Modeling, Testing, and Analysis of Volvo Truck Tractor Cabins

Cooperative Research and Development Final Report

CRADA Number: CRD-09-361

NREL Technical Contact: Jason Lustbader

NREL is a national laboratory of the U.S. Department of Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5100-72456
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NOTICE

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<u>**Cooperative Research and Development Final Report**</u>

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Volvo Trucks North America

CRADA number: CRD-09-361

CRADA Title: Modeling, Testing, and Analysis of Volvo Truck Tractor Cabins

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$ 50,000.00
TOTALS	$ 50,000.00

Abstract of CRADA Work:

Annual fuel use for sleeper cab truck rest period idling is estimated at 667 million gallons in the United States, or 6.8% of long-haul truck fuel use. Truck idling during a rest period represents zero freight efficiency and is largely done to supply accessory power for climate conditioning of the cab. This project aimed to reduce heating, ventilating, and air conditioning (HVAC) loads and resulting fuel use from rest period idling by using efficient long-haul truck thermal management systems while maintaining occupant comfort. Enhancing the thermal performance of cab/sleepers will enable smaller, lighter, and more cost-effective idle reduction solutions. In addition, if the fuel savings provide a one- to three-year payback period, fleet owners will be economically motivated to incorporate them. This project evaluated several promising candidate technologies through experimentation and modeling to determine their effectiveness in reducing rest period HVAC loads. Load reduction strategies were grouped into the focus areas of solar envelope, occupant environment, conductive pathways, and efficient equipment. Technologies in each of these focus areas were investigated. The most promising of these technologies were then combined with the goal of exceeding a 30% reduction in HVAC loads. These technologies included “ultra-white” paint, advanced insulation, and advanced curtain design. This poject showed more than a 35.7% reduction in rest period idle air conditioning loads using thermal load reduction technologies. Overall heat transfer coefficient testing during cab heating, showed a 43% reduction in heating load using this technology package.

Summary of Research Results:

Task 1. Model Volvo truck cabin using CoolCalc tool

Using dimensional data and thermal property information supplied by Volvo, NREL will create a basic geometry and thermal model within CoolCalc, NREL's rapid HVAC analysis tool. The tool will then predict heating and cooling thermal loads within the truck cabin environment for a given set of conditions. Volvo will provide truck and cab dimensions and assist NREL in working with Volvo suppliers to obtain material properties and information. Volvo will also provide a 77" sleeper cab with battery powered HVAC system.

A CoolCalc model of a Volvo test "buck" (shown in Figure 1) was built from computer-aided design files of the vehicle geometry and other vehicle information supplied by Volvo, as well as information collected at NREL. When information was not available, model parameters were estimated to most closely match the configuration of the actual Volvo test bucks undergoing thermal testing at the VTIF. Test bucks were used in place of complete vehicles to reduce cost and improve adaptability.

Figure 1: Test bucks on test pad

The CoolCalc model geometry is show in figure 2 below.

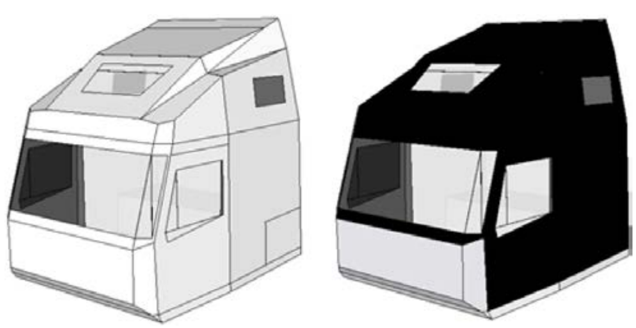

Figure 2: CoolCalc model geometry

This model was used to investigate national heating and cooling thermal loads for different paint colors, shown in figure 3.

