Electric Drive Vehicle Climate Control Load Reduction




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National Renewable Energy Laboratory
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Project ID: VSS097

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Overview

Timeline

Project Start Date: FY12
Project End Date: FY15
Percent Complete: 20%

Budget

Total Project Funding (to date): $ 1,700 K
Funding received prior to FY13: $ 800 K
Funding for FY13: $ 900 K
Partner In-Kind Cost Share: $ 182 K *

*** Not included in total**

Barriers

- **Risk – customer acceptance of electric-drive vehicles (EDVs)**
- **Cost – cost premium for EDVs**
- **Life – battery and temperature**
- **Human thermal comfort is difficult to quantify, but critical to climate control energy use**

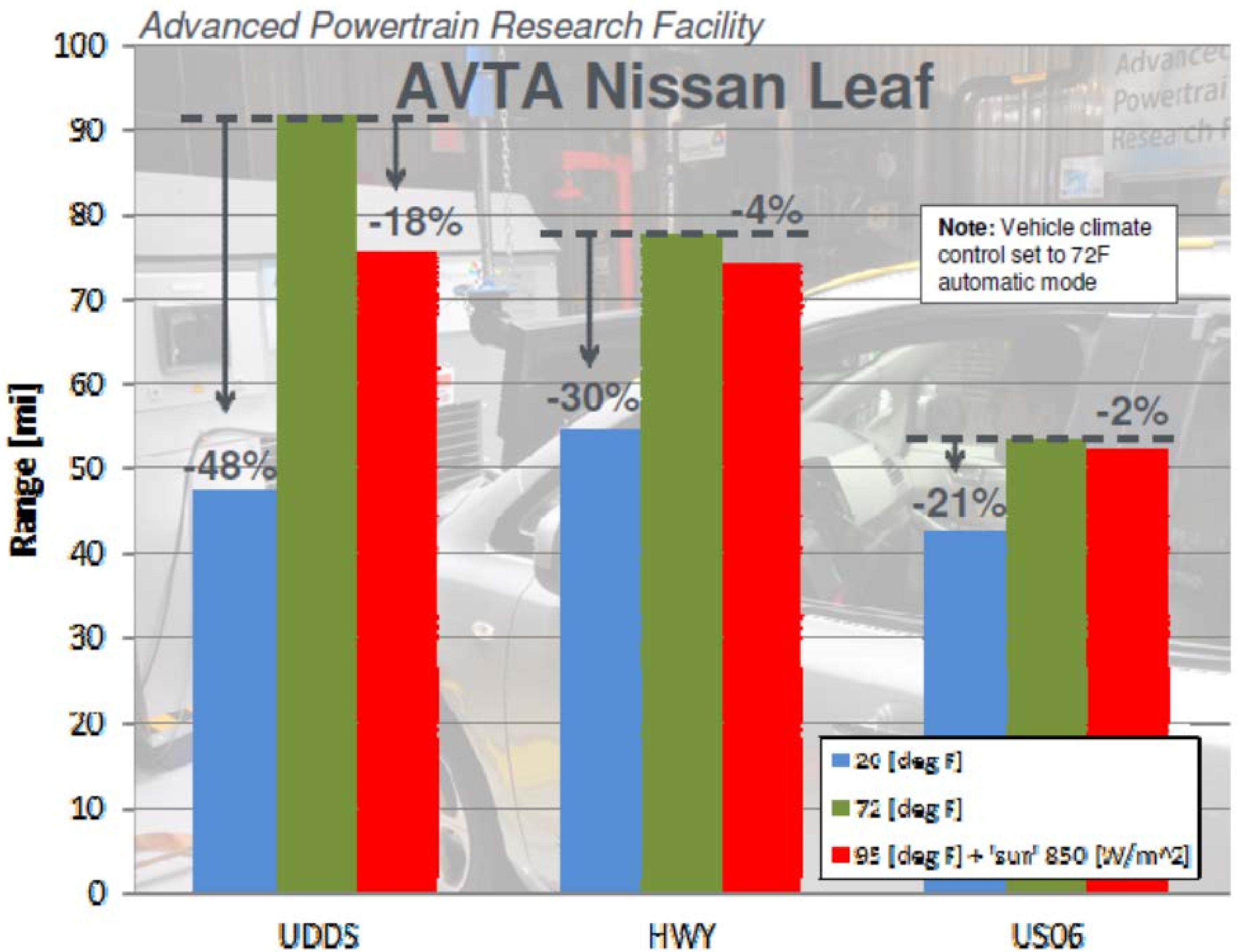
Partners

- Interactions/ collaborations
  - Ford
  - Bayer
  - Pittsburgh Glass Works (PGW)
  - Solutia
  - Faurecia
  - Exa
  - ThermoAnalytics
  - Argonne National Laboratory
- Project Lead
  - National Renewable Energy Laboratory

Relevance – Overcoming Barriers to EVs

- **Risk Aversion**
  - Manufacturers are building EVs at low volume
  - Range anxiety can be an issue
  - OEMs design vehicles to maximize customer satisfaction (range and thermal comfort are linked to satisfaction
- **Cost – Premium price for EVs**
  - Climate control impact on range also affects battery size
  - What if the battery size (and initial cost) could be reduced through lower energy consumption by the climate control system?
- **Lifespan – Higher Li-ion battery temperatures can lead to degradation and reduced life**
  - Depending on battery location and cooling strategy, the cabin climate control system can impact battery temperature
  - Designing batteries to account for high-temperature degradation leads to larger (and higher cost) batteries
- **Thermal Comfort**
  - Historically climate control system designs are validated using air temperatures and limited subjective testing, with little regard for energy use
  - EVs cannot afford excessive energy use for climate control
  - A new way of looking at climate control design with a focus on thermal comfort is required
- **Heating Technology**
  - Conventional vehicles heat cabins with engine waste heat, but EVs do not have an engine
  - Stored electrical energy used for cabin heating takes valuable energy away from propulsion
  - Electric heaters are a lower cost option, but only have a coefficient of performance (COP)=1

Relevance – Impact of Climate Control on a Nissan Leaf



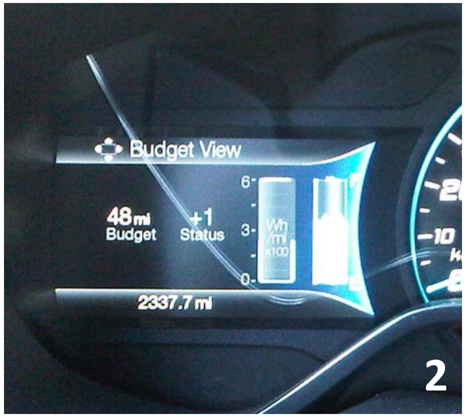
Relevance – Support Broad VTO Efforts

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

- **DOE VTO MYPP**
  - "…..development of advanced vehicles and components to maximize vehicle efficiency ….."
- **President's EV-Everywhere Grand Challenge**
  - A goal of EV Everywhere is to have automobile manufacturers produce a car with sufficient range that meets consumer's daily transportation needs
  - "Currently, these climate control loads on a PEV can double vehicle energy consumption, effectively halving vehicle range. EV Everywhere will focus on the following specific research areas:
    - Energy Load Reduction and Energy Management
    - Advanced HVAC Equipment
    - Cabin Pre-Conditioning"

Relevance – Objectives

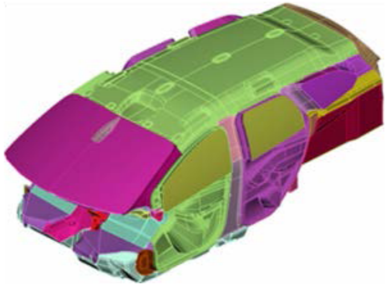
- **Minimize the impact of climate control on grid-connected EDV (GCEDV) range**
- **Reduce size of the battery by minimizing**
  - Energy consumption of vehicle climate control
  - Time the battery exceeds the desired temperature range
- **Develop new strategies for thermal comfort evaluation**



- **Increase electric range by 10% during operation of the climate control system through improved thermal management**
  - Maintain or improve occupant thermal comfort

Approach/Strategy

- **Engage team members (OEMs & suppliers) to obtain in-kind support and guidance for NREL research**
  - Obtain results that are relevant to auto industry
  - Impact efficiency of future vehicles
  - Coordinate closely with Ford



- **Develop and evaluate the effectiveness of strategies to reduce climate control loads**
  - Evaluate promising techniques in outdoor vehicle thermal soak tests
    - Heating and cooling
    - Conduct transient and steady-state thermal tests using the standard vehicle onboard thermal systems and an offboard vehicle climate control load hardware emulator system
  - Conduct thermal analyses (computational fluid dynamics [CFD], RadTherm, human thermal comfort)
    - Investigate massively parallel computing using new NREL cluster and Exa CFD software

- **Leverage zonal climate control approach developed under DOE's thermoelectric HVAC projects**
- **Investigate new thermal comfort evaluation techniques**

Approach/Strategy – Work Plan

- **FY12–13**
  - Develop cooperative research and development agreements (CRADAs) with automobile manufacturers
  - Conduct vehicle thermal analyses and tests to evaluate the effectiveness of potential strategies to reduce the climate control loads
  - Determine value proposition of reducing climate control loads (range and battery size)
- **FY14–15**
  - Work with automobile manufacturers to incorporate most promising technologies into a research vehicle

Approach – Initial Focus Areas

Zonal approach to climate control

Active/passive ventilation

Solar-reflective glazing/shading

Cabin & battery preconditioning

Advanced seating concepts

Advanced insulation materials

Thermal Load Reduction

Maintain or Improve Thermal Comfort

Approach – Crosscutting within VTO

- **DOE VTO**
  - John Fairbanks: Leveraging thermoelectric research
- **National Lab**
  - ANL Advanced Powertrain Research Facility (APRF) vehicle data

Approach – Milestones

Month/Year	Description
Sept/2012	Milestone • Acquire OEM partner and initiate baseline thermal testing of EVs
Sept/2013	Milestone • Results from vehicle thermal test and analyses identify potential benefits of thermal load reduction and efficient equipment while maintaining or improving thermal comfort levels

