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: 90%

Barriers

- **Risk Aversion** – *Industry lacks key performance data on* heating, ventilation, and air conditioning (*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.*

Budget

Total Project Funding:
(CoolCab/CoolCalc)
DOE Share: **$1,510K/$915K**
Contractor Share: **$500K***

Funding Received in FY14: $450K/$300K

Funding for FY15: $400K/$300K

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

Partners

- Collaborations
  - Volvo Trucks
  - Daimler Trucks (SuperTruck)
  - Kenworth (PACCAR)
  - PPG Industries
  - Aearo Technologies LLC, a 3M Company
- Project lead: National Renewable Energy Laboratory (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

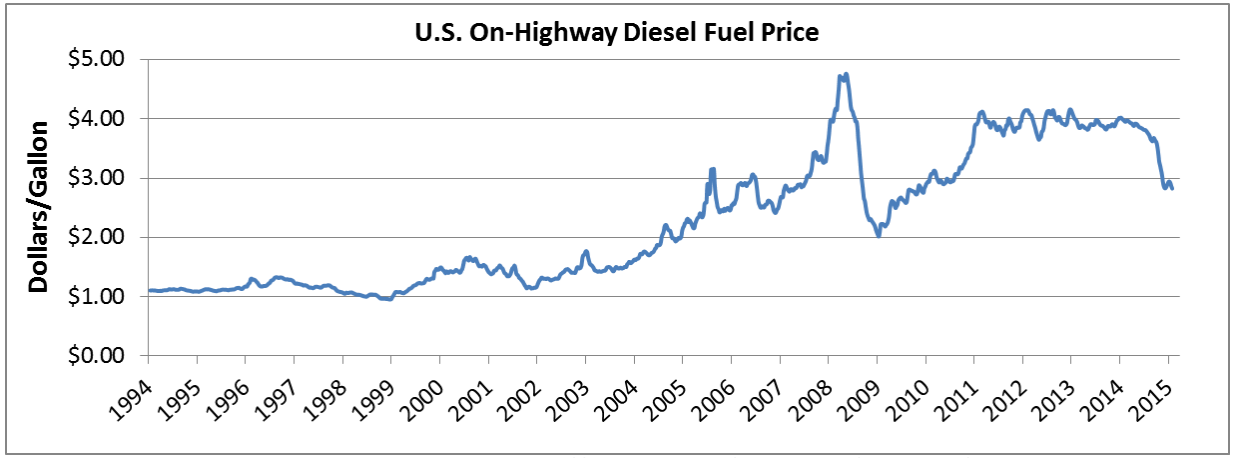
THE OPPORTUNITY

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

ALIGNMENT WITH DOE

- Support Vehicle Systems Simulation and Testing (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 2015

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.

*SMART – Specific, Measurable, Achievable, Realistic, and Timely

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 quantify fuel savings.**

Advanced Insulation — M1


[1]

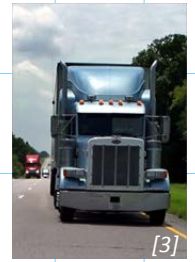
Solar Reduction: Paints, Films, Glazing — M2


[2]

Conditioned Volume Management — M3

Cab Design Demonstration — M4

Quantify Fuel Savings — M5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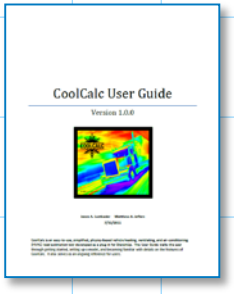
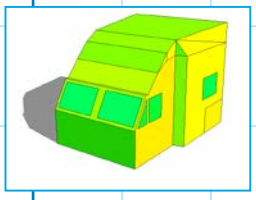
CoolCalc

M1. Write user guide and prepare 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.

