NREL
NATIONAL RENEWABLE ENERGY LABORATORY

CoolCab Test and Evaluation & CoolCalc HVAC Tool Development


[1]

U.S. Department of Energy
Annual Merit Review

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Project ID #VSS075

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

Overview

Timeline

Project Start Date: FY11
Project End Date: FY15
Percent Complete: 70%

Budget

Total Project Funding:
(CoolCab/CoolCalc)
DOE Share: **$1060K / $615K**
Contractor Share: **$488K***

Funding Received in FY13: $400K/$300K

Funding for FY14: $450K/$300K

**Direct funds and in-kind contributions (not included in total)*

Barriers

- **Risk Aversion** – *Industry lacks key performance data on HVAC loads and truck cab thermal load reduction technologies*
- **Cost** – *Truck fleets operate on small profit margins and are sensitive to purchase costs for equipment*
- **Computational Models, Design And Simulation Methodologies** – *Industry lacks adequate heavy-duty truck thermal load models*

Partners

- Collaborations
  - Volvo Trucks
  - Daimler Trucks (SuperTruck)
  - Kenworth (PACCAR)
  - PPG Industries
  - 3M, Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems
  - Dometic Environmental Division
  - Sekisui S-LEC America
- Project lead: NREL

Relevance – Project Description

THE CHALLENGE

- **667 million gallons of diesel fuel used annually for long-haul truck rest period idling[1]**
  - 6.8% of total long-haul fuel use[1]
- **Increased idling regulation at the local, state, and national level[2]**
- **Large uncertainty with technology payback period and effectiveness**
- **Truck fleets operate over a wide range of environmental and use conditions**
- **Solutions must be effective over seasons and modes of operation**

1. Gaines, L., Vyas, A., and Anderson, J., "Estimation of Fuel Use by Idling Commercial Trucks," 85th Annual Meeting of the Transportation Research Board, Washington, D.C., Paper No. 06-2567, January 22-26, 2006.
2. Roeth, M., Kircher, D., Smith, J., and Swim, R., "Barriers to the Increased Adoption of Fuel Efficiency Technologies in the North American On-Road Freight Sector," Report for the International Council for Clean Transportation. NACFE. July 2013.

Relevance – Project Description

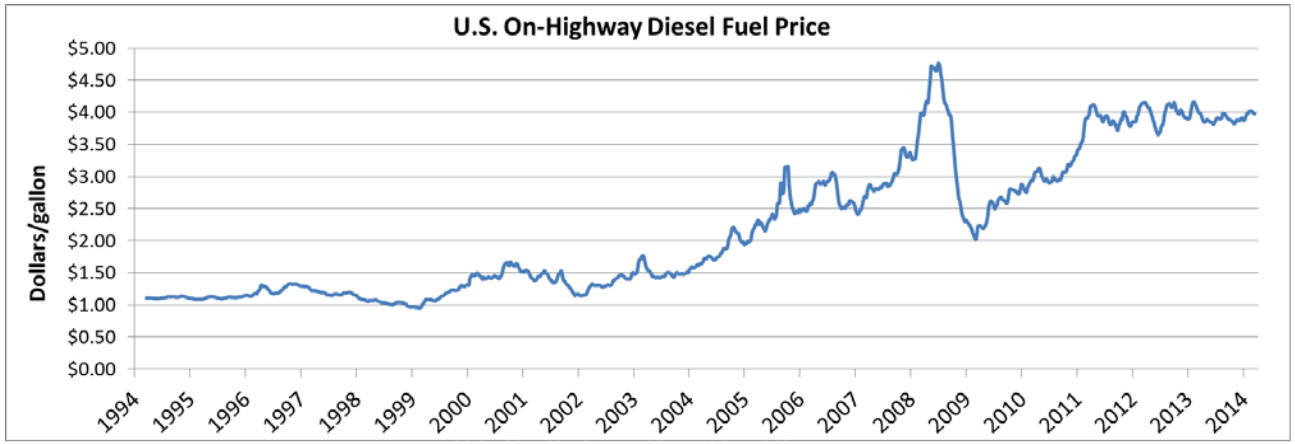
THE OPPORTUNITY

- Reducing idling loads will enable idle-reduction technologies
- Fleets are economically motivated by a 3-year or better payback period
- Effective solutions needed to meet regulations
  - Anti-idling products on the market supply loads, not reduce them
- Fuel use and payback period quantification aid in overcoming barriers

Alignment with DOE

- Support VSST Key Goals for 2011-2015 Program Plan:

  *Expand activities to develop and integrate technologies that address ..., **auxiliary load reduction**, and **idle reduction** to greatly improve commercial vehicle efficiency*
- Support SuperTruck and 21st Century Truck Partnership goals



Data Source: EIA Short-Term Energy Outlook http://www.eia.gov/petroleum/gasdiesel/, April 2014

Relevance – CoolCab SMART Goal

Demonstrate at least a 30% reduction in long-haul truck idle climate control loads with a 3-year or better payback period by 2015

- Work with industry partners to develop effective, market-viable solutions using a system-level approach to research, development, and design
- Design efficient thermal management systems that keep the occupants comfortable without the need for engine idling
- Develop analytical models and test methods to reduce uncertainties and improve performance in idle-reduction technologies

Milestones – Combined Project Plan

FY 2011				FY 2012				FY 2013				FY 2014				FY 2015			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

CoolCab

M1. Quantify impact of advanced insulation on cab idle reduction systems ✓
M2. Quantify impact on paint, films, and glazings on cab idle reduction systems ✓
M3. Design idle reduction systems using zonal, comfort based, and ventilation control approaches ✓
M4. Develop effective advanced full cab design in collaboration with industry partners
M5. Work with industry partners to demonstrate fuel savings

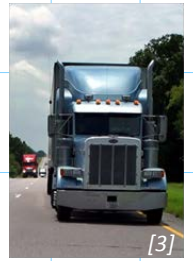
Advanced Insulation — M1

Solar Reduction: Paints, Films, Glazing — M2

Conditioned Volume Management — M3

Cab Design Demonstration — M4

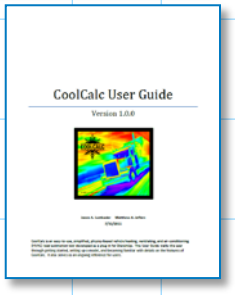
Demonstrate fuel savings — M5



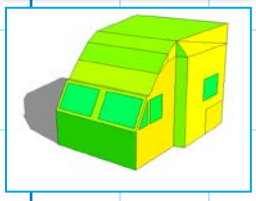
CoolCalc

M1. Write user guide and prepared first release of CoolCalc ✓
M2. Add functionality for full modeling process within the GUI environment – geometry to loads ✓
M3. Enable rapid parametric design analysis tools to estimate HVAC impacts at a national level ✓
M4. Develop process and tools for estimating fuel use and payback period
M5. Work with industry partners to demonstrate fuel use and payback-period driven design

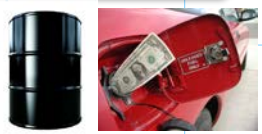
Initial Release — M1



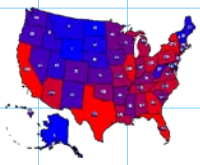
Full Modeling Process, Release — M2

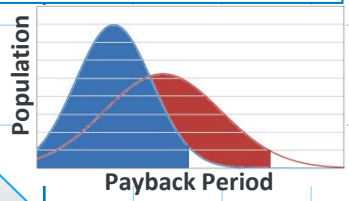


National-level HVAC Analysis — M3



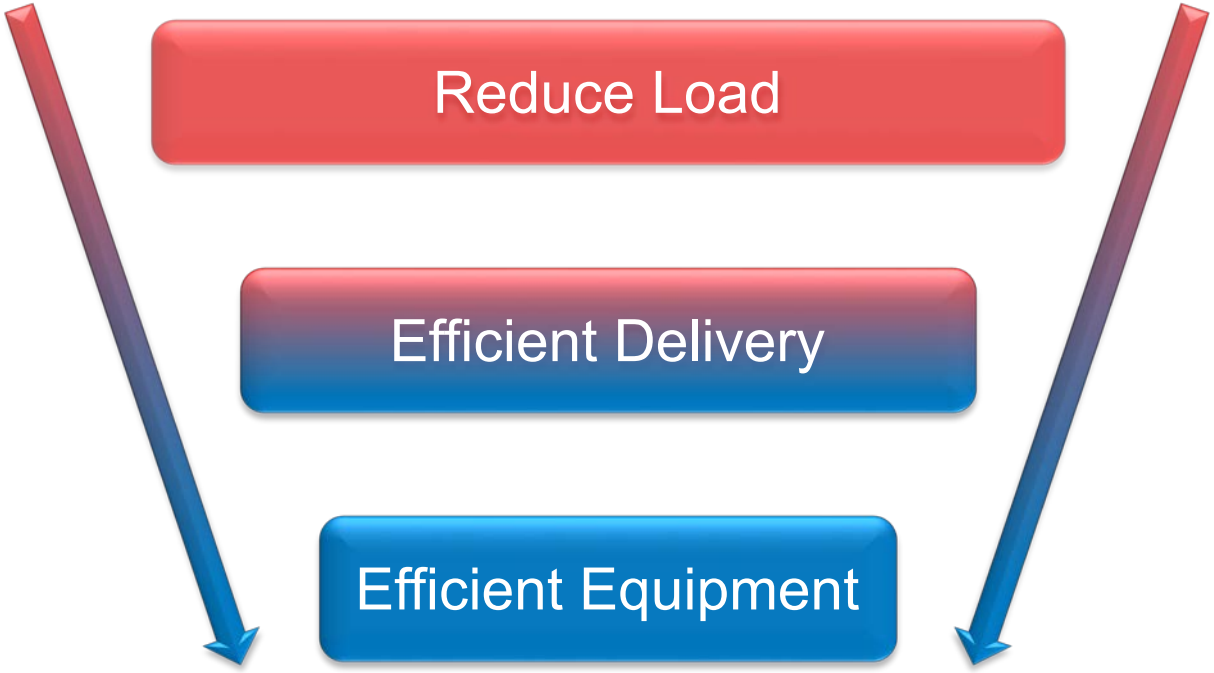
Fuel Use and Payback — M4





Fuel Use Driven Design — M5

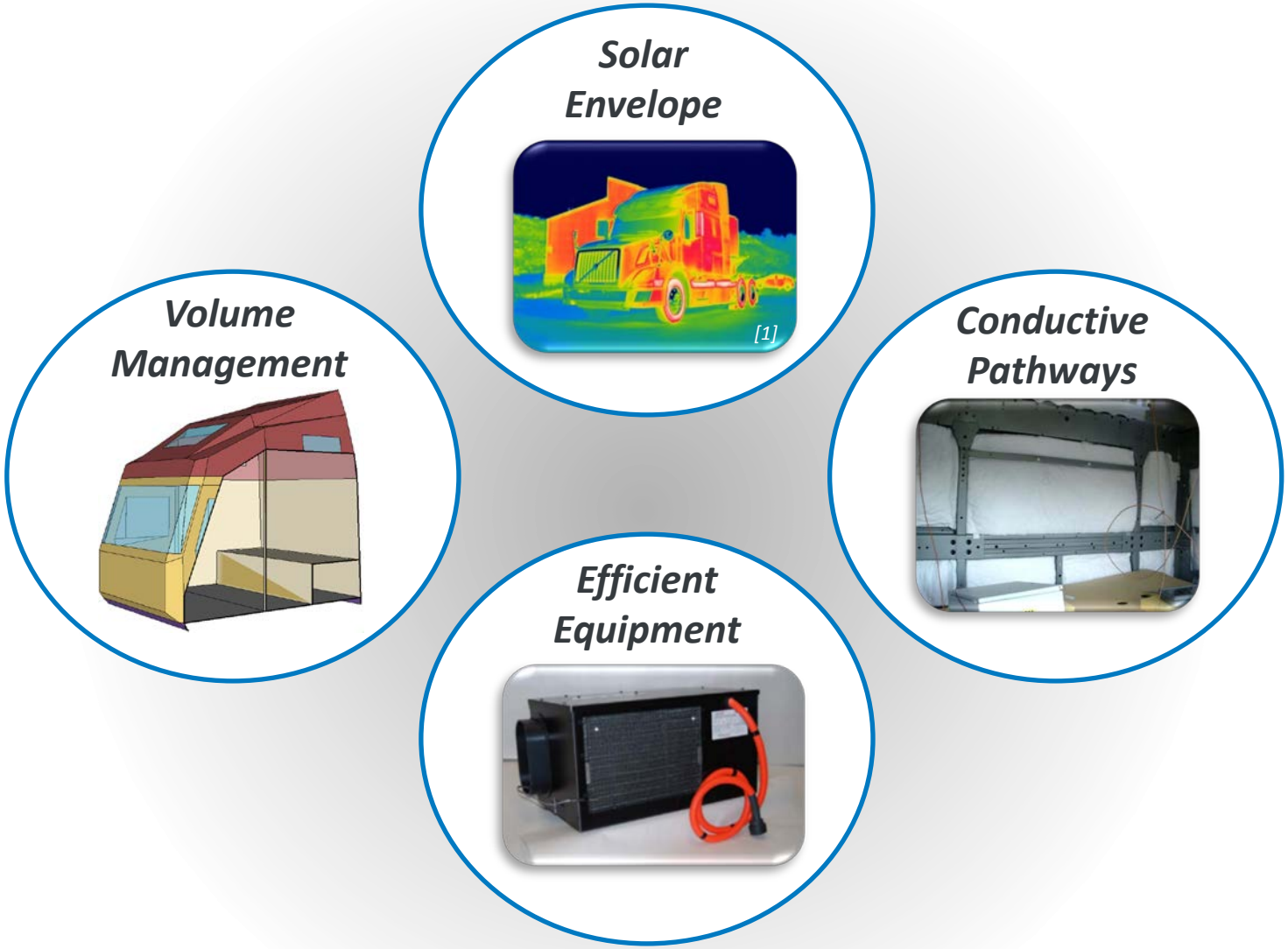
Approach – System Level



Reductions in load have a larger impact on fuel use due to equipment and delivery losses.