Accomplishments: Vehicle Testing

Hot Thermal Soak Test

7

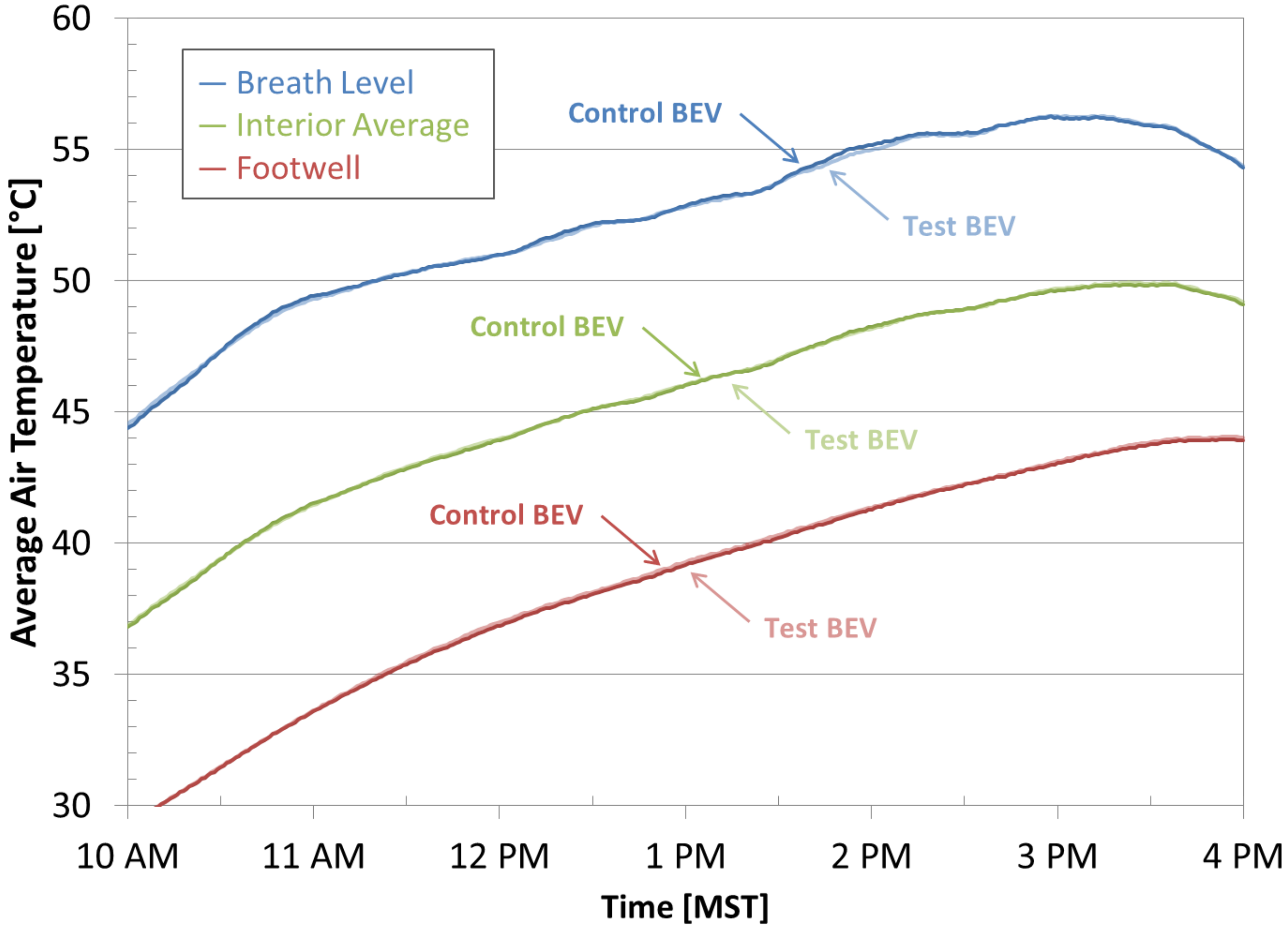
- **CRADA with Ford**
  - Focus Electric
- **Baseline thermal characterization**
- **Definition of adjustments**
  - Enables future comparison
  - Control vehicle used to determine the interior temperatures of test vehicle if it had not be modified
- **24-hour undisturbed thermal soak test period**
  - 4 baseline test days
  - 2 check days
- **40+ calibrated thermocouples per vehicle:**
  - Opaque surfaces, glazing surfaces and shielded air
  - Interior and exterior measurements
  - Max $U_{95} = \pm 0.18°C$

Vehicle Testing – Hot Thermal Soak

Average Air Temperatures

Air temperatures match very closely between test and control Focus EVs

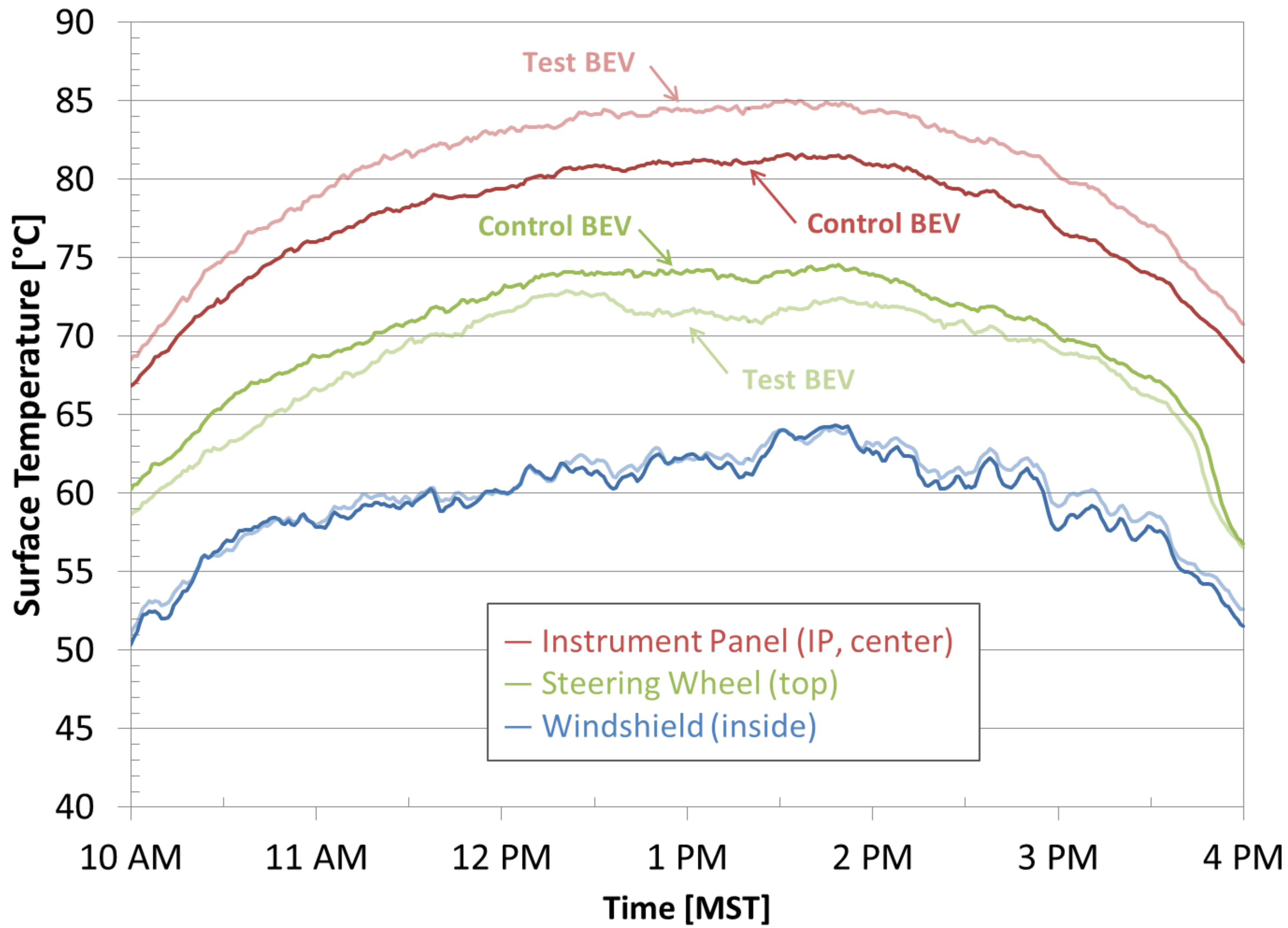
Breath-level and footwell temperatures are avg. of 4 TCs, interior is avg. of all 8 TCs



Vehicle Testing – Hot Thermal Soak

Instrument Panel, Steering Wheel & Windshield Temperatures

Most measurement locations match very closely, but a few show consistent temperature offsets resulting from inherent vehicle differences



