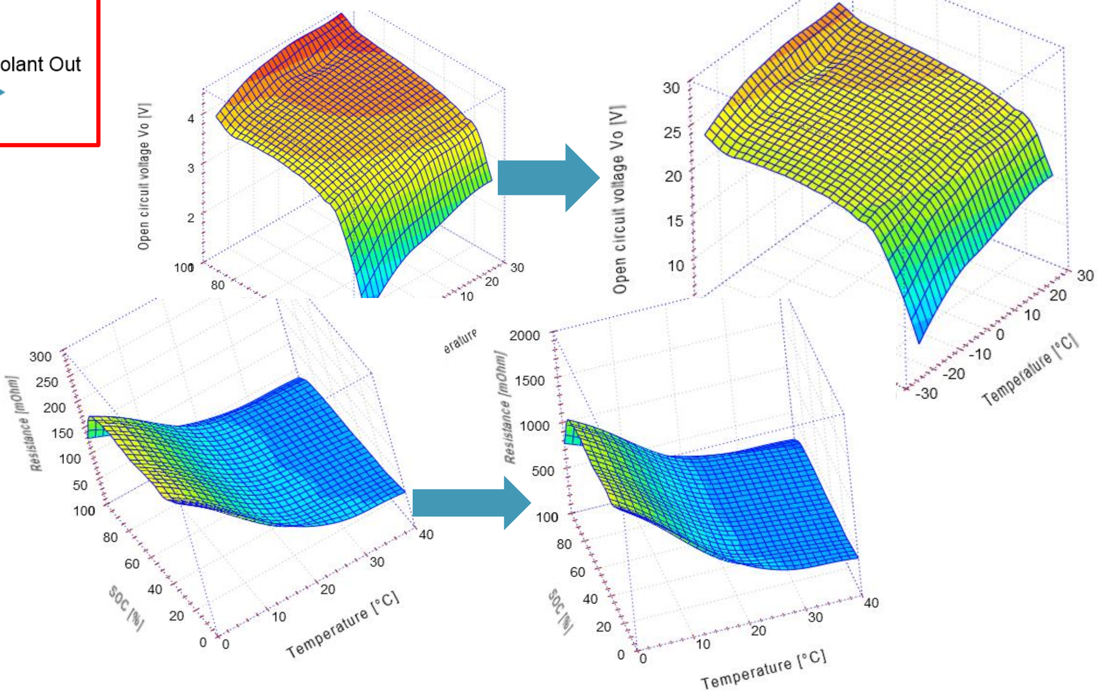


Reduce Amount of Cells



Module has 6s74p layout
→ module voltage ~25.2V

6 cells in series are summarized to one cell
→ $V_{0,Cell}$ from 4.2V to 25.2V

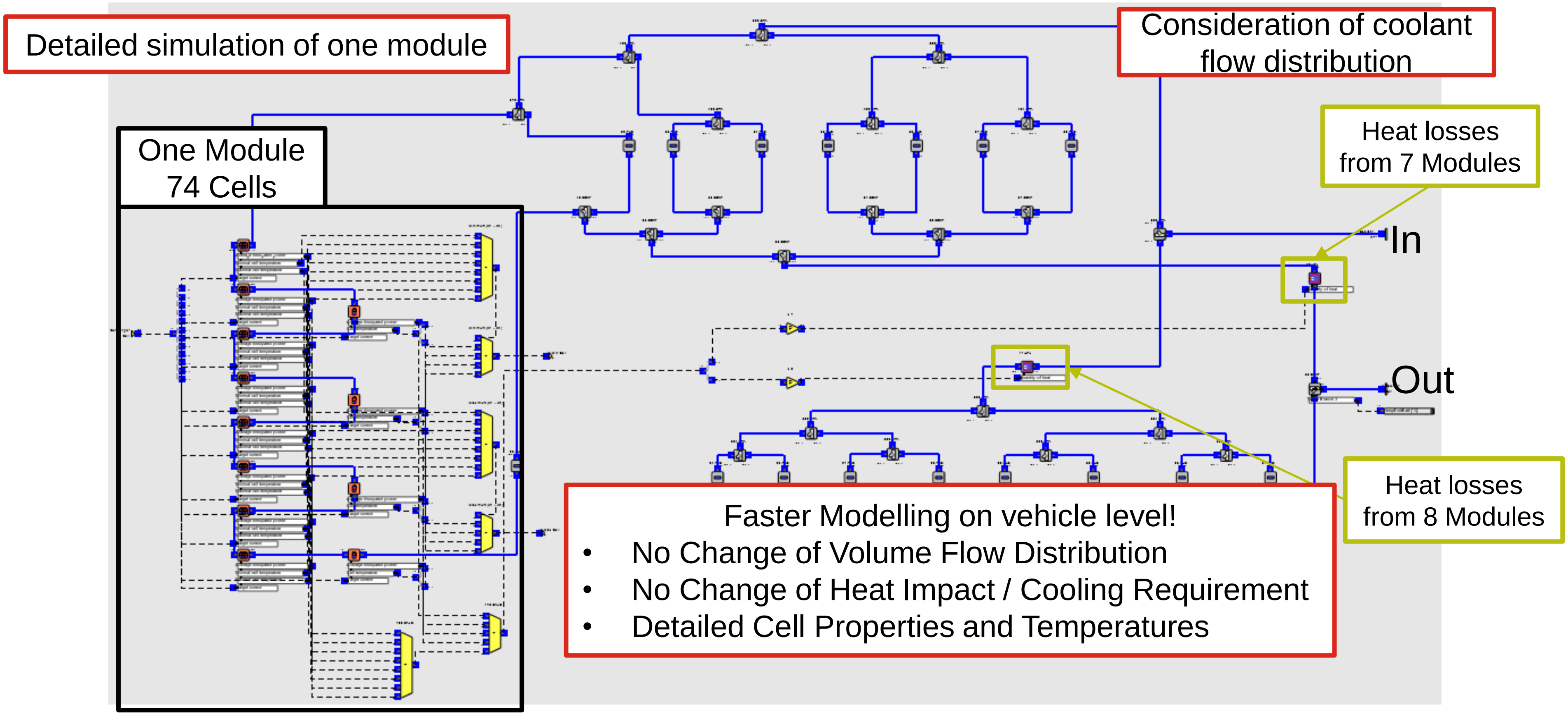


6 cells in series are summarized to one cell
→ $R_{i,Cell} * 6$

7104/6 = 1184 Cells left!

