

Co-Simulation of a BEV thermal management system in KULI and MATLAB Simulink with focus on model-based feedforward and feedback control of the HVAC system

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ECS Simulation Conference 2023

Linz, 11.05.2023



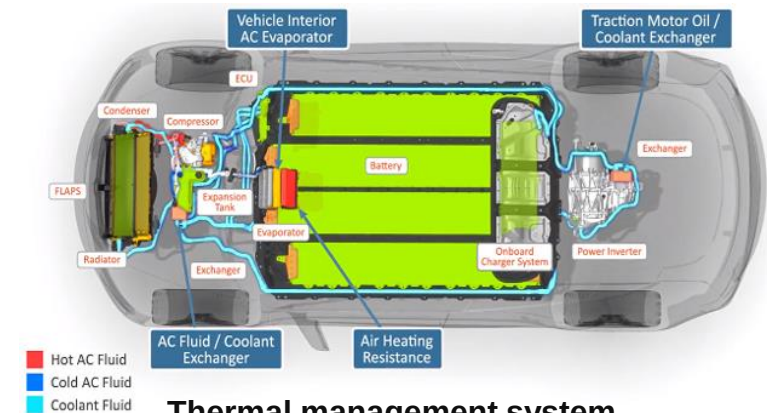
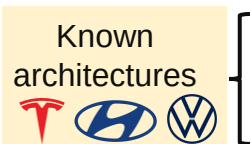
Institute of Thermodynamics
and Sustainable Propulsion Systems

Motivation of thermal management optimization

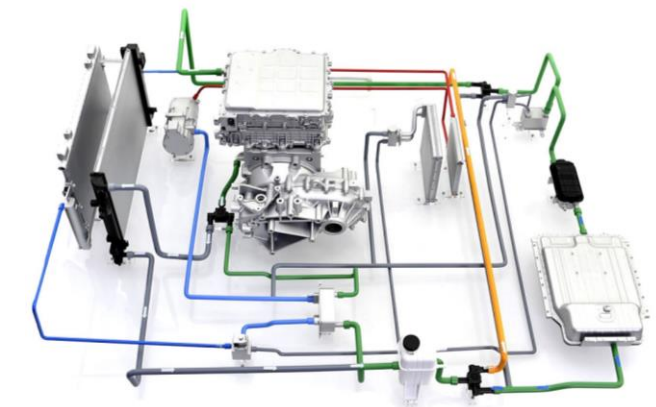
Shift in mobility to **alternative propulsion technologies (BEV, FCEV)**

- Potentials and **challenges in development**
 - absence of waste heat from ICE
 - increasing power demand of auxiliary consumers
 - **but** high cooling requirements for fuel cell

→ *New heating and cooling concepts in BEV and FCEV*
- **Efficient thermal management as a key technique**
 - Potentials
 - increasing energy efficiency
 - enhancing lifetime of components and vehicle
 - Challenges
 - narrow temperature ranges for battery and fuel cell
 - temperatures at different levels



Thermal management system of Tesla Model 3



Thermal management system of Hyundai Niro EV

Objectives & Modeling approach

▪ Objectives

- Analysis of a BEV in a *full vehicle simulation* with focus on thermal management
- Setup of a *co-simulation* in KULI and MATLAB
- Investigation of *energy consumption shares* in WLTC at various operating points

▪ Co-simulation to combine the advantages of...

- KULI: extensive libraries for thermo-hydraulic modeling of fluid circuits and also powertrain components
- MATLAB: high degrees of freedom for mathematical-physical modeling

▪ Modeling approach with focus on scientific aspects

- Gain in-depth expertise in the entire modeling of thermal management systems
 - Fluid circuits
 - Powertrain components and **Batteries**
 - Development of a model-based **HVAC control** unit
 - KULI components represent actuators and sensors in the air conditioning unit
 - MATLAB function blocks are used to control these components
- ...necessary for further research on system architecture optimization

→ Demonstration of the **extensive functions of KULI** in the co-simulation framework

Analyzed vehicle: Tesla Model 3 Long Range RWD (MY 2018, Europe)

Technical Data

Motor

- Interior permanent magnet synchronous
- Power (peak) 239 kW
- Torque (peak) 420 Nm

