CoolCab Test and Evaluation & CoolCalc HVAC Tool Development

US Department of Energy
Annual Merit Review

Presenter & P.I.:
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Wednesday May 15, 2013

Project ID # VSS075

Overview

Timeline

Project Stage II Start Date: FY11

Project Stage II End Date: FY15

Percent Complete: 50%

Budget

Total Project Stage II Funding:

DOE Share: **$975K**

Contractor Share: **$321K**

Funding Received in FY12: $475K

Funding for FY13: $700K

**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*

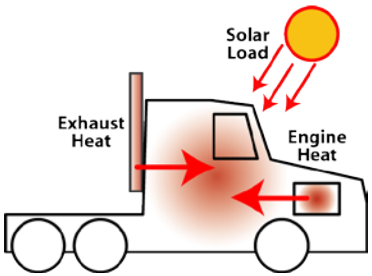
Partners

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

Overview | Approach | Accomplishments | Future Work | Summary

Relevance – Project Description

THE CHALLENGE

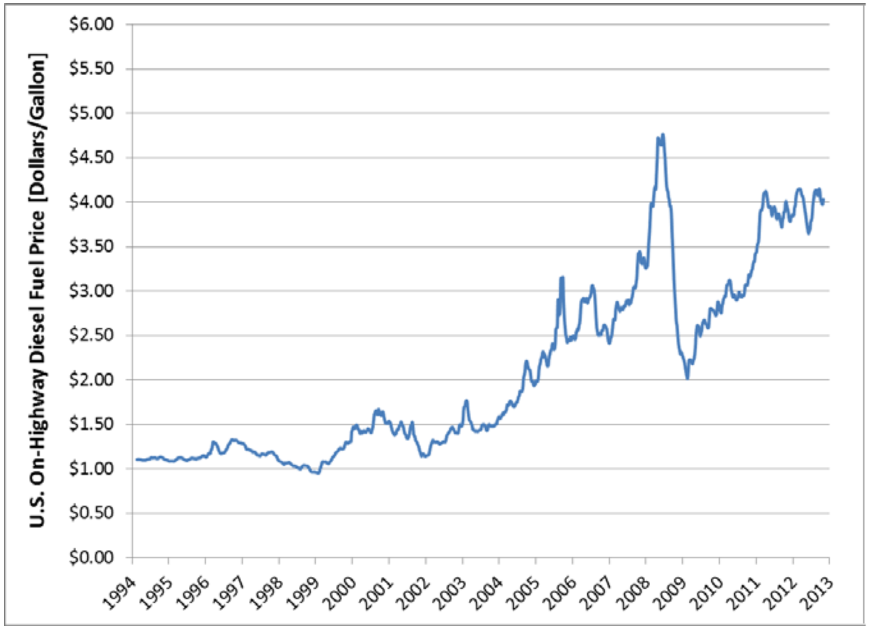


- **838 million gallons of diesel fuel used annually for long-haul truck rest period idling***
  - 6.8% of total long-haul fuel use **
  - More than 2 billion gallons with workday idling**
- **Idling is done to:**
  - Heat or cool the cab/sleeper
  - Keep the fuel warm (prevent gelling)
  - Keep the engine warm (startup)
- **Truck fleets operate over a wide range of environmental and use conditions**

* 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.

THE OPPORTUNITY

- Reducing the load will enable idle reduction technologies
- Fleet owners and operators are economically motivated
  - 2- to 3-year payback
  - Direct impact on bottom line



Data Source: EIA Short-Term Energy Outlook
http://www.eia.gov/petroleum/gasdiesel/, March 2012

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 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


[1]

Advanced Idle System and Controls → M3

Cab Design Demonstration → M4

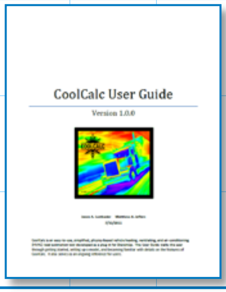
In Use Quantification → M5


[2]

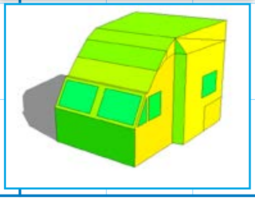
CoolCalc

M1. Wrote user guide and prepared first release of CoolCalc ✓
M2. Add functionality for full modeling process within the GUI environment, from geometry to loads. ✓
M3. Enable rapid parametric design analysis tools to estimate impacts on fuel use and payback period.
M4. Work with industry partners to demonstrate fuel use and payback-period driven design.

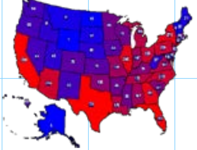
Initial Release → M1



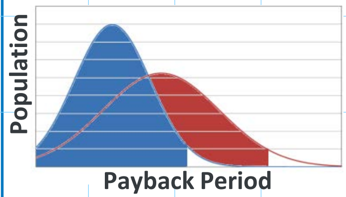
Full Modeling Process, Release → M2



Fuel use and Payback → M3

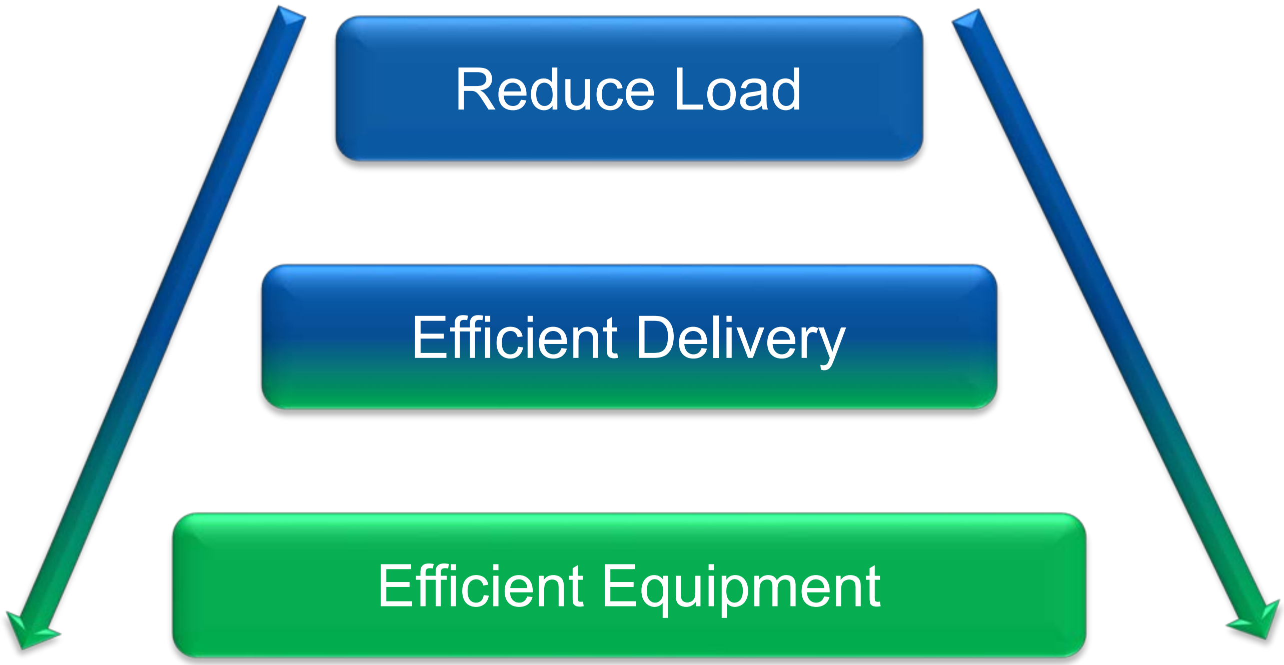


Fuel Use Driven Design → M4



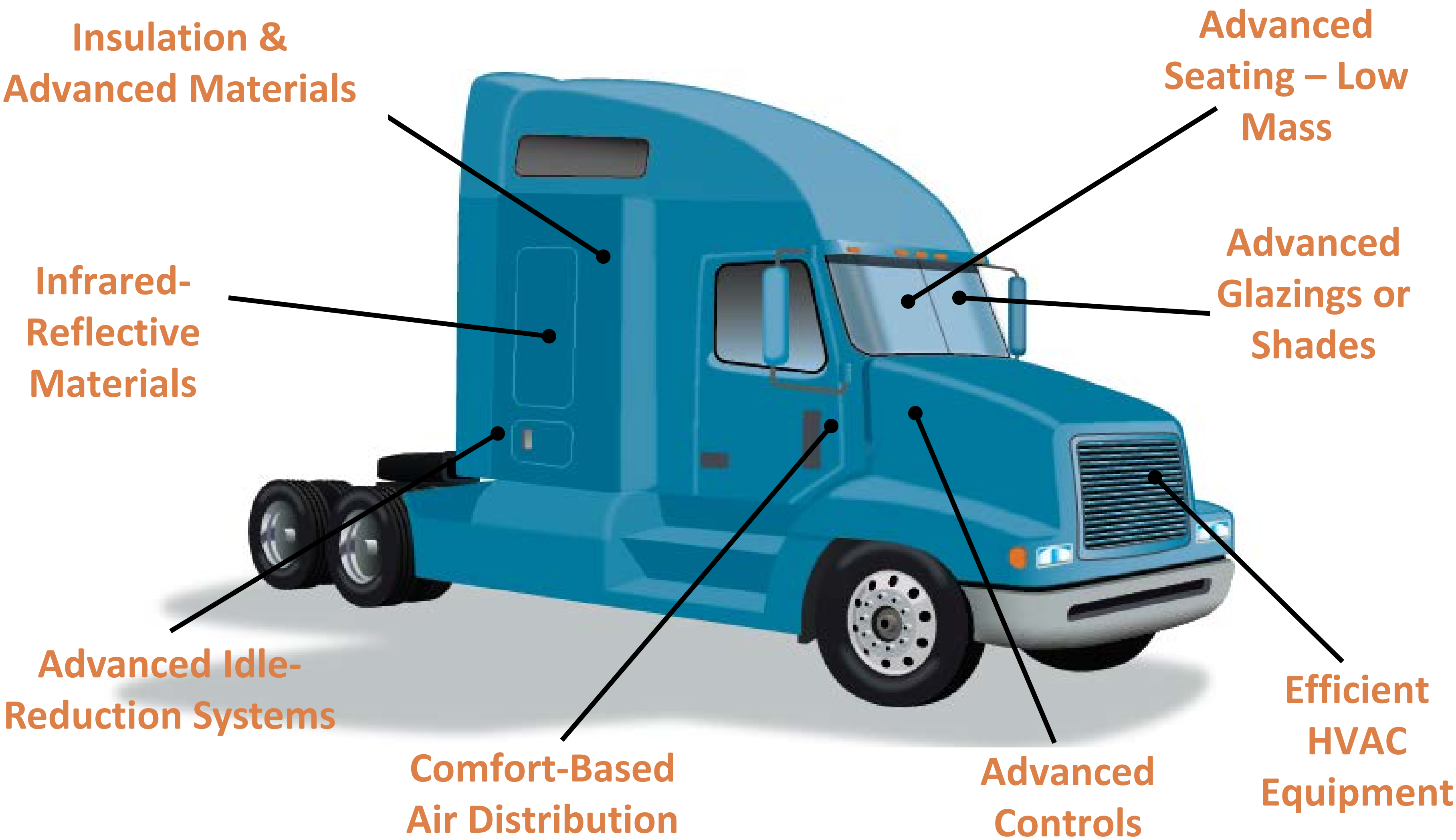
Approach – System Level

System Level Solution



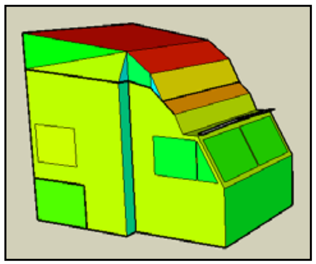
Reductions in load have a larger impact on fuel use due to equipment and delivery losses.