Simplification of Battery Pack

For Faster Vehicle Model Simulation with Detailed Cell Properties

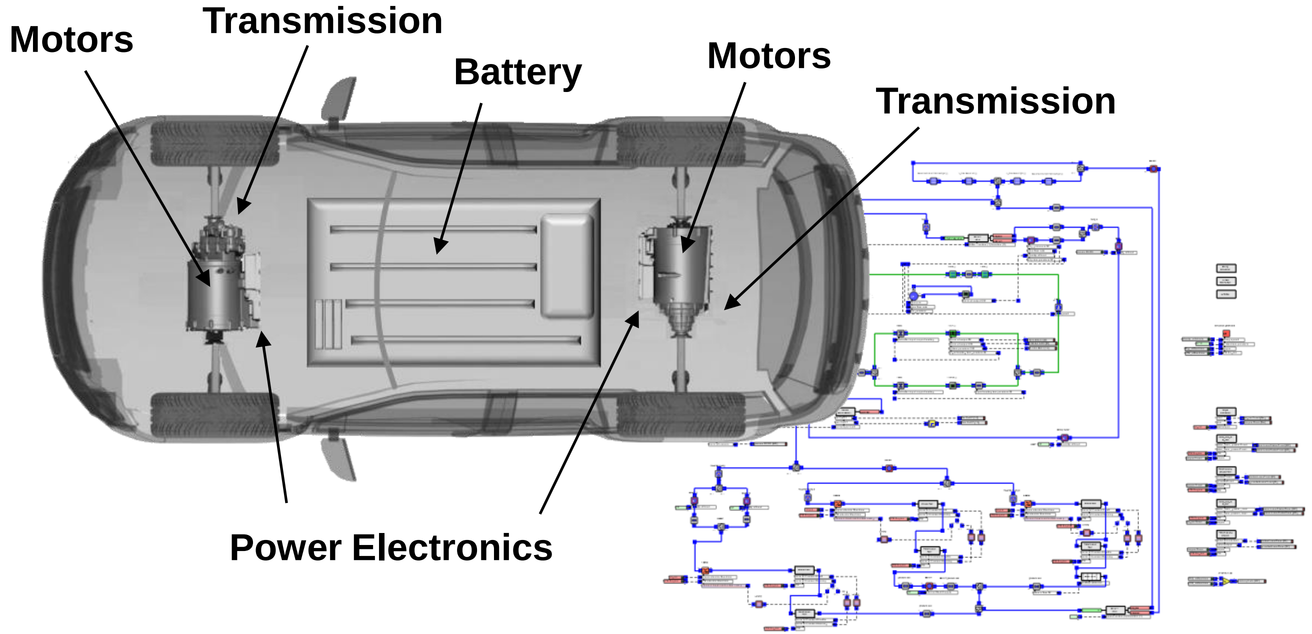


Faster Modelling on vehicle level!

- No Change of Volume Flow Distribution
- No Change of Heat Impact / Cooling Requirement
- Detailed Cell Properties and Temperatures

Agenda
Complete Vehicle Simulation

Thermal Management Simulation of…



… and of the **complete vehicle model**.

- **Motor/Inverter**
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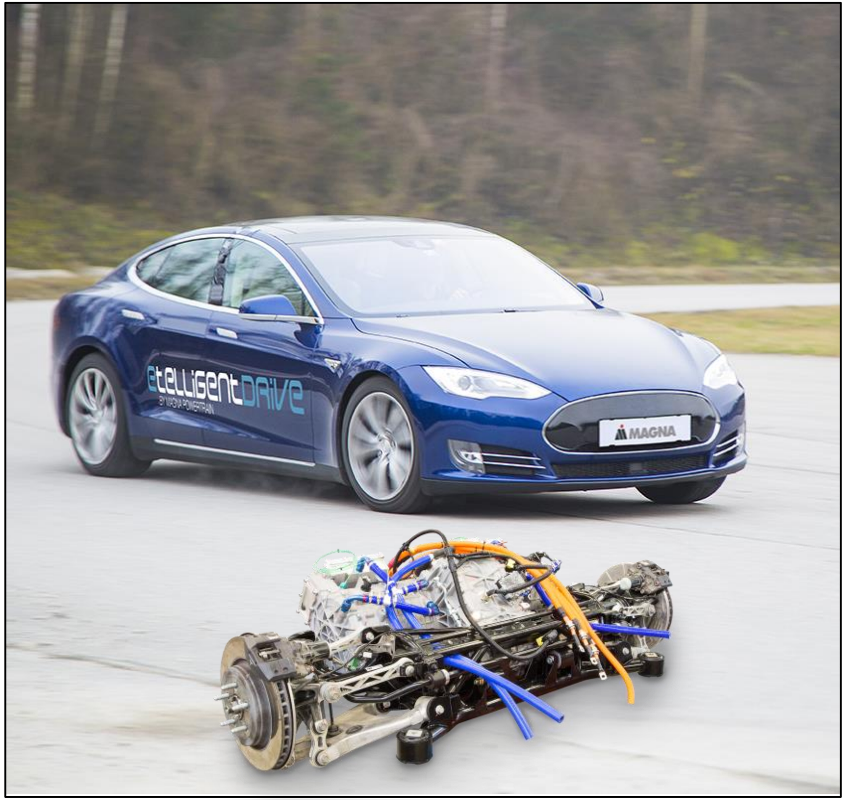
- **Vehicle Model**
  - E1 Democar

Magna Powertrain Electric Vehicle Demonstrator



Objectives:

- Demonstrate eDrive product capabilities
- Proof system and vehicle Integration capabilities
- Vehicle controls: improved stability and handling
- Electronic Torque Vectoring (eTV)

Technical Data:

Front Axle: Highly Integrated eDrive System, with ASM

Peak power	140kW (for 60s)
Peak Torque	3300Nm (10s)
Inverter (integrated)	$500A_{rms}$

Rear Axle: Highly Integrated eDrive System, 2 x ASM with summation gearbox, with axle lock clutch (eTV)

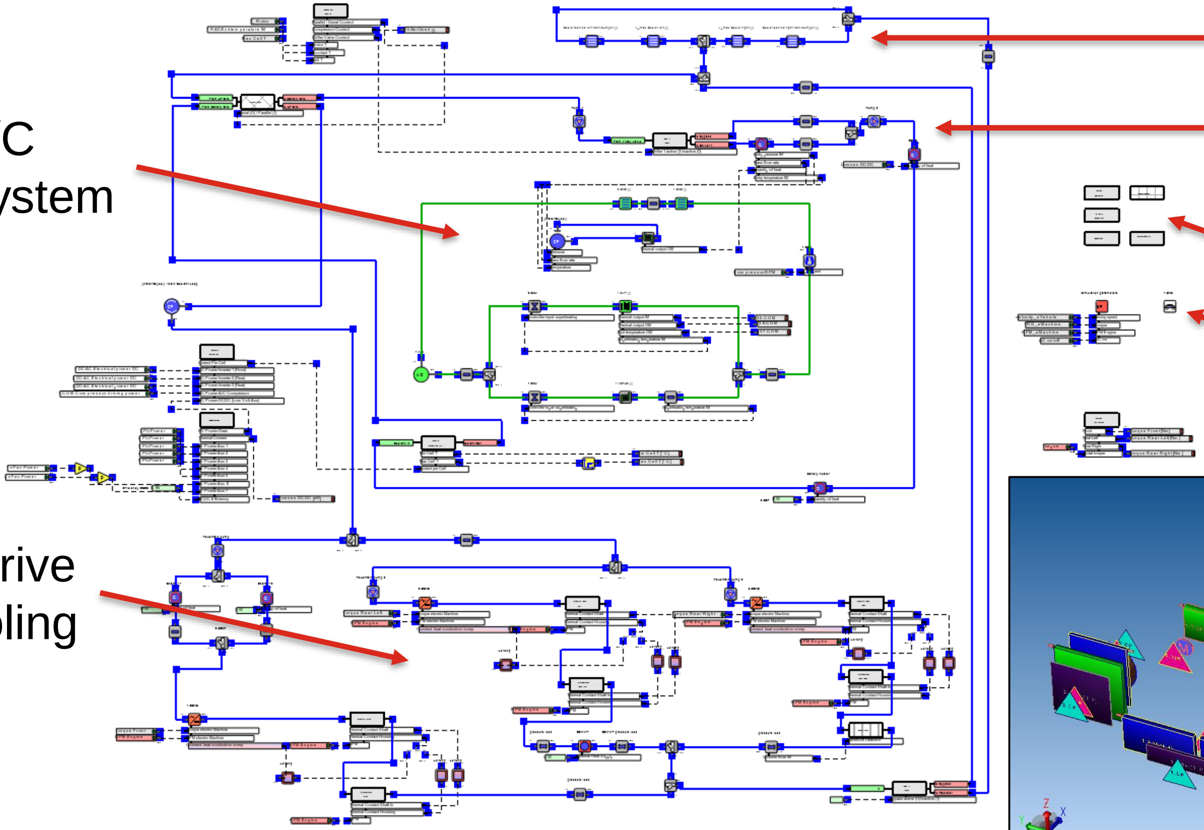
Peak power	280kW (for 20s)
Peak Torque	6600Nm (10s)
Inverter (integrated)	$2x\ 500A_{rms}$

Both drives:
Liquid cooled Inverter, e-Motor stator and rotor
Enhanced thermal management
Rare Earth free