Battery technology

- Battery type Lithium-Ion
- Cell type 21700 (cylindrical)
- Battery capacity 75.0 kWh
- Pack consists of 4416 cells in groups of 46 cells per brick in 4 modules (2x 23s, 2x 25s)

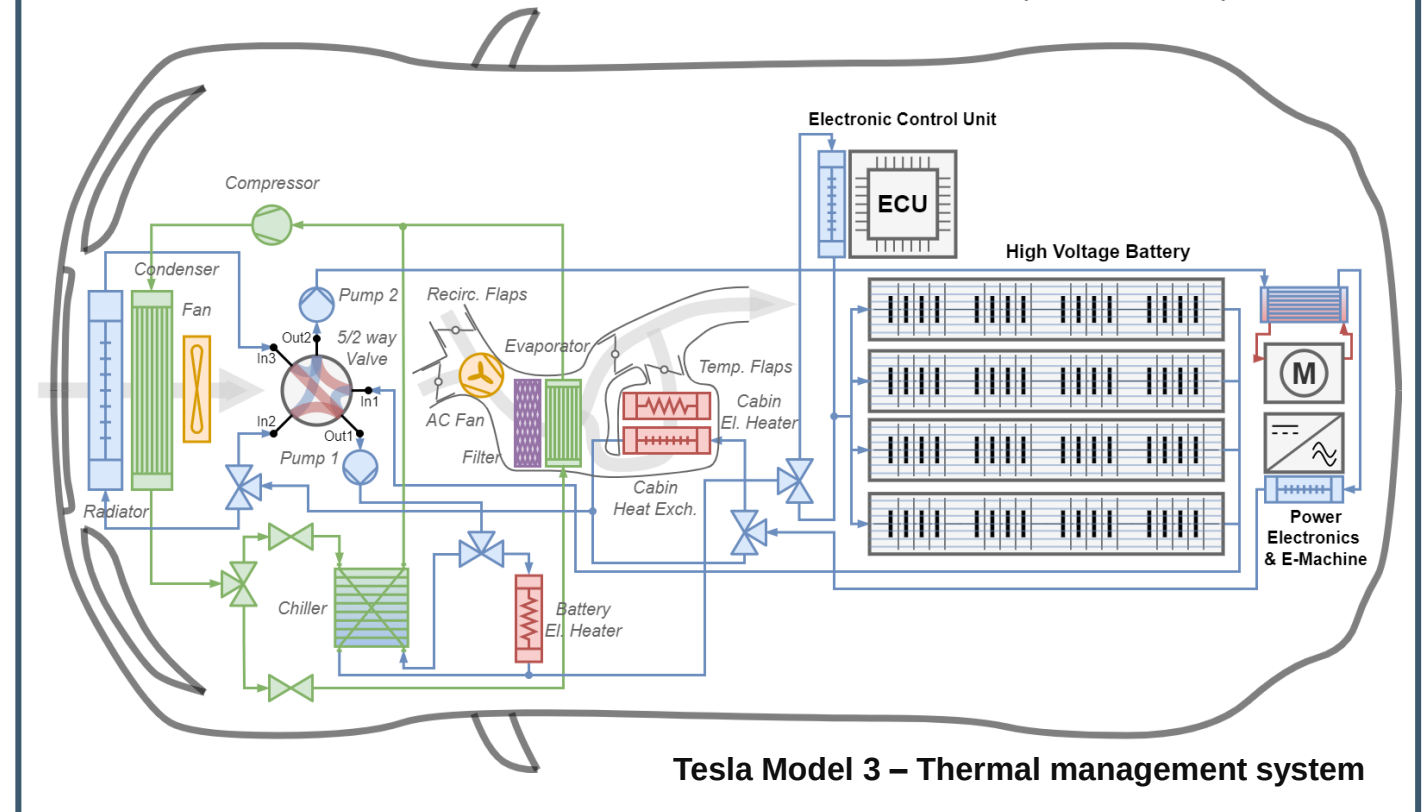
Thermal management system

- Battery conditioning
- Power electronics & Motor conditioning
- Heating, Ventilation and Air conditioning (HVAC)

→ *superbottle valve* for (de-)coupling coolant circuits to increase efficiency and lifetime of vehicle as a whole



Tesla Model 3 (Model 3, n. d.)



