

CoolCab Test and Evaluation & CoolCalc HVAC Tool Development



U.S. Department of Energy
Annual Merit Review

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Thursday, May 12, 2011

Project ID: VSS037

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

Overview

Timeline

- Project start date: FY06
- Project end date: FY13
- Percent complete: 60%

Budget

- Total project funding
 - DOE share: \$2,200k
 - Contractor share*: \$602k
- FY10 Funding: \$900k
- FY11 Funding: \$500k

**Shared resources and direct funds*

Barriers

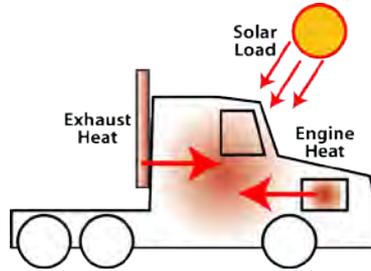
- **Risk Aversion** – *Industry lacks key performance data on HVAC loads and truck cab thermal load reduction technologies*
- **Cost** – *Truck fleets operate on small profit margins and are sensitive to purchase costs for equipment*
- **Computational models, design and simulation methodologies** – *Industry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

Partners

- Interactions
 - Kenworth Truck Company (PACCAR)
 - Volvo Truck
 - Oshkosh
 - International
 - Dometic
- Project lead: NREL

Project Description - Relevance

THE CHALLENGE



- Sleeper cab hotel load idling uses more than 838 million gallons of fuel annually*
 - More than 2 billion gallons with workday idling **
- Idling is done to
 - Heat or cool the cab/sleeper
 - Keep the fuel warm (gelling)
 - Keep the engine warm (startup)
- Varying thermal conditions inhibit the use of idle reduction technologies

THE OPPORTUNITY

- Reducing the load will enable idle reduction technologies
- Fleet owners and operators economically motivated
 - 2-year payback
 - Direct impact on bottom line



Data Source: EIA Short-Term Energy Outlook
<http://www.eia.doe.gov/emeu/aer/txt/ptb0524.html>, March 2011

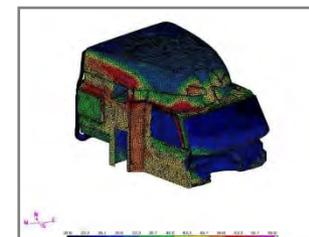
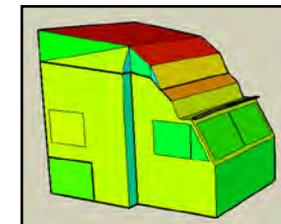
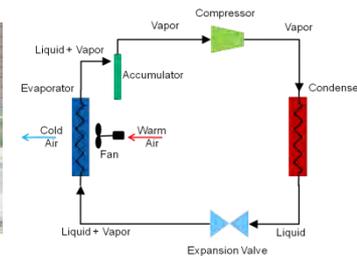
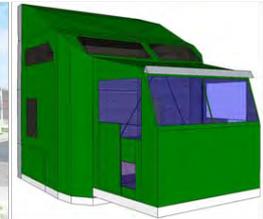
* Stodolsky et al., *Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks*. 2000. ANL/ESD-43
** Gaines et al., "Estimation of Fuel Use by Idling Commercial Trucks," 85th Annual Meeting of the Transportation Research Board, Washington, D.C., January 22–26, 2006, Paper No. 06-2567.

Objectives – Relevance

- Overall Objectives
 - Design efficient thermal management systems that keep the occupants comfortable without the need for engine idling, helping to reduce the 838 million gallons of fuel used for truck hotel loads every year
 - Research and develop technologies to reduce truck cab thermal load through testing and analysis
 - Develop tools and test methods to assess idle reduction technologies
 - Work with industry partners to develop and apply viable solutions
- FY11 Objectives
 - Release, refine, and utilize CoolCalc to help predict HVAC load and idle reduction in sleeper cabs
 - Experimentally characterize performance of thermal load reduction technologies

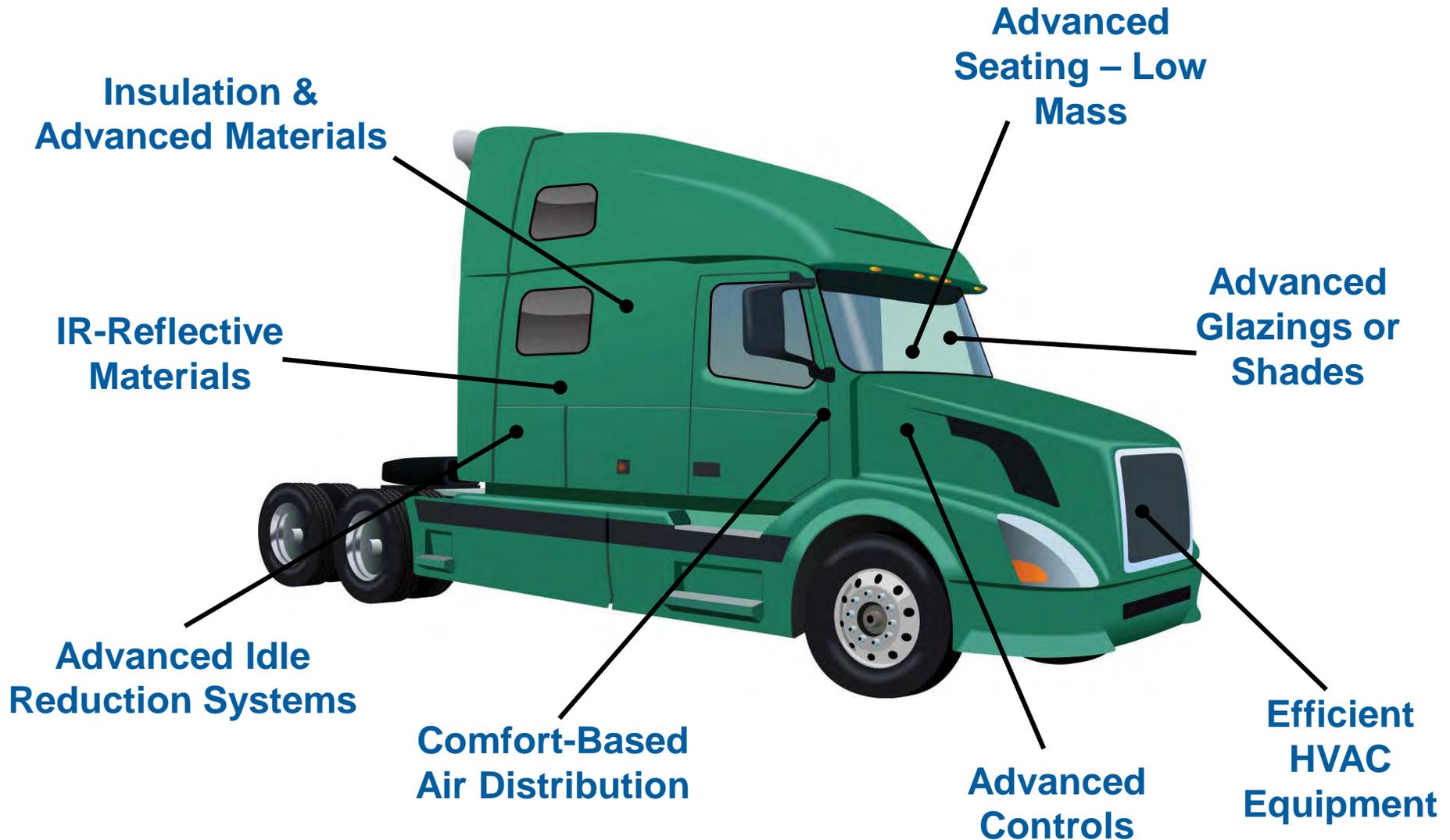
Milestones – Relevance

Year	Month	Key Milestone
2010	Aug	<ul style="list-style-type: none"> CoolCalc validated with test data
2010	Sept	<ul style="list-style-type: none"> Completed testing of Volvo 770 Developed A/C system model framework and integrated with CoolCalc Demonstrated CoolCalc and A/C model link to Autonomie vehicle model Beta release of CoolCalc
2011	April	<ul style="list-style-type: none"> SAE World Congress paper and presentation
2011	July	<ul style="list-style-type: none"> Release first version of CoolCalc with user guide
2011	Sept	<ul style="list-style-type: none"> Complete Volvo 670 truck summer thermal testing Assess thermal load and idle reduction technologies