Approach – Advanced Technologies

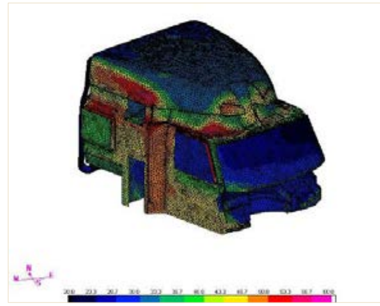


Approach – Suite of Tools

CoolCalc



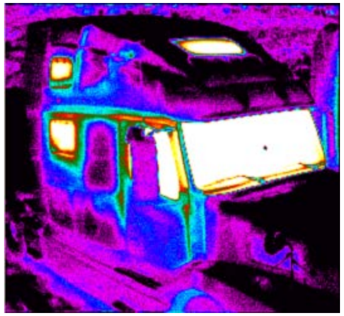
Load Estimation

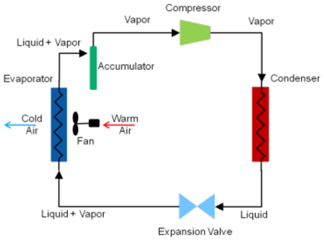


Computational Fluid Dynamics - Fluid Flow

Testing

In-Use Validation





A/C Model – *Compressor Power*

Fuel Consumption

Vehicle Modeling

Overview | Approach | Accomplishments | Future Work | Summary

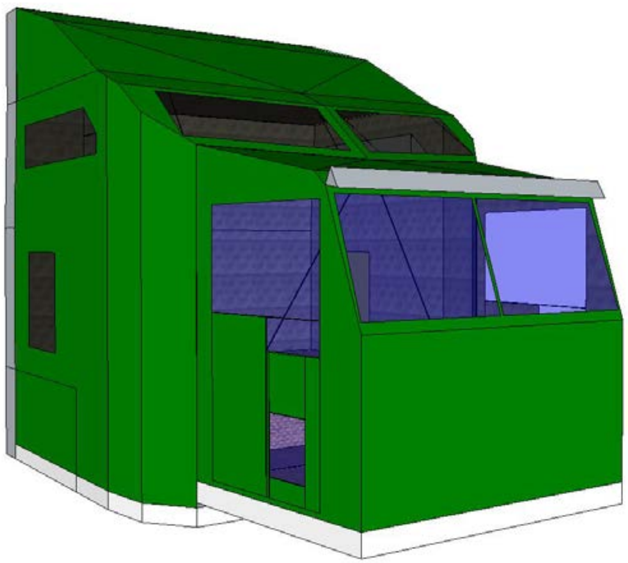
Approach – CoolCalc

Rapid HVAC Load Estimation

- **Advantages**
  - Physics-based model, no meshing
  - Flexible geometry
  - Less time intensive
  - Excludes unnecessary detail
  - Easy to use
- **Applications**
  - Trade-off studies
  - Technology impact estimation
  - Preliminary design
  - Focus more detailed CFD studies
- **Key Input Parameters**
  - Truck cab geometry
  - Material properties
  - Climatic conditions
  - A/C System settings
- **Outputs**
  - Thermal loads for various weather & operating conditions
  - Potential load reduction estimates
  - Fuel use impacts

Leverages:
- EnergyPlus
- OpenStudio
- SketchUp

1.



1. Lustbader et al., "CoolCalc: A Long-Haul Truck Thermal Load Estimation Tool," SAE World Congress, Detroit, MI, April 12-14, 2011, Paper No. 2011-01-0656

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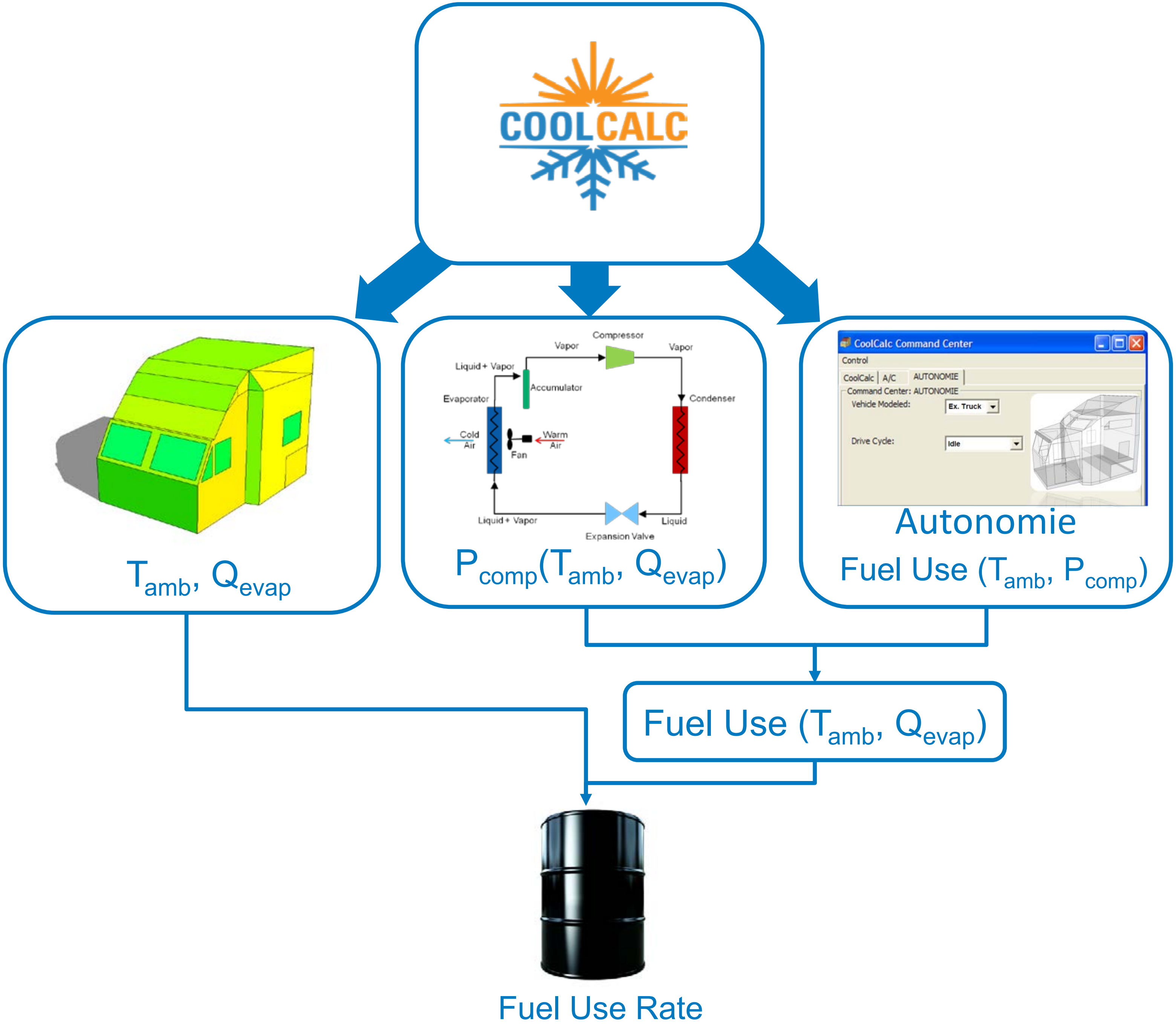

COOLCALC
Compressor
Vapor
Vapor
Liquid + Vapor
Accumulator
Evaporator
Condenser
Cold Air
Fan
Warm Air
Liquid + Vapor
Liquid
Expansion Valve
CoolCalc Command Center
Control
CoolCalc
A/C
AUTONOMIE
Command Center: AUTONOMIE
Vehicle Modeled:
Ex. Truck
Drive Cycle:
Idle
T_{amb}, Q_{evap}
$P_{comp}(T_{amb}, Q_{evap})$
Autonomie
Fuel Use (T_{amb}, P_{comp})
Fuel Use (T_{amb}, Q_{evap})
Fuel Use Rate

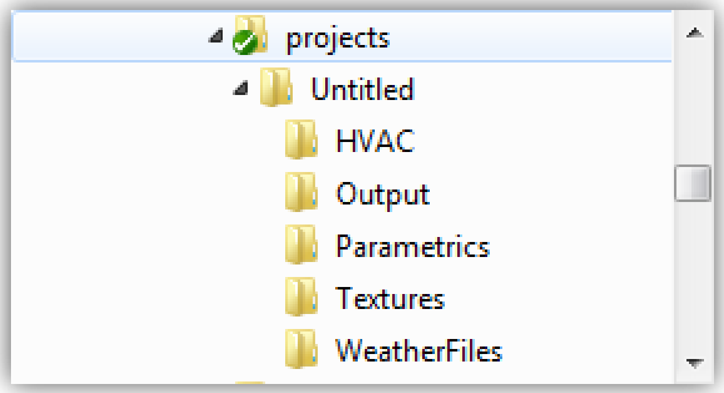
Approach – CoolCab Project Phases

- **Phase I – Baseline Testing and Model Development**
  - Characterize test truck performance as received
  - Calibrate control truck
  - Build and validate CoolCalc models
- **Phase II – Thermal Load Reduction**
  - CoolCalc and A/C model studies
  - Modify vehicle with thermal management technologies
  - Measure impact on temperature and heat loss
- **Phase III – Idle Reduction**
  - Characterize the impact of thermal load reduction technologies on idle reduction systems
  - Measure A/C and heater load reduction
  - Model fuel use impacts over range of operating conditions

Accomplishments – CoolCalc Development

Code Improvements & New Features

- **Improved organization, documentation and stability of source code**
  - Implemented "project-based" file structure
  - Created Bug Tracker for error reporting and new feature suggestions
  - Developed error-submission process



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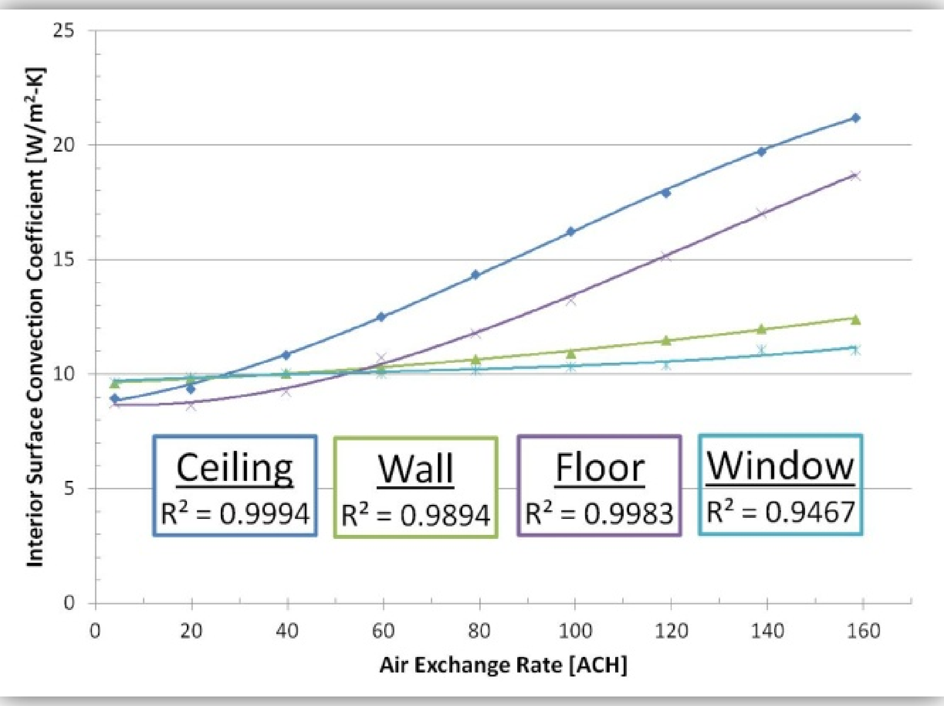
- **Developed and implemented custom interior convection models**
  - Correlations created from CFD simulations for light- and heavy-duty vehicles
  - Separate correlations applied to four surface types: Floor, Wall, Window and Ceiling