Approach – Overall Strategy

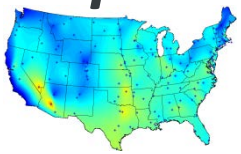
Technology Focus Areas



Approach – Overall Strategy

Modeling

Impact



Solar Envelope

Volume Management

Conductive Pathways

Efficient Equipment

Testing

Industry Collaboration

Approach – Advanced Technologies

Conductive Pathways

Solar Envelope

Volume Management

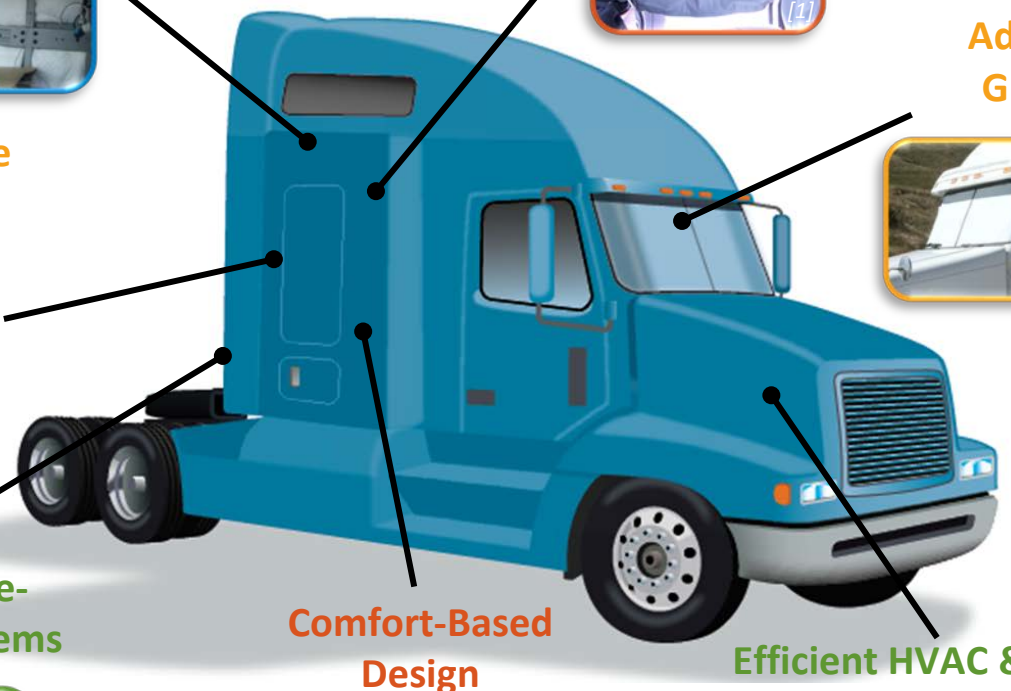
Efficient Equipment

Insulation & Advanced Materials

Curtains & Shades

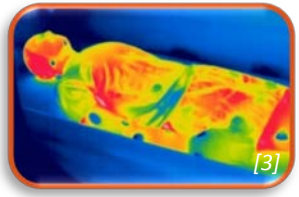
Advanced Glazings

Opaque Surface Treatment



Advanced Idle-Reduction Systems

Comfort-Based Design

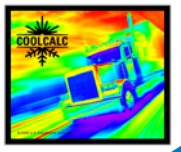


Efficient HVAC & Controls

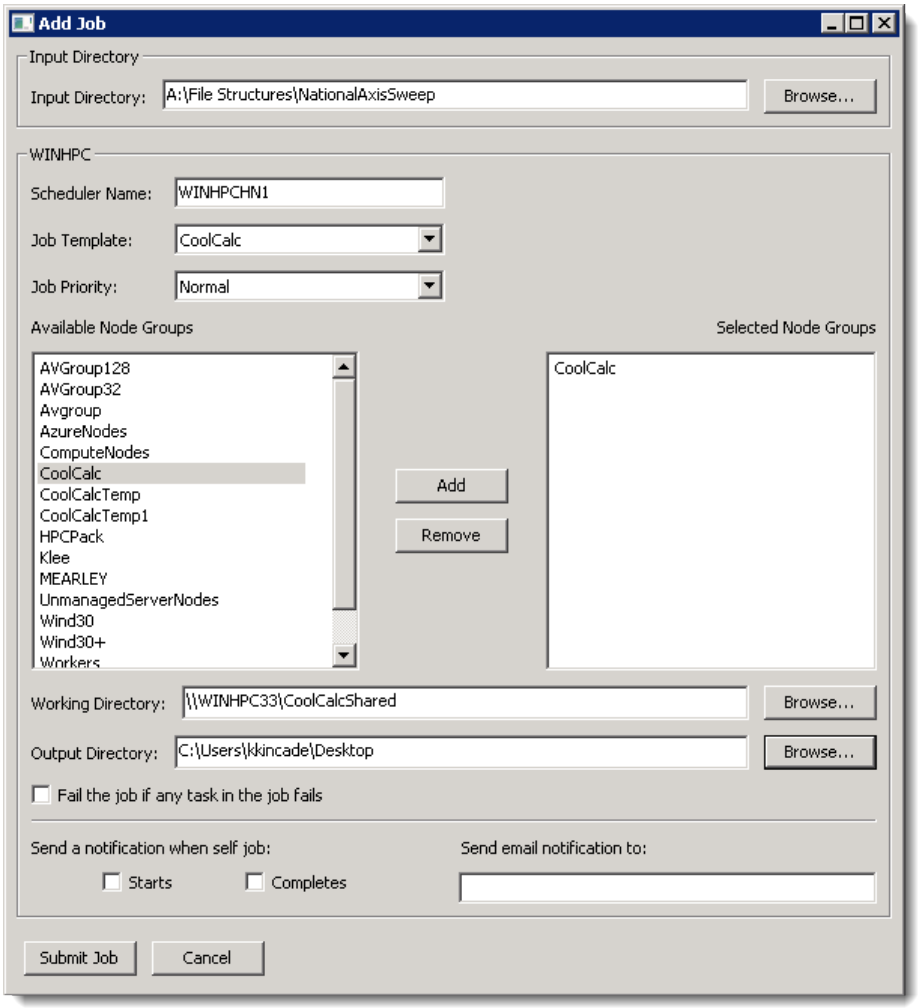
Accomplishments – CoolCalc Development

Release of CoolCalc versions 2.3 and 2.4 to select industry partners

Modeling



- **Added parallel run capability and large-scale analysis tools**



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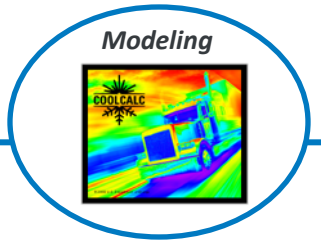
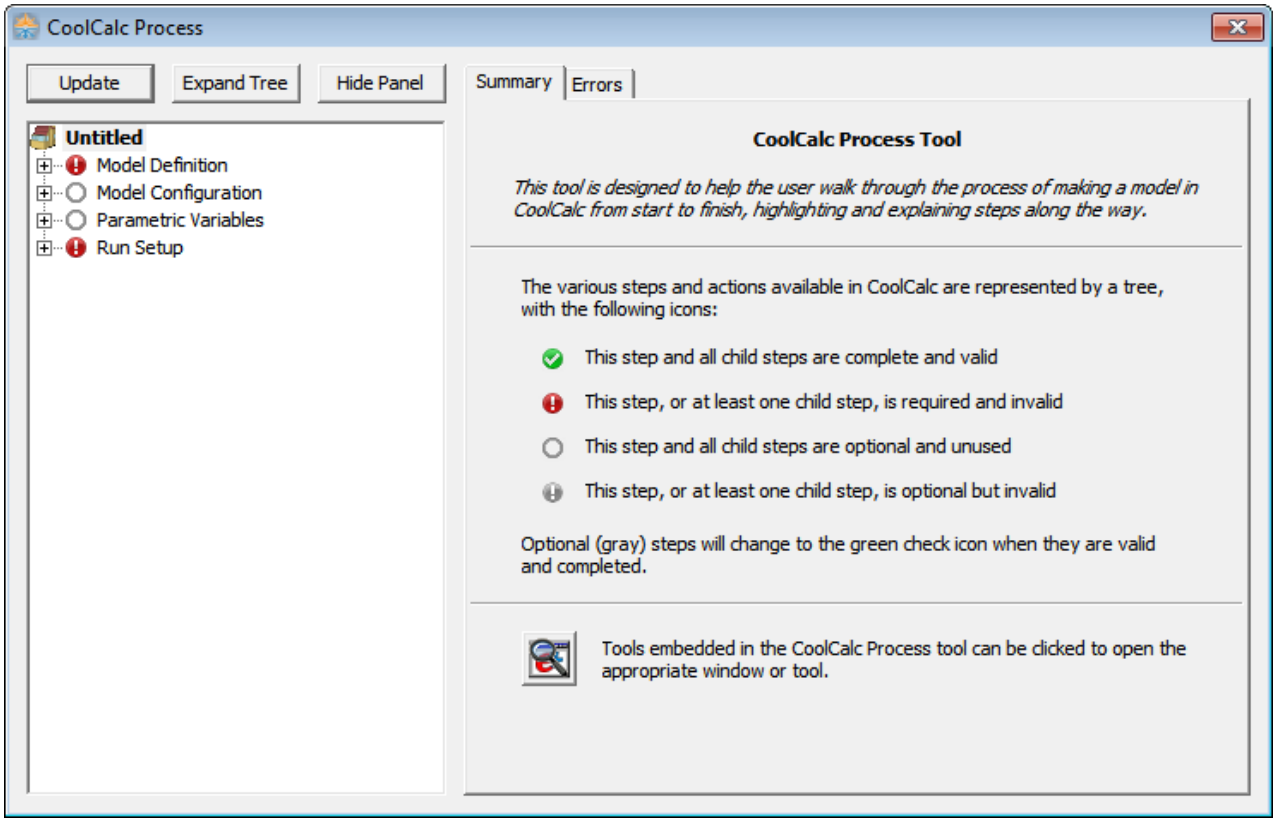


- **Added parallel run capability and large-scale analysis tools**
- **Process-driven tool**



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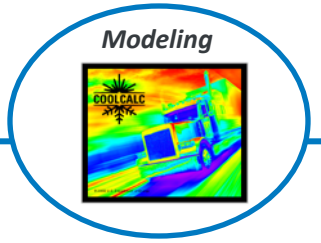
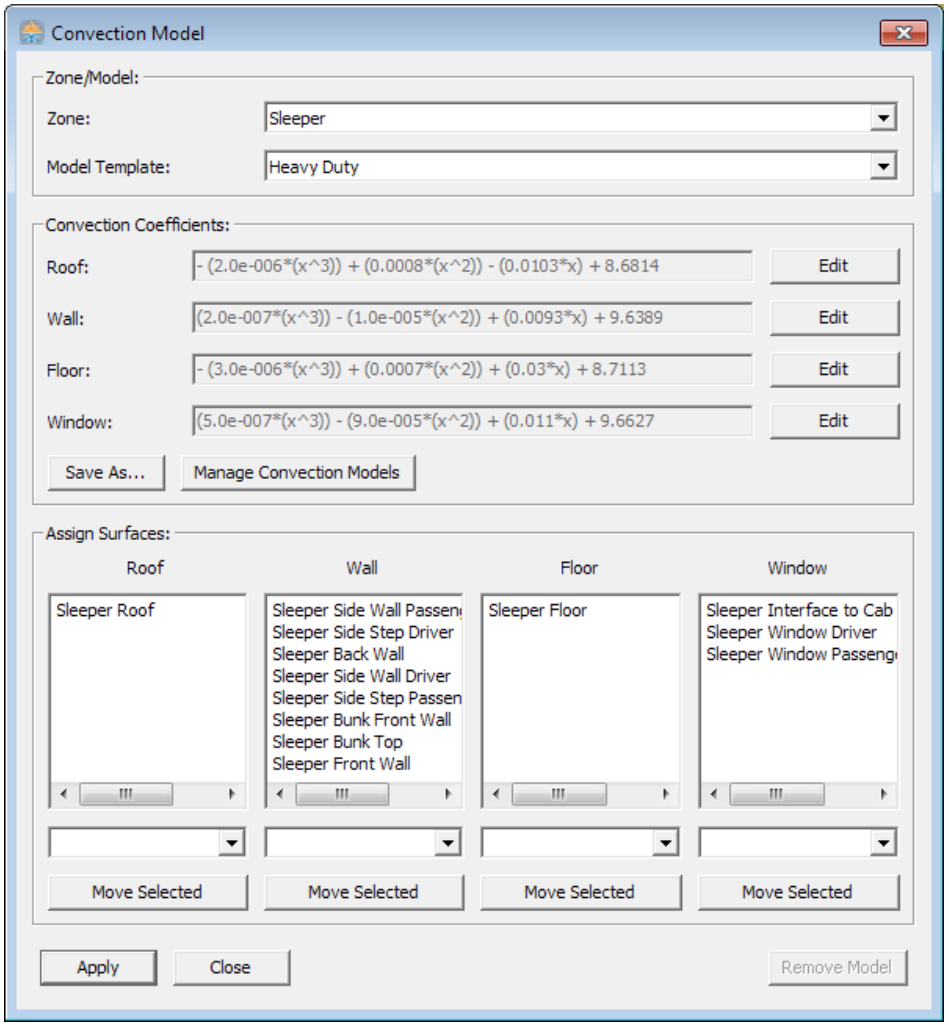