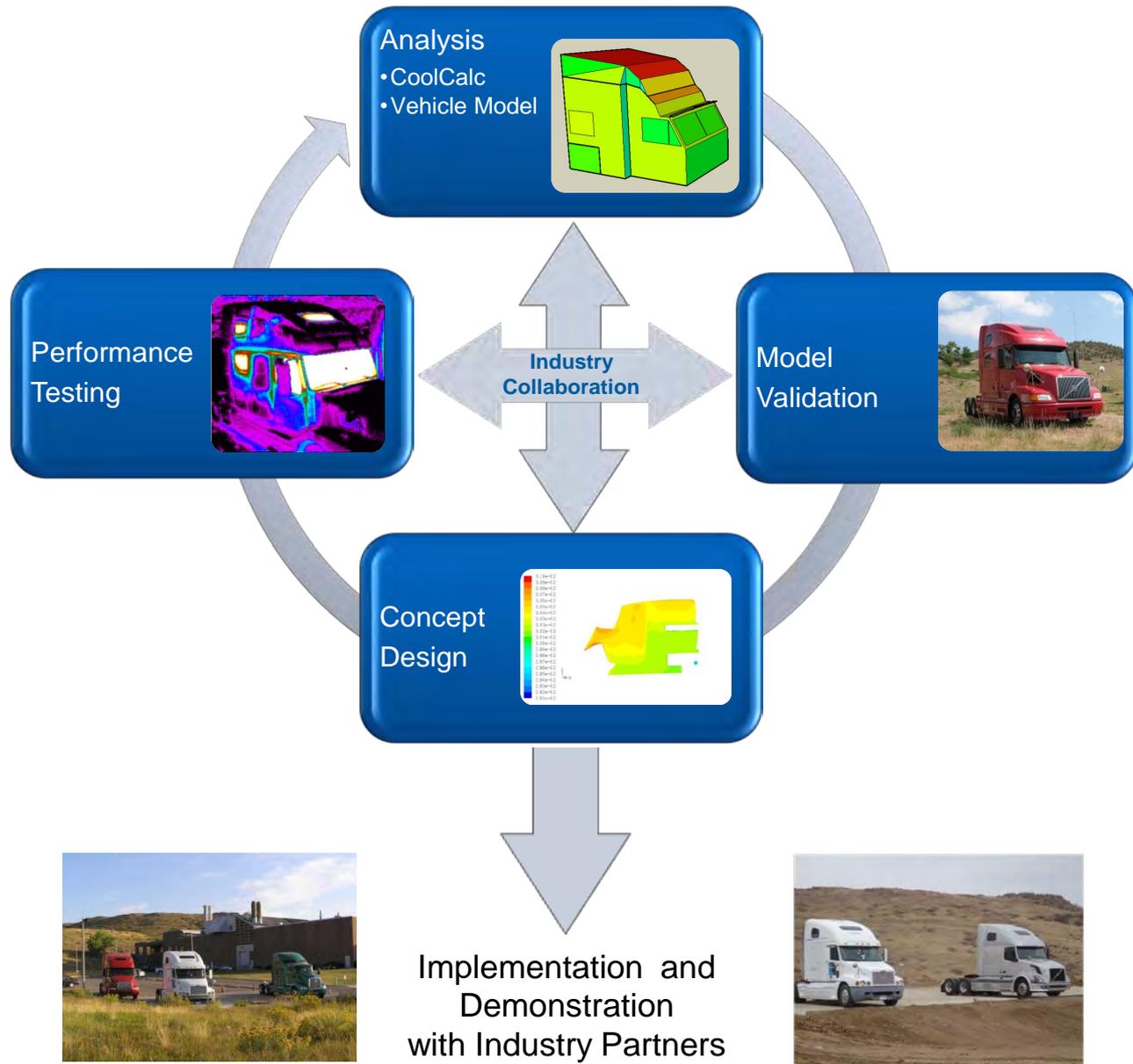


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Advanced Technologies - Approach



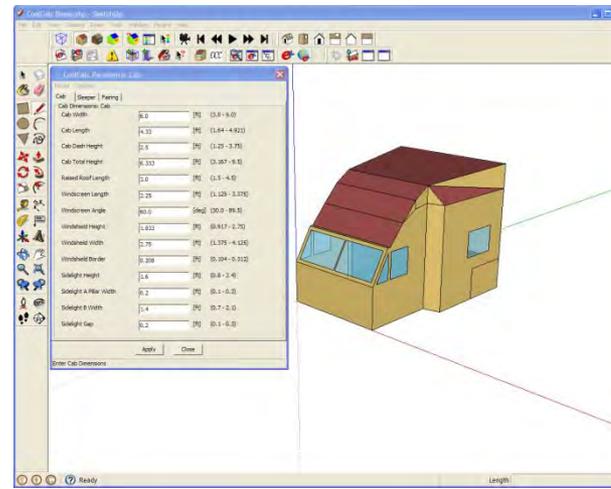
Technology Development Process – Approach



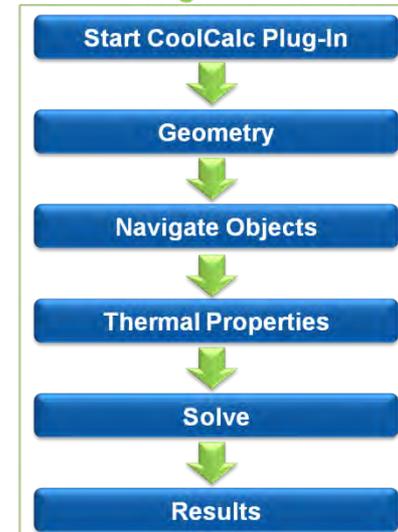
Photograph references:
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4th row left [3], 4th row right [4]

CoolCalc Background

- Physics-based model
 - No meshing
 - Flexible geometry
 - Easy to use and less time-intensive
 - No unnecessary detail
- Applications
 - Trade-off studies
 - Technology impact estimation
 - Preliminary design
 - Focus computational fluid dynamics (CFD) studies
- Key input parameters
 - Truck cab geometry
 - Material properties
 - Climatic conditions
 - A/C system settings
- Outputs
 - Calculate thermal loads
 - Estimate potential load reduction



Modeling Flow Chart

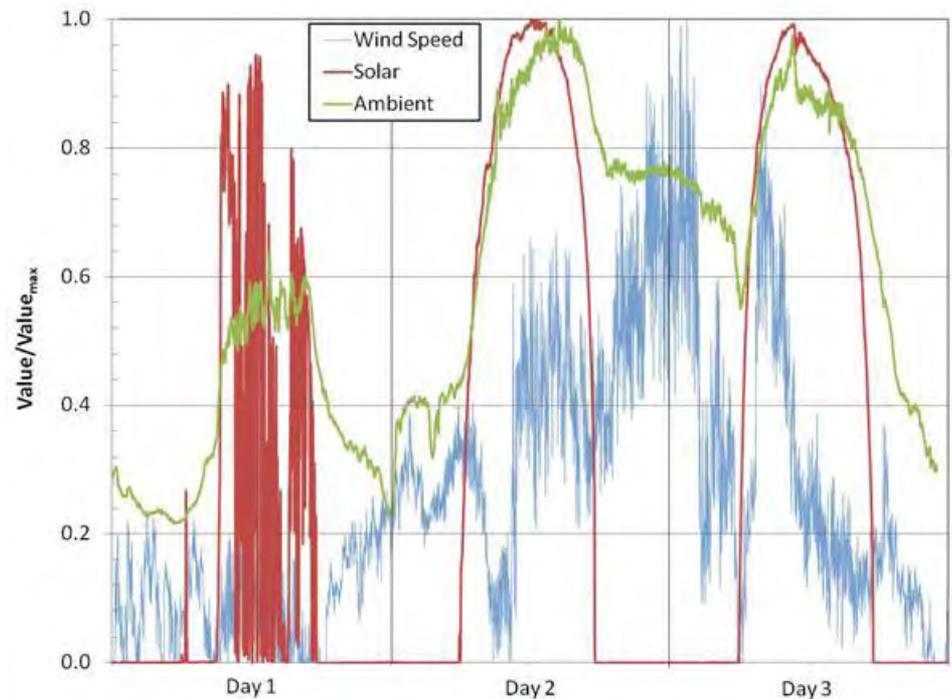
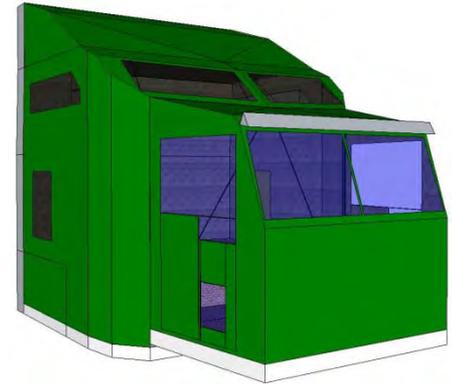


Leveraged Approach

- NREL's Open Studio Plug-In (2008)
- DOE's EnergyPlus
- SketchUp
 - “3D for Everyone”
 - Designed to be “intuitive, flexible, and easier to use”