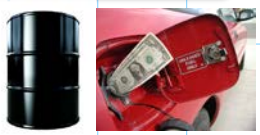
Initial Release — M1



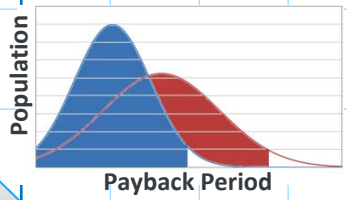
Full Modeling Process, Release — M2



National-Level HVAC Analysis — M3

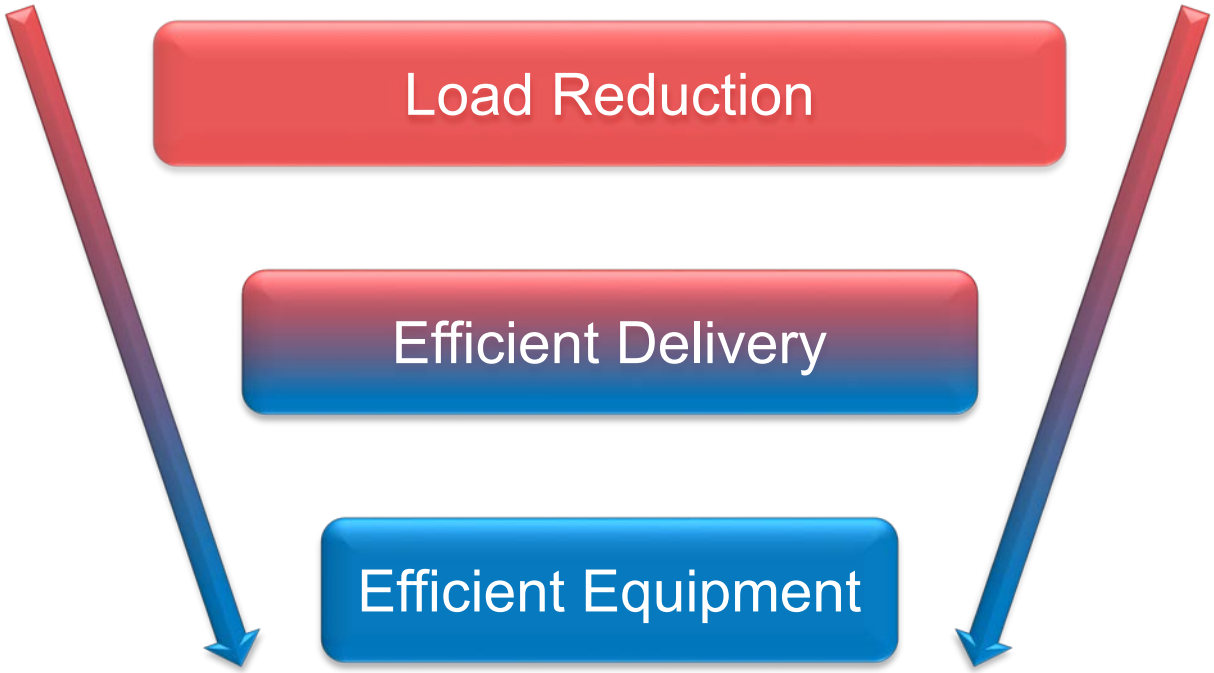


Fuel Use and Payback — M4



Fuel Use Driven Design — M5

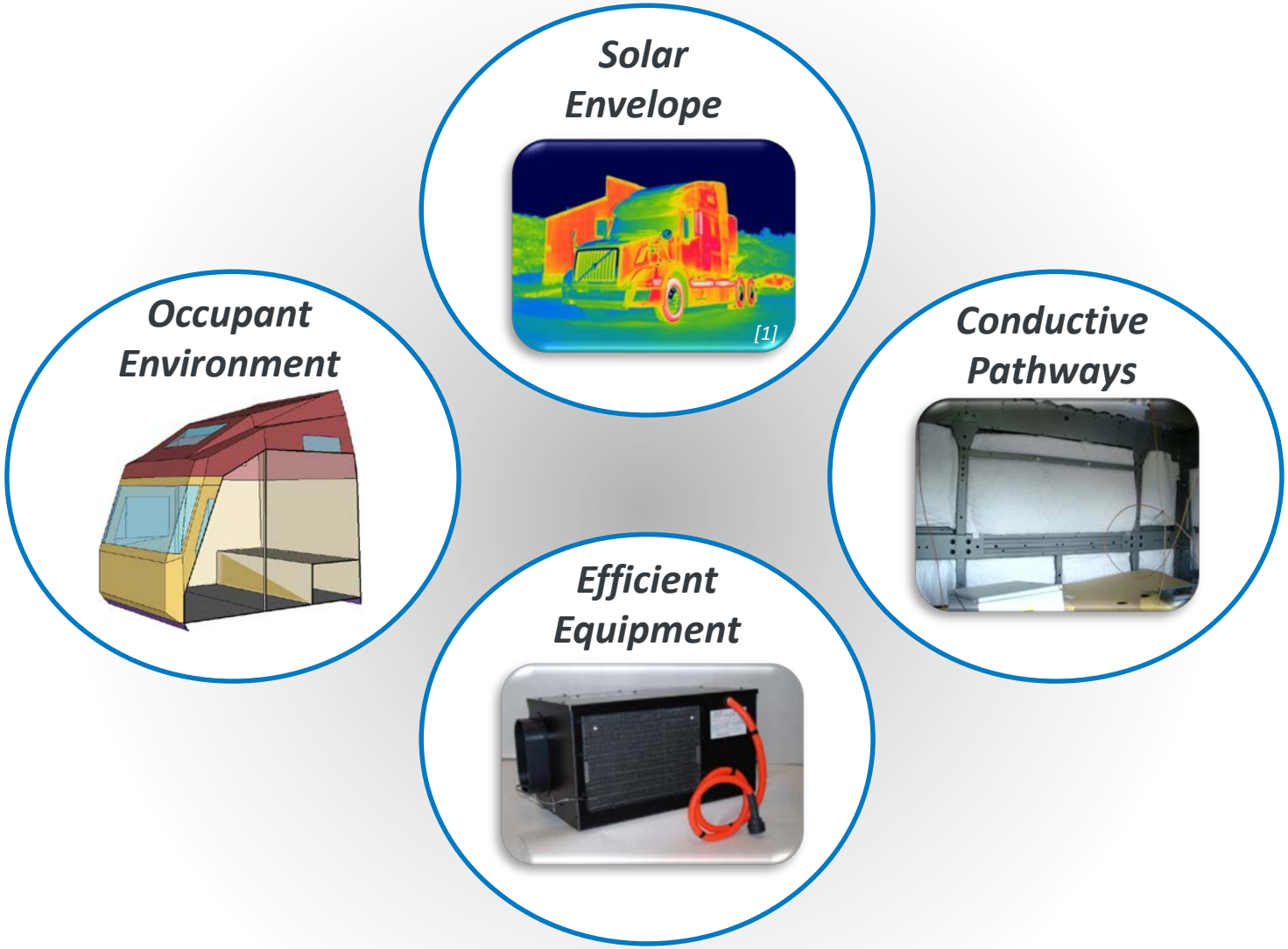
Approach – System Level



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

Approach – Overall Strategy

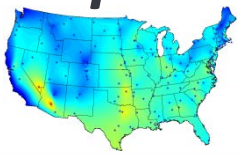
Technology Focus Areas



Approach – Overall Strategy

Modeling

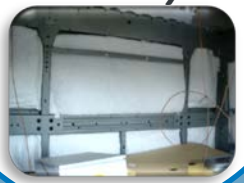
Impact



Solar Envelope

Occupant Environment

Conductive Pathways



Efficient Equipment

Testing

Industry Collaboration

Approach – Advanced Technologies

Conductive Pathways

Solar Envelope

Occupant Environment

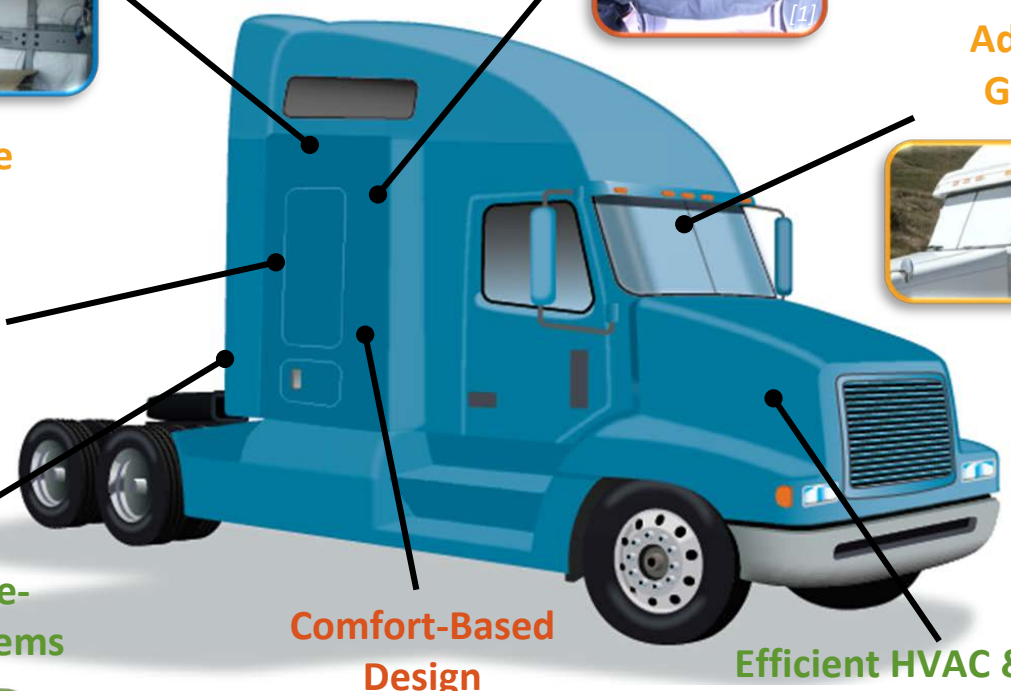
Efficient Equipment

Insulation & Advanced Materials

Curtains & Shades

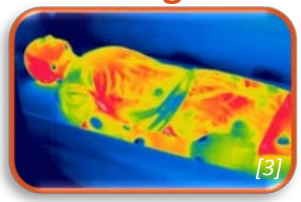
Advanced Glazings

Opaque Surface Treatment



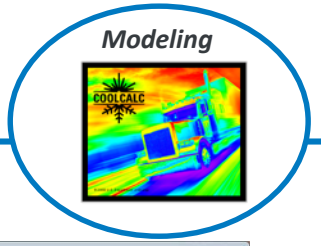
Advanced Idle-Reduction Systems

Comfort-Based Design



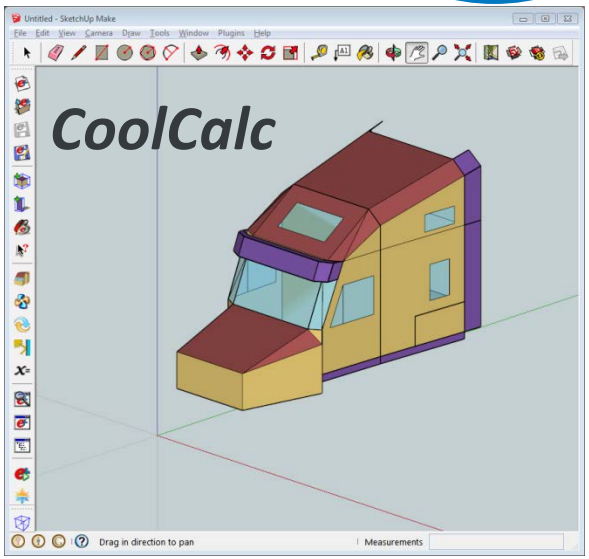
Efficient HVAC & Controls

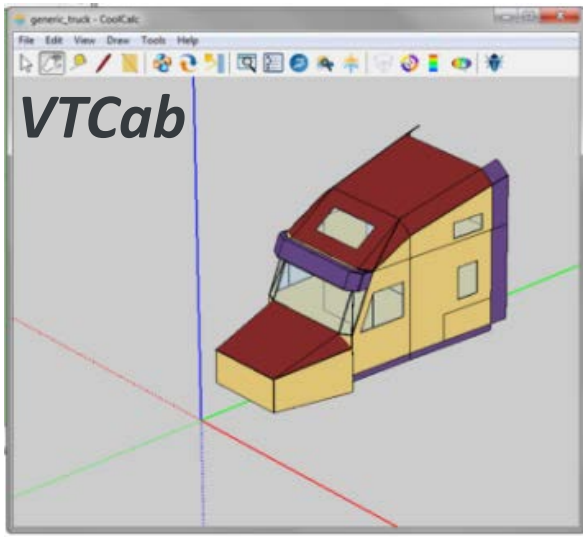
VTCab: Stand-Alone Version of CoolCalc



Existing Limitations to CoolCalc

- Dependence on SketchUp interface and updates
- Dependence on EnergyPlus thermal solver
- Three-component installation process.

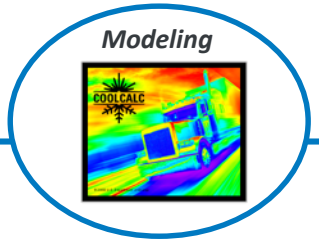




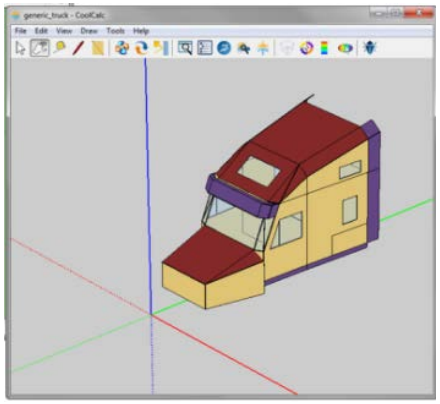
Advantages of VTCab over CoolCalc

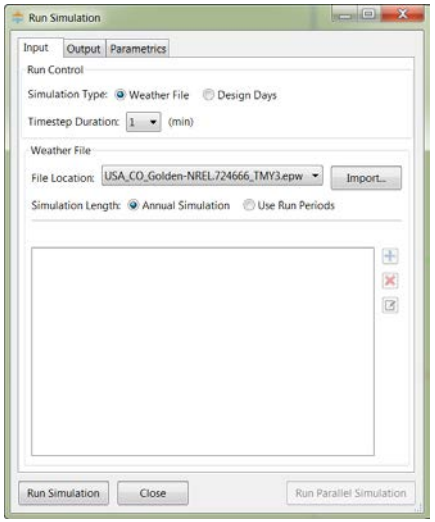
- Stand-alone execution
- Additional programming flexibility
- Model-specific tools only
- Bundle with EnergyPlus into one installer
- Ability to move to MATLAB/Simulink solver.

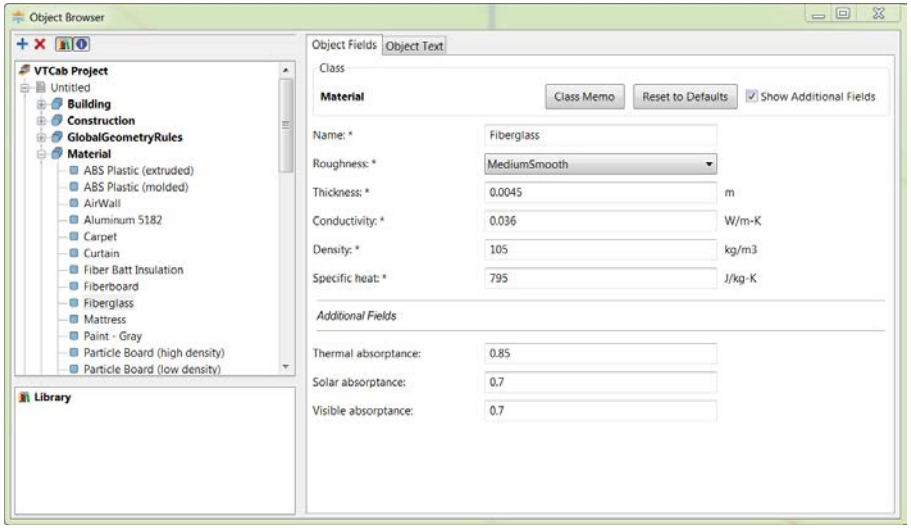
VTCab Development



- Integrated with EnergyPlus Version 8.1
- Implemented rendering for vehicle models—visual display, rotation, panning, zooming
- Object Browser to add, edit, or delete EnergyPlus objects
- Run Simulation window refactored and implemented with enhanced stability
- File structure design was refactored and implemented
- COLLADA (.dae) importer
- Developed and validated generic truck model

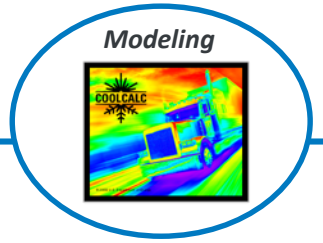


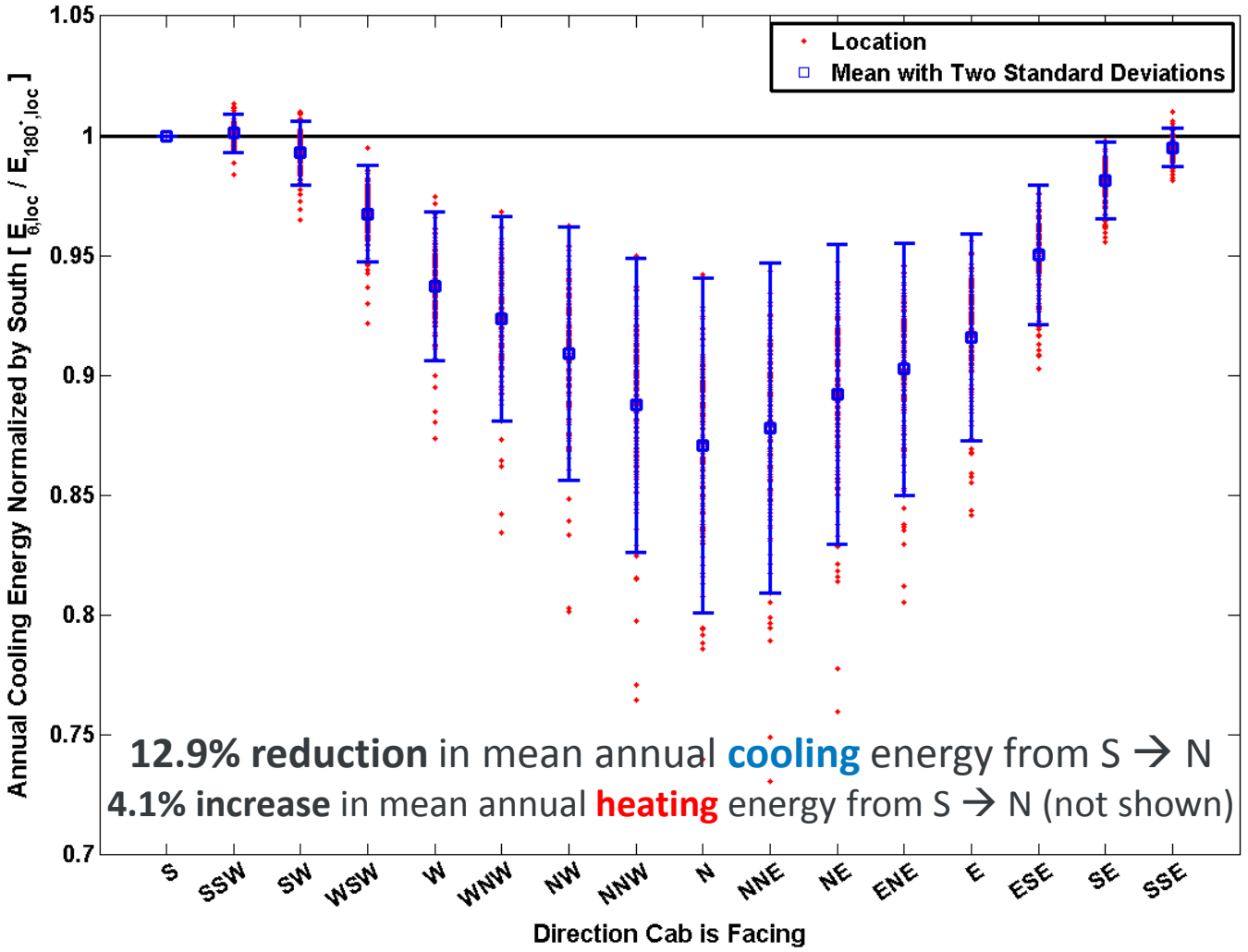




Technology Screening for Experimentation

Orientation Study—Potential for Significant Load Reduction





- National-level analysis using 48 contiguous United States
- Reference climate control set-point of 25°C (77°F).

