
THERMO
ANALYTICS

Balancing Range and Occupant Thermal Comfort for Mass Transit Applications

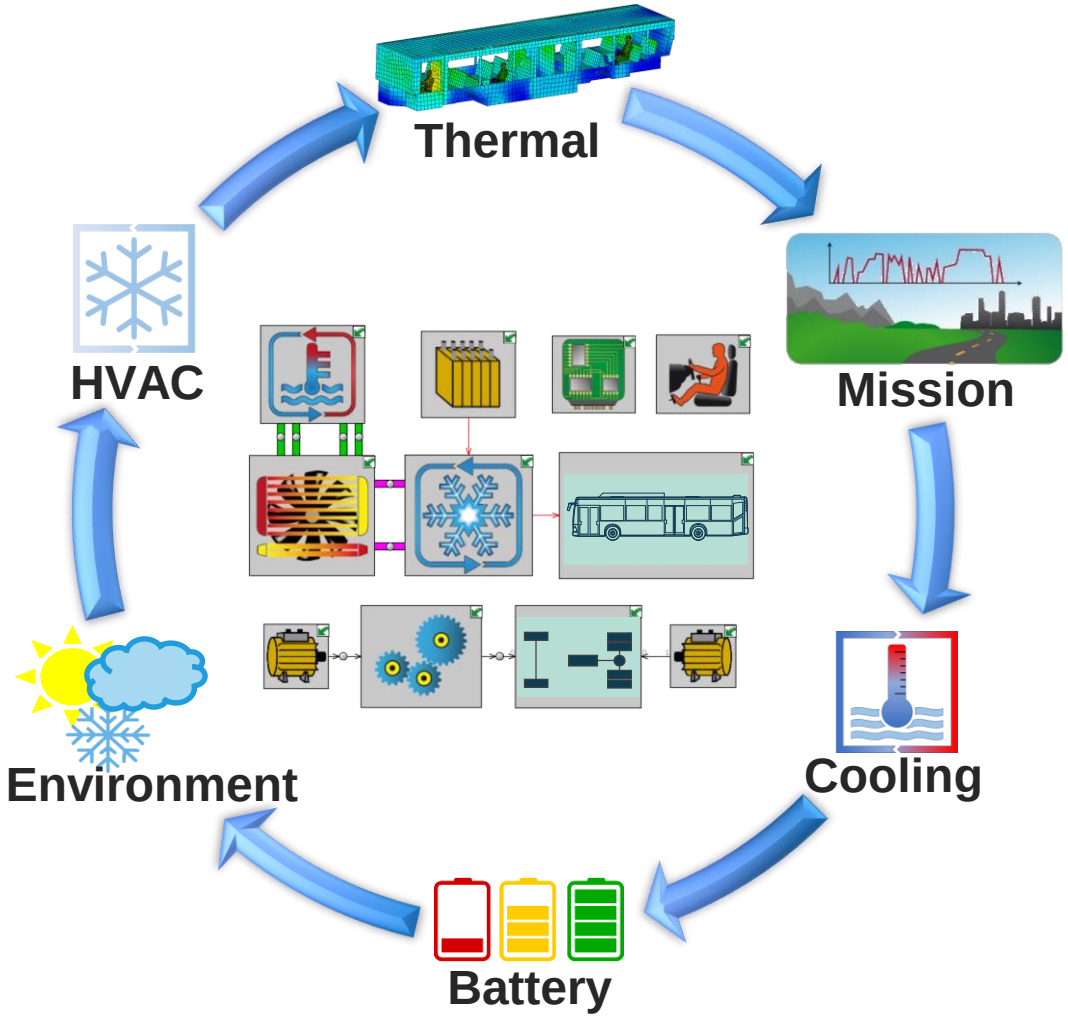
Marek Lehocky – Gamma Technologies

Jon Juszkiewicz - ThermoAnalytics

THERMO ANALYTICS

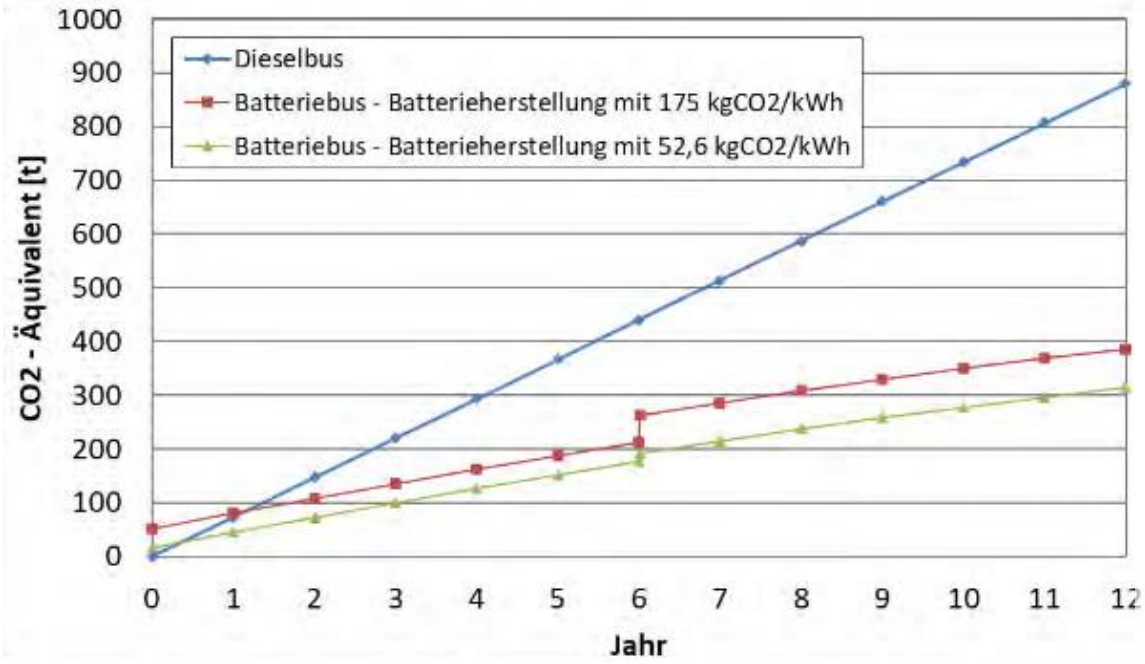
Agenda

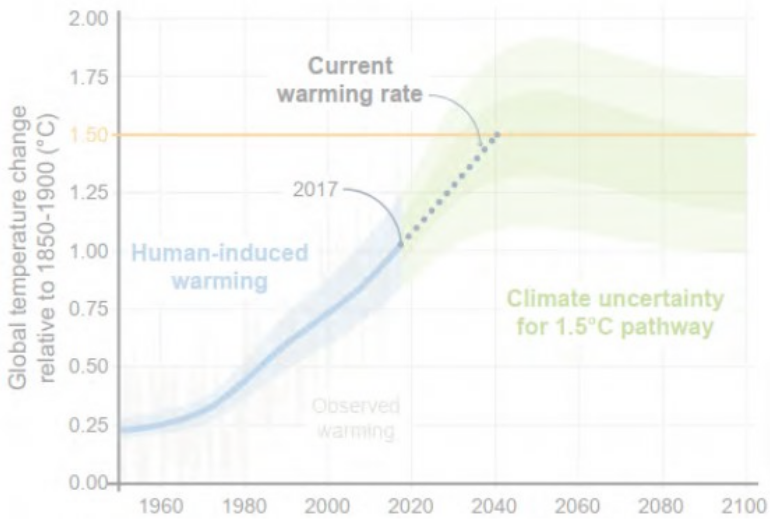
1. The Importance of Reducing CO_2 Emissions
2. Range Vs. Cabin Conditioning
3. Electric Buses
4. Integrated Systems Modeling
5. Cabin Simulation Options
6. Integrated Modeling Workflow
7. Integrated Model Setup
8. Environmental Metrics
9. Thermal Sensation
10. Thermal Comfort
11. Integrated Model Results
12. Energy and Occupant Perception
13. Conclusions

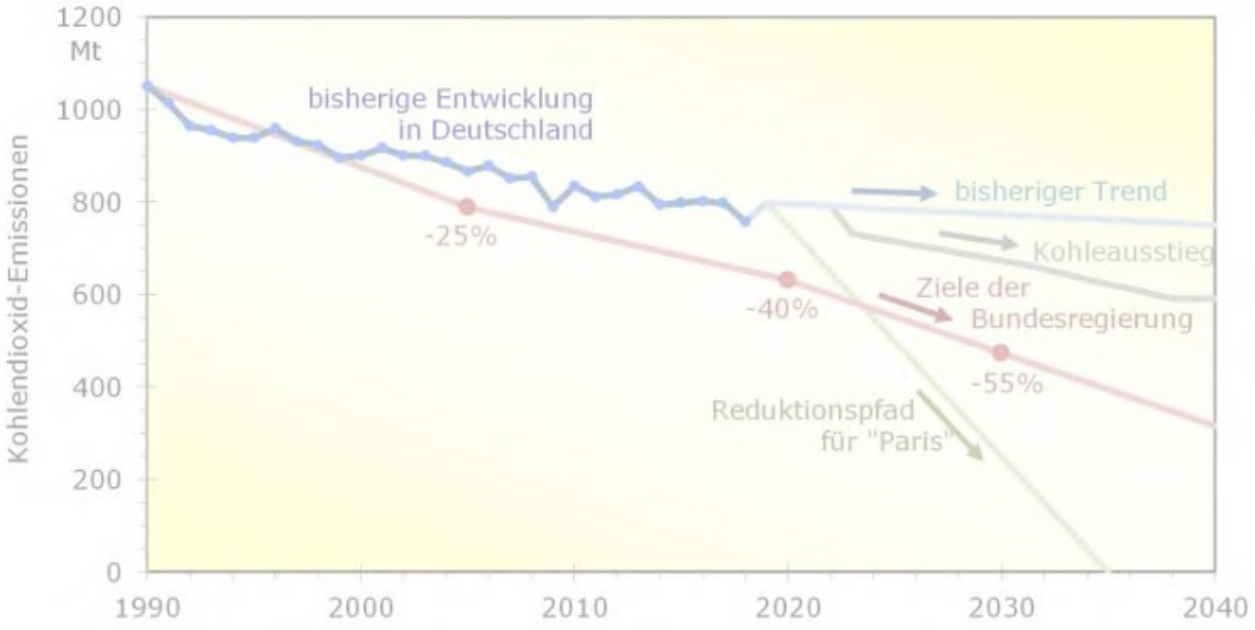


The importance of Reducing CO_2 Emissions

- Greenhouse gas emissions are causing a rise in global temperatures
- Reduction and mitigation strategies are being aggressively pursued in all sectors
- Electric busses are one part of this solution