Tesla S / Magna E1 Simulation Model Overview

A/C System

E-Drive Cooling

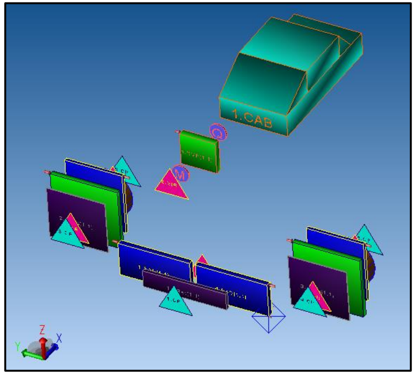


Cooling Pack

Battery Cooling

Driving Sim Thermal Control

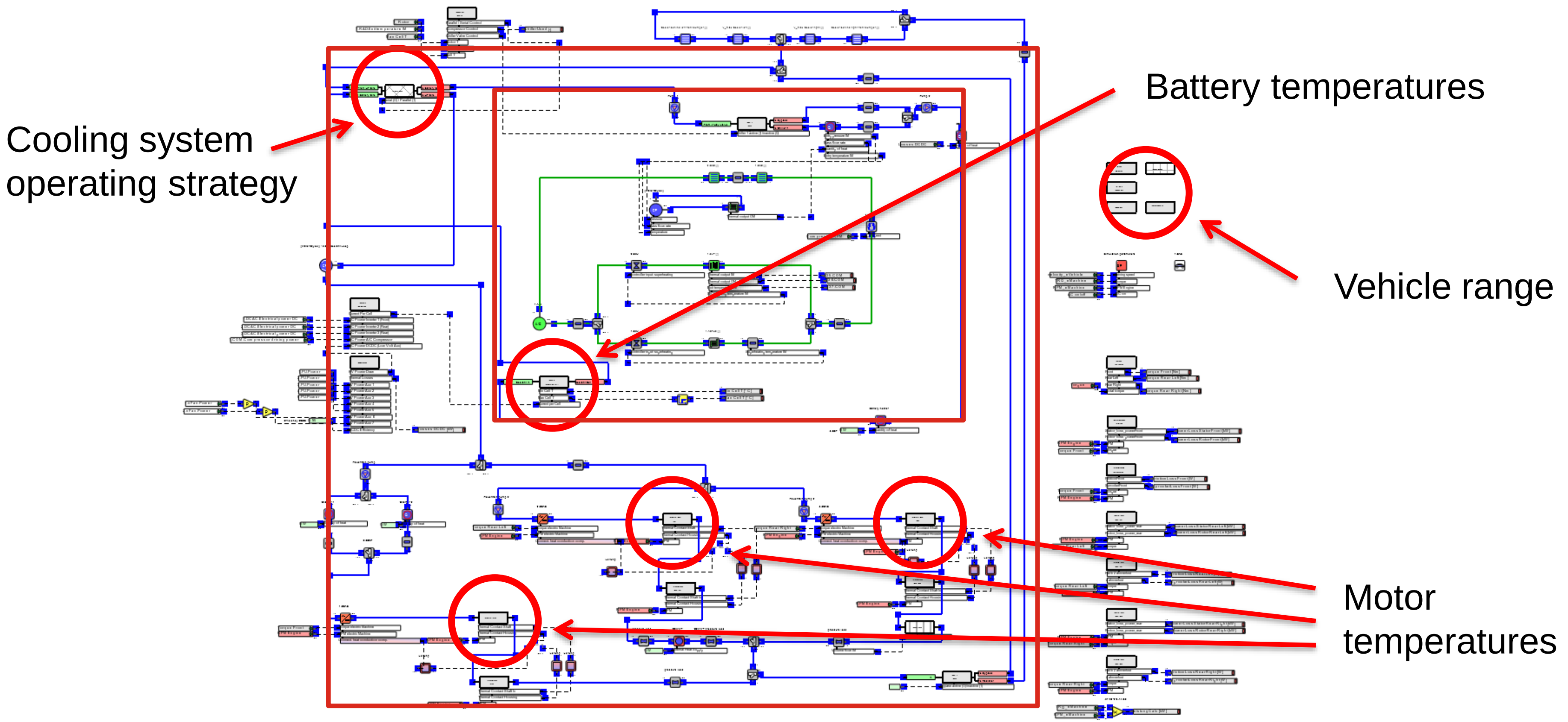
Cabin Model



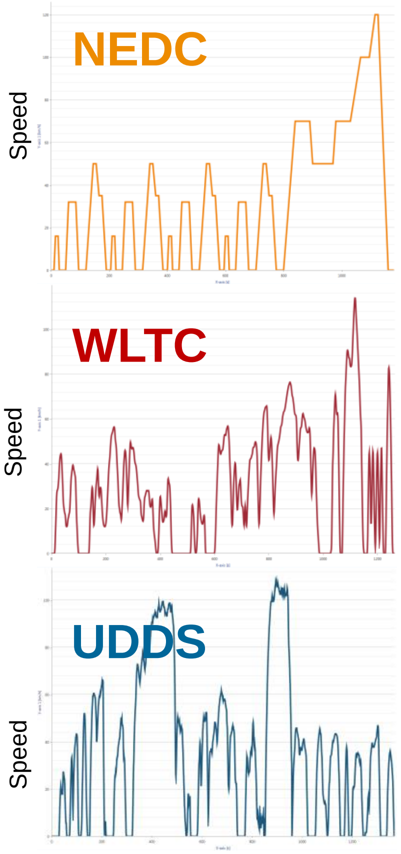
3D/1D Component Models in this Vehicle Model

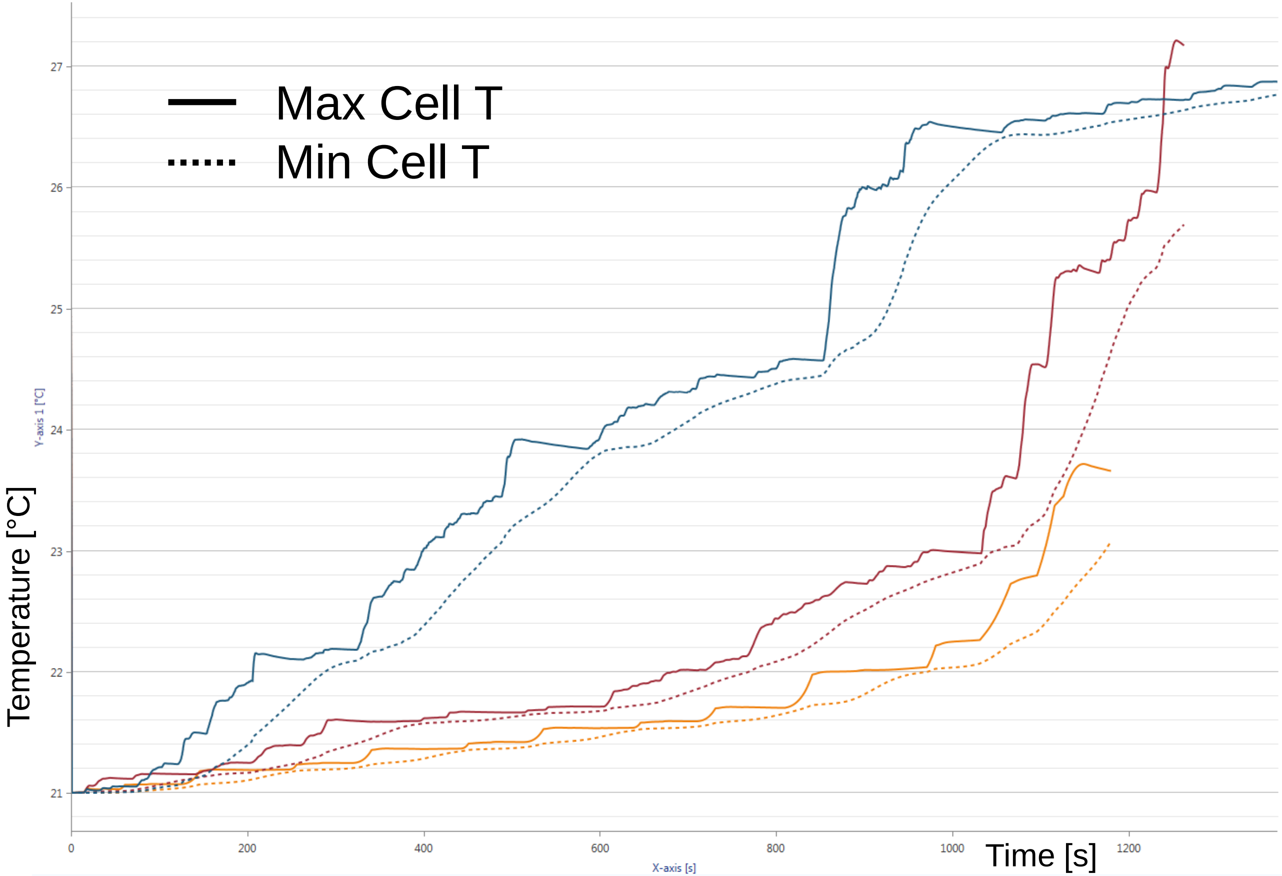
- **Electric Motors**: Modeled as 1D thermal networks calibrated with 3D CFD results and validated with measurements
- **Transmission Systems**: same approach as motors
- **Battery**: 1D simulation model, currently partially calibrated, final model will be calibrated based on test data
- **Underhood air flow**: Flow distribution calibrated to fit test data. Calibration based on CFD is possible but was not used in this project
- **Cabin**: Partially calibrated based on test data. Complete calibration would require CFD simulation… not done yet!