Prior Accomplishment: Experimental Technology Screening

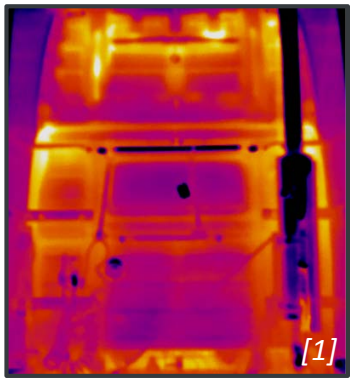
Prior Work Suggests Insulation, Paint, and Curtains for Complete Cab

Insulation

Insulation Package Evaluations

Heating Testing: 26%–36% reduction

A/C Testing: 20%–34% reduction


[1]


[2]

Paint

Paint Evaluations—A/C Testing

Black to White: 20.8% reduction

Blue to SR Blue: 7.3% reduction

Curtains & Shades

Idealized Sleeper Curtain

A/C Testing: 12.7% reduction

Idealized Glazings Film

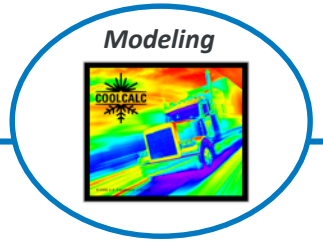
A/C Testing: 13.3% reduction

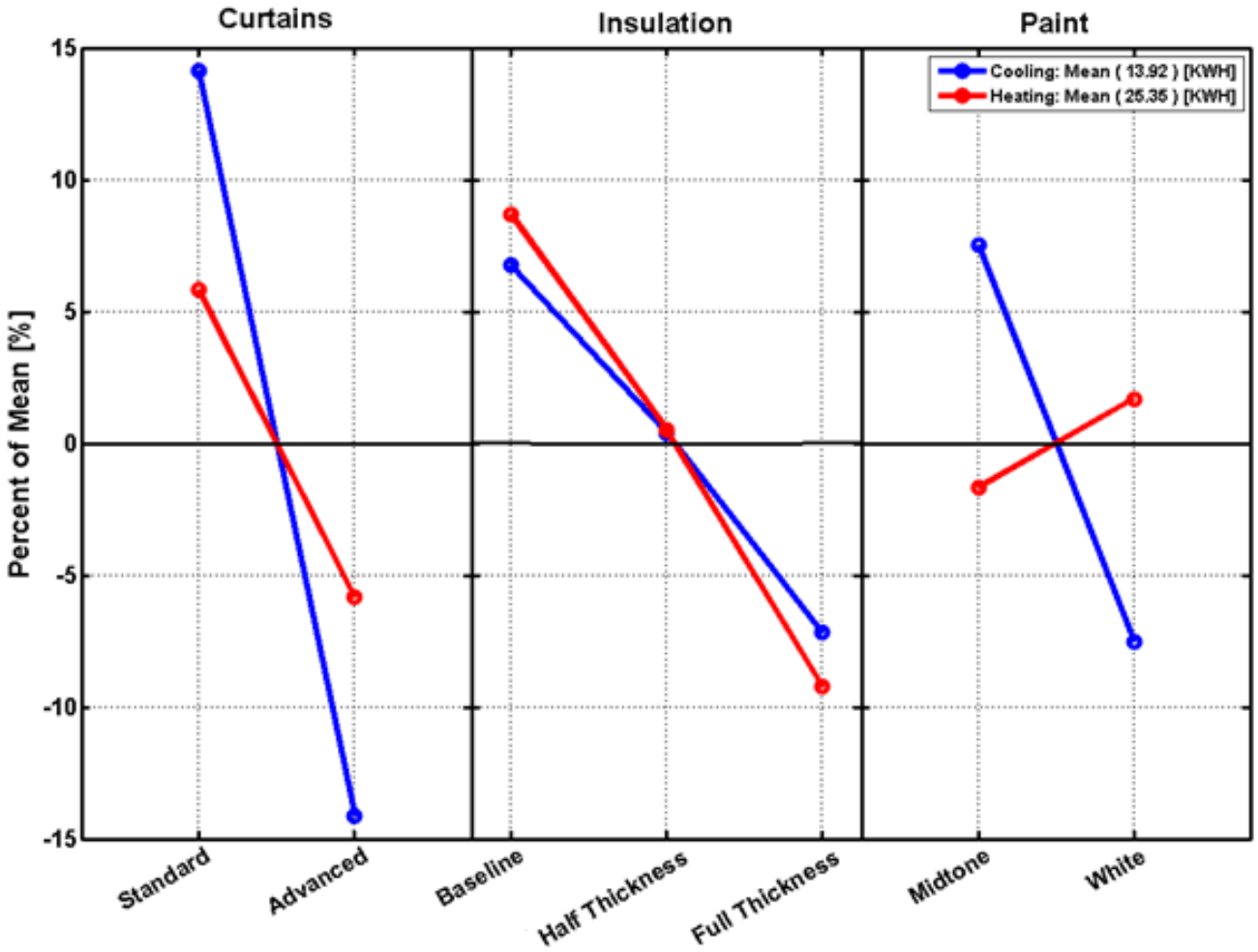

[3]


[4]

Technology Screening for Experimentation

CoolCalc Used to Quantify Impacts of Complete-Cab Technologies



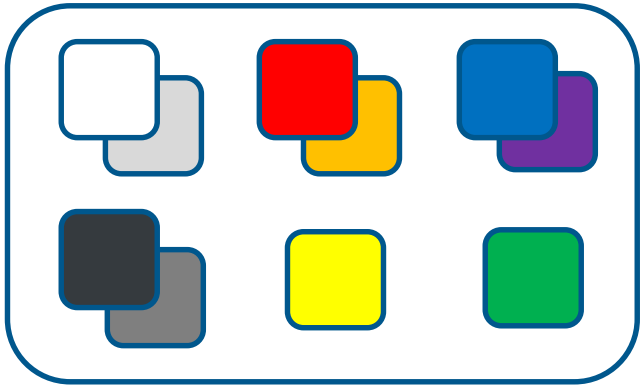


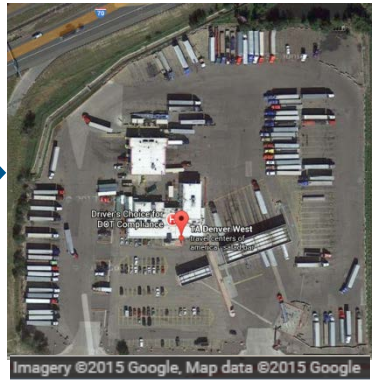
- National level analysis—locations across 48 contiguous United States
- Results based on 95th percentile for cooling and heating thermal loads.

National Average Solar Paint Color Determination

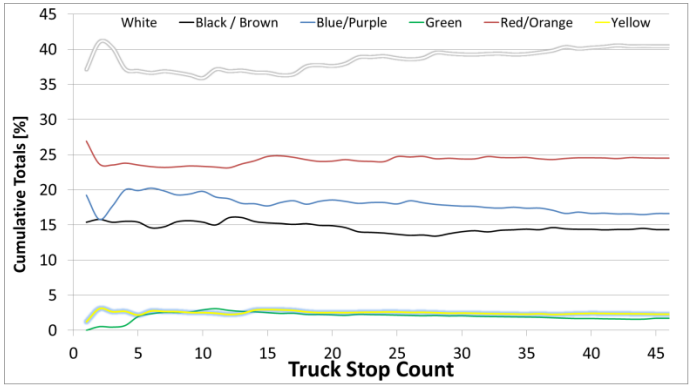
Identification of a Color that Behaves Like National Statistical Average

Identify Color Groups

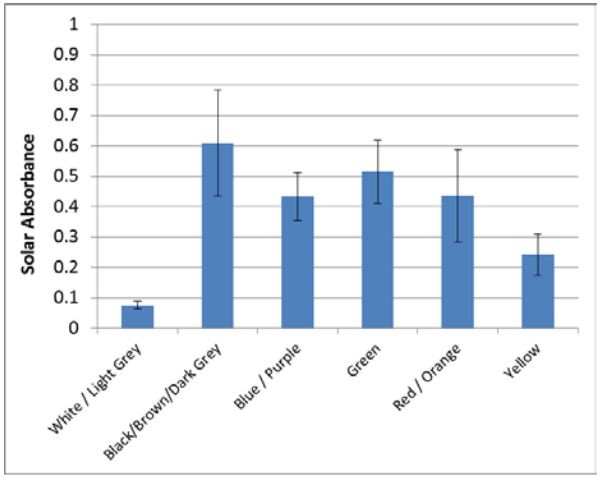




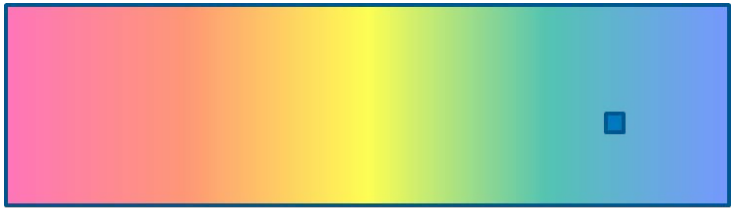
Count trucks until results converge

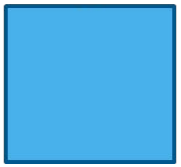


Apply color count weighting to average properties



Choose paint that has average paint properties



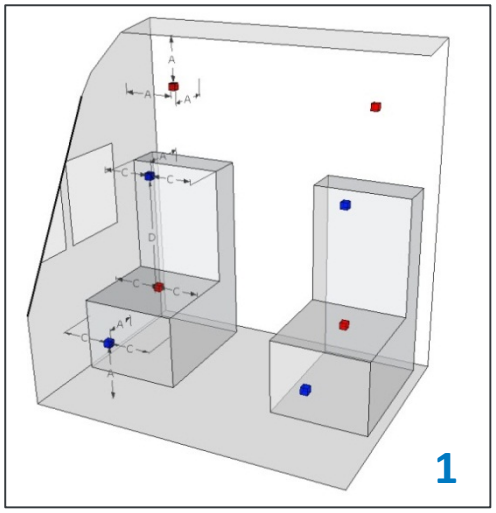


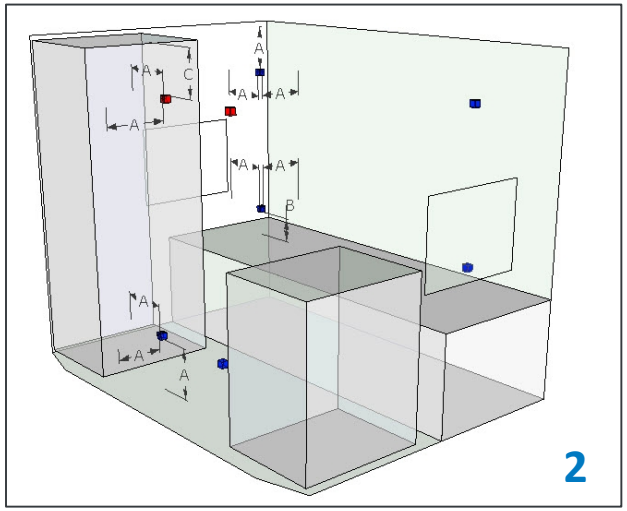
Target Solar Reflectivity = 0.37

National Average Solar-Color for Experimental Evaluation

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)