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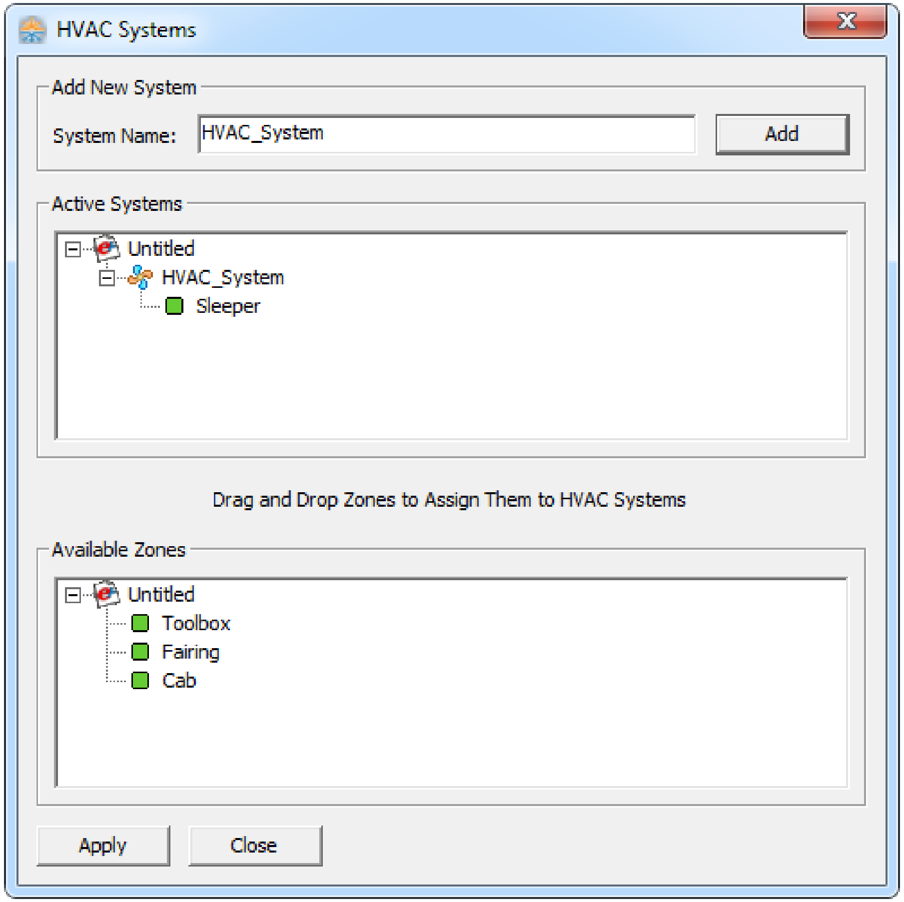
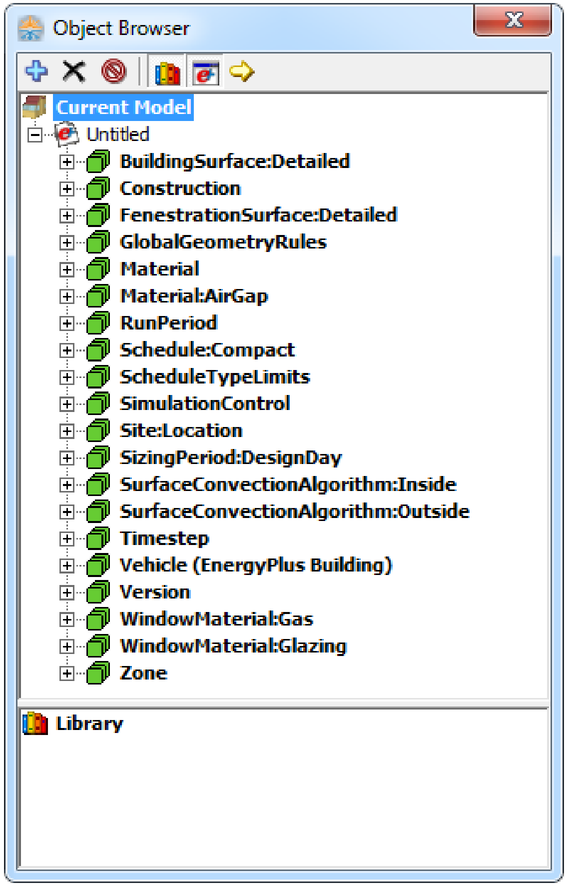
- **Developed and implemented custom interior convection models**
  - Correlations created from CFD simulations for light- and heavy-duty vehicles
  - Separate correlations applied to four surface types: Floor, Wall, Window and Ceiling
- **Default HVAC system and GUI implemented**
  - Reduces development time for new users
  - Heating, air-conditioning or both
  - Apply to any zone (cab or sleeper)



Accomplishments – CoolCalc Development

Code Improvements & New Features

- **Object Browser GUI expanded to cover all EnergyPlus objects**



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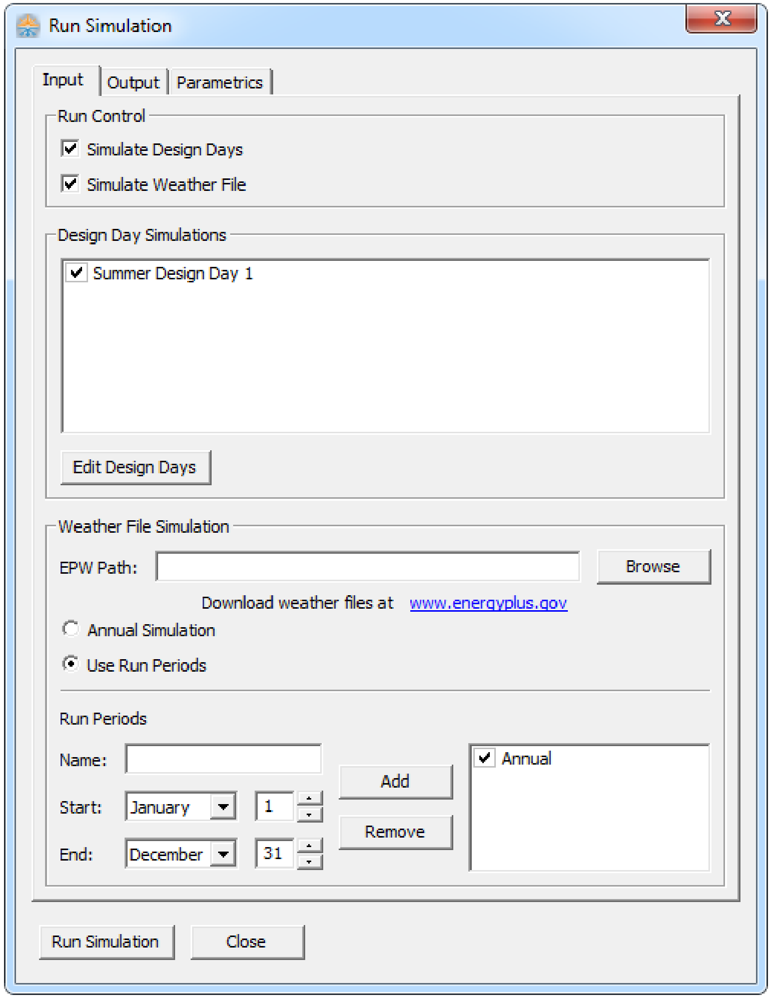
Code Improvements & New Features

- **Object Browser GUI expanded to cover all EnergyPlus objects**
- **Run Simulation GUI was enhanced**
  - Input tab:
    - Control simulations with design days, typical meteorological year (TMY) weather files and run periods



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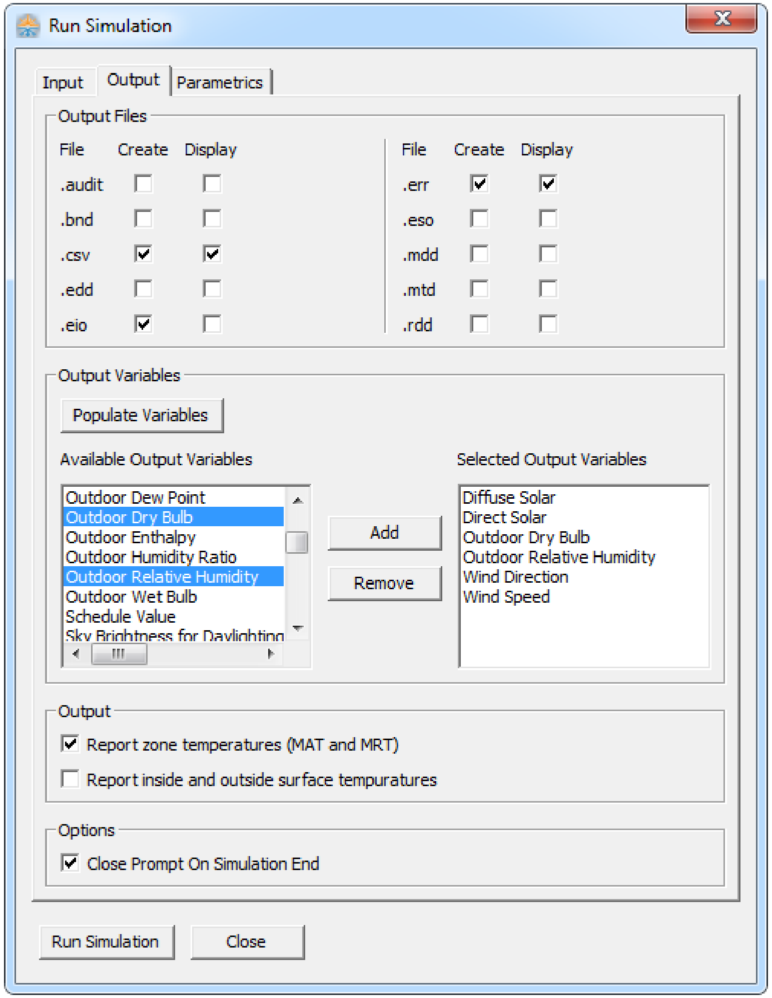

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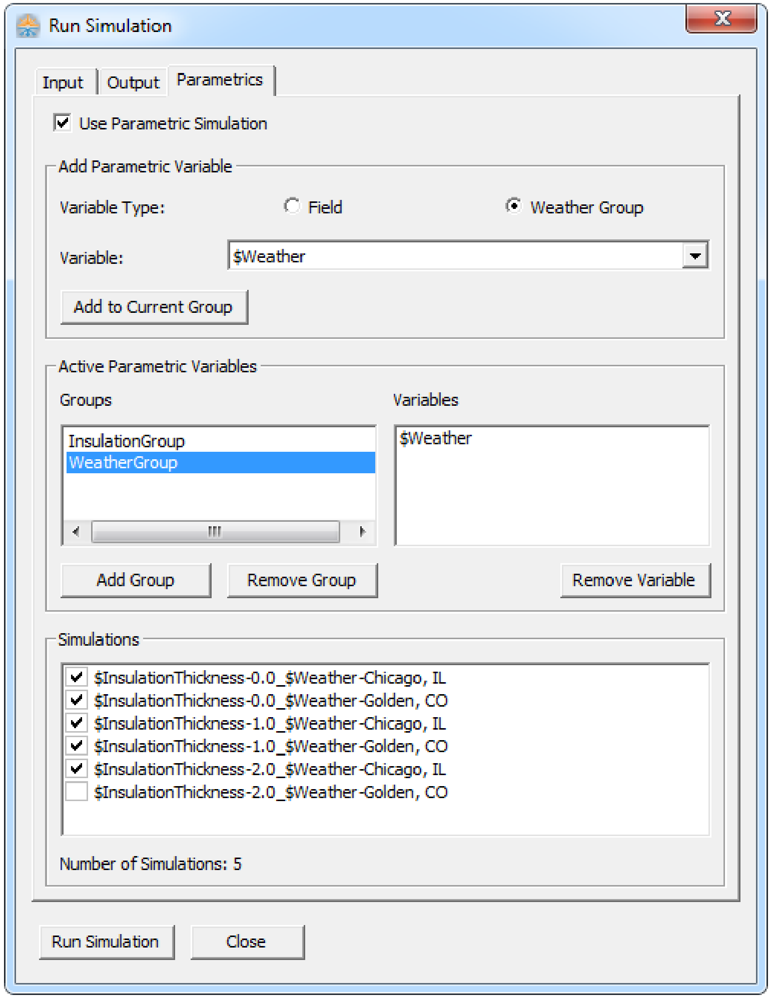
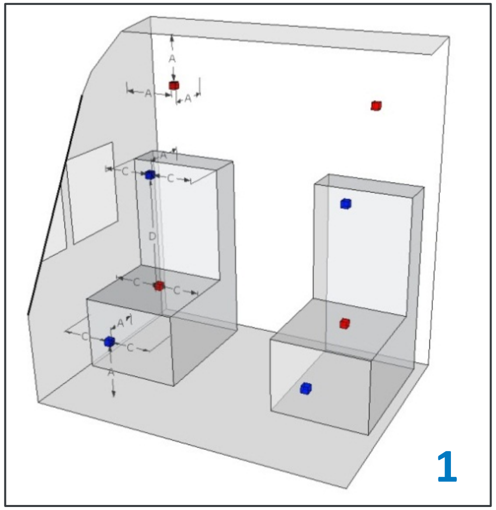
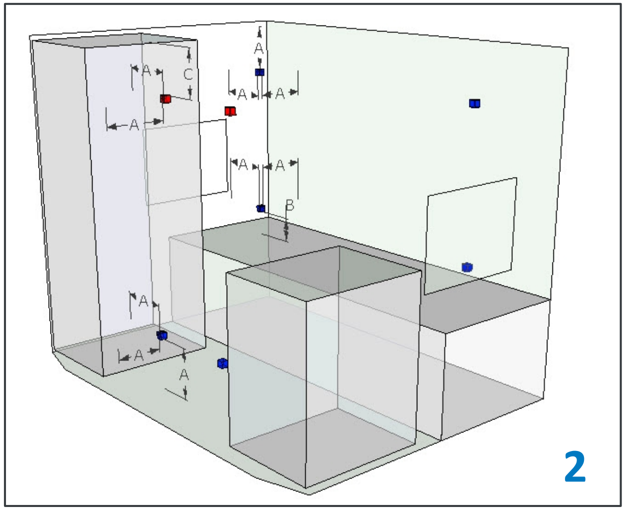
  - Output tab:
    - Populate list of available output variables & custom-define list
    - Select variable groups and control output files
  - Parametrics tab:
    - Access parametric variables defined for object parameters and weather files
    - Setup multi-dimensional (up to full-factorial) parametric simulations to run sequentially



Phase I – 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)