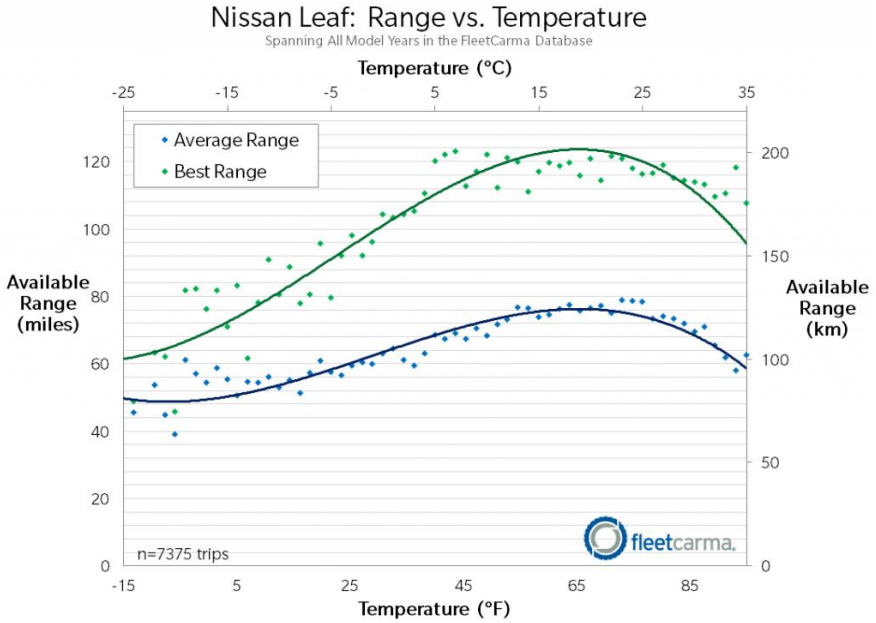


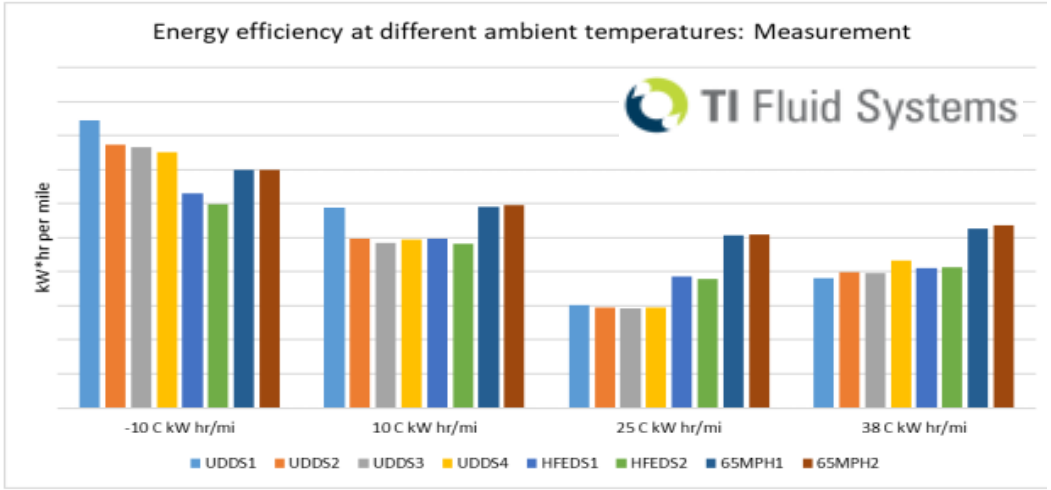




Range Vs. Cabin Conditioning

- Air conditioning significant energy consumer
  - 2013 fleetcarma database
    - ~35% in Winter, ~25% in Summer
  - 2020 NAF winter testing of 20 vehicles:
    - Average range reduction by about 10-30%
  - TI Fluid Systems measurement
    - -10°C: High PTC heater consumption
    - 25°C: A/C almost idle
    - 38°C: Cooling cabin and battery





Typical thermal driving cycles were recorded

Electric Buses

- Municipalities around the world are seeing electric buses as critical for future urban mobility

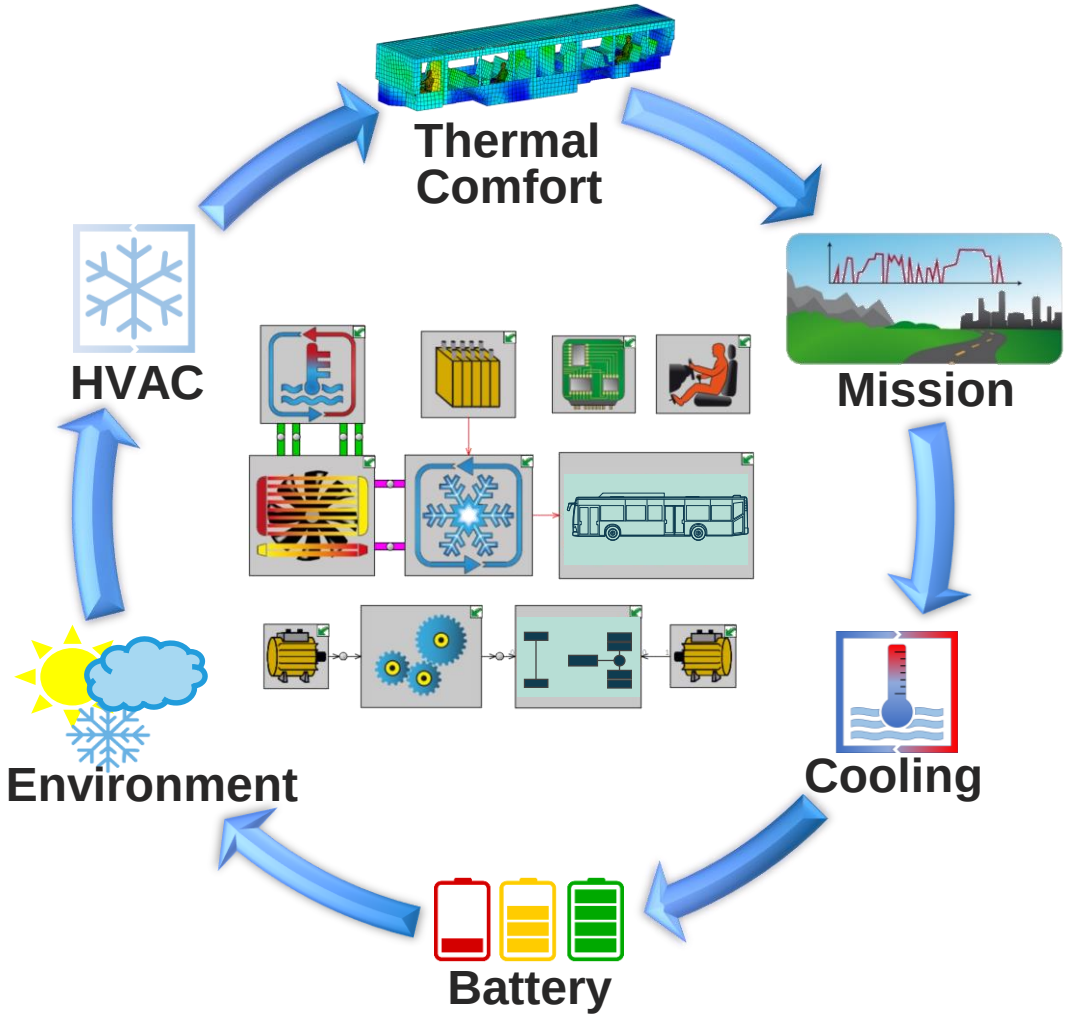
- Fully electric busses have no waste heat to condition the cabin with
  - Heating is critical in many parts of the world
    - 60-70% of the time in Western-Europe
  - HVAC consumption can be 60% of battery capacity
  - HVAC energy consumption adversely affects range

- Buses offer unique challenges compared to commercial vehicles
  - Multiple Occupants
  - Time on vehicle varies
  - Doors opening and closing

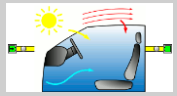
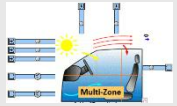
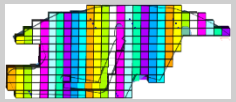
Integrated System Modeling

- Electrification is driving a shift to integrated systems modeling
  - Complex Component and System Interactions
  - Limited energy capacity

- Integrated modelling provides:
  - Earlier understanding of systems interactions
  - Lower cost and faster turn around than physical testing
  - Increased numbers of design iterations



Cabin Simulation Options

Number of Fluid Volumes	Real Time Simulation	Controls Simulation	Long Transient Simulation	Predictive Capability
1 	✓	✓	✓	- -
1-10 	✓	✓	✓	- -
1k-10k 	✓	✓	✓	+
1M+ 	✗	✗	✗	+ +

Cabin Simulation Options

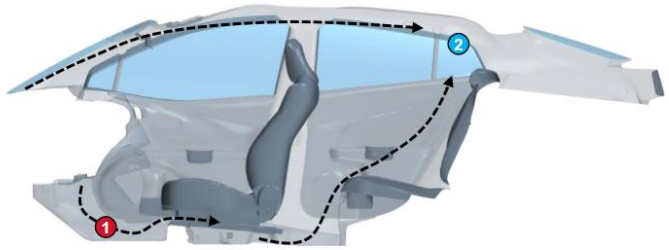
- Simulation method has been validated on several published cases
  - Toyota Motor Europe
  - Volvo Cars

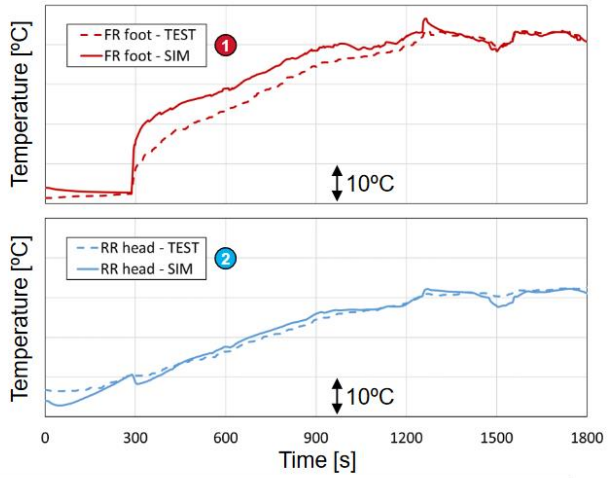
- Many unpublished validation cases

Initial results – Air temperature

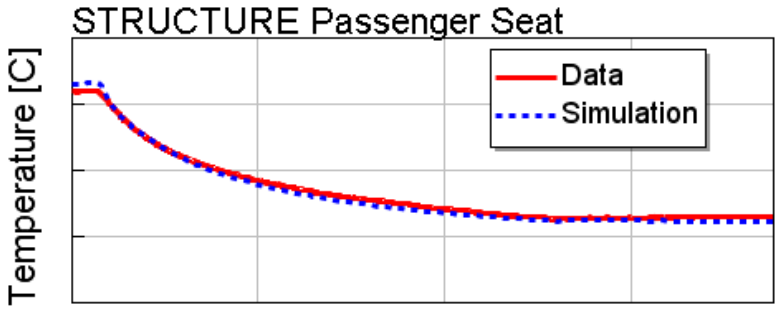
Model shows good prediction, but accuracy near cabin flow inlets to be improved

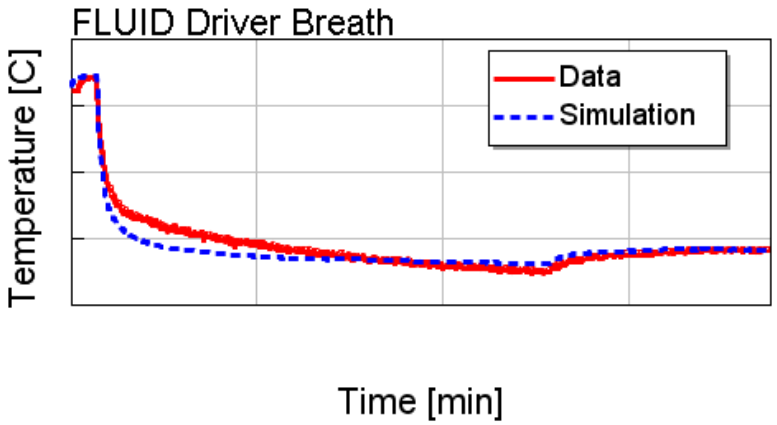
Simulation conditions	
Ambient:	Winter
HVAC setting:	Cabin heating
Driving cycle:	WLTC
Model inputs:	CWT test data





※ CWT = Climatic Wind Tunnel





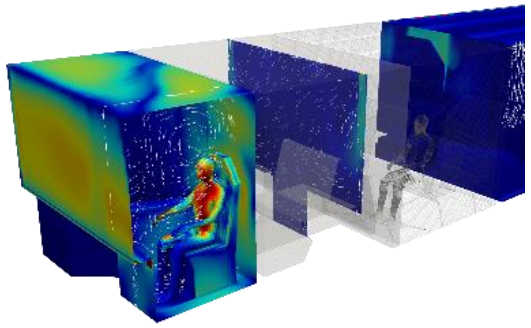
Integrated Modeling Workflow

- Unique technology allows fast, 3D-resolved cabin simulation
  - Including physiology-based comfort simulation
  - CFD results are automatically mapped to coarser-grid GT-SUITE solution
  - GT-Converge can be used for easy and fast 3D-CFD simulation