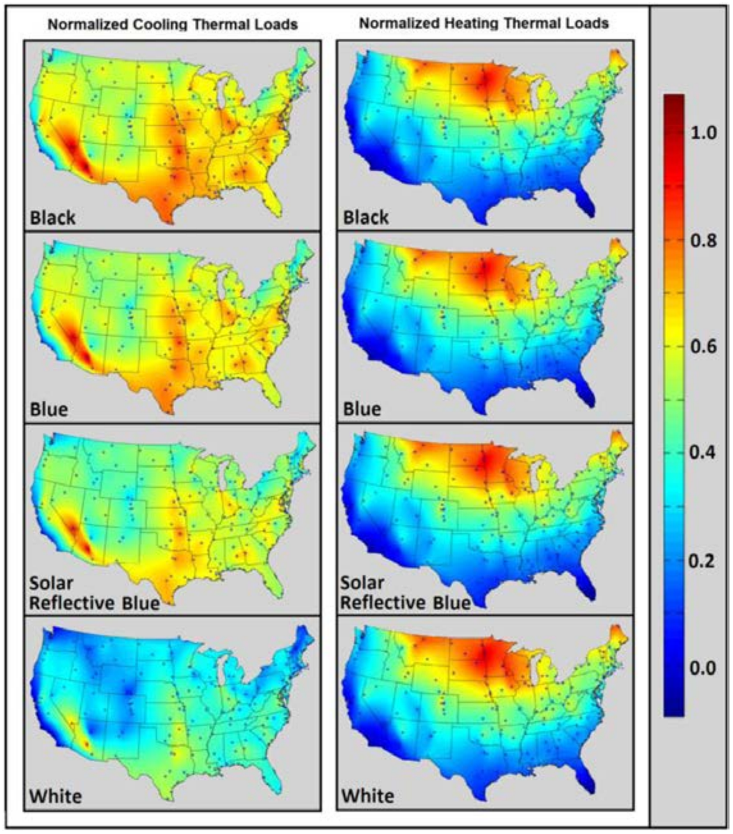

Figure 3: These are National daily cooling (left) and heating (right) sleeper HVAC thermal loads for the four cab paint colors of interest. The data represent the 95th percentile thermal loads and are normalized based on peak load.

Additional details of this work were published at SAE World Congress [1].

Task 2. Instrument and test Volvo baseline truck

The truck supplied by Volvo will be instrumented for outdoor thermal testing. The testing to be performed includes co-heat tests to measure thermal conductivity and calculate R-values and solar soak tests to measure daytime heat gain from the sun. Specific tasks include:

2.1 Instrument control vehicle

Thermocouples: Install temperature sensors (thermocouples) to obtain average cabin and sleeper area temperatures during testing.

Heat Flux Gauges: Install heat flux gauges to measure heat flow through cabin walls.

Heat Source: Install electric heaters to heat truck interior. Install circulation fans to provide more evenly distributed heated air.

2.2 Instrument test vehicle: Install required sensors in Volvo tractor exactly as installed in control vehicle in 2.1.

2.3 Install data acquisition hardware.

2.4 Perform co-heat test to calculate UA value for each truck. Start cabin air circulation fans (described above), and heat both truck interiors to 40ºC to simulate a typical cab temperature differential in a test ambient of about 15ºC.

2.5 Perform solar soak test. Ensure heaters and circulation fans are not operating by disconnecting the power to these devices. Using the data acquisition system, begin logging all temperatures in both trucks in the morning to capture peak sun intensity from about noon–2 p.m.

NREL's facility is located in Golden, Colorado, at an elevation of 5,997 feet at latitude 39.7 N and longitude 105.1 W. The experimental setup included two current model Volvo cab test bucks. Both bucks were the cab section from a representative truck in current production provided by Volvo Trucks North America. One buck was utilized as the control buck. The other was modified as the test buck.

For the experimental setup, the test and control bucks were oriented facing solar south and separated by a distance of 25 feet to maximize solar loading and minimize shadowing effects. To keep the firewalls from receiving direct solar loads, a firewall shade cloth was implemented on both the control and test bucks. In each vehicle, the sleeper curtain and four shades were available for use, depending on the test being conducted. The shades available were the front privacy, cab skylight, and two bunk window curtains.