- **Added parallel run capability and large-scale analysis tools**
- **Process-driven tool**
- **Convection model GUI**



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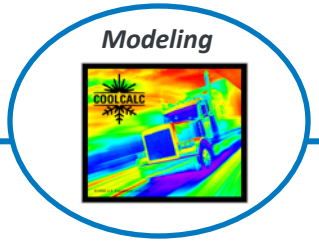
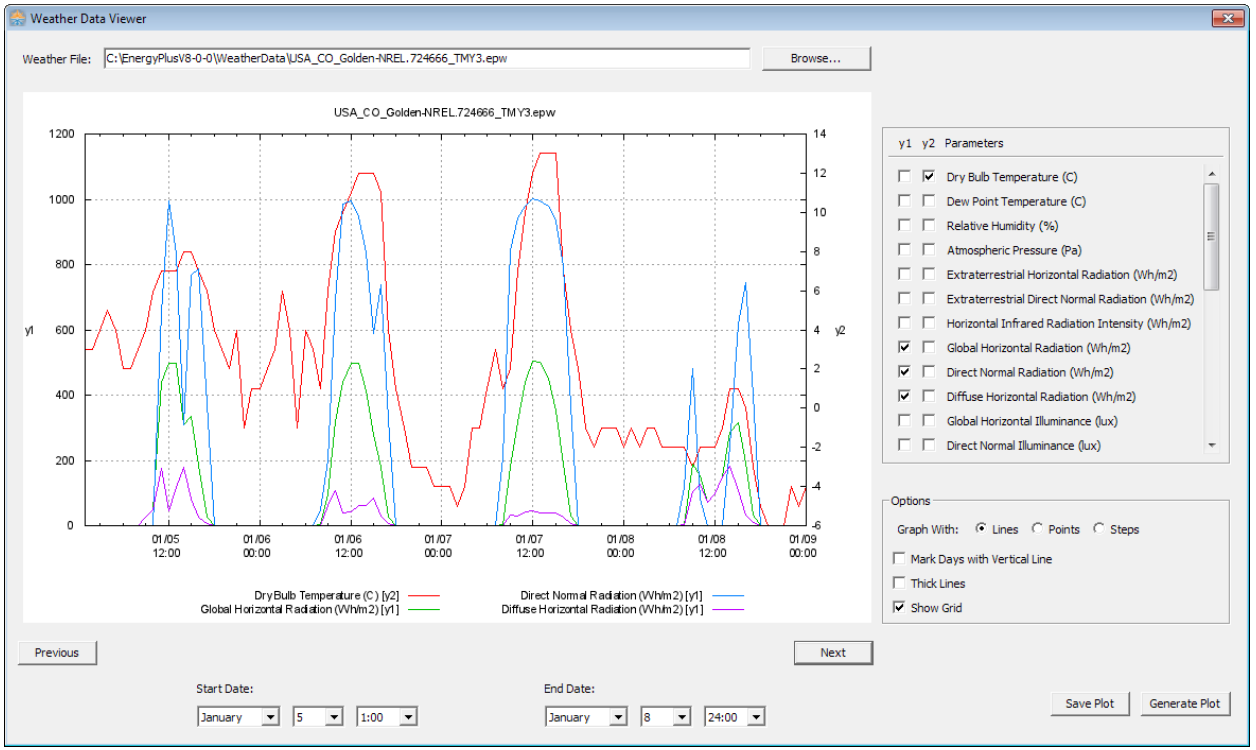


- **Added parallel run capability and large-scale analysis tools**
- **Process-driven tool**
- **Convection model GUI**
- **Weather Viewer Tool**



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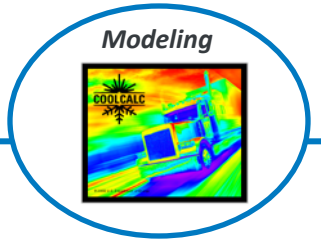

- **Added parallel run capability and large-scale analysis tools**
- **Process-driven tool**
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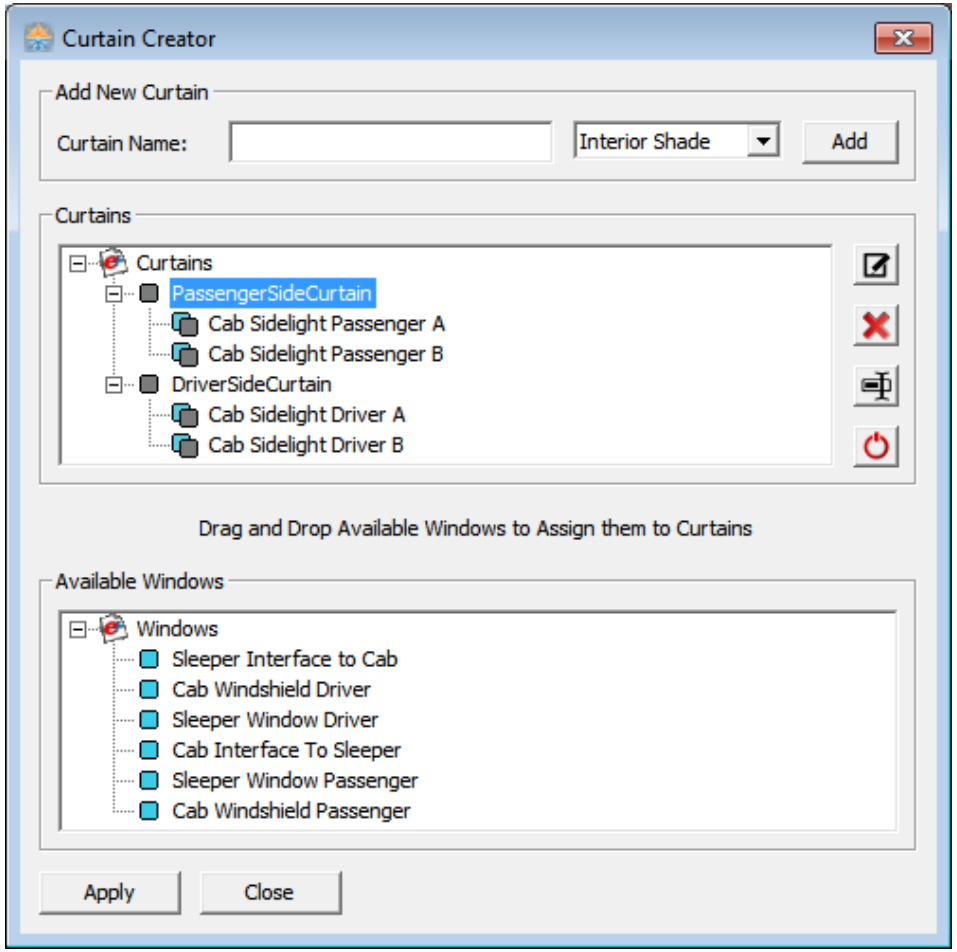
- **Additional tools and improvements**
  - Curtain Creation Tool
  - Schedule manager GUI
  - Animation and rendering updates
  - Stability and usability improvements



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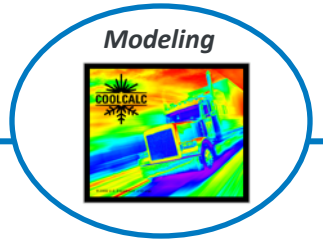

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  - Curtain Creation Tool
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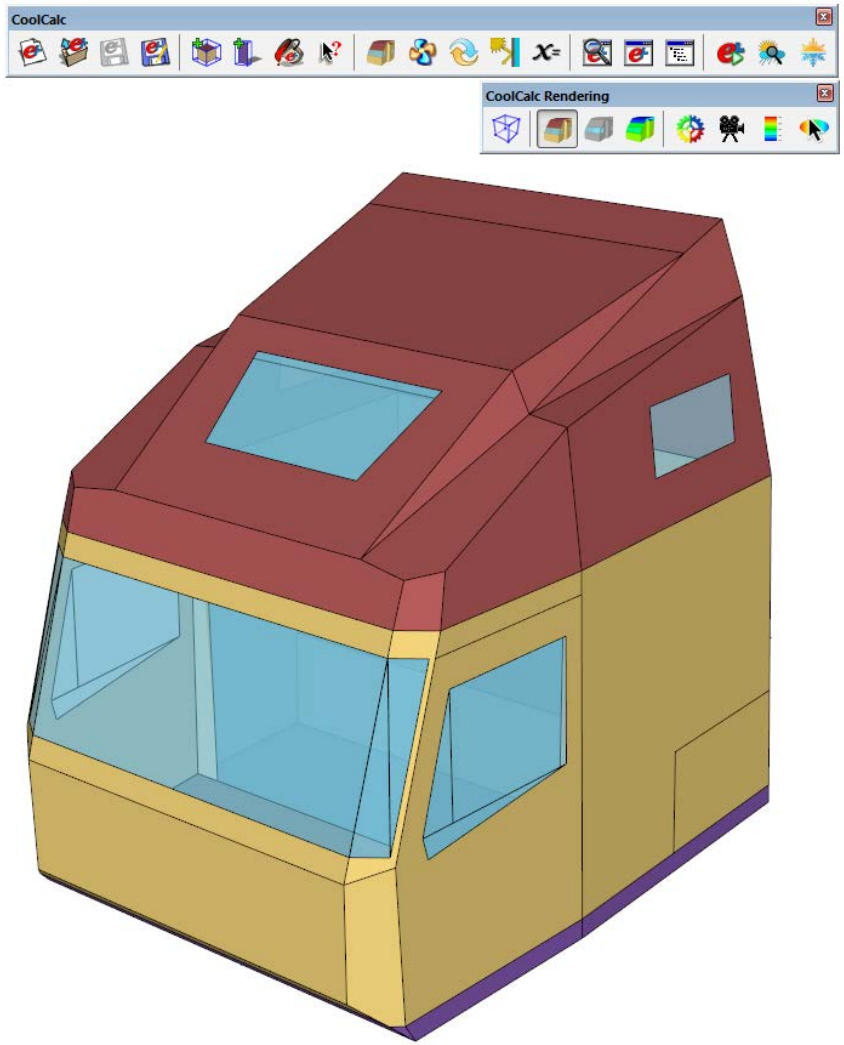
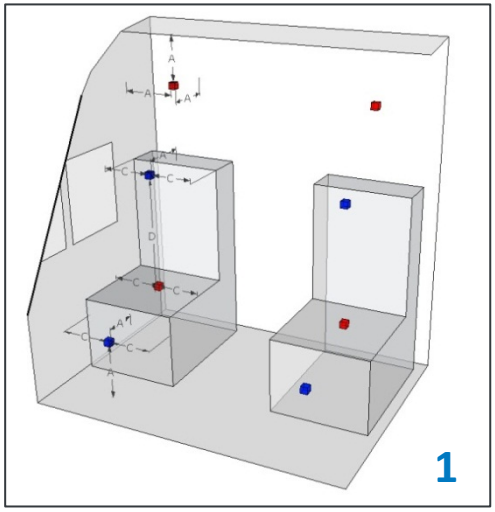
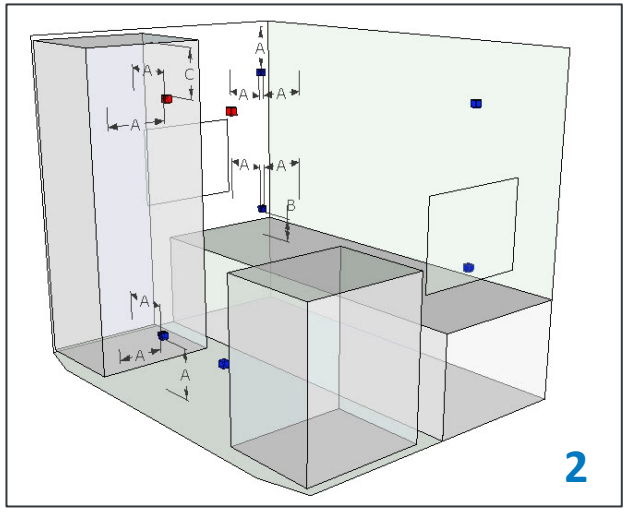
  - Animation and rendering updates
  - Stability and usability improvements
- **Updated for EnergyPlus and SketchUp compatibility**
- **Released Versions 2.3 and 2.4 to industry partners**



Accomplishments – Testing Experimental Setup

- Test truck, test "buck" cab, control "buck" cab
  - South-facing vehicles
  - Buck firewall shade cloths
- Local weather station at test site
  - Solar, wind, ambient temperature, pressure, and RH
- Dometic A/C Systems: 2,050 W (7,000 BTU/hr)
  - Set points of 22.2°C (72°F) and 26.7°C (80°F)