Validation

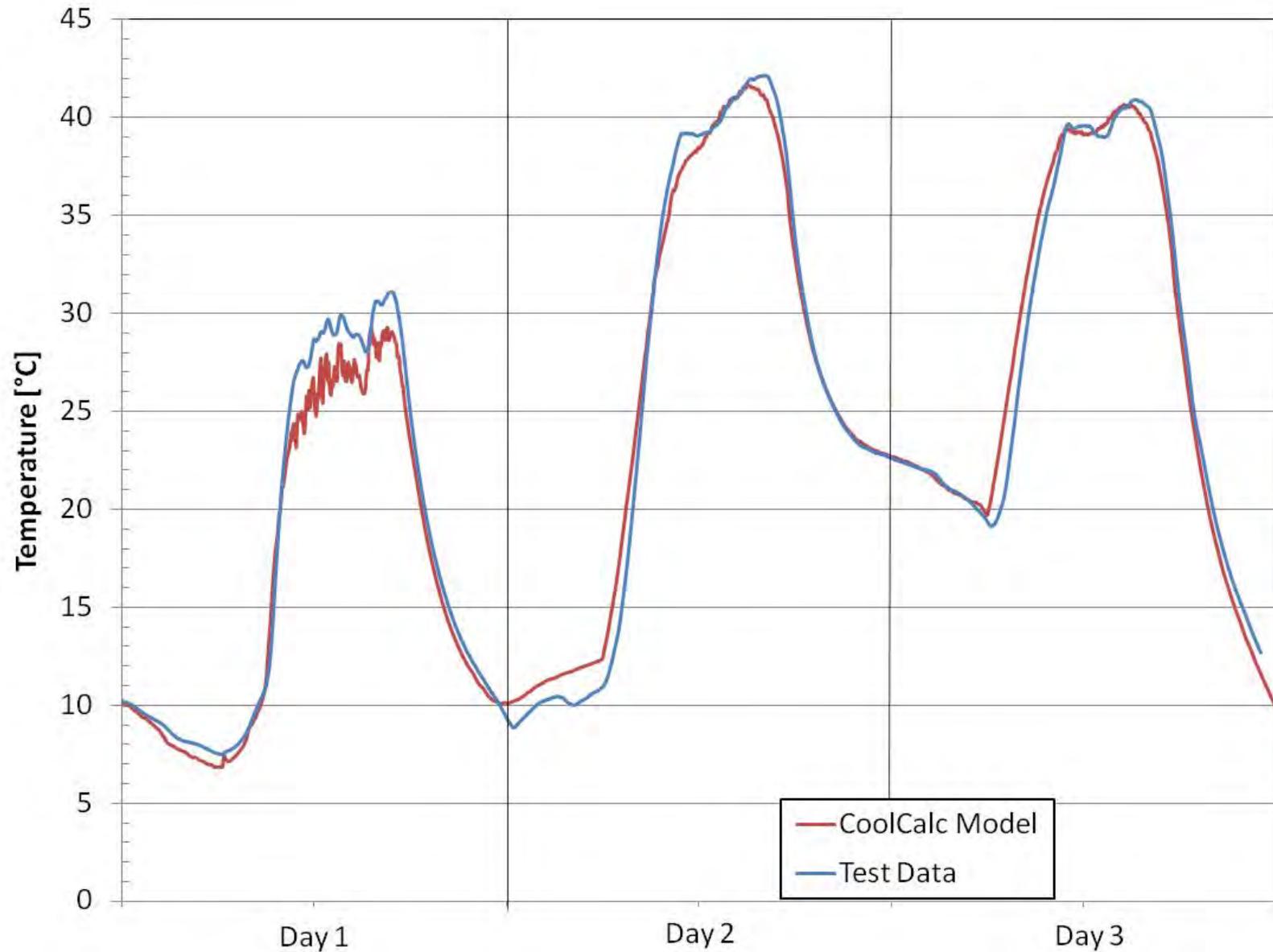
- Truck OEM information
 - CAD geometry
 - Material & construction properties
- Input environmental data
 - Ambient temperatures and humidity
 - Wind speed and direction
 - Solar intensity and cloud coverage
 - Atmospheric pressure
 - Global coordinates
- 3 days with varying weather conditions
 - Golden, CO, summer months
 - Day 1: Cool, cloudy
 - Day 2: Warm, sunny, windy afternoon
 - Day 3: Warm, sunny, less wind in afternoon



Photograph references: 1st row [1]

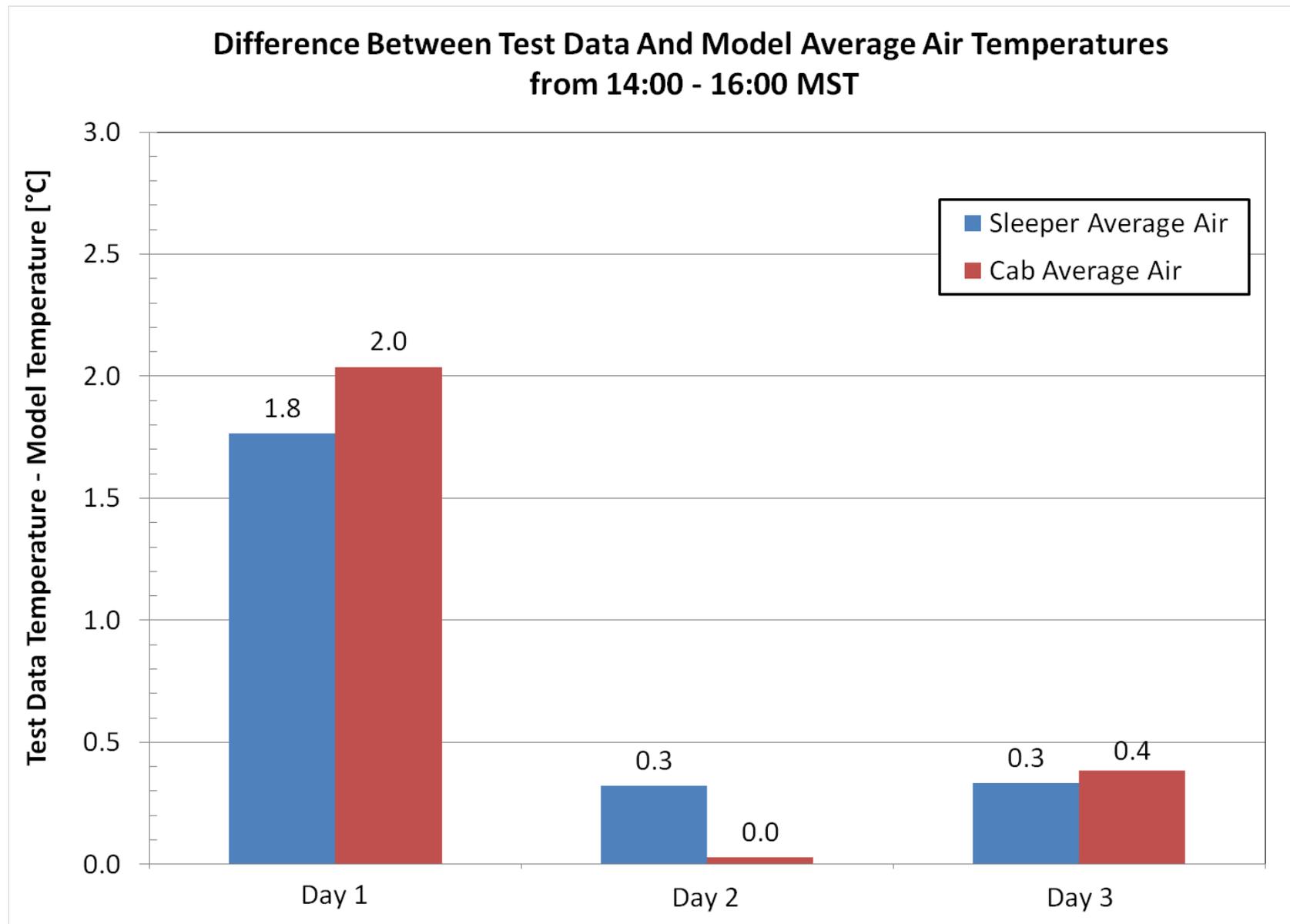
Average Air Temperature in Sleeper – Accomplishments

Matching peak and trends well



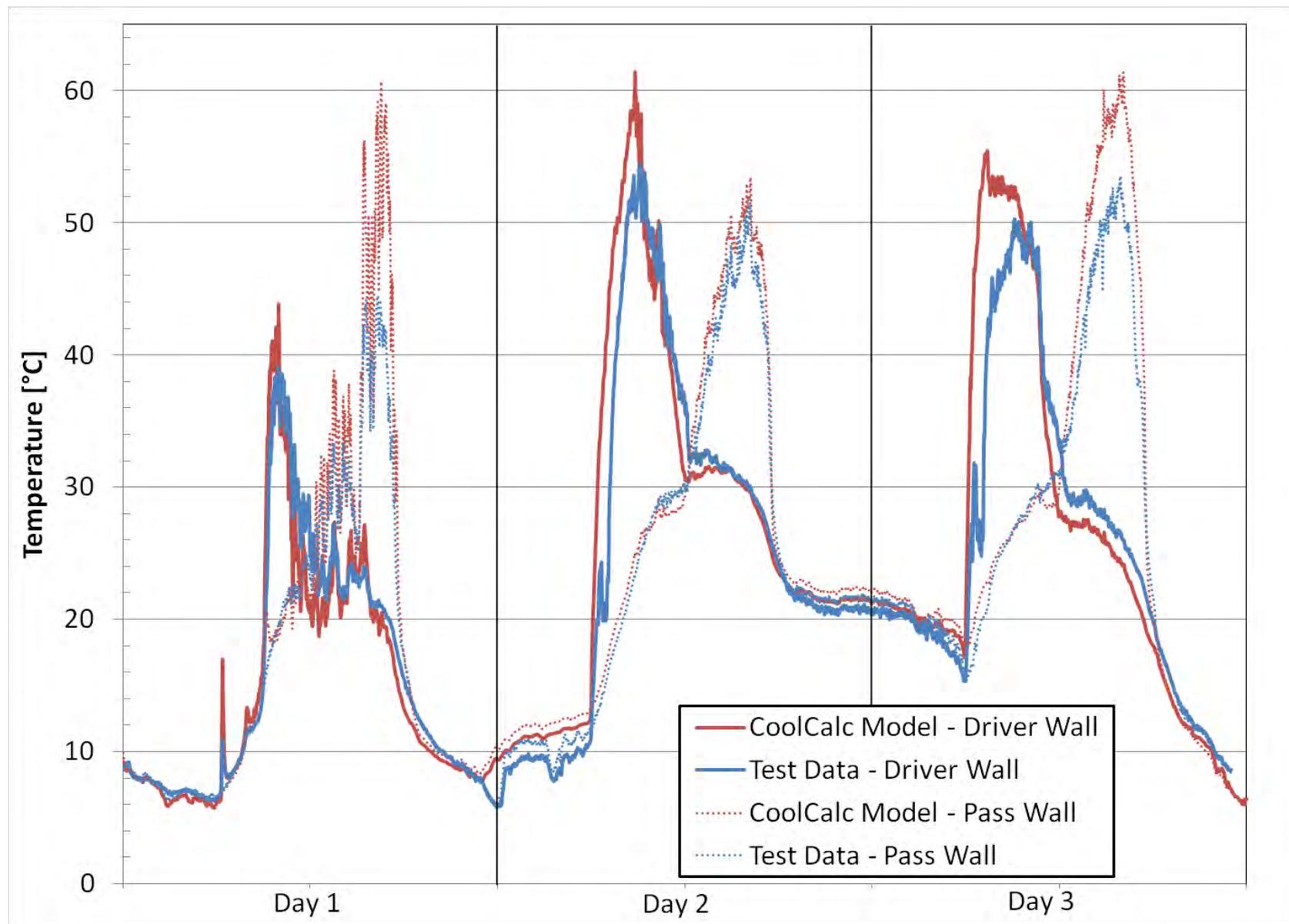
Peak Soak Air Temperatures – Technical Accomplishments