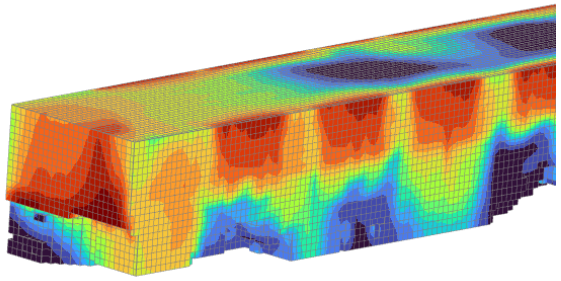
CFD tool of choice

CONVERGENT SCIENCE

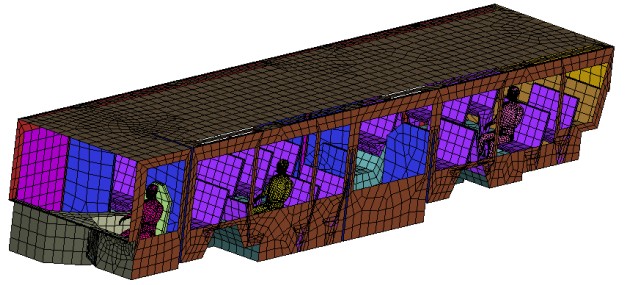
GT-CONVERGE



GT-SUITE



TAITherm



Fluid temperature
Species propagation

Thermal structure solution
Passenger comfort/sensation

Integrated Modeling Workflow

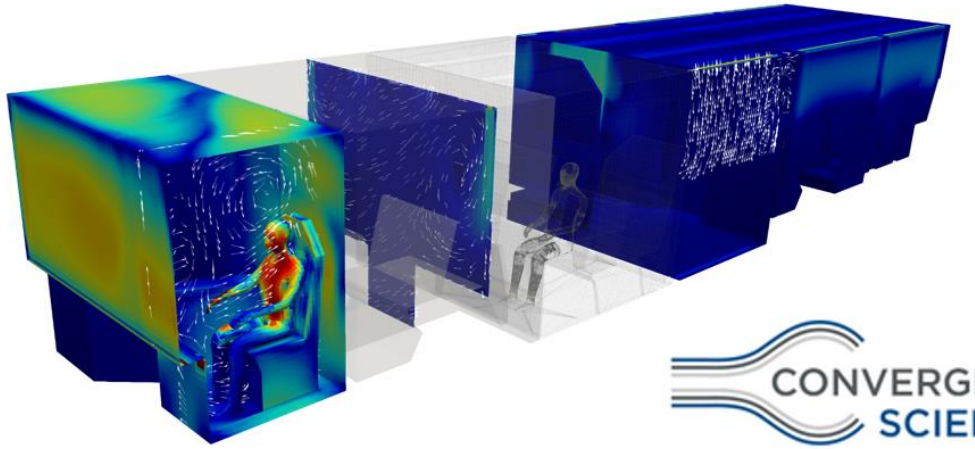
- Unique technology allows fast, 3D-resolved cabin simulation
  - Including
  - CFD resu
  - GT-Conve

solution

GT Converge

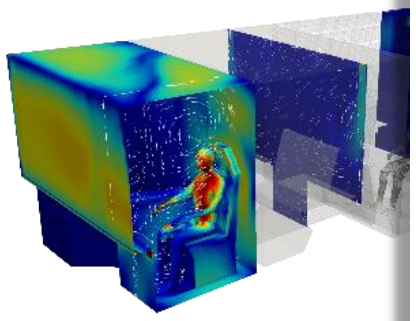
GT-Converge: Integrated CFD solution allows early-stage investigations with detailed flow results

- Seamless integration within the GT-SUITE and TAITherm coupling process
- Automatically generate data for fast drive-cycle simulation
  - Varying blower speeds
  - Varying outlet vent configuration



CONVERGENT SCIENCE

CFD tool of choice



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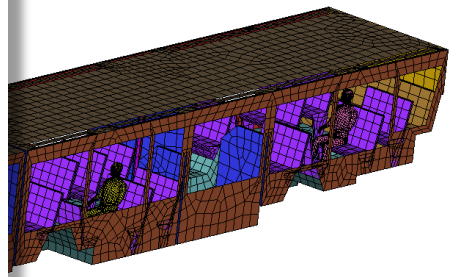
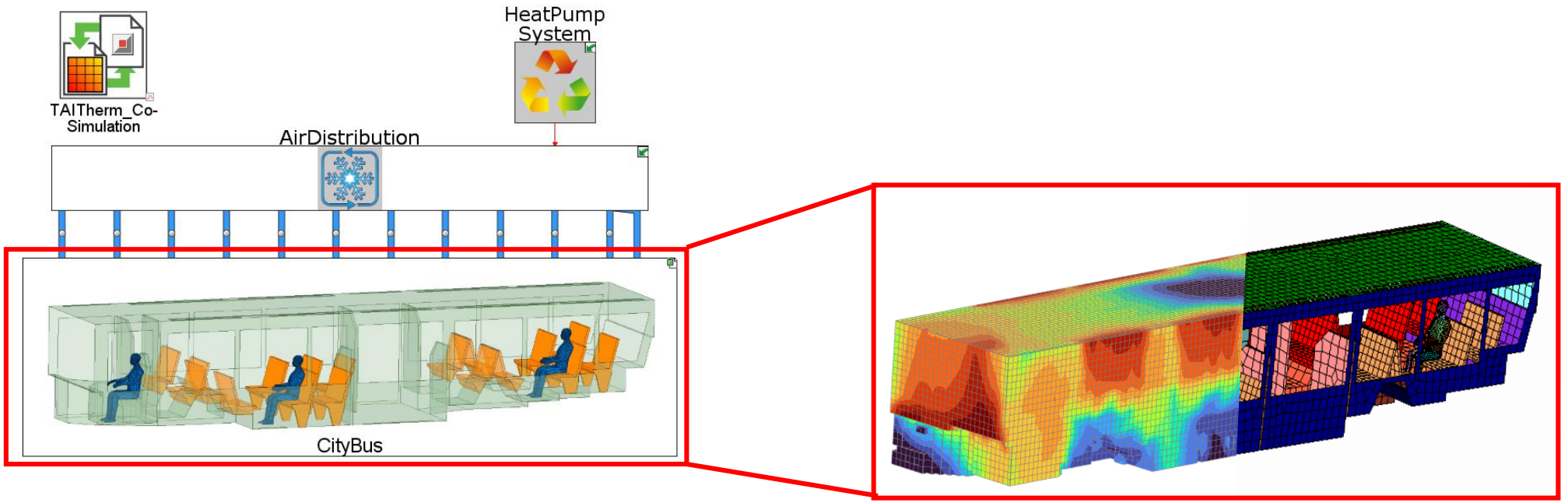


Thermal structure solution
Passenger comfort/sensation

Integrated Model Setup

Flexible platform allows testing of different system combinations and topologies under varying boundary conditions



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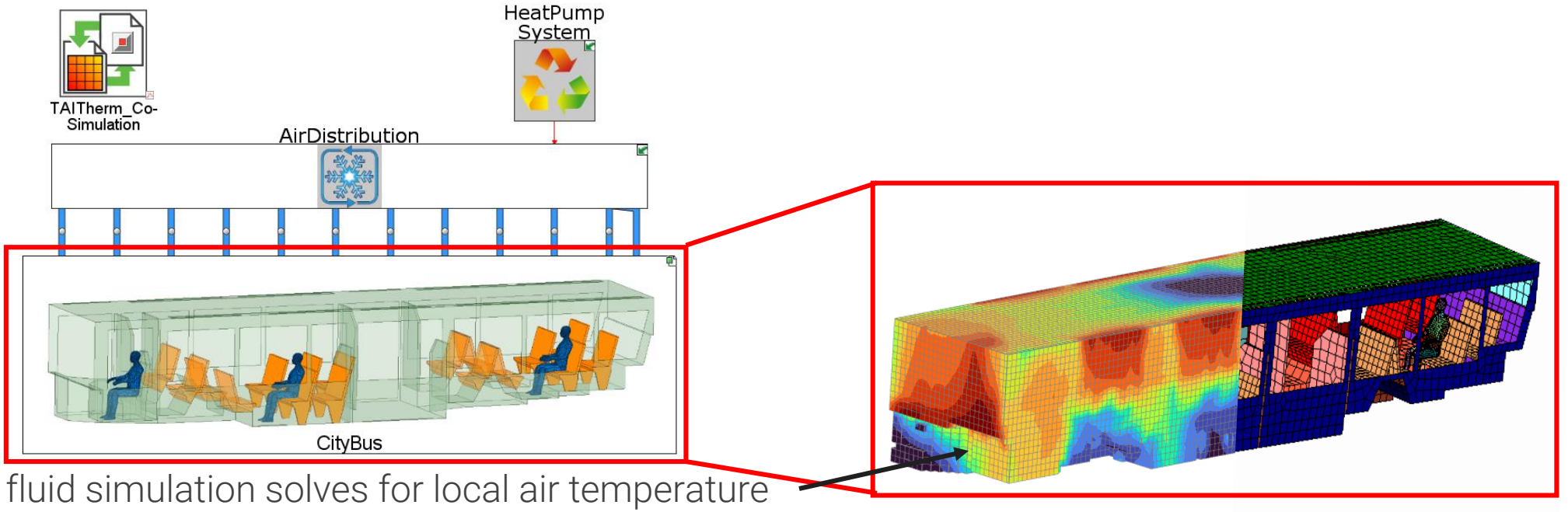

Fast running fluid simulation solves for local air temperature

- Flow solver uses mapped CFD data for advection field
- Temperatures are calculated based on inlet conditions
- Orders of magnitude faster than CFD solution

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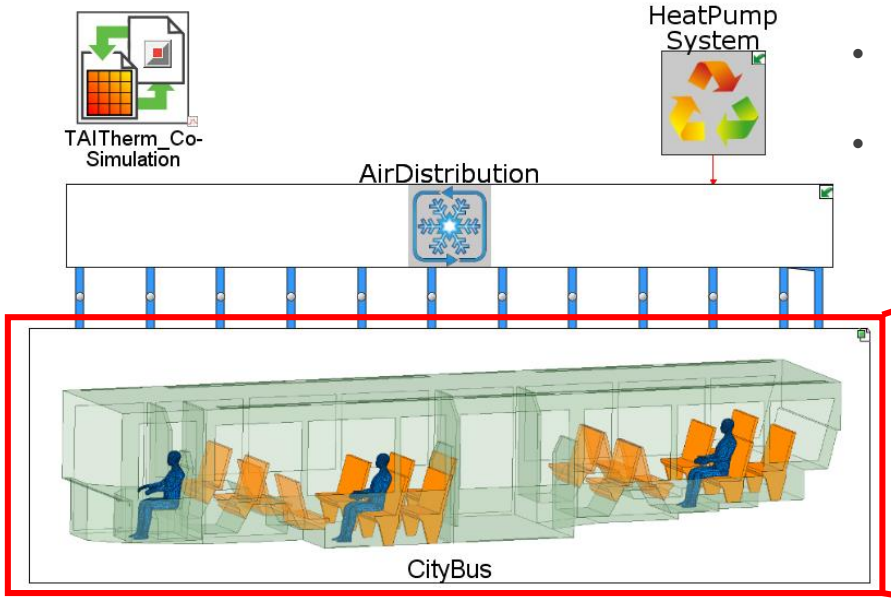
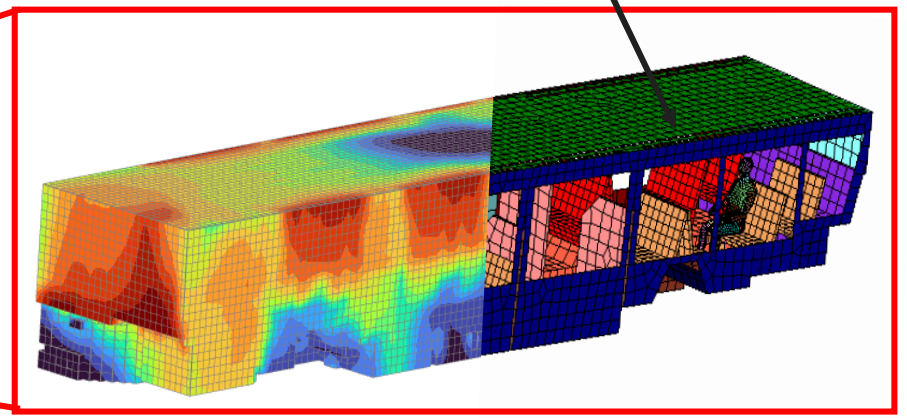


