Connected Electric Vehicle Optimised for Life, Value, Efficiency and Range

Advanced Thermal Management
An Enabler of Long Distance Capability?

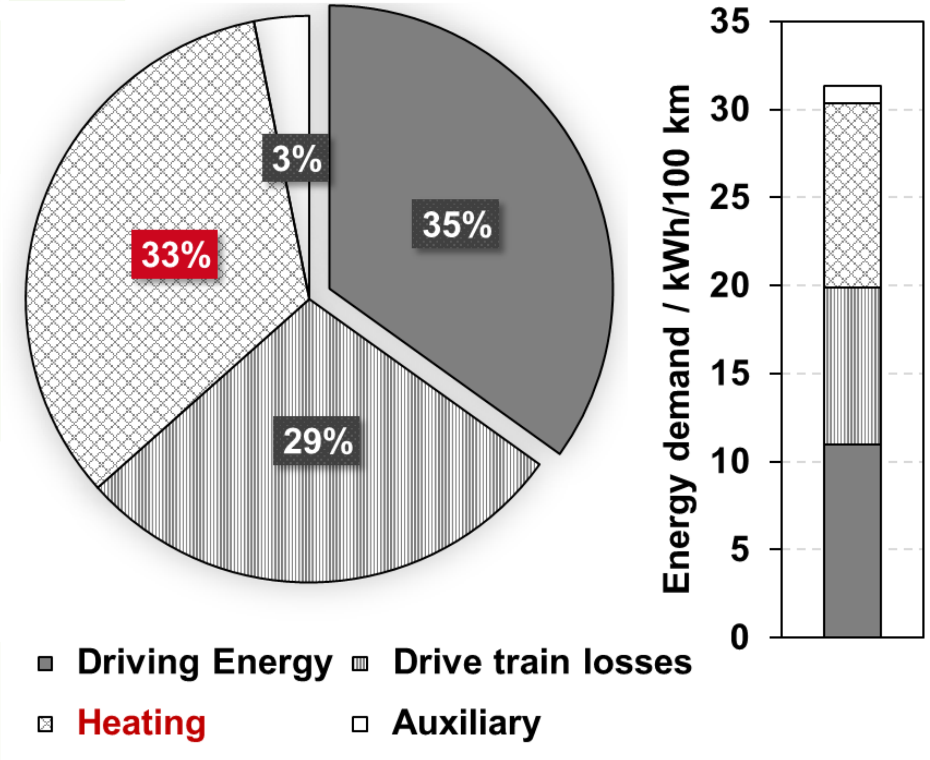
Alexander Wahl, Patrick Schutzeich
RWTH Aachen
27.09.2022

„We do now see that thermal systems in combustion vehicles were oversized and that the controls were not sufficiently accurate“
– A consortium member

Thermomanagement of electric vehicles
Energy demand at –20°C in WLTP cycle

ENERGY DEMAND DISTRIBUTION IN WLTP AT -20°C

REFERENCE VEHICLE A-SEGEMENT



GENERAL ASPECTS OF BEV THERMAL SYSTEMS

- Thermal systems in BEV can have significant impact on energy consumption
- Cooling or heating at high/low temperatures has significant impact on the driving range
- For enabeling long distance travelling, energy saving in the thermal system is a key aspect

Agenda

- Aspects of Thermal Management on Long Distance Capability

- System Engineering Centered Development

- Hardware Solutions
  - Bosch’s flexible Skateboard Approach
  - Heat Panels for fast Cabin Comfort (Ford)

- Software Solutions
  - Predictive Powertrain Conditioning
  - Predictive Cabin Conditioning

BEV Long Distance Capability

Thermal field weakening
E-Motor Design
Predictive Controls
Operation Strategy
E-Motor Sizing
Charging Scheduler
EcoRouting
Terrain Information
Motor Design
Photovoltaic Roof (Energy Harvesting)
Battery Design
SiC Inverters
Waste Heat Recovery
HV Energy Management
Preconditioning
Eco Charging
Battery Sizing
ChargeProcess
Heating Panels
Eco Driving
Thermal Management
Heat Pump
Cabin Climatization
Powertrain Concepts
DCDC Controls
Deceleration Management
BEV Long Distance Capability
Range Estimation
Battery State Estimation
Thermal system layout
Driver Interpretation
Inverter Controls
LV Energy Management
Shutter
Camera Rear View Systems
Fast Charging
Gear Box Controls
Optimal Vehicle Speed
Integrated Vehicle Design
Torque Split
Regeneration
Aerodynamics
Data Management
Low Resistance Wheel
Commercial Vehicle Boundaries
Sailing
Driver Advisory System
Weight Optimization

BEV Long Distance Capability

CEVOLVER

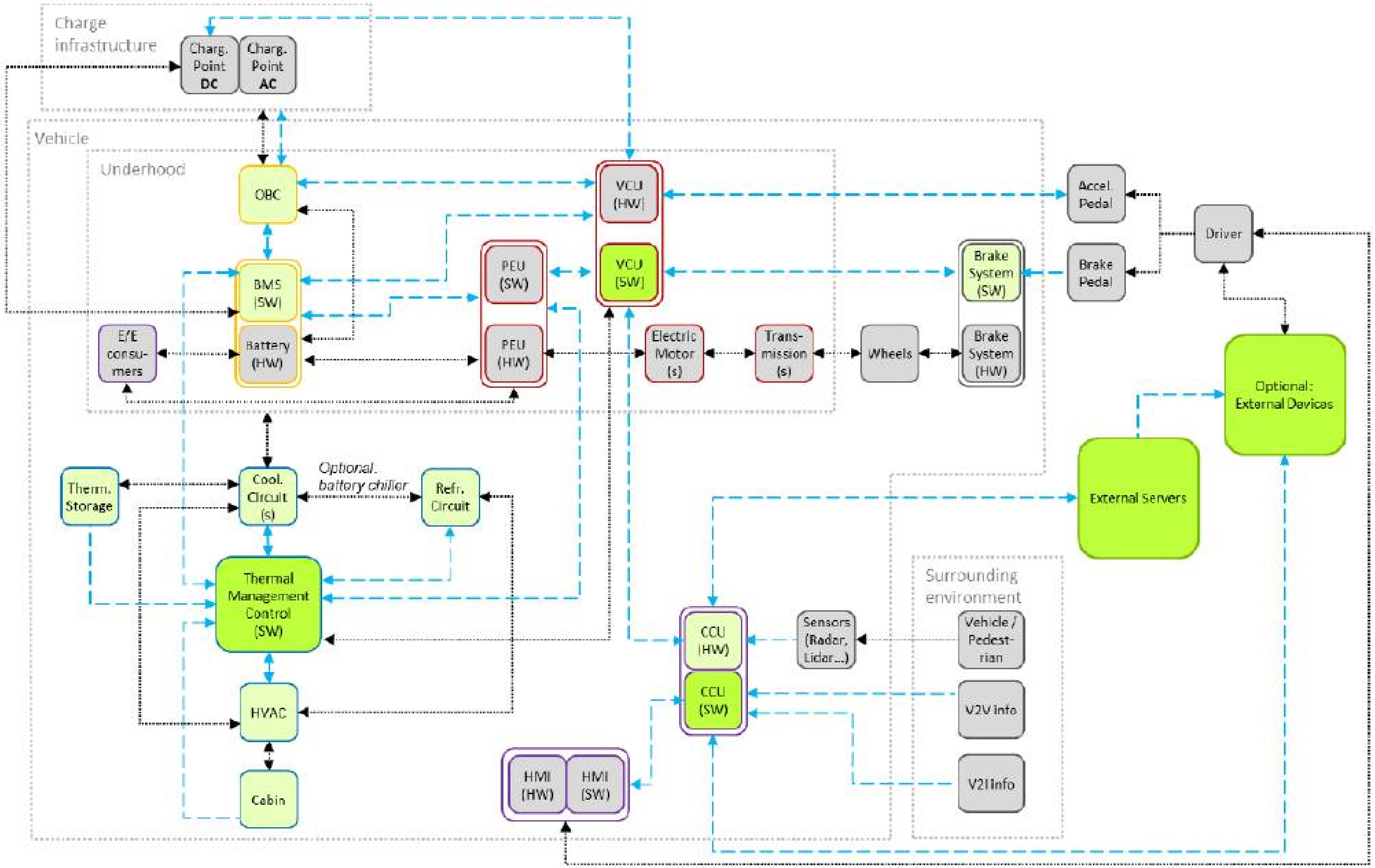
E-Motor Sizing
Photovoltaic Roof (Energy Harvesting)
Battery Design
Waste Heat Recovery
Charging Scheduler
Terrain Information
E-Motor Design
Predictive controls
Operation Strategy
EcoRouting
Motor Design
SiC Inverters
Eco Charging
HV Energy Management
Preconditioning
Battery Sizing
Eco Driving
ChargeProcess
Thermal Management
Heating Panels
Thermal field weakening
Heat Pump
Cabin Climatization
Powertrain Concepts
Range Estimation
Battery State Estimation
DCDC Controls
Deceleration Management
BEV Long Distance Capability
Thermal system layout
Driver Interpretation
Inverter Controls
Aerodynamics
Data Management
Commercial Vehicle Boundaries
LV Energy Management
Shutter
Camera Rear View Systems
Fast Charging
Waste heat integration
Gear Box Controls
Torque Split
Regeneration
Low Resistance Wheel
Optimal Vehicle Speed
Sailing
Integrated Vehicle Design
Driver Advisory System
Weight Optimization