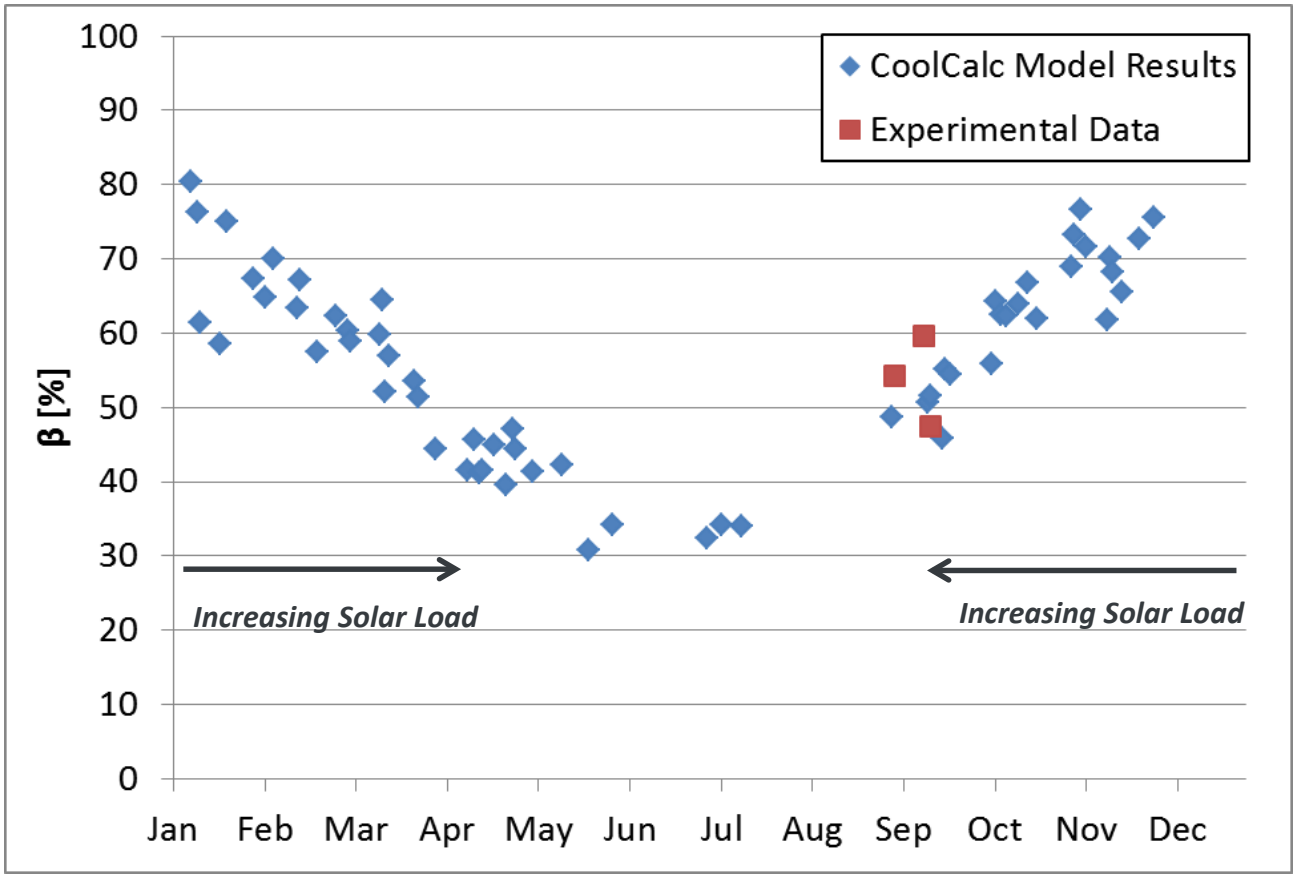


(1) Cab and (2) sleeper thermocouple locations; dimensions are A = 12", B = 6”, C = 18”; blue = TMC standard, red = NREL added.

- 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

Experimental Testing—Rotational Results

Strong Agreement with Experimental and Model Results



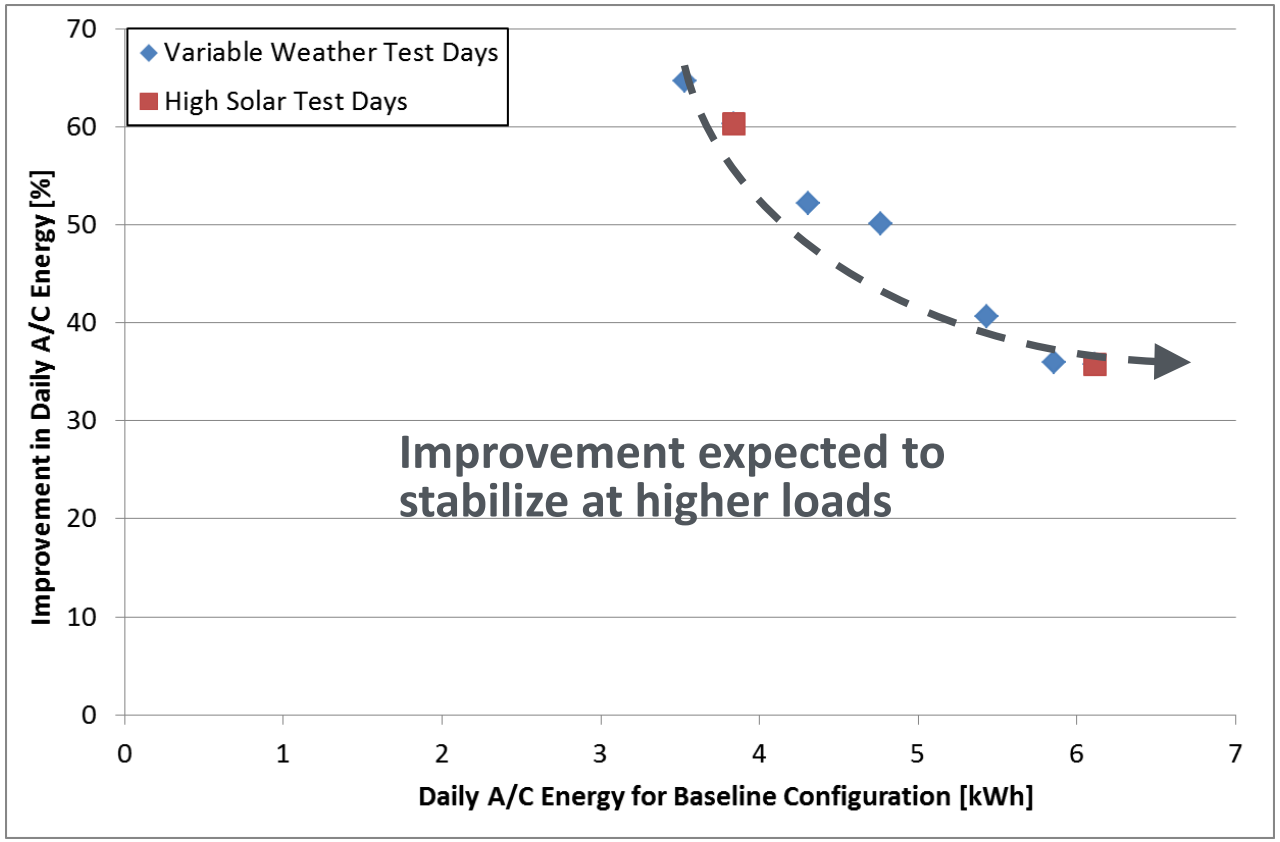
Vehicle Orientation

- Seasonal impact on results due to sensitivity of orientation to solar load
- Strong model and experimental agreement.

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

Experimental Testing—Complete Cab Solution

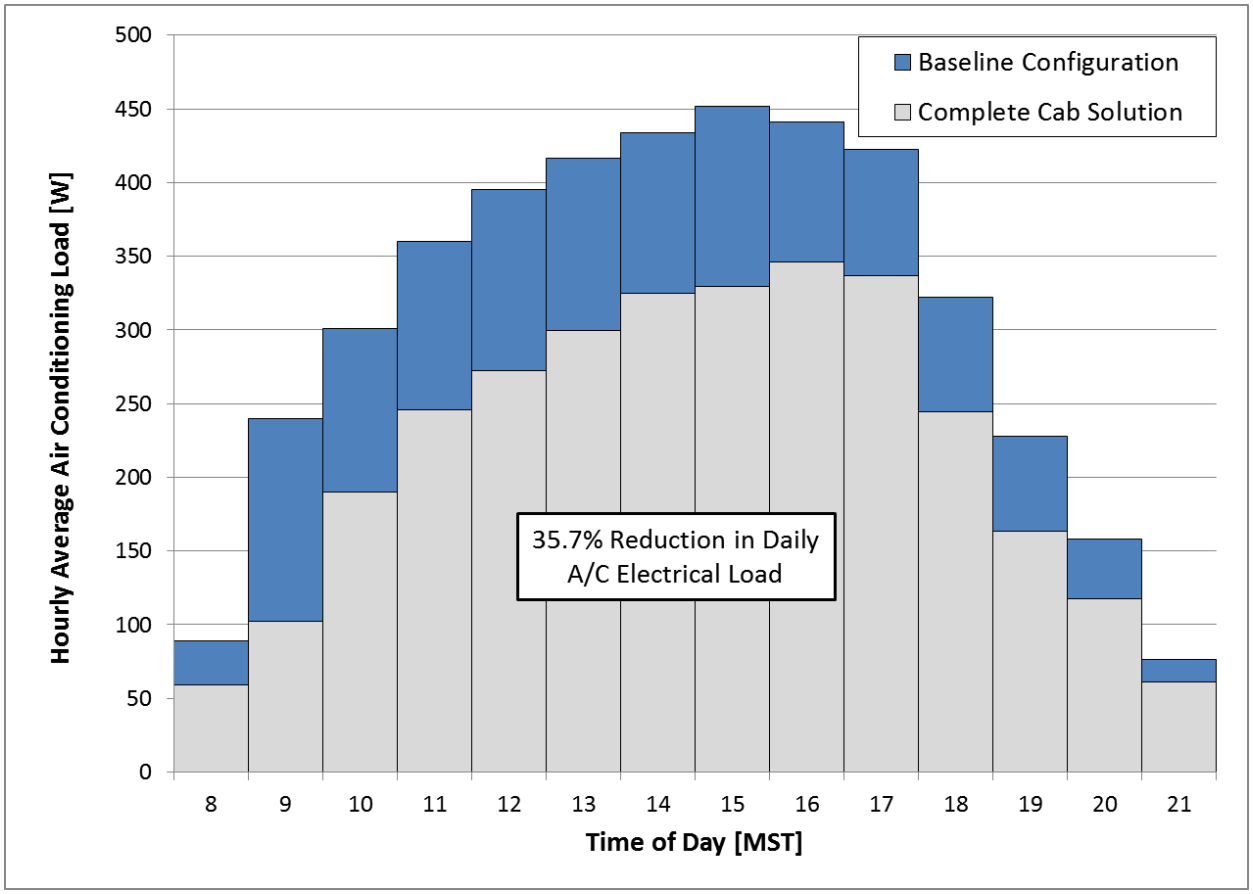
Dependence of Improvement on Daily A/C System Load