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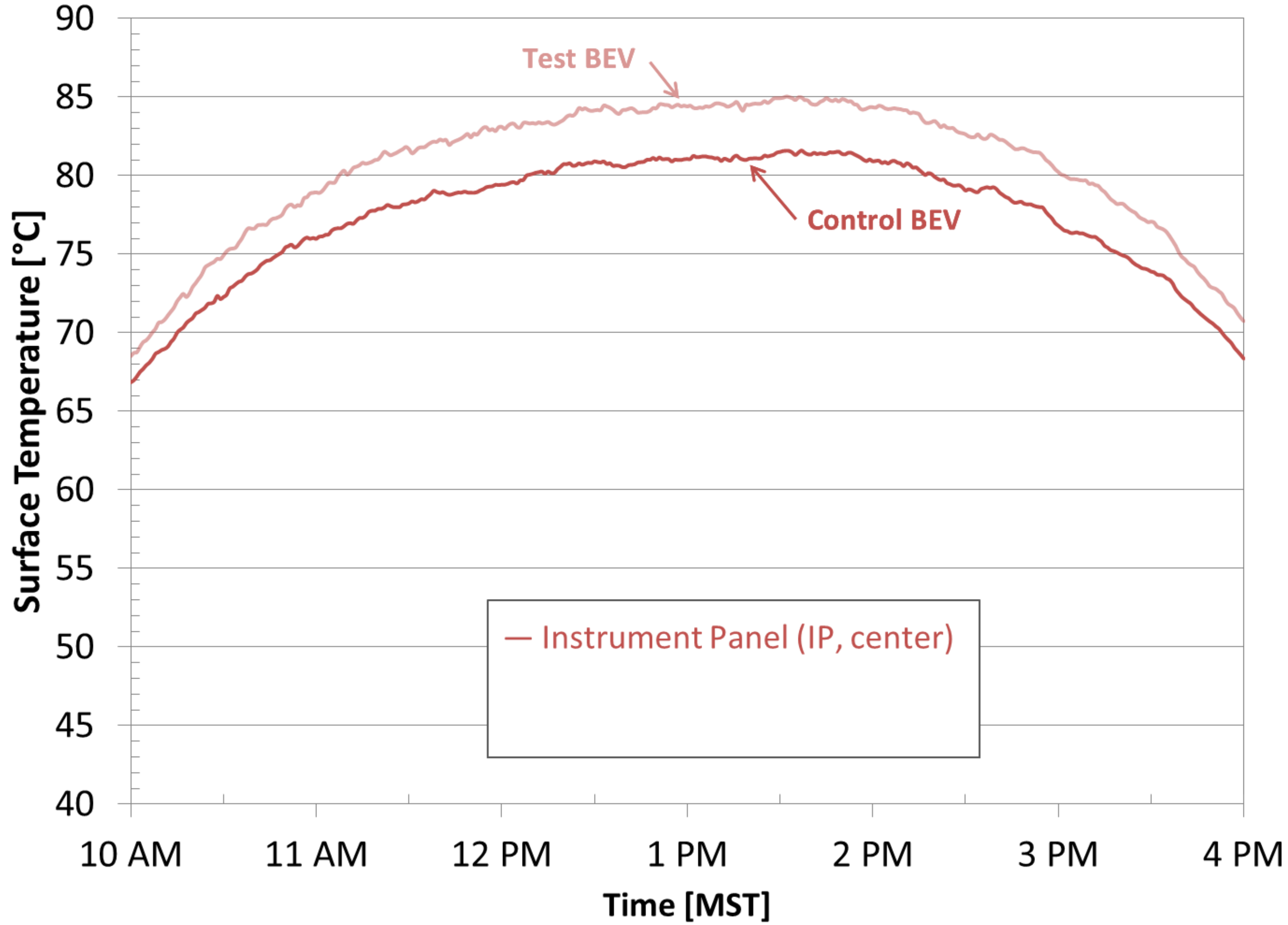
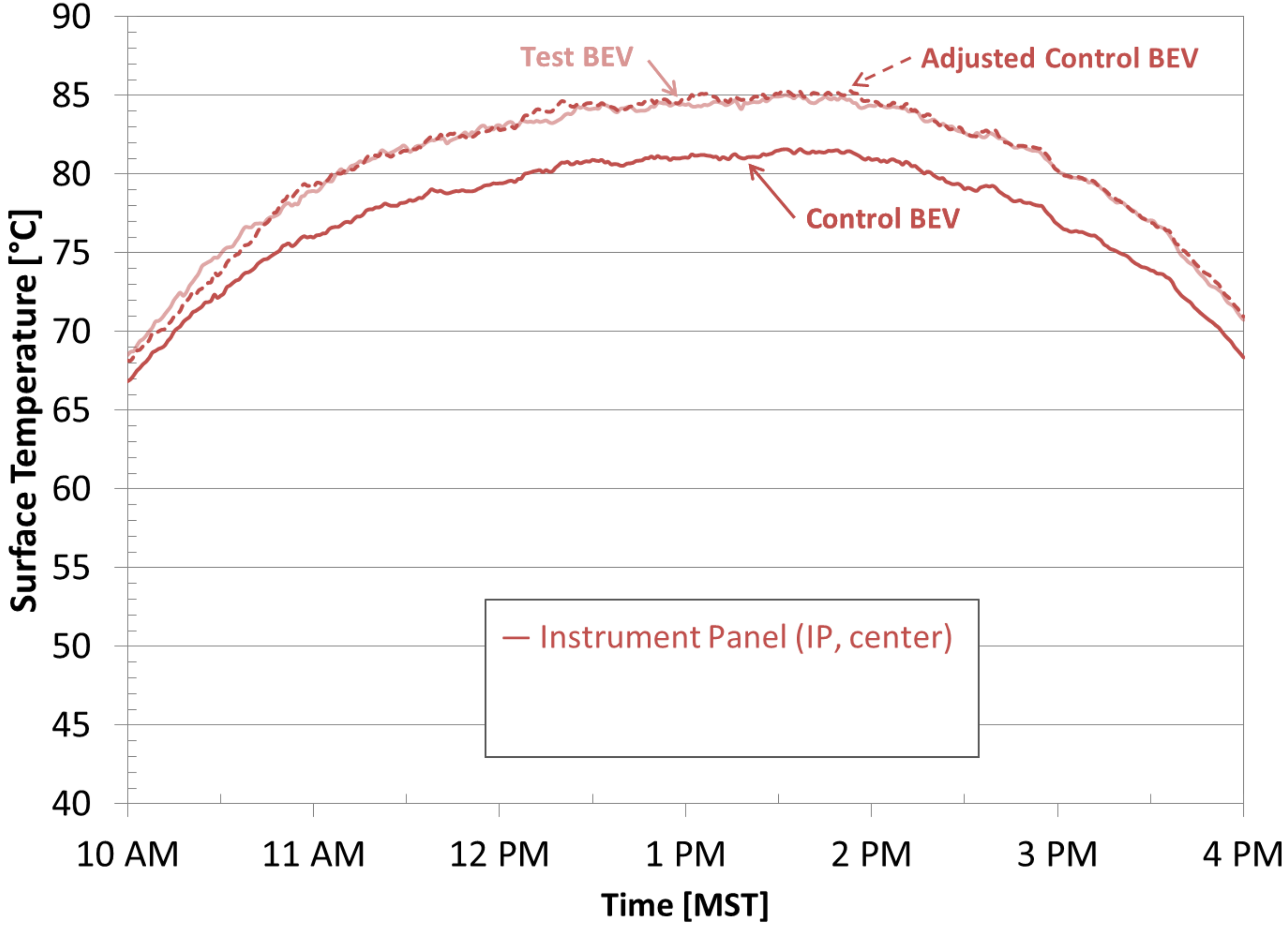


Vehicle Testing – Hot Thermal Soak

Example Control BEV Temperature Adjustments – Instrument Panel

Temperature adjustments for some channels are calculated from 4 baseline test days and verified with 2 check days



Vehicle Testing – Preliminary A/C Cool-Down

Using Onboard A/C System

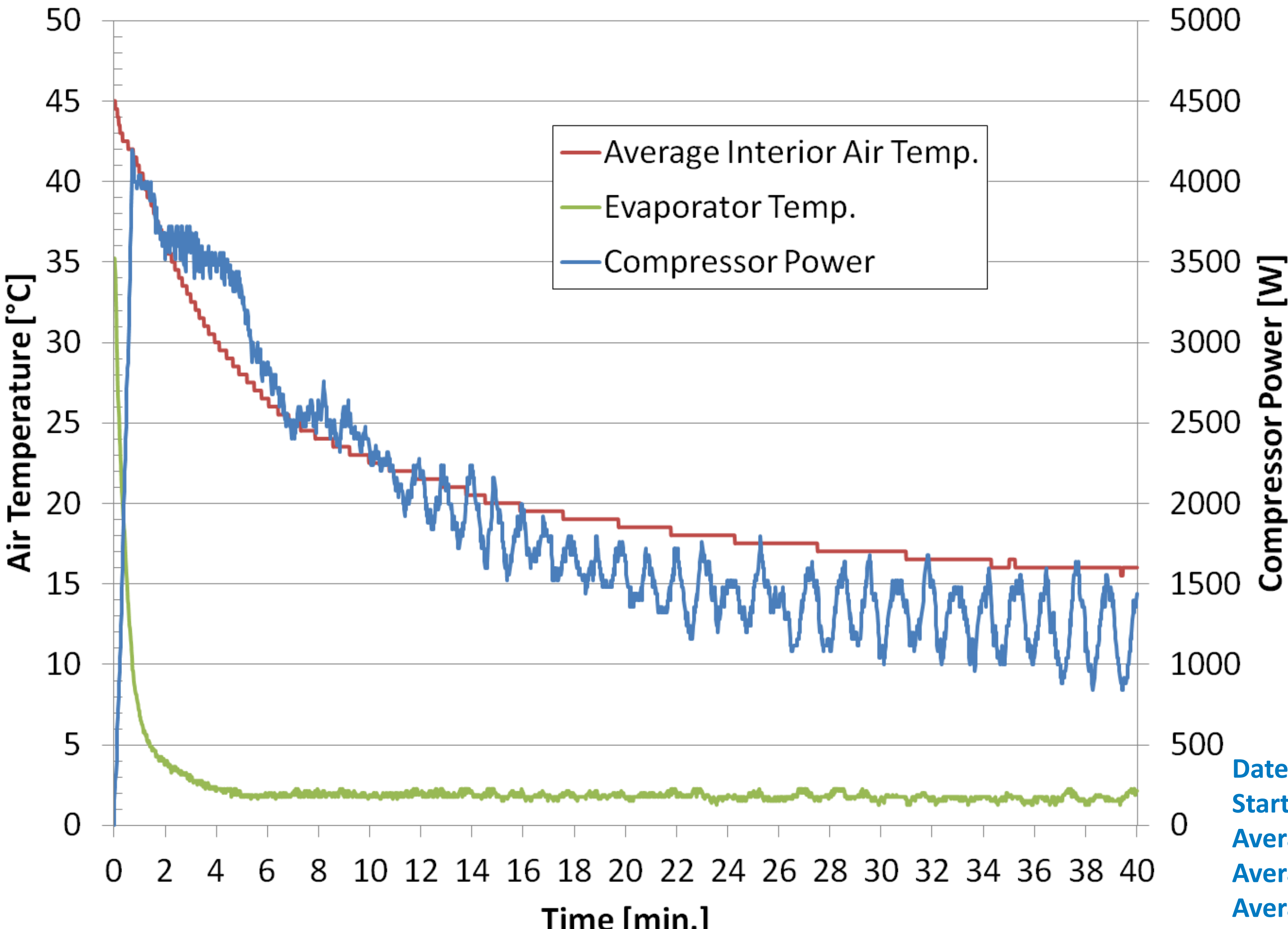
- **Data acquisition**
  - 40+ temperature measurements (same as soak test)
  - Additional data logged through vehicle CAN bus:
    - Battery voltage and current
    - Compressor speed and power
    - Evaporator temperature and set point
    - Interior temperature
    - Ambient temperature
    - Air flow rate, recirculation fraction

- **Test conditions**
  - Hot thermal soak throughout morning
    - Warm ambient, low wind and uninterrupted solar loading
  - On-board A/C system started around midday to begin cool-down
- **Characterized A/C control settings**