Agenda

- Aspects of Thermal Management on Long Distance Capability
- System Engineering Centered Development
- Hardware Solutions
  - Bosch’s flexible Skateboard Approach
  - Heat Panels for fast Cabin Comfort (Ford)
- Software Solutions
  - Predictive Powertrain Conditioning
  - Predictive Cabin Conditioning

Redesign of Thermal Systems using Systems Engineering

CEVOLVER



SYSTEMATIC ANALYSIS

- Abstraction of the system for better understanding of implications
- System needs to function as a whole due to interactions with other systems

Intention: Rethinking current concepts

Legend:

Interfaces

Energy / Physical

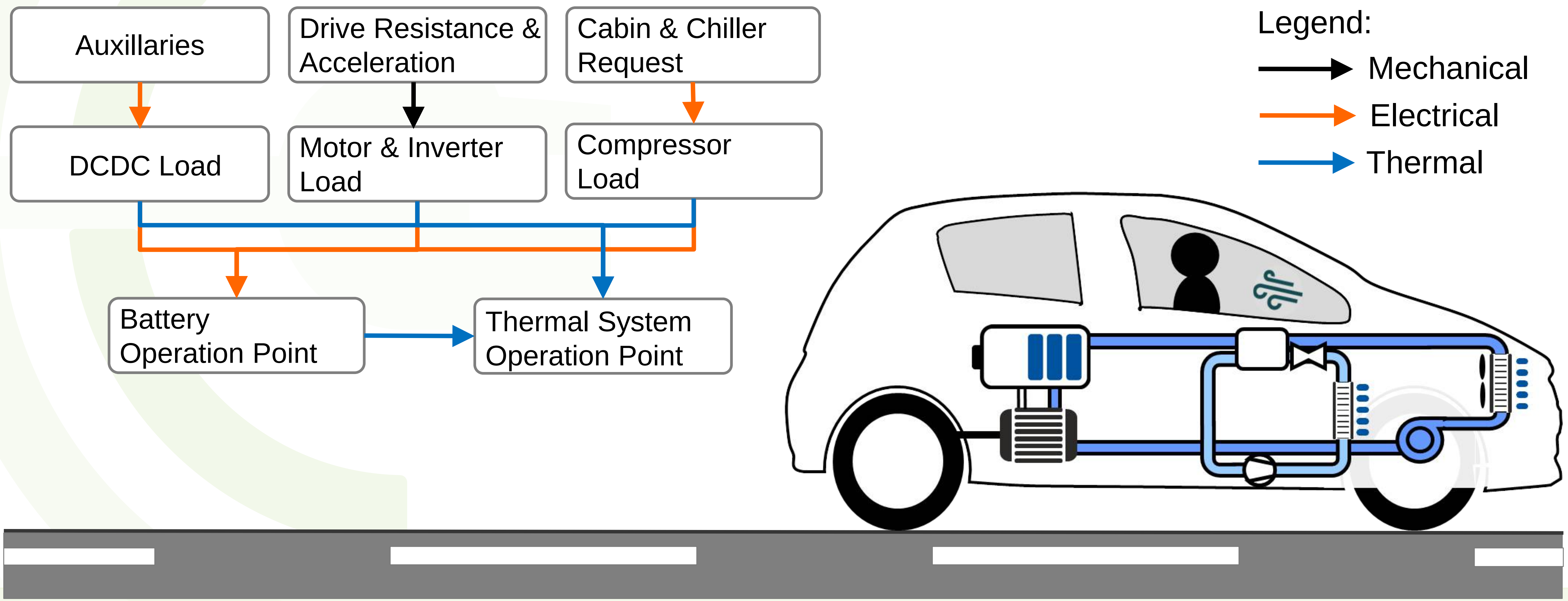
Data (Signals)

Coolant System | Battery System | E/E

E-Drive System | External Servers | Others

The Thermal System as Central Participant in Vehicle Operation

MECHATRONICAL & THERMAL PATH

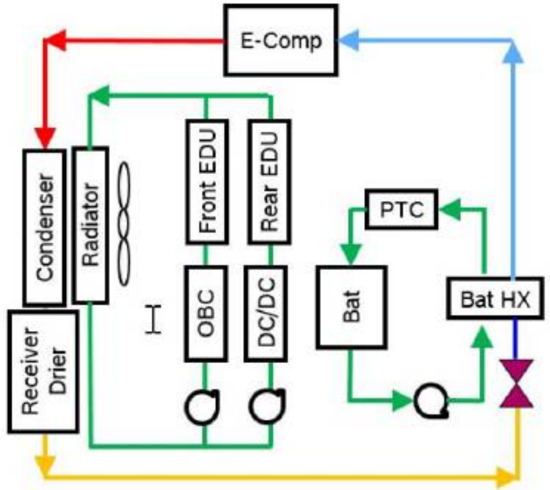


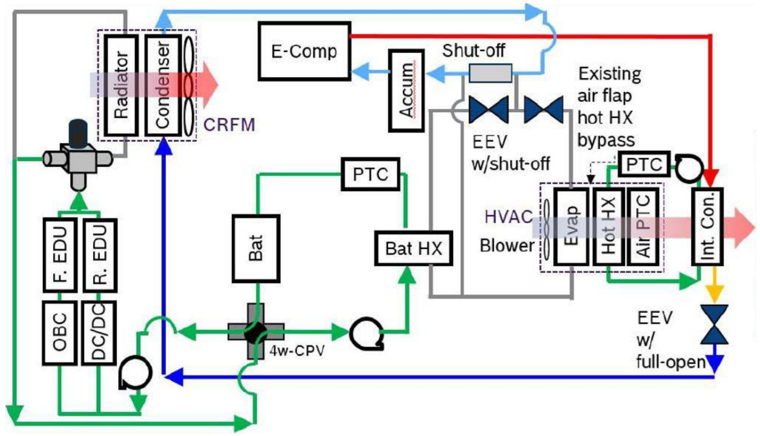
Agenda

- Aspects of Thermal Management on Long Distance Capability
- System Engineering Centered Development
- Hardware Solutions
  - Bosch’s flexible Skateboard Approach
  - Heat Panels for fast Cabin Comfort (Ford)
- Software Solutions
  - Predictive Powertrain Conditioning
  - Predictive Cabin Conditioning