Tesla Model 3 – Thermal management system

Setup of KULI simulation model



Co-Simulation Methodology & Setup

Longitudinal dynamics

- calculation of driving power

Power split of powertrain & brakes

- split of driving power as function of power flows and SOC

Power Electronics & E-Motor

- efficiency as function of operating point
- thermal model for calc. of temperatures at motor cooling channel

temperatures at interfaces t_i
 speeds of coolant pumps $n_{pump,i}$
 speeds of fans and blowers $n_{fan,i}$
 valve positions $x_{valve,i}$
 driving velocity v_{drive}
 ambient conditions $t_{amb}, p_{amb}, \varphi_{amb}$

Air conditioning unit & cabin

- HVAC air path
- Refrigerant circuit substituted with heat sources and sinks

Cooling package

- cooling air path

Battery

- math.-phys. modeling of cell and extrapolation of battery
- thermal model for calc. of temperatures at battery cooling channel

Interface & Control unit

- interface for data exchange with KULI
- control strategy

heat flows at interfaces $\dot{Q}_i$
 power of coolant pumps $P_{pump,i}$
 power of fans and blowers $P_{fan,i}$
 actual states of fluids $t_{fluid,i}, p_{fluid,i}$
 actual state of cabin $t_{cab}, p_{cab}, \varphi_{cab}$

Superbottle 5/2 way valve

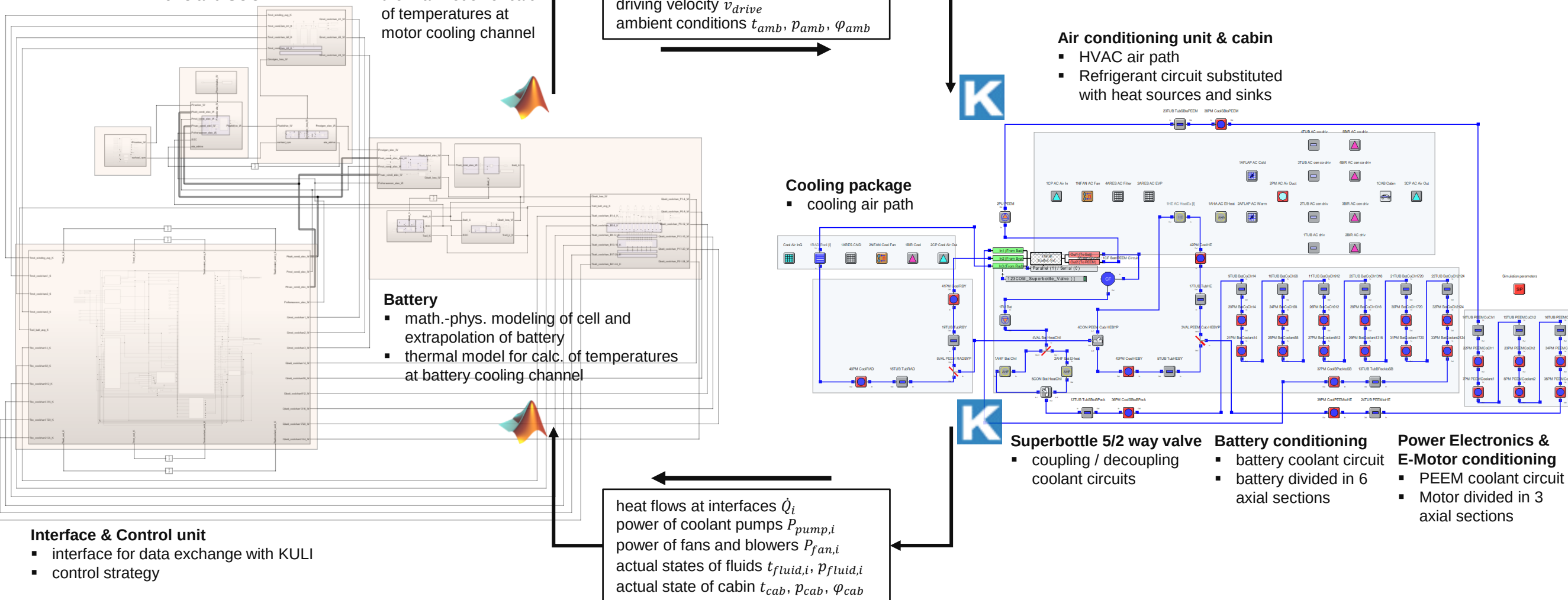
- coupling / decoupling coolant circuits