Peak average temperature within 2 °C for the 3 validation days



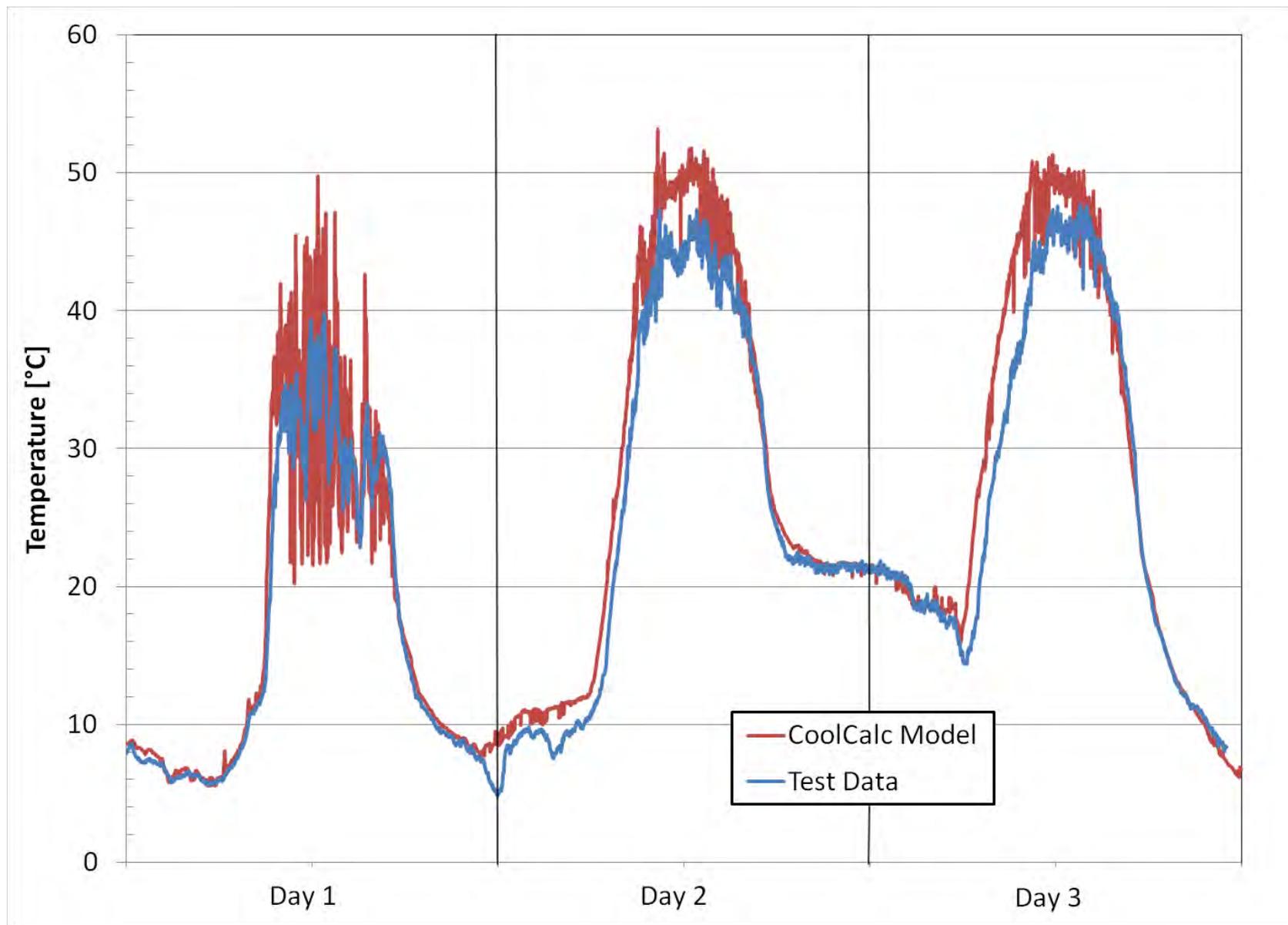
Sleeper Exterior Side Wall Temperature – Technical Accomplishments

Good agreement, may have more separation with low wind



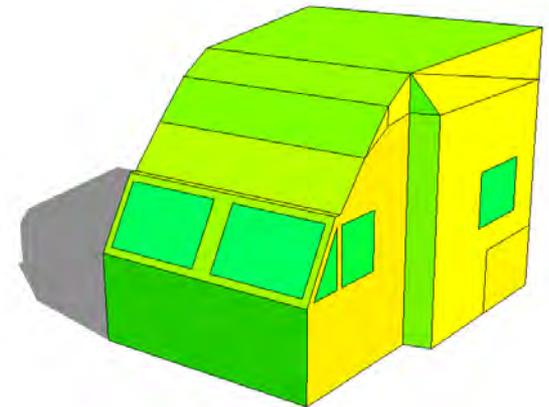
Windshield Exterior Surface Temperature – Accomplishments

Lack of window thermal mass causes higher frequency response on cloudy day 1



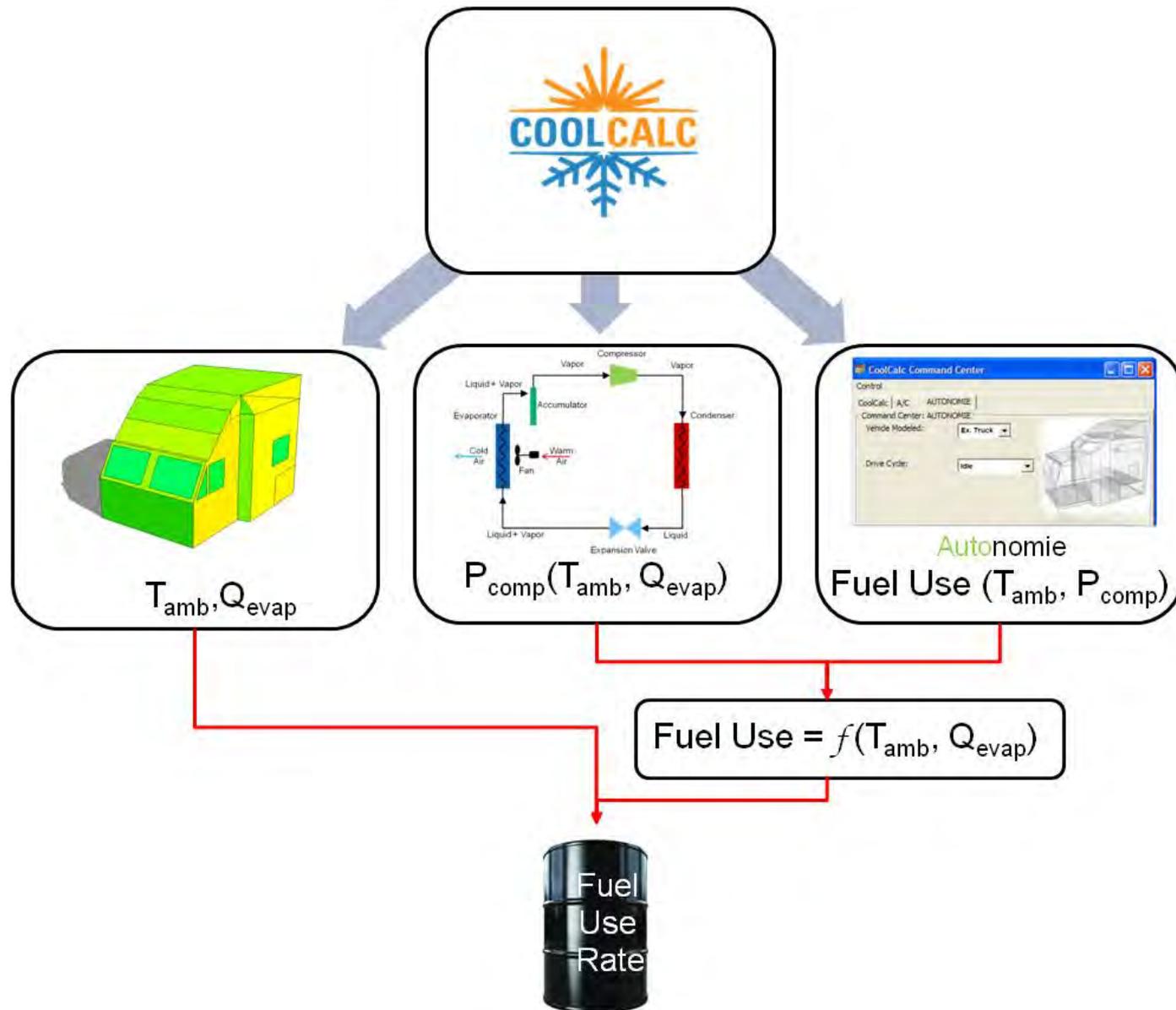
CoolCalc Development – Accomplishments

- Enhanced functionality
 - Improved geometry interface
 - Added material property modification features
 - CoolCalc Command Center
 - Set CoolCalc A/C system variables
 - Define detailed A/C model inputs and run model
 - GUI framework to set and run Autonomie
 - Improved coding framework and enhanced code robustness
- Released CoolCalc beta to industry partners: Kenworth, Oshkosh, and Volvo
 - “I can easily see that CoolCalc is a very powerful and promising software. It can simulate transient cabin heat loads much faster than any other products that we use. CoolCalc has a great potential of reducing our test expense and becoming a major tool for HVAC and cabin insulation design with accurately predicting cabin temperature in various load conditions. I hope you continue to develop this nice product and expand its capabilities to cover more detailed HVAC integration and military vehicle heat load requirements.” – Industry Beta User