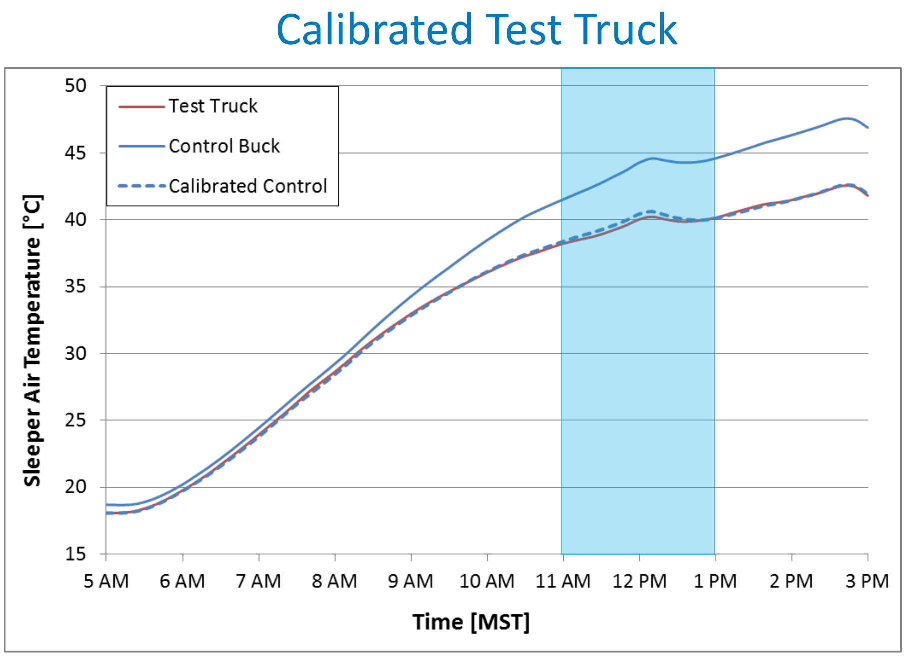
(1) Cab and (2) Sleeper thermocouple locations, dimension A = 12", B = 6", C = 18", blue – TMC standard [5], red – NREL added

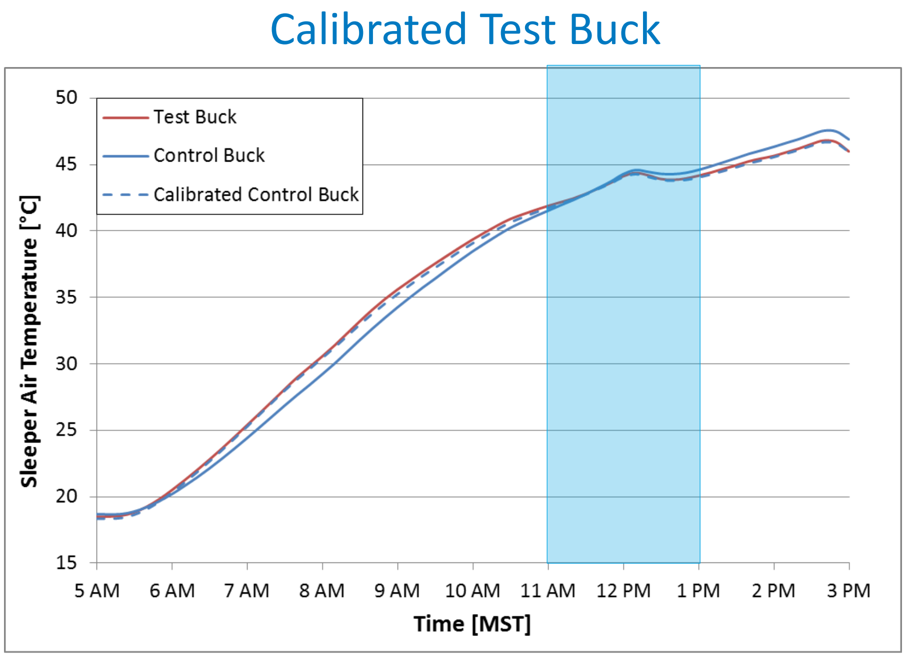
40 thermocouples per vehicle:

- Air and surface locations, following TMC recommended practice with additional locations
- $U_{95} = \pm 0.3°C$

Phase I – Calibration Validation

Test Truck and Test Buck validation indicate high accuracy in calibration routine





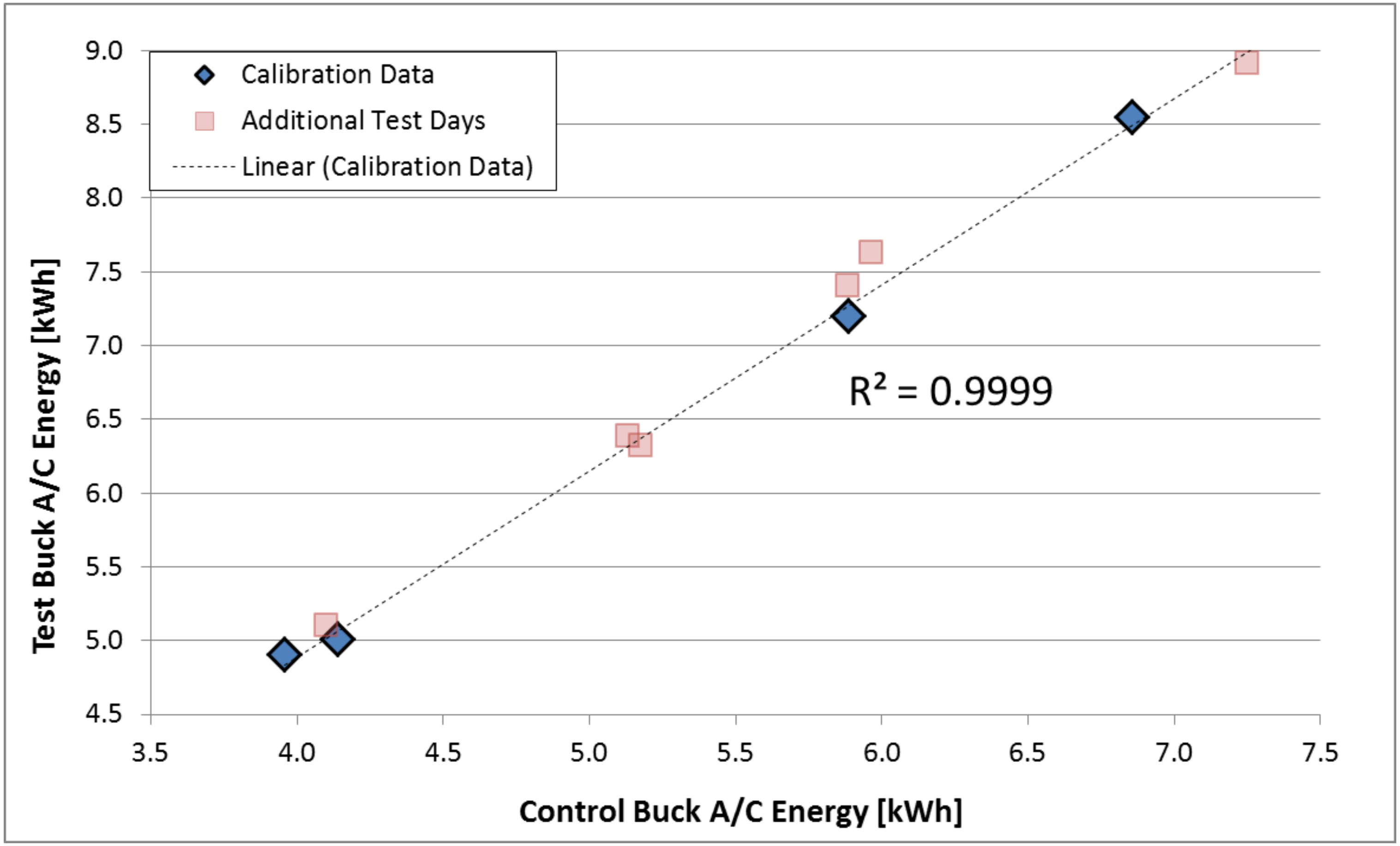
Blue bands indicate periods of peak solar loading (11:00 am – 1:00 pm MST)

For peak solar loading time of 11:00 pm to 1:00 pm

- **Calibrated Test Truck (left): within ± 0.6°C**
- **Calibrated Test Buck (right): within ± 0.4°C**

Phase I – A/C Calibration

Strong correlation between Test Buck and Control Buck A/C loads



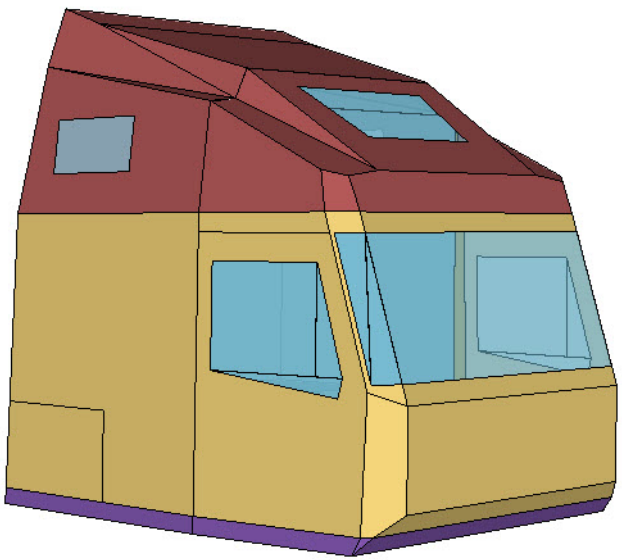
Additional Test Days

- **Partially cloudy weather, not included in calibration**
- **Confirm relationship between two test configurations**

Phase I – CoolCalc Model Development

Developed CoolCalc model based on experimental setup and collected data

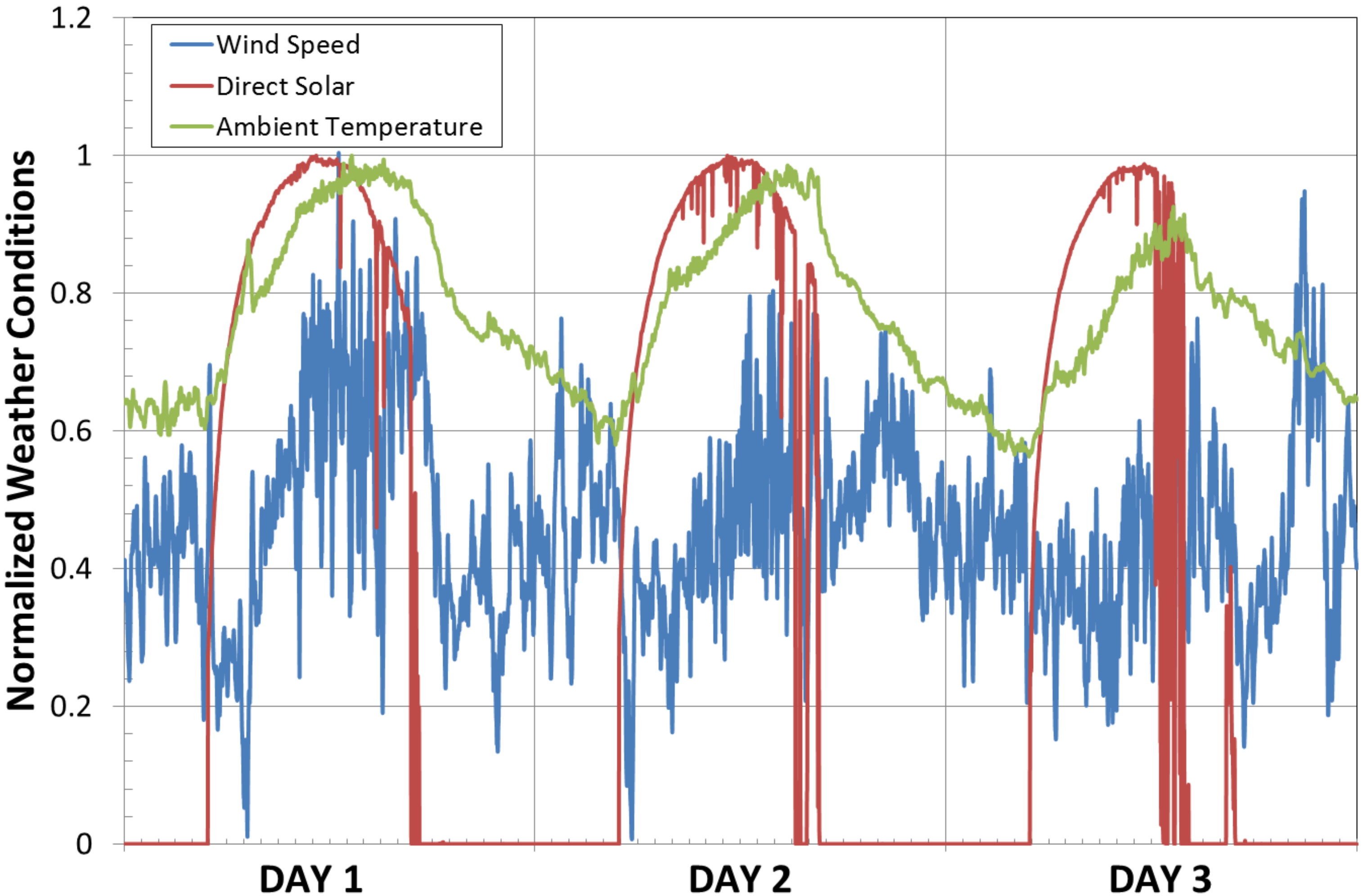
- **Model drawn from CAD geometry**
- **Material properties and wall constructions provided by Volvo**
- **Air infiltration test results and other measured parameters used as model inputs**
- **Simulations used actual weather data**