Focus Points for the Simulation

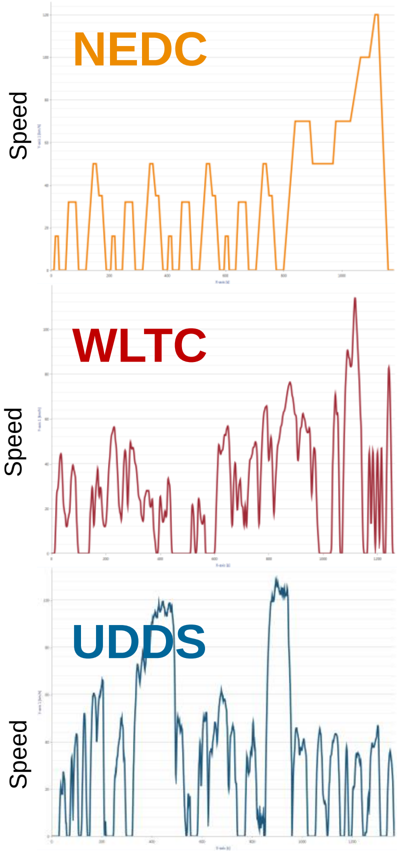


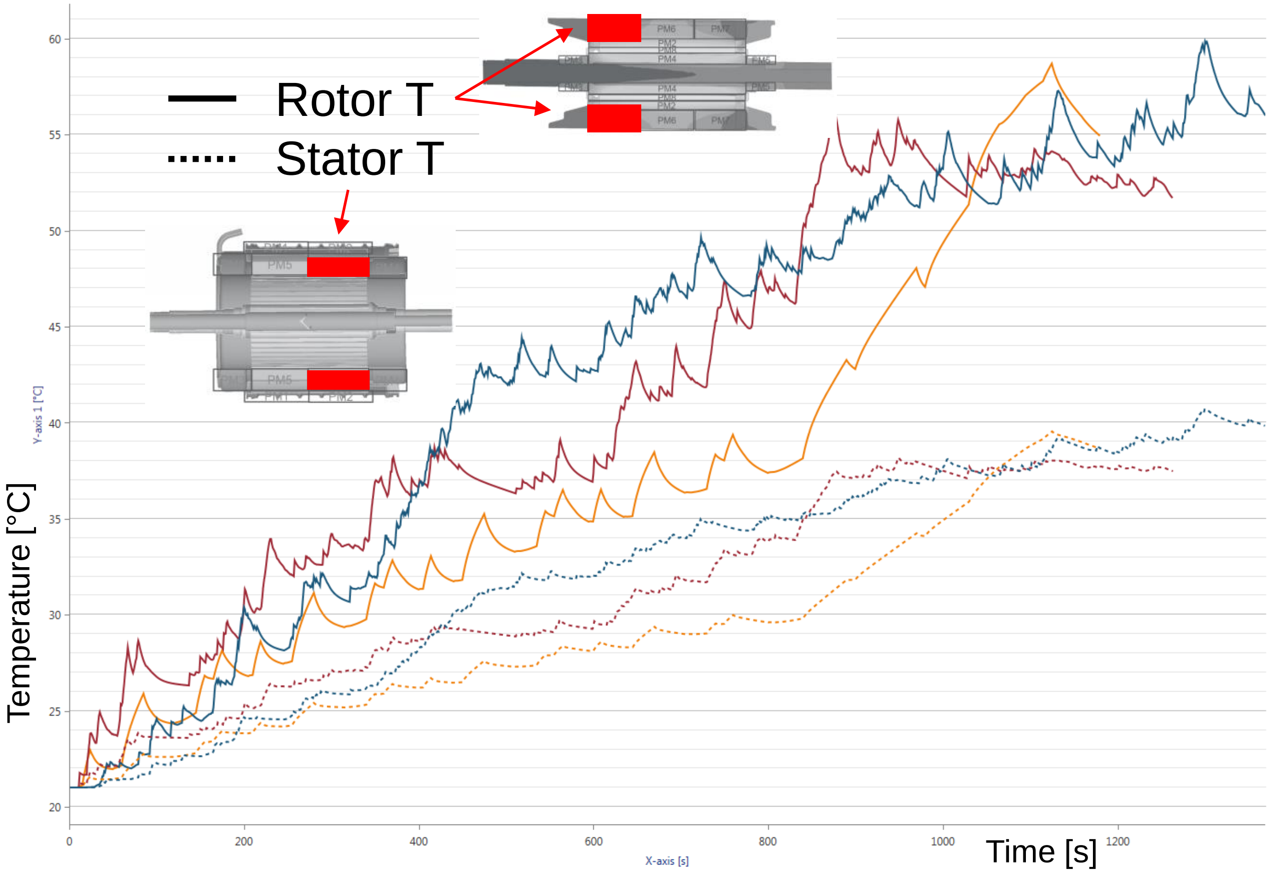
Battery Pack
Cell Temperatures for Different Drive Cycles @ 21°C