Fuel Use Estimation Process – Accomplishments

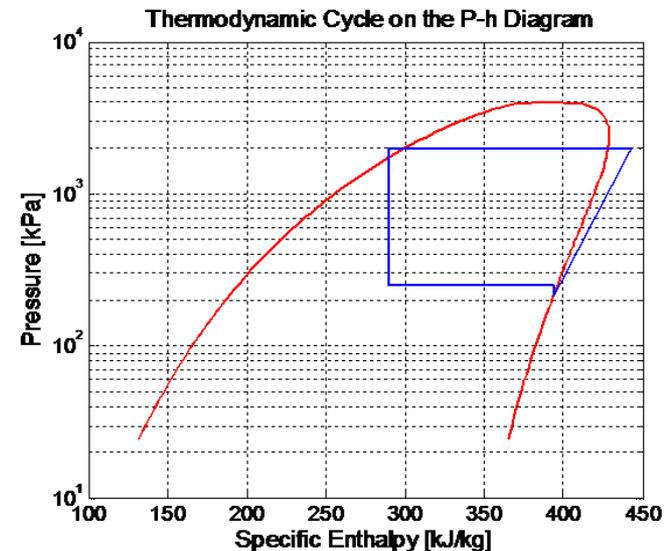
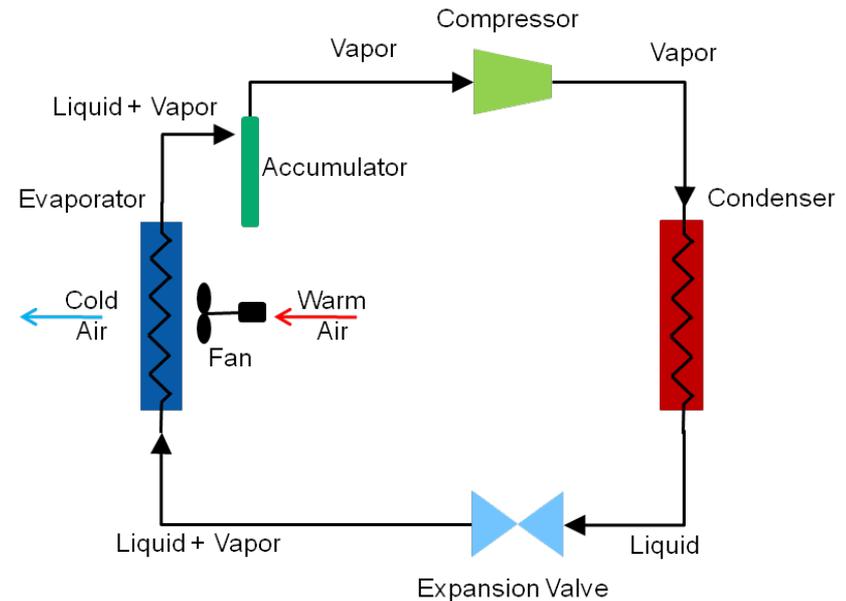
Used thermal loads to estimate fuel use



A/C Model Overview – Technical Accomplishments

A/C system model framework for coefficient of performance estimation

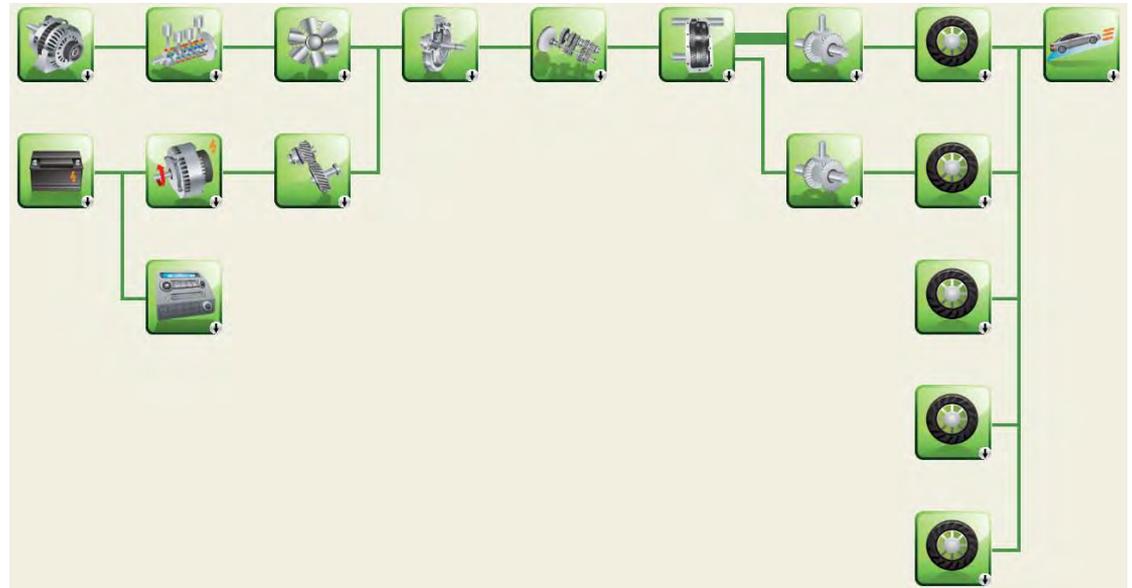
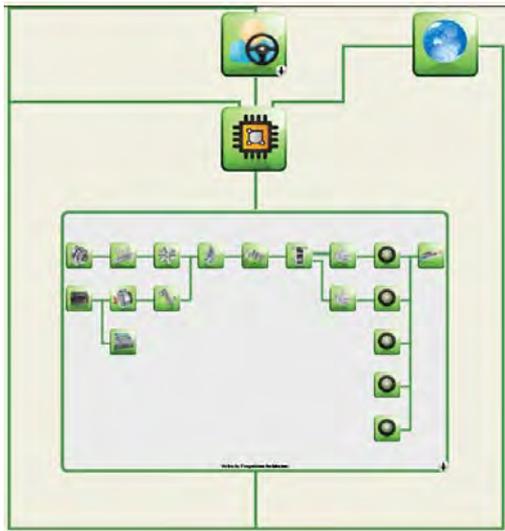
- A/C system model framework
 - Lump-sum model for accumulator
 - 1-D model for condenser and evaporator
 - Current heat transfer models are for simple geometry
 - Near isentropic compression with adiabatic efficiency as input
- Allows for addition of detailed models one component at a time
- Used for light-duty vehicle (LDV) project: “LDV HVAC model development and validation”



Autonomie Simulation

Vehicle model-based fuel use estimation

- Vehicle: Class 8 Truck
 - conv_class8_linehaul_dm_4wd_10speed_default
 - Caterpillar 324 kW engine model from ADVISOR
- Drive Cycle: Idle