Vehicle Testing – Preliminary A/C Cool-Down

Automatic A/C Control Setting, 15°C Set Point

Electric compressor oscillates but never cycles off as mechanical compressors do

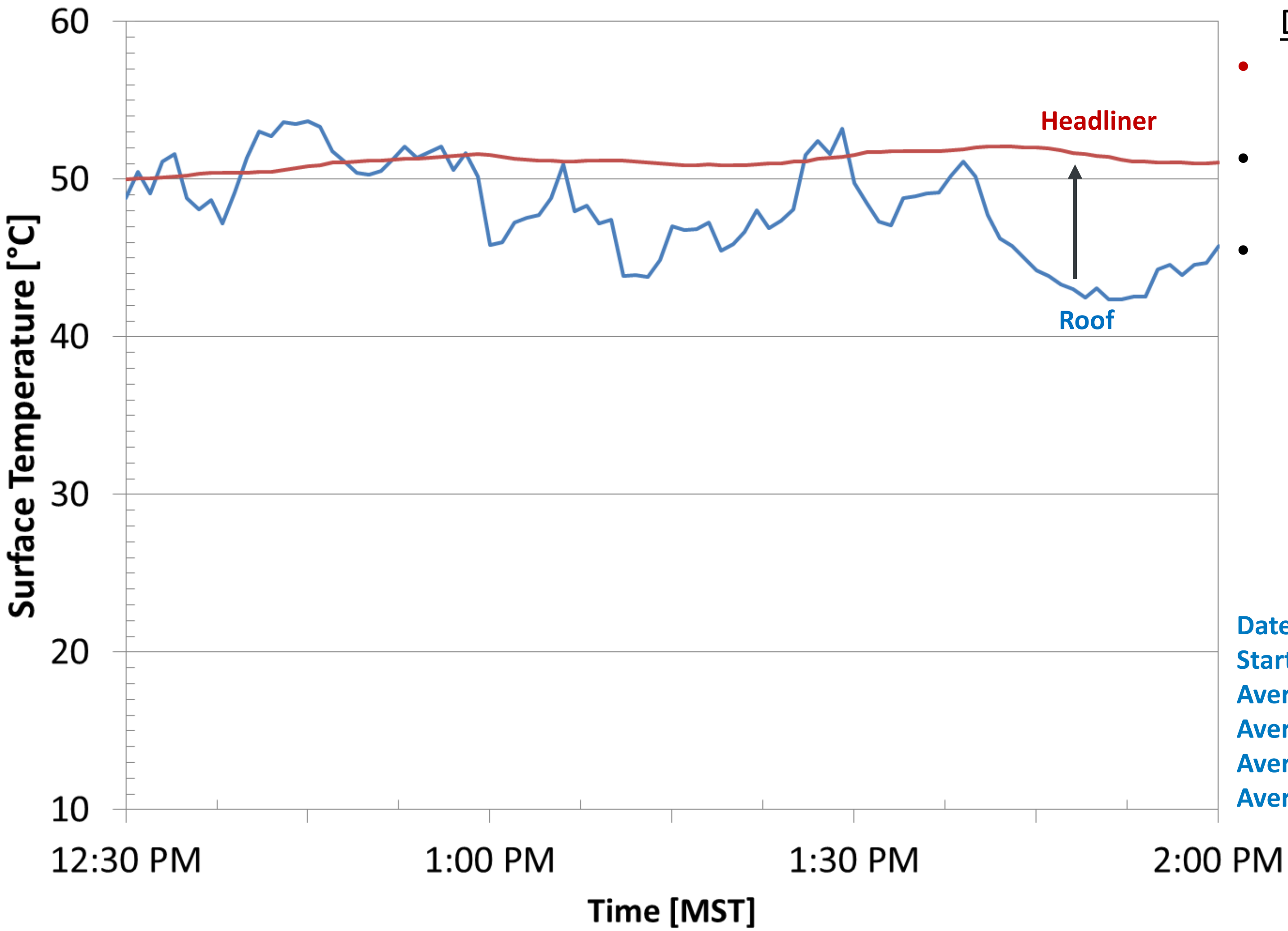


Date: 9/14/2012
Start time = 12:56 pm MST
Average direct solar = 978.6 W/m²
Average diffuse solar = 60.0 W/m²
Average ambient air temp = 23.0°C
Average wind speed = 2.2 m/s

Vehicle Testing – Preliminary A/C Cool-Down

AUTO A/C Control Setting, 15°C Set Point

Insulation is not always advantageous



During Thermal Soak

- Headliner is hotter than roof surface
- Heat is rejected through roof
- Insulation detrimental

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Vehicle Testing – Preliminary A/C Cool-Down

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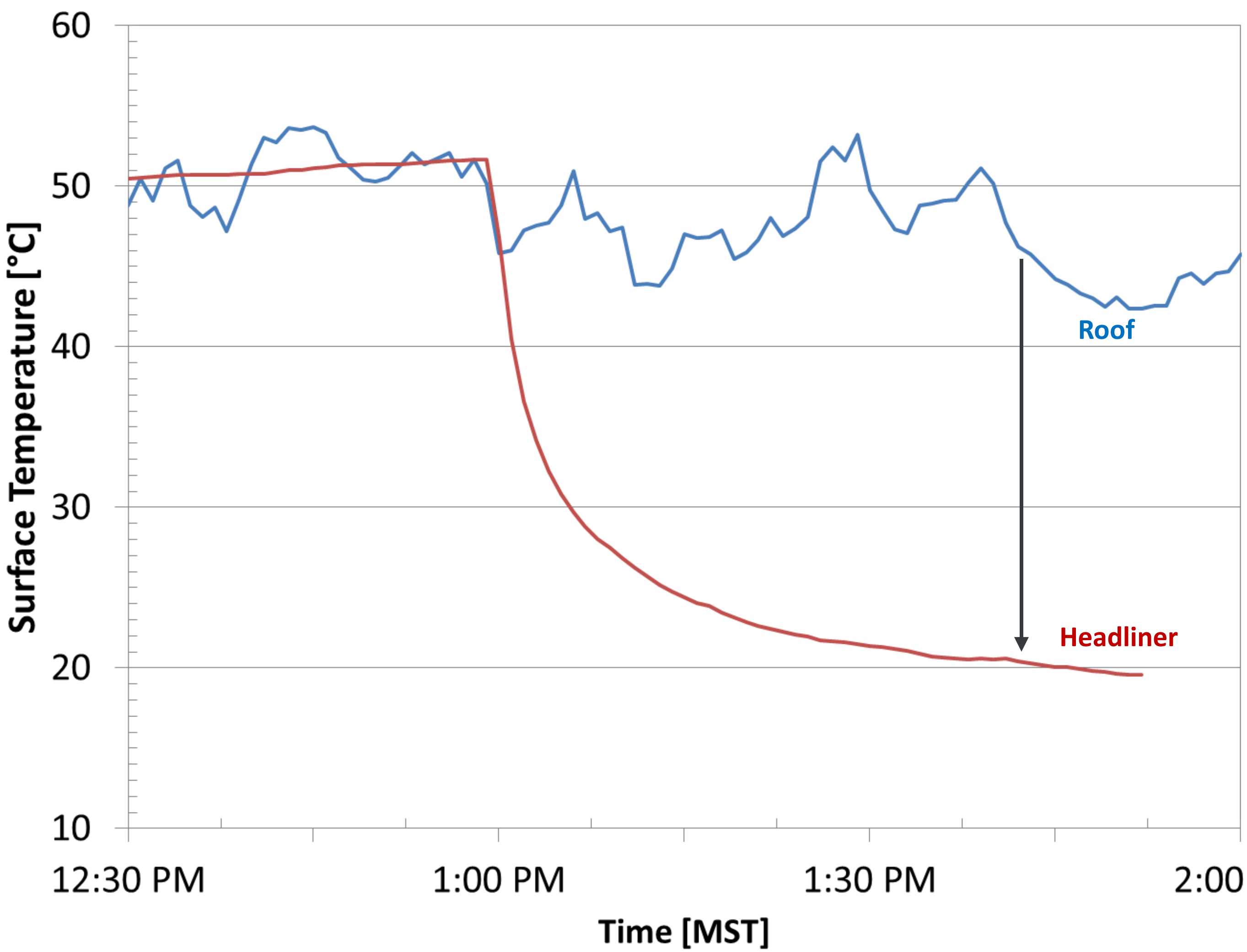


During Thermal Soak

- Headliner is hotter than roof surface
- Heat is rejected through roof
- Insulation detrimental

After Cool-Down

- Headliner is cooler than roof surface
- Heat enters through roof
- Insulation beneficial

Date: 9/14/2012
Start time = 12:56 pm MST
Average direct solar = 978.6 W/m^2
Average diffuse solar = 60.0 W/m^2
Average ambient air temp = 23.0°C
Average wind speed = 2.2 m/s

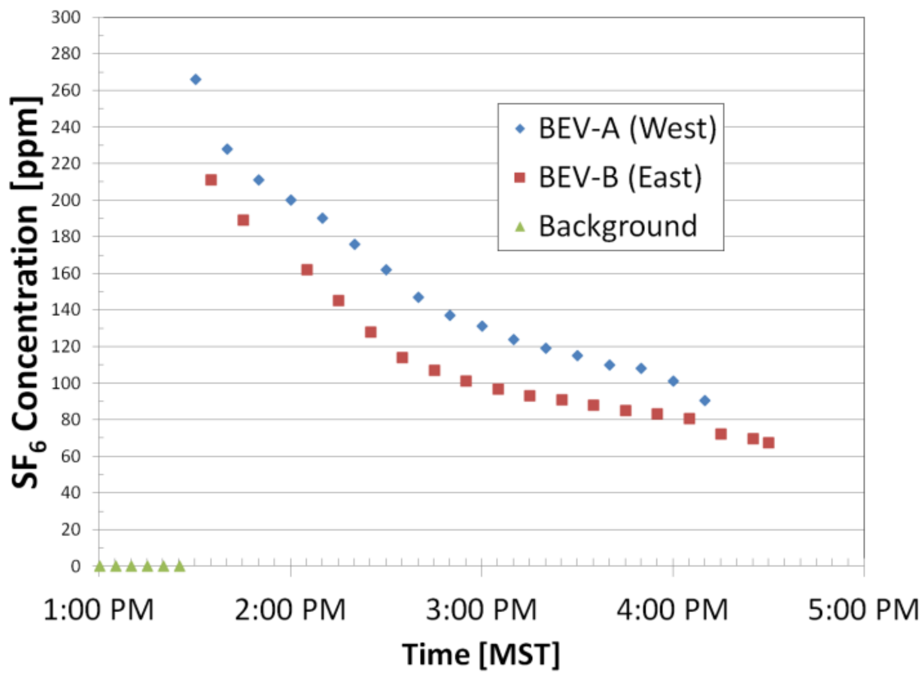
Vehicle Testing – Outside Air Infiltration