Battery conditioning

- battery coolant circuit
- battery divided in 6 axial sections

Power Electronics & E-Motor conditioning

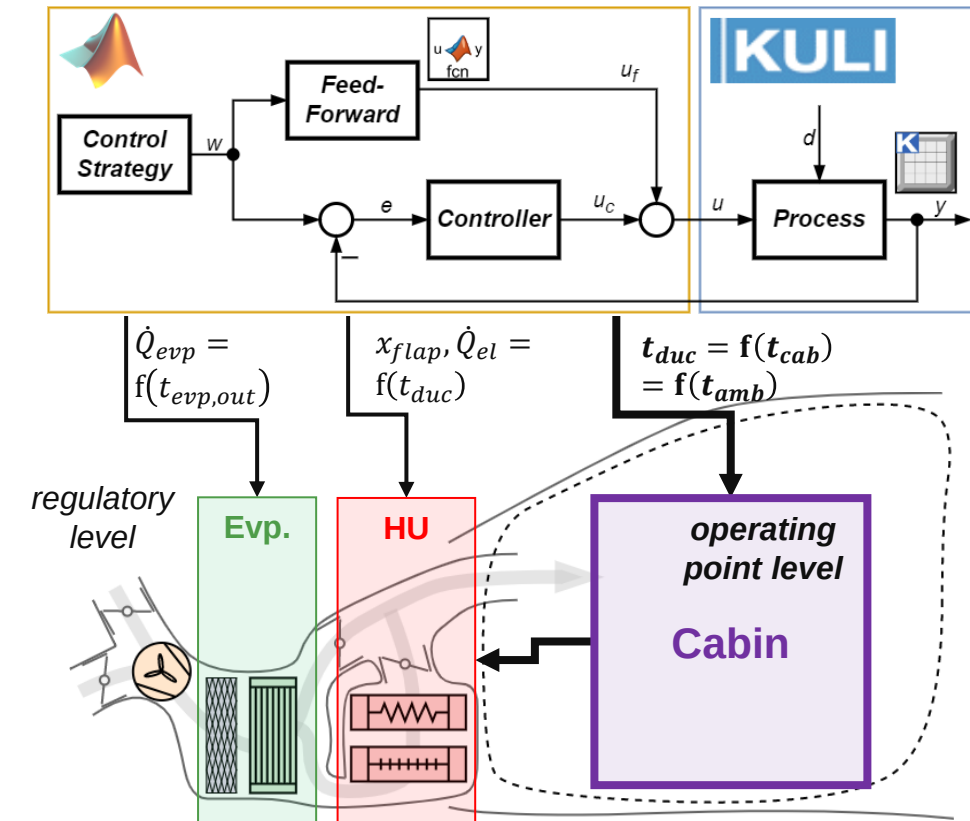
- PEEM coolant circuit
- Motor divided in 3 axial sections