Phase I – CoolCalc Model Validation

Actual NREL site weather days were used as inputs to the model

Normalized weather conditions for three consecutive thermal soak validation days



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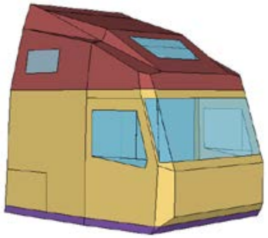
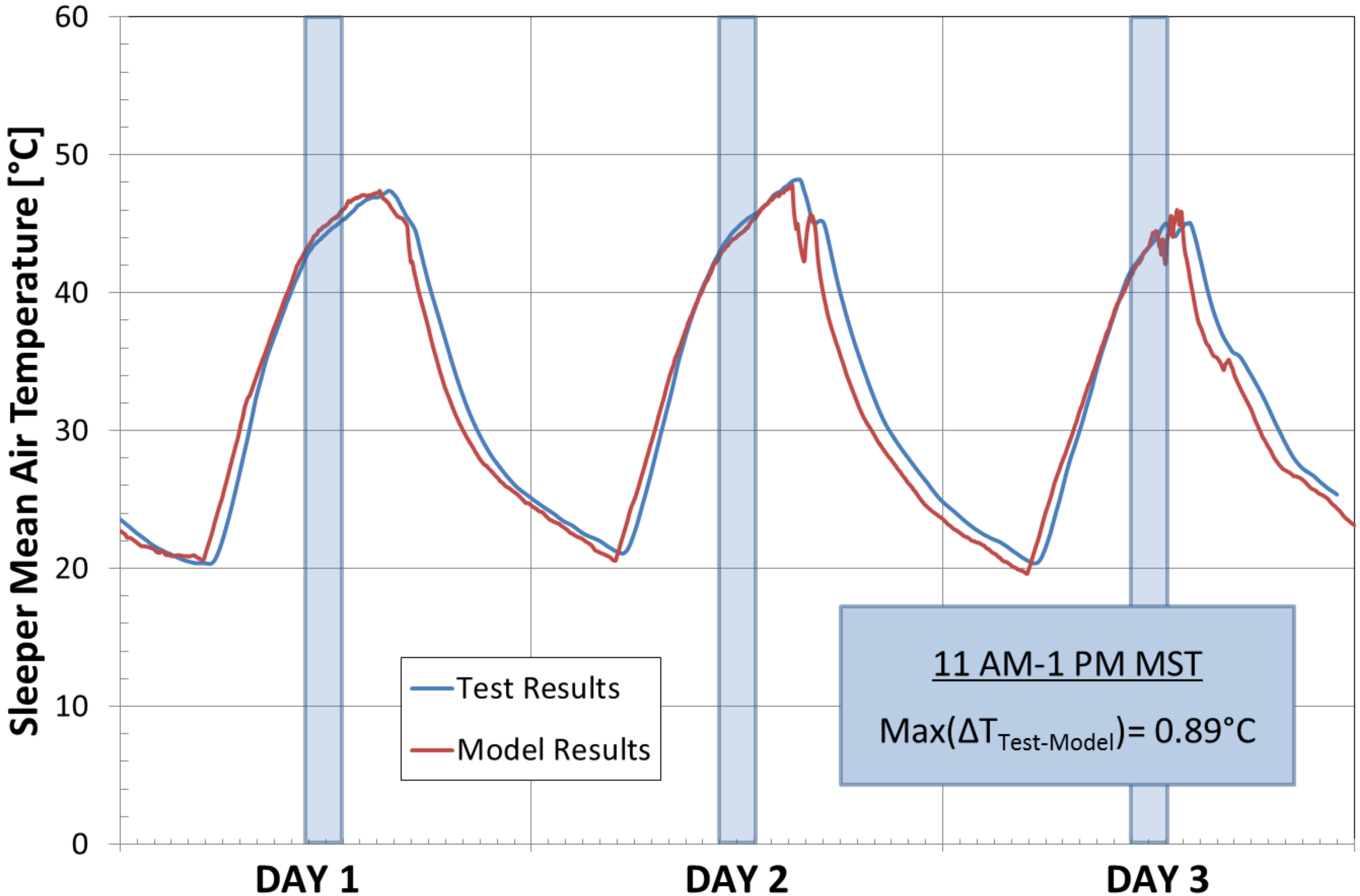
Phase I – CoolCalc Model Validation

Model results closely match test data





Blue bands indicate periods of peak solar loading (11 am - 1 pm MST)

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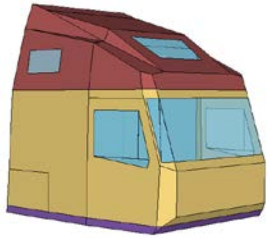
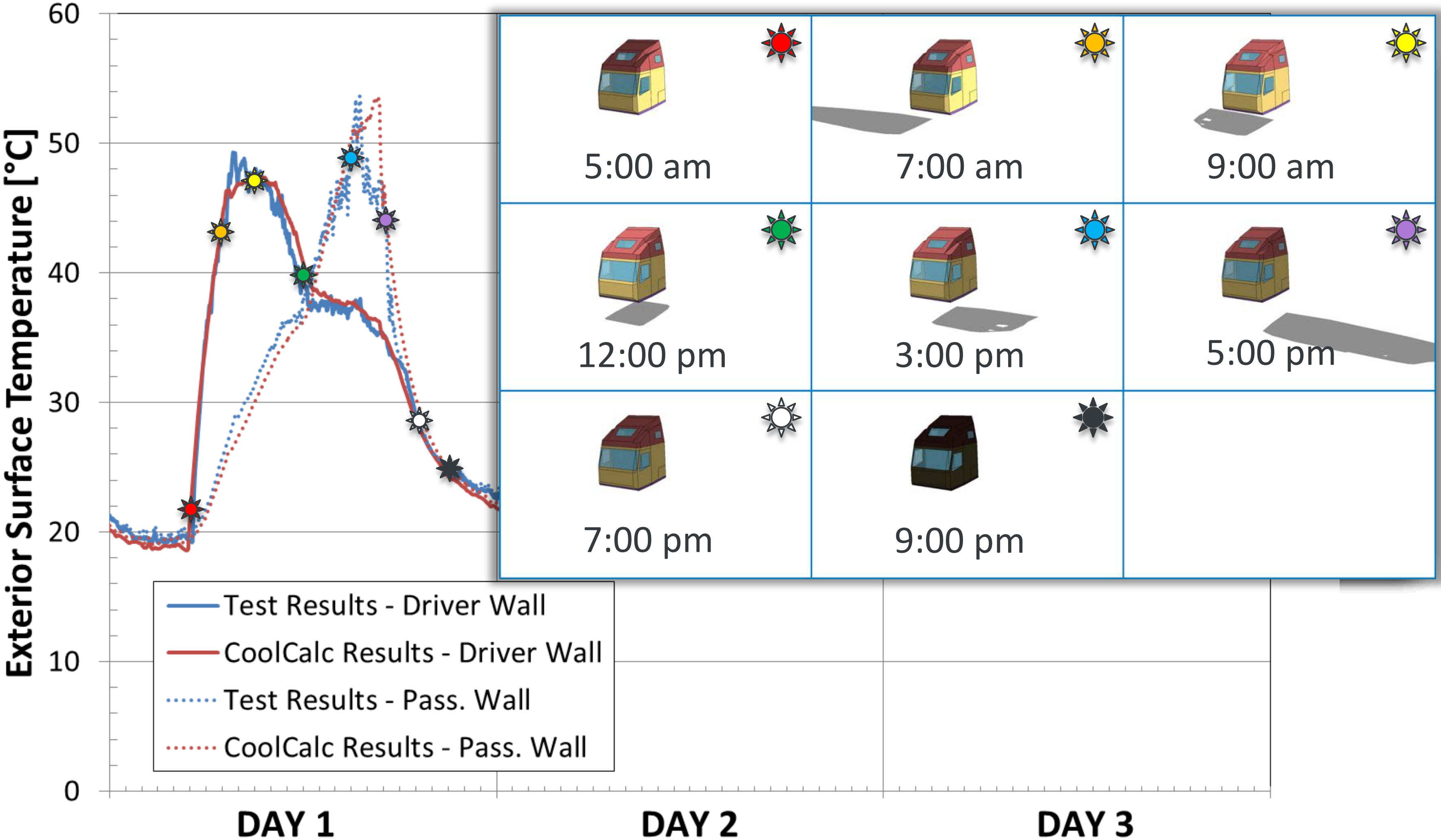
Phase I – CoolCalc Model Validation

CoolCalc tracks the sun and captures diurnal solar impacts

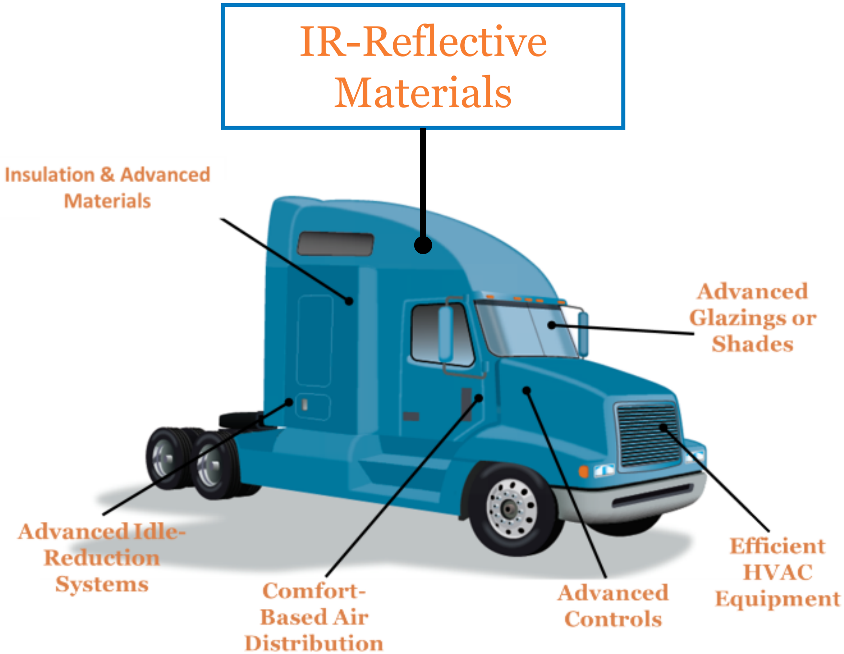




Phase II – Technologies for Evaluation

Opaque surface treatment

- **Evidence from light-duty vehicles**
  - Opaque surface treatment could reduce breath air temperature by 28% of theoretical maximum*
  - A 4°- 6°C reduction in cabin air temperature with a silver car compared to a black car**