Baseline Configuration	Complete Cab Solution
 [1]	 [2]
National Average Paint	Ultra-White Paint
Stock Insulation	Advanced Insulation
Stock Sleeper Curtain	Advanced Sleeper Curtain
Stock Privacy Shades	Advanced Privacy Shades

Experimental Testing—Complete Cab Solution

35.7% Reduction in Daily A/C Energy with Complete Cab Solution



Baseline Configuration	Complete Cab Solution
	
National Average Paint	Ultra-White Paint
Stock Insulation	Advanced Insulation
Stock Sleeper Curtain	Advanced Sleeper Curtain
Stock Privacy Shades	Advanced Privacy Shades

Exceeded target of 30% reduction for cooling loads

Experimental Testing—Complete Cab Solution

Strong Impact of Advanced Curtains and Shades

	Paint	Insulation	Curtain	Improvement [%]
Baseline	National Avg.	Standard	Standard	
Config. A	Ultra-White	Advanced	Advanced	35.7%
Config. B	Ultra-White	Advanced	Standard	21.1%
Config. C	Ultra-White	Advanced	None	11.6%

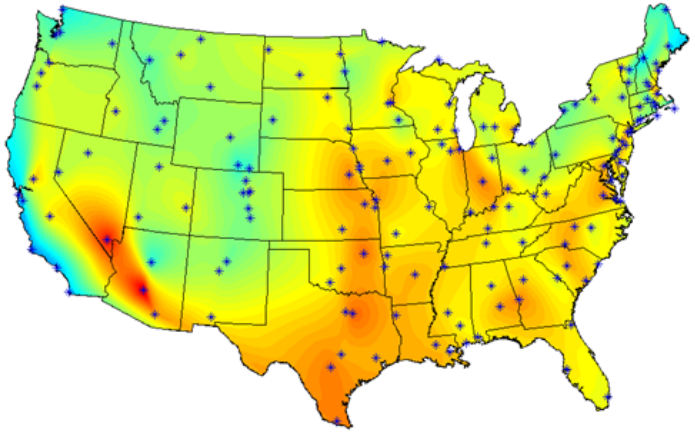
- **Strong impact of advanced curtains and shades**
- **Paint and insulation effective even without curtains and shades.**

CoolCalc Modeling—Complete Cab Solution

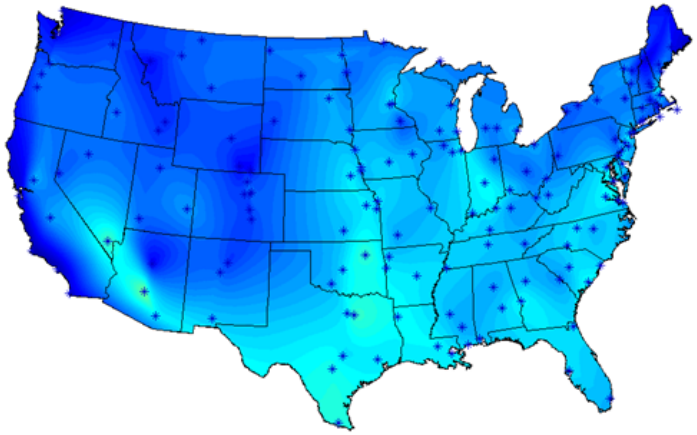
Large National Impact for Complete Cab Solution on Cooling Loads

95th Percentile of Cooling Days

Baseline Configuration



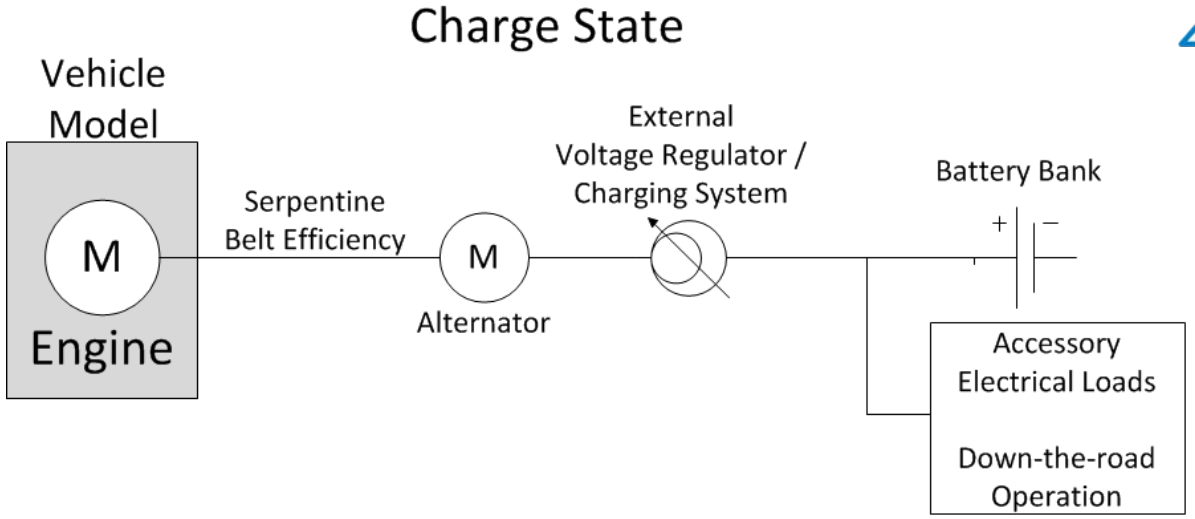
Complete-Cab Solution

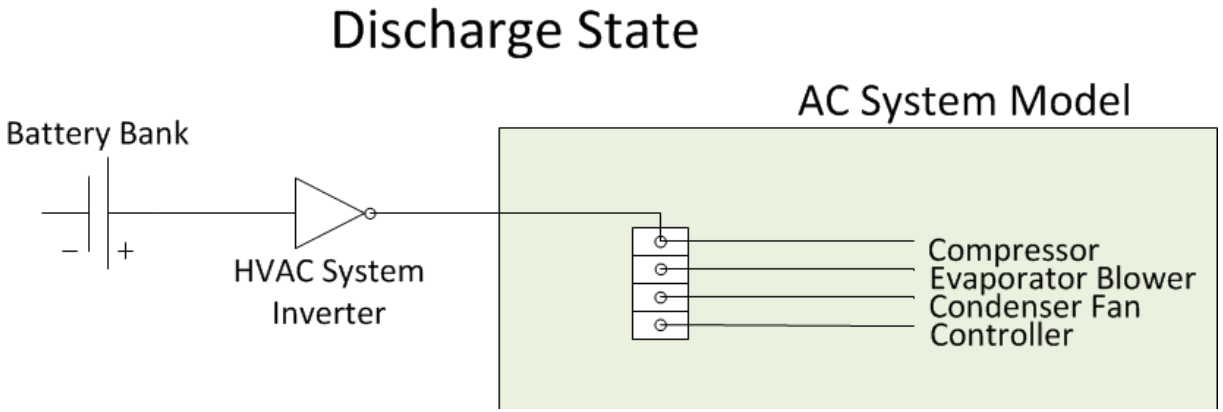


Daily Cooling Thermal Load [kWh]

CoolCalc Modeling—Electric A/C Systems

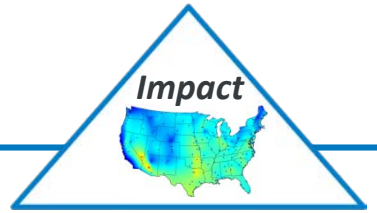
Approach to Modeling Auxiliary Electric Sleeper System Performance





CoolCalc Modeling—Electric A/C Battery Sizing

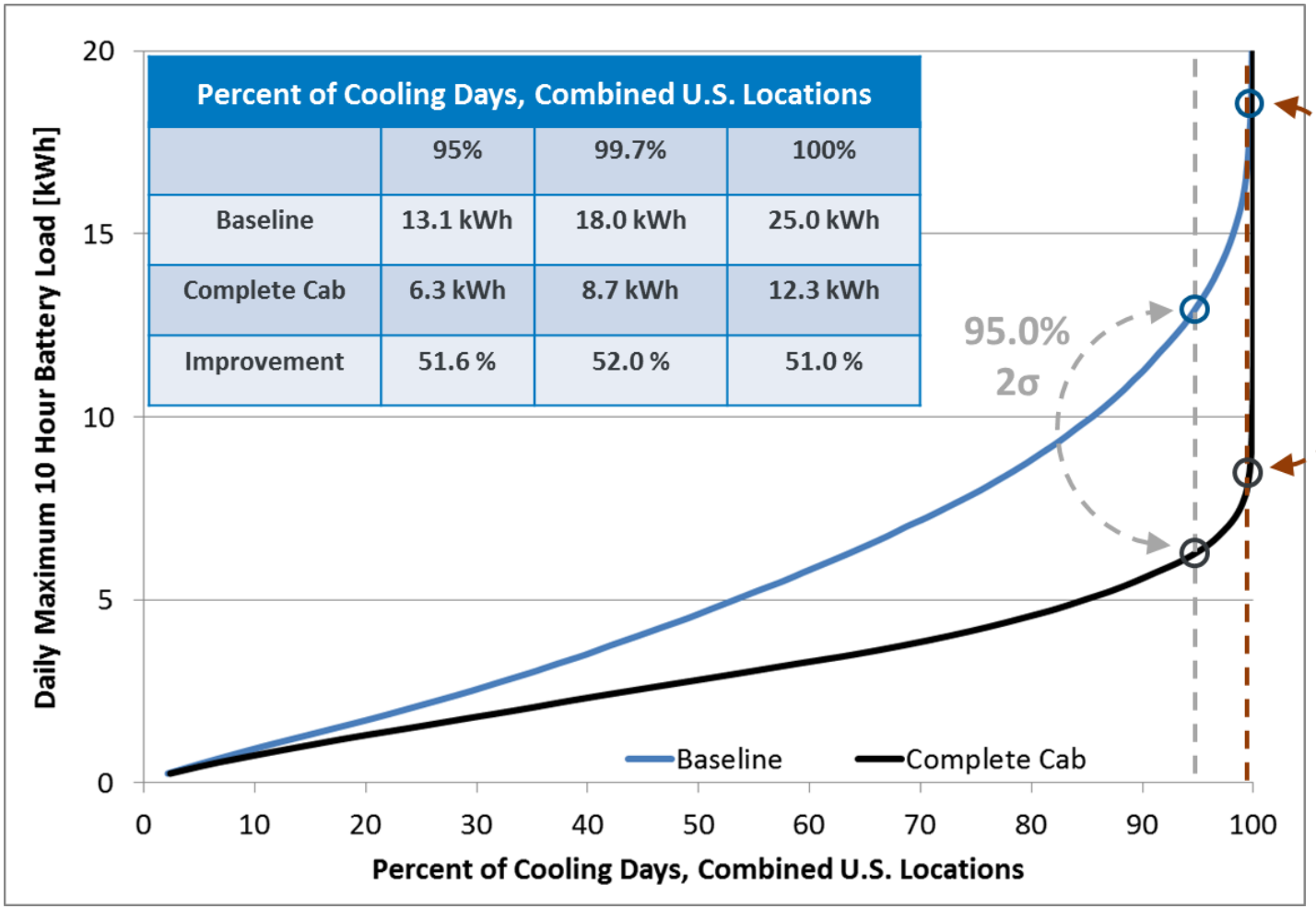
National-Level Analysis Applied to Guide System Design