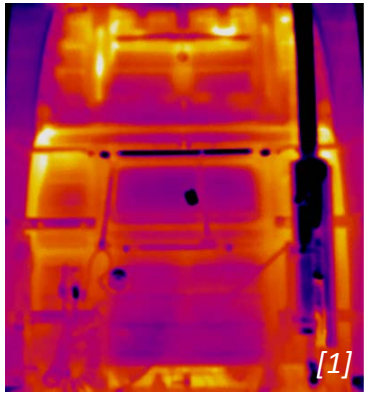
(1) Cab and (2) Sleeper thermocouple locations, dimension A = 12", B = 6", C = 18", blue – TMC standard [5], red – NREL added

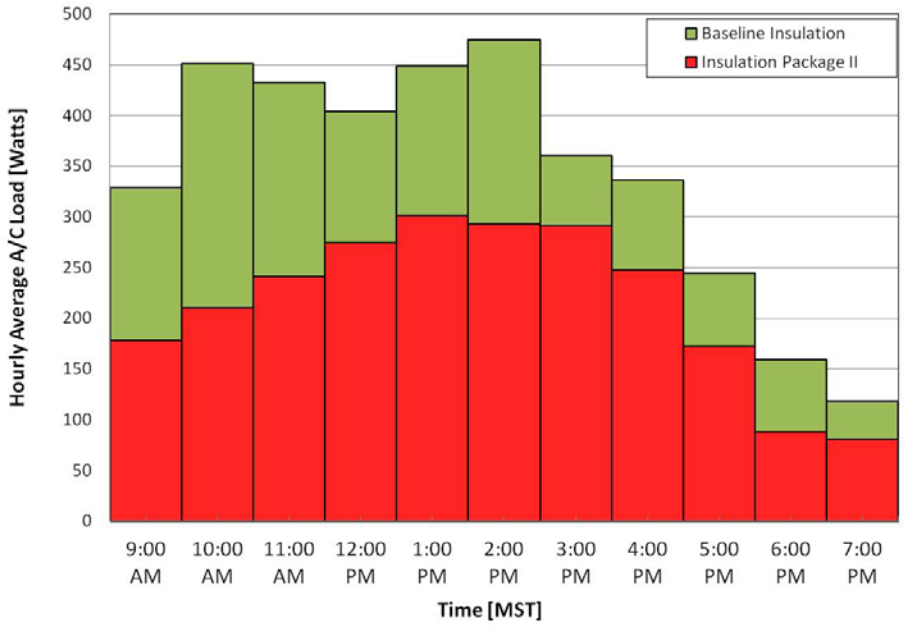
- 40 thermocouples per vehicle
  - *Air and surface locations, following TMC-recommended practice with additional locations*
- U_{95} = ± 0.3°C
- A/C Power = ± 15 W

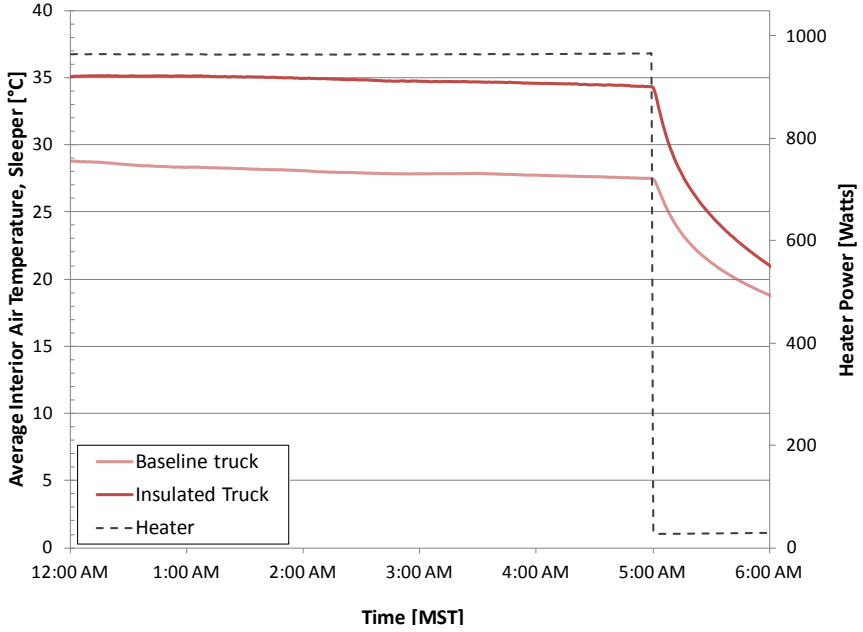
Accomplishments – Previous Work Highlights

Insulation Package Evaluations
E-A-R™ Thermal Acoustic Systems

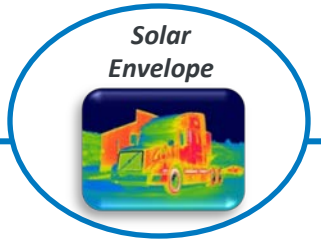
- **Heating Testing:** 26%–36% reduction in heat loss
- **A/C Testing:** 20%–34% reduction in A/C energy use





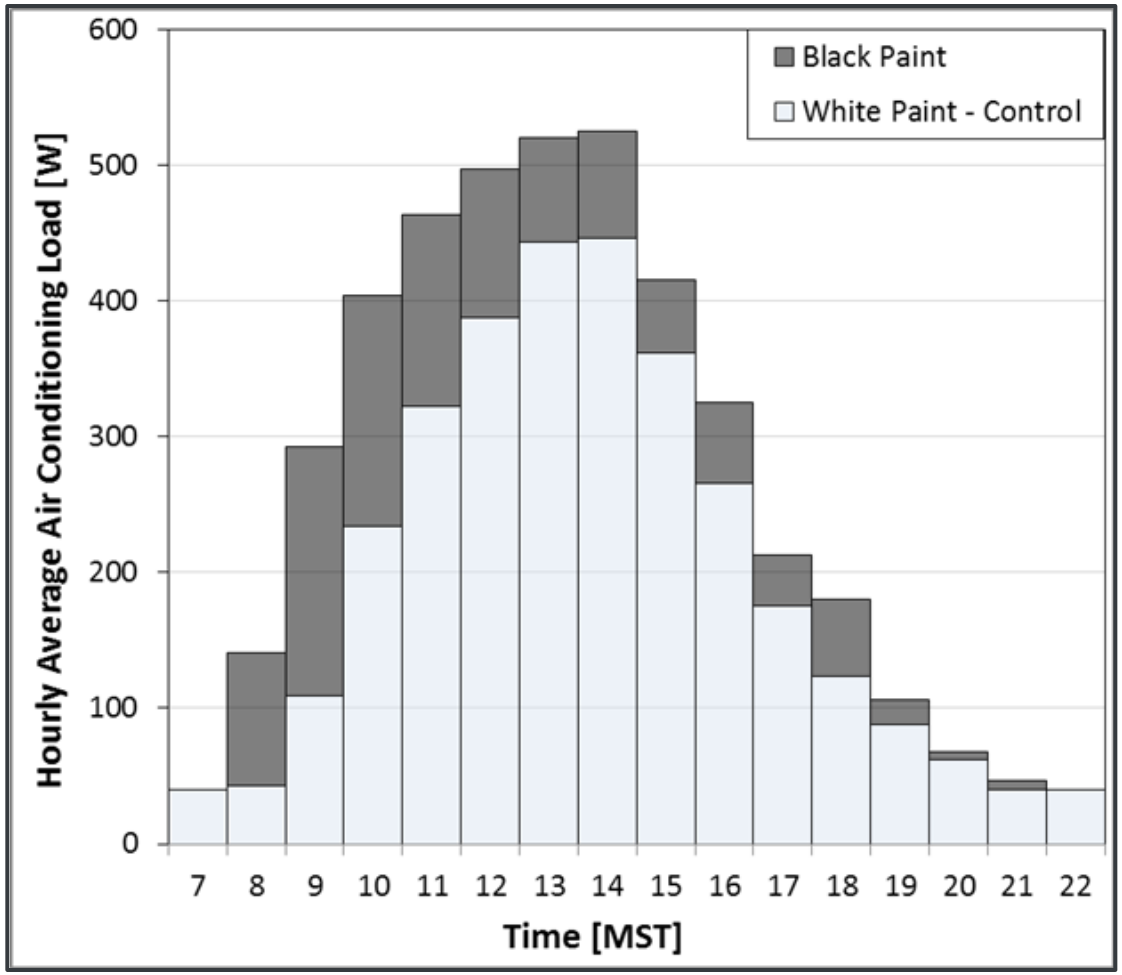


Accomplishments – Previous Work Highlights



Paint Evaluation, Phase I: Black to White Evaluation

- **A/C Testing**: 20.8% reduction in daily A/C system energy
- **Thermal Soak Testing**: 31.1% of maximum possible interior air temperature reduction



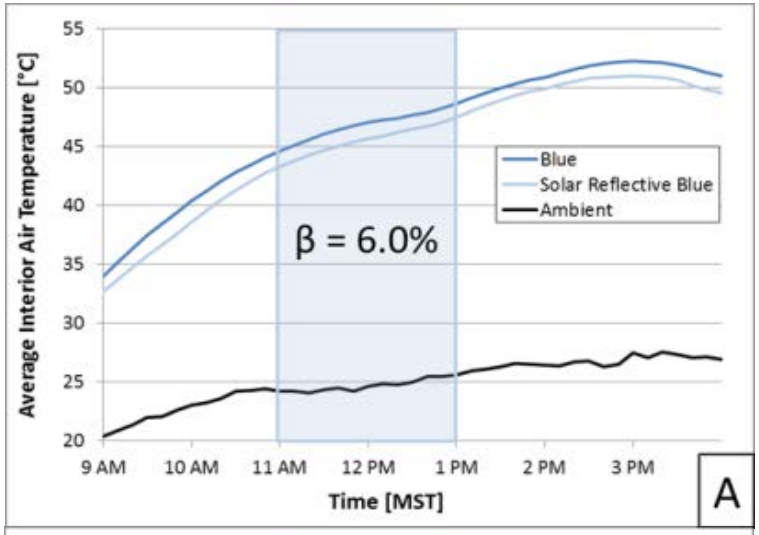
Accomplishments – Advanced Paints, Phase II

Experiment and CoolCalc agreement, blue → solar reflective blue

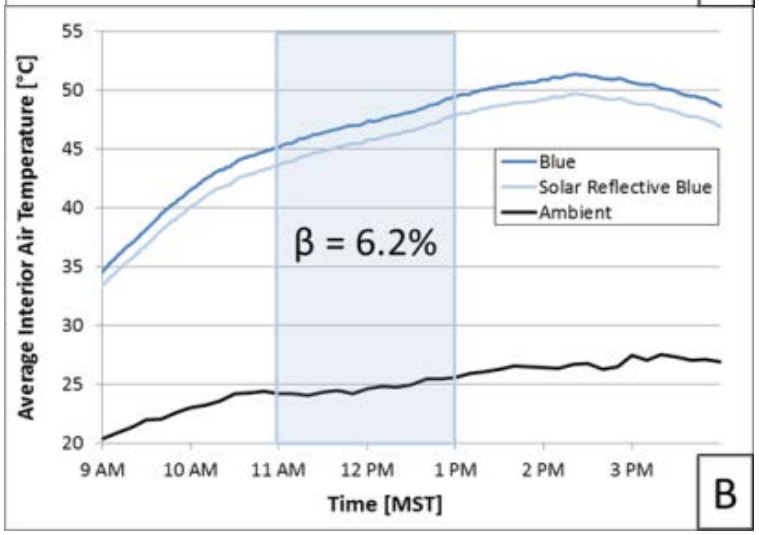
Solar Envelope

Thermal Soak Testing

Experiment



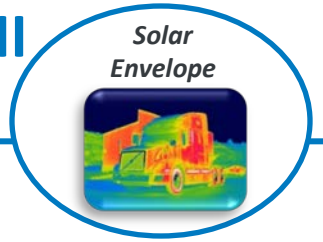
CoolCalc Model



$$\beta = \frac{\overline{T}_{baseline} - \overline{T}_{modified}}{\overline{T}_{baseline} - \overline{T}_{ambient}} \cdot 100\%$$

Accomplishments – Evaluation of Advanced Paints, Phase II

7.3% reduction in daily A/C energy from blue to reflective blue



A/C Testing

- 563-Wh battery energy savings
- 9.4% reduction in battery capacity
- 12-kg reduction in battery weight