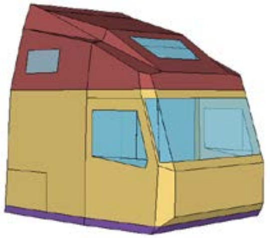


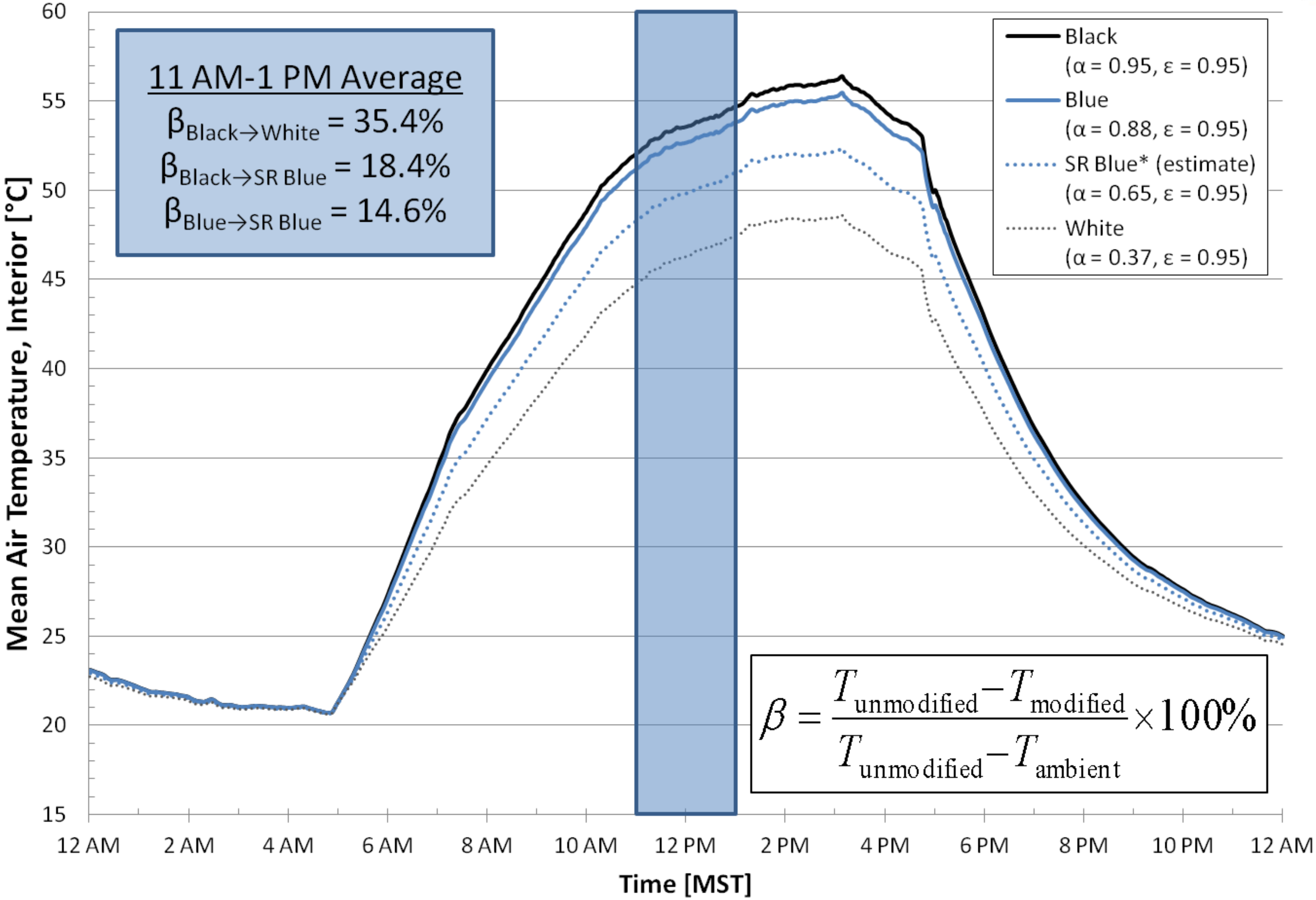
Heavy-Duty		*Light-Duty*		
$\frac{\text{Opaque Surface Area}}{\text{Glazing Surface Area}}$	>	$\frac{\text{Opaque Surface Area}}{\text{Glazing Surface Area}}$	→	***Larger Impact***

* Rugh, J., Farrington, R. *Vehicle Ancillary Load Reduction Project Close-Out Report*, National Renewable Energy Laboratory, NREL/TP-540-42454, January 2008.
** Levinson, R., Pan, H., Ban-Weiss, G., Rosado, P., Paolini, R., Akbari, H. "Potential benefits of solar reflective car shells: Cooler cabins, fuel savings and emissions," *Applied Energy*, 2011, 88, 4343-4357.

Phase II – CoolCalc Absorptivity Study

Validated CoolCalc model used to predict impact of paint absorptivity





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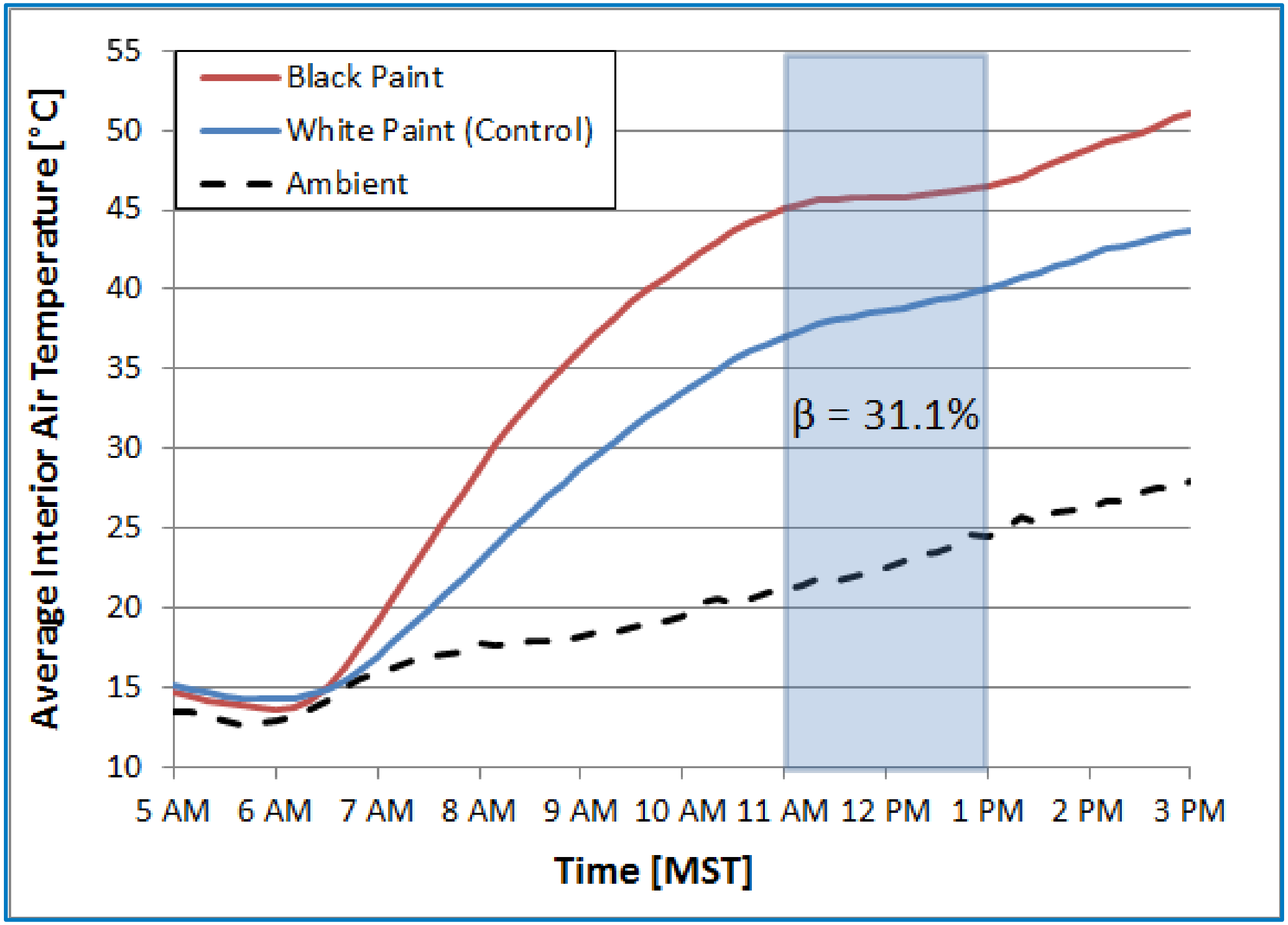
Phase II – Thermal Soak Testing

31% of maximum air temperature reduction from a black to white colored cab



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

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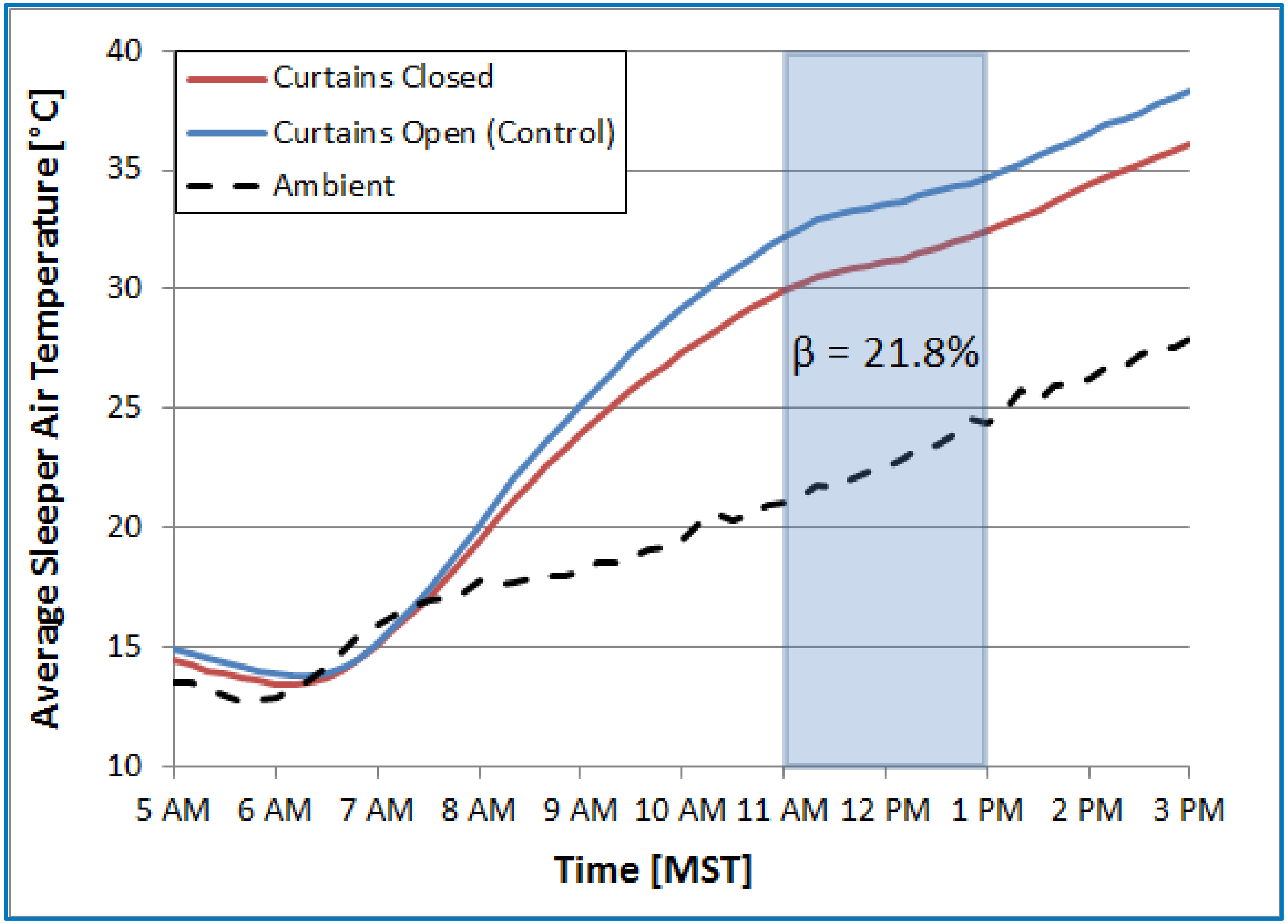
Phase II – Thermal Soak Testing

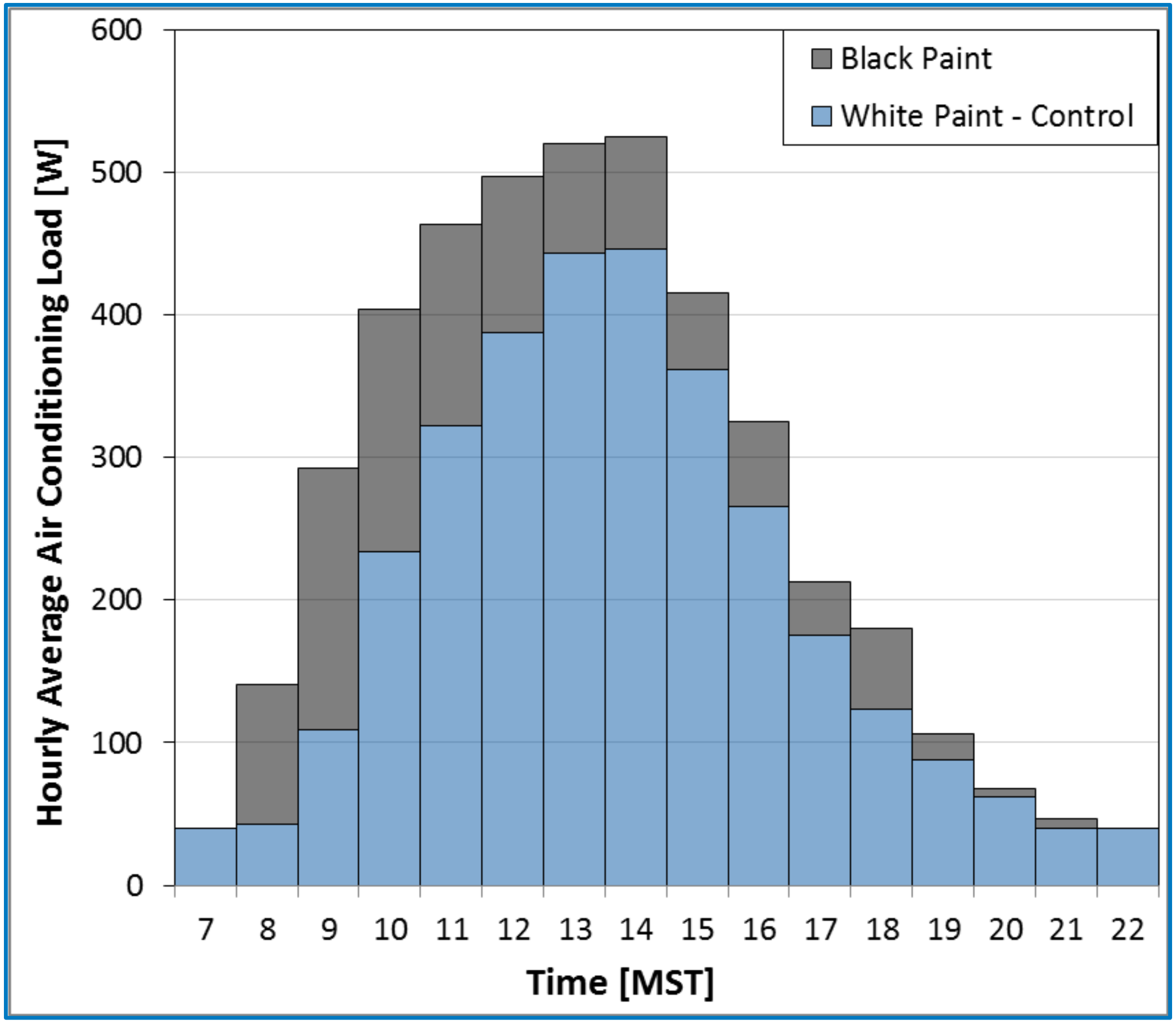
Using all curtains, measured a 21.8% of maximum possible sleeper air temperature reduction