Example Results—Auxiliary A/C System Battery Sizing

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

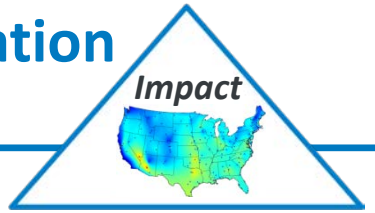
Percent of Cooling Days, Combined U.S. Locations			
	95%	99.7%	100%
Baseline	13.1 kWh	18.0 kWh	25.0 kWh
Complete Cab	6.3 kWh	8.7 kWh	12.3 kWh
Improvement	51.6 %	52.0 %	51.0 %



Relevance | Approach | Accomplishments | Collaborations | Future Work

Accomplishments: CoolCalc Modeling—Fuel Use Estimation

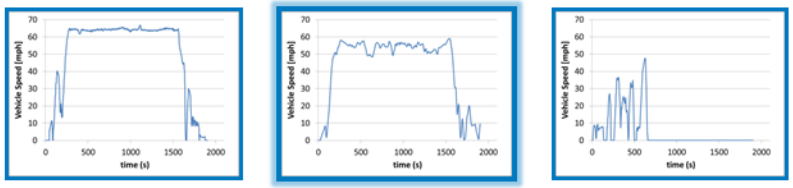
Battery Recharge Algorithm



Step 1. Determine the battery depletion for that Day

June 10
Final SOC = 0.40

Step 2. Select a Drive Cycle



Step 3: Calculate fuel use at each timestep

- Step 3a: Determine charge current
- Step 3b: Determine alternator efficiency
- Step 3c: Calculate accessory power
- Step 3d: Calculate vehicle fuel use
- Step 3e: Add incremental fuel use

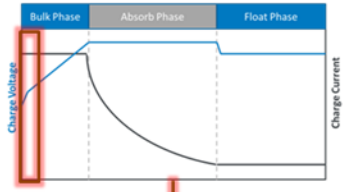
Step 4: Perform Step 3 at new timestep

Step 5: Repeat process for remaining drive cycles

**State of charge (SOC)*

Step 3.

Step 3a. Battery Charging Algorithm

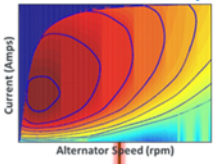


$i_{battery} + i_{other}$

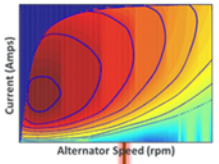
Fuel Use Without Battery Charging

i_{other}

Step 3b. Alternator Map



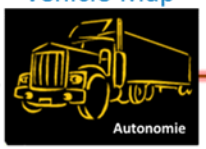
Alternator Map



Step 3c.

$$P_{accessory} = i_{tot} * V_{bus} * \eta_{regulator} * \eta_{alternator} * \eta_{belt}$$

Step 3d. Vehicle Map



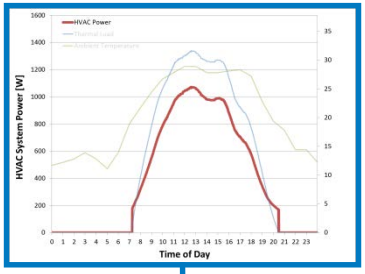
Vehicle Map

Step 3e. Battery Recharge Fuel Use

Step 4.

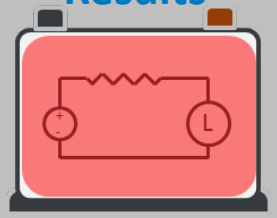
Accomplishments: CoolCalc Modeling—Fuel Use Estimation

HVAC Load Profile

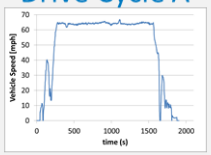


HVAC Energy

Recharge Results

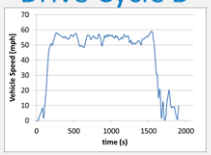


Drive Cycle A



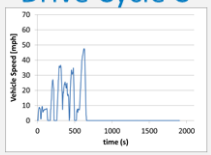
Fuel Use

Drive Cycle B



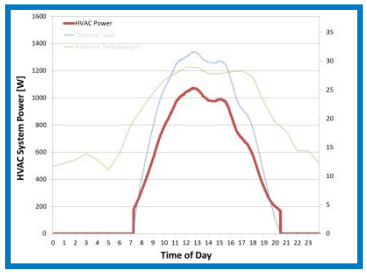
Fuel Use

Drive Cycle C



Fuel Use

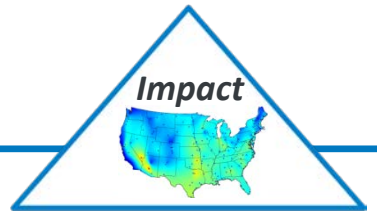
Cycle Weighting Fractions: **86%** **9%** **5%**

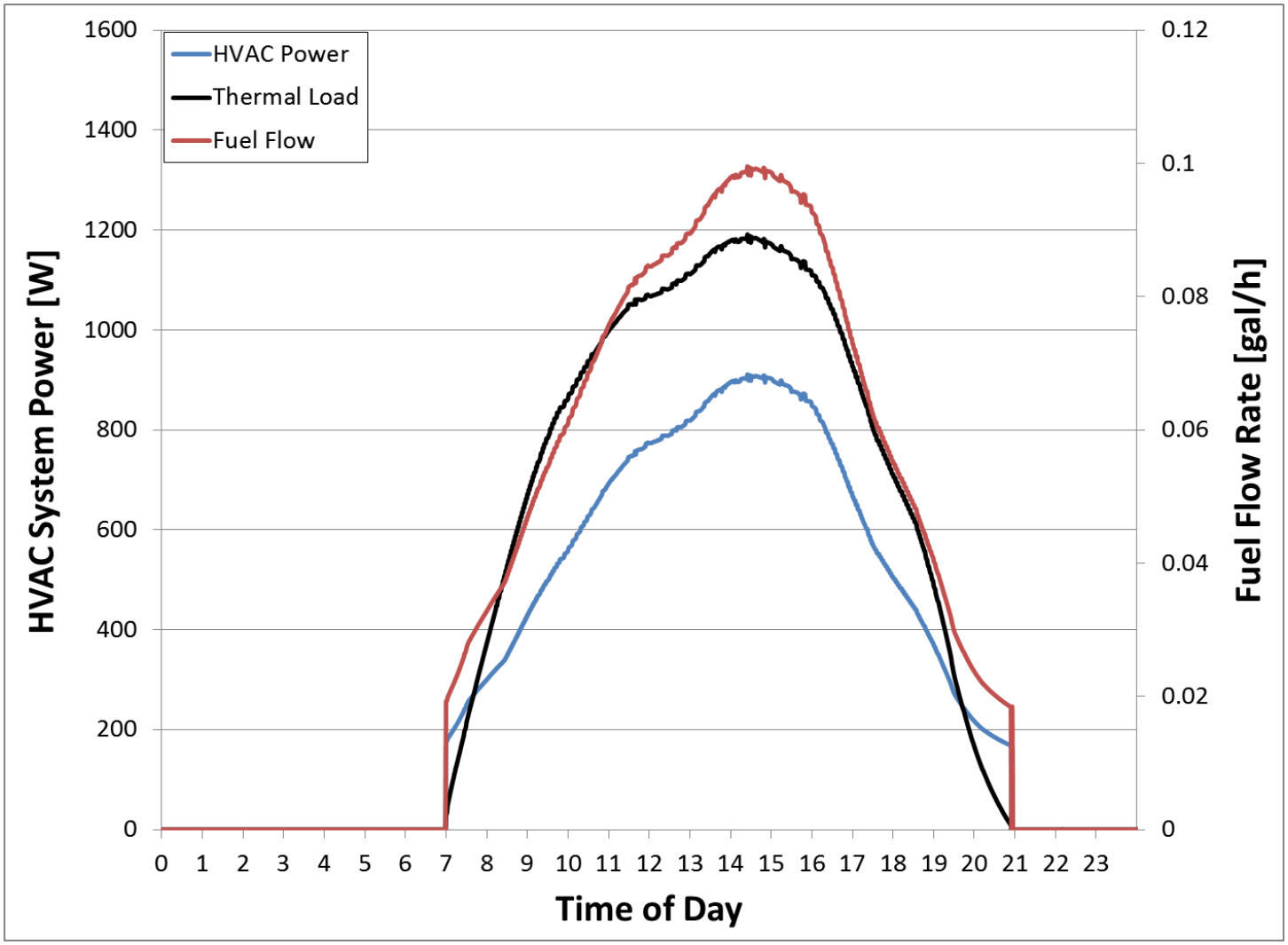


HVAC Energy

Fuel Use

CoolCalc Modeling—Fuel Use Estimation





Responses to FY14 AMR Reviewer Comments

Comment:	…there is no problem. However, it would be very helpful to use the knowledge base of the partner organizations to get a good estimate on fuel savings potential (refer to the last of the critical assumptions and issues).
Response:	We agree that leveraging the knowledge base of our partner organizations is important for getting good estimates on fuel saving potential. We are working closely with our partners to review our approach, assumptions, and results. When available, we will use input assumptions from our partners.

Comment:	The reviewer suggested that what is perhaps needed more is to relate this to real world driving cycles, and the relationship with the partners should be leveraged here to quantify this better. It may even be beneficial to bring in some trucking companies as partners.
Response:	For the initial analysis we are using standard drive cycles and weighting methods established by the heavy-duty greenhouse gas emissions model (GEM). In parallel to this standard approach, we are working with partners and our Fleet Testing and Analysis group to determine real world drive cycles. Data are currently limited for this application, but they are working on obtaining a larger data set that can be used to develop data-based drive cycles.

Comment:	The reviewer thought that the most important aspect of the project going into the future was to have very reliable fuel use and payback period analysis.
Response:	We strongly agree that the most important aspect of the project going forward is the fuel use and payback period analysis. In order to develop a strong fuel use and payback period analysis method, it has been necessary to significantly develop the CoolCalc modeling tool in addition to national-level analysis and post-processing tools. It is our belief that these models are only as good as the experimental data they are validated against, and the outdoor testing work feeds heavily into this development. Fuel use and payback period estimation requires multiple analysis pieces and assumptions that we have been working on developing and testing. We are integrating these building blocks and gaining confidence in both the methodology and results at a national level. We will continue to make fuel use and payback period analysis the top priority for the remainder of the project.