Bosch Skateboard Platform
Flexible Development Approach

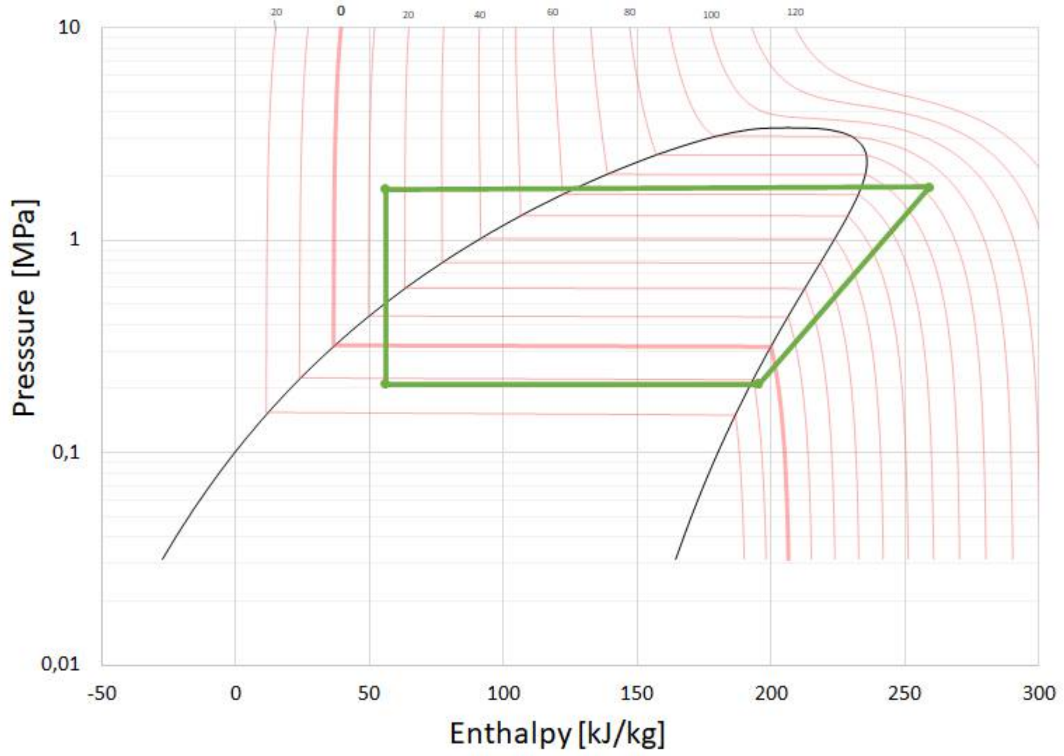
- The skateboard was built up developing E/E, chassis, powertrain and thermal system
- Thermal system can be flexibly developed on skateboard
- Several iterations and simulations run for optimization of system
- Two systems were built up and tested