Multi-layer shell conduction walls

- Highly accurate, fast running thermal wall temperatures
- Increased fidelity with consider layers of trim, insulation, and body



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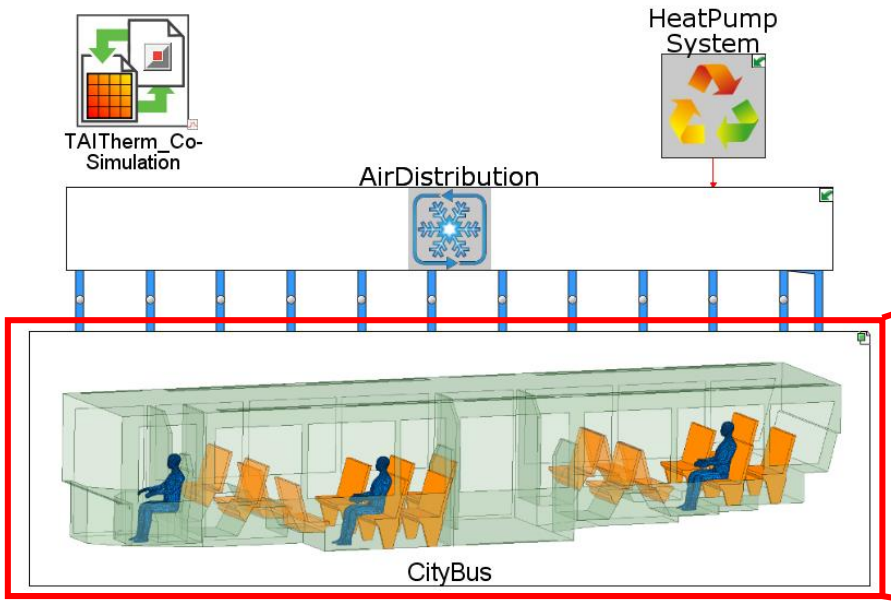
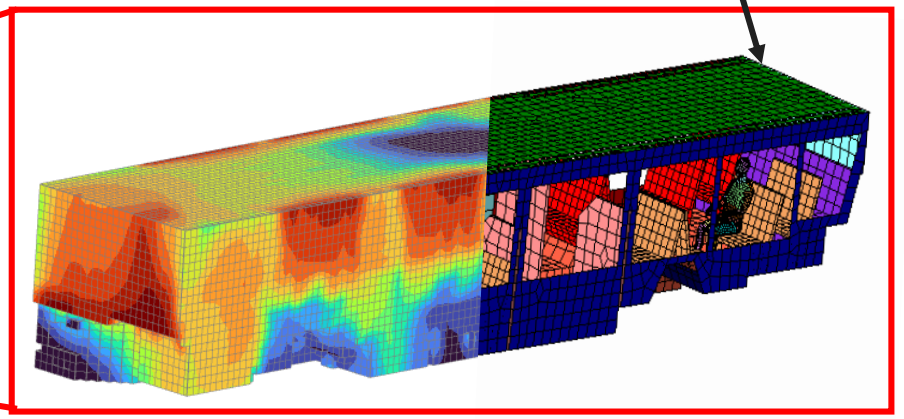


Correlation used for exterior convection

- Save simulation time by not simulating exterior flow
- Accurate correlation for A-B design studies
- External flow data can be used to improve accuracy



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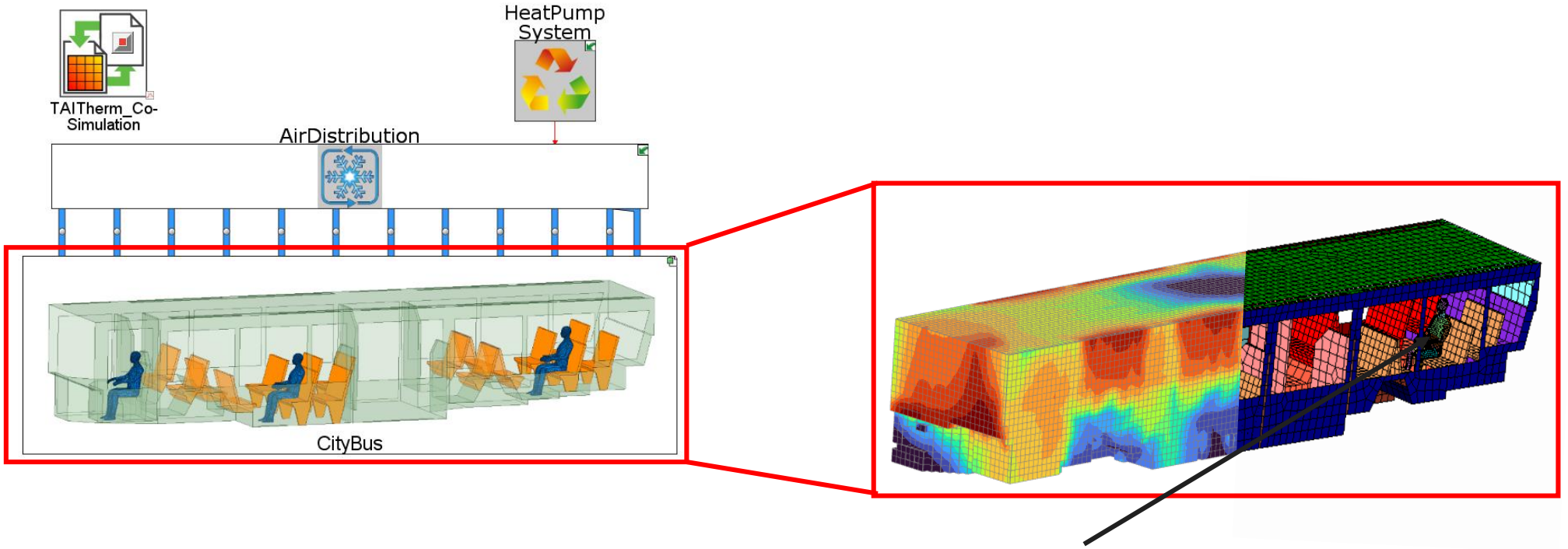

Human Thermal Physiology Manikins

- Consistent assessment of occupant thermal state
- Accurate predication of thermal sensation and comfort enabled by industry leading human thermal physiology model

Integrated Model Setup

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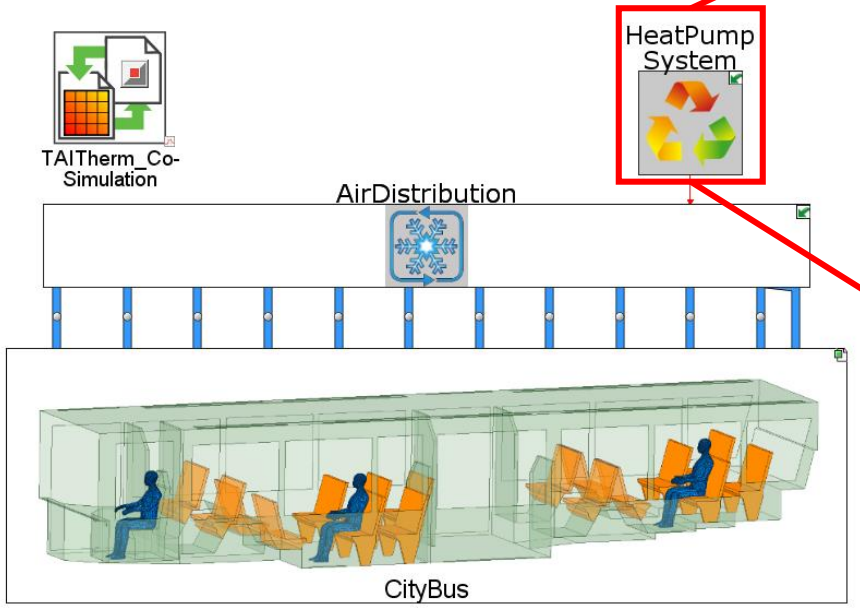
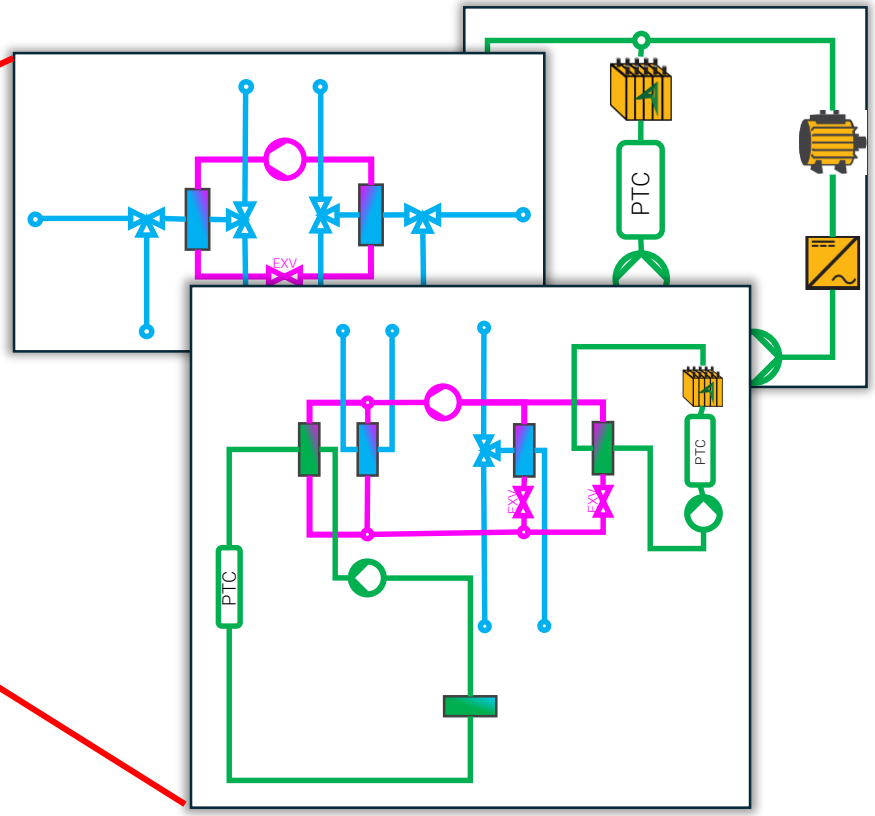
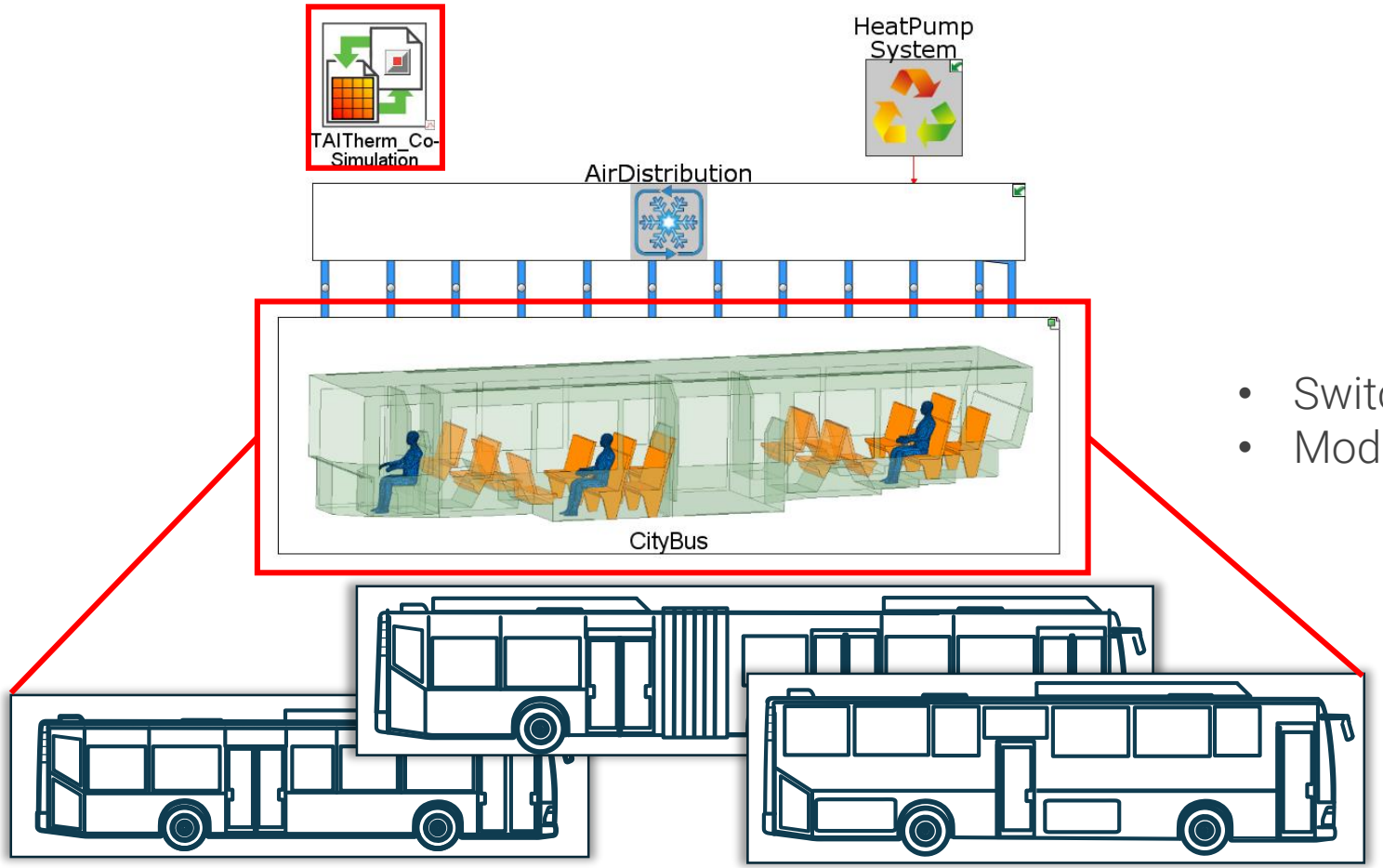