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
- PPG Industries
  - Evaluated advanced paint technology
- Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems
  - Evaluated insulation packages
- Measurement Technology Northwest
  - Thermal manikin testing
- Dometic Environmental Corporation
  - Tested with electric A/C systems

Proposed Future Work and Remaining Challenges and Barriers

- Complete overall heat transfer (UA) heating tests of complete cab package.
- Refine approach and assumptions with industry partners and complete national-level HVAC load, fuel use, and payback period analysis.
- Test final A/C load reduction configuration.
- Transition approach, tools, and methods to broader commercial vehicle focus.

Summary/Conclusions

Test Configuration	Beta	Cooling Reduction [% of A/C]	Potential Impact
Vehicle Orientation	53.9%	N/A	Immediate payback "decision" for load reduction
Complete Cab with Advanced Curtains		35.7%	A/C performance aimed towards meeting SMART goal
Complete Cab with Stock Curtains		21.1%	
Complete Cab without Curtains		11.6%	

- **Added CoolCalc features** – Simplified HVAC system option, implemented process tool, developed post-processing tool.
- **VTCab preliminary development** – Implemented rendering functionality, object browser, and run simulation dialog, and revised file structure and COLLADA file importing capability.
- **Generic truck model** – Implemented generic truck models into CoolCalc as project templates.
- **National average solar-color** – Determined national average solar paint color for experimental evaluation of paint as part of the complete cab evaluation.
- **Applied CoolCalc to guide outdoor testing**
  - Modeling of the complete cab solution was used to show a strong national impact of the system for summer testing.
  - A 12.9% reduction in mean annual cooling energy was obtained by orienting the vehicle north compared to south.

Contacts

Special thanks to:

- **David Anderson and Lee Slezak**
  Vehicle and Systems Simulation and Testing

For more information:

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303-275-4443

[1]

Photo Credits

- **Slide 1**
  1. Photograph of NREL's Vehicle Test Pad (VTP), Dennis Schroeder, NREL, 2011
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  1. Truck insulation, Travis Venson, 2011
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  3. Truck picture, NREL Image Gallery, 14180
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  1. Thermal image of truck, Dennis Schroeder, NREL, 2013
- **Slide 9**
  1. Photos of trucks on VTP, Cory Kreutzer, NREL, 2012
- **Slide 10**
  1. Truck curtains, Travis Venson, 2011
  2. Truck glazing film, Cory Kreutzer, NREL, 2013
  3. Thermal image of Newton manikin, Dennis Schroeder, NREL, 2013
  4. Buck painted black, Cory Kreutzer, NREL, 2012
  5. Compressor, Jason Lustbader, NREL
- **Slide 14**
  1. Thermal image of truck, Travis Venson, 2011
  2. Test bucks, Cory Kreutzer, NREL, 2012-2013
  3. Photograph of sleeper curtain barrier, Cory Kreutzer, NREL, 2013
  4. Photograph of white glazing film, Cory Kreutzer, NREL, 2013
- **Slide 16**
  1. Rest-stop satellite image, Google
- **Slide 17**
  1. Photograph of NREL's Vehicle Test Pad (VTP), Dennis Schroeder, NREL, 2011
  2. Photograph of test vehicles, Cory Kreutzer, NREL, 2014
- **Slide 18**
  1. Photograph of vehicle orientation study, Cory Kreutzer, NREL, 2014
- **Slide 20**
  1. Photograph of complete cab solution baseline test bucks, Cory Kreutzer, NREL, 2014
  2. Photograph of complete cab solution ultra-white configuration, Cory Kreutzer , NREL, 2014
- **Slide 29**
  1. Photograph of Daimler truck, Travis Venson, 2011
  2. Photograph of Volvo truck, Cory Kreutzer, NREL, 2013
  3. Photograph of Kenworth truck, Ken Proc, NREL, 2010
  4. Photograph of Vehicle Test Pad, Dennis Scrhoeder, NREL
- **Slide 32**
  1. Photograph of trucks on VTP, Cory Kreutzer, NREL, 2012

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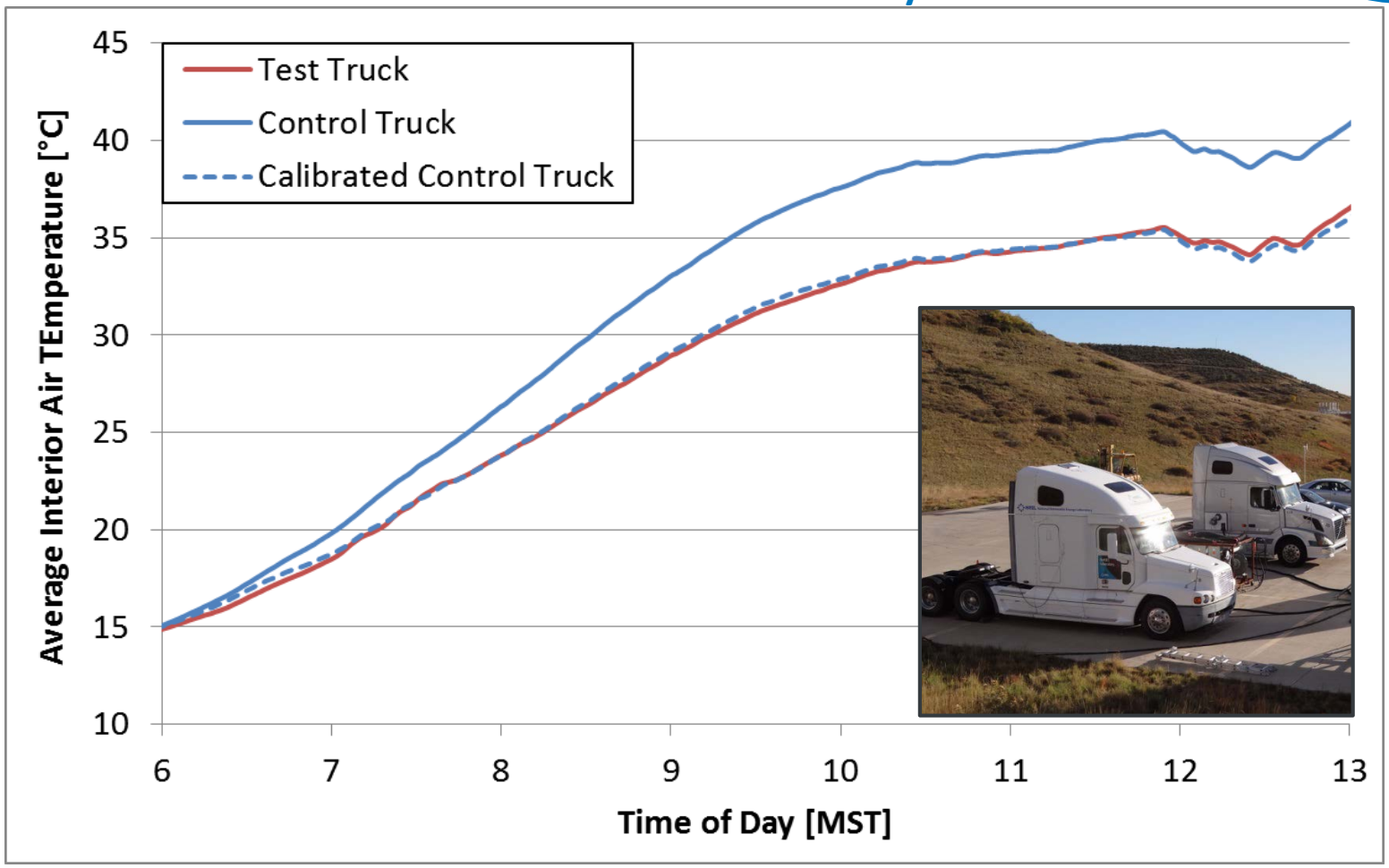
Technical Back-Up Slides

(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.)

Experimental Testing—Soak Baseline

Calibration Verification Indicates High Accuracy in Calibration

Soak calibration check day

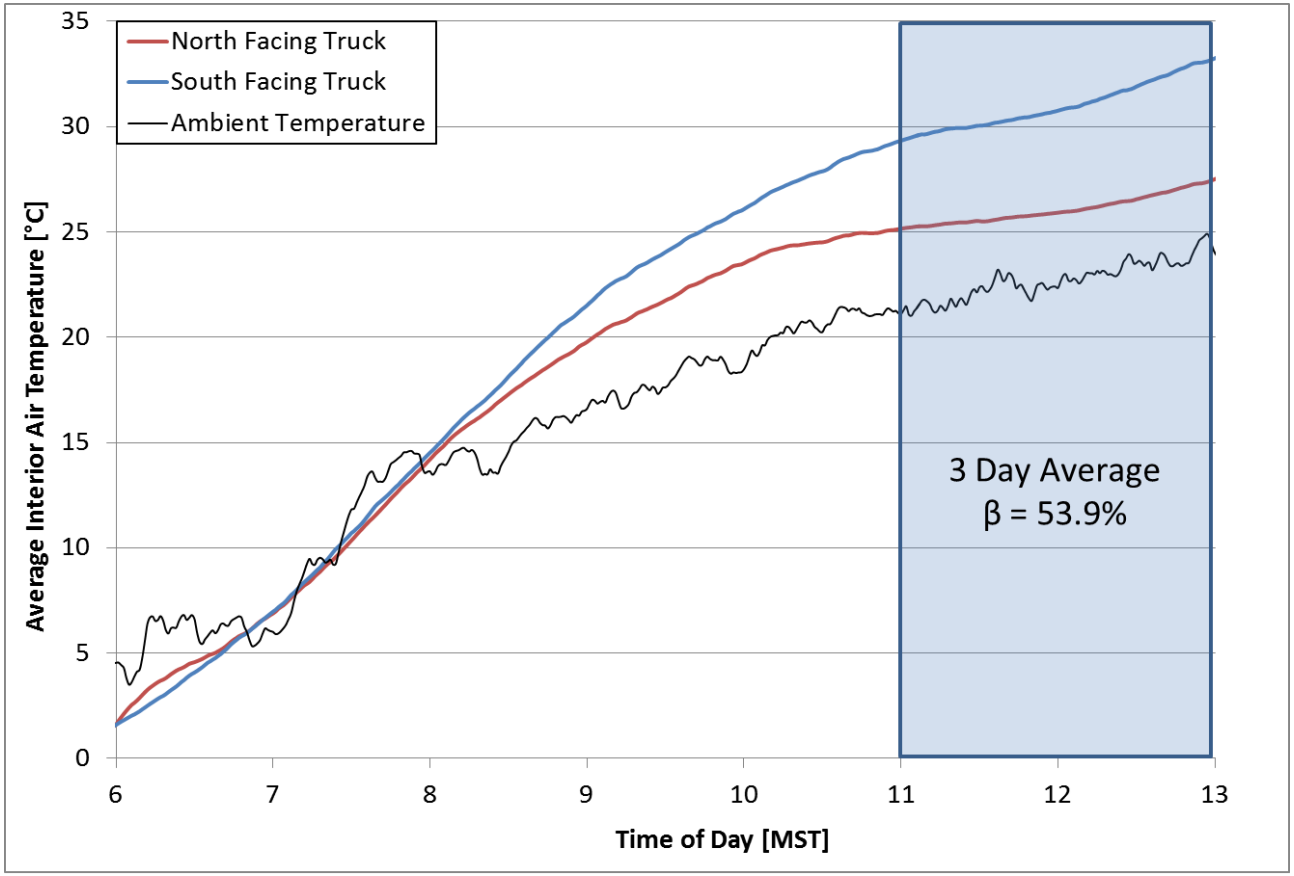


- Calibration used for advanced glazings and rotational testing
- Within 0.2°C after calibration from 11 a.m. to 1 p.m.