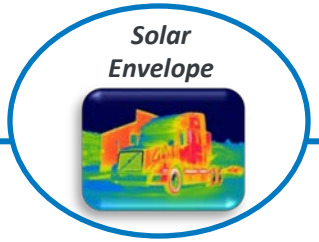
7.3% reduction in daily A/C energy

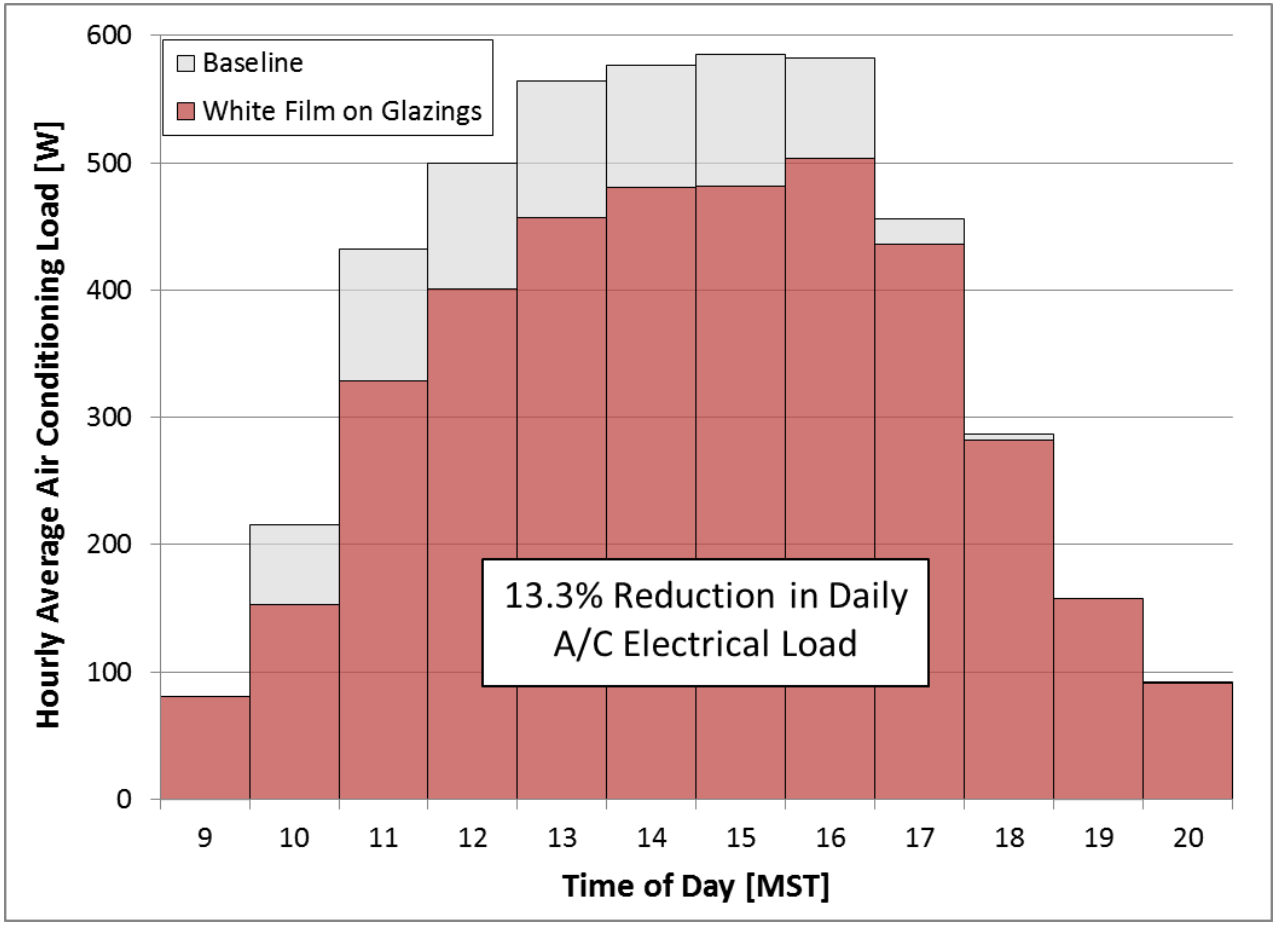
Blue Paint	
Emittance	0.950
Solar-weighted Reflectivity	0.120
Solar-weighted Absorptivity	0.880

Solar Reflective Blue Paint	
Emittance	0.948
Solar-weighted Reflectivity	0.258
Solar-weighted Absorptivity	0.742

Accomplishments – Evaluation of Load Through Glazings

13.3% reduction in daily A/C energy with film over glazings





Potential Areas of Impact:
Improved glazings and privacy curtains

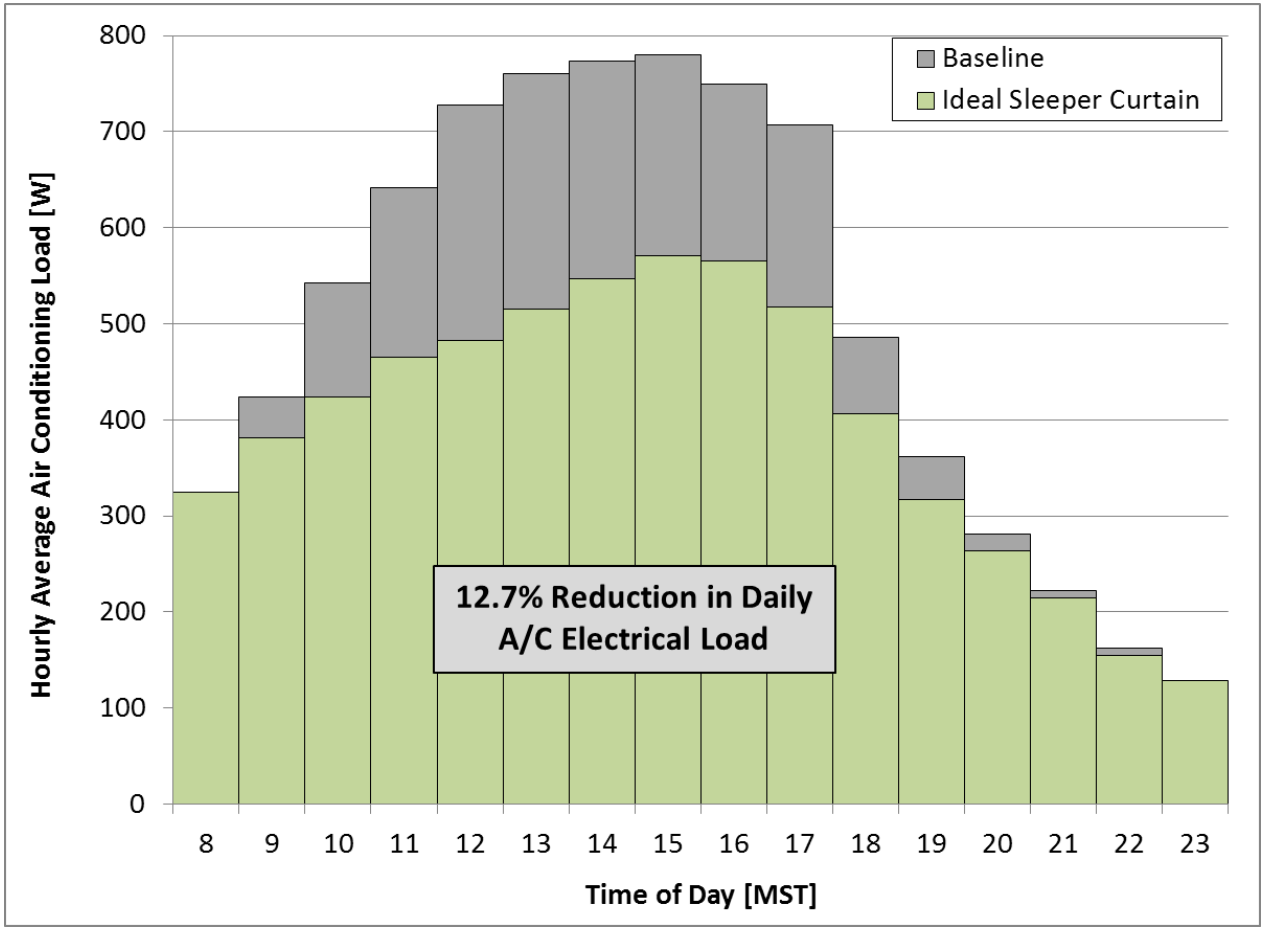
- 604 Wh battery energy savings
- 10.1% reduction in battery capacity
- 13-kg reduction in battery weight

Baseline Test Configuration – All curtains closed
White Film Test Configuration – Privacy curtains open, sleeper curtain closed

Accomplishments – Opportunities for Improved Sleeper Curtain

12.7% reduction in daily A/C energy with idealized sleeper curtain

- CoolCalc analysis identified potential for sleeper curtain improvements



Idealized Sleeper Curtain

Radiant barrier, foam insulation, no air gaps

- 1,153 Wh battery energy savings
- 19.2% reduction in battery capacity
- 25-kg reduction in battery weight

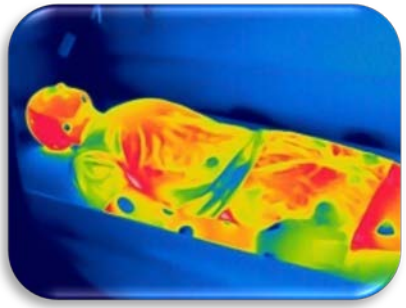
Baseline Test Configuration – All curtains closed, standard sleeper curtain in use

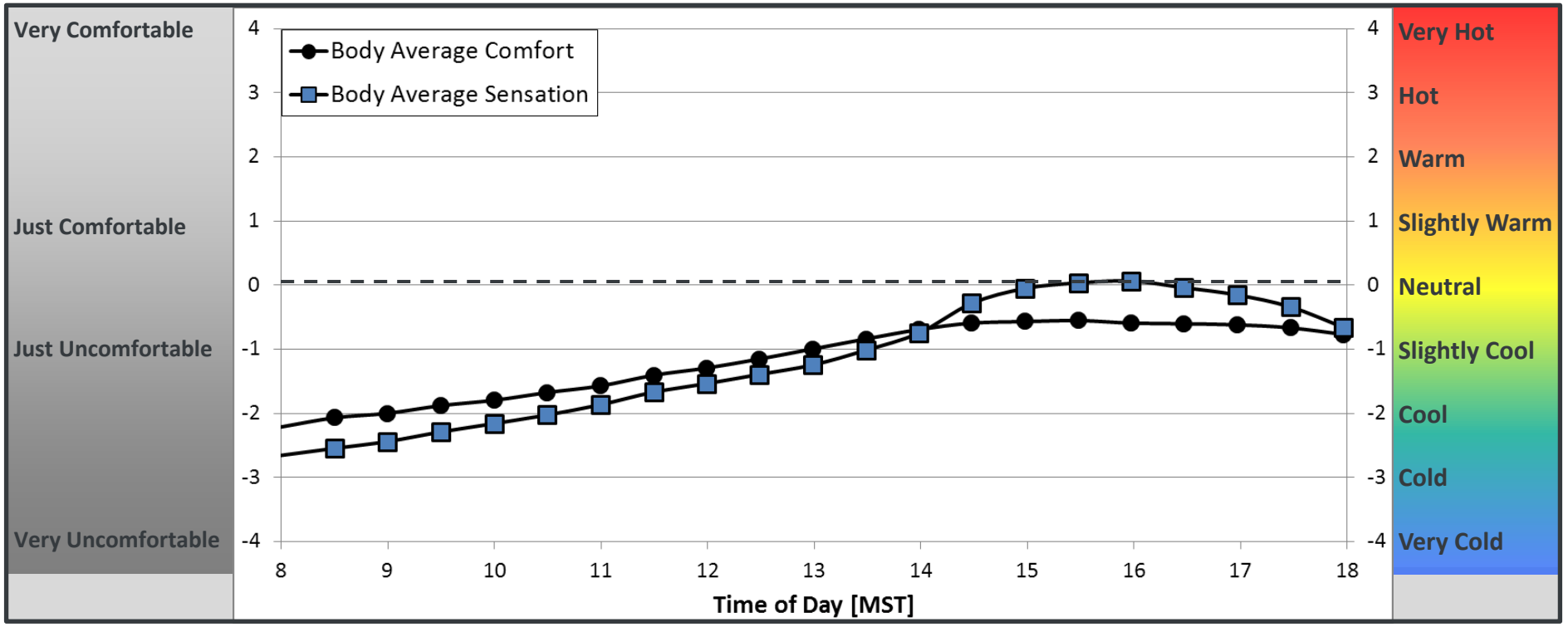
Accomplishments – Manikin Baseline Testing

Baseline characterization for typical resting cooling conditions

Baseline manikin A/C test conditions

- Standard A/C test configuration (curtains closed)
- Climate control of entire sleeper air volume
- 72°F set point