Model-based control of the HVAC system

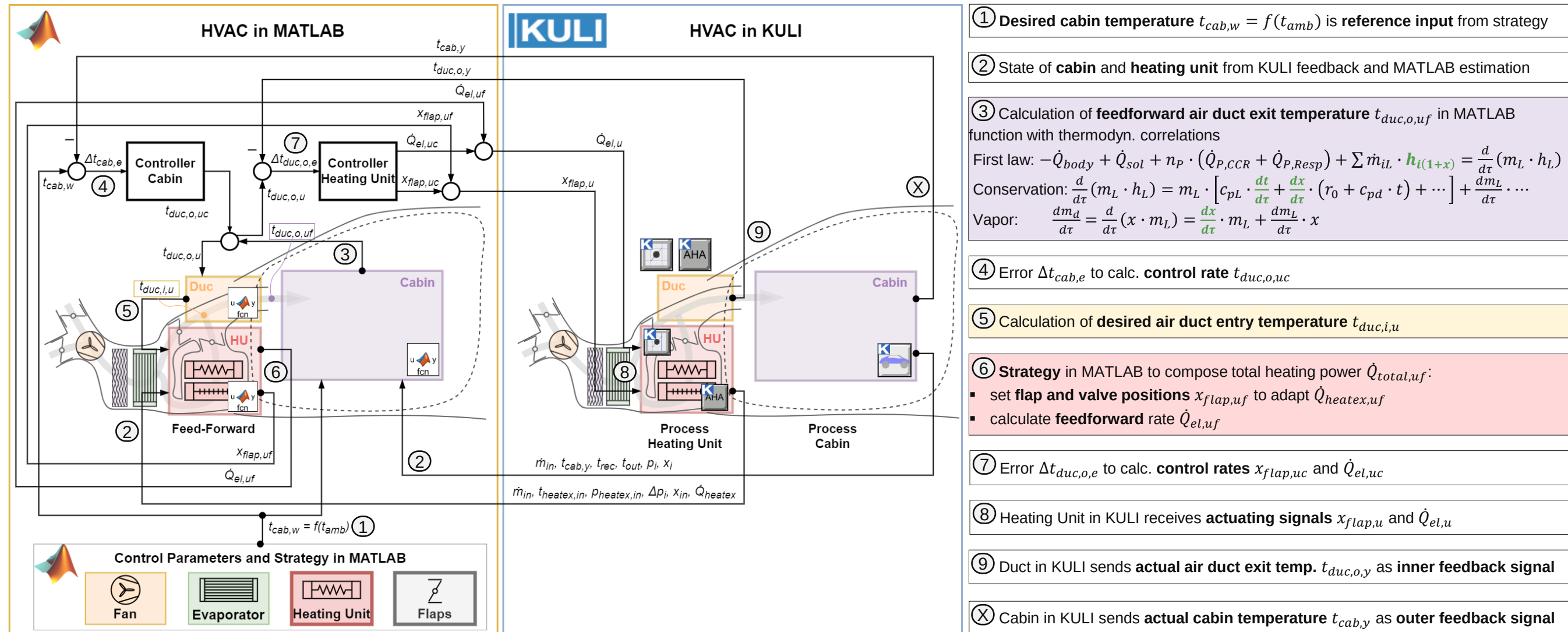
Motivation & Methodology

- **Motivation:** HVAC is a significant auxiliary consumer in BEV^[1]
→ optimization on system level requires accurate HVAC modeling
- **Target:** setup of an automatic HVAC control in co-simulation
- **Methodology:** control of **KULI HVAC air path** with **model-based feedforward via MATLAB**
 - **KULI** for 1-dimensional modeling of HVAC unit
 - modeling the “real” **HVAC air path**
 - receives **actuator** signals
 - sends **sensor** signals
 - **MATLAB Simulink** for control of HVAC components
 - implementation of a **control strategy**
 - simultaneous calculation of **thermodynamic models** of...
 - evaporator,
 - heating unit and cabin
 ...for **feedforward control**.
 - **Control of...**
 - evaporator exit temperature
 - cabin air temperature on operating point level (via air ducts temperature on regulatory level)^[2]



Model-based control of the HVAC system

Cascade control of cabin air temperature t_{cab} via heat flows in heating unit $\dot{Q}_{heatex}$, $\dot{Q}_{el}$