A National Instruments SCXI data acquisition system was used to record measurements at a sampling frequency of 1.0 Hz, which was averaged over 1-minute intervals. Each cab had over 40 calibrated type K thermocouples for a variety of surface and air temperature measurements. An isothermal bath and a reference probe were used for thermocouple calibration, achieving a U95 uncertainty of ±0.32°C in accordance with American Society of Mechanical Engineers standards. Air temperature sensors were equipped with a double concentric cylindrical radiation shield to prevent errors resulting from direct solar radiation. The heater electrical power consumption was measured using Yokogawa watt meters with the accuracy of ±0.2% reading. Weather data were collected from both NREL's Solar Radiation Research Laboratory and NREL's Vehicle Testing and Integration Facility weather stations, which together feature more than 160 instruments dedicated to high-quality measurements of solar radiation and other meteorological parameters.

The interior air temperature was determined as an average of the combined sleeper and cab air temperatures. The average interior cab air temperature was calculated by averaging six thermocouples with four located in accordance with the American Trucking Association Technology Maintenance Council's recommended practice RP422A. Similarly, the average sleeper air temperature was calculated by averaging eight thermocouples with six located in accordance with RP422A. The addition of two thermocouples located in both the cab and sleeper air spaces improved the average air temperature measurement by more accurately capturing the air temperature distribution.

Testing and modeling were used to down-select technologies to develop a Complete-Cab Thermal Load Reduction Package. The Complete-Cab Thermal Load Reduction Package was composed of advanced privacy and sleeper curtains designed by NREL, an advanced insulation package provided by Aearo Technologies, and an ultra-white paint provided by PPG Industries. Air conditioning tests, figure 4, showed energy consumption was reduced by at least 35.7% for Colorado summer environmental conditions. Further details were published at SAE [2].

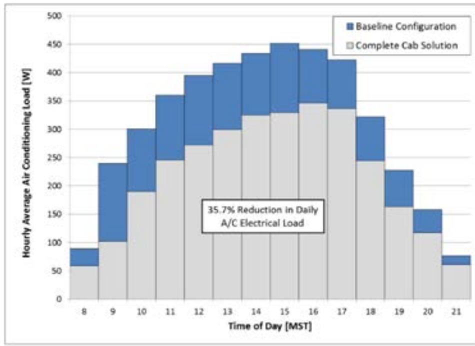

Figure 4: Hourly electrical A/C load for maximum tested daily load condition

The UA test procedure used to measure the heating performance of the Complete-Cab Thermal Load Reduction Package was conducted at night to eliminate solar loading effects. The sleeper air temperature of both bucks was controlled to 32°C using a forced air heater. This temperature was selected to provide a sufficient temperature difference of at least 10°C from the environment over the extended test season.

To account for normal day-to-day variations in weather conditions, the control buck was used as a reference. All vehicles will have some thermal performance variation due to differences in climate control systems, manufacturing, leakage, and other factors. To account for this, the control cab was calibrated to the test cab while both bucks were in a baseline configuration. The control cab can then be used as an accurate reference for the behavior of the test cab in a baseline configuration.

The test buck thermal load reduction package was tested for multiple configurations as summarized in Table 1. Applying only the advanced curtains and shades to the standard insulation resulted in a 20.6% reduction in UA. The advanced insulation alone was also effective at reducing the heating load, yielding a 20.7% reduction in UA. Applying the full thermal load reduction package with both advanced curtains and shades resulted in a 43% reduction in UA. Additional details were published in an SAE journal [3].

Table 1: Thermal load reduction with advanced insulation

Configuration	Insulation	Privacy shades on windshield	Sleeper curtains	Reduction in UA	Standard Deviation (σ)
Baseline with sleeper curtains closed	Standard	Standard	Standard	-	-
Advanced curtains	Standard	Advanced	Advanced	20.6%	0.9%
Advanced insulation	Advanced	Standard	Standard	20.7%	0.4%
Complete cab solution	Advanced	Advanced	Advanced	**43.0%**	**1.6%**

Results from solar soak tests conducted at NREL for blue and solar refective blue paint can be seein in figure 5 below [1].