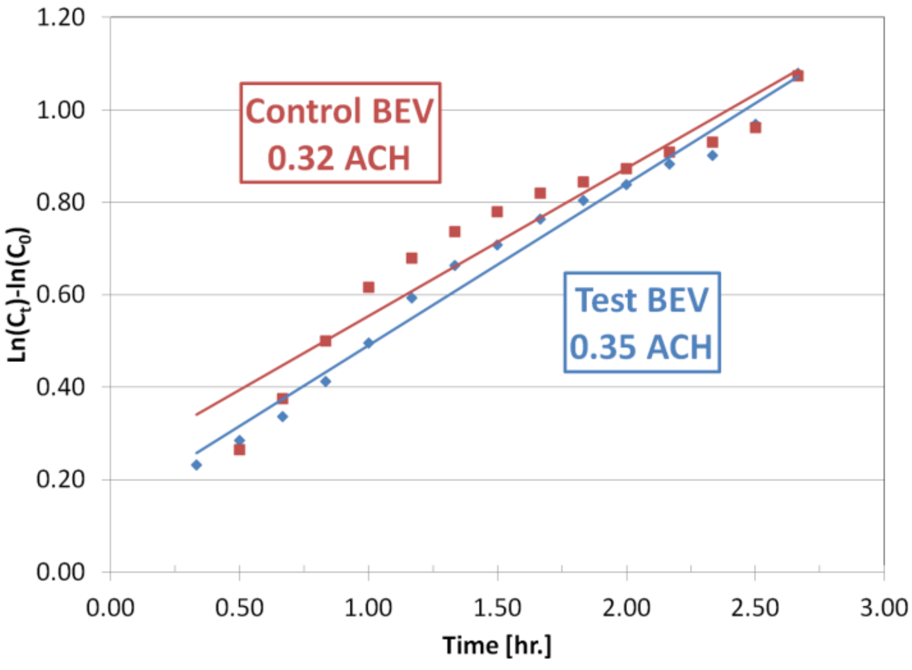
Test Parameters and Results

- **Tracer gas decay test**
  - Sulfur hexafluoride (SF_6)
  - Vehicles sampled simultaneously, under identical weather conditions
  - Tests conducted on passenger compartment and trunk air space

	Passenger Compartment	**Trunk**
Test BEV	0.32 ACH	0.53 ACH
Control BEV	0.35 ACH	0.51 ACH

ACH = Air Changes per hour

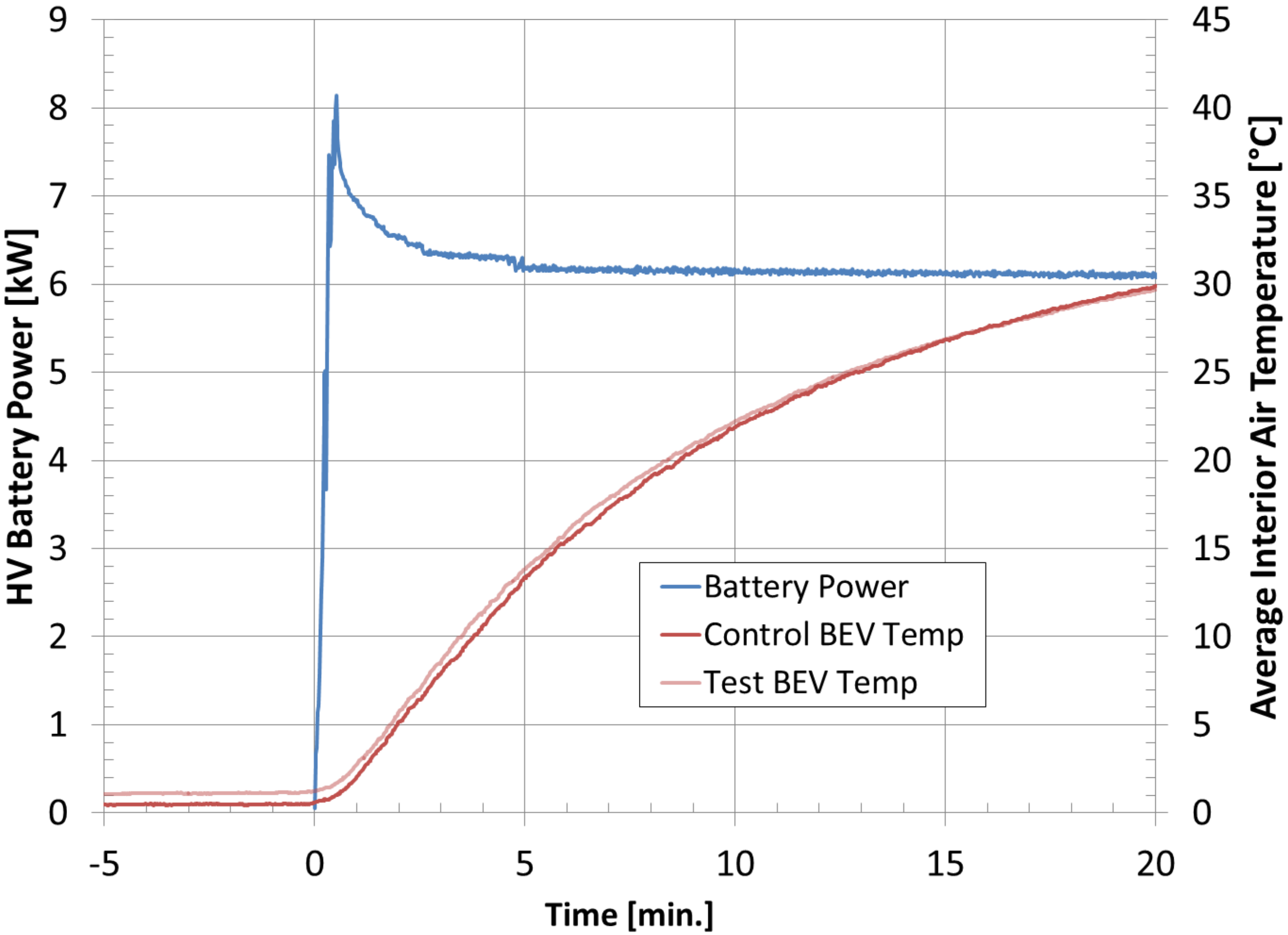




Vehicle Testing – Preliminary Warm-Up

Max Heater Control Setting, 30°C Set Point

Battery power peaks at 8.1 kW when heating begins
Vehicle interior reaches 30°C in 20 minutes



Date: 3/28/2013
Start time = 5:30 am MST (prior to sunrise)
Average ambient air temp = 1.4°C
Average wind speed = 1.5 m/s

Vehicle Testing

Test Summary

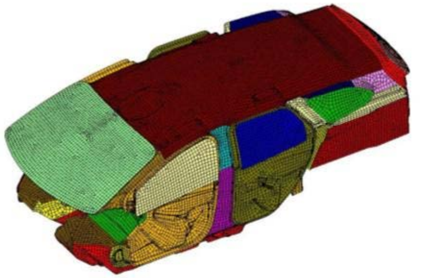
- **Hot thermal soak**
  - Most measurements correlated closely between test and control BEVs
  - Temperature adjustments were calculated and applied to account for inherent vehicle differences
  - Soak test data used to validate vehicle model
- **Preliminary A/C cool-down**
  - Established CAN communication with BEV
  - Developed test strategies for quantifying A/C performance under various control settings
- **Preliminary heater warm-up**
- **Air infiltration**
  - Natural air infiltration is low and very similar between vehicles, supporting the control/test vehicle relationship
  - Air exchange rates used to improve model input parameters

Vehicle Testing

Future Activities

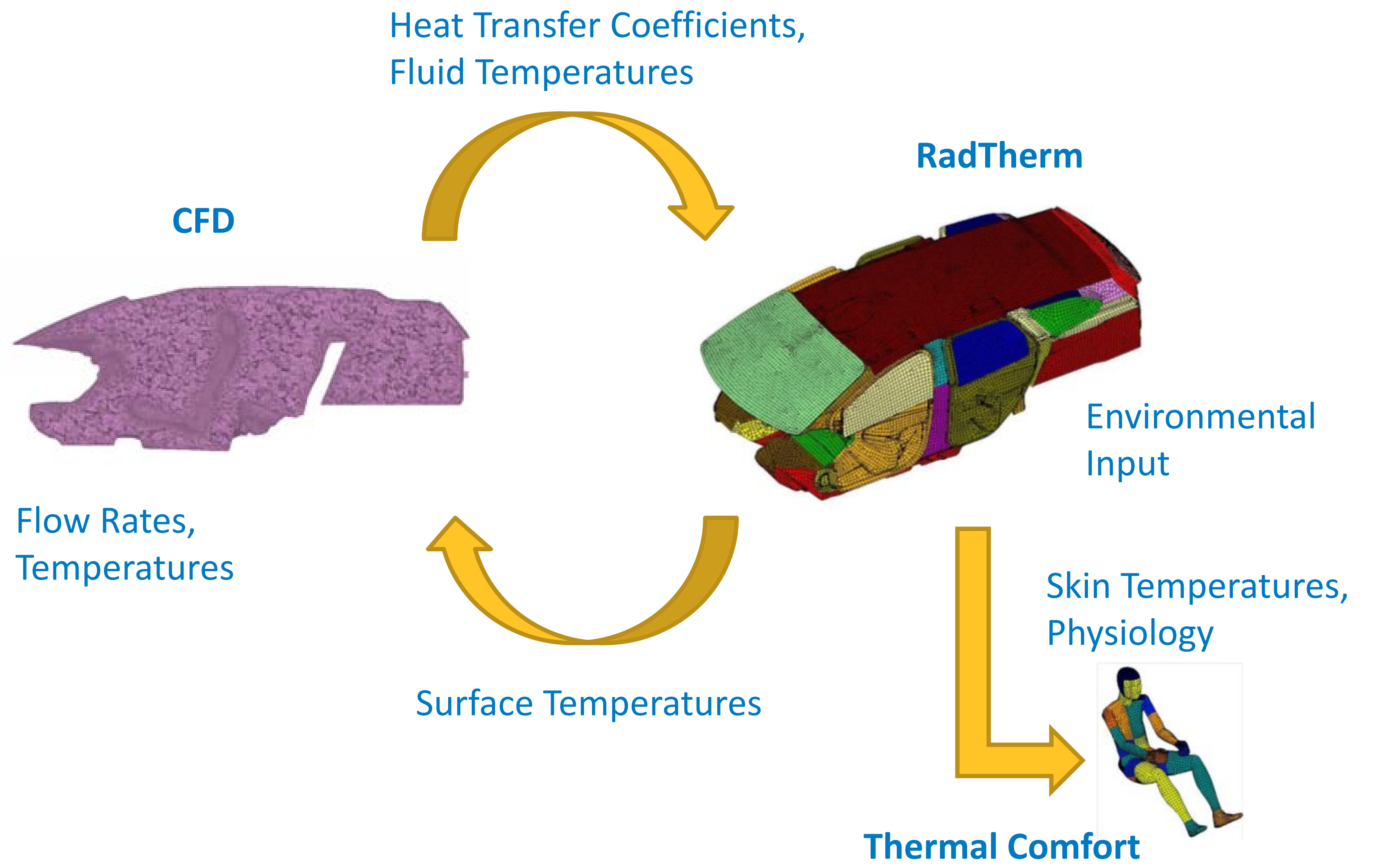
- **Complete baseline testing**
  - Transient cooling
  - Cold thermal soak
  - Transient heating
  - Steady-state heating
- **Finalize test plan**
- **Pre-screen test configurations through modeling and analysis, evaluate performance based on:**
  - Energy consumption
  - Human thermal comfort
- **Test promising configurations of thermal load reduction technologies**

