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Impact of Paint Color on Rest Period Climate Control Loads in Long-Haul Trucks

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Abstract

Cab climate conditioning is one of the primary reasons for operating the main engine in a long-haul truck during driver rest periods. In the United States, sleeper cab trucks use approximately 667 million gallons of fuel annually for rest period idling. The U.S. Department of Energy's National Renewable Energy Laboratory's (NREL) CoolCab Project works closely with industry to design efficient thermal management systems for long-haul trucks that minimize engine idling and fuel use while maintaining occupant comfort.

Heat transfer to the vehicle interior from opaque exterior surfaces is one of the major heat pathways that contribute to air conditioning loads during long-haul truck daytime rest period idling. To quantify the impact of paint color and the opportunity for advanced paints, NREL collaborated with Volvo Group North America, PPG Industries, and Dometic Environmental Corporation. Initial screening simulations using CoolCalc, NREL's rapid HVAC load estimation tool, showed promising air-conditioning load reductions due to paint color selection. Tests conducted at NREL's Vehicle Testing and Integration Facility using long-haul truck cab sections, “test bucks,” showed a 31.1% of maximum possible reduction in rise over ambient temperature and a 20.8% reduction in daily electric air conditioning energy use by switching from black to white paint. Additionally, changing from blue to an advanced color-matched solar reflective blue paint resulted in a 7.3% reduction in daily electric air conditioning energy use for weather conditions tested in Colorado. National-level modeling results using weather data from major U.S. cities indicated that the increase in heating loads due to lighter paint colors is much smaller than the reduction in cooling loads.

Introduction

Cab climate conditioning is one of the primary reasons for operating the main engine in a long-haul truck during driver rest periods. In the United States, sleeper cab trucks use an estimated 667 million gallons of fuel annually for rest period idling [1]. This represents 6.8% of the total estimated long-haul truck fuel use. An additional 2.4 billion gallons of fuel are used annually for commercial truck workday idling [1]. Idling represents a zero freight efficiency operating condition for the truck. With the recent high prices of diesel, fuel is one of the largest trucking costs per mile at 35% of the total [2]. Therefore, the increasing cost and cost volatility of fuel provides a significant financial incentive to reduce fuel use. Recent federal, state, and city anti-idling regulations [3] are providing further incentive to reduce truck idling. One example is the idle reduction technology credit in the Heavy-Duty Greenhouse Gas Emissions Standards, which are set to begin in 2014 [4].

An opportunity exists to reduce fuel use and emissions associated with idling by reducing thermal loads and improving the efficiency of climate control systems. Enhancing the thermal performance of cab/sleepers will enable smaller, lighter, and more cost-effective idle reduction solutions. In addition, if the fuel savings from new technologies provide a one- to three-year payback period [5], fleet owners will be economically motivated to incorporate the new technologies. Therefore, financial incentive provides a pathway to rapid adoption of effective thermal load and idle reduction solutions.

The U.S. Department of Energy's National Renewable Energy Laboratory's (NREL's) CoolCab project is researching efficient thermal management systems to maintain cab occupant comfort without the need for engine idling. The

CoolCab project uses a system-level approach that addresses thermal loads, designs for occupant thermal comfort, and maximizes equipment efficiency. In order to advance the goals of the CoolCab project and the broader goals of increased national energy security and sustainability, the CoolCab team works closely with industry partners to develop and apply commercially viable solutions to reduce national fuel use and industry costs. In order to reduce thermal and resulting idle loads in long-haul trucks, NREL has identified air volume management, conductive pathways, and solar envelope as focus areas for potential technologies. A previous study published by the group focused on the effect of insulation packages on heating and cooling idle loads [6]. The present study focuses on reducing the solar envelope loads through the application of production and advanced paint colors. Prior studies on light-duty vehicles showed opportunity for reducing cooling load by changing vehicle exterior paint color. Rugh et al. showed a 28% of theoretical maximum breath air temperature reduction by applying aluminum foil to exterior opaque surfaces, quantifying the maximum potential improvement [7]. Levinson et al. showed a 4°-6°C reduction in cabin air temperature with a silver car compared to a black car [8]. The larger opaque-to-glazing surface ratio of long-haul sleeper cabs compared to light-duty vehicles suggests a potentially higher sensitivity of thermal loads to opaque surface treatment. This study investigates the thermal loads of a long-haul sleeper cab in engine-off rest period operation using black, white, blue, and an advanced color-matched solar reflective paint. This advanced paint is designed to have a very similar color as traditional paint in the visible spectrum while having an increased reflectivity in the infrared region. Solar reflective paint could provide a means to reduce loads while maintaining paint color selection for branding and aesthetic purposes.