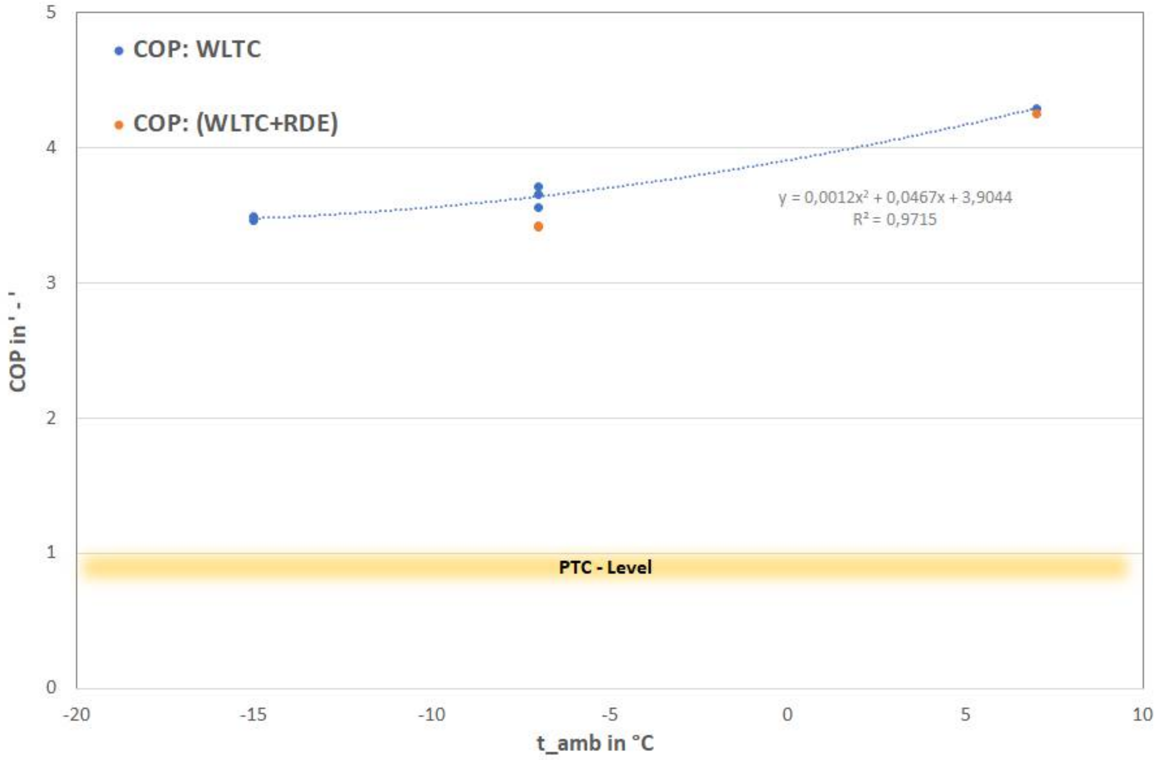


Bosch Skateboard Platform
Thermal Design – Heat Pump Results at -7°C

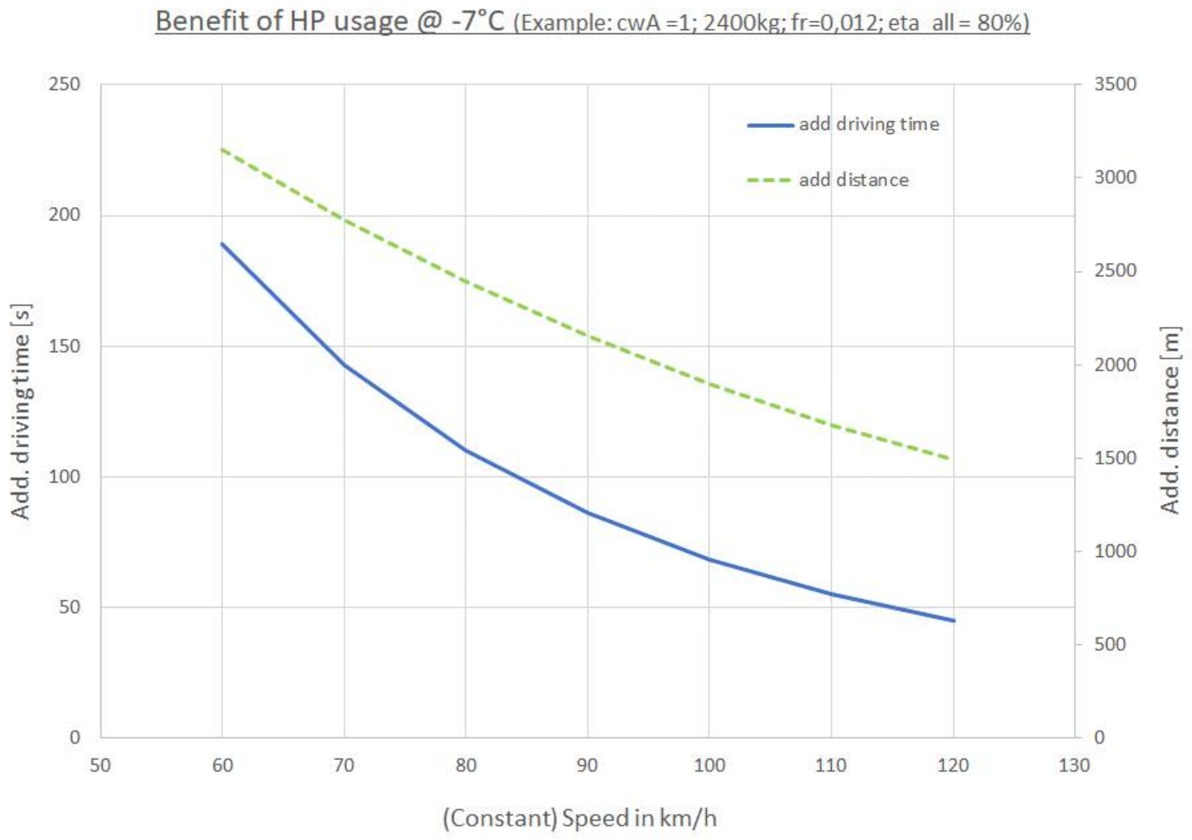
Heat Pump Process



Thermodynamic COP



Bosch Skateboard Platform
Thermal Design – Heat Pump Results at -7°C



- Tests with PTC and heat pump were conducted
- Energy consumption at WLTC
  - Heat Pump: 1.1kWh
  - PTC: 1.6kWh
- Savings for a WLTC on battery level: 4.8%
- Range improvement at highway condition (90km/h) ~2050m additional range for after driving WLTC

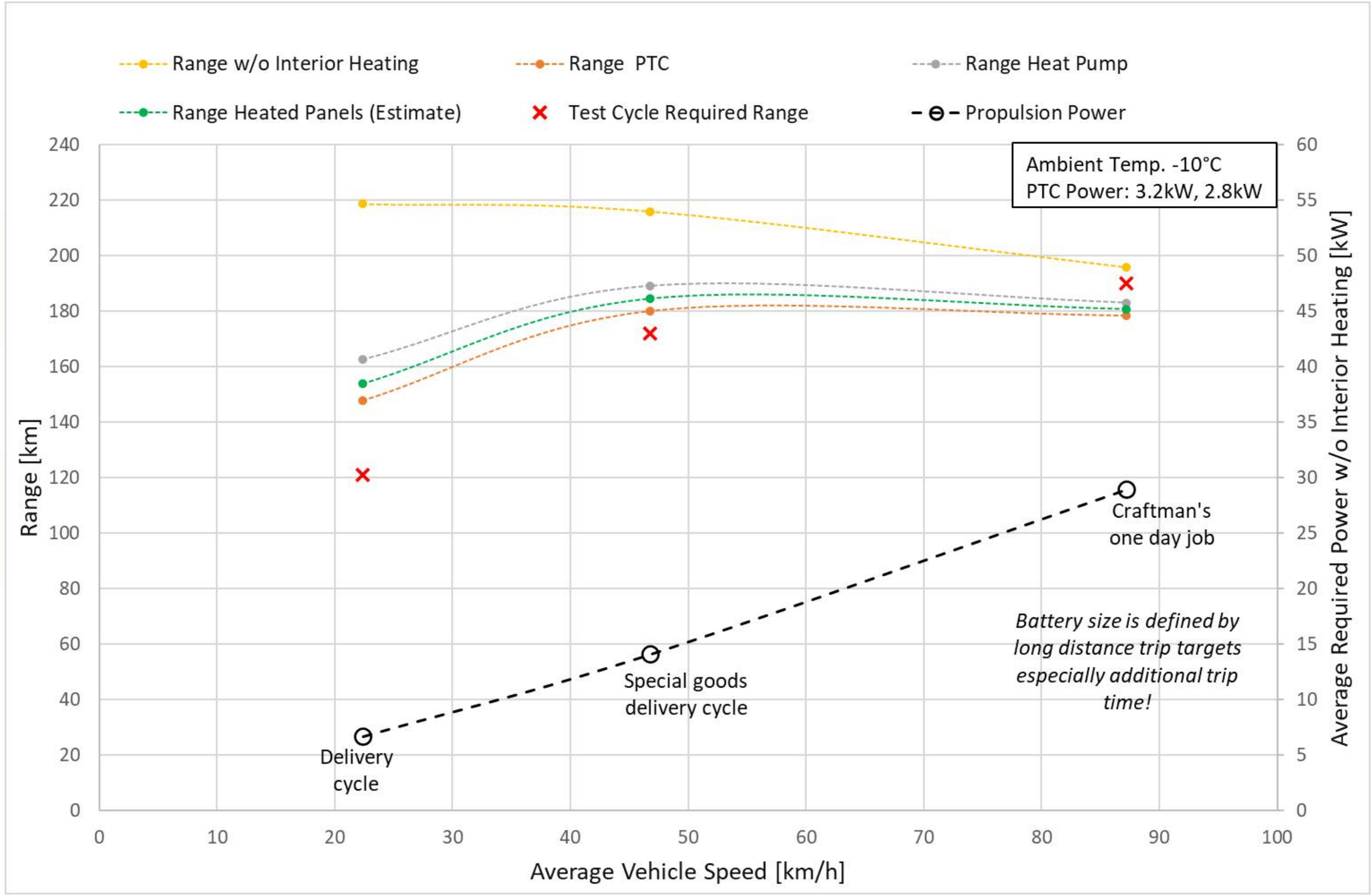
Heat Panels for fast Cabin Comfort (Ford)
Hardware Integration

- Use Case: Parcel delivery service
- Frequent door opening cools the cabin esp. in winter conditions
- Solution:
  - Heating panels for fast driver comfort
  - Low time constant → Immediate comfort increase
  - Energy demand: ~250W
  - Reduced hardware costs especially compared to a heat pump system

Heated Panel Position	Temperature Set Point
Door Top	40°C
Door Side	60°C
Seat Head	40°C
Seat Arm	40°C
Sun Visor	60°C
Dash Lower	60°C
Rear Wall	60°C
Floor Mat	50°C