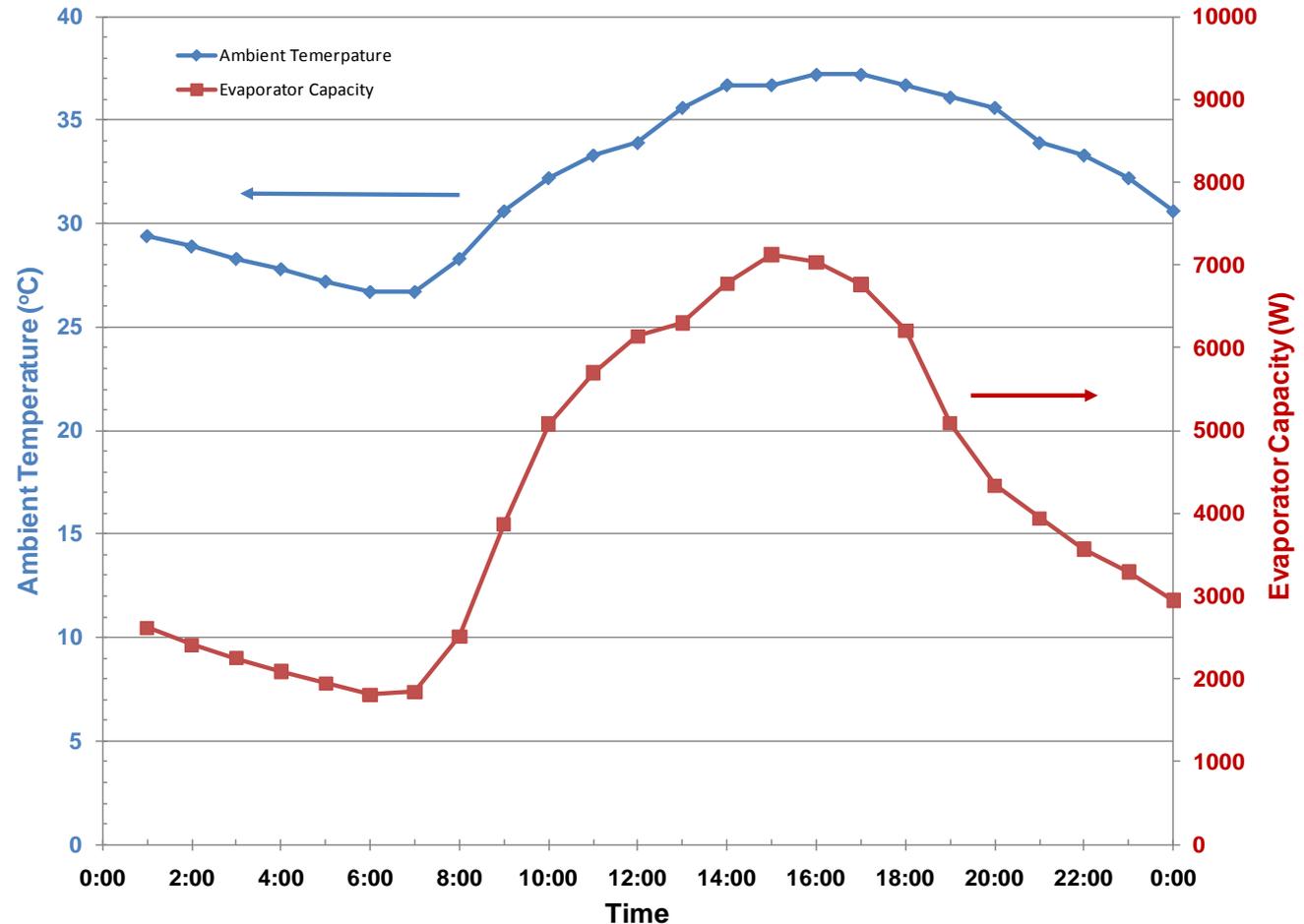


Example – CoolCalc Generates Evaporator Capacity and Temperature vs. Time

CoolCalc Inputs

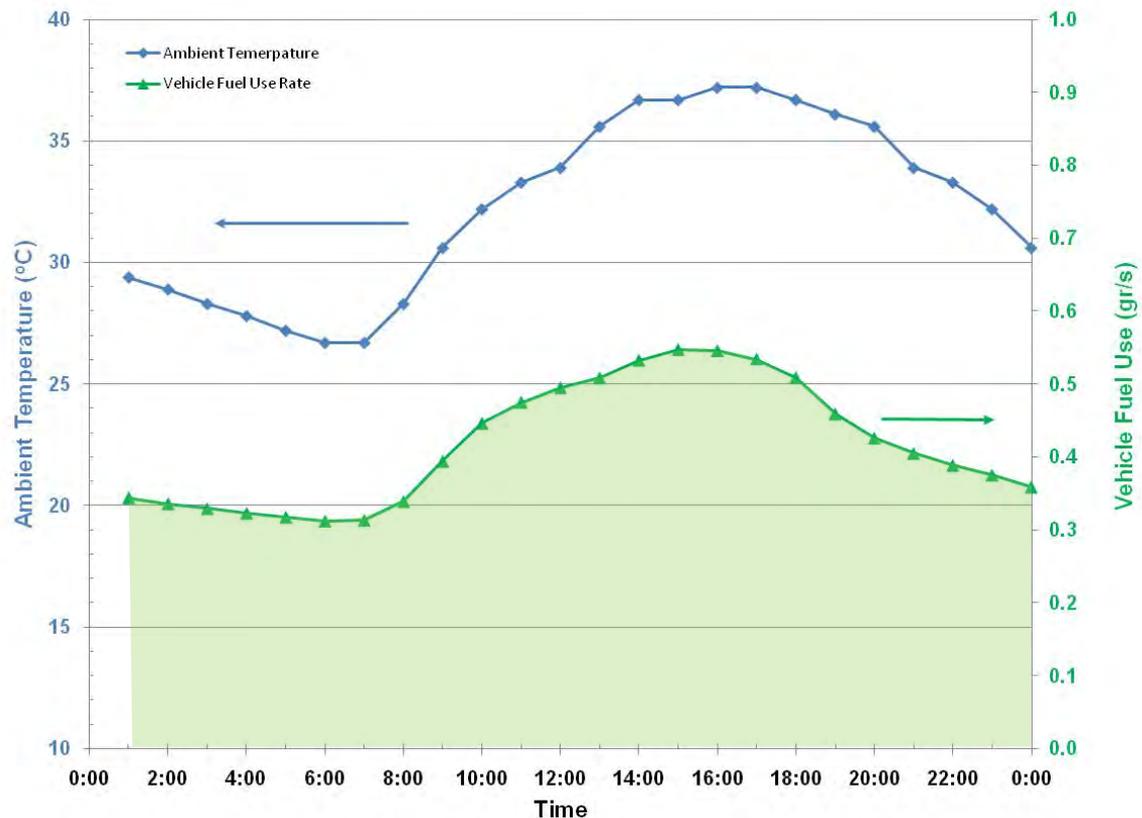
- Example truck
 - Idle
- Environment
 - TMY3 weather data
 - Phoenix airport
 - August 15, 2002
- HVAC Settings
 - A/C on
 - 68°F / 20°C control-cab interior
 - 400 CFM, 0.19 m³/s
 - Outside air

CoolCalc Results



Example – A/C Fuel Use for the Day

- Assume main engine would be on only when the A/C is on
- 11.4 gallons used for climate control in Phoenix on August 15th over 24 hrs



Vehicle Testing

- Kenworth, Volvo, and baseline truck
- Instrumentation
 - 42 thermocouples/truck
 - 26 air & 16 surface
 - 2 humidity sensors
 - 1 pyranometer
 - 1 anemometer
 - Environmental data collected at NREL's weather station



Goals

- Collect data for CoolCalc validation
- Determine possible load reduction due to radiant barriers and insulation

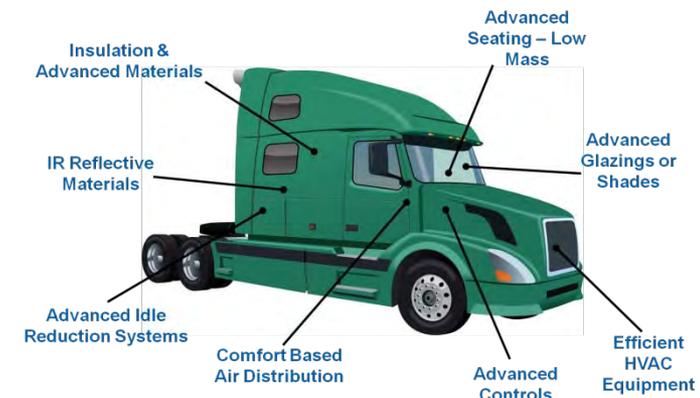
Photograph references: 1st row [1]

CoolCab Test Approach

- Phase I – Baseline Characterization
 - CoolCalc validation data set
 - Correlate control and test truck
- Phase II – Idle Reduction Opportunities
 - Quantify maximum possible improvement to thermal performance
 - e.g., insulation and radiant barriers

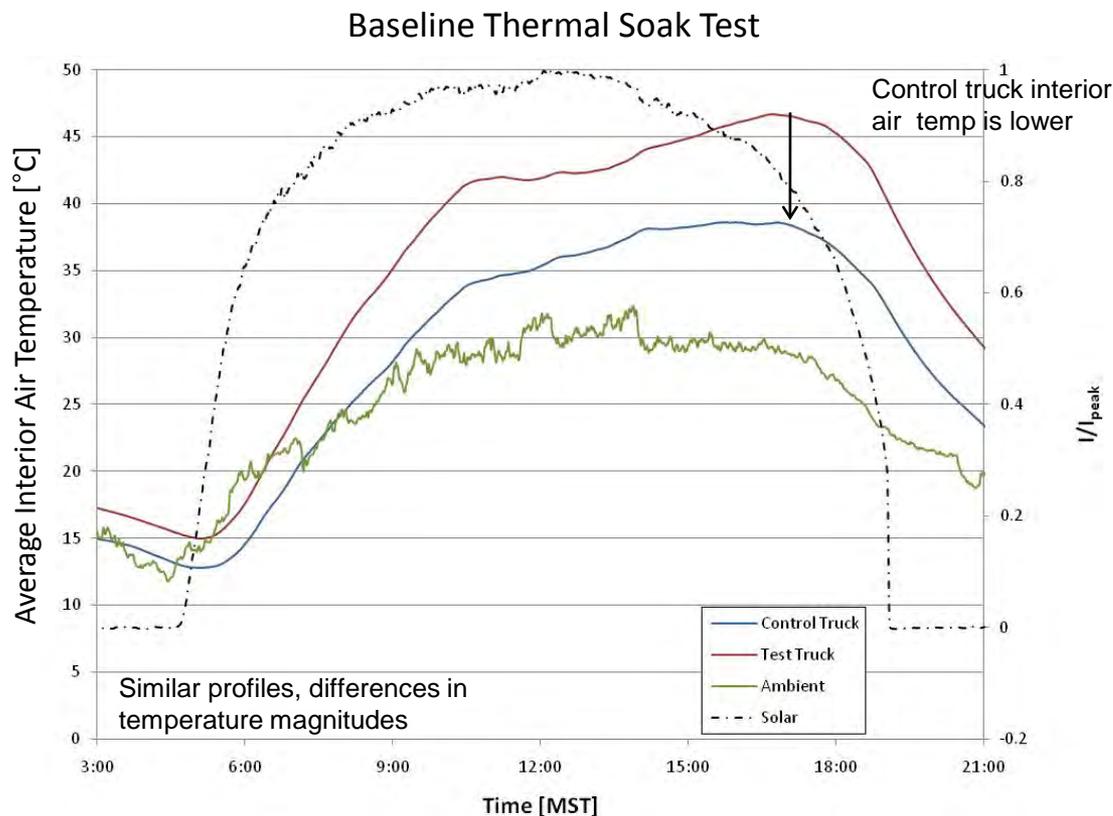


- Phase III –Technology Characterization (Future)
 - Characterize commercially viable and state-of-the-art technology
 - Identify opportunities for advanced technologies