Thermal Analysis – Objective



- **Evaluate the effectiveness of strategies to reduce the climate control loads using thermal analyses:**
  - CFD
  - RadTherm
  - Human thermal comfort
- **Leverage zonal climate control approach developed under DOE's thermoelectric HVAC projects**
- **Investigate new thermal comfort evaluation techniques**

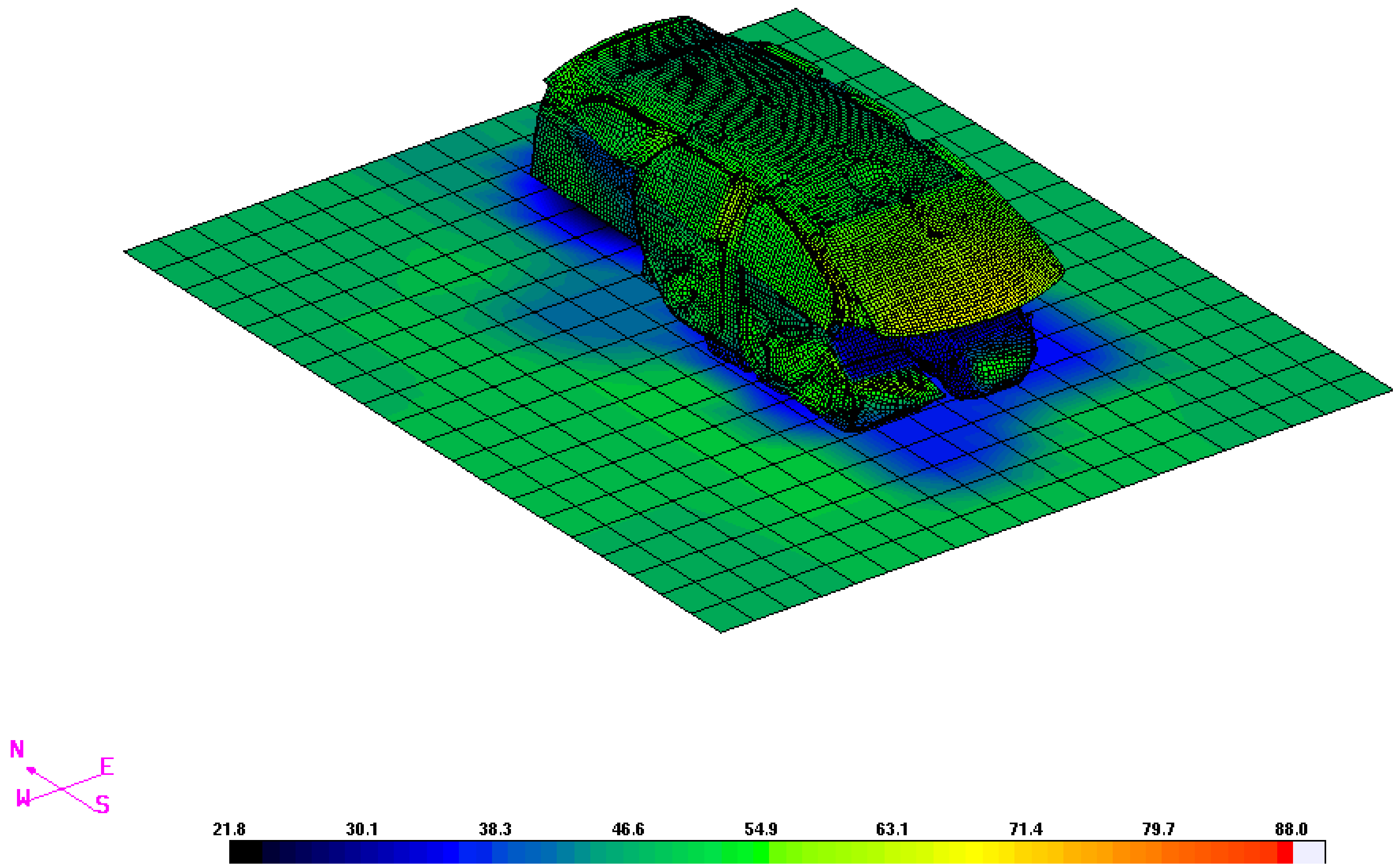
Thermal Analysis – Methodology



Thermal Analysis – Soak Results

Exterior Surface Temperatures

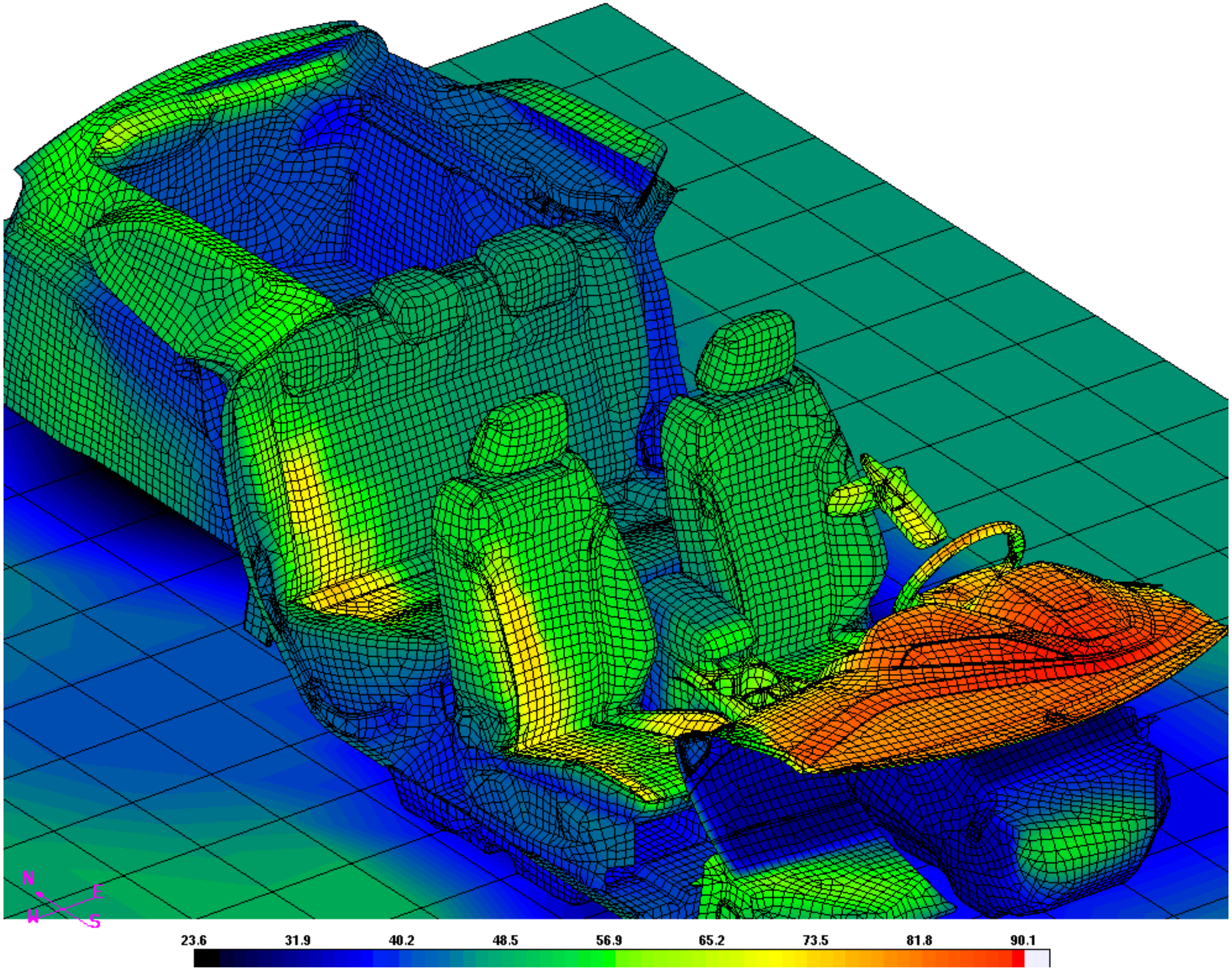
→ note south-facing orientation



Thermal Analysis – Soak Results

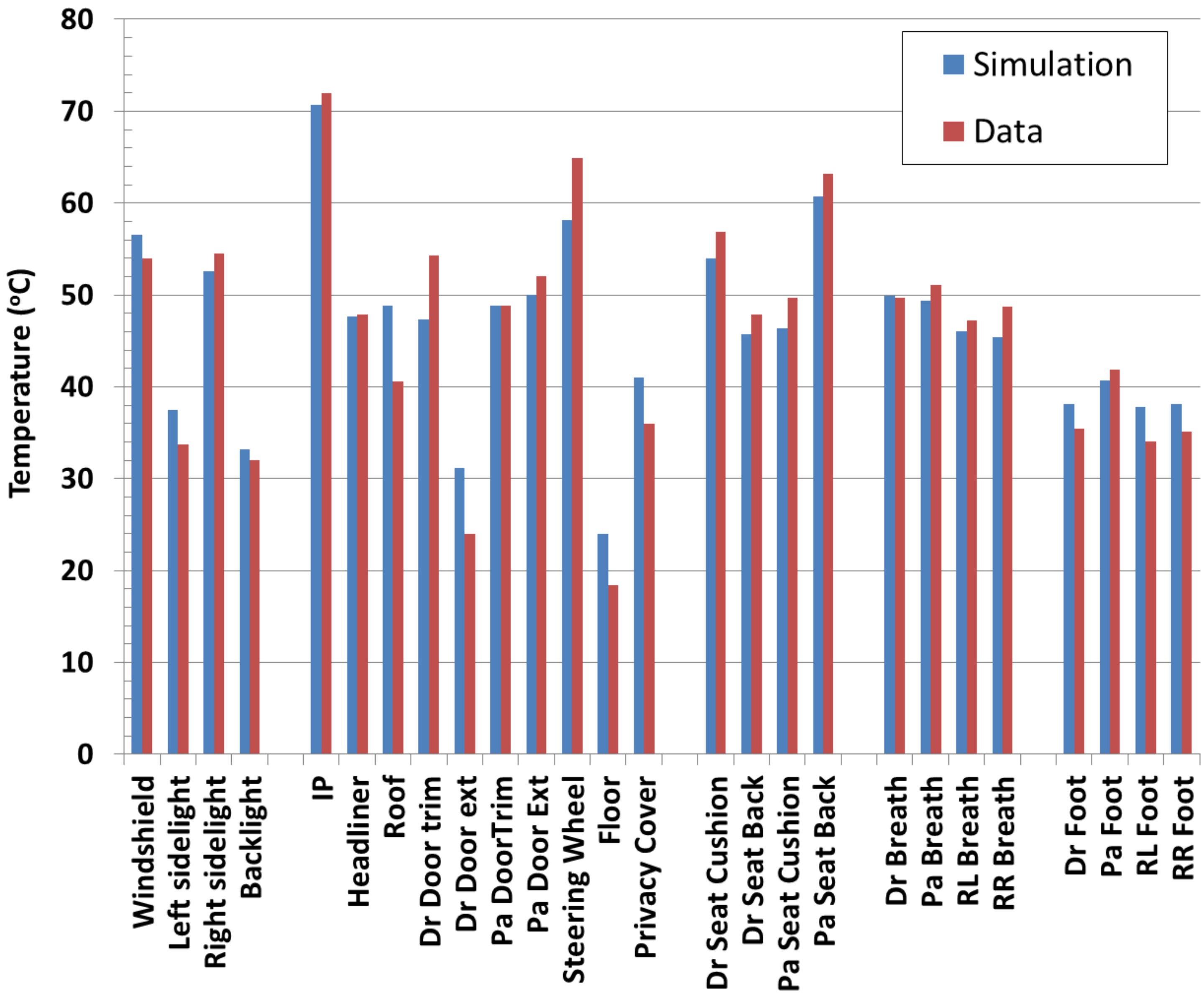
Interior Surface Temperatures

→ note IP temperature and shadows on seats



Thermal Analysis – Soak Results

Comparison of Temperatures (Simulation vs. Data)