Heat Panels for fast Cabin Comfort (Ford)
Analysis of Different Heating Measures

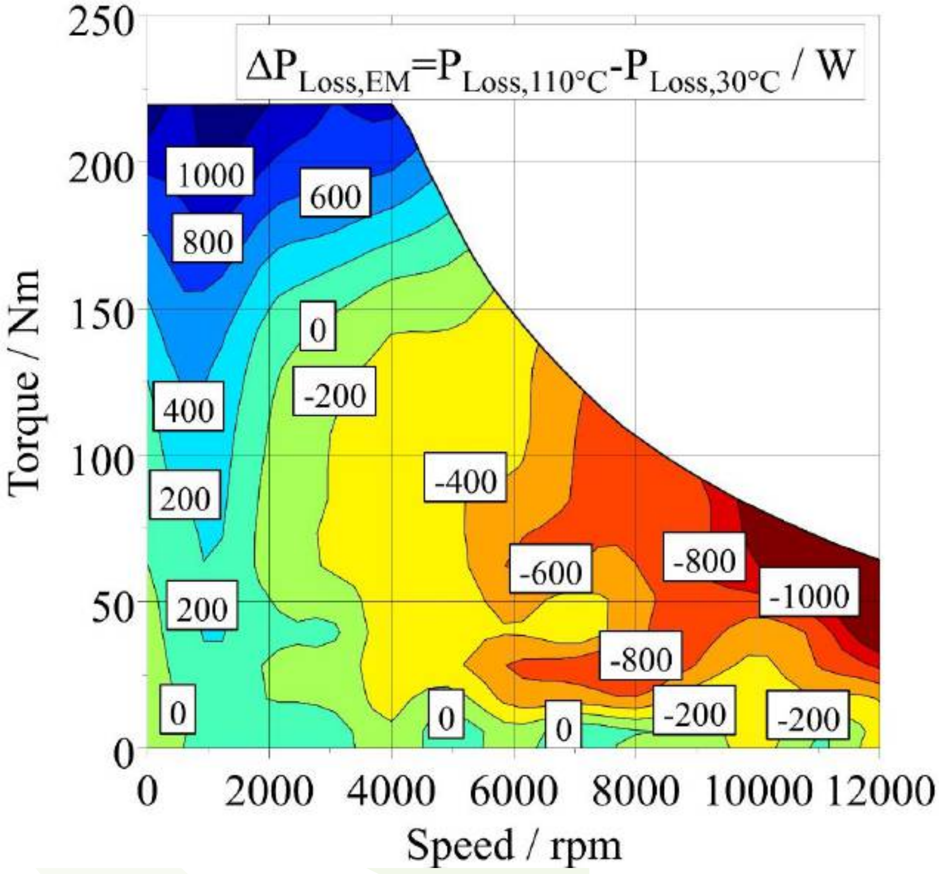
- Different relevant load cases have been analysed towards hardware measures
- Depending on the Use Case different measures are advantegous
- One reason is the cycle length and the frequency of door openings
- Due to cost aspects and fast comfort increase heating panels are advantegous especially for the delivery cycle use case



Agenda

- Aspects of Thermal Management on Long Distance Capability
- System Engineering Centered Development
- Hardware Solutions
  - Bosch's flexible Skateboard Approach
  - Heat Panels for fast Cabin Comfort (Ford)
- Software Solutions
  - Predictive Powertrain Conditioning
  - Predictive Cabin Conditioning

Temperature Dependent Efficencies
Electric Motor Characteristic Map



Total Power Loss in PMSM:

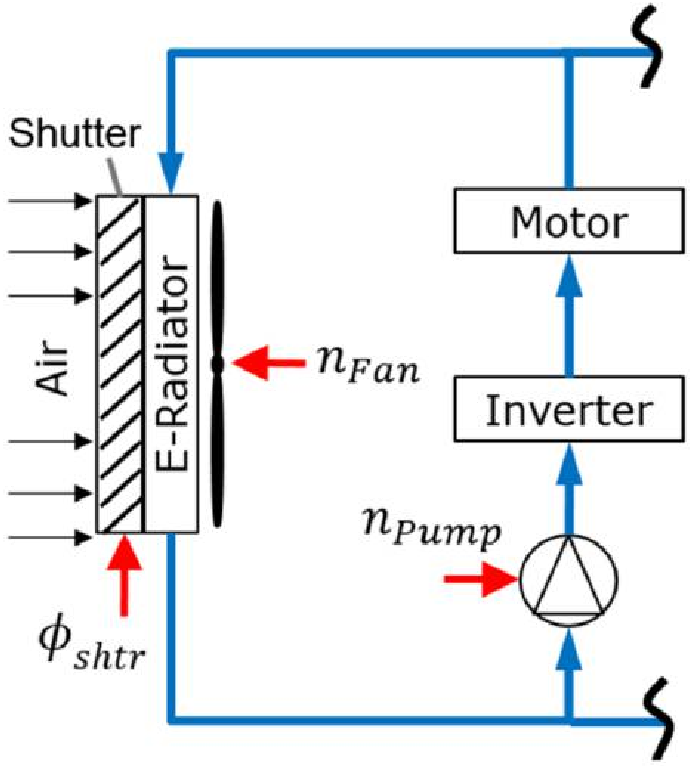
$$P_{Loss,Tot,PMSM} = P_{Loss,Copper} + P_{Loss,Iron} + P_{Loss,Magnet} + P_{Loss,Mech}$$

- Loss mechanisms:
  - Copper losses: $P_{Loss,Copper}$
  - Iron losses: $P_{Loss,Iron}$
  - Magent losses: $P_{Loss,Magnet}$
  - Mechanical losses: $P_{Loss,Mech}$
- The temperature dependence is mainly due to thermal field weakening so less current needs to be invested.
- Additionally, the copper losses itself are temperature dependent:

$$P_{Loss,copper} = i^2 \cdot \rho_{Cu}(T) \cdot \frac{l}{A} = i^2 \cdot \rho_0 \cdot [1 + \alpha \cdot (T - T_0)] \cdot \frac{l}{A}$$

Wahl, Alexander et al., Efficiency increase through model predictive thermal control of electric vehicle powertrains, *Energies, 2022, 14*

Powertrain Thermal System Layout
System of Investigation



General:

- For understanding the function behaviour & obtaining first gains a simplified thermal layout was chosen

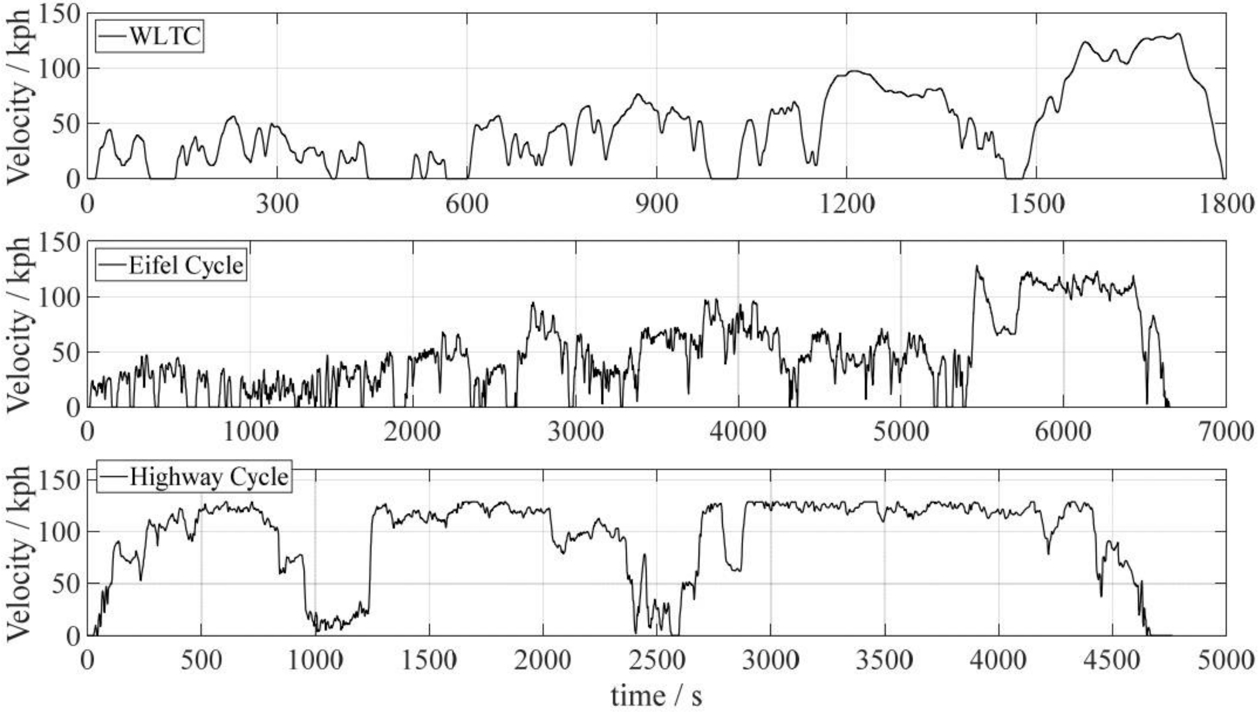
Target:

- The overall system shall be operated at minimum energy invested
- Pump and fan provide cooling, but cost electical energy
- Sweetspot between actuators and temperature dependent efficencies to be found

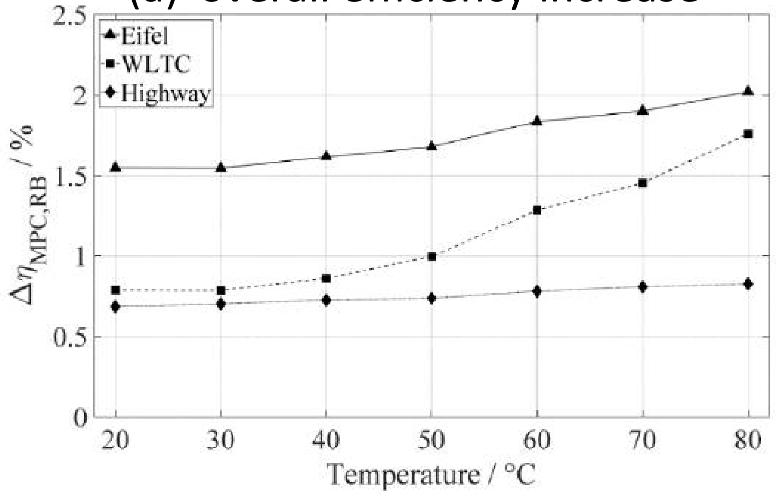
Wahl, Alexander et al., Efficiency increase through model predictive thermal control of electric vehicle powertrains, *Energies, 2022, 14*

Simulative Results
As published in [1]

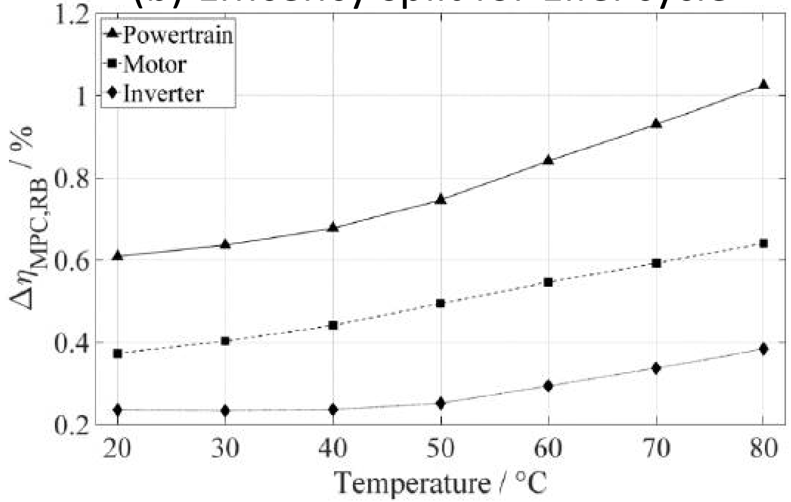
Investigated drive cycles



(a) overall efficiency increase

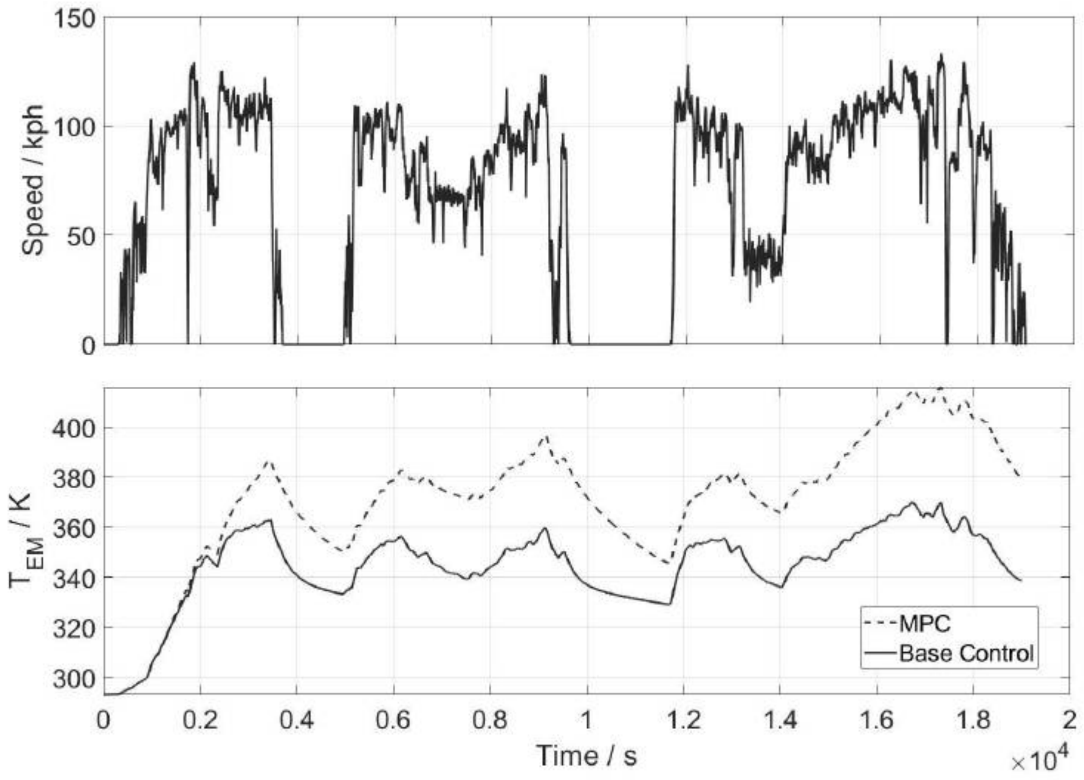


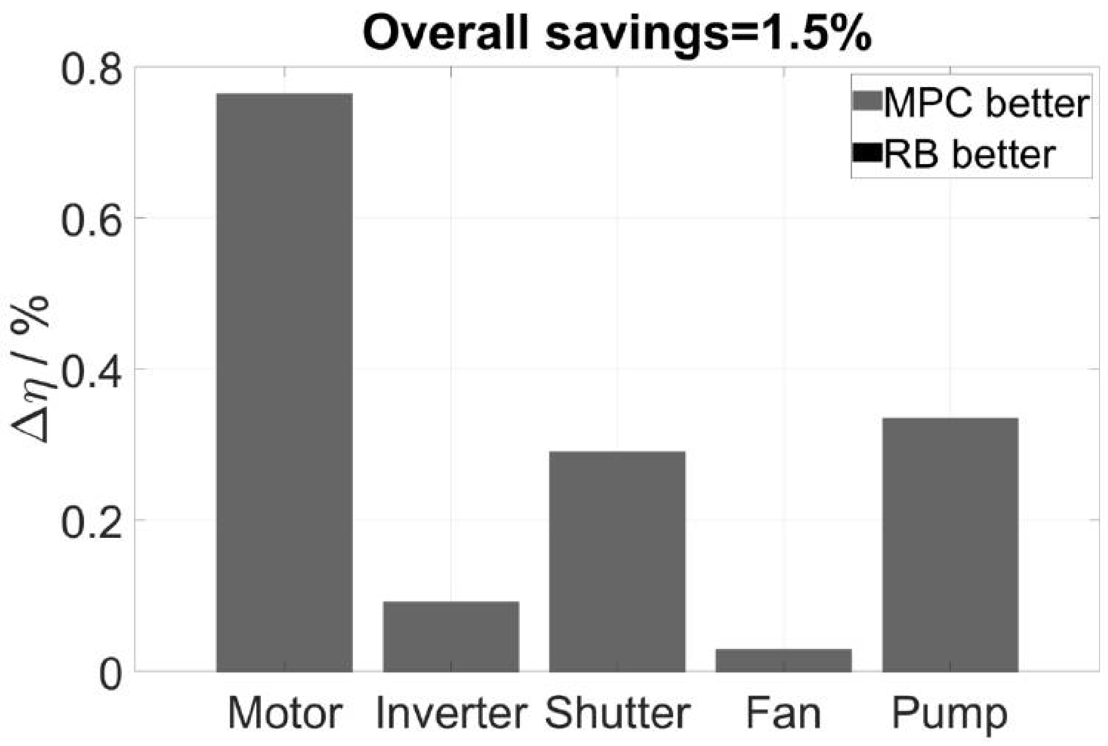
(b) Efficency split for Eifel cycle



[1] Wahl, Alexander et al., Efficiency increase through model predictive thermal control of electric vehicle powertrains, *Energies, 2022, 14*

