CoolCab Test and Evaluation &
CoolCalc HVAC Tool Development

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US 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: FY06
Project End Date: FY15
Percent Complete: 55%

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

Budget

Total Project Funding:
DOE Share: $2,700K
Contractor Share*: $810K

Funding Received in FY11: $500K
Funding for FY12: $475K

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

Partners

• Collaborations
  – Daimler Truck (SuperTruck)
  – Kenworth Truck (PACCAR)
  – Volvo Truck
  – Oshkosh
  – 3M
  – Dometic
  – Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems

• Project lead: NREL
Relevance – Project Description

THE CHALLENGE

• 838 million gallons of diesel fuel used annually for long-haul truck rest period idling*
  – 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

THE OPPORTUNITY

• Reducing the load will enable idle reduction technologies
  – 2- to 3-year payback
  – Direct impact on bottom line

* Stodolsky et al., *Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks*. 2000. ANL/ESD-43

Data Source: EIA Short-Term Energy Outlook
http://www.eia.gov/petroleum/gasdiesel/, March 2012
Demonstrate at least a 30% reduction in long-haul truck idle climate control loads with a 3-year or better payback period by 2015.
Relevance – Objectives

• Overall Objectives
  – 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
  – Apply analytical tools and test methods to research and develop technologies to reduce costs of idle reduction systems
  – Collaborate with industry partners to develop and apply viable solutions to enable market penetration

• FY12 Objectives
  – Characterize the performance of thermal load and idle reduction technologies through field testing and evaluation
  – Release, refine, and utilize CoolCalc to help predict HVAC load and idle reduction in sleeper cabs
  – Identify impacts on fuel economy over a wide range of operating conditions
## Milestones

<table>
<thead>
<tr>
<th>Date</th>
<th>Key Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 2011</td>
<td>• SAE World Congress paper and presentation</td>
</tr>
<tr>
<td>July 2011</td>
<td>• Released initial version of CoolCalc &amp; user guide</td>
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</tbody>
</table>
| September 2011 | • Completed technology evaluations on trucks  
|            | • Assessed the impact of thermal- and idle-reduction systems                  |
| April 2012 | • Developed and validated CoolCalc model of Volvo truck  
|            | • Applied model to guide summer testing                                      |
| July 2012  | • SAE Commercial Vehicles Engineering Congress (COMVEC) paper                 |
| September 2012 | • Complete testing of truck and test bucks  
|            | • Assess the impact of thermal and idle reduction technologies  
|            | • Estimate impact on fuel use                                                |
| October 2012 | • SAE Thermal Management Systems Symposium  
|            | • SAE World Congress paper                                                    |
Decreases in load have a larger impact on fuel use due to equipment and delivery losses.
Approach – Advanced Technologies

- Insulation & Advanced Materials
- IR-Reflective Materials
- Advanced Idle Reduction Systems
- Comfort-Based Air Distribution
- Advanced Controls
- Advanced Seating – Low Mass
- Advanced Glazings or Shades
- Efficient HVAC Equipment
Approach – Suite of Tools

**Detailed Analysis**
- CFD – Fluid Flow

**Load Estimation**
- A/C Model – Compressor Power

**Fuel Consumption**

**Testing**

**Vehicle Modeling**

**CoolCalc**

**In-Use Validation**

A/C Model – Compressor Power
CoolCalc Rapid HVAC Load Estimation

- **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**
  - Calculate loads
  - Estimate potential load reduction
  - Fuel use impacts

Autonomie
Fuel Use (T_{amb}, P_{comp})

\[ P_{\text{comp}}(T_{\text{amb}}, Q_{\text{evap}}) \]

Fuel Use Rate

T_{\text{amb}}, Q_{\text{evap}}
Approach: CoolCab Project Phases

• **Phase I – Baseline Testing and Model Development**
  – Build and validate CoolCalc models
  – Characterize test truck performance as received
  – Calibrate control truck

• **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
Technical Accomplishment – CoolCalc

• Initial release of CoolCalc to industry partners

• CoolCalc User Guide
  – Helps users through entire simulation process from installation to processing simulation results
  – Serves as a reference for performing the most important/frequent tasks
  – Trouble-shooting common errors

• Improved robustness and usability
Technical Accomplishment – Volvo CoolCalc Model

Developed CoolCalc model of Volvo truck

1
Technical Accomplishment – Preliminary Validation

Preliminary model results demonstrate good correlation to test data
Technical Accomplishment – Preliminary Validation

Impacts of weather, solar angle, and vehicle orientation are captured in the model.