- Switch complete topologies
- Switch Refrigerant Fluids (R134a, CO2, R260…)
- Switch components (heat exchanger selection)

Integrated Model Setup

Flexible platform allows testing of different system combinations and topologies under varying boundary conditions

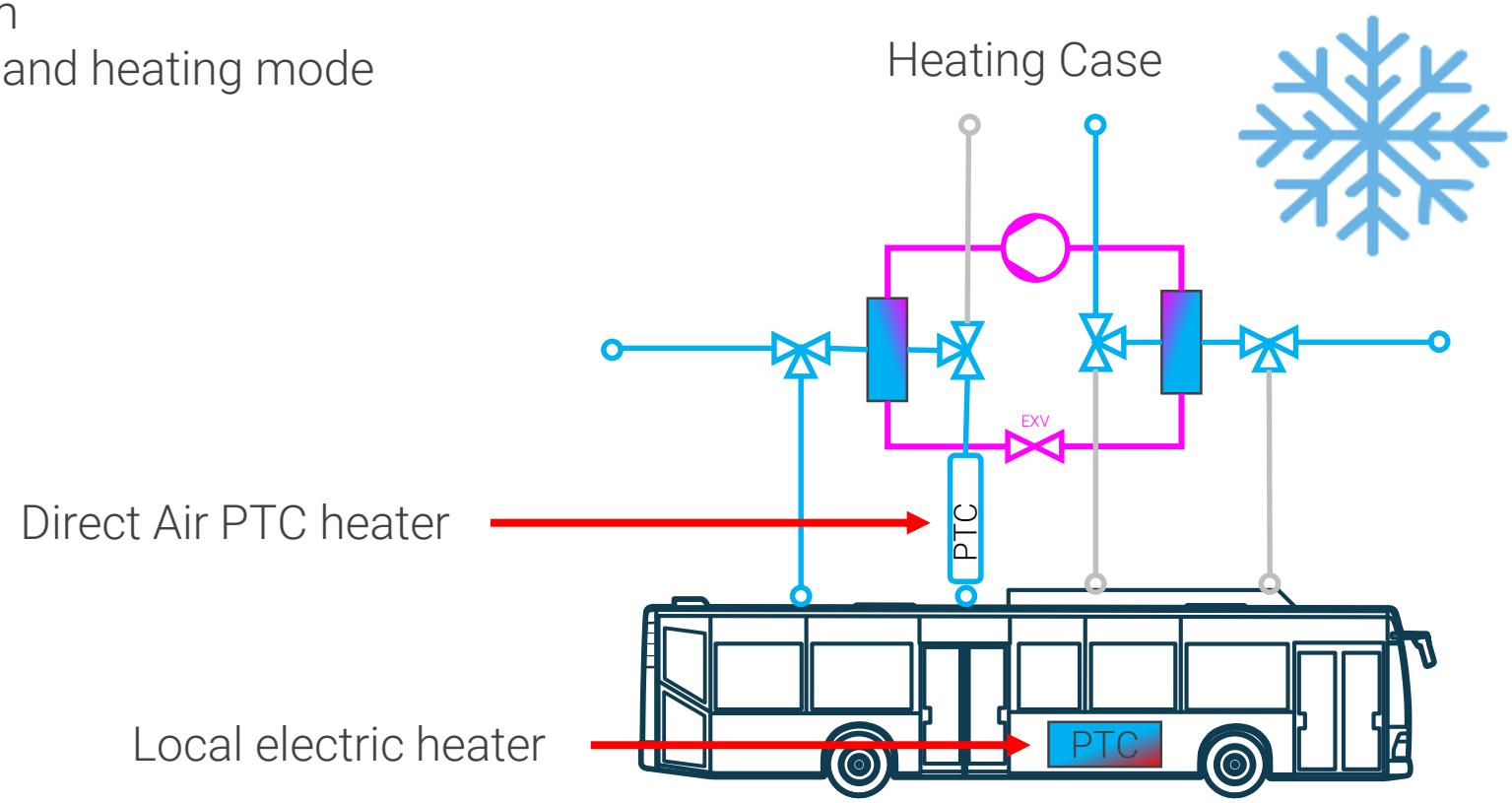


- Switch bus cabin type (city, articulated, travel)
- Modify air distribution and heating system

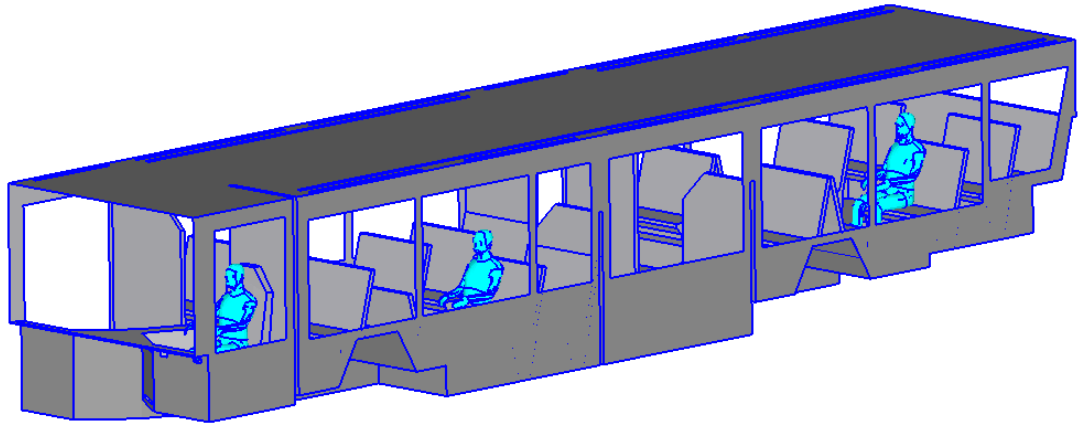
Integrated Model Use-Case

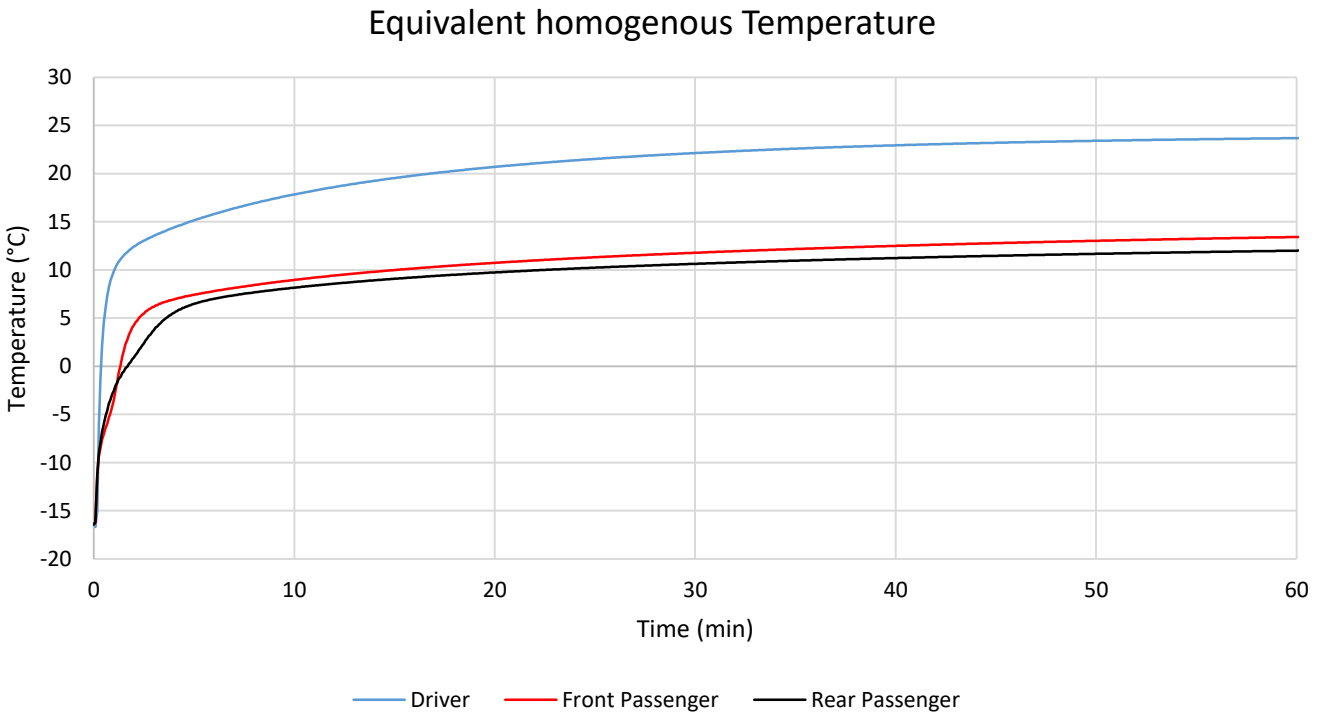
Simulation task: evaluate heat-pump system control strategies
- Heat-pump with air PTC heater
- Heat-pump with air PTC heater + local heater