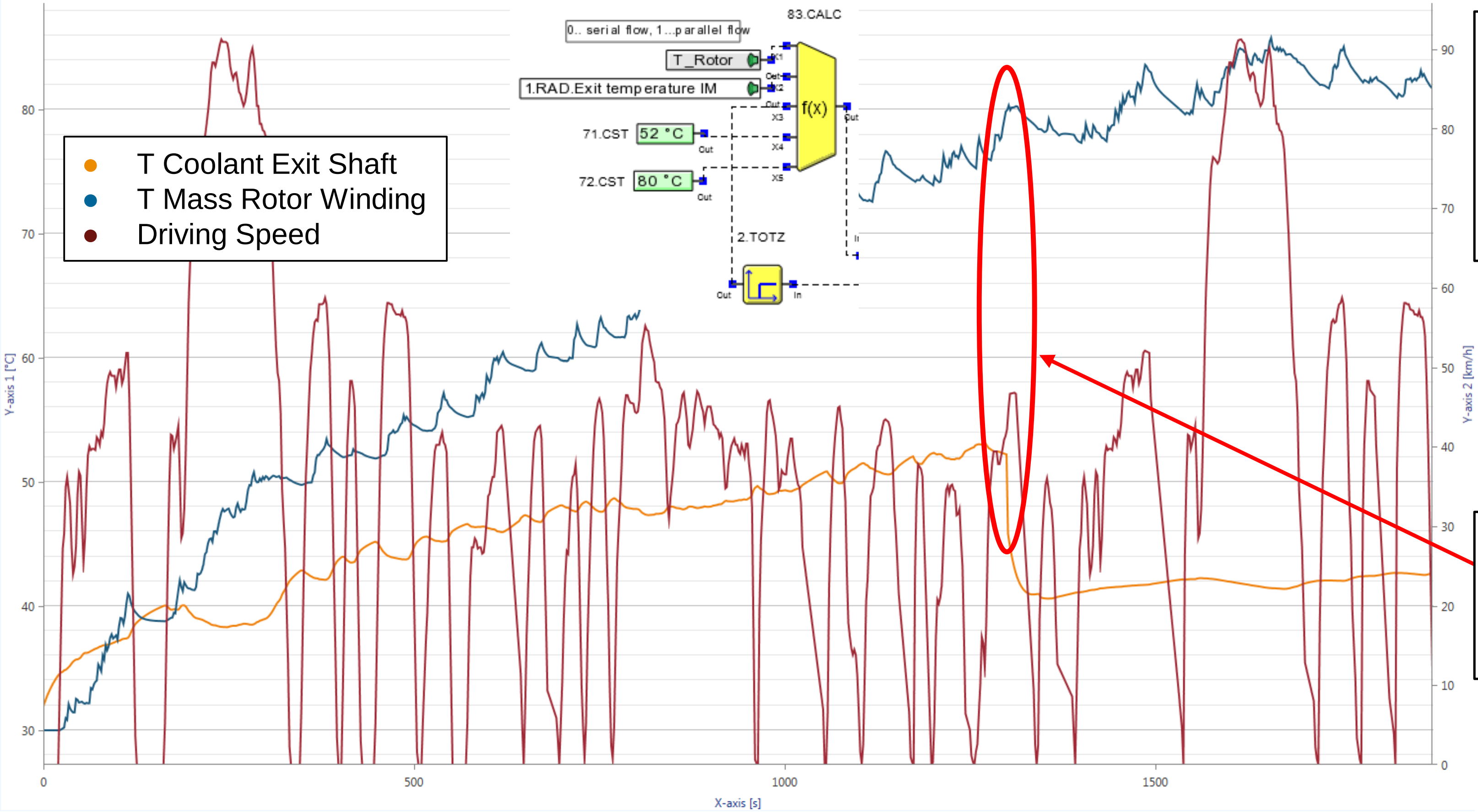


Electric Powertrain
Rear Motor T for Different Drive Cycles @ 21°C





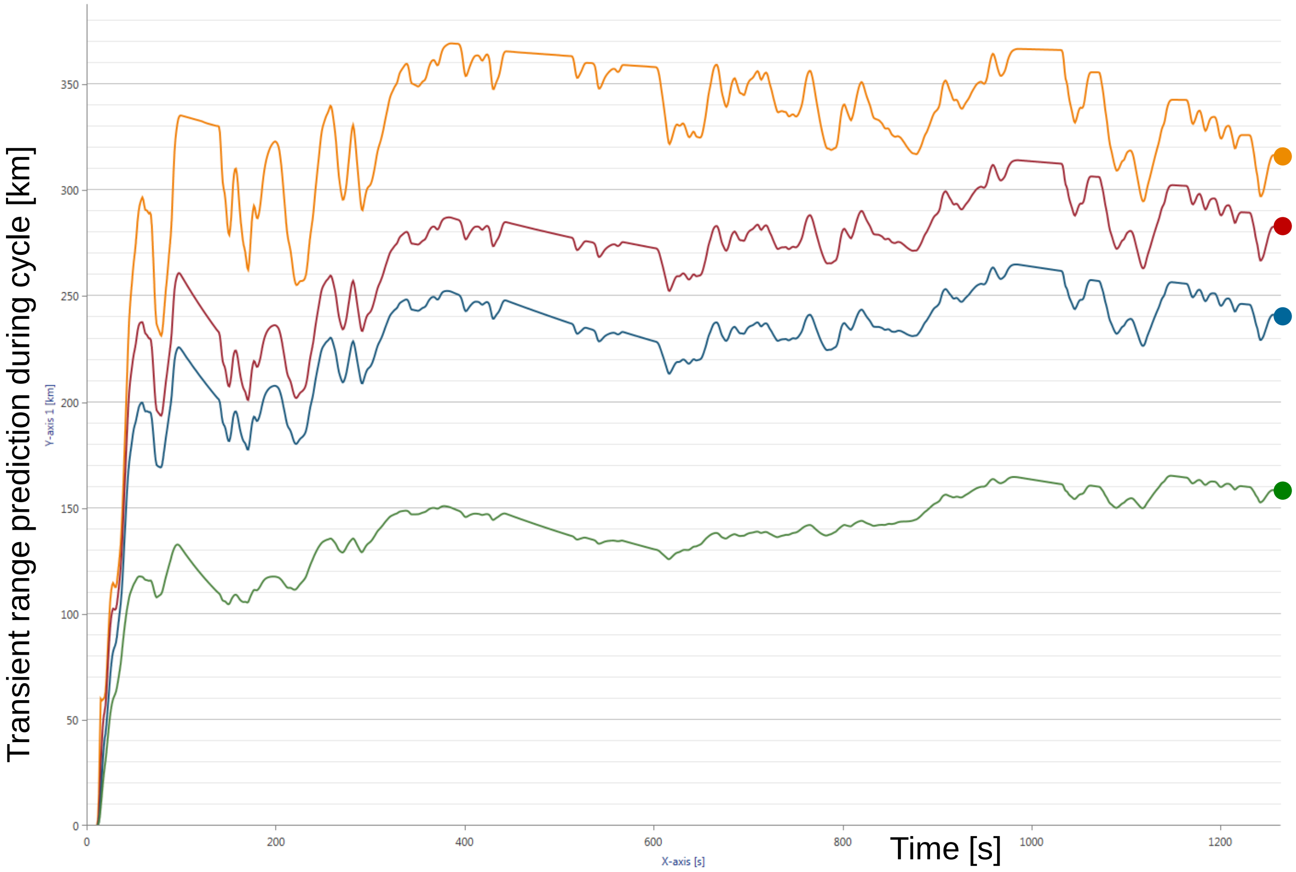
Cooling System Operating Strategy FTP75

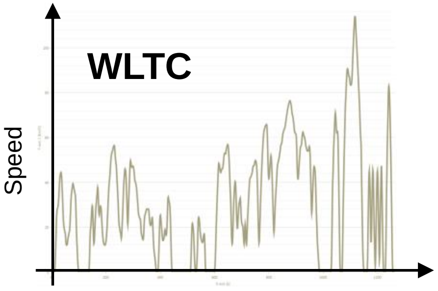


FAN:
2000 rpm
ambient temperature:
30°C

4-way valve opens when $T_{rotor} > 80°C$

Vehicle Range
Ambient Temperature Influence on WLTC Range





Vehicle Range
Impact of Battery Heating for WLTC at -10°C

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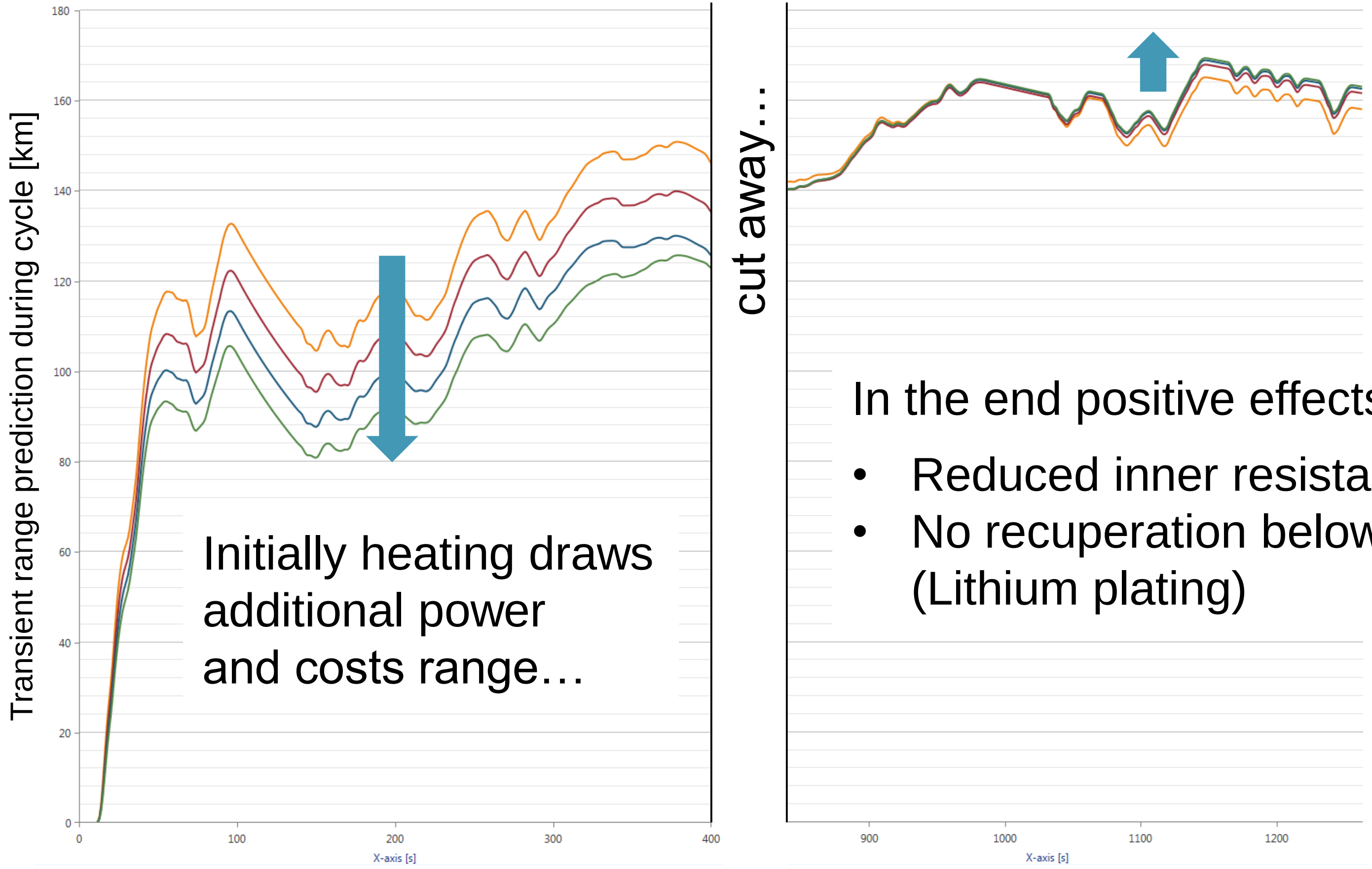