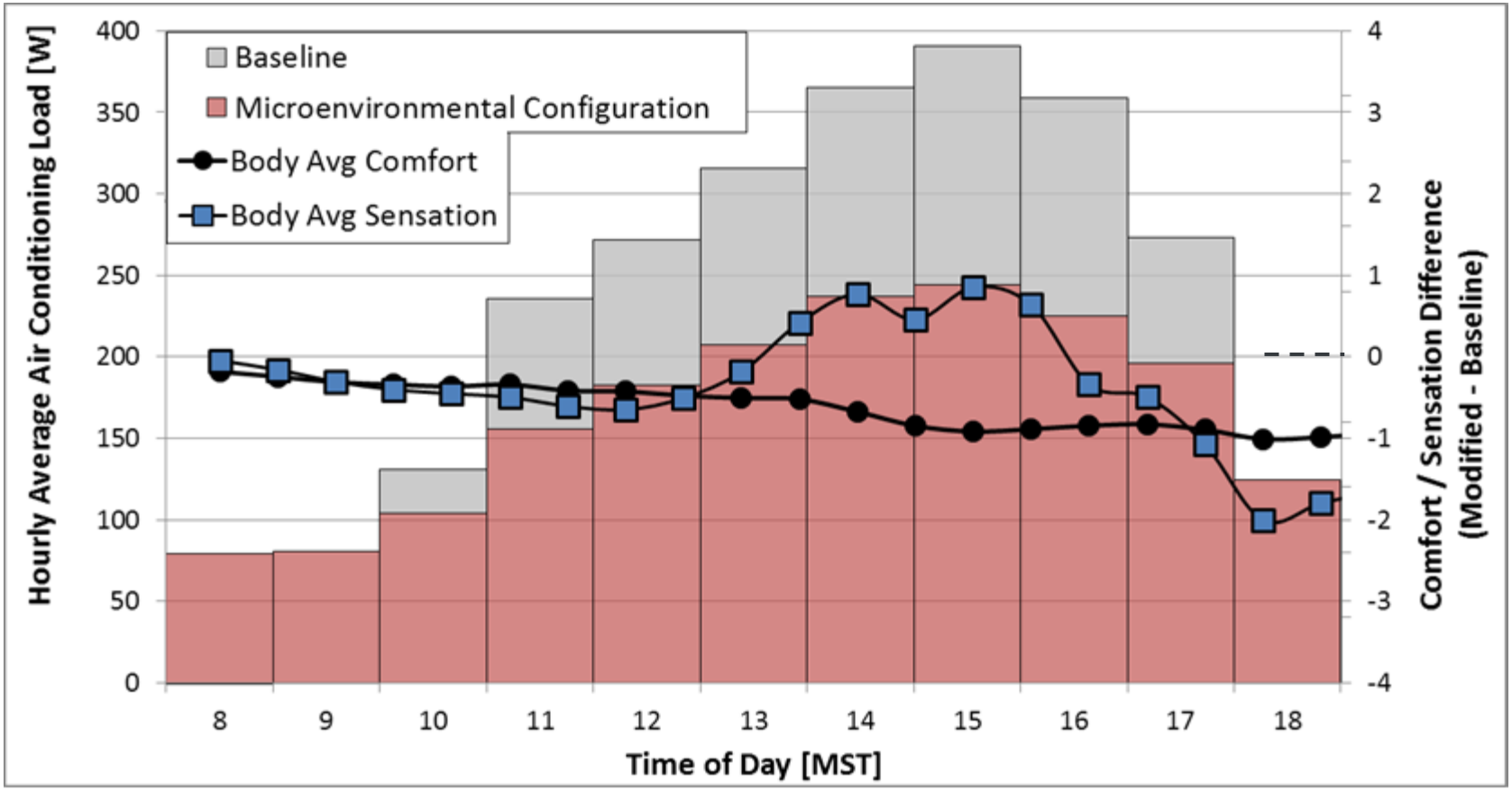




Accomplishments – Sleeper Microclimate Evaluation

23.8% reduction in daily A/C energy with microclimate configuration

- Increased control temperature from 72°F to 76°F to reduce overcooling
- Submitted a provisional patent application



Comfort Difference Scale
Positive Values = More comfortable than baseline
Negative Values = Less comfortable than baseline

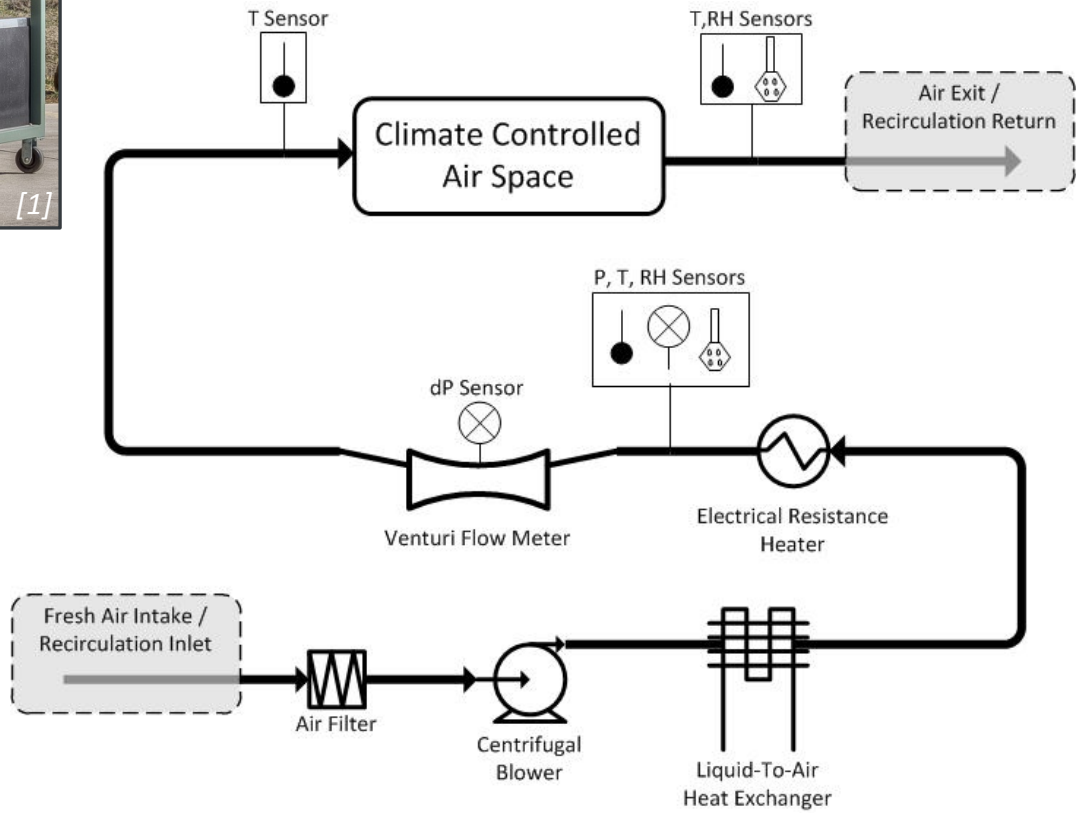
Sensation Difference Scale
Positive Values = Warmer sensation than baseline
Negative Values = Colder sensation than baseline

Accomplishments – Experimental Test Capabilities Development

Emulators provide controllable boundary conditions to a vehicle

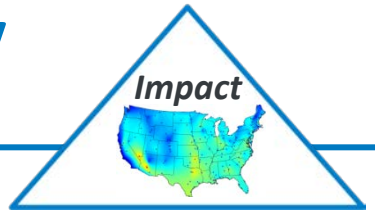
HVAC Emulators

- Direct measurement of thermal load
- Heating or cooling
- Prescribed boundary condition at air inlets to vehicle
- Variable control strategies



Accomplishments – Paint Impact Model Study

Leveraging high performance computing



CoolCalc with high-performance computing system

Individual Tasks

Completed Tasks

CoolCalc / HPC Interface

High-performance Computing (HPC) Server and Job Manager

Node 1

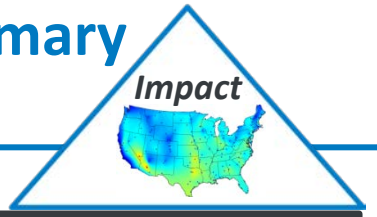
Node 2

Node i

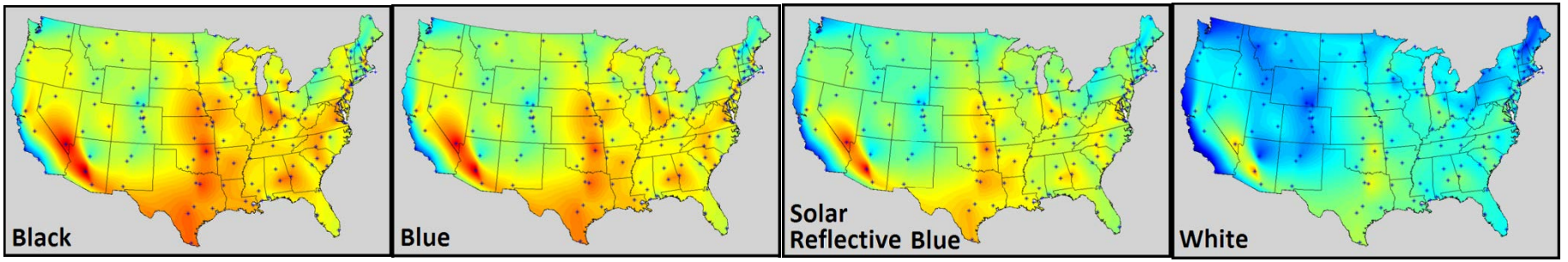
Relevance | Approach | Accomplishments | Collaborations | Future Work

Accomplishments – 95% Heating and Cooling Loads Summary

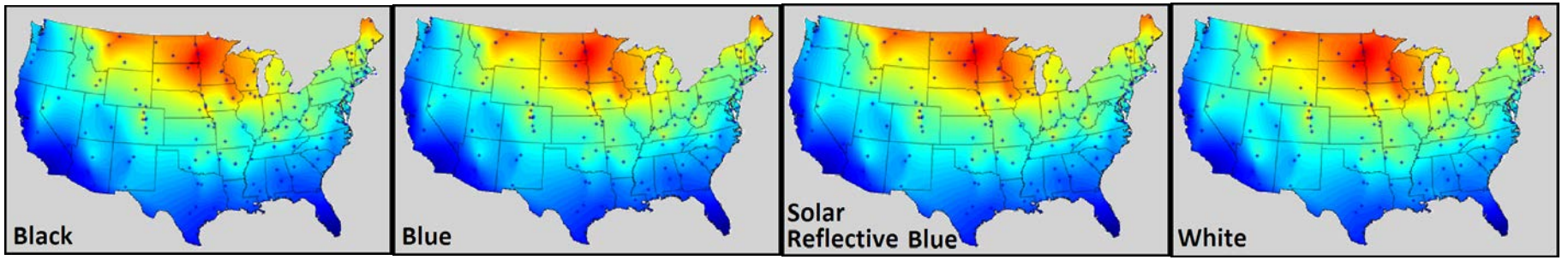
Significant cooling load reduction, insignificant heating load change

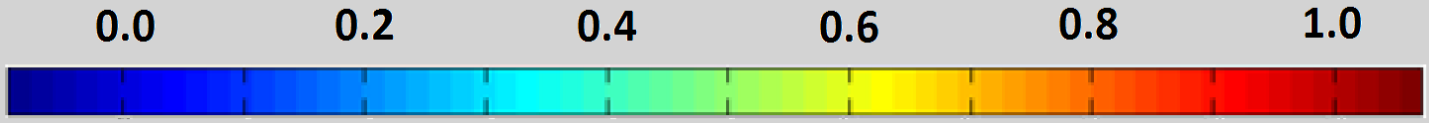


Normalized Cooling Thermal Loads



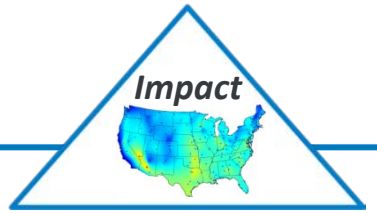
Normalized Heating Thermal Loads





Accomplishments – Auxiliary AC System Battery Sizing

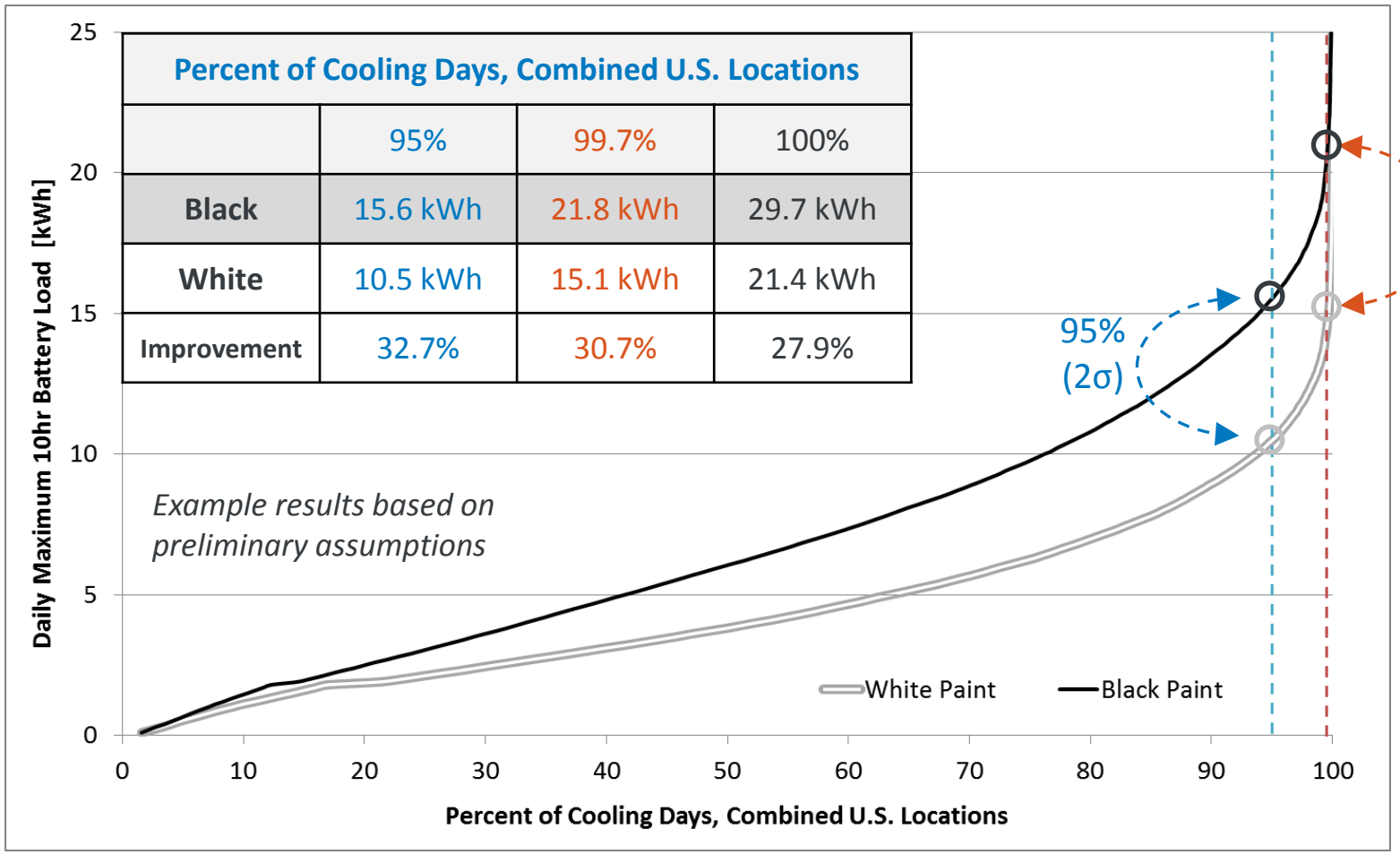
National-level analysis applied to guide system design