System configuration:
- City bus
- Non-reversing CO2 heat-pump system
  - Air flaps switch between cooling and heating mode
- -10°C ambient temperature



Environmental Metrics

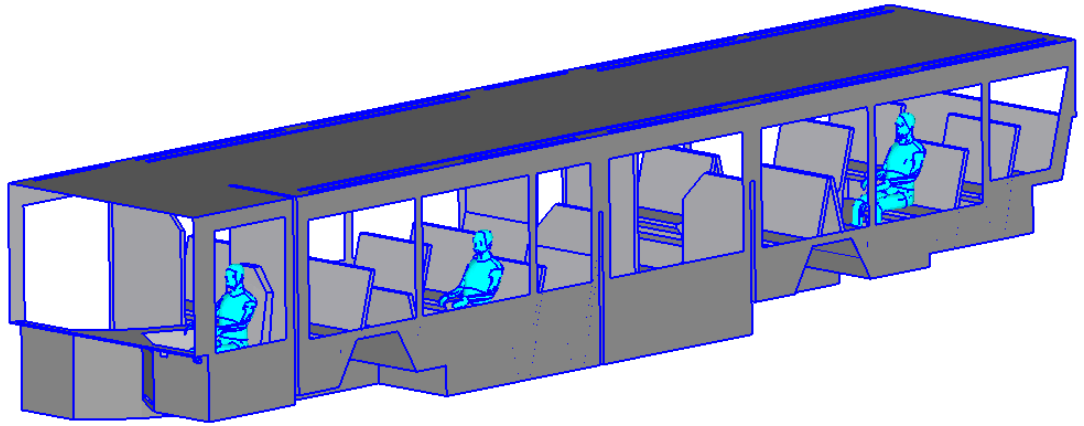


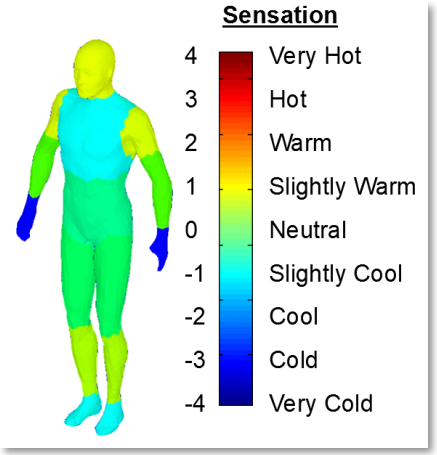


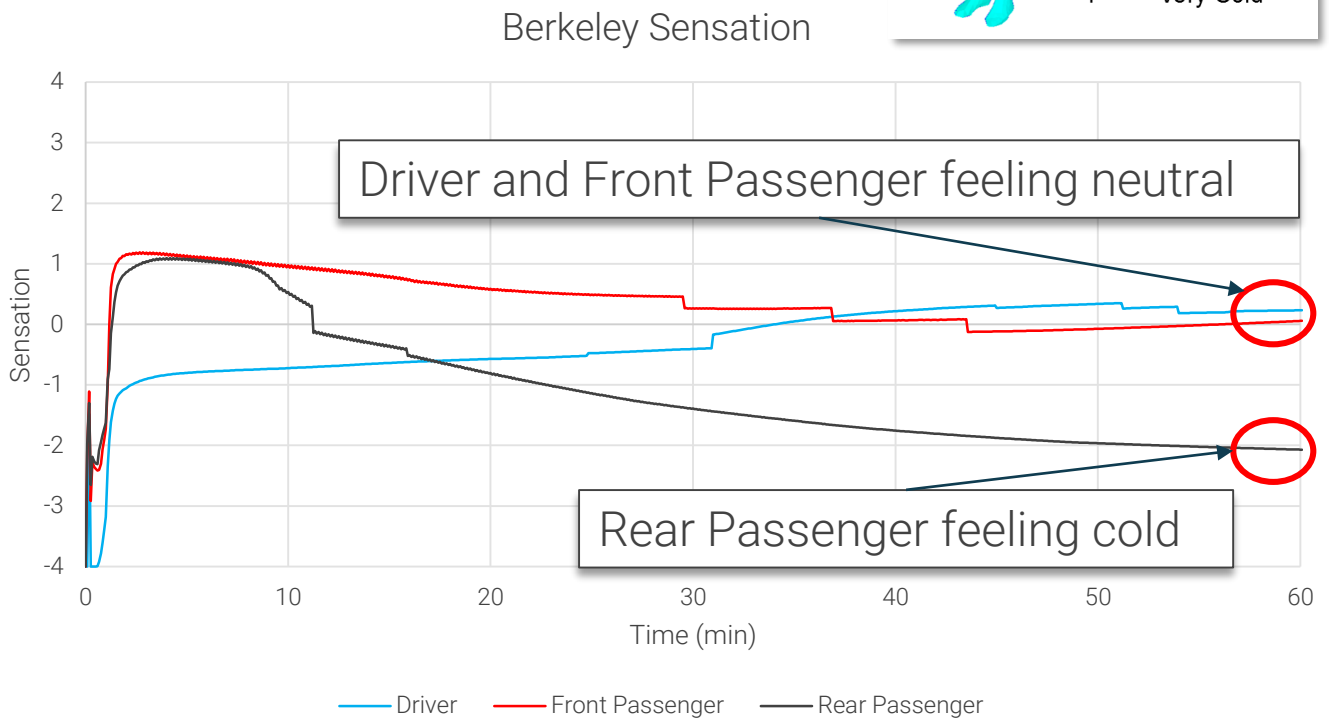
Equivalent Homogenous Temperature = f(MRT, Tamb)

- EHT measures environmental conditions
- Can be used as design target
- Can be related to occupant sensation

Thermal Sensation



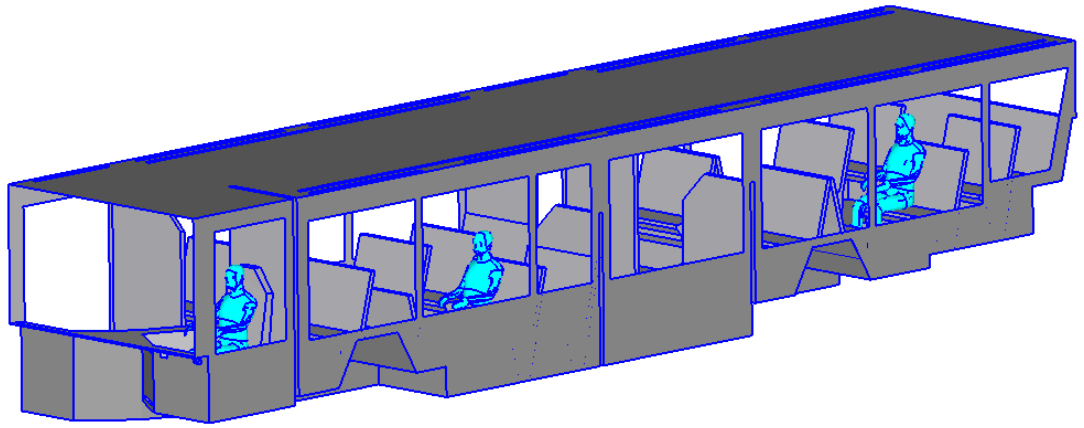


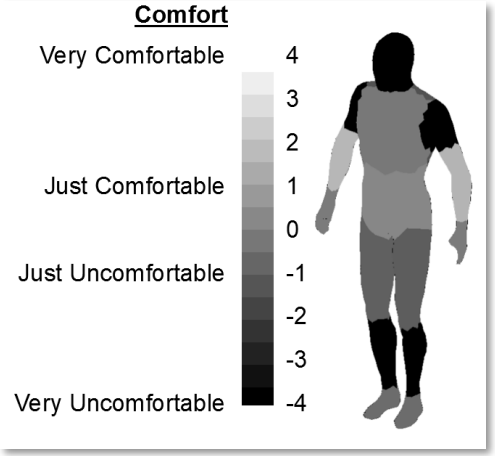


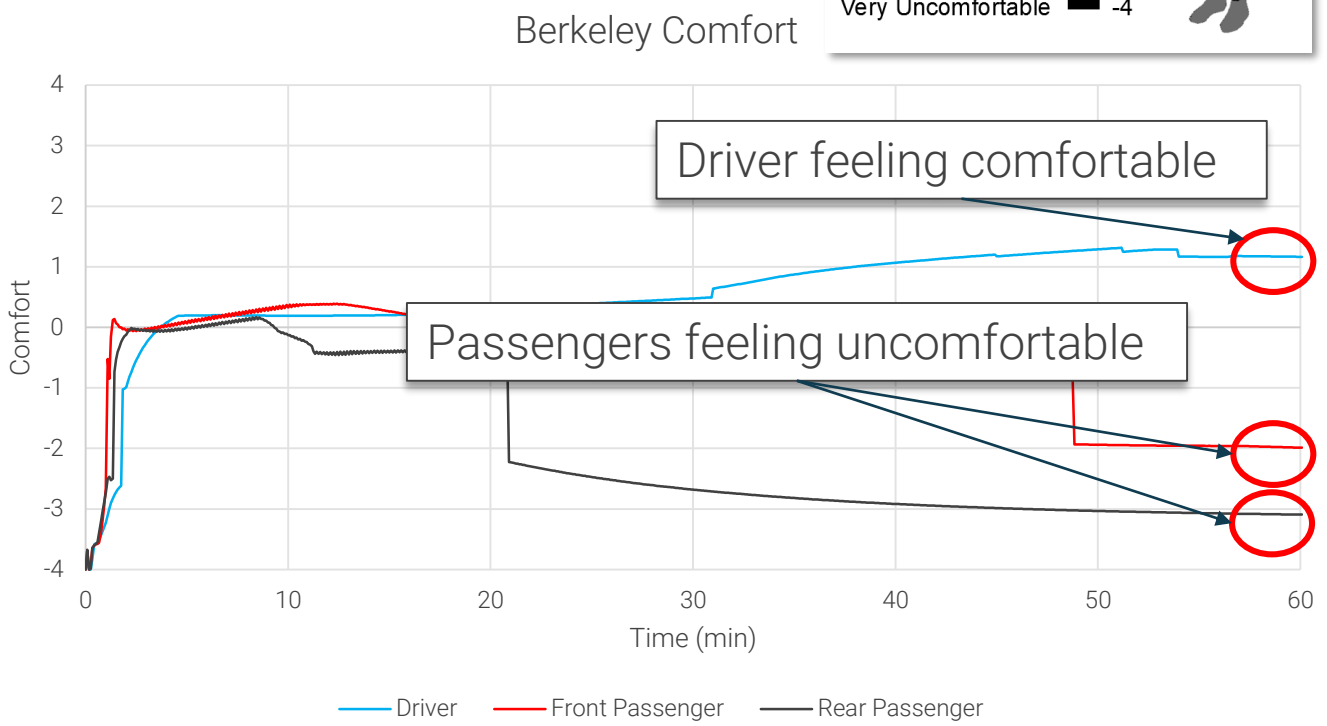
Berkley Sensation = f(Tsk, Tcore, DTsk/dT, DTcore/dT)

- Sensation measures how warm or cold a feeling is

Thermal Comfort







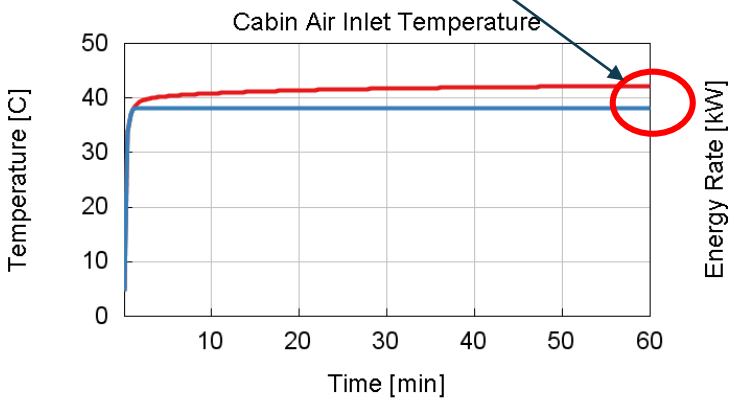
Berkley Sensation = f(sensation)