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

Phase III – A/C Power Consumption

20.8% reduction in daily A/C system energy switching from a black colored cab to white



Two day average

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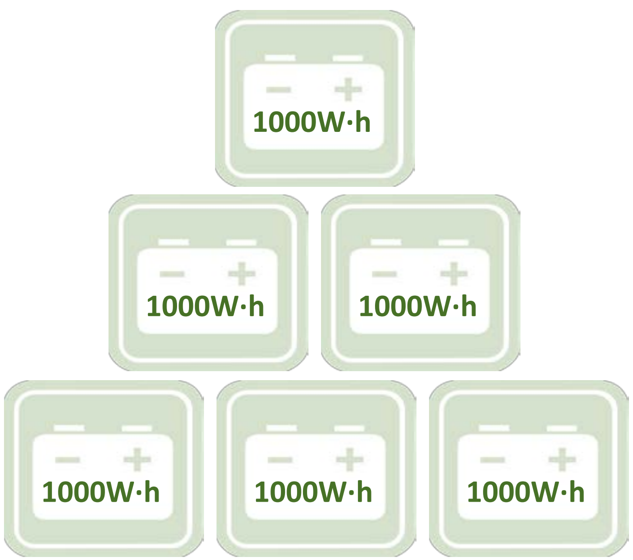
Phase III – A/C Battery Evaluation

16.7% reduction in A/C battery capacity & 22 kg weight reduction with no additional cost

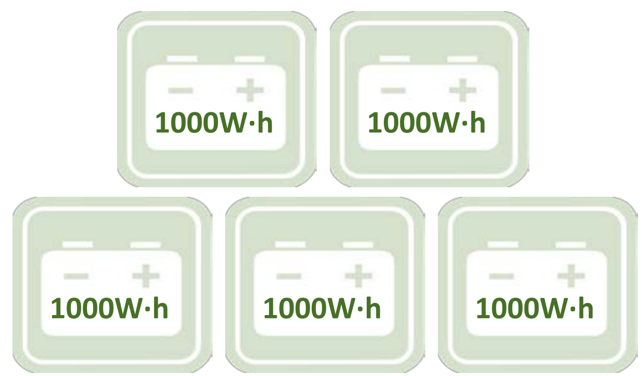
20.8% reduction in daily A/C power consumption translates to:

- **1001 W·h battery energy savings over the daytime test period**
- **16.7% reduction in battery capacity**
- **22 kg reduction in battery pack weight**

Standard System Battery Pack



Reduced A/C Load Battery Pack



Fuel Use Estimation Methodology

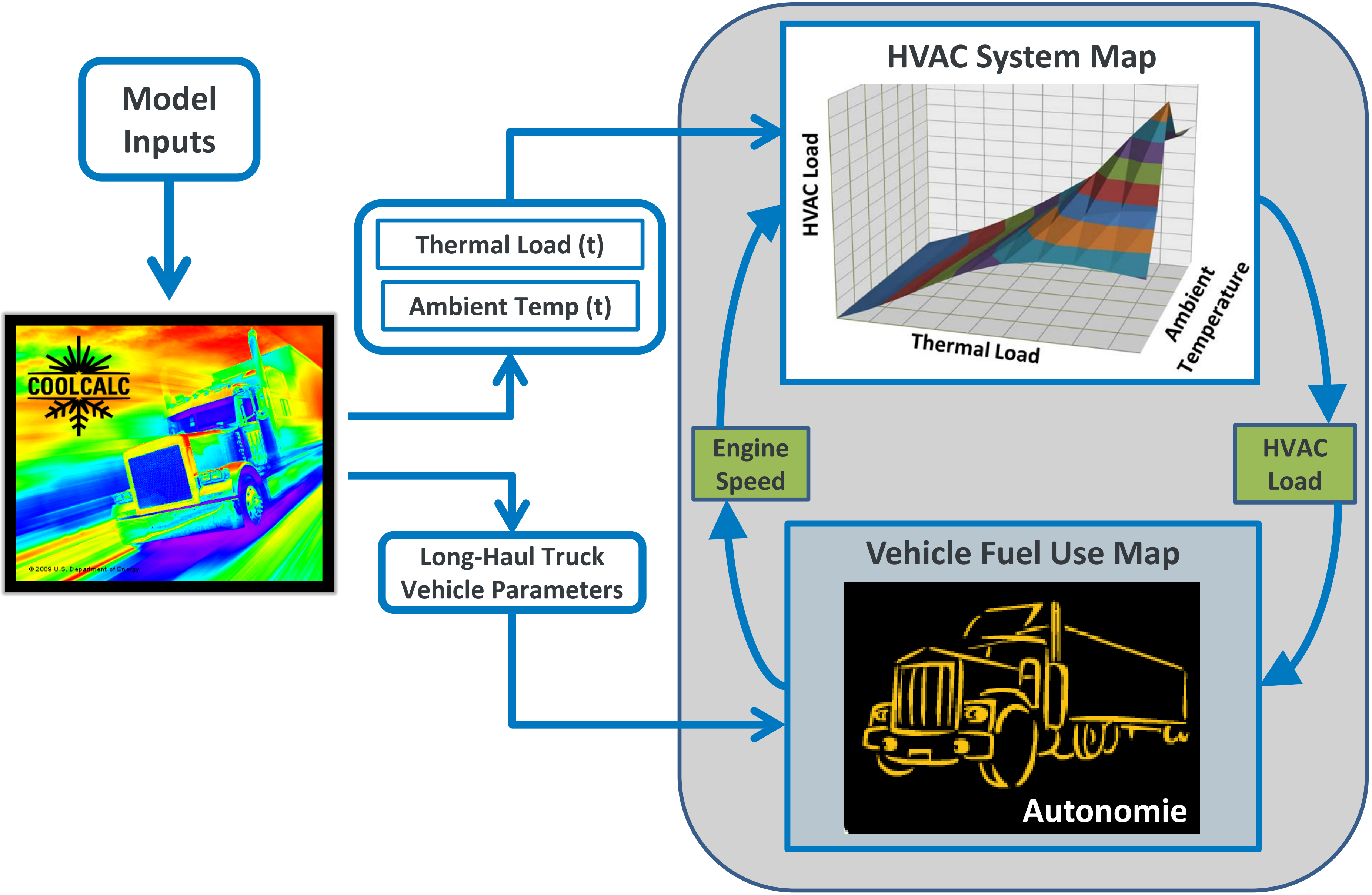
Model Inputs

Thermal Load (t)

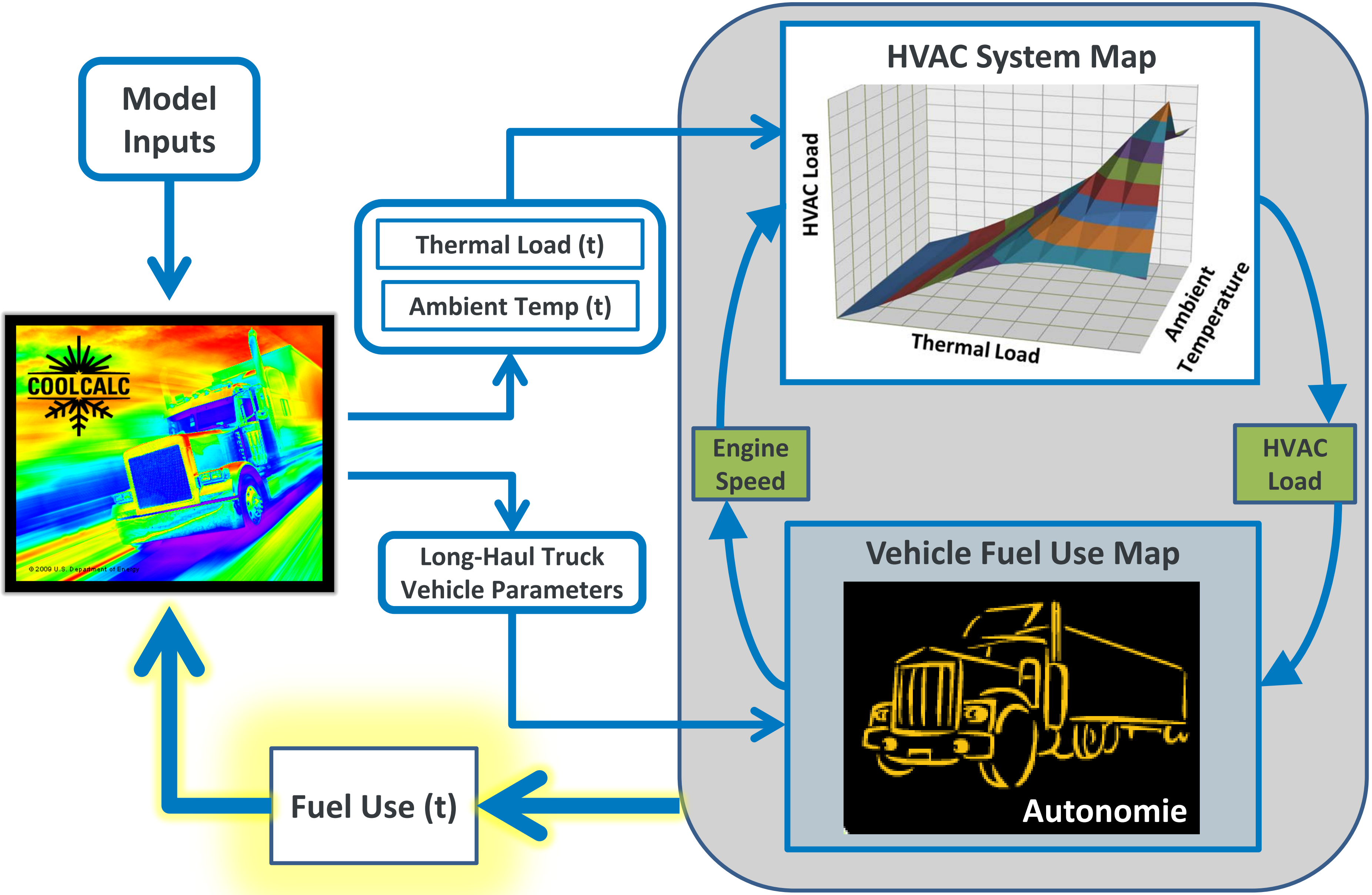
Ambient Temp (t)