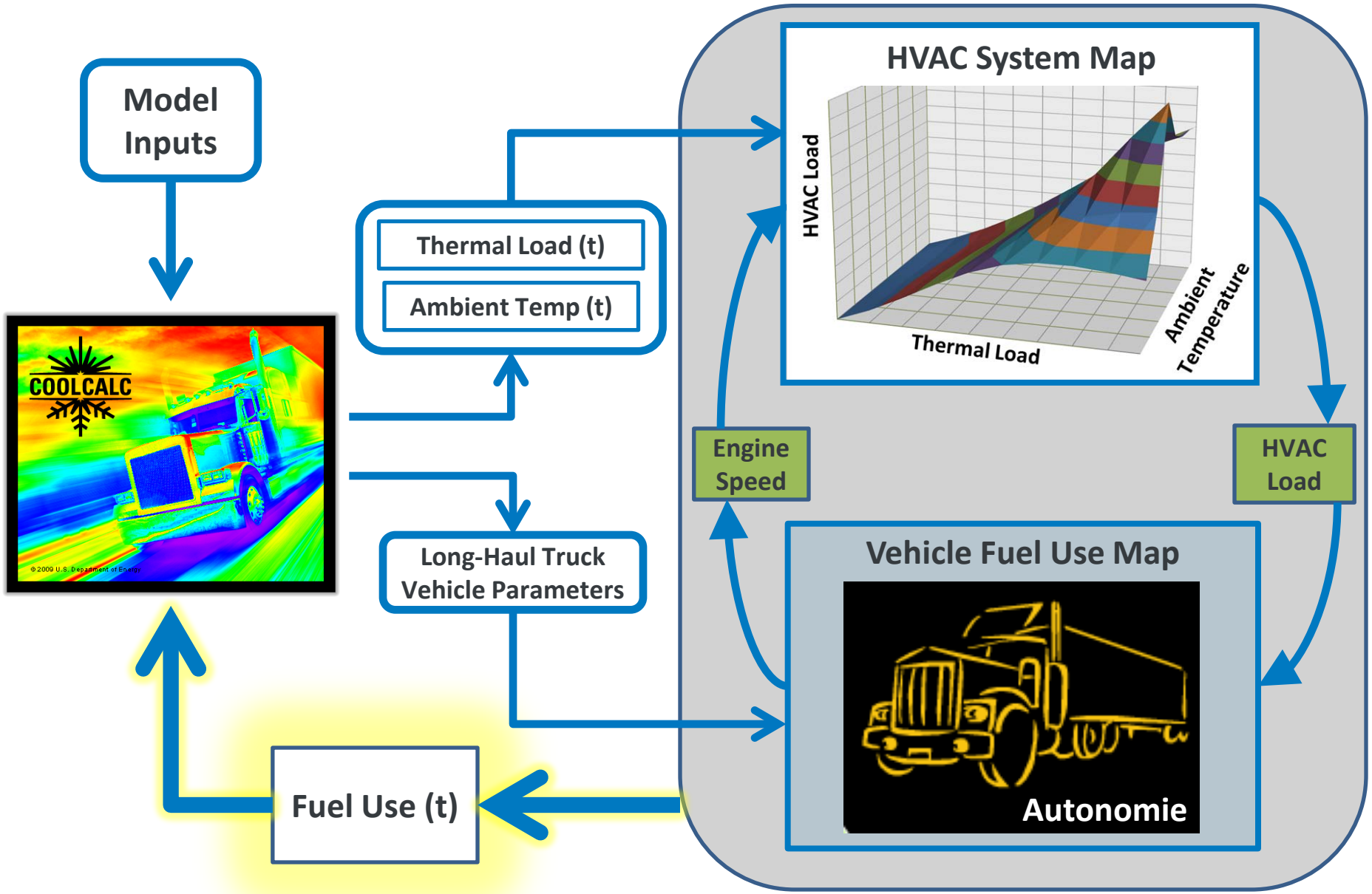
Example Results – Auxiliary AC System Battery Sizing

Dependent on A/C System Performance, Inverter Efficiency, Climate Control Settings

Percent of Cooling Days, Combined U.S. Locations			
	95%	99.7%	100%
Black	15.6 kWh	21.8 kWh	29.7 kWh
White	10.5 kWh	15.1 kWh	21.4 kWh
Improvement	32.7%	30.7%	27.9%



Accomplishments – Fuel-use Estimation Methodology



Test Trucks & Collaboration with OEMs

Volvo Trucks

Technology Focus Area Evaluation

NREL-owned Truck

Baseline Vehicle

Volvo Trucks

Full Cab Technology Evaluation

Kenworth Trucks

Technology Focus Area Evaluation

Daimler Trucks North America

Tested as part of SuperTruck project

Collaboration with Suppliers

Advanced Paints

PPG Industries

Advanced Glazings

Sekisui

Solar Envelope

Thermal Manikin

Measurement Technologies Northwest

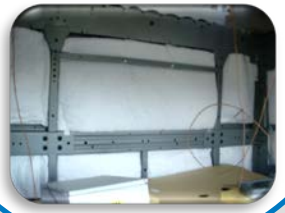
Volume Management

Efficient Equipment

Auxiliary AC System

Dometic

Conductive Pathways



Insulation, Glazings

Bayer

Insulation

E·A·R Aearo Technologies
a 3M Company

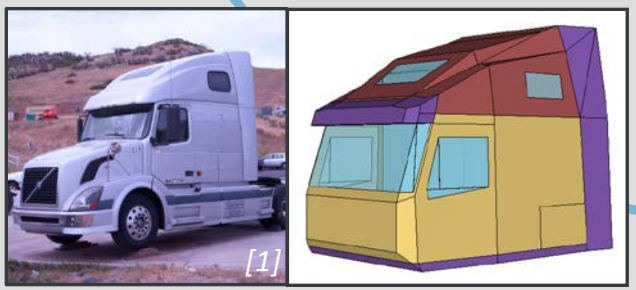
Collaborations – CoolCalc Industry Partners

Daimler

E·A·R Aearo Technologies
a 3M Company

Oshkosh Corporation

Volvo



Kenworth

Bayer

Relevance | Approach | Accomplishments | Collaborations | Future Work

Responses to FY13 AMR Reviewer Comments

Comment:	This reviewer stated that heating energy requirements were not addressed. The data reported for cooling situations was good, but this may not translate to the heating side. For example, a white paint job is good for cooling, but not for heating. This aspect really needed to be addressed to make sure that the results/conclusions were valid whether the vehicle is operated in a hot or cold zone.
Response:	We strongly agree that for a load-reduction technology such as paint to be successful, heating and cooling applications must be evaluated. For the paint evaluation in FY12, focus was placed on cooling-load evaluation because it was expected that the effect of paint color on cooling load would be much more significant than for heating loads. High heating loads are expected for northern climates during the time of year that has low solar loads. National-level CoolCalc modeling results presented this year for heating and cooling confirm these assumptions that low-absorptivity paint has a strong benefit for cooling loads while having little or no impact on heating loads in the contiguous United States.
Comment:	The reviewer added that it was not clear how the project would first split the dictionary to determine if the majority of opportunity for 30% reduction was on the heating or the cooling side. If it was an 80% heating issue and 80% effort (for example only) was focused on cooling efficiencies, then this would be a very ineffective approach. A couple years into the effort it seemed there would have been some insights into this fundamental question.
Response:	Three of the four technology focus areas (volume management, conductive pathways, and efficient equipment) impact both heating and cooling. The focus of last year's presentation was the solar envelope work, which is the only focus area that does not impact both heating and cooling. Additionally, discussions with OEMs have made it clear that cooling is a larger challenge due to widespread adoption of idle-off, fuel-fired heaters combined with a lack of quality A/C solutions. That said, technologies that reduce the thermal load will enable more cost-effective cooling solutions and reduce fuel use for heating. The presentation has been tailored to increase the clarity of the broader thermal (heat/cooling) load-reduction approach.
Comment:	The reviewer was under the impression that systems were already fielded to address anti-idling laws, and commented that the presentation did not lay out the current market landscape cleanly. It was not clear to this reviewer if the technologies under consideration were not yet adopted widely and if this was an enabler to support more beneficial technologies.
Response:	Both anti-idling laws and fuel costs are driving the long-haul trucking industry to find effective solutions for rest-period idle reduction. Thirty-one states currently have regulations on idle reduction, and there are national-level greenhouse gas regulation credits for idle reduction. Fuel costs and new anti-idle laws are strongly motivating the industry to find effective solutions. There is a range of anti-idling systems (our partner Dometic is one of the suppliers); however, they do not provide complete solutions that meet the industry's needs effectively. These systems do not address the opportunity for load reduction. Our project seeks to reduce the loads through improved design to help make these idle-off systems cheaper, more effective, and more widely accepted by the industry. The presentation has been improved to make this more clear.

Proposed Future Work

- **FY14**
  - Bring together knowledge and tools to develop and demonstrate full-cab thermal design concepts to meet project goal
  - Complete fuel use and payback-period analysis process
    - Quantify fuel savings and economic trade-offs for technologies over a wide range of use and weather conditions
  - Improve capabilities and use CoolCalc to assist with fuel use and payback-period driven design
  - Continue to test advanced climate control load-reduction technologies
- **FY15**
  - Implement a full-cab solution at the prototype level and demonstrate the potential fuel savings of the system
  - Demonstrate fuel use and payback-period driven design by working with industry partners

Summary/Conclusions

Test Configuration	Beta	Cooling Reduction [% of A/C]	Potential Impact
Black to White **(Previous result)**	31.1%	20.8%	No cost immediate payback
Blue to Solar Reflective Blue	6.0%	7.3%	Benefit while maintaining branding and aesthetics
Film over Glazings	N/A	13.3%	Advanced glazings Improved privacy curtains
Idealized Sleeper Curtain	N/A	12.7%	Improved sleeper-curtain design
Microclimate Configuration	N/A	23.8%	Condition occupant rather than vehicle interior

- **Added CoolCalc features** – Parallel run capability, large-scale analysis tool, process-driven tool, convection model GUI, weather-viewer tool
- **Applied CoolCalc to guide outdoor testing** – Solar-reflective paint and sleeper curtain
- **CoolCalc model prediction** of beta for solar soak testing of paints was within 4.5% of experimental results
- **National-level paint analysis** confirmed strong sensitivity of cooling loads and showed insensitivity for heating loads to paint color
- **Developed HVAC emulators** for direct measurement of thermal load in vehicles

Contacts

Special thanks to:

- **David Anderson and Lee Slezak**
  Advanced Vehicle Technology Analysis and Evaluation Vehicle Technologies Program

For more information:

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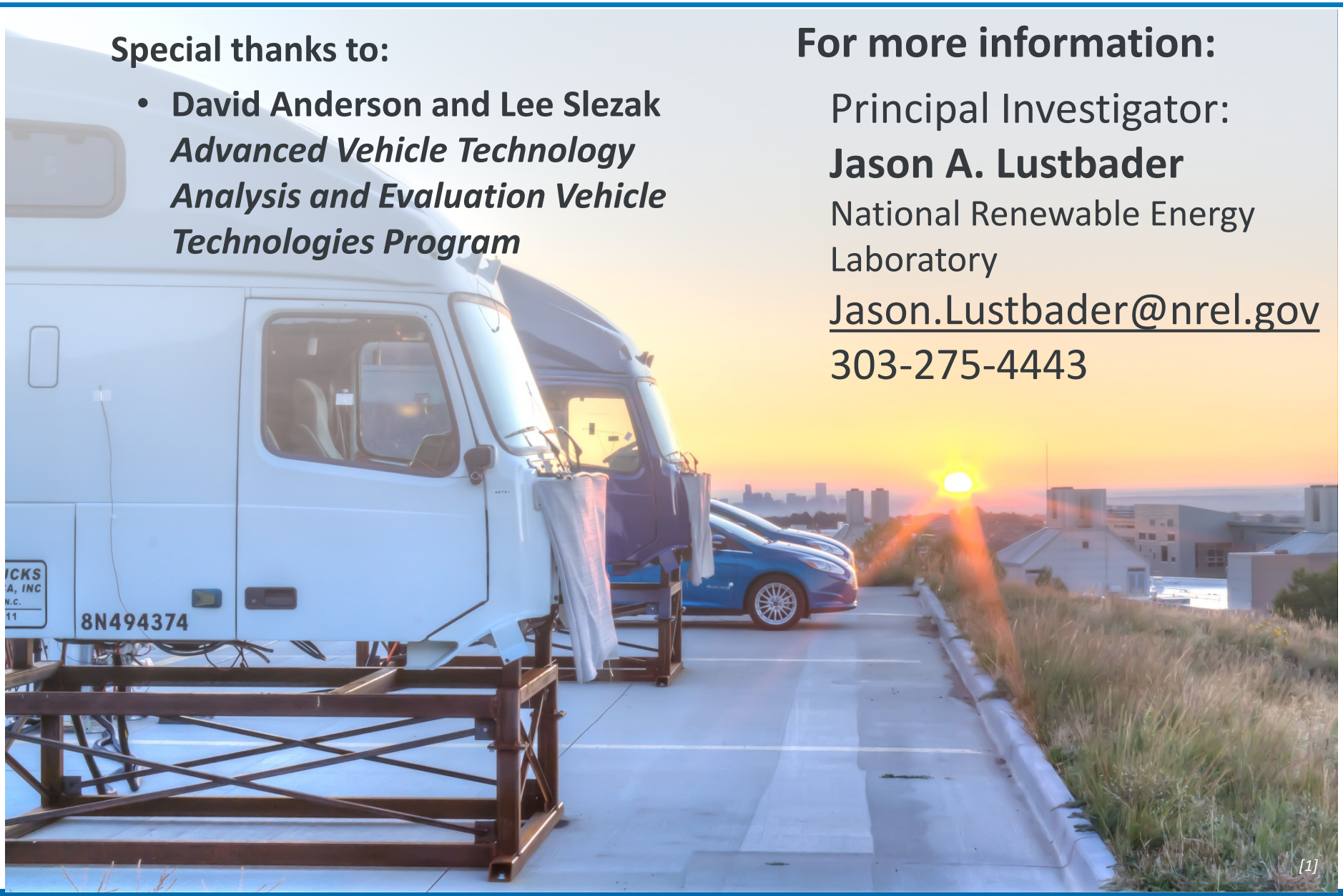