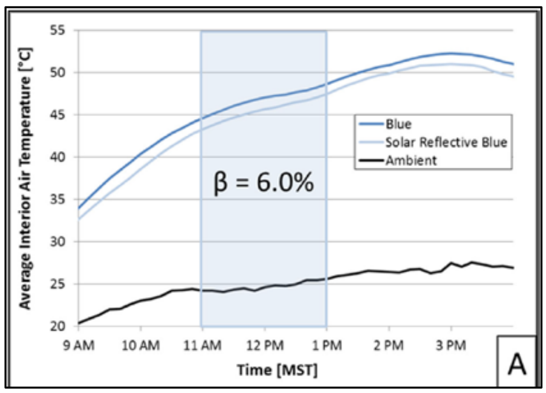

Figure 5: Thermal soak results with blue and solar reflective blue opaque surfaces

Task 3. Correlate CoolCalc model with baseline test results

Results from testing in Task 2 will be compared to the predicted results from the CoolCalc tool in Task 1. Differences between modeled and tested results will be investigated and the model will be refined as necessary to accurately predict heating and cooling loads. Test data will be used to validate the CoolCalc load calculation tool so that accurate predictions of potential thermal load reductions can be made.

A custom weather file was created from data collected with the weather stations during testing. The model used the same south-facing orientation, thermal soak configuration, and weather conditions experienced by the test bucks. The model was then validated against experimental thermal soak test data to verify its accuracy.

Comparison of the model and experimental results for three consecutive days (Figure 6A) shows close agreement in trends and peak air temperatures for a variety of weather conditions. The maximum difference between experimental and model average sleeper air temperature during the hours of peak solar load (11 a.m.−1 p.m. MST) was 0.89°C. Exterior surface temperature comparisons, shown in Figure 6B, between model and test results demonstrate that the model accurately captures the effect of solar position and vehicle orientation.

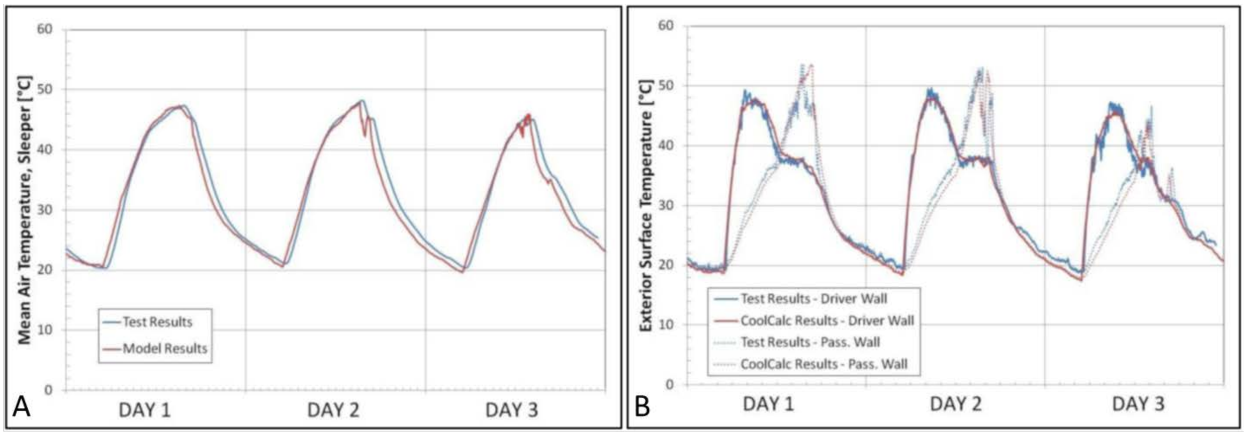

Figure 6: Validation of CoolCalc model with test data A. Mean air temperature B. Exterior surface temperature

[1] J. A. Lustbader *et al.*, “Impact of Paint Color on Rest Period Climate Control Loads in Long-Haul Trucks,” SAE International, Warrendale, PA, SAE Technical Paper 2014-01–0680, Apr. 2014.

[2] J. A. Lustbader, C. Kreutzer, S. Adelman, S. Yeakel, and J. Zehme, “Sleeper Cab Climate Control Load Reduction for Long-Haul Truck Rest Period Idling,” 2015.

[3] J. A. Lustbader *et al.*, “Long-Haul Truck Sleeper Heating Load Reduction Package for Rest Period Idling,” *SAE Int. J. Passeng. Cars - Mech. Syst.*, vol. 9, no. 2, Apr. 2016.

Subject Inventions Listing:

None

Report Date:

2 February 2018

ROI #:

None

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