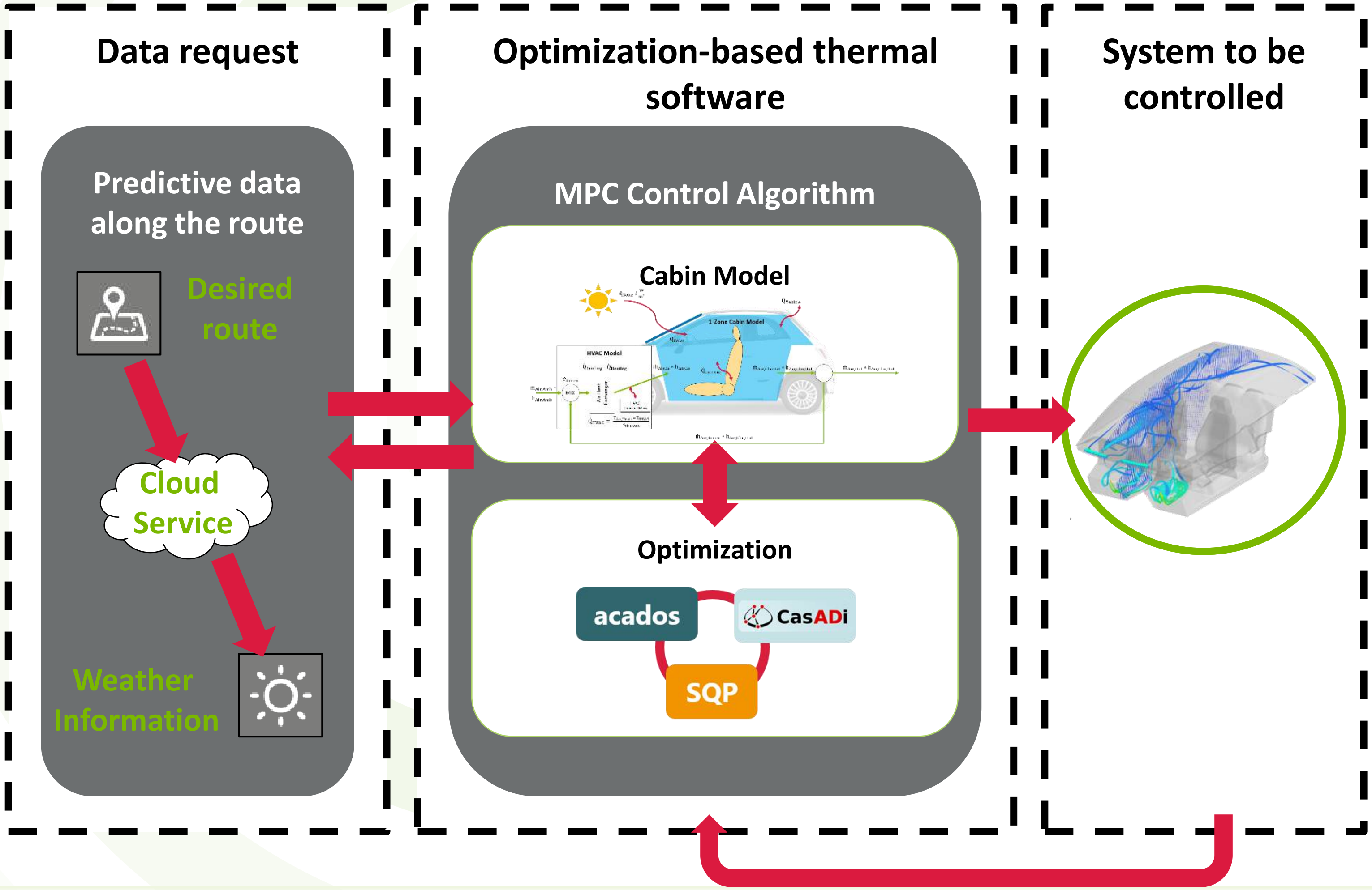
Simulative Results of Long Distance Trip Turin – Ceriale Roundtrip 350km





→The savings reflect a distance increase of 10.5km on a 700km roundtrip

Functional architecture for optimizing cabin climatization using predictive data



State variables $\mathbf{x_i}$, Control variables $\mathbf{u_i}$

$$x_i = \begin{bmatrix} T_{Air,Cbn} \\ T_{Interior} \\ T_{HVAC} \end{bmatrix}, u_i = \begin{bmatrix} r_{Cooling} \\ r_{Blower} \\ r_{Heating} \\ r_{Fresh\ Air} \end{bmatrix}$$

Nonlinear MPC

$$x_i(k+1) = f(x_i(k), u_i(k))$$
$$y(k) = f(x_i(k), u_i(k))$$

Constraints

$$\begin{bmatrix} T_{Air,Cbn,min} \\ T_{Interior,min} \\ T_{HVAC,min} \end{bmatrix} \leq x_i(\cdot|k) \leq \begin{bmatrix} T_{Air,Cbn,max} \\ T_{Interior,max} \\ T_{HVAC,max} \end{bmatrix}$$

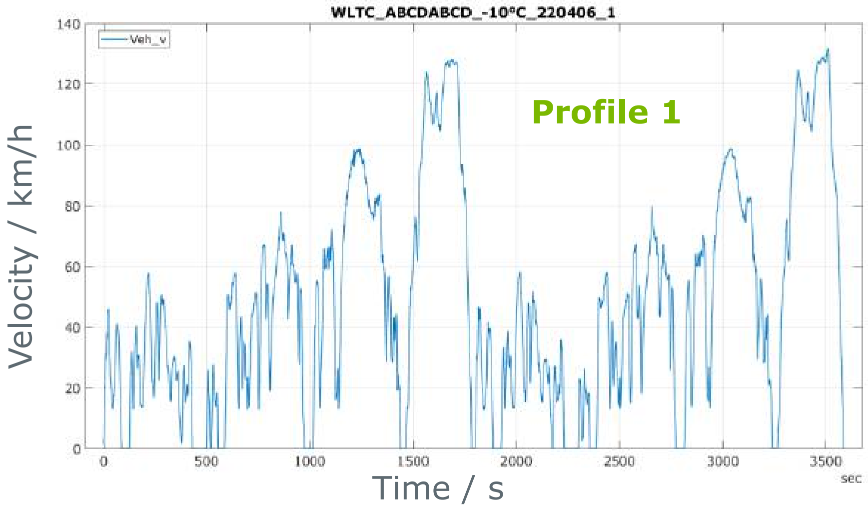
$$\begin{bmatrix} r_{Cooling,min} \\ r_{Blower,min} \\ r_{Heating,min} \\ r_{FreshAir,min} \end{bmatrix} \leq u_i(\cdot|k) \leq, \begin{bmatrix} r_{Cooling,max} \\ n_{Blower,max} \\ r_{Heating,max} \\ r_{FreshAir,max} \end{bmatrix}$$