Experimental Testing—Rotational Results

53.9% of Maximum Possible Reduction in Rise Over Ambient Temp

Vehicle soak baseline is obtained prior to evaluation.

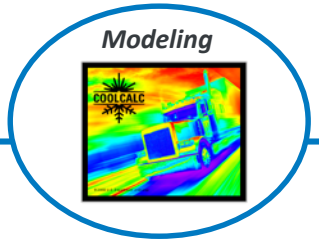


Vehicle Orientation

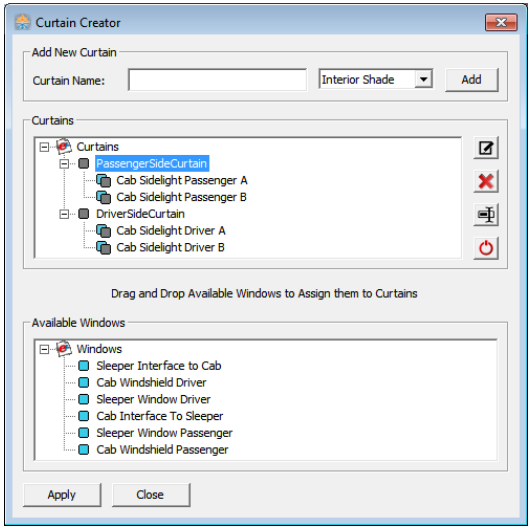
- Three-day average
- Daily clearness index greater than 0.525
- Significant impact, no cost
- FY15 follow-up work for A/C performance

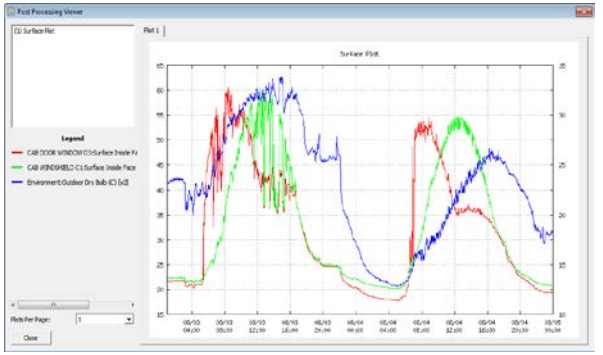
$$\beta = \frac{\overline{T}_{baseline} - \overline{T}_{modified}}{\overline{T}_{baseline} - \overline{T}_{ambient}} \cdot 100\%$$

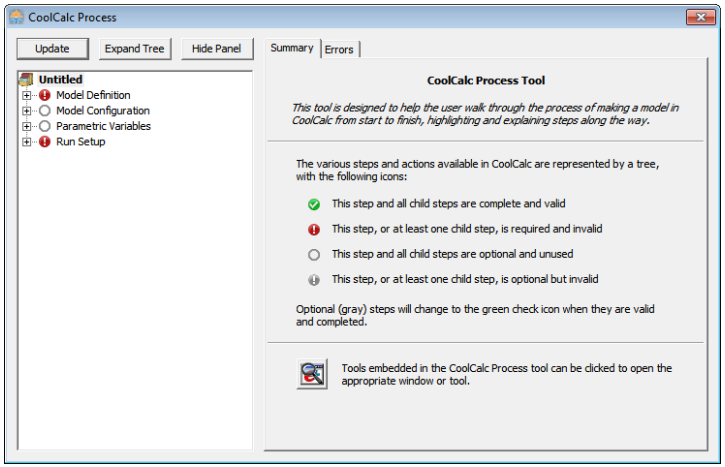
CoolCalc FY14 Development Highlights

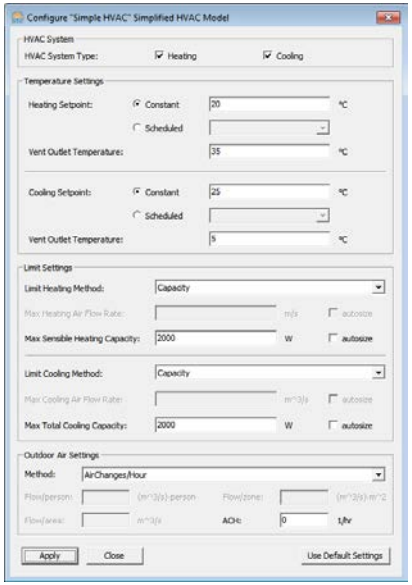


- Updated for compatibility with EnergyPlus v8.1.
- Added “simplified” HVAC option to HVAC tool.
- Updated rendering and animation settings/controls.
- Implemented Process tool for interactive documentation.
- Developed Post-Processing tool for rapid display of simulation results.





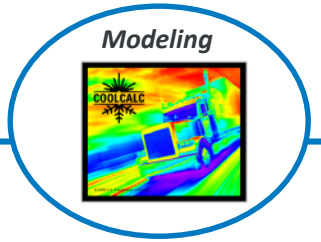




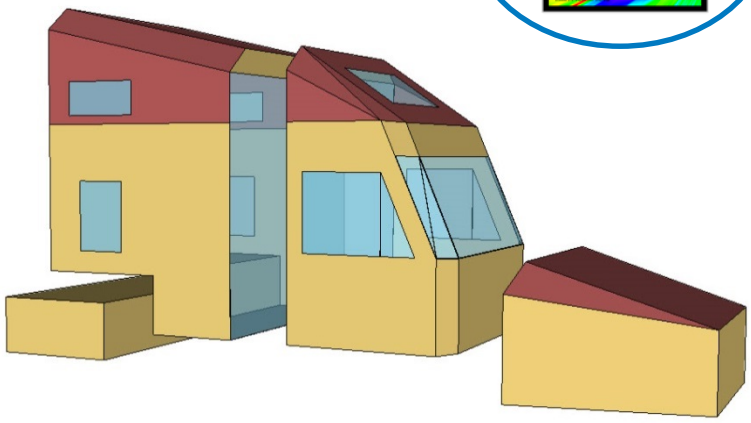
Relevance | Approach | Accomplishments | Collaborations | Future Work

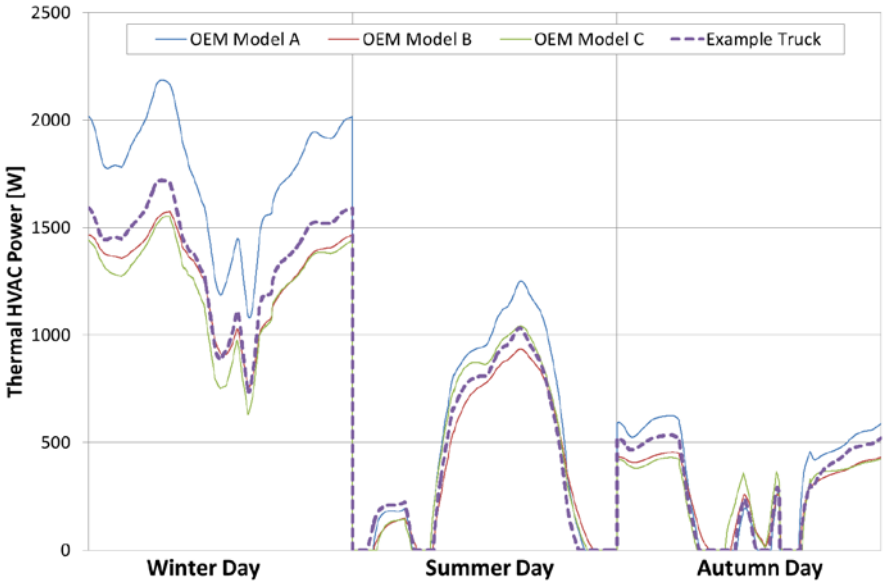
Generic Truck Model Development

Representative Model for OEM-Independent Analysis



- Model of a generic long-haul truck
  - Representative of a modern truck cabin
  - Reduces the need for original equipment manufacturer (OEM) data
  - Reduces model development time
  - Enables OEM-independent analyses
- Thermal soak and sleeper HVAC simulations performed
- Performance trends are within the range of values for the reference models



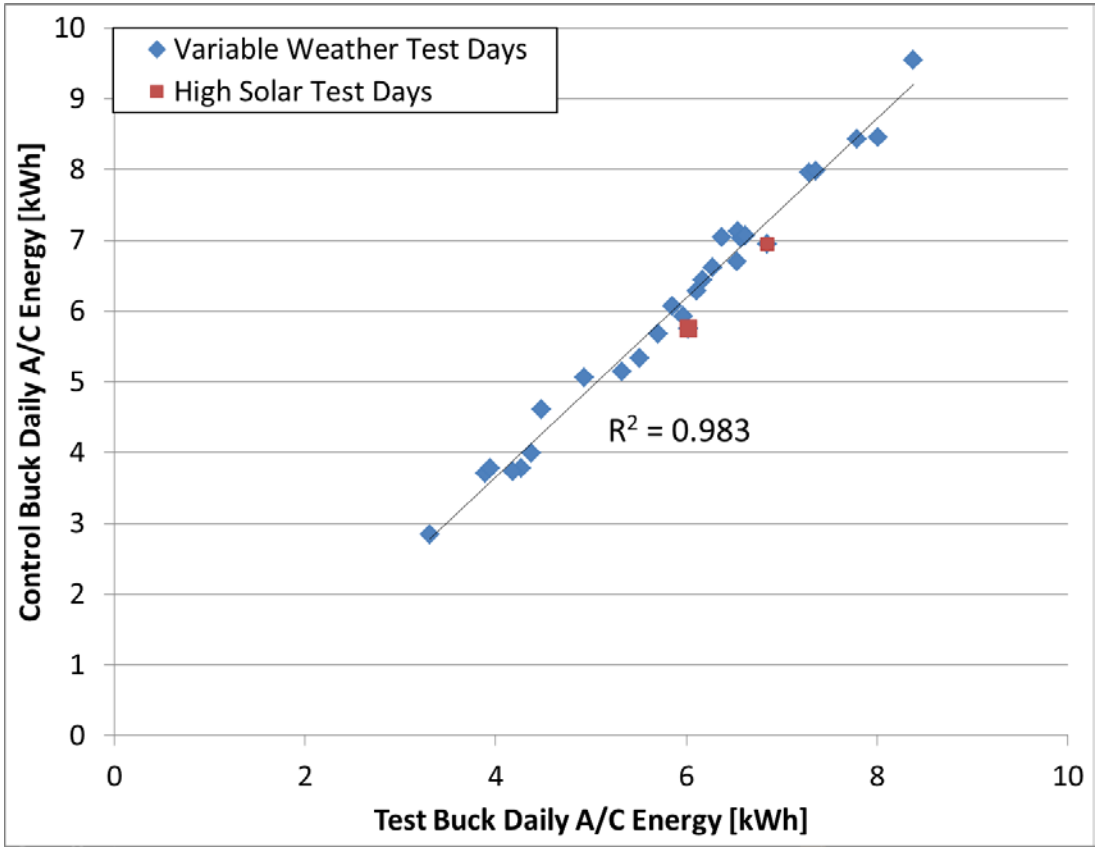


Experimental Testing—A/C Baseline

Strong Correlation Despite Limited High Solar Test Days

Baseline Configuration

- National average solar-color
- Baseline insulation
- Stock curtains and shades.



Average of all days used—limited number of clear solar test days