Approach

NREL collaborates with original equipment manufacturers and suppliers to develop and implement a strategic three-phase approach capable of producing commercially viable solutions to enable idle reduction systems. This three-phased approach was developed to evaluate commercially available and advanced vehicle thermal management and idle reduction technologies. The three phases are Baseline Testing and Model Development, Thermal Load Reduction, and Idle Reduction. Each phase features application of NREL's suite of thermal testing and analysis tools.

In Phase I, Baseline Testing and Model Development, thermal data is collected on a test and control vehicle simultaneously. Several days of data are collected for each test procedure under varying weather conditions. The data is used to calibrate the control vehicle to represent an unmodified baseline test vehicle. Once the control vehicle is calibrated to predict the performance of the test vehicle, validation tests are conducted. Validation data is collected with the control and test vehicles under unmodified baseline conditions. Calibration coefficients are applied to the control vehicle validation data, and the results are used to confirm the accuracy of the calibration. Baseline performance data of the test vehicles is also used for development and validation of CoolCalc models [9].

In Phase II, Thermal Load Reduction, CoolCalc parametric studies are used as a screening tool for potential thermal load reduction technologies. Reductions in cab/sleeper thermal loads are quantified through experimental investigation of selected commercial and advanced technologies identified from CoolCalc modeling.

In Phase III, Idle Reduction, the most promising of the evaluated technologies are researched further by closely collaborating with industry partners and their suppliers to design and evaluate cab thermal packages that improve thermal performance, reduce climate control loads, and enable market penetration of idle reduction systems. In this phase, vehicles are equipped with commercial and advanced cab thermal management packages coupled with an idle reduction system. NREL experimentally characterizes the impact of these technologies on idle loads. CoolCalc analysis and vehicle simulations are also used to characterize the reduction in idle loads and fuel consumption over a wide range of use and environmental conditions.

The test program was conducted at NREL's Vehicle Testing and Integration Facility (VTIF), shown in Figure 1, during the months of May through September. The 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 an NREL-owned test truck and two 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 while the other was experimentally modified.

Figure 1. NREL's Vehicle Testing and Integration Facility

For the experimental setup, the truck, test buck, and control buck were oriented facing south and separated by a distance of 25 feet to maximize solar loading and minimize shadowing effects. To keep the buck firewalls from receiving direct solar loads, a firewall shade cloth was implemented on both the control and test bucks. In each vehicle, five curtains were available for use depending on the test being conducted. The curtains available were the privacy, cab skylight, sleeper, 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 one-minute intervals. Among the three vehicles, over 140 calibrated type K thermocouples were used. An isothermal bath and reference probe were used for thermocouple calibration, achieving a U_{95} uncertainty of ±0.32°C in accordance with ASME standards [10]. Air temperature sensors were equipped with a double concentric cylindrical radiation shield to prevent errors due to direct solar radiation.

Weather data was collected from both NREL's Solar Radiation Research Laboratory and NREL's VTIF weather station [11], which together feature more than 160 instruments dedicated to high-quality measurements of solar radiation and other meteorological parameters.