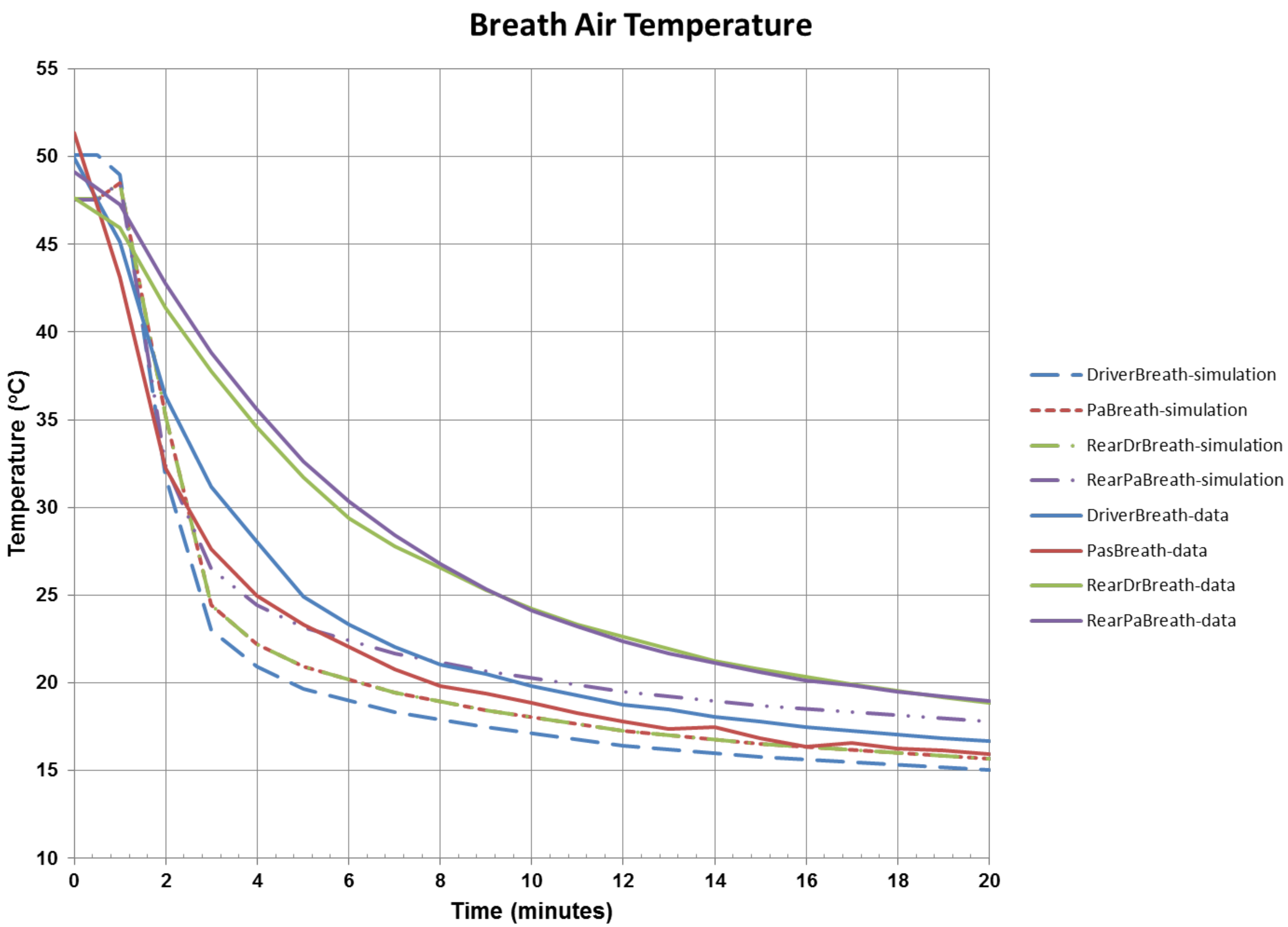
Thermal Analysis – Soak Results

Discussion

- **Comparison to data is excellent**
- **Breath air temperatures are slightly low and foot air temperatures are slightly high**
- **Significance**
  - Enables evaluation of the impact of load reduction technologies during a thermal soak
  - Defines initial conditions for transient analysis

Thermal Analysis – Cool-Down Results

Comparison of Air Temperatures (Simulation vs. Data)



Thermal Analysis – Cool-Down Results

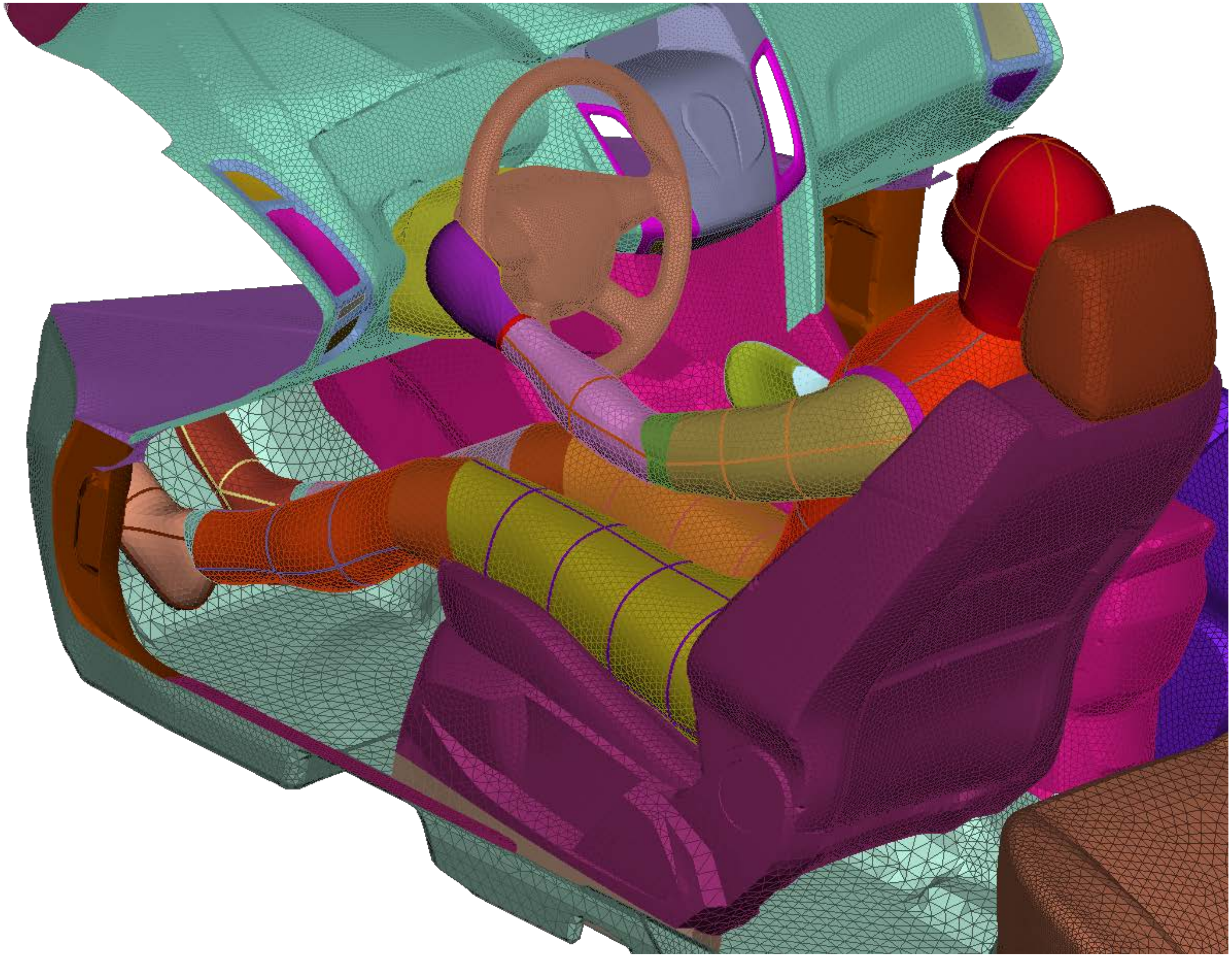
Discussion

- **Comparison to data is acceptable**
- **Trends are adequate for trade-study analysis of load reduction and zonal strategies**
- **Potential improvements to future cool-down simulations**
  - Vent aiming
  - Flow rates
  - Initial temperatures