Baseline Characterization – Technical Accomplishment

Thermal soak profiles, overall heat transfer coefficient (UA), and heat loss paths



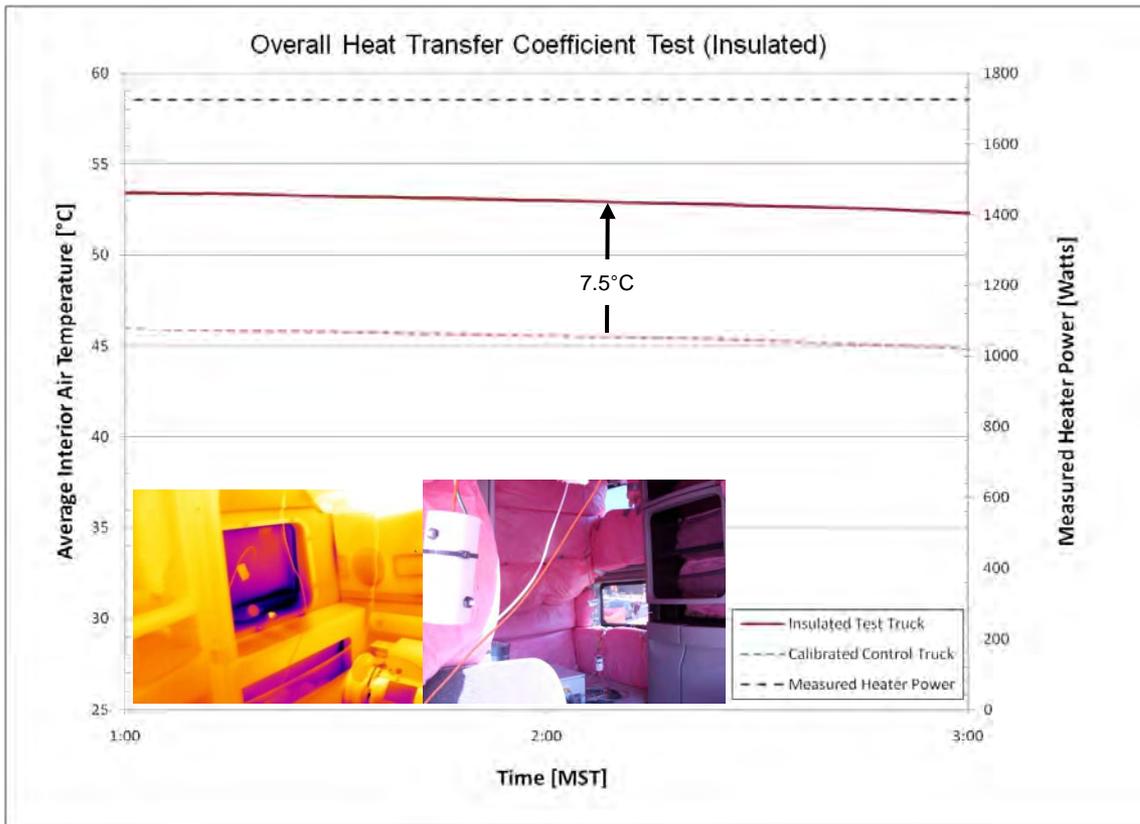
Photograph references: 1st row [1], 2nd row [2]

$$UA = \frac{\text{Measured Heater Power}}{\bar{T}_{air, truck} - \bar{T}_{air, ambient}}$$

Baseline	UA [W/K]	UA [W/K]	UA [W/K]
Test	Truck A	Truck B	Truck C
Average	51.7 ± 2.4	65.93 ± 0.46	90.04 ± 1.07

Insulated Truck Test – Technical Accomplishment

20% reduction in heat loss for insulated truck



- Heater on overnight
- Test truck modified
- Control truck unmodified
- Similar interior air temperatures for control truck between days
- R-19, 6.5 inches thick
- Insulation results in a 20% reduction in heat transfer

$$\dot{Q}_{heater} = UA(\bar{T}_{air,interior} - \bar{T}_{ambient})$$

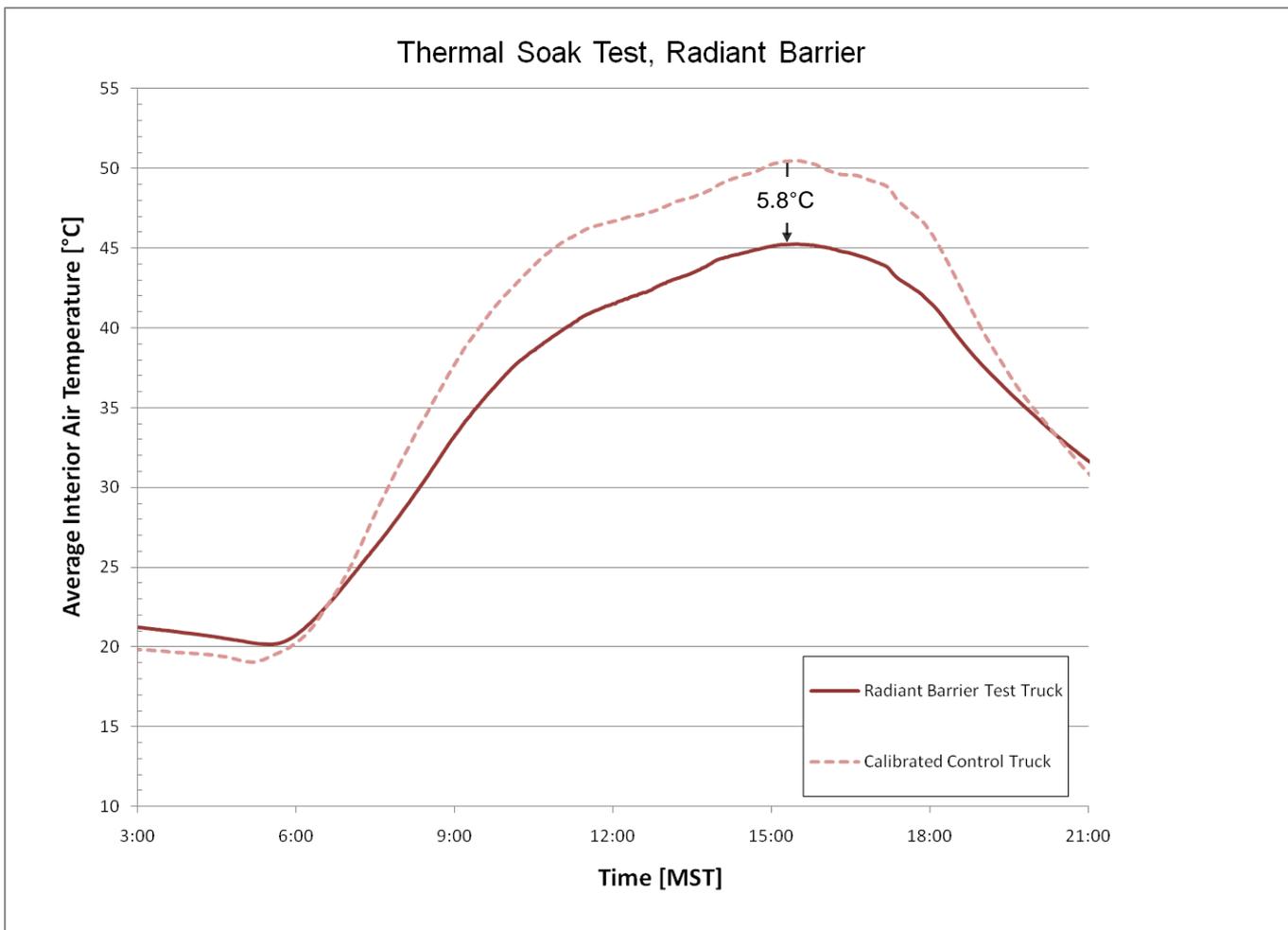
$$\theta = 1 - \left[\frac{\overline{UA}_{modified}}{\overline{UA}_{unmodified}} \right] \cong 20\%$$

	UA [W/K]	UA [W/K]	θ [%]
5 Test Repetitions	Modified Truck	Unmodified Truck	Percent Reduction
Average	54.2 ± 2.3	68.0 ± 2.6	20.3 ± 0.8

Photograph references: 1st row left [1], 1st row right [2]