Thermal soak tests were conducted to evaluate the impact of paint in an engine-off solar loading condition on interior air temperatures in a test truck or buck ($\overline{T}_{\text{modified}}$) compared to interior air temperatures in the baseline buck ($\overline{T}_{\text{baseline}}$). During summer operation with passive vehicle thermal load reduction technologies, the best possible steady-state performance is to reduce the interior temperature to ambient temperature. The percent of maximum possible temperature reduction (β) was developed to describe this maximum possible reduction in interior air temperature rise above ambient ($\overline{T}_{\text{ambient}}$), as described in Equation 1. A β value of 0% indicates that the technology under evaluation did not change the rise over ambient temperature, while a β value of 100% indicates the technology reduced the interior air temperature in the modified vehicle to equal the temperature of ambient air in the environment.

$$\beta = \frac{\overline{T}_{\text{baseline}} - \overline{T}_{\text{modified}}}{\overline{T}_{\text{baseline}} - \overline{T}_{\text{ambient}}} \cdot 100\% \qquad (1)$$

For the evaluation of β, the interior air temperature was determined as a volume weighted 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 [12] as shown in Figure 2A. Similarly, average sleeper air temperature was calculated by averaging eight thermocouples with six located in accordance with RP422A, illustrated in Figure 2B. The addition of two thermocouples located in both the cab and sleeper air spaces improved the accuracy of the average air temperature by more accurately capturing the air temperature distribution. During testing, it was determined that the cab footwell air temperature measurements were exposed to occasional direct solar radiation. Due to the increased variability that would occur in the calculation of average interior air temperature, these two measurements were omitted from the calculation.

For the thermal soak testing, data was collected for a time interval from 5:00 a.m. to 3:00 p.m. MST. During baseline thermal soak measurements, all privacy curtains were removed. The thermal soak performance of the bucks in their baseline conditions was used to characterize and calibrate the inherent differences between the two bucks. Calibration was accomplished by collecting four days of baseline data and generating a time-of-day dependent correction factor between the control buck and test buck. Solar load intensity peaked at approximately 12:00 p.m. daily during thermal soak testing. In addition, peak differential temperatures were found to occur within the 11:00 a.m. to 1:00 p.m. MST time interval corresponding to this peak solar load. Therefore, interior air and ambient temperatures from 11:00 a.m. to 1:00 p.m. MST were used for the calculation of β.

For quantifying idle load reduction of paint, daytime rest period air conditioning (A/C) tests were conducted on an electric no-idle A/C system. A 2,050 W (7,000 Btu/hr) Dometic electric A/C system [13] was installed in the sleeper compartment of each vehicle. For A/C experimentation, all five curtains were utilized on the control and test buck. All curtains were employed to match the expected standard configuration during a rest period operation. The test period was defined as A/C system first-on to last-off to quantify the daily A/C energy consumption. A standard battery-powered A/C system containing four 1,500 W·h lead acid batteries and weighing a total of 132 kg (291 lb) was used for the calculation of system improvements in the results section. A/C electrical power consumption was measured using a Load Controls Incorporated model UPC adjustable capacity power sensor. The power sensor was calibrated to ±15 W. Air conditioning systems were controlled to a target sleeper air temperature of 22.2°C (72°F). Calibration of the modified buck A/C system was performed by collecting multiple days of baseline data. A clear solar day with insignificant cloud cover was required for data to qualify as a baseline test day.

NREL's CoolCalc software was used to model the impact of paint on vehicle temperature and heating, ventilation, and air conditioning (HVAC) loads. CoolCalc is an easy-to-use, simplified, physics-based HVAC load estimation tool that requires no meshing, has flexible geometry, excludes unnecessary detail, and is less time-intensive than more detailed computer-aided engineering modeling approaches. For these reasons, it is ideally suited for performing rapid trade-off studies, estimating technology impacts, and sizing preliminary HVAC designs. CoolCalc complements more detailed and expensive computer-aided engineering tools by first exploring the design space to identify promising technologies and specific parameters that require deeper investigation.

CoolCalc, described in more detail in [9], was built on NREL's original OpenStudio platform as a plug-in extension for the SketchUp three-dimensional design software (now owned by

Trimble), and has been adapted to better suit the transportation industry. DOE's EnergyPlus software (developed for building energy modeling) is used as the heat transfer solver for CoolCalc.