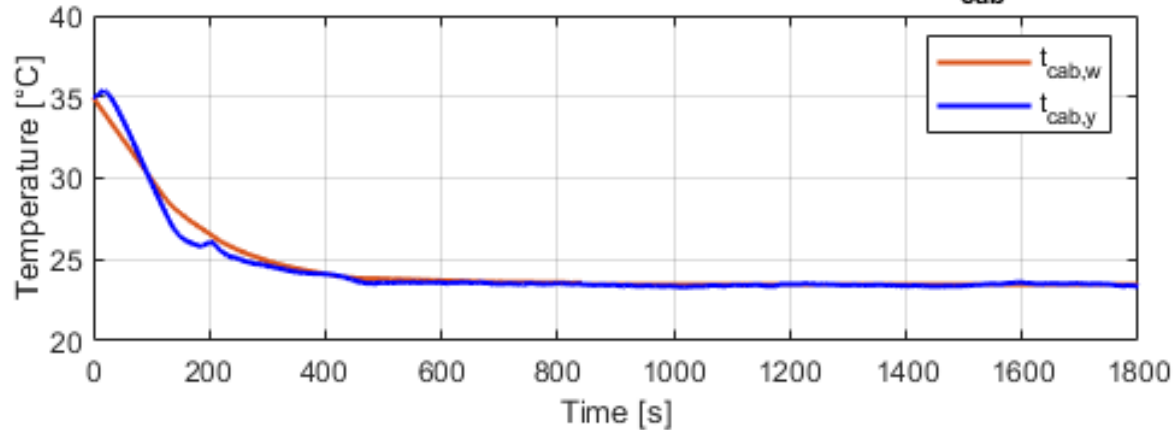
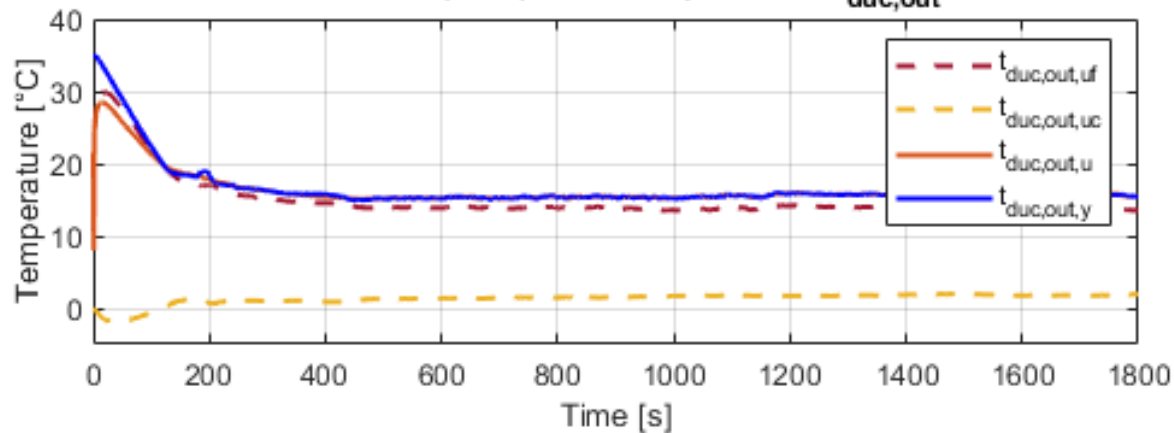