Radiant Barrier Testing – Technical Accomplishment

31% of maximum possible reduction in interior air temperature with radiant barrier



Reflectivity, $\rho = 0.97$



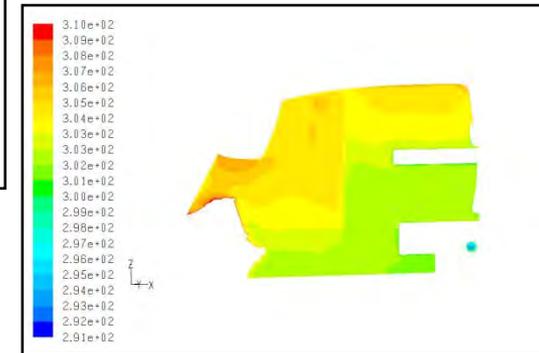
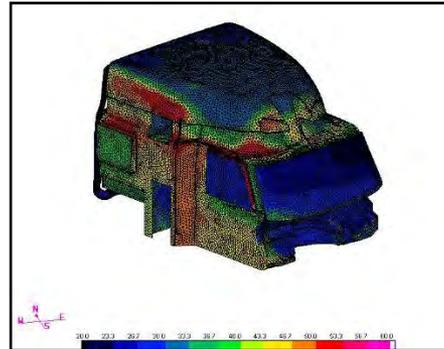
Photograph references:
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$$\beta = \frac{T_{\text{unmodified}} - T_{\text{modified}}}{T_{\text{unmodified}} - T_{\text{ambient}}} \times 100\%$$

$\beta = 31\%$ of the maximum possible interior air temperature reduction

Collaboration

- 21st Century Truck Partnership
- International, ProStar
 - Developed CFD model, validated, and applied to thermal load reduction study
- Kenworth, T660 Sleeper Cab
 - Fully instrumented and tested for thermal-load measurements
 - Used data to validate the CoolCalc model
- Volvo, 770 and 670 Sleeper Cabs
 - 770 thermal testing completed
 - 670 test bed for different materials, coatings, and glazings
 - Evaluate onboard idle reduction technologies
- In discussions with OEMs and suppliers on possible advanced idle reduction projects this summer



Photograph references: 3rd row [1]

Future Work

- FY11
 - Release first version of CoolCalc with user guide
 - Apply CoolCalc to idle reduction technology research
 - Screen thermal load reduction technologies and predict impacts
 - Validation with Volvo data
 - Test thermal load and idle reduction technology on Volvo 670
 - Air conditioning thermal load tests
 - Thermal load technology evaluations
- FY12
 - Improve CoolCalc for partner implementation
 - Apply CoolCalc with integrated A/C model to idle reduction technology modeling
 - Using NREL's analysis tools and test methods, assist truck manufacturers to reduce thermal loads and enable advanced idle reduction technologies
 - Validate and develop capabilities for LDV load prediction

Summary

- **DOE Mission Support**

- Overcome barriers to the adoption of market-viable and efficient thermal management systems that keep the cab comfortable without the need for engine idling, helping to reduce the 838 million gallons of fuel used for truck hotel loads every year.

- **Approach**

- Work with industry partners to develop effective market-viable solutions using a system-level approach to research, development and design.
- Address thermal load reduction of the cab, effective delivery of conditioning to the occupants for thermal comfort, and the use of efficient equipment.

Summary

- **Technical Accomplishments**

- CoolCalc
 - Validated CoolCalc using experimental data
 - Enhanced functionality, added features, and improved robustness of CoolCalc
 - Released beta version of CoolCalc to industry partners for feedback
- Completed testing of Volvo 770
 - 20% reduction in heat loss for insulated truck
 - 31% of maximum possible reduction in interior air temperature with radiant barrier
- Developed A/C system model framework and integrated with CoolCalc
- Demonstrated CoolCalc and A/C model link to Autonomie vehicle model

- **Collaborations**

- Kenworth (PACCAR)
 - Kenworth provided truck and vehicle information for model validation
- Volvo
 - Completed 770 testing and now testing 670
 - Investigating advanced idle reduction technologies
- Oshkosh
 - Beta testing CoolCalc

Contacts

Special thanks to:

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



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Photograph References

Slide 5

1. Kenworth truck photograph: Brianna Rister, NREL
2. Volvo truck photograph: Brianna Rister, NREL
3. Volvo trucks photograph: Travis Venson, NREL

Slide 7

1. Volvo truck thermal image: Ken Proc, NREL
2. Volvo truck photograph: Ken Proc, NREL
3. Trucks photograph: Brianna Rister, NREL
4. Volvo trucks photograph: Travis Venson, NREL

Slide 9

1. Kenworth truck photograph, NREL

Slide 20

1. Trucks photograph: Brianna Rister, NREL

Slide 21

1. Trucks photograph: Brianna Rister, NREL
2. Insulation photograph: Travis Venson, NREL

Slide 22

1. Infrared image: Ken Proc, NREL
2. Infrared image: Ken Proc, NREL

Slide 23

1. Infrared image: Travis Venson, NREL
2. Insulation photograph : Travis Venson, NREL

Slide 24

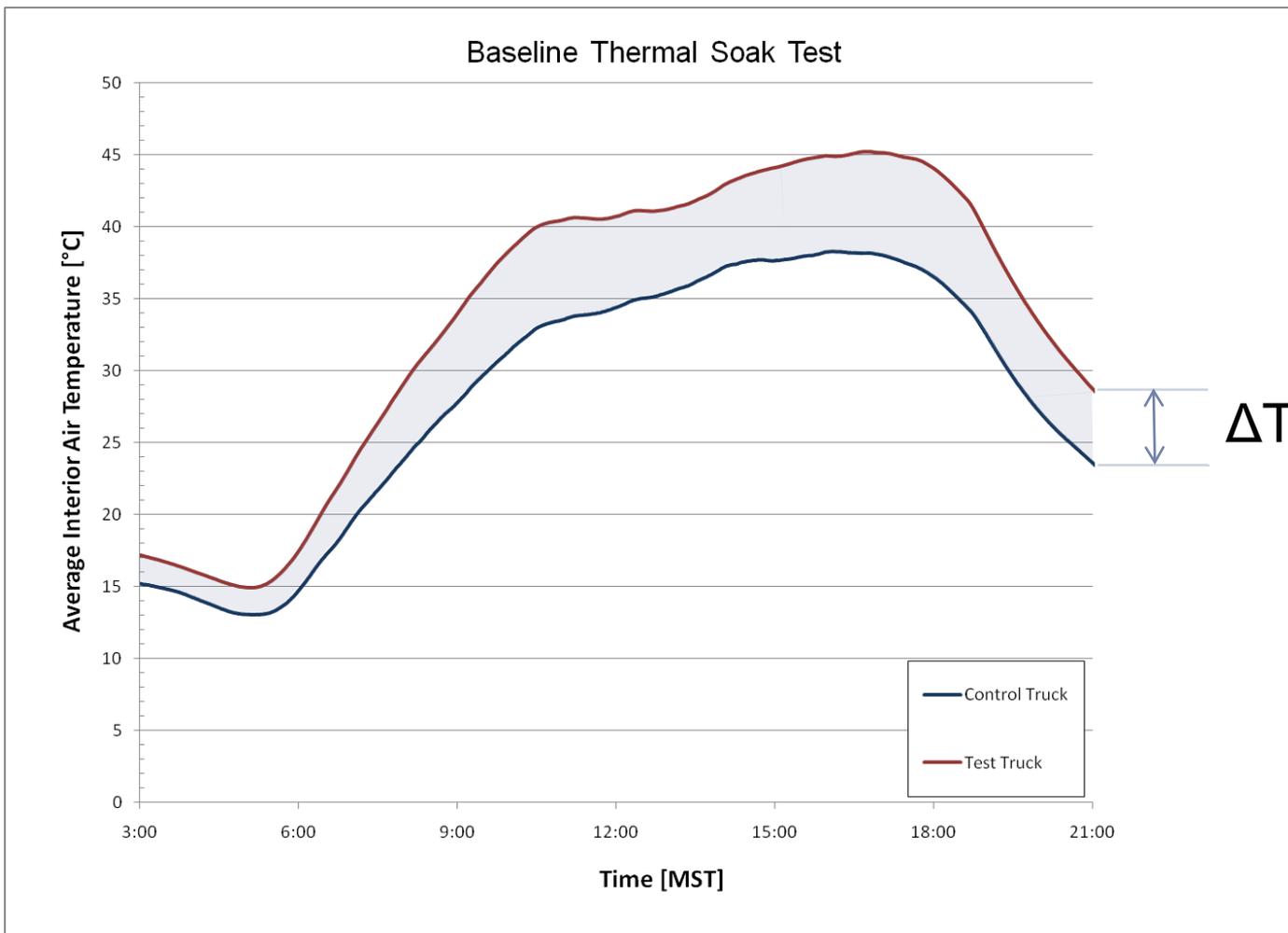
1. Radiant barrier photograph: Travis Venson, NREL
2. Radiant barrier photograph: Travis Venson, NREL

Slide 25

1. Trucks photograph: Brianna Rister, NREL

Technical Back-Up Slides

Baseline Data Analysis to Calibrate Control Truck



$$\Delta T_{Trucks} = T_{Test} - T_{control}$$

where: T= average interior air temp

ΔT_{Trucks}

- Collect many days of baseline data
- Select days with similar solar load, wind speed, and cloud coverage to modified test day
- Characterize daily average ΔT_{trucks} profile
- Adjust measured control truck data by ΔT_{trucks}
- Validate process with other days