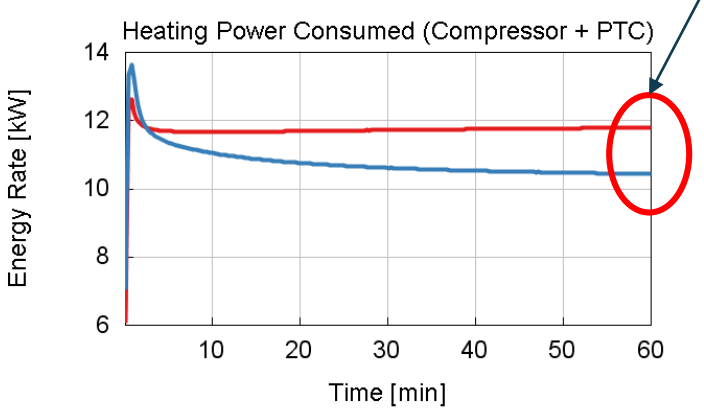
- Comfort is a measure of how good or bad a sensation feels

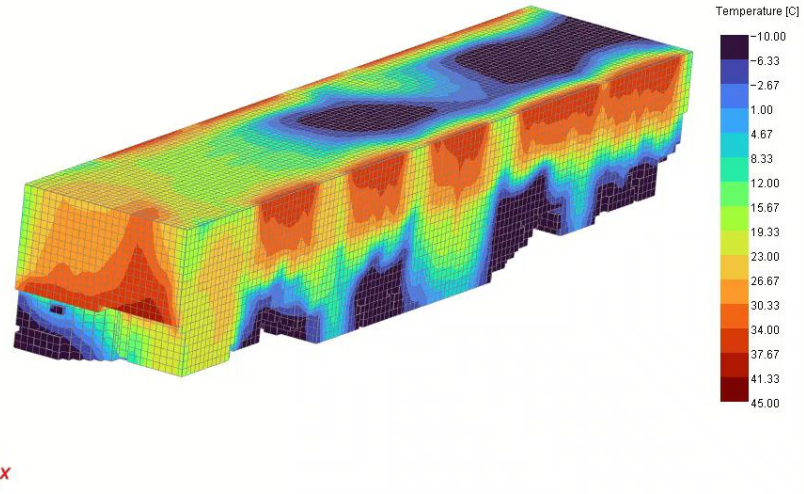
Integrated Model Results – Heat Pump Performance

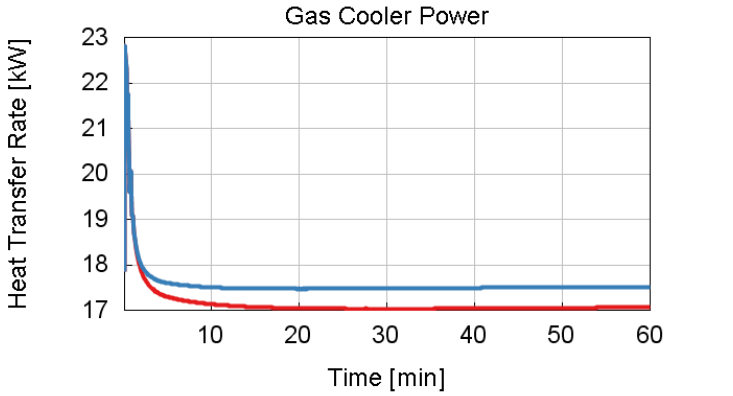
~4°C temperature difference

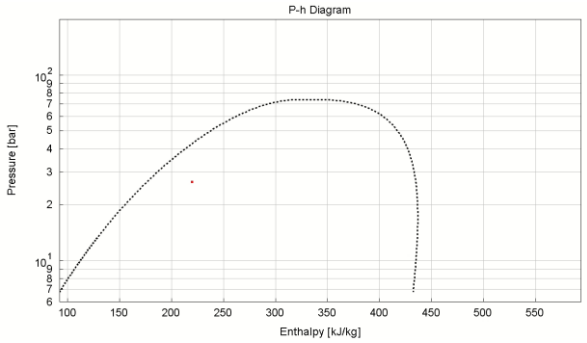
~ 1,4kW energy saving potential









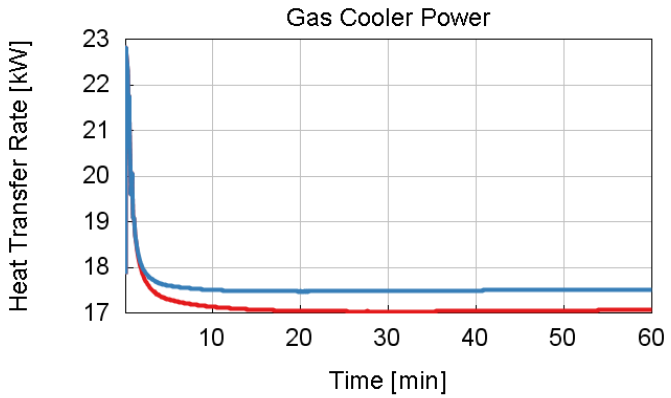


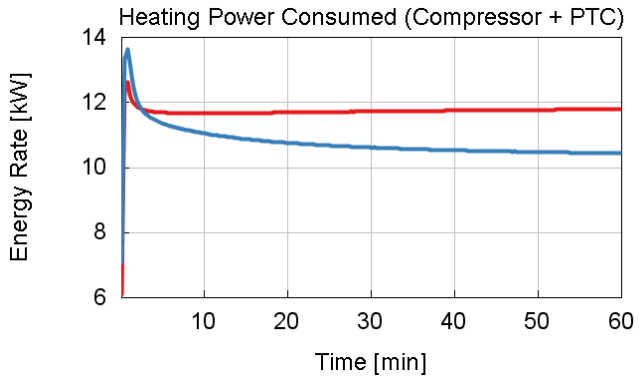
Direct Heating

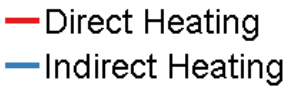
Indirect Heating

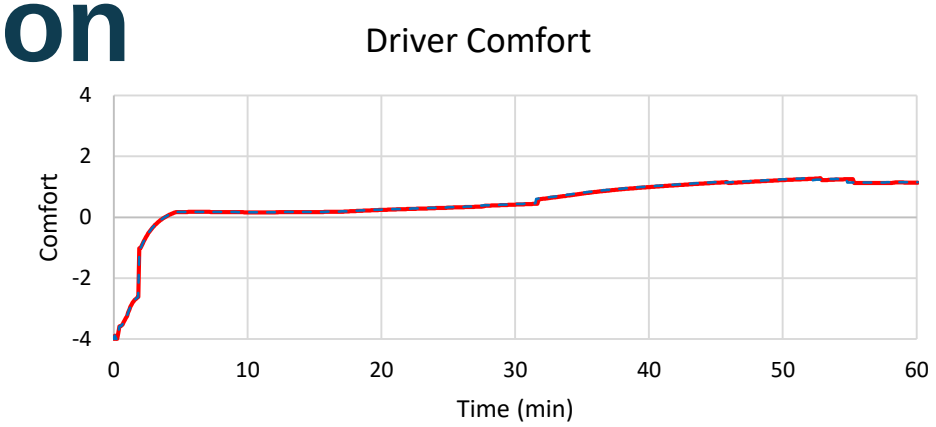
Energy and Occupant Perception

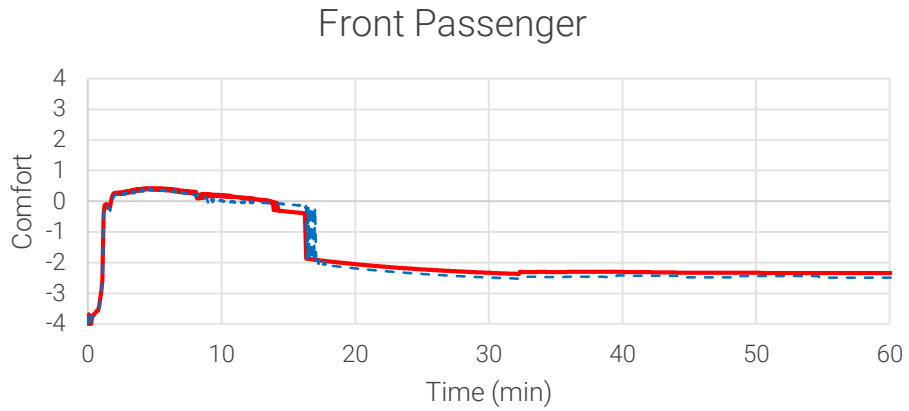
- Heat pump systems can be used to reduce the bus energy consumption
  - Energy savings can be used to extend range
  - Occupant comfort is unchanged