Simulation results & Insights – Cabin

Case 4 – cool down process

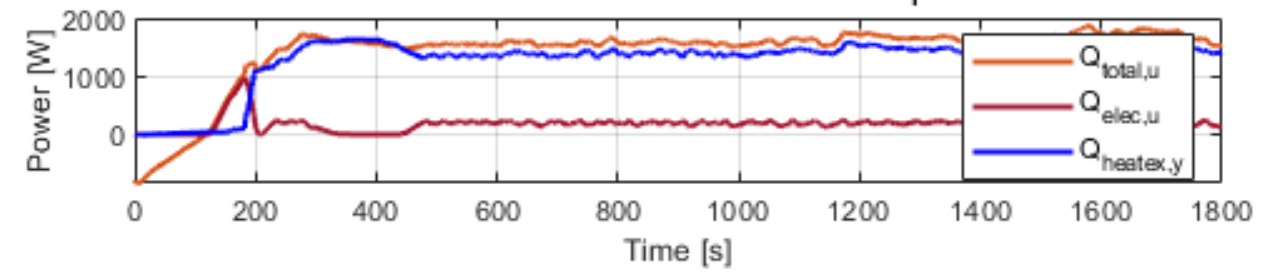
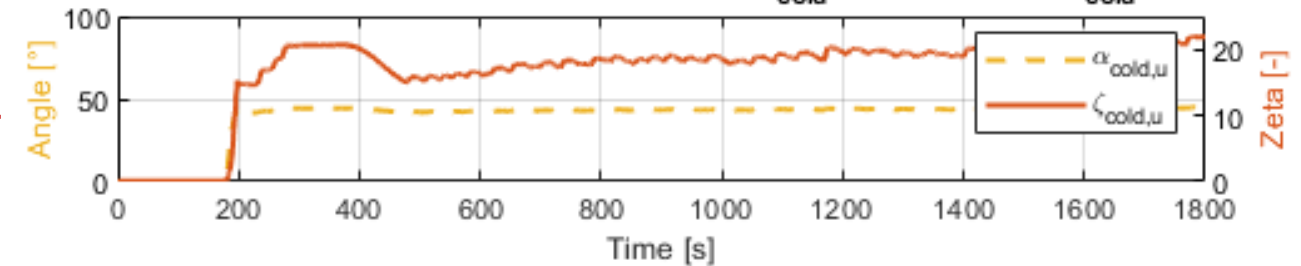
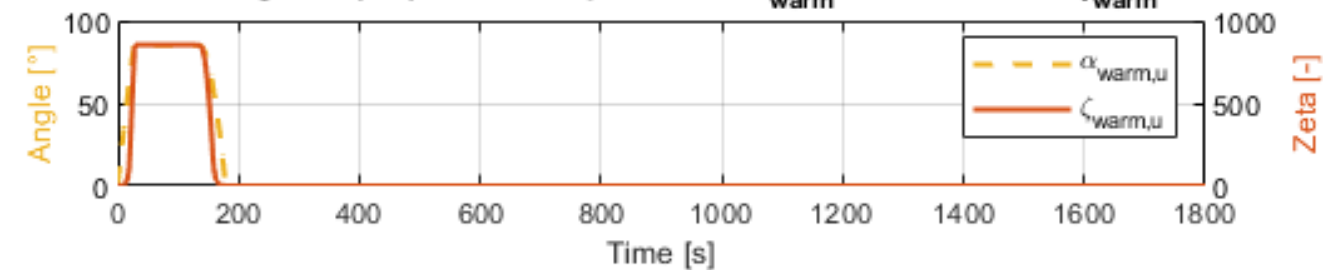
Malaga in June: $t_{amb} = t_{init} = 35\text{ }^{\circ}\text{C}$

Driving cycle: WLTC class 3

Pass. Comp. (CAB-1CAB) - Cabin temperatures t_{cab} Air Ducts (DUC) - Exit temperatures $t_{duc,out}$ 

Cabin air temperature:

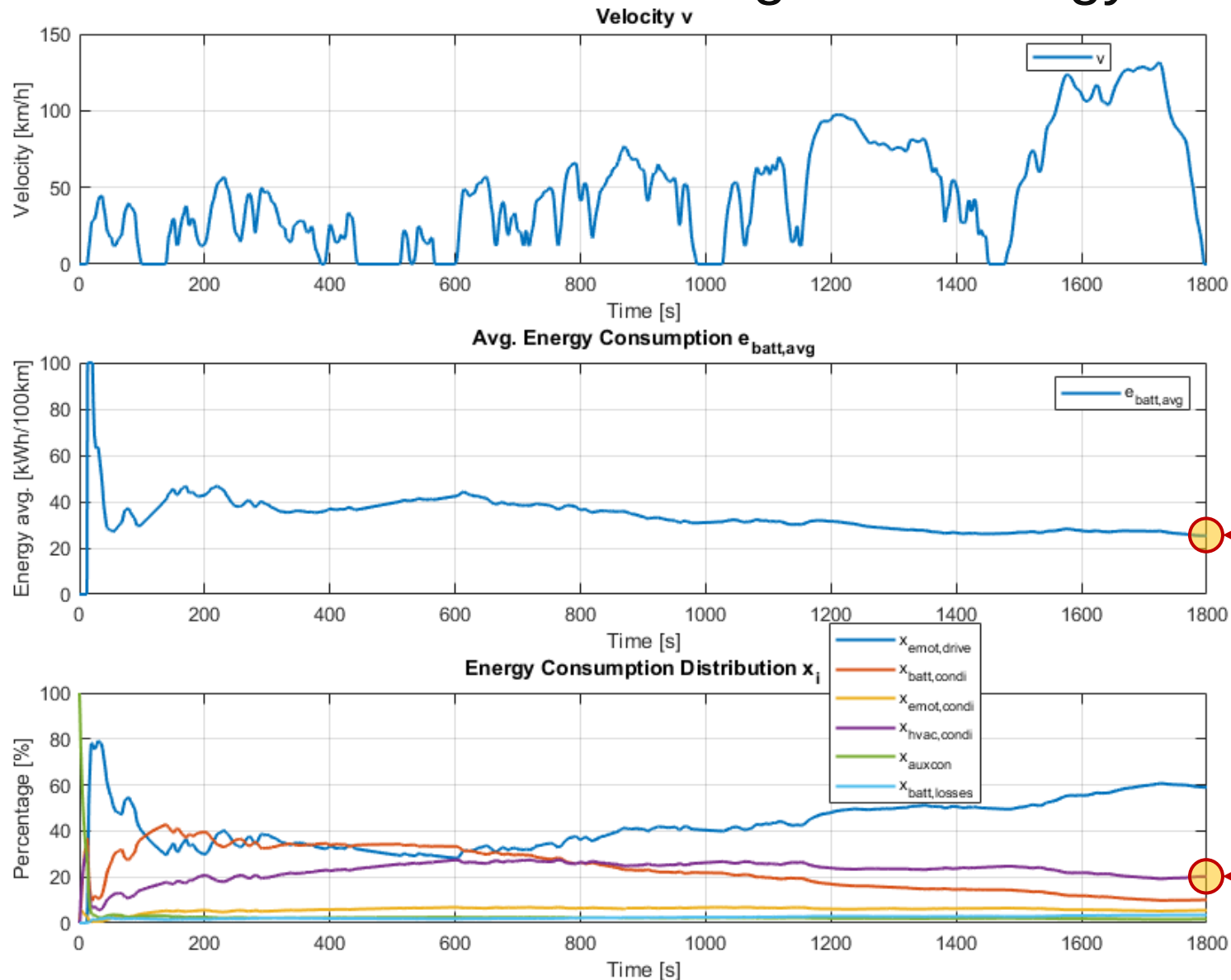
- mean absolute deviation of $d_{\bar{x}} = 0.2079\text{ }^{\circ}\text{C}$
- with quite accurate feedforward share $t_{duc,out,uf}$
- control share mainly necessary to reach steady-state $t_{cab,w}$

Heating Unit (HU) - Heat flows Q_i Heating Unit (HU) - Cold Flap Position α_{cold} and Zeta Value ζ_{cold} Heating Unit (HU) - Warm Flap Position α_{warm} and Zeta Value ζ_{warm} 

Heat flows in Heating Unit:

- composition of total heating power demand $\dot{Q}_{total,u}$
- in first phase, higher share of $\dot{Q}_{elec,u}$
- then, warm flap opens to increase $\dot{Q}_{heatex,u}$ and decrease $\dot{Q}_{elec,u}$

Simulation results & Insights – Energy Consumption



Case 4 – cool down process

Malaga in June: $t_{amb} = t_{init} = 35\text{ }^{\circ}\text{C}$

Driving cycle: WLTC class 3

Average energy consumption at $\tau = 1800\text{ s}$ in [kWh/100km]:

- Co-Simulation: $e_{batt,avg,cosim} = 25.35$
 - Values for validation^[1]:
 - WLTP manufacturer data: $e_{batt,avg,WLTP} = 16.00$
 - with ambient corr. (+20%) $e_{batt,avg,WLTP,corr} = 19.25$
 - ADAC Ecotest: $e_{batt,avg,ADAC} = 20.90$
 - with ambient corr. (+20%) $e_{batt,avg,ADAC,corr} = 25.15$
- ...but, thermal management control with additional optimization potentials

Energy consumption shares at $\tau = 1800\text{ s}$ in [%]:

- Co-Simulation:
 - HVAC (only): $x_{HVAC,cosim} = 20.26\text{ }%$
 - Thermal mgmt. (total): $x_{TMS,cosim} = 35.82\text{ }%$

→ Conclusions^[2]:

- thermal management as a key technique in BEV
- high demands on accurate modeling of thermal behavior of cabin and control of HVAC unit, to be able to assess thermal management measures on vehicle level

References

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A faint, grayscale background image of a classical building with a large dome and columns, likely the main building of TU Graz.

Thank you for your attention!

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Research Area „Propulsion Systems“

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