Surface Temperature - Exterior Side Walls

![Graph showing surface temperature over days for different conditions.

- Test Data - Driver Wall
- CoolCalc - Driver Wall
- Test Data - Pass. Wall
- CoolCalc - Pass. Wall

Days: Day 1, Day 2, Day 3

Surface Temperature [°C]
Technical Accomplishment – CoolCalc Application

Generic cab model shows reduction in sleeper air temperature during thermal soak
# Technical Accomplishment – CoolCalc Application

Generic cab model shows 25% maximum possible air temperature reduction from paint

## Radiant Barrier Results

<table>
<thead>
<tr>
<th>Baseline Configuration</th>
<th>Modified Configuration</th>
<th>$\beta$ - Average Air Temp Reduction, Cab</th>
<th>$\beta$ - Average Air Temp Reduction, Sleeper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Paint</td>
<td>Aluminum Radiant Barrier</td>
<td>24%</td>
<td>27%</td>
</tr>
<tr>
<td>Green Paint</td>
<td>Aluminum Radiant Barrier</td>
<td>17%</td>
<td>20%</td>
</tr>
<tr>
<td>White Paint</td>
<td>Aluminum Radiant Barrier</td>
<td>3%</td>
<td>5%</td>
</tr>
</tbody>
</table>

## Paint Results

<table>
<thead>
<tr>
<th>Baseline Configuration</th>
<th>Modified Configuration</th>
<th>$\beta$ - Average Air Temp Reduction, Cab</th>
<th>$\beta$ - Average Air Temp Reduction, Sleeper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Paint</td>
<td>White Paint</td>
<td>22%</td>
<td>25%</td>
</tr>
<tr>
<td>Green Paint</td>
<td>White Paint</td>
<td>15%</td>
<td>16%</td>
</tr>
</tbody>
</table>

\[
\beta = \frac{\bar{T}_{\text{baseline}} - \bar{T}_{\text{modified}}}{\bar{T}_{\text{baseline}} - \bar{T}_{\text{ambient}}} \times 100\%
\]
Technical Accomplishment – Impact of Solar Reflective Film
Identified 8% reduction in A/C load through application of a solar reflective film

- **3M Solar Reflective Film**
  - Applied to cab/sleeper exterior
  - 1-2°C reduction in temperatures
  - 8% reduction in A/C load
  - More effective on darker trucks

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**Thermal Soak Test**

**10-Hour Idle A/C Test**

- Baseline Paint
- Solar Reflective Film
Technical Accomplishment – Infrared Imaging

Identified opportunities to reduce heat loss/gain in walls, roof cap, structural members, and glass

Rear View - structural members

Isometric view – roof cap and glass

Side View – sleeper walls
Technical Accomplishment – Impact of Insulation Package I
Reduced heating and cooling loads by 26% and 20%, respectively

- E-A-R™ Thermal Acoustic Systems
  - Insulation Package I
    - Installed in sleeper walls and roof
    - 26% reduction in heating load
    - 20% reduction in A/C load
Technical Accomplishment – Impact of Insulation Package II
Reduced heating and cooling loads by 36% and 34%, respectively

- E-A-R™ Thermal Acoustic Systems
  Insulation Package II
  - Installed in sleeper walls and roof
  - Added insulation in channels
  - 36% reduction in heating load
  - 34% reduction in A/C load

![Graph showing temperature and power consumption](image-url)
Technical Accomplishment – Idle Reduction System
Identified opportunities to reduce battery pack capacity by 23%

- Dometic Electric A/C System
  - Battery or shore-powered A/C system
  - Batteries charge from alternator
  - Provides 10 hours of idle-free cooling
  - Identified opportunities to reduce battery capacity by 23%, ~ 1 battery

<table>
<thead>
<tr>
<th>Test Configuration</th>
<th>Battery Energy Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Reflective Film</td>
<td>7%</td>
</tr>
<tr>
<td>Insulation Package I &amp; Film</td>
<td>20%</td>
</tr>
<tr>
<td>Insulation Package I</td>
<td>15%</td>
</tr>
<tr>
<td>Insulation Package II</td>
<td>23%</td>
</tr>
</tbody>
</table>
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 CoolCalc model, validation 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
- **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

- **FY12**
  - Improve CoolCalc and add functionality for partner implementation
  - Apply CoolCalc model to characterize technologies over a range of operating conditions
  - Complete validation of Volvo model
  - Interface with A/C model to characterize fuel impacts
  - Evaluate advanced technologies on test bucks and heavy vehicles
  - A/C emulator test bench, UA, thermal soak
  - Characterize technologies identified by CoolCalc analysis