Long-Haul Truck Vehicle Parameters

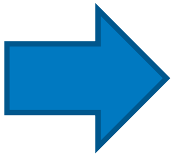
Fuel Use Estimation Methodology

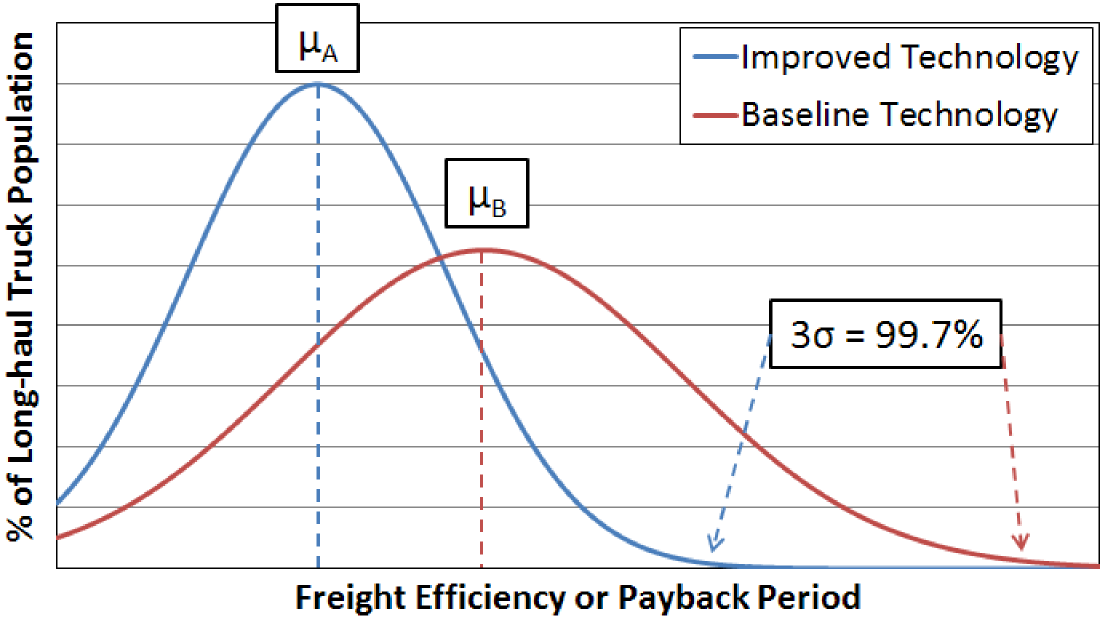


Fuel Use Estimation Methodology



Fuel Use Estimation Methodology



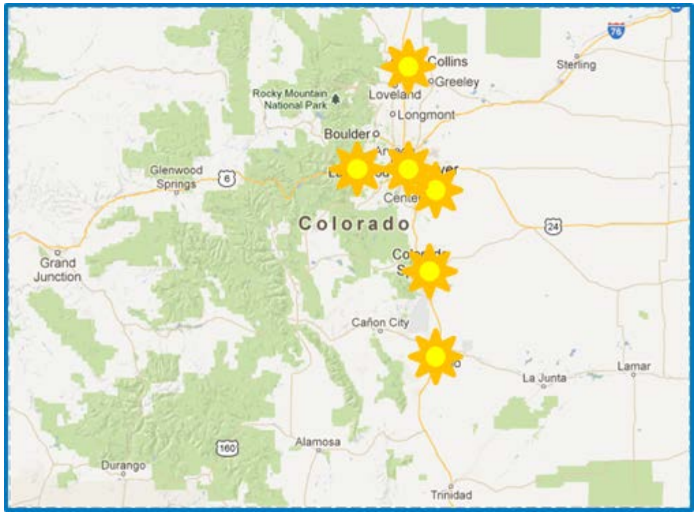


Overview | Approach | Accomplishments | Future Work | Summary

Fuel Use Estimation: Example Application

Understanding use distribution is crucial for systems design

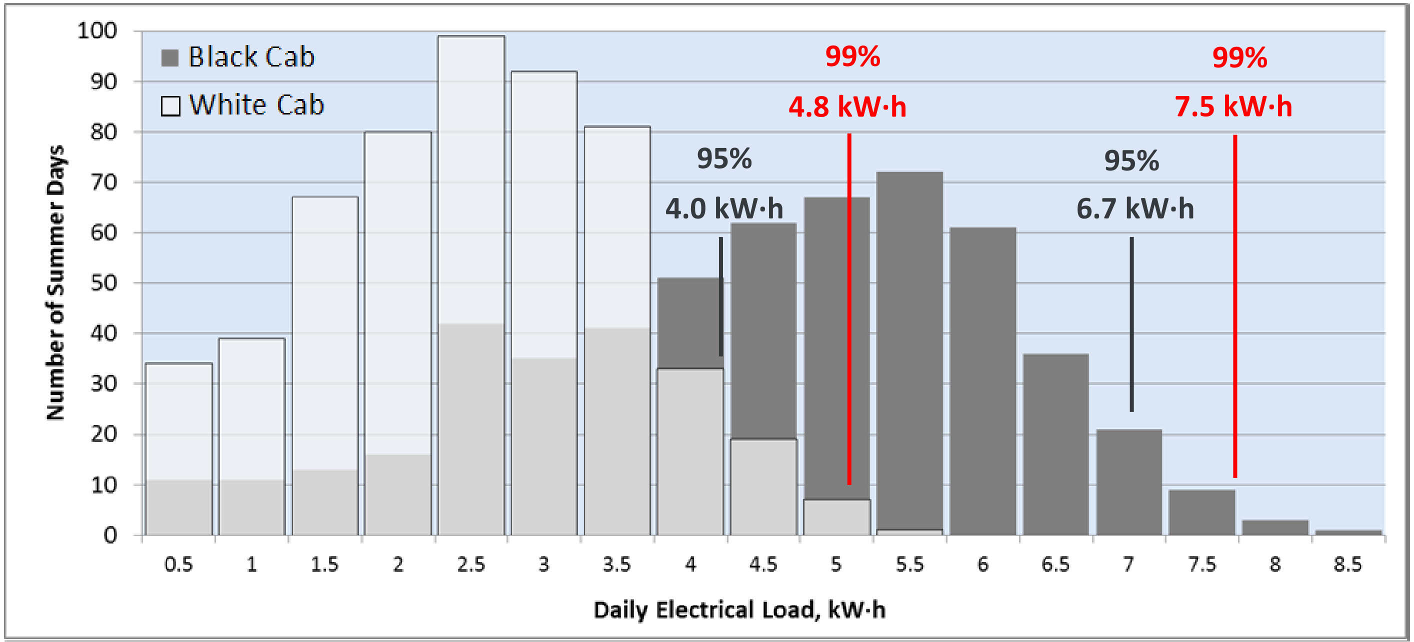
Map of Colorado TMY Data



Sleeper A/C System Battery Sizing

Design Criteria:

- Colorado TMY summer, June – August
- Average of six major Colorado cities
- Cab paint color, black versus white
- Size batteries for 95% versus 99% of days



Fuel Use Estimation, Next Steps 2013

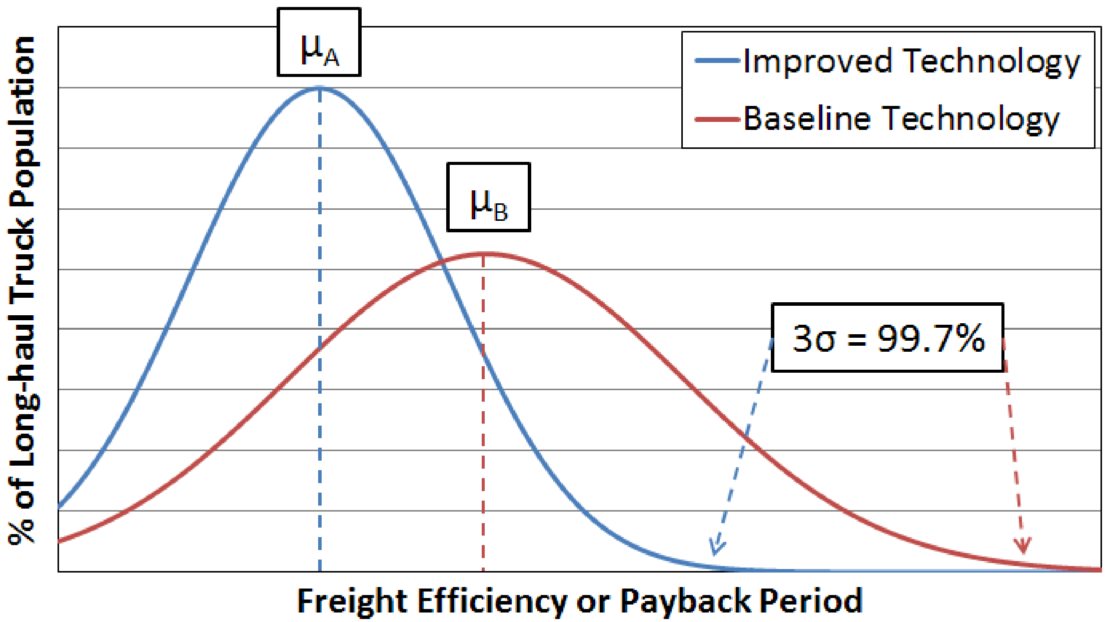
National level analysis required for accurate technology evaluation

- **Incorporate vehicle model for HVAC load -> Fuel Use**
- **Expand to national level climate evaluation**
- **Apply driver work behavior statistics**

50 most populated US cities

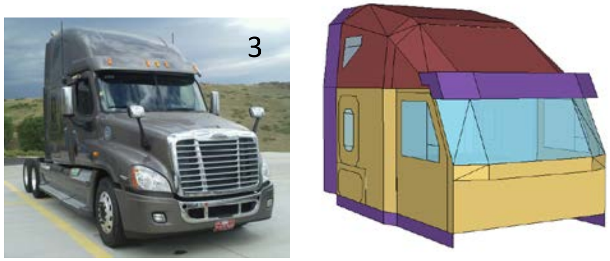
End Result:

National level fuel use and payback period estimations for load reduction technologies



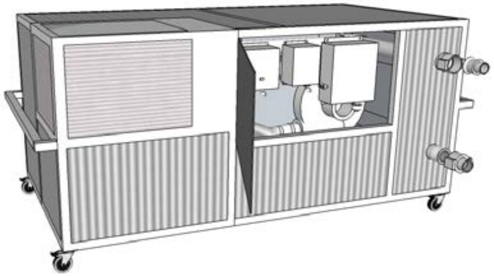
Collaboration

- 21st Century Truck Partnership
- Kenworth
  - Fully instrumented and tested for thermal-load measurements
  - Developed, validated, and released CoolCalc model
- Volvo Trucks
  - Completed thermal testing
  - Developed and validated CoolCalc model,
  - CoolCalc model application in progress
- Daimler Truck, Super Truck Program
  - Completed thermal testing of Super Truck
  - Developed and validated CoolCalc model
- Oshkosh Truck
  - CoolCalc Beta testing
  - CoolCalc modeling
- PPG Industries
  - Evaluated advanced paint technology
- 3M Renewable Energy Laboratory
  - Evaluated solar reflective film
- Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems
  - Evaluated insulation packages
- Dometic Environmental Corporation
  - Evaluated electric A/C system



Proposed Future Work

- **FY13**
  - Test advanced climate control load reduction technologies with an emphasis on advanced controls and thermal comfort, leveraging new capabilities
  - 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
  - Release new version of CoolCalc to industry partners
- **FY14**
  - Bring together knowledge and tools to develop and demonstrate full cab thermal design concepts to meeting project goal
  - Improve capabilities and use CoolCalc to assist with fuel use and payback-period driven design



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
    - Improvements to capabilities and robustness, released to partners
    - Used CoolCalc to inform testing
    - Developed process for fuel use driven design
  - Truck Testing
    - Paint color, black to white
      - 31% of maximum air temperature reduction
      - 20.8% reduction in daily A/C system energy
      - 16.7% reduction in A/C battery capacity & 22 kg weight reduction with no additional cost
    - Encouraging modeling results for solar reflective paint
    - 21.8% of maximum possible sleeper air temperature reduction using curtains

- **Collaborations**
  - Volvo Trucks – testing, analysis, and CoolCalc model development
  - Daimler Trucks – supported Daimler's Super Truck program through testing and analysis
  - Kenworth Truck – extended Cooperative Research and Development Agreement (CRADA), CoolCalc beta testing
  - Oshkosh Corporation – CoolCalc beta testing and application
  - PPG Industries – tested paint impacts, looking at advanced paint in spring
  - Dometic Corporation's Environmental Division– evaluated no-idle, battery-powered A/C system
  - 3M – evaluated solar reflective film technology
  - Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems – tested commercial and advanced insulation packages

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Contacts

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

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Image References

- **Slide 1**
  1. Photograph of NREL’s Vehicle Test Pad (VTP), NREL photographer Dennis Schroeder, 2011
- **Slide 3**
  1. Photograph of Volvo truck, Ken Proc, 2009
- **Slide 5**
  1. Test vehicles, Matt Jeffers, 2012
  2. Truck picture, NREL Image Gallery, 14180
- **Slide 6**
  1. Photograph of Kenworth truck, Ken Proc, 2009
  2. Aerial photograph of VTP, Travis Venson, 2011
  3. Photograph of Volvo truck, Travis Venson, 2010
  4. Photograph of Freightliner truck and Volvo test bucks, Travis Venson, 2012
- **Slide 9**
  1. Photograph of VTP, NREL photographer Dennis Schroeder, 2011
- **Slide 11**
  1. Photograph of trucks on VTP, Ken Proc, 2009
  2. Thermal image, Travis Venson, 2010
  3. Photograph of electric A/C system courtesy of Dometic, 2011
- **Slide 19**
  1. Photograph of Volvo truck, Travis Venson, 2011
  2. Test vehicles, Matt Jeffers, 2012
- **Slide 22**
  1. Photograph of test bucks, Matt Jeffers, 2012
- **Slide 28**
  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 29**
  1. Photograph of test vehicles, Cory Kreutzer, 2012
- **Slide 38**
  1. Photograph of Kenworth truck, Ken Proc, 2009
  2. Photograph of Volvo truck, Travis Venson, 2010
  3. Photograph of Daimler truck, Travis Venson, 2011
  4. Aerial photograph of VTP, Travis Venson, 2011
- **Slide 41**
  1. Daimler Super Truck Logo, Courtesy of Daimler Trucks, 2011
- **Slide 42**
  1. Photograph of VTP, NREL photographer Dennis Schroeder, 2011