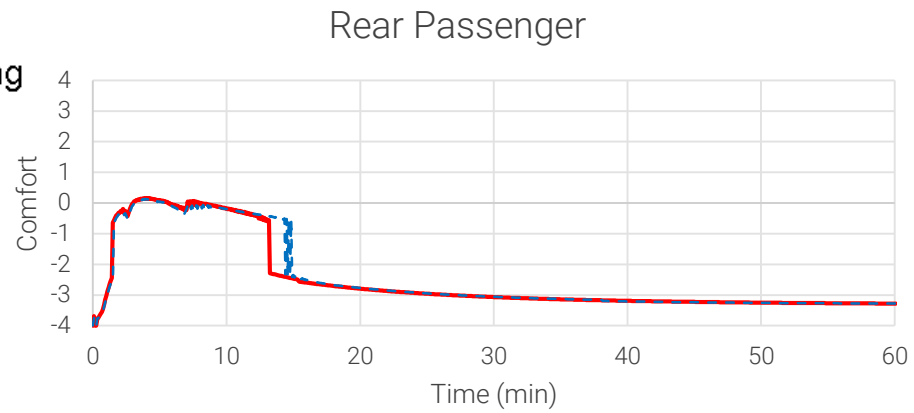






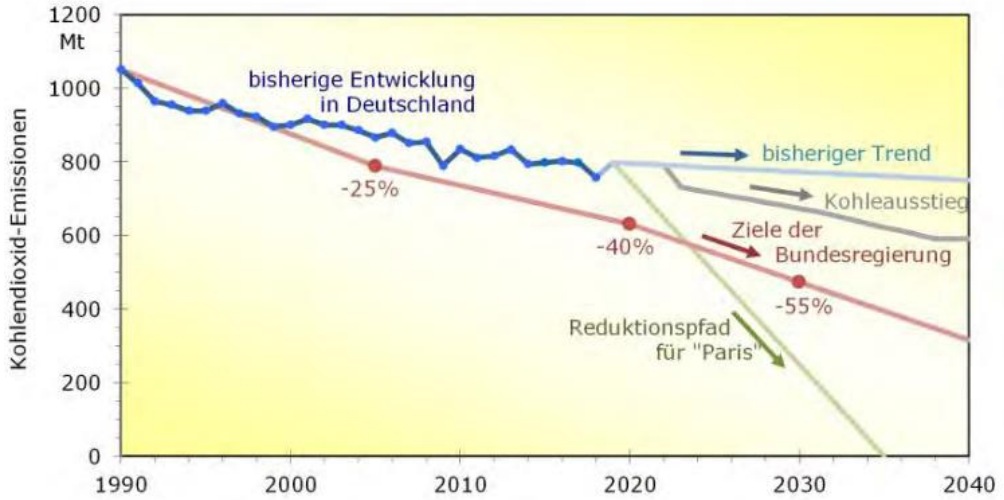


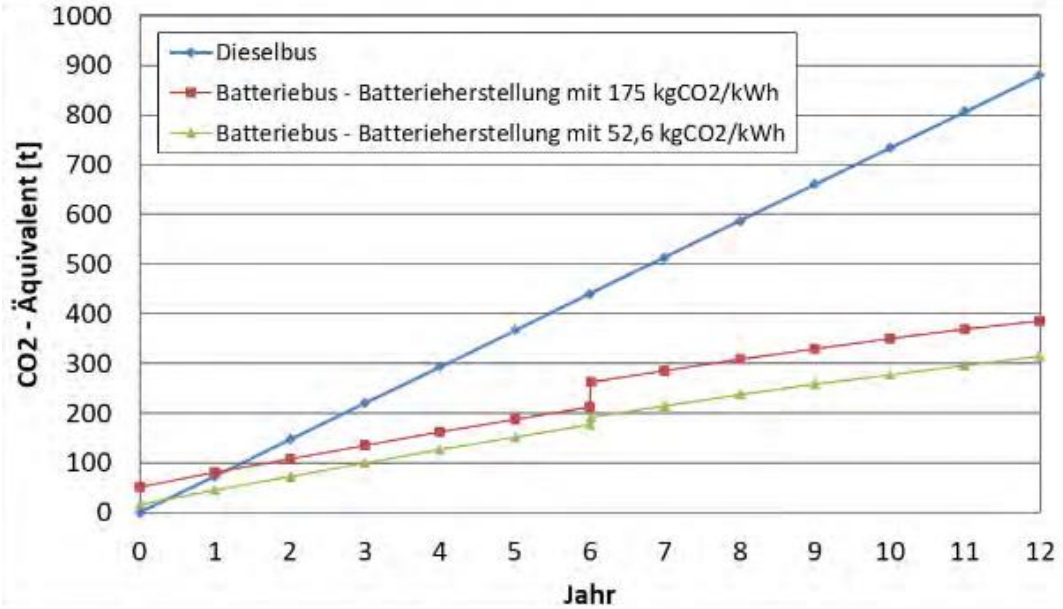




Conclusions

- Emissions Management is a driving factor in electrification
  - Commercial vehicles are an important part of the solution





Conclusions

- Emissions Management is a driving factor in electrification
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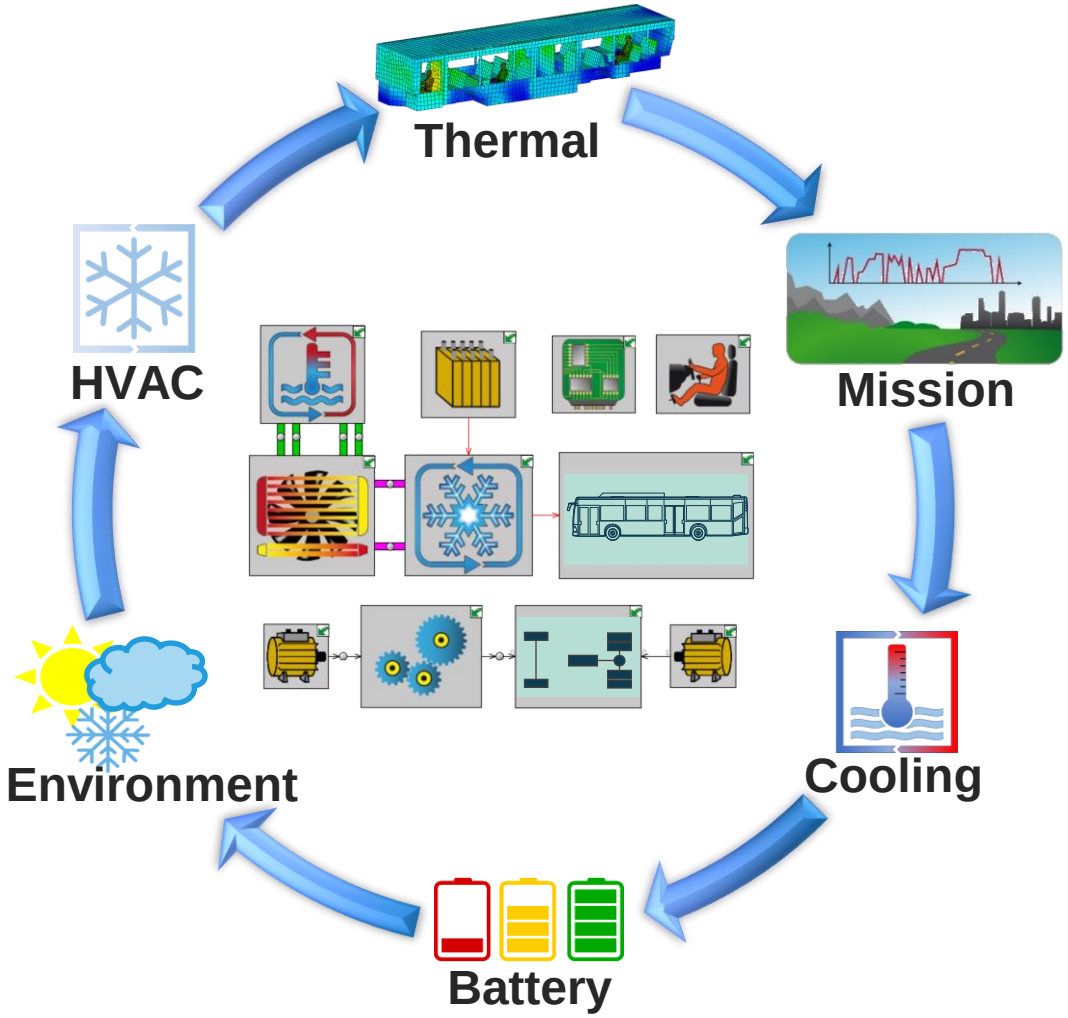
- Integrated system simulation provides unprecedented insights in system performance
  - Rapid, low-cost, accurate design explorations
  - Links design targets (range) with design requirements (occupant comfort)
  - Coupled GT-SUITE and TAITherm simulation offer optimal simulation times for various model fidelities



Conclusions

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- Integrated system simulation provides unprecedented insights in system performance
  - Rapid, low-cost, accurate design explorations
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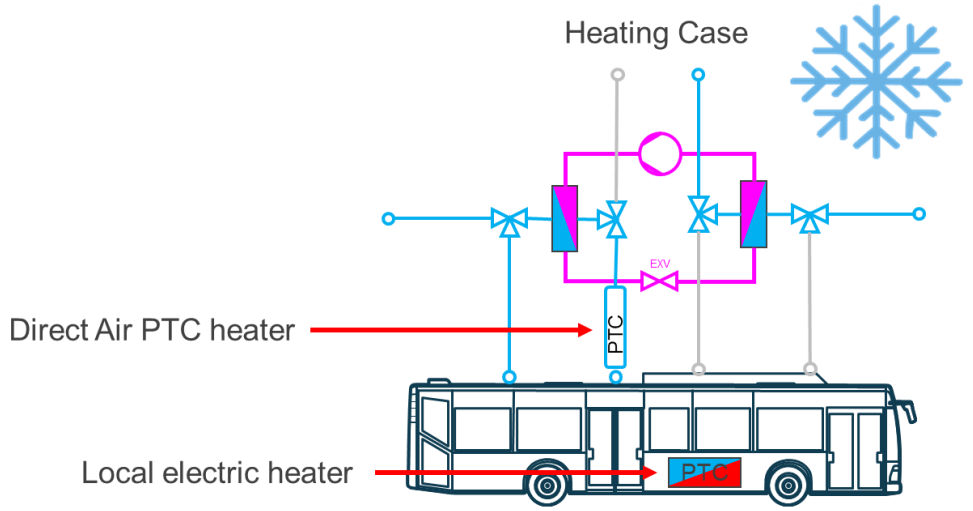
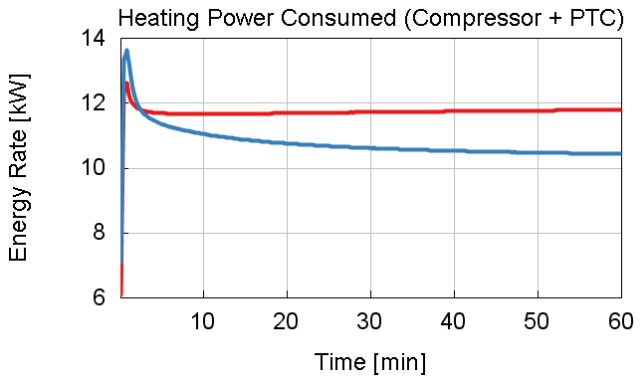
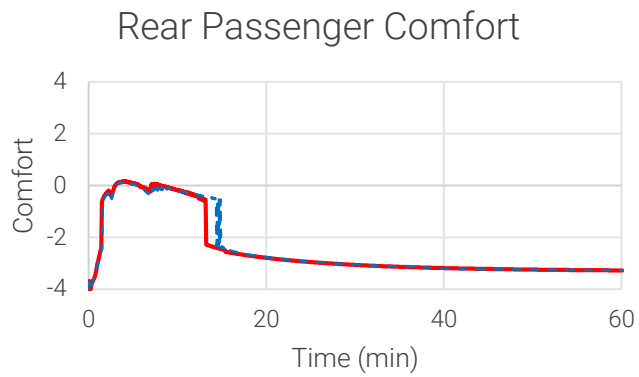
- Heat pumps can be used to reduce energy consumption
  - Extends vehicle ranges
  - Maintains occupant perception







Thank you

US Location

ThermoAnalytics HQ
23440 Airpark Blvd.
Calumet, MI 49913

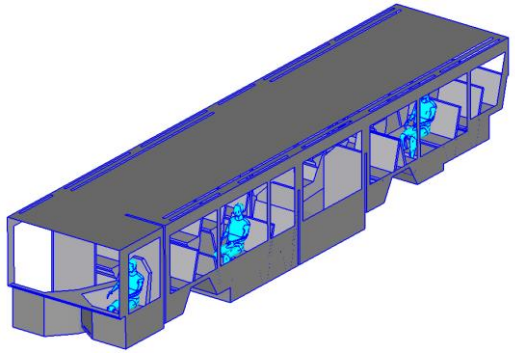
Marek Lehocky

M.Lehocky@gtisoft.com

Jon Juszkiewicz

jrj@thermoanalytics.com

Human Thermal Physiology Modeling



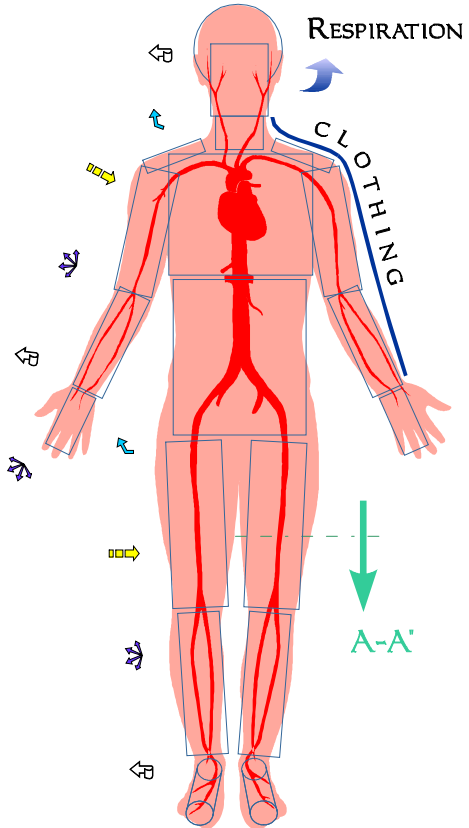
TAITherm Thermal Solver

- Convection/Conduction/Radiation
- Environmental loading

TEQ, MRT, PPD, PMV

Thermal Sensation

Thermal Comfort



Physiology Model

- Metabolic Heating
- Shivering/Sweating
- Blood flow
- etc.