- **FY13**
  - Work with industry partners to evaluate and implement advanced thermal and idle load reduction technologies
  - Move toward in-use demonstration and evaluation
  - Quantify fuel savings and economic trade-offs for technologies over a wide range of use and weather conditions
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
    o Refined interface and improved robustness
    o Released with user guide to industry partners
    o Developed and began validation of a model for Volvo
    o Applied model to characterize technologies
  – Truck Testing
    o 36% reduction in heat loss for insulated truck
    o 34% reduction in idle A/C load for insulated truck
    o Characterized impact of solar reflective film
    o Identified opportunities to reduce idle A/C system battery capacity by 23%

• Collaborations
  – Volvo – testing, analysis, and CoolCalc model development
  – Daimler – supported Daimler’s Super Truck program through testing and analysis
  – Kenworth – extended Cooperative Research and Development Agreement (CRADA), CoolCalc beta testing
  – Oshkosh – CoolCalc beta testing and application
  – 3M – evaluated solar reflective film technology
  – Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems – tested commercial and advanced insulation packages
  – Dometic – evaluated no-idle, battery-powered A/C system
Contacts

Special thanks to:

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

For more information:

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303-275-4443
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 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 12**
  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 14**
  1. Photograph of Volvo truck, Travis Venson, 2011

- **Slide 20**
  1. Thermal images (3), Travis Venson, 2011

- **Slide 21**
  1. Photograph of truck insulation package I, Travis Venson, 2011

- **Slide 22**
  1. Photograph of truck insulation package II, Travis Venson, 2011

- **Slide 23**
  1. Photograph of electric A/C system courtesy of Dometic, 2011

- **Slide 24**
  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 27**
  1. Daimler Super Truck Logo, Courtesy of Daimler Trucks, 2011

- **Slide 28**
  1. Photograph of VTP, NREL photographer Dennis Schroeder, 2011
Technical Back-Up Slides
Three validation days with varying weather conditions were used:

**Day 1:**
- Cloudy
- Low wind
- Low temperature

**Day 2:**
- Sunny → cloudy
- Late wind peak
- Avg. temperature

**Day 3:**
- Few clouds
- Variable wind
- High temperature
Technical Back-Up Slide – Baseline Test Process
Validate CoolCalc truck models and calibrate control truck performance to baseline test truck

1. Acquire 3 or more days of data
2. Characterize daily averages $\Delta T_{\text{trucks}}$ profile
3. Adjust measured control truck data by $\Delta T_{\text{trucks}}$
4. Validate process with other days

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

- **Purpose**
  - Characterize air changes per hour (ACH)
  - Data are used as CoolCalc input
  - Measure of air leakage in truck

- **Test Methodology**
  - Inert gas ($\text{SF}_6$) released in cab
  - B&K gas analyzer measures PPM of $\text{SF}_6$ (3-hour period minimum)

Infrared Imaging

- **Purpose**
  - Characterize high heat loss paths in cab construction
  - Used to identify insulation opportunities

- **Test Methodology**
  - Outdoor, overnight
  - Heater on inside cab (1,200 W)
  - Infrared camera
Technical Back-Up Slide – Test Procedures, Thermal Soak and UA

Are used to characterize thermal performance of commercially available and advanced technologies

**Thermal Soak**

- **Purpose**
  - Characterize impact of solar load on vehicle temperatures

- **Test Methodology**
  - Vehicle exposed to solar loads (800-1,000 W/m²) in an engine-off configuration
  - Low wind speed (< 5 m/s)

**Overall Heat Transfer (UA) Test**

- **Purpose**
  - Very similar to TMC RP 422A
  - Characterize impact of insulation

- **Test Methodology**
  - Outdoor, overnight test (no solar)
  - Heater inside cab/sleeper
  - Heater power at 1,000 watts ($Q_{heater}$)
  - Interior and exterior air temps measured ($\Delta T = T_{air, truck} - T_{air, ambient}$)
  - Overall heat transfer (UA) calculated

\[
UA = \frac{Q_{heater}}{T_{air, truck} - T_{air, ambient}}
\]
Technical Back Up-Slide – Test Procedures, Idle A/C Test

A/C testing is used to directly link thermal management to idle reduction

• **Purpose**
  – Determine A/C system power required to maintain set point temperature
  – Characterize thermal load reduction technologies impact on idle reduction

• **Test Methodology**
  – Outdoor, daytime test
  – Electric A/C set point of 73°F
  – Weather conditions are measured
  – 24 hours of data are collected at set point, 10-hour rest time used
  – Sleeper curtain closed
  – A/C power is measured