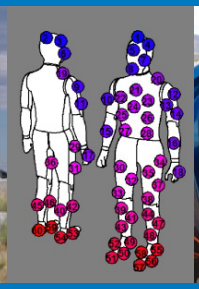
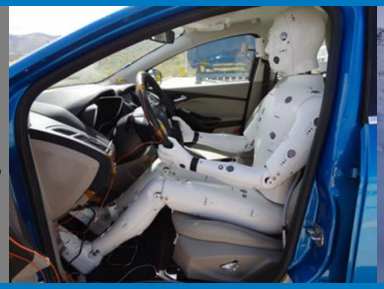
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Electric Drive Vehicle Climate Control Load Reduction

P.I.: John P. Rugh
National Renewable Energy Laboratory
June 17, 2014

Project ID: VSS097

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

Project Start Date: FY12
Project End Date: FY15
Percent Complete: 50%

Barriers

- **Range impact of climate control**
- **Cost – cost premium for EDVs**
- **Life – battery and temperature relationship**

Budget

Total Project Funding (to date): $2,600K
Funding received in FY13: $900K
Funding for FY14: $900K
Partner in-kind cost share: $225K *

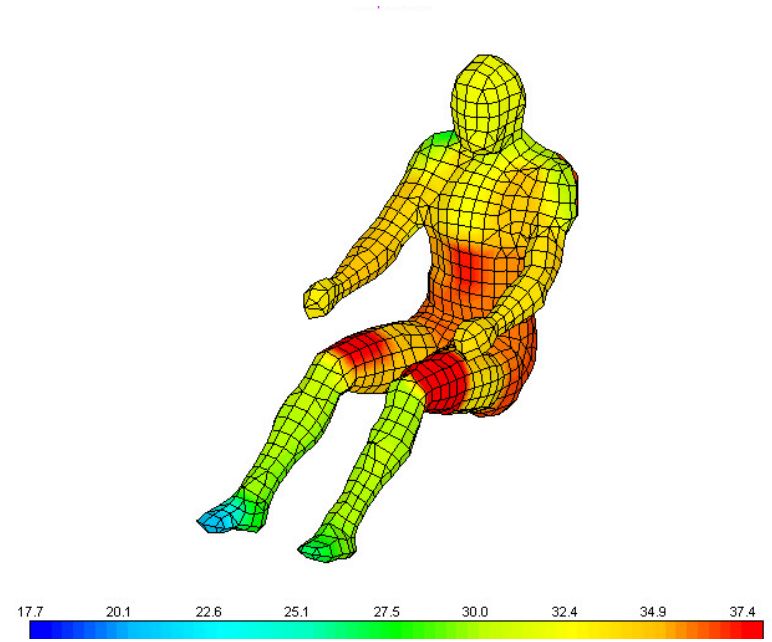
*** Not included in total**

Partners

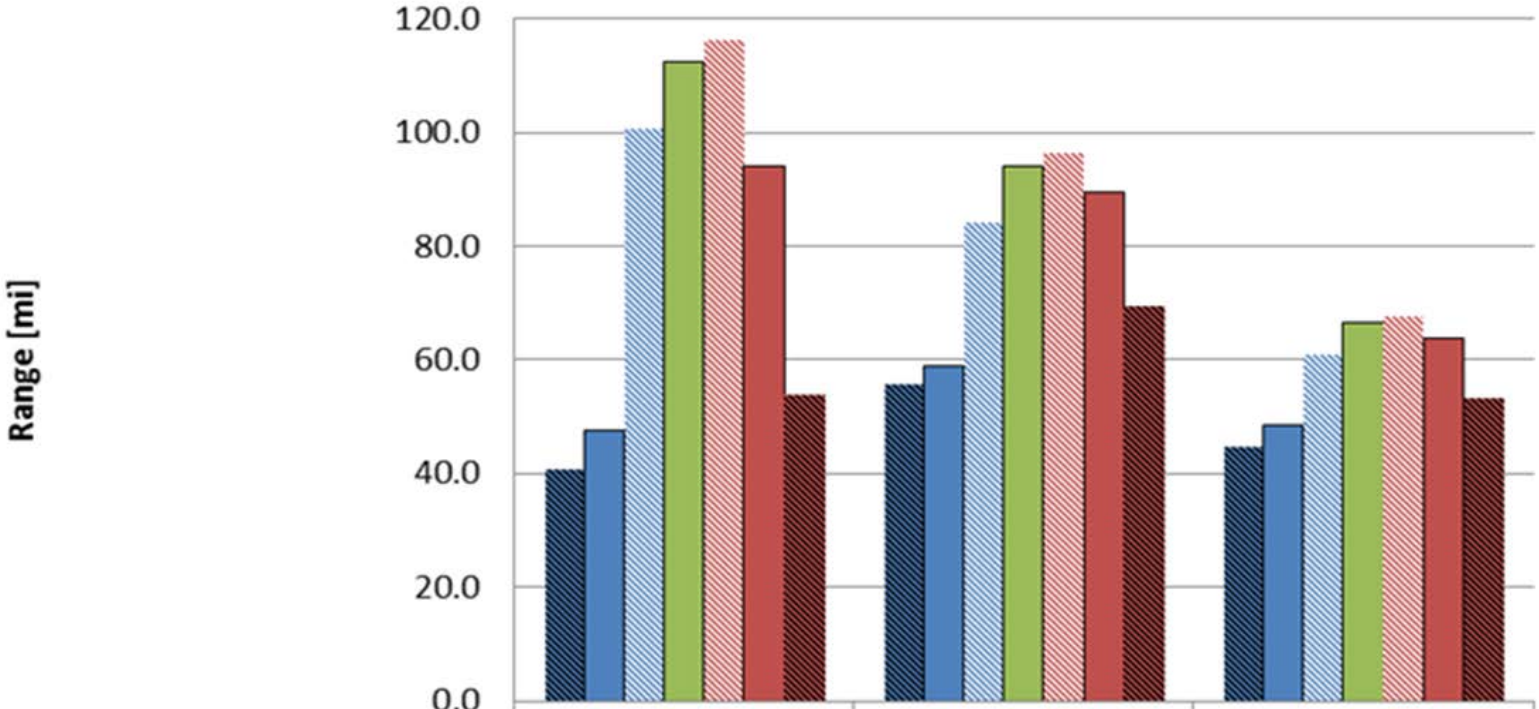
- Interactions/collaborations:
  - Ford
  - Measurement Technologies Northwest (MTNW)
  - ThermoAnalytics
  - Gentherm
  - Eastman Chemical (Solutia)
  - Argonne National Laboratory (ANL)
- Project Lead:
  - National Renewable Energy Laboratory

Relevance – Overcoming Barriers to EDVs

- **Range impact of climate control**
- **EDV batteries**
  - Cabin temperature can impact the battery
- **Cabin heating technology**
  - Stored electrical energy used for cabin heating takes valuable energy away from propulsion
- **A new way of looking at climate control design with a focus on human thermal comfort is required**



Relevance – Climate Control Reduces the Electric Range of a Ford Focus EDV



	UDDS	HWY	US06
20F Ambient with Max heat	41.0	55.8	44.8
20F Ambient with 72F Cabin	47.7	58.9	48.7
20F Ambient with no heat	100.7	84.2	61.1
72F Ambient with Climate off	112.5	94.0	66.5
95F Ambient with no AC	116.4	96.5	67.7
95F Ambient with 72F Cabin	94.0	89.3	63.9
95F Ambient with Max AC	53.9	69.6	53.3

Source: Argonne National Laboratory's Advanced Powertrain Research Facility

Relevance – Support Broad VTO Efforts

- **U.S. DRIVE Vehicle Systems Analysis Technical Team**
- **DOE VTO Multi-Year Project Plan**
  - "…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 cars with sufficient range that meet consumers' 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"

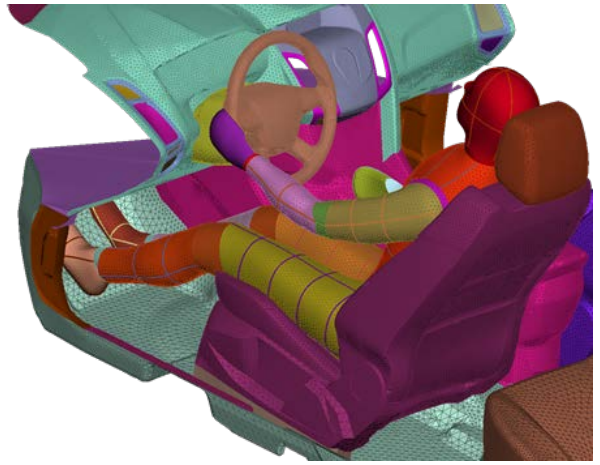
Relevance – Objectives

- **Minimize the impact of climate control on grid-connected EDV 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 (CRADA)
- **Develop and evaluate the effectiveness of strategies to reduce climate control loads**
  - Evaluate promising techniques in outdoor vehicle thermal soak tests
  - Conduct thermal analysis
- **Leverage zonal climate control approach developed under DOE's thermoelectric HVAC projects**
- **Investigate new thermal comfort evaluation techniques**



CRADA = cooperative research and development agreement
HVAC = heating, ventilation and air conditioning
OEM = original equipment manufacturer

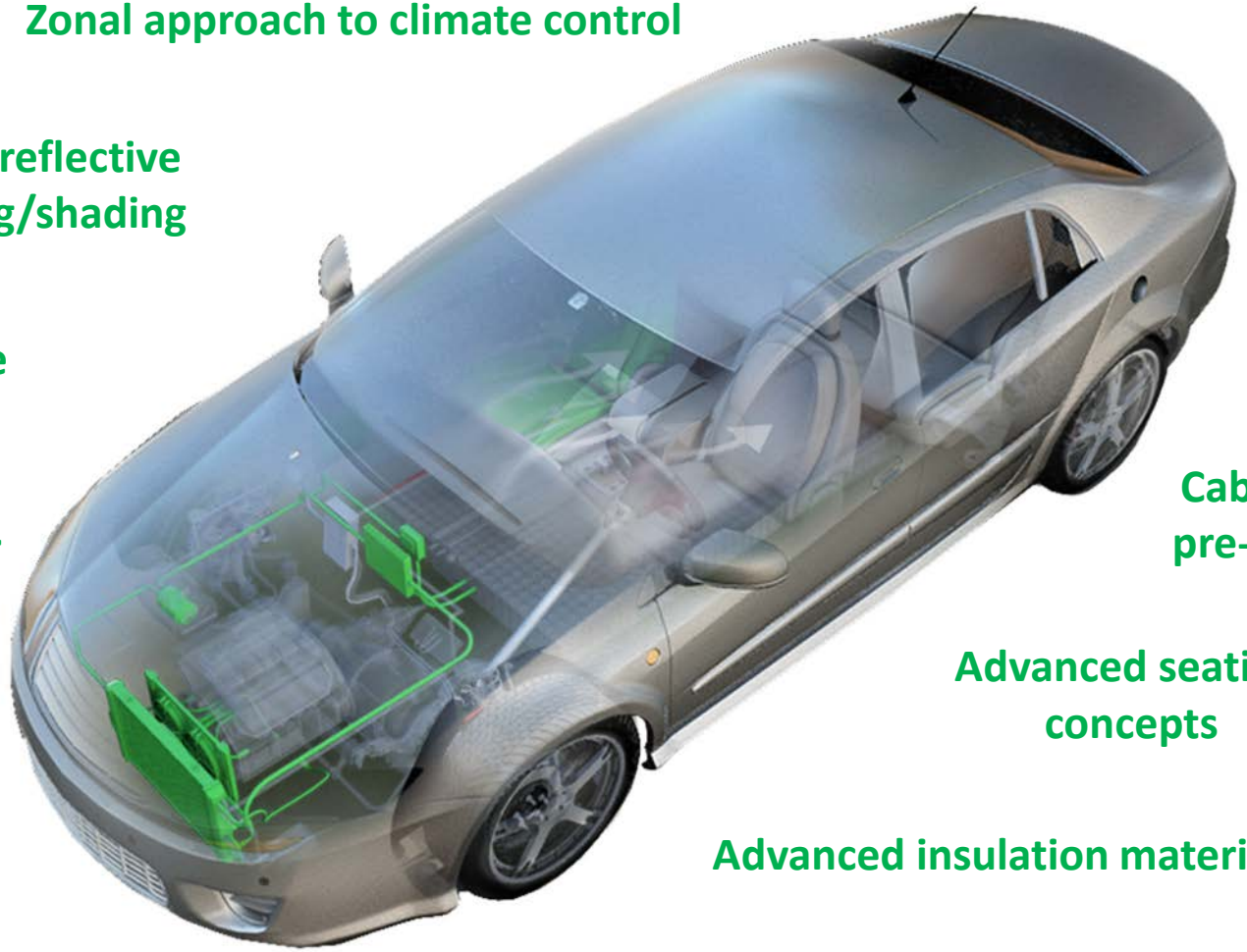
Approach – Focus Areas

Zonal approach to climate control

Solar-reflective glazing/shading

Active/passive ventilation

Heated interior surfaces



Cabin & battery pre-conditioning

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
  - ANL – Autonomie vehicle model

Approach – Milestones

Month/Year	Description
Q2 Mar. 2014	Milestone • Complete cold weather testing on the Focus Electrics and assess thermal load reduction and zonal configurations during heating mode
Q4 Sept. 2014	Milestone • Submit a summary of the task for the DOE annual report

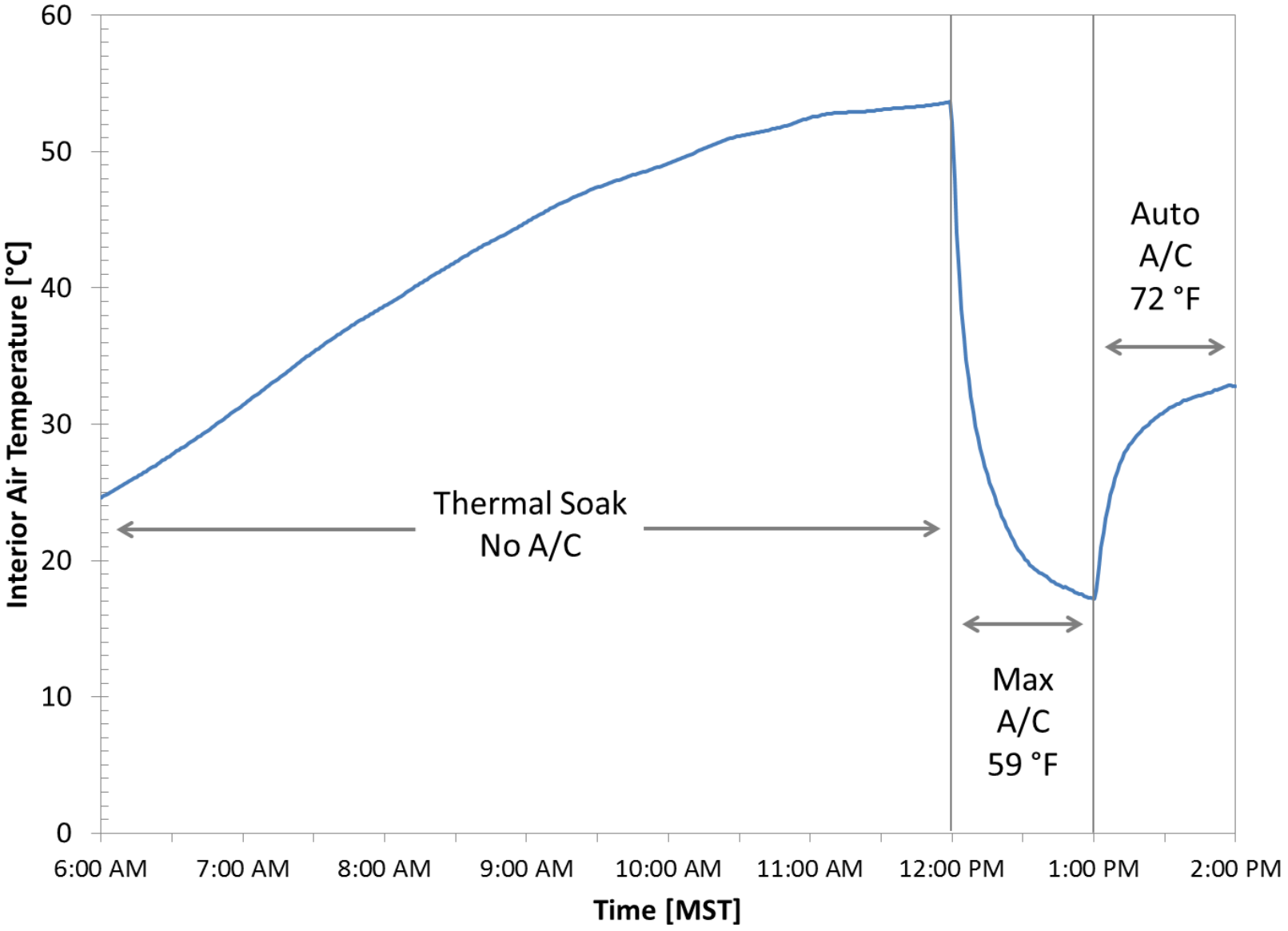
Accomplishments: Vehicle Testing

Enhanced Outdoor Thermal Testing of EDVs

- **Two Ford Focus EDVs**
  - Same interior and exterior
  - Control and modified vehicles
- **Test setup enhancements**
  - Level 2 vehicle chargers
  - Interior relative humidity sensors
  - Power transducers on high-voltage batteries and cabin heaters
  - Access to vehicle CAN bus data
  - Remote voice control of Control BEV HVAC settings
  - External control of HVAC blower duty cycle

Accomplishments: Vehicle Testing

Developed a Warm Weather Test Procedure

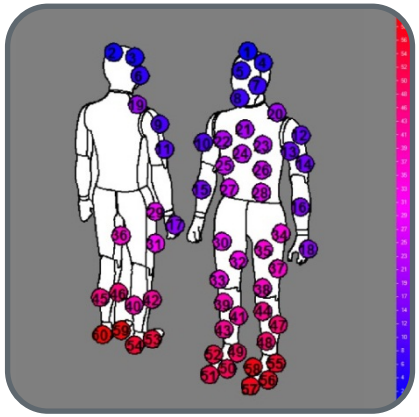


Accomplishments: Vehicle Testing

Developed an Approach for Human Thermal Comfort Assessment

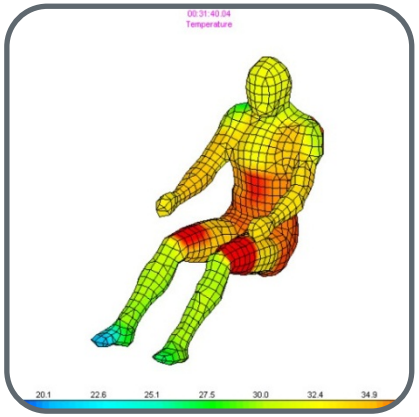
HVAC Manikin

HVAC Manikin placed in test BEV during thermal tests



ThermDAC

ThermDAC software logs data from Manikin sensors



RadTherm

RadTherm software performs thermal comfort simulation from test data

RadTherm model improvements:

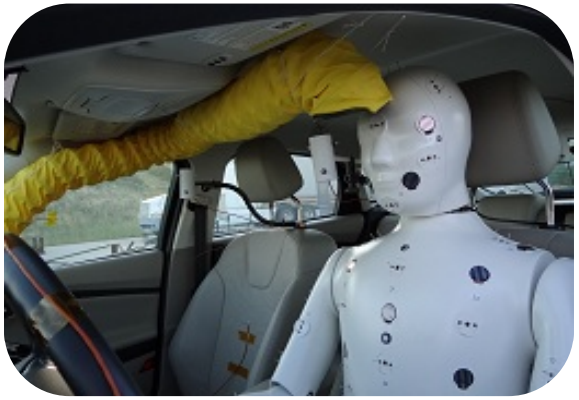
1. Applied realistic temperature profiles to seat boundary conditions
2. Updated thermal initialization of model

Accomplishments: Vehicle Testing

Zonal Climate Control Test Configurations

Driver Vents Only

- Passenger vents closed
- Only driver panel vents active



Overhead Vent

- Passenger panel vent routed to headliner
- Driver vents still active

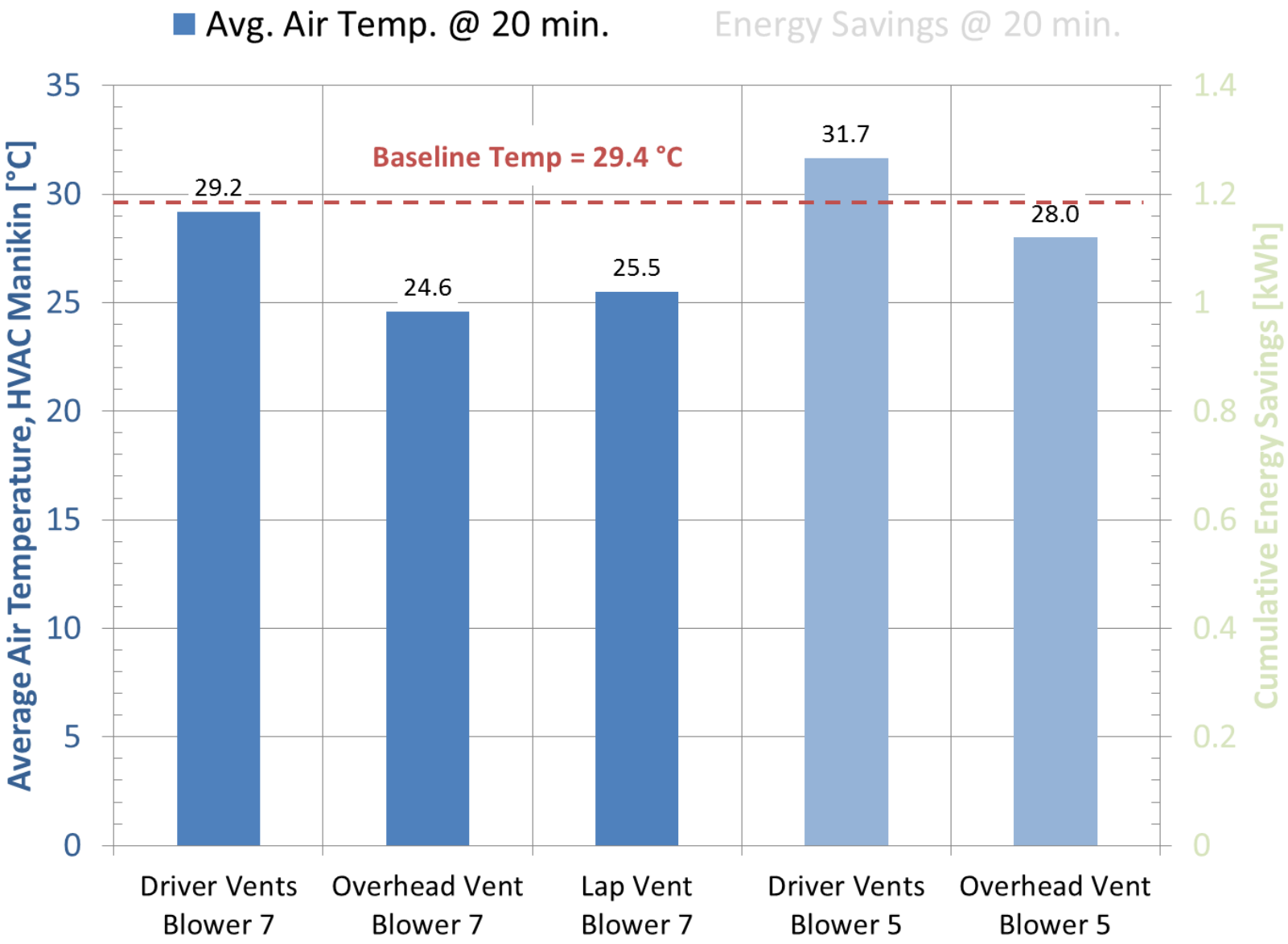
Lap Vent

- Passenger panel vent routed to console
- Driver vents still active

To reduce energy consumption, focus on where the occupants are located instead of cooling or heating the entire passenger compartment

Accomplishments: Vehicle Testing

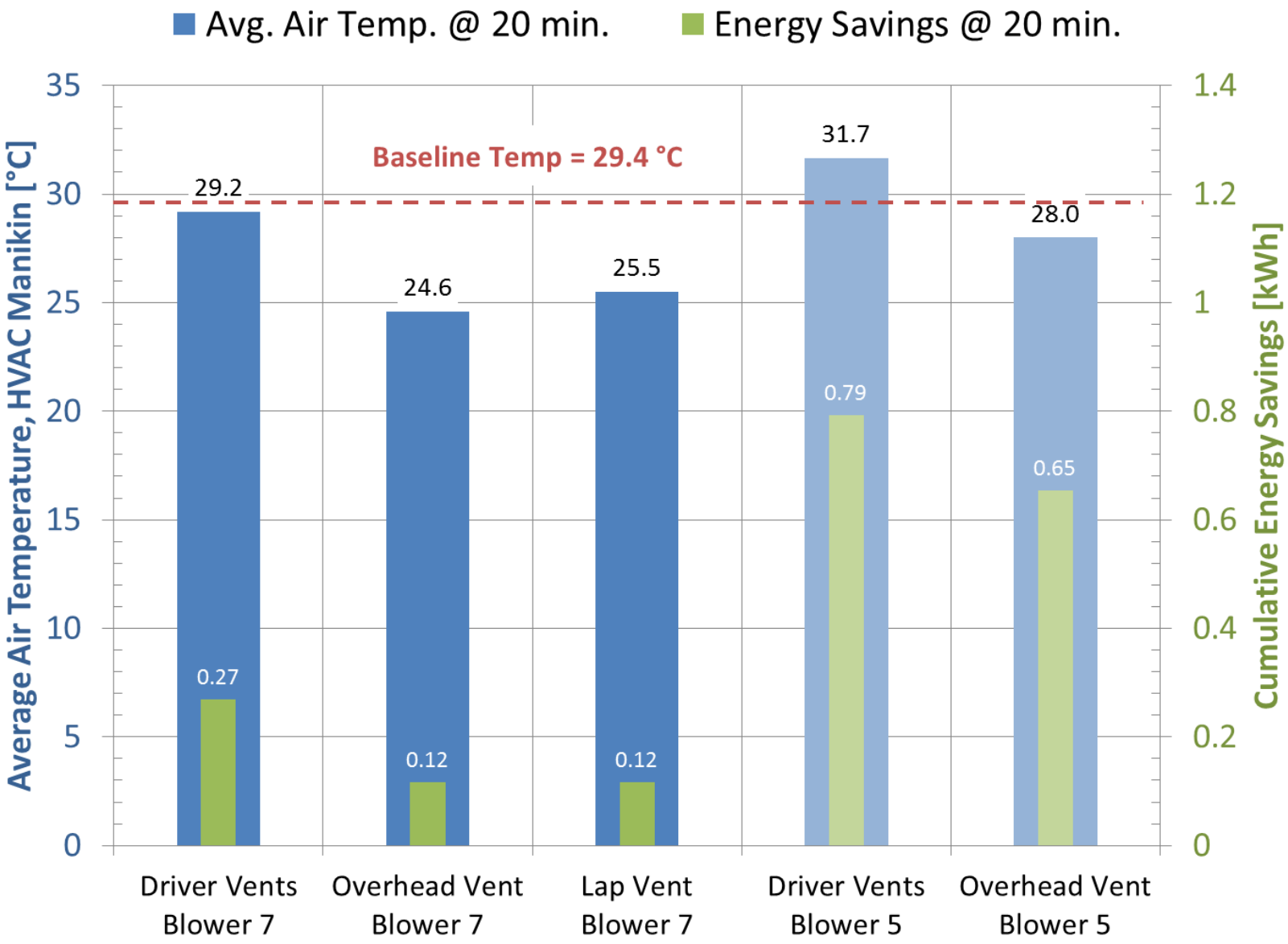
Zonal Configurations Had Lower Driver Air Temperatures and Lower Flow Rates



Accomplishments: Vehicle Testing

Zonal Configurations Resulted in Energy Savings

Maximum Potential Savings Case
1. Maximum A/C settings
2. Hot soak with solar load
3. Transient cool-down



Accomplishments: Vehicle Testing

Thermal Load Reduction Test Configurations

Reduce solar energy entering through the glass

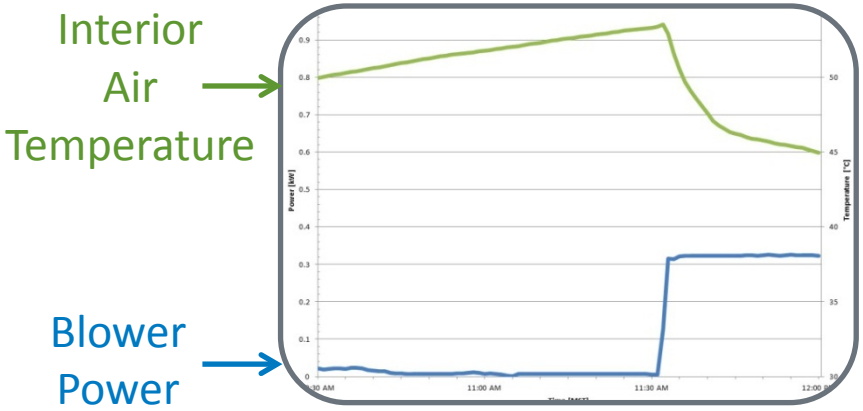
Solar-Reflective Film

- Applied to all glazing

White Film

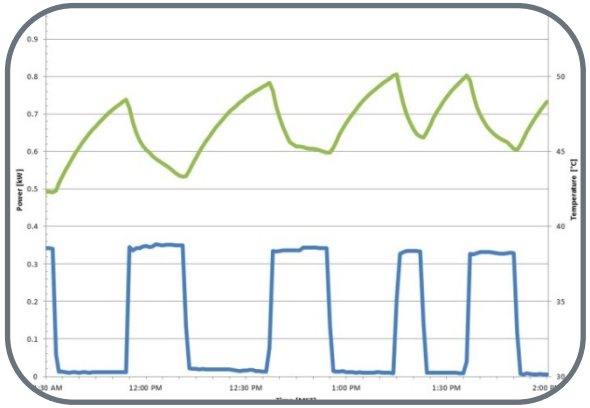
- Applied to all glazing

Remove energy that entered the vehicle



Continuous Ventilation

- Blower setting 7, Initiated just prior to drive

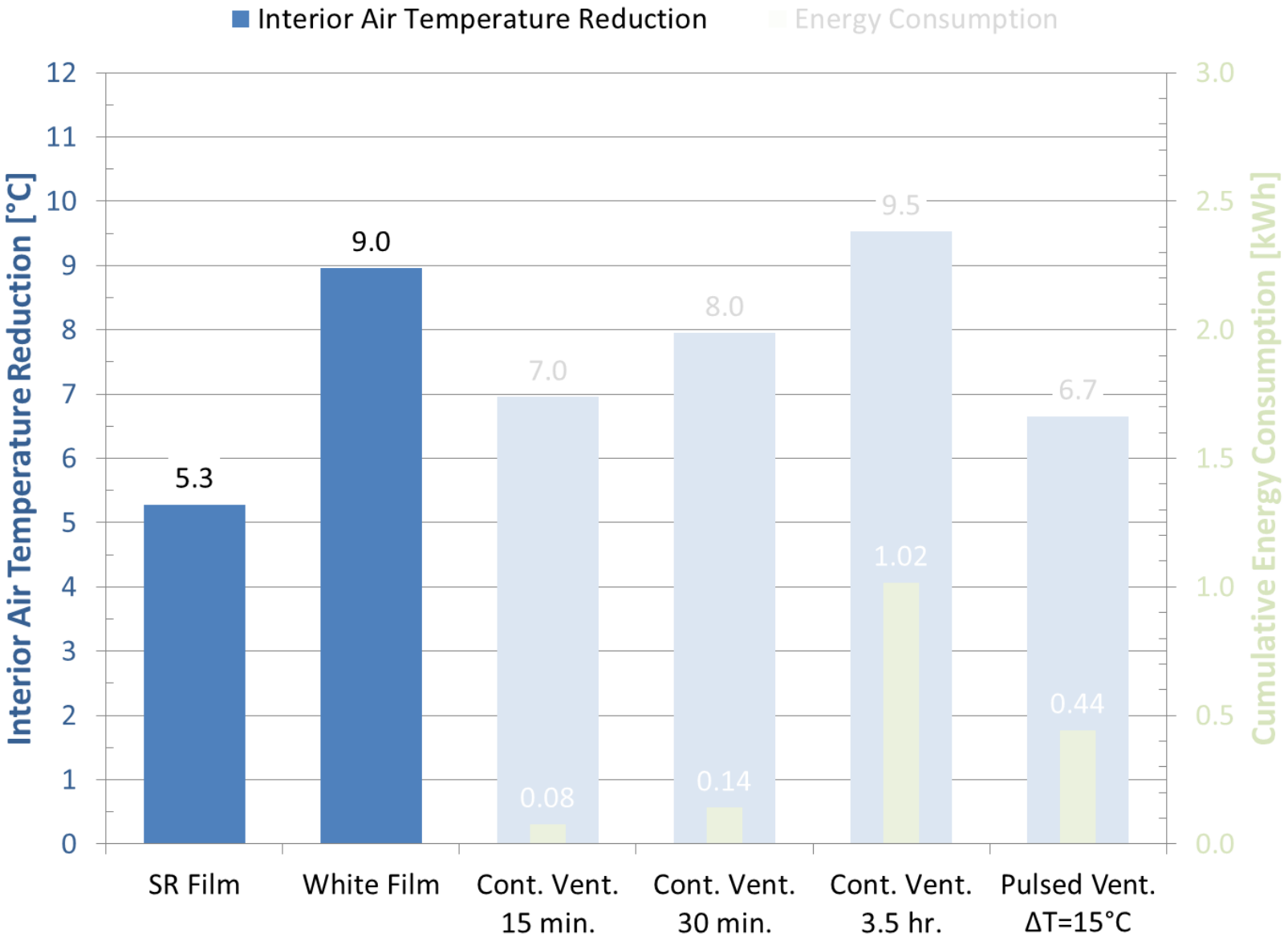


Pulsed Ventilation

- Blower setting 7, Active during thermal soak

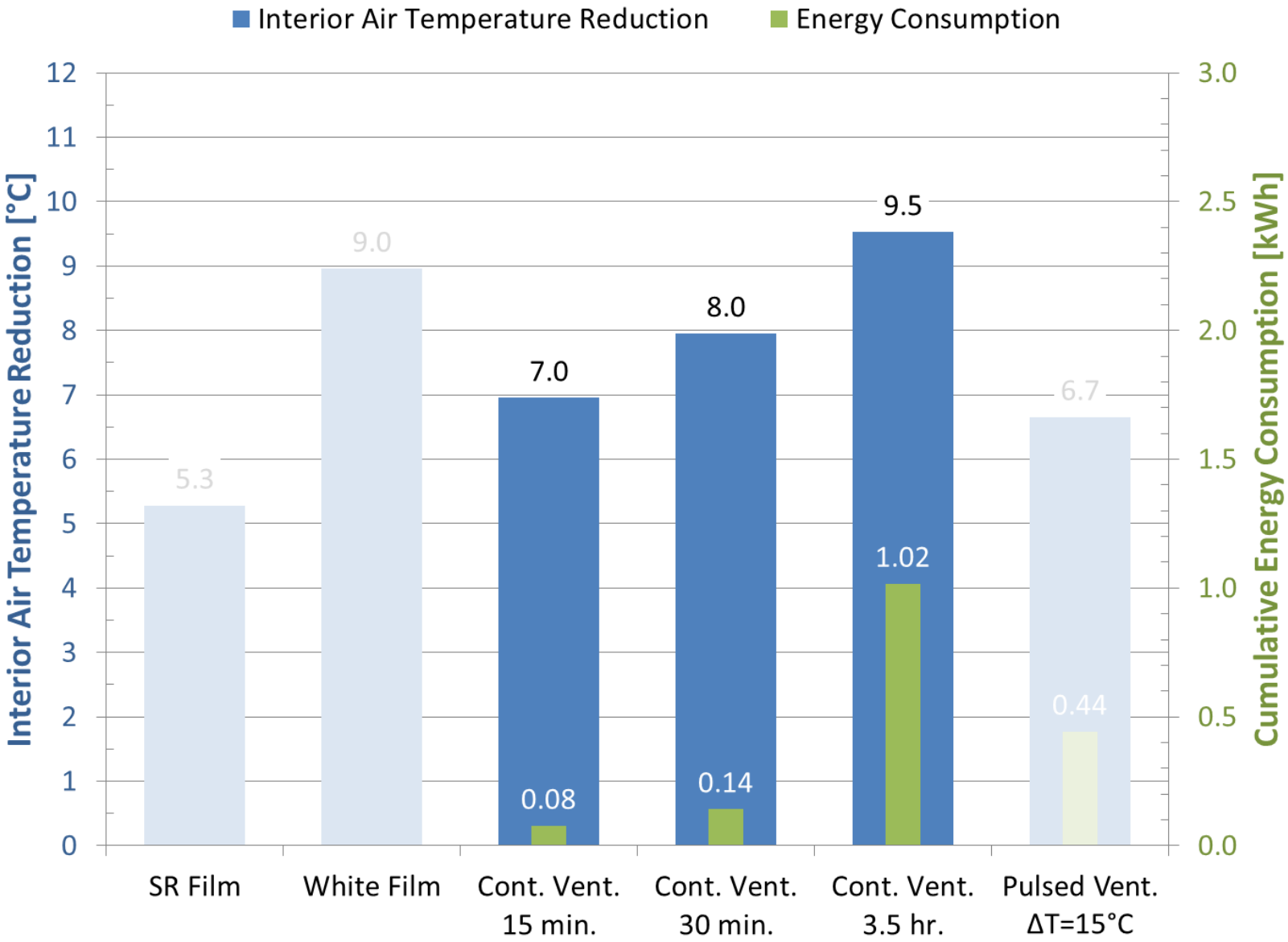
Accomplishments: Vehicle Testing

Interior Air Temperature Reduction of 5.3°C Achieved With Solar Reflective Film



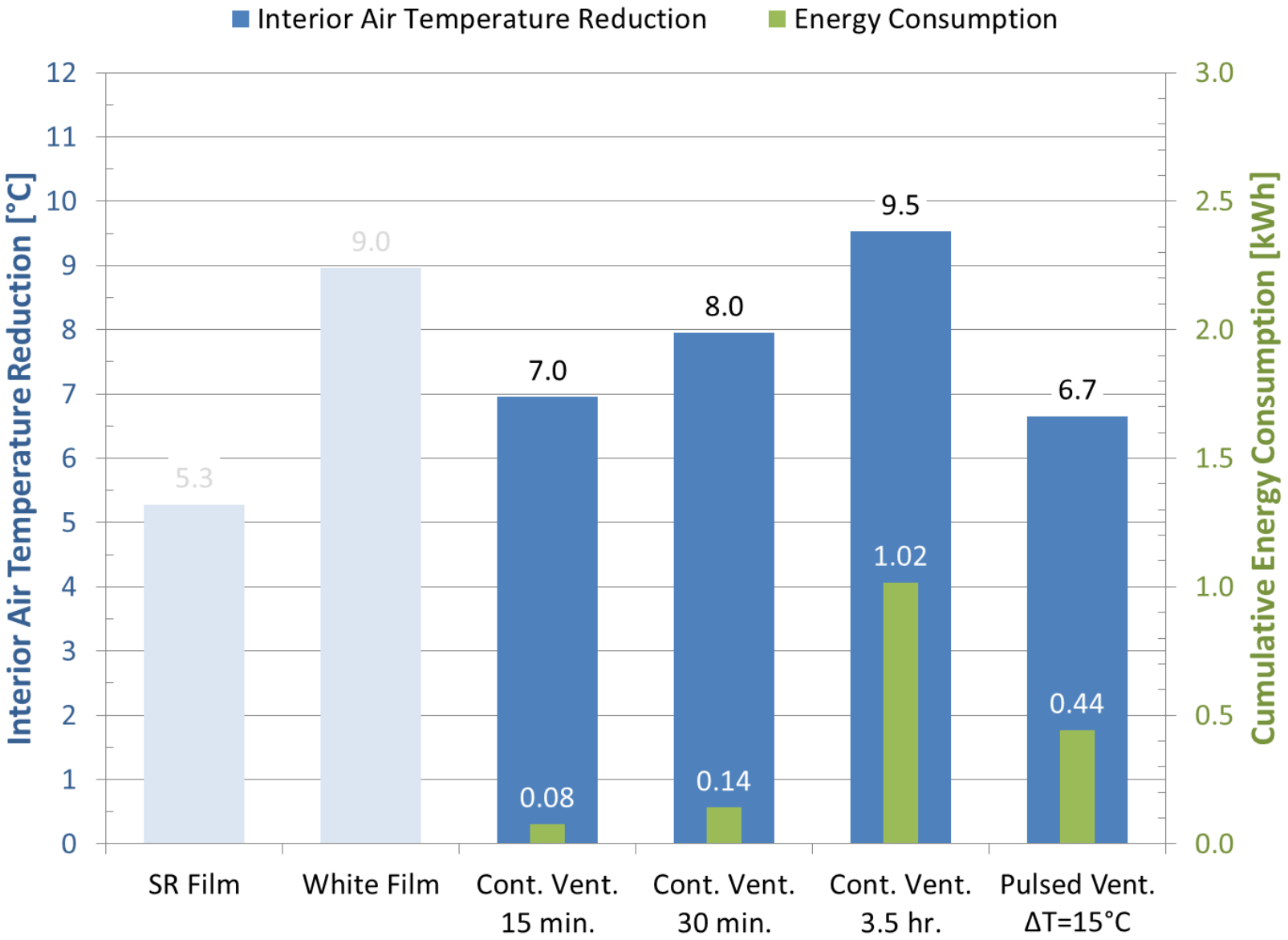
Accomplishments: Vehicle Testing

15- or 30-Minute Pre-Ventilation is an Effective Strategy



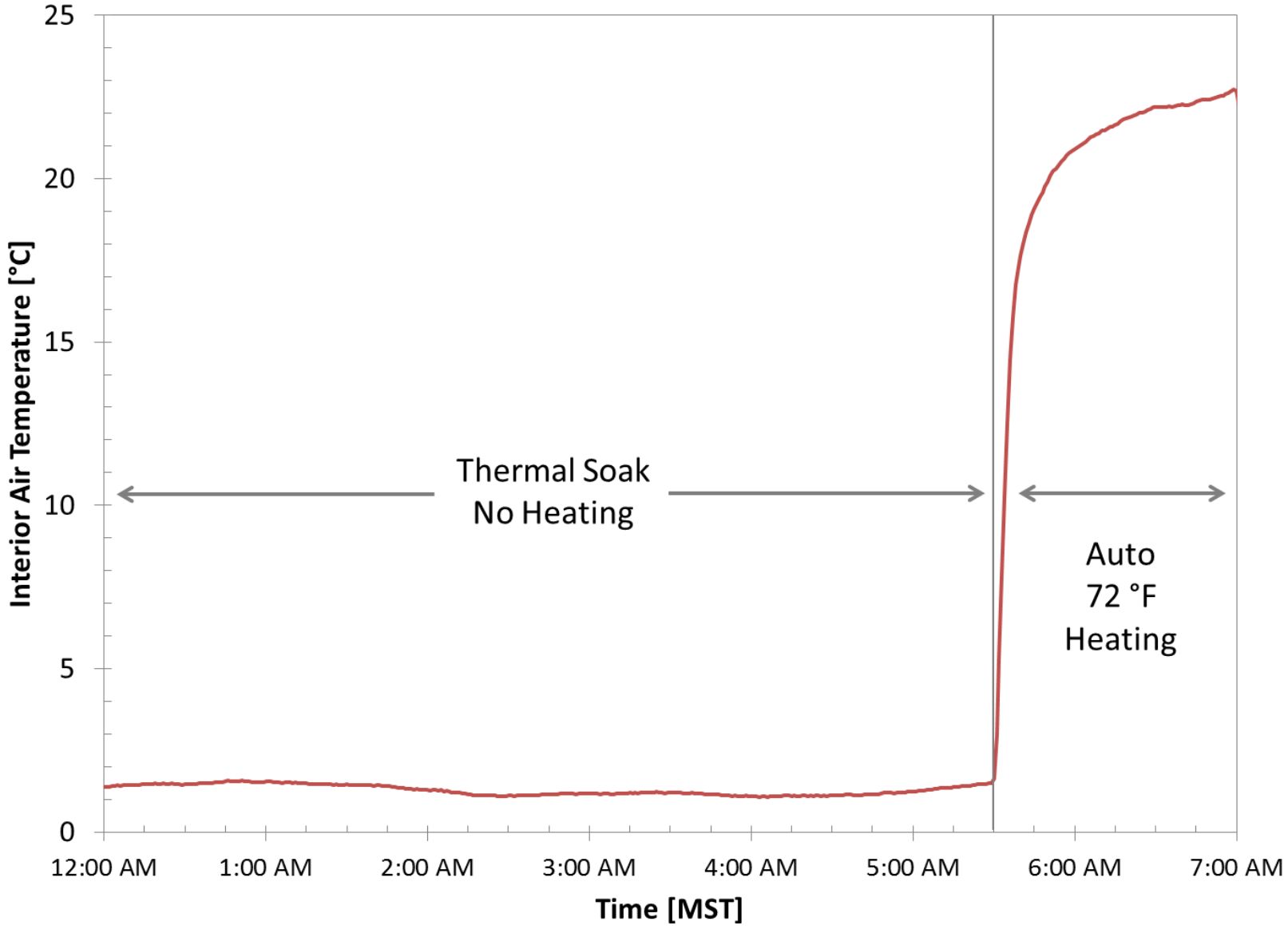
Accomplishments: Vehicle Testing

Pulsed Venting Also Reduced Air Temperatures, but Consumed More Energy



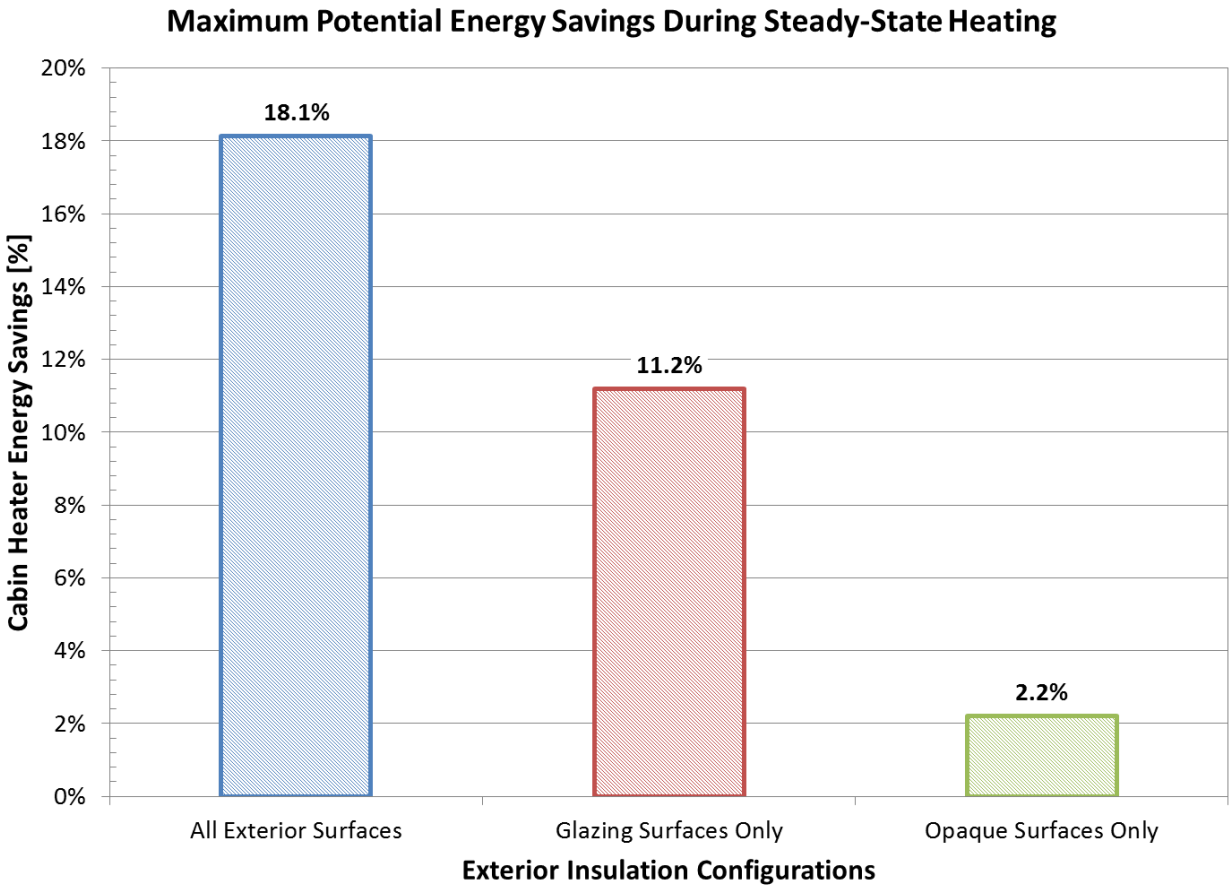
Accomplishments: Vehicle Testing

Developed a Cold Weather Test Procedure



Accomplishments: Vehicle Testing

Cold Weather Insulation Test Configurations and Results



- **Increased body insulation resulted in a 2% reduction in steady-state heating energy**
  - Will consider impact of increased weight on overall vehicle range benefit
- **Potential for further energy savings from increasing glazing thermal resistance**

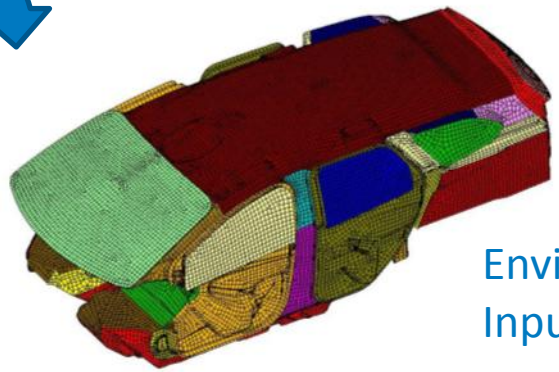
Accomplishments: Thermal Analysis

Methodology

Heat Transfer Coefficients,
Fluid Temperatures

RadTherm

Computational Fluid Dynamics



Environmental Input

Flow Rates,
Temperatures

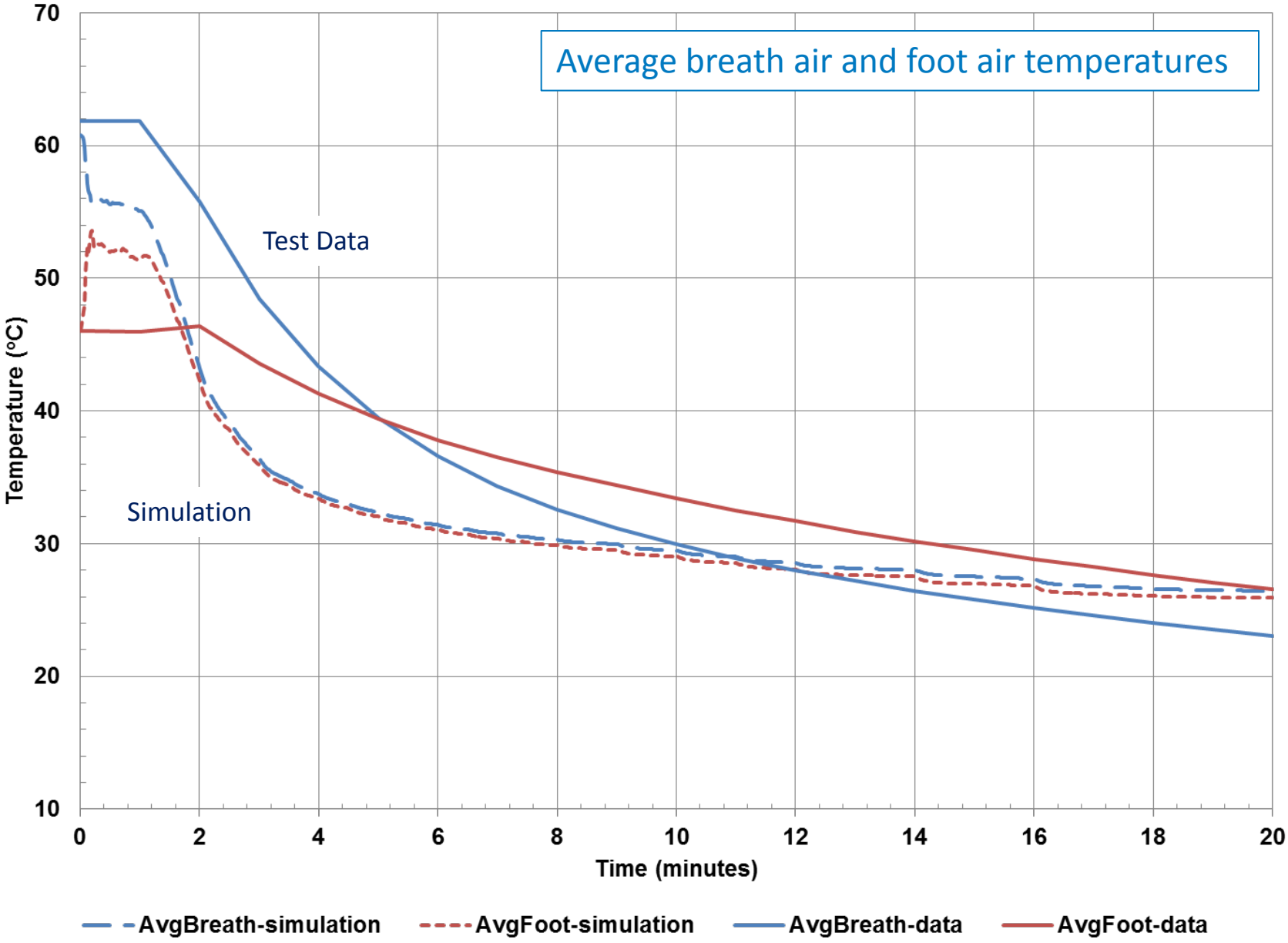
Surface Temperatures

Skin Temperatures,
Physiology

Thermal Comfort

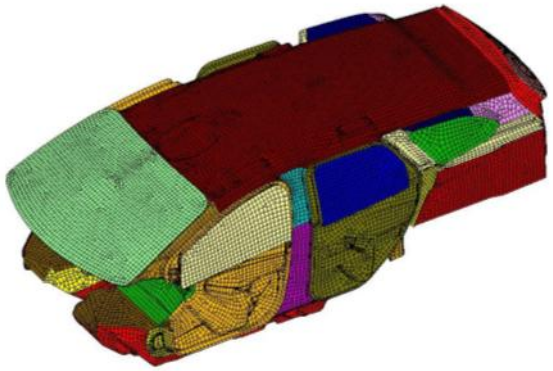
Accomplishments: Thermal Analysis – Baseline Cooldown

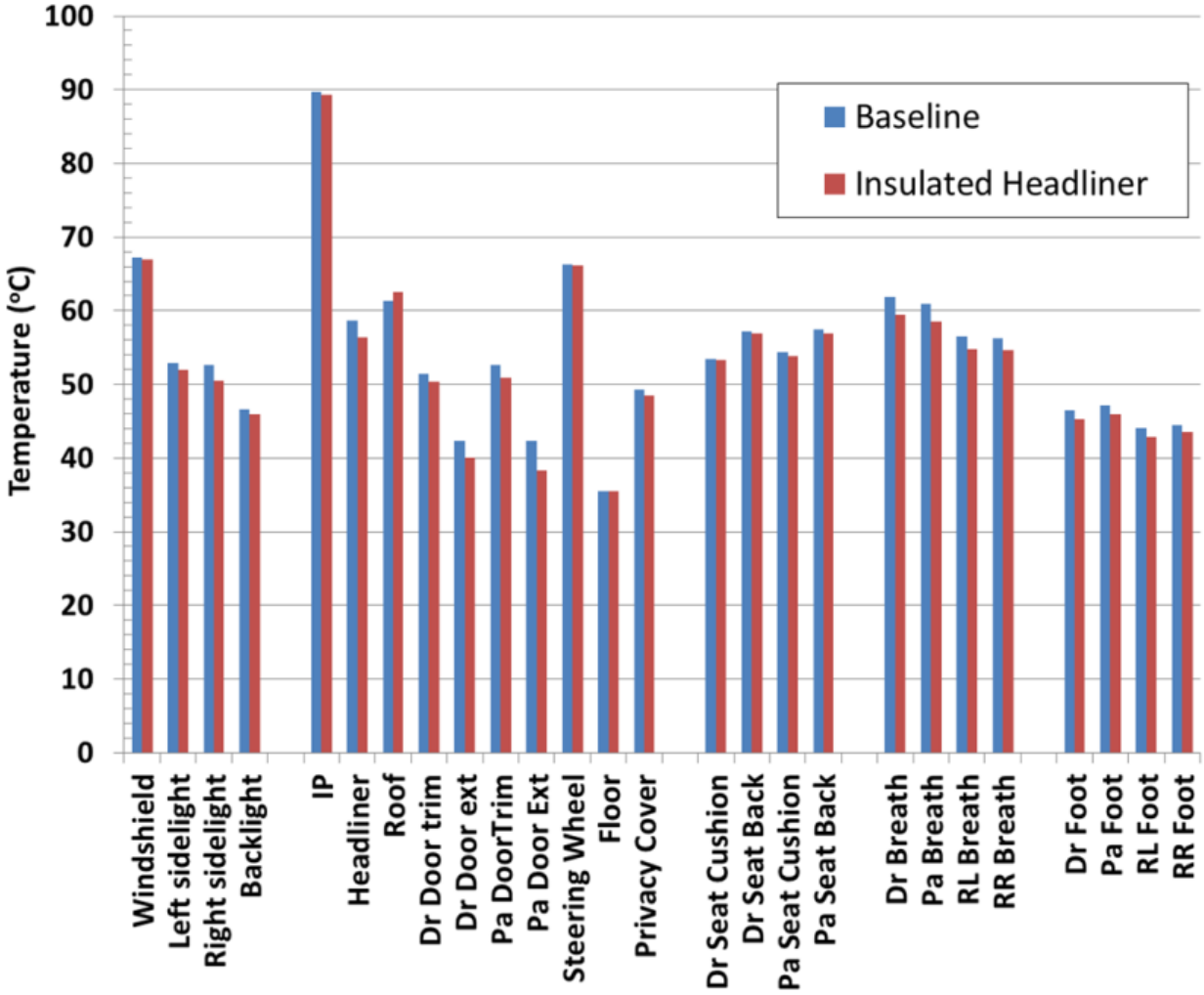
Reasonable T_{air} Comparison between Simulation Results vs. Test Data



Accomplishments: Thermal Analysis – Insulation (Soak)

Headliner Thermal Resistance Increased by a Factor of 3.8

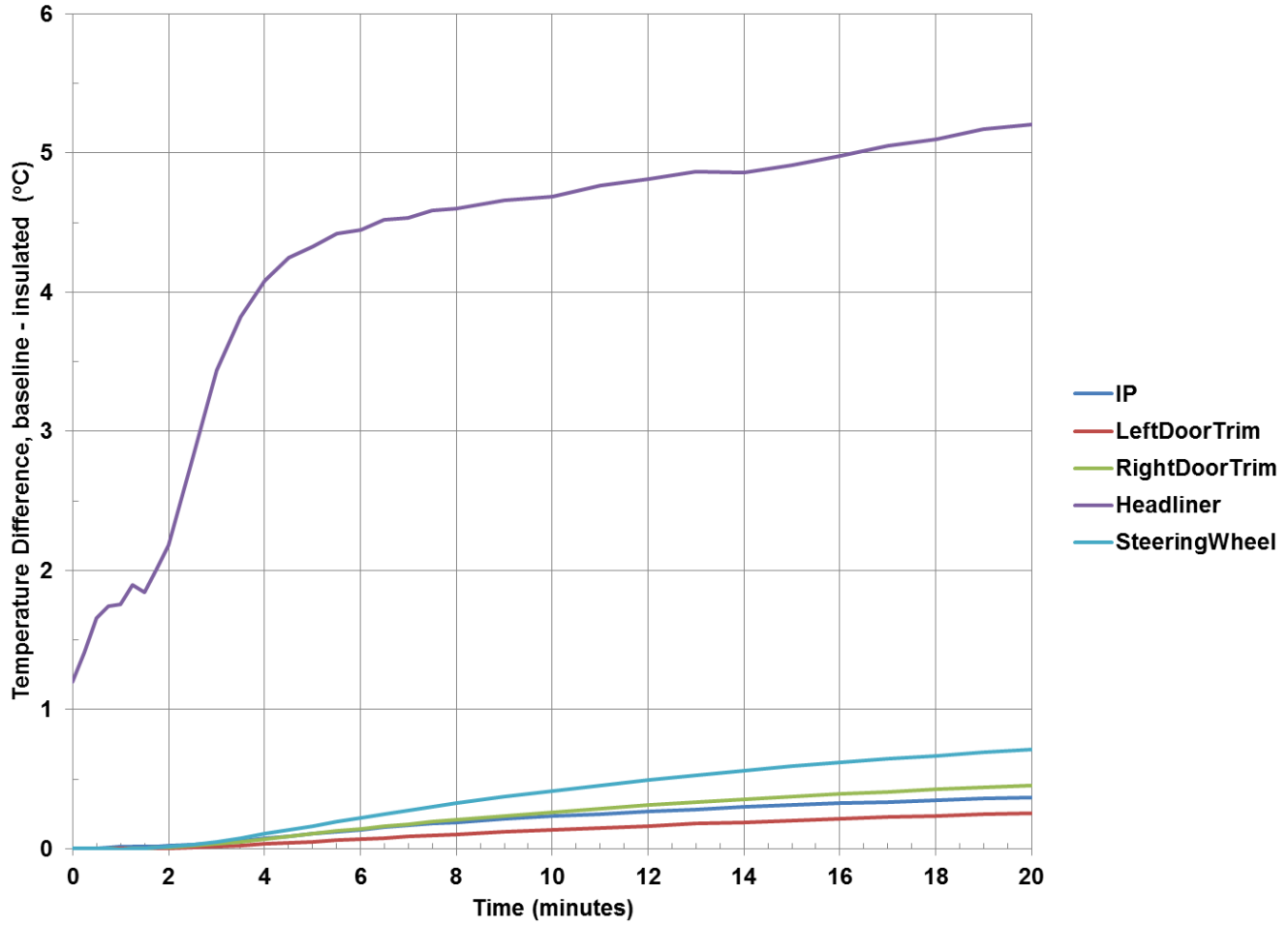




- **Reduced headliner and breath air temperatures (2–2.5°C) during soak**

Accomplishments: Thermal Analysis – Insulation (Cooldown)

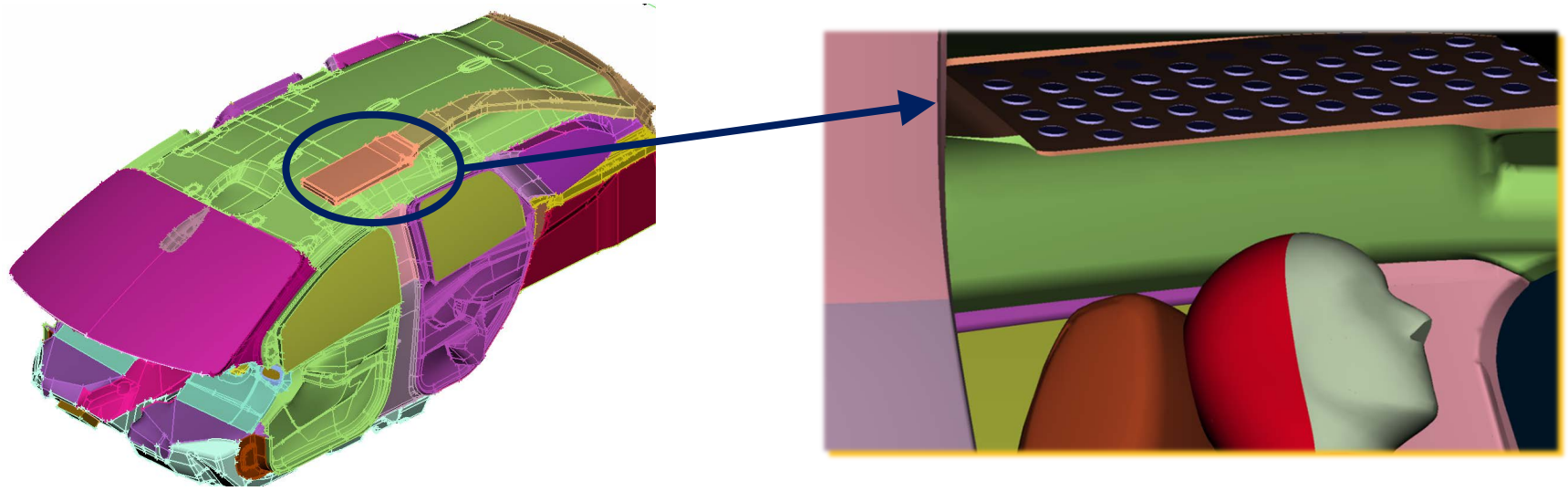
Less Than 1 C Decrease in Average Cabin Temperature During Cooldown



- **Headliner surface temperature was reduced by more than 5°C during cooldown**
- **Headliner insulation**
  - By itself does not significantly impact interior temperatures and A/C capacity
  - Could be part of a thermal load reduction system solution

Accomplishments: Thermal Analysis – Overhead Vent

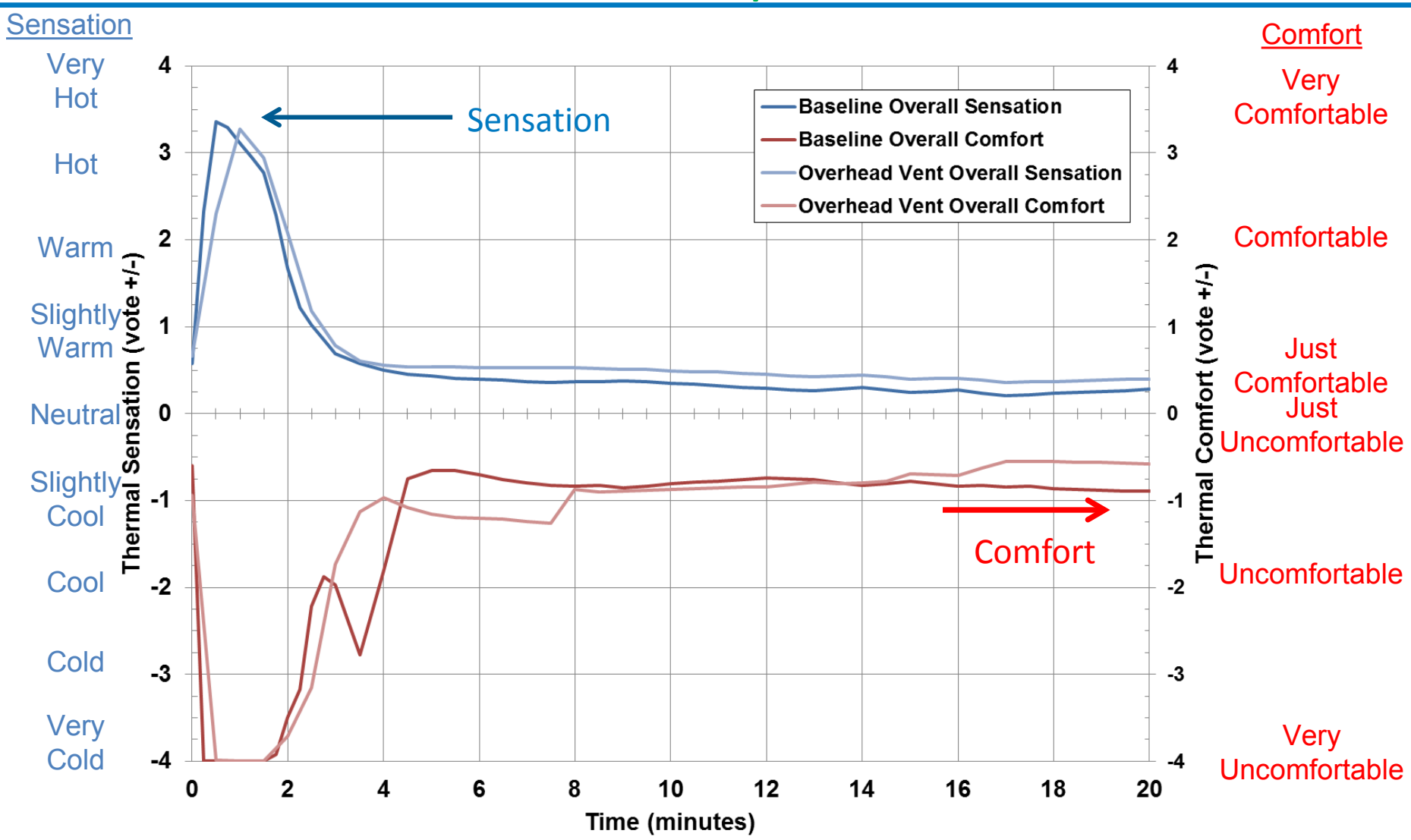
Zonal Configuration – Overhead A/C Vent



- **Objective: climate control design with a focus on human thermal comfort**
- **Real-world configuration of an overhead vent**
  - Incorporated overhead vent geometry from a Ford thermoelectric HVAC project vehicle into Focus EDV
- **Modifications to base model A/C boundary conditions**
  - Closed passenger side panel vents
  - Reduced flow to driver side panel vents
  - 60 cfm to overhead vent

Accomplishments: Thermal Analysis – Overhead Vent

Evaluation of the Effect of an Overhead A/C Vent on Human Thermal Comfort

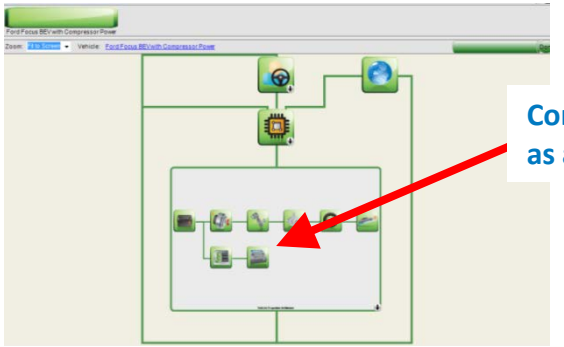


- Reduced A/C flow by 28% and maintained nearly identical thermal sensation and comfort
- Overhead (zonal) A/C vent has the potential to reduce A/C capacity by 28%

Accomplishments: Vehicle Simulation – Range Impact

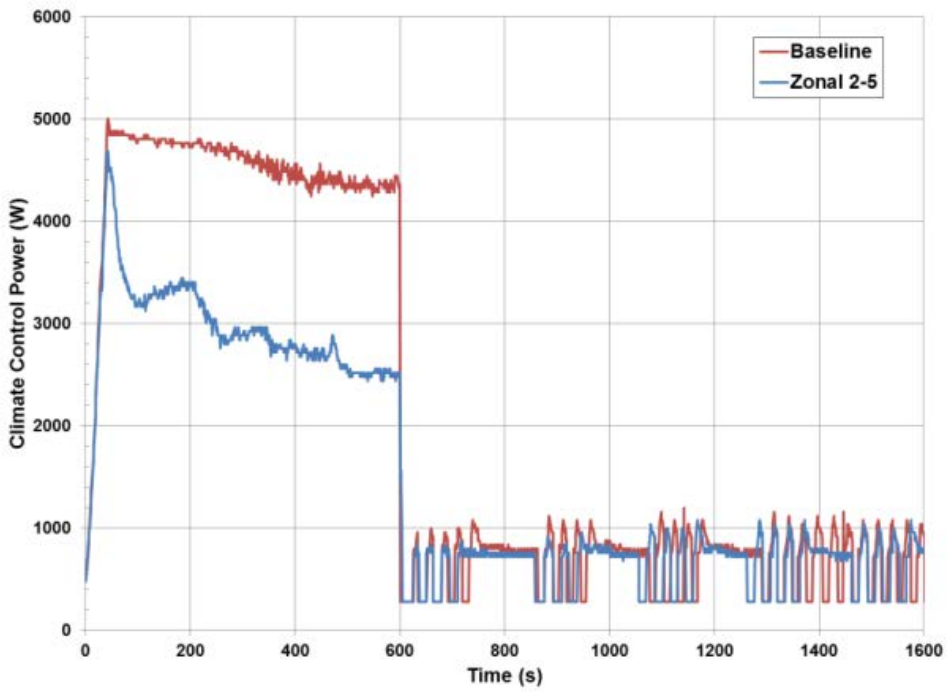
A/C Power from Testing Input into an Autonomie Model of a Focus Electric

- Drive cycles selected to yield a typical drive duration
  - UDDS (23 min.)
  - Double SC03 (19.8 min.)
  - Double HWFET (25.5 min.)
- Calculate energy used for each cycle, then project range based on usable battery state of charge (assume 70%)
- Composite A/C power profile
  - Max A/C for first 10 min.
  - Auto 72°F for remainder



Compressor power input as accessory load

Autonomie Focus BEV model



Accomplishments: Vehicle Simulation – Range Impact

Potential for Zonal Climate Control to Improve EV Range

- Impact of baseline A/C
  - 21% to 38% range reduction
- Potential mitigation
  - 7% to 15% improvement in range over baseline A/C from using an overhead vent
    - with reduced A/C capacity (blower setting 5)
    - and equivalent thermal comfort

Predicted Focus Electric Range (miles)				
Drive Cycle	No A/C	Baseline A/C	Zonal 2-5 A/C	Increase of Zonal 2-5 over baseline
SC03	90.3	56.6	65.1	15%
UDDS	92.2	57.0	65.5	15%
HWFET	80.4	63.7	68.5	7%

Range improvement in moderate environmental conditions and longer trip lengths will be less

Collaboration and Coordination

- **Automotive Industry**
  - Ford
  - Gentherm
  - Eastman Chemical (Solutia)
- **Thermal Manikin**
  - MTNW
- **Software**
  - ThermoAnalytics
- **DOE VTO Crosscutting**
  - John Fairbanks: Leveraging thermoelectric research
- **National Lab Crosscutting**
  - ANL – vehicle model and test data

Future Work

- **Remaining FY14**
  - Conduct heated windshield defog testing
  - Conduct Round 2 summer testing
    - Test more aggressive vehicle configurations for warm weather operation
    - Assess complex interactions between combined configurations
    - Evaluate cold weather solutions for unintended consequences in warm weather
  - Develop a process to calculate the expected impact on range for a typical EV in the United States
- **FY15**
  - Work with MTNW and ThermoAnalytics to improve the HVAC manikin test and analysis process
  - Implement most promising zonal climate and thermal load reduction strategies on the Focus Electric test vehicle

Summary

- **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
- **Collaborations**
  - Automobile manufacturers
  - Automotive Tier 1 suppliers
  - Software developers
  - National laboratories

Summary (cont.)

Technical Accomplishments

- **Evaluated three zonal cooling configurations with a new thermal manikin**
  - Up to 16.7% reduction in energy consumption after 20 minutes for the same climate control settings
  - Up to 41.3% energy savings and improved cooling with reduced blower setting
- **Evaluated thermal load reduction strategies**
  - Interior air temperature reduction of 5.3°C achieved with solar-reflective film in thermal soak test
  - 30-minute pre-ventilation with HVAC blower reduced interior air temperature by 8.0°C, consumed 0.14 kWh
- **Improvement in range over baseline A/C using zonal A/C varies from 7% to 15%**

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Acknowledgements and Contacts

Special thanks to:

David Anderson
Lee Slezak
Vehicle Technologies Office

For more information:

John P. Rugh – Task leader and PI
National Renewable Energy Laboratory
john.rugh@nrel.gov
303-275-4413

Team Members:

Larry Chaney
Cory Kreutzer
Matt Jeffers
Jeff Tomerlin

Responses to Previous Year Reviewers' Comments

Comment	Response
• Reviewer would have liked to see defog (dehumidification) and defrost (removal of ice) included in this study	• Working with Ford, we have prioritized testing of defogging of the windshield. This testing is ongoing, and includes the evaluation of a heated windshield.
• Reviewer commented that the baseline needs to be better characterized, especially for extreme environments such as Phoenix, Arizona or Fairbanks, Alaska	• Vehicle manufacturers design climate control systems to perform in extreme environments. However, our partners have guided us to concentrate on improving performance in moderate conditions where many trips occur.
• Two reviewers commented on progress against the $1.7 million spent so far	• The start of the project was delayed due to executing the CRADA in FY12. The budget was $1.7 million, but the actual project cost through March of 2013 was $900K

Photo Credits

Slide 1	Matt Jeffers, NREL
Slide 3	Matt Jeffers, NREL
Slide 6	Matt Jeffers, NREL
Slide 7	Matt Jeffers, NREL
Slide 11	Matt Jeffers, NREL
Slide 12	Matt Jeffers, NREL
Slide 13	Matt Jeffers, NREL
Slide 14	Matt Jeffers, NREL
Slide 17	Matt Jeffers, NREL
Slide 21	Matt Jeffers, NREL
Slide 22	Matt Jeffers, NREL
Slide 35	Cory Kreutzer, NREL