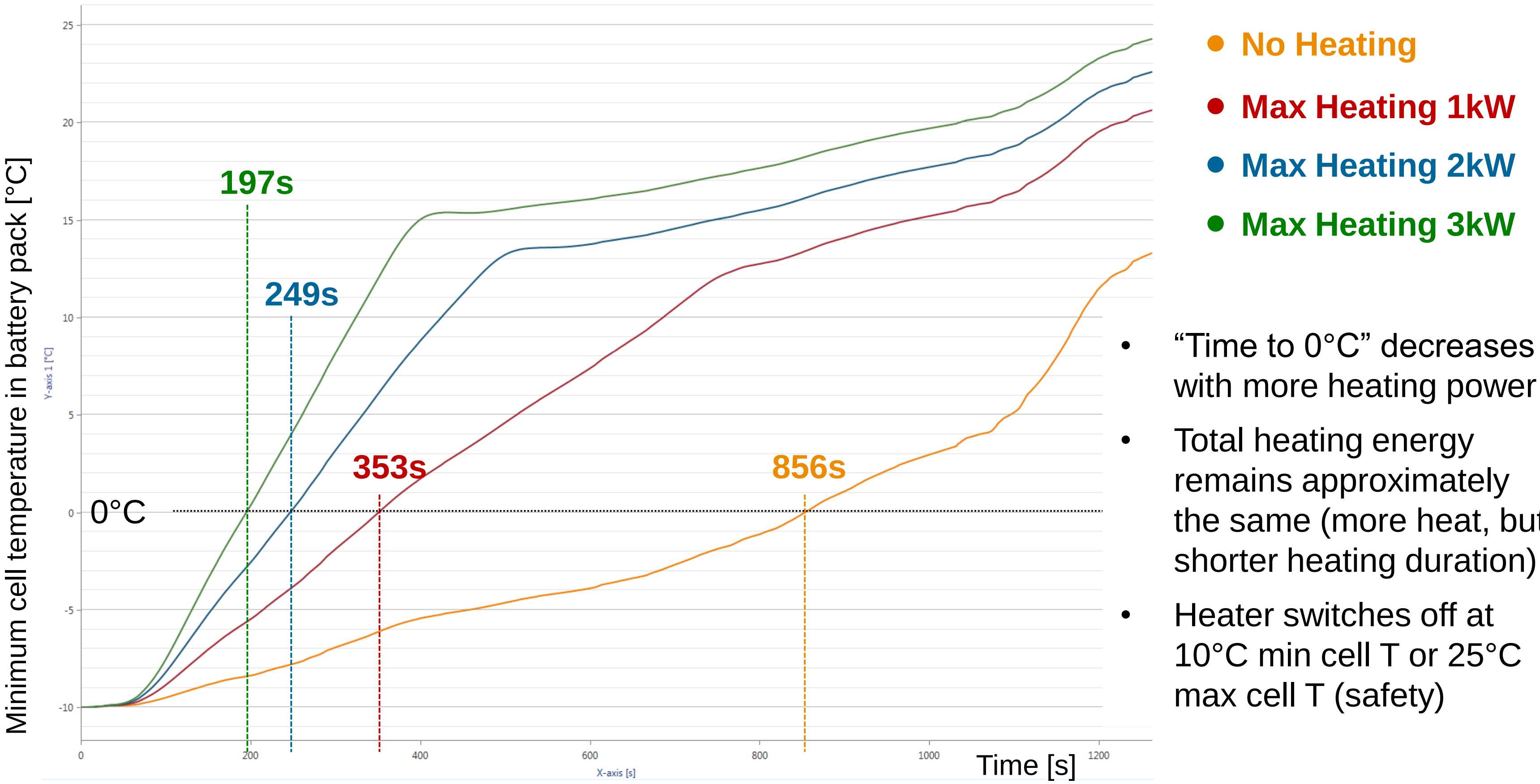


Initially heating draws additional power and costs range…

In the end positive effects dominate:

- Reduced inner resistance at higher T
- No recuperation below 0°C cell T (Lithium plating)

Vehicle Range
Impact of Battery Heating for WLTC at -10°C



- “Time to 0°C” decreases with more heating power
- Total heating energy remains approximately the same (more heat, but shorter heating duration)
- Heater switches off at 10°C min cell T or 25°C max cell T (safety)

Summary

- A combined 3D / 1D approach combines fast simulation times (~ real time) with selective high levels of detail
- This allows investigation of complex interactions in complete vehicle thermal management simulation models combining
  - Powertrain Cooling & Driving Simulation
  - Battery Cooling & VTM Strategies
  - HVAC System & Comfort Strategies
  - Cabin model
- **Specifically for electric vehicles understanding these interactions is essential!**

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DRIVING **EXCELLENCE.**
INSPIRING **INNOVATION.**