Thermal Comfort Analysis

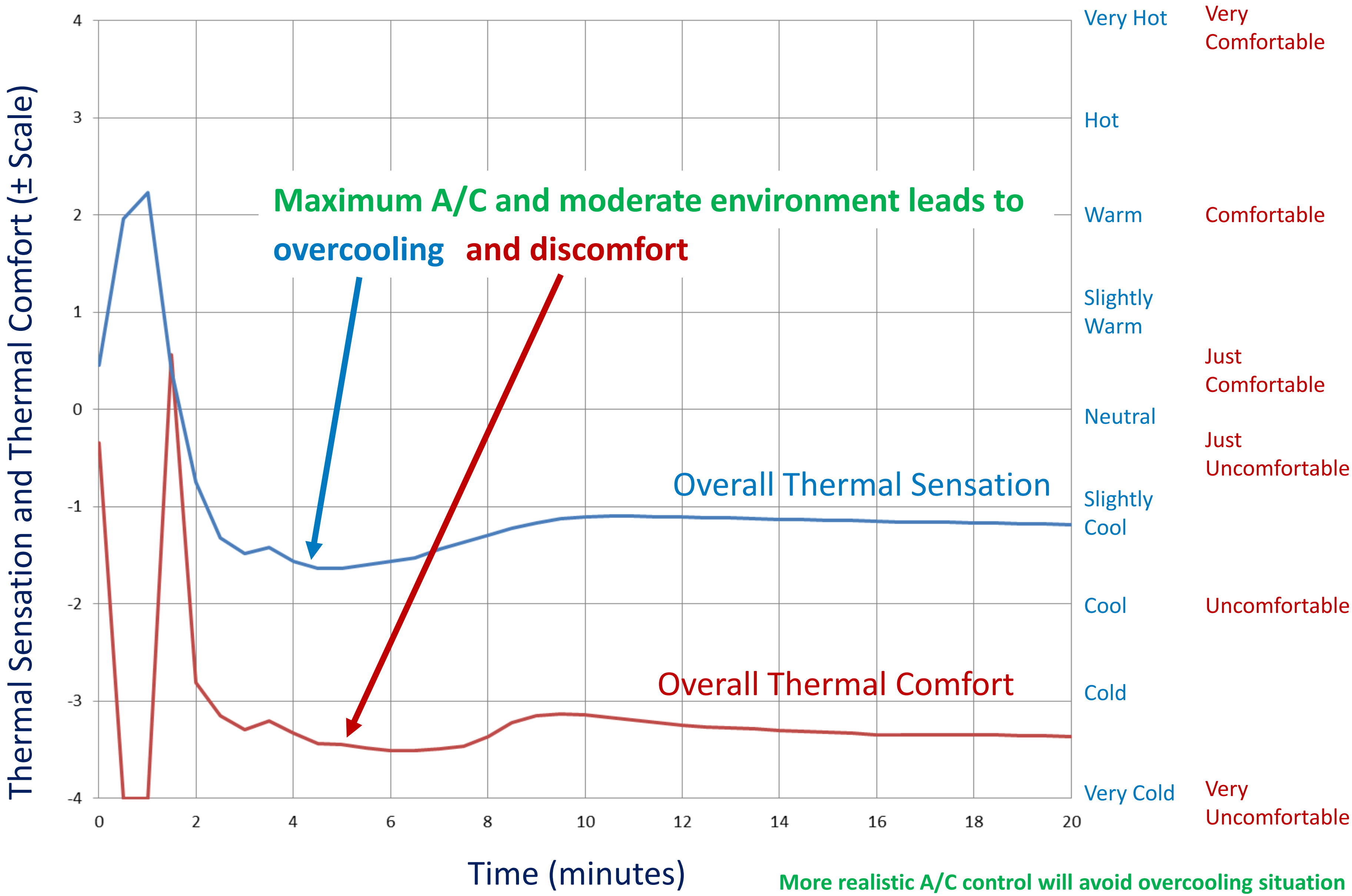
Added Manikin to Model

Virtual manikin in Focus Electric for thermal comfort analysis (meshed)



Thermal Comfort Analysis

Cool-Down with Manikin – Preliminary



More realistic A/C control will avoid overcooling situation

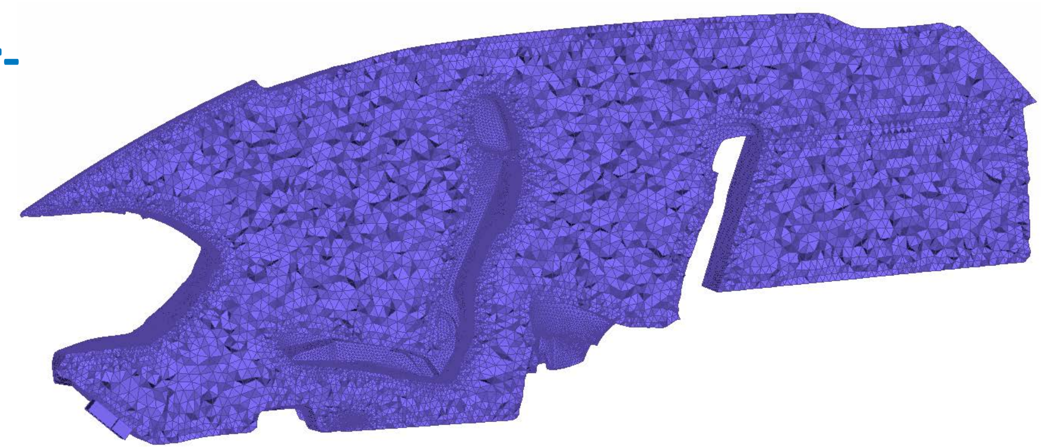
Thermal Analysis – Future Plans

- **Finish cool-down and baseline thermal comfort analysis**
- **Baseline warm-up analysis**
- **Leverage zonal climate control approach developed under DOE's thermoelectric HVAC projects**
    - Cool/heat the passenger, not the cabin
- **Investigate reducing thermal loads**
- **Investigate new thermal comfort evaluation techniques**

Exa Collaboration

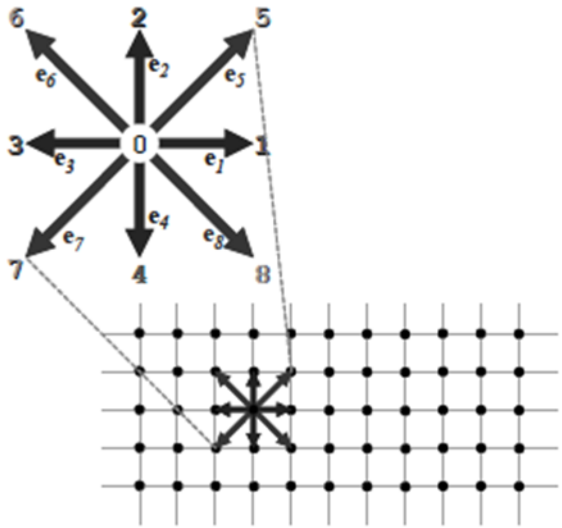
Problem

- **CFD using traditional Navier-Stokes solutions is time consuming**
  - Meshing
  - Solving



Potential Solution

- **Exa PowerFLOW**
- **Lattice Boltzmann solution**
- **Ability for extreme parallelization**
- **Leverage NREL cluster**
- **Other advantages**
  - OEMs interested in this technique
  - Exa linking with Radtherm



Collaboration

- **Automotive Industry**
  - Ford
  - Bayer Material Science
  - Pittsburgh Glass Works (PGW)
  - Solutia
  - Faurecia
- **Software**
  - Exa
  - ThermoAnalytics
- **DOE VTO Crosscutting**
  - John Fairbanks: Leveraging thermoelectric research
- **National Lab Crosscutting**
  - ANL APRF vehicle data

Summary

EV Everywhere Grand Challenge

- **DOE Mission Support**
  - Reduced EDV climate control energy use may reduce costs and improve range, which would accelerate consumer acceptance, increase EDV usage, and reduce petroleum consumption
- **Overall Approach**
  - Work with automobile manufacturers to assemble a team that may include suppliers for glazings, seats, insulation, EDV thermal systems, and HVAC systems
  - Conduct thermal analyses (CFD, RadTherm, human thermal comfort)
  - Evaluate promising techniques in outdoor vehicle tests (hot and cold thermal soak, cool-down, warm-up)
  - Consider thermal effects on the trade-off between electric range and initial battery energy/cost
  - Leverage DOE's thermoelectric HVAC projects and the zonal climate control approach

Summary (cont.)

- **Technical Accomplishments**
  - Signed CRADA with Ford
  - Completed baseline hot-weather characterization testing on two Ford Focus Electric vehicles
    - Defined adjustments to compensate for the inherent differences between vehicles in future tests
  - Completed initial thermal soak CFD simulations
    - Most locations compared well to test data
- **Collaborations**
  - Automobile manufacturers
  - Automotive Tier 1 suppliers
  - Software developers

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Vehicle Testing – Hot Thermal Soak

Typical Weather Conditions For Hot Thermal Soak Test