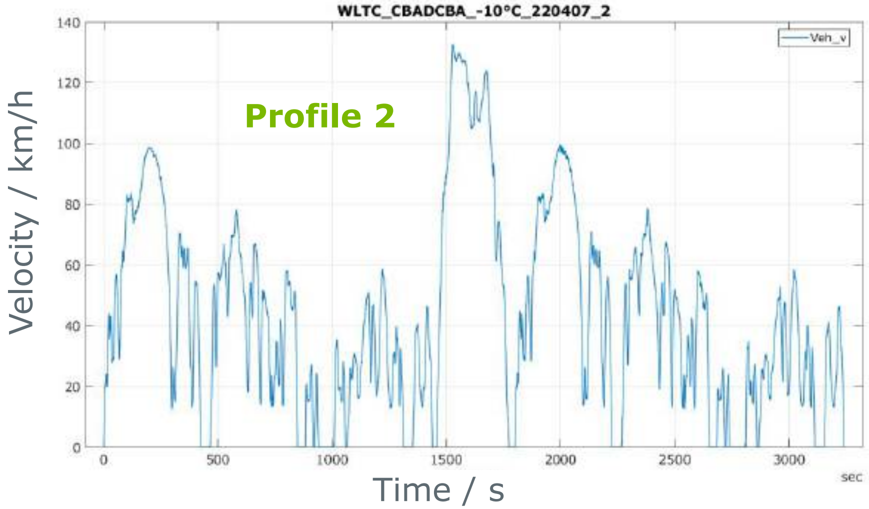
Vehicle Measurements for the Optimized Cabin Conditioning with CRF Validator 1

OVERVIEW OF THE CRF MEASUREMENT CAMPAIGN

MEASUREMENT BOUNDARIES

- Measurements in conditioned roller dyno
- 2 different driving profiles based on WLTC Phases
  - Use case: Commute to work
  - 2 Different speed profiles
- Two different ambient conditions
  - -10 °C & 35 °C
- Various baseline and advanced measurements

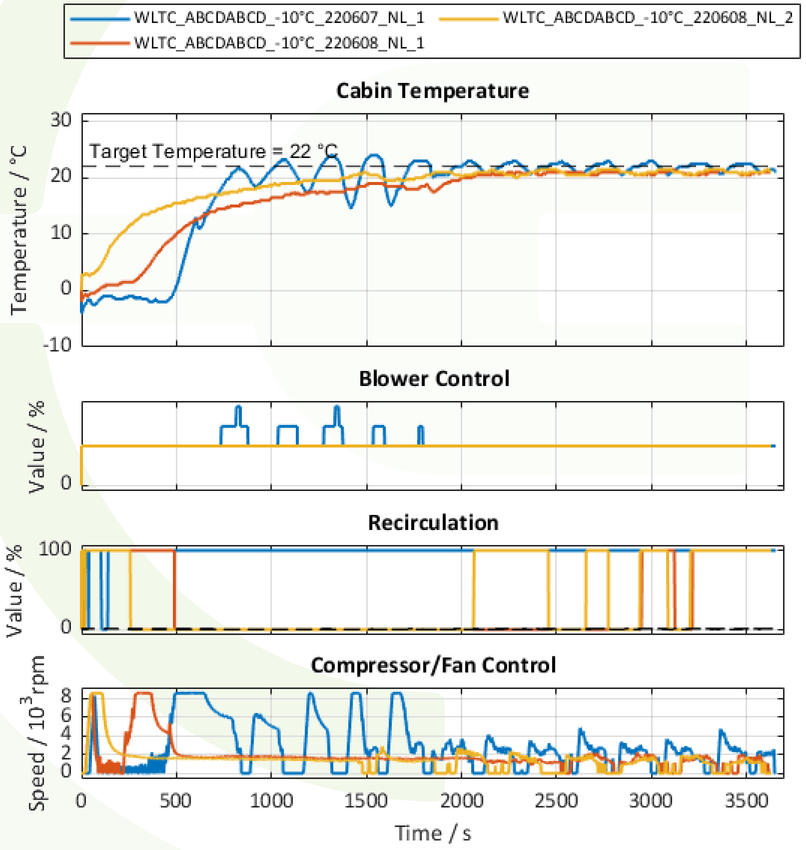




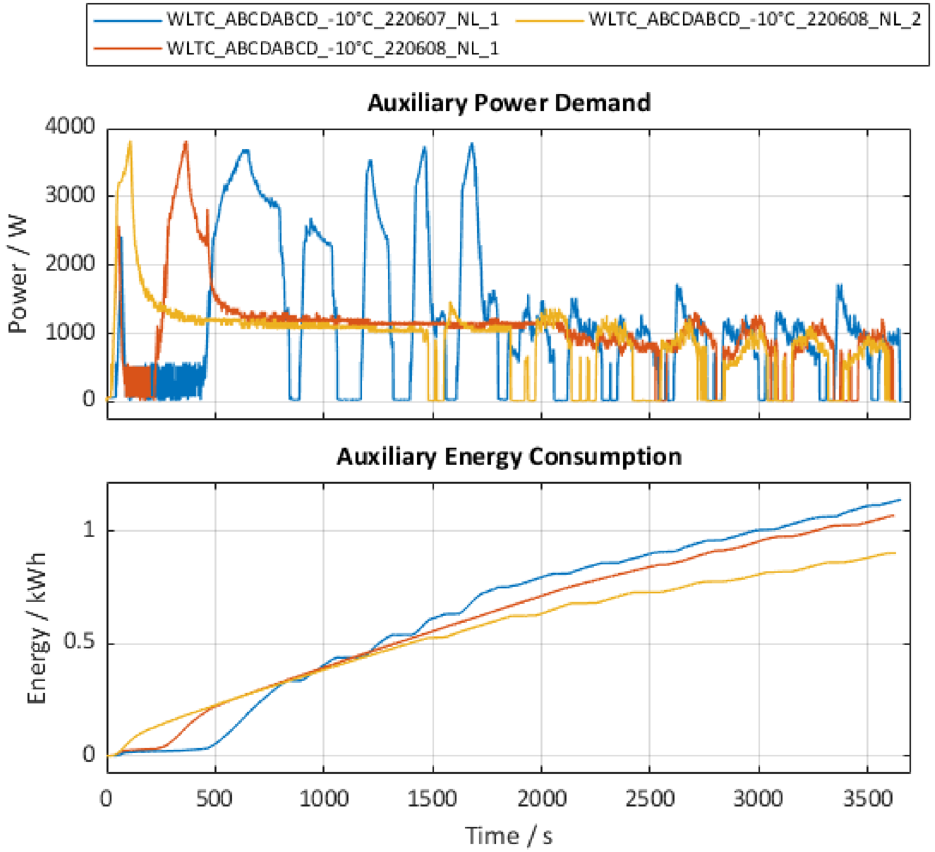
Exemplary Measurement Results for the CRF Validator 1

SPEED PROFILE 1 (HOME → WORK) | -10 °C

CABIN TEMPERATURE & CONTROLS



AUXILIARY ENERGY CONSUMPTION



Evaluation of the new functionalities for cabin conditioning

SUMMARY

CRF VALIDATOR 1

- Savings range from **13.4 %** to **32.3 %** for cold ambient conditions for the auxiliary energy consumption for specific measurements
- Lower savings potential on auxiliary level for hot ambient conditions (max. **6.4 %** for specific measurements)
- Main savings due to:
  - Utilization of recirculation rate
  - Improved control of the fan
  - More efficient operation of the compressor due to improved set points
- In average the following energy savings could be achieved (average of all measurements conducted):
  - Hot case (35 °C): **2.5 %**
  - Cold Case (-10 °C): **1.3 %**

Conclusion

Is Advanced Thermal Management An Enabler of Long Distance Capability?

- The thermal system has still the highest energy consumption after the powertrain
- Heat pumps have shown in the project to be an effective measure to enhance the range for highway drives
- For special use cases, heating panels can be advantegous over a heat pump
- Thermal system controls are an important contributor to future savings especially cabin conditioning