[1]

Image References

- **Slide 1**
  1. Photograph of NREL's Vehicle Test Pad (VTP), NREL photographer Dennis Schroeder, 2011
- **Slide 6**
  1. Truck insulation, Travis Venson, 2011
  2. Test vehicles, Matt Jeffers, 2012
  3. Truck picture, NREL Image Gallery, 14180
- **Slide 8**
  1. Thermal image of truck, Dennis Schroeder 2013
- **Slide 9**
  1. Photos of trucks on VTP, Cory Kreutzer 2012
- **Slide 10**
  1. Truck curtains, Travis Venson, 2011
  2. Truck glazing film, Cory Kreutzer 2013
  3. Thermal image of Newton Manikin, Dennis Schroeder 2013
- **Slide 17**
  1. Photograph of trucks on VTP, Matt Jeffers 2012
  2. Test vehicles, Matt Jeffers, 2012
- **Slide 18**
  1. Thermal image of truck, Travis Venson, 2011
- **Slide 19**
  1. Photograph of test bucks, Cory Kreutzer, 2012 (note, shade cloth on black buck firewall was added to represent as-tested configuration since no picture was available)
- **Slide 20**
  1. Photograph of test bucks, Cory Kreutzer, 2012-2013
- **Slide 22**
  1. Photograph of truck glazing film, Cory Kreutzer 2013
- **Slide 23**
  1. Photograph of sleeper curtain barrier, Cory Kreutzer 2013
- **Slide 27**
  1. Photograph of HVAC emulator, Cory Kreutzer 2013
- **Slide 32**
  1. Photograph of NREL truck, Cory Kreutzer, 2012
  2. Photograph of Volvo truck, Cory Kreutzer, 2013
  3. Photograph of Kenworth truck, Travis Venson, 2011
  4. Photograph of Daimler truck, Travis Venson, 2011
- **Slide 34**
  1. Photograph of Volvo truck, Travis Venson, 2010
  2. Photograph of Kenworth truck, Ken Proc, 2009
- **Slide 47**
  1. Photograph of trucks on VTP, Cory Kreutzer 2012

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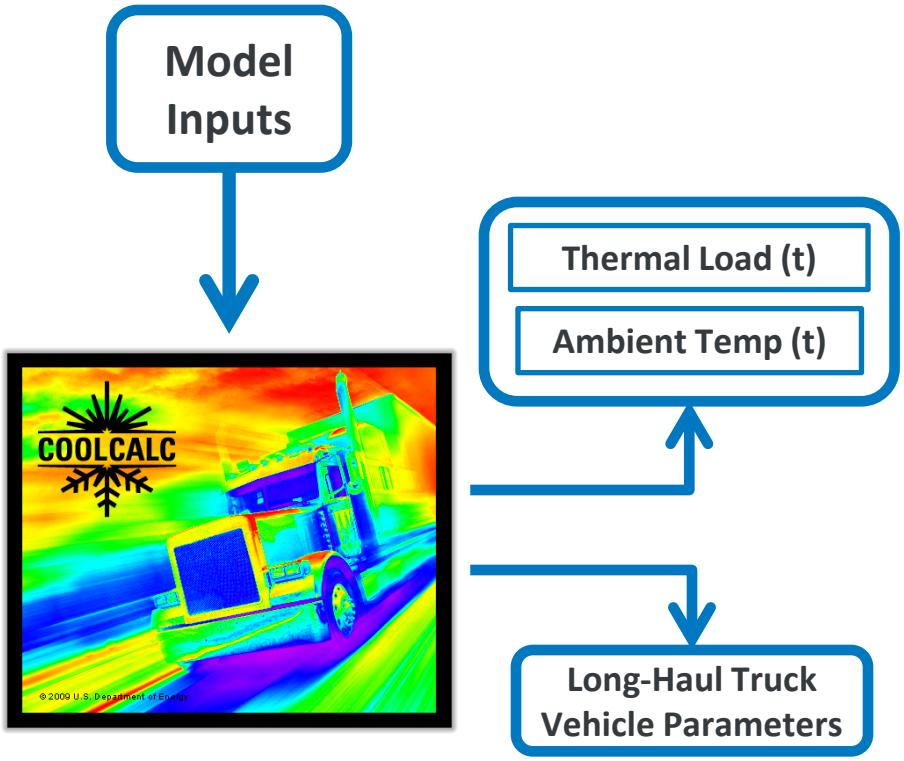
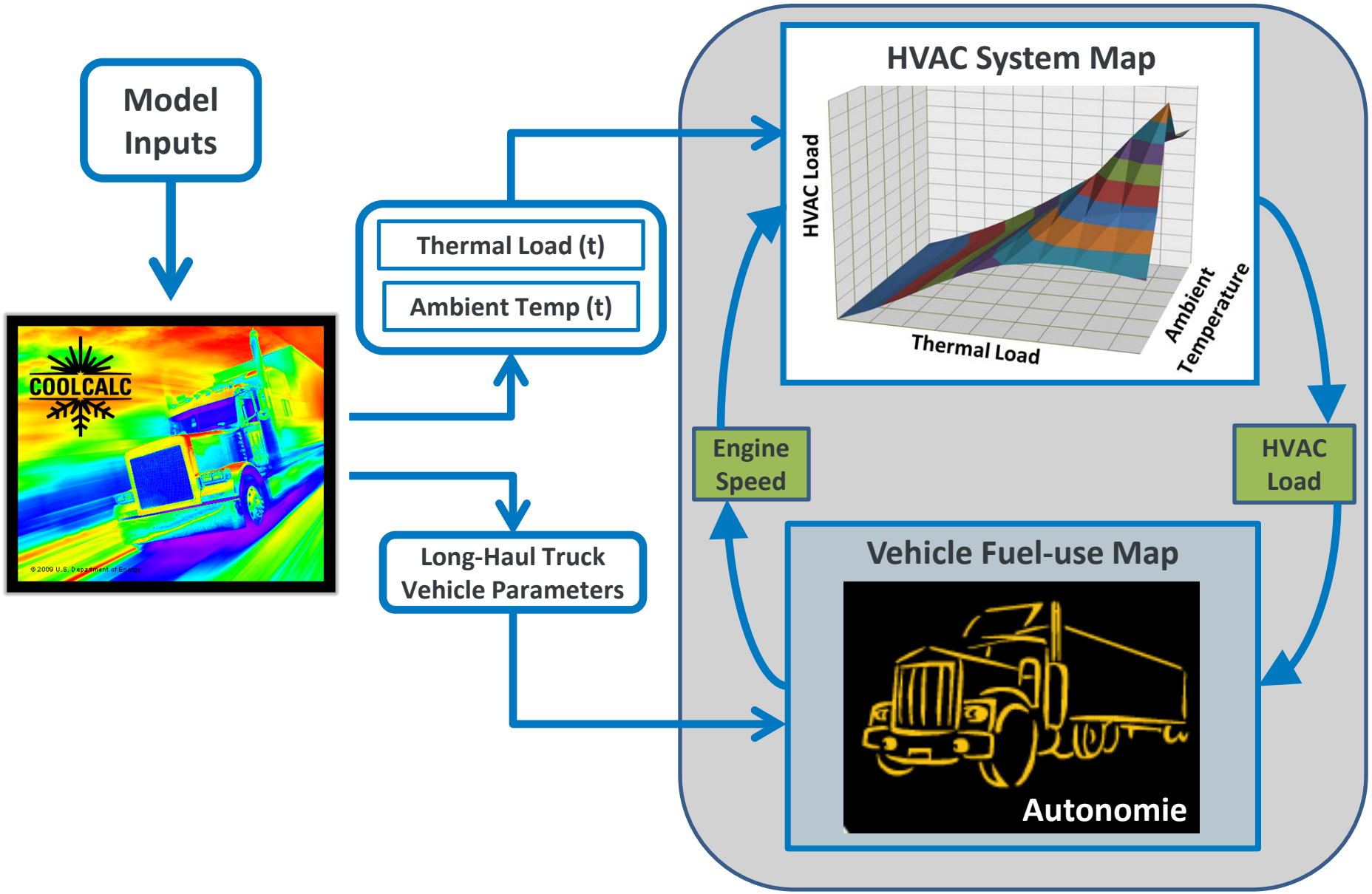
Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

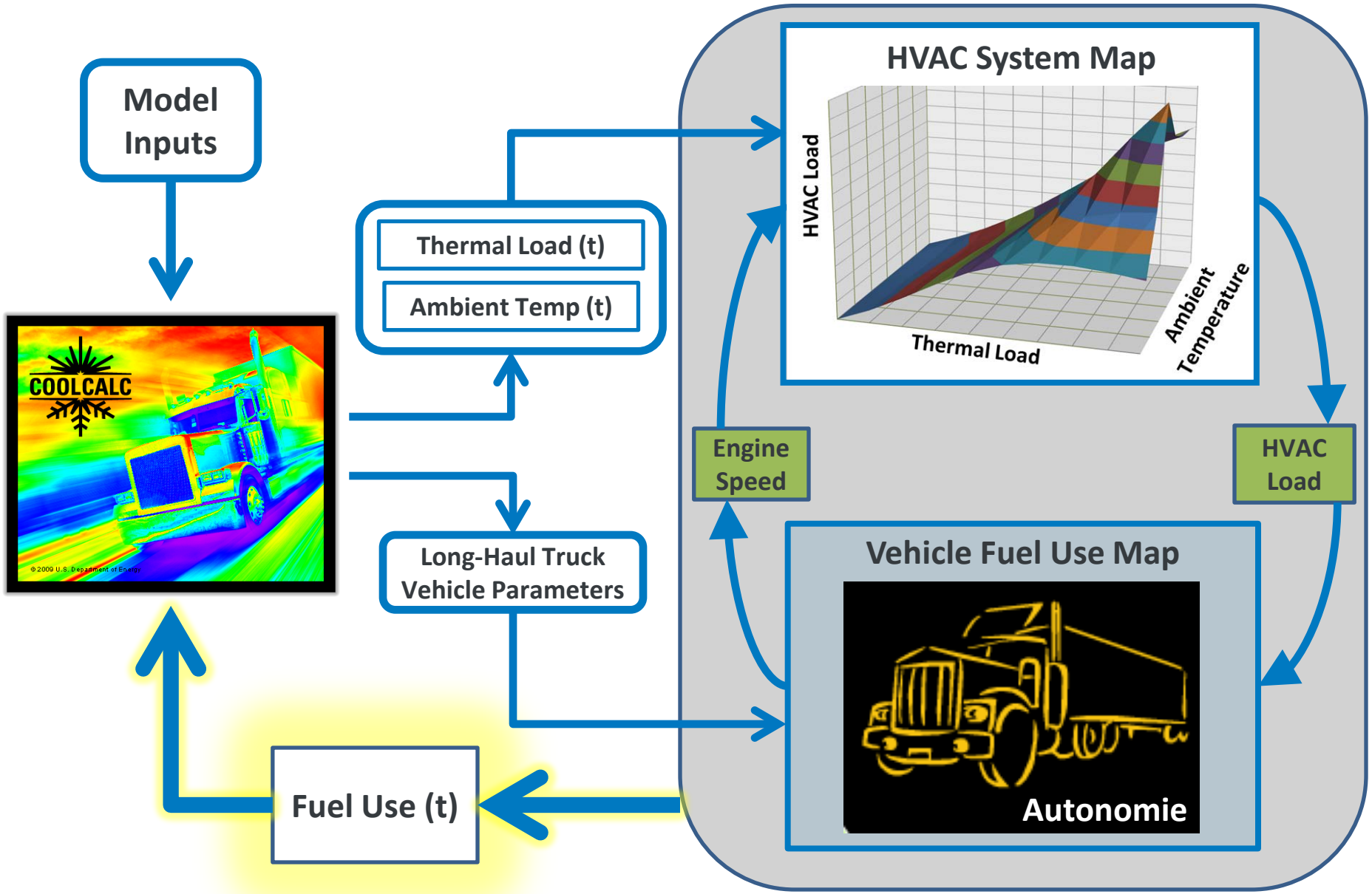
Fuel Use Estimation Methodology



Fuel Use Estimation Methodology



Fuel Use Estimation Methodology



Fuel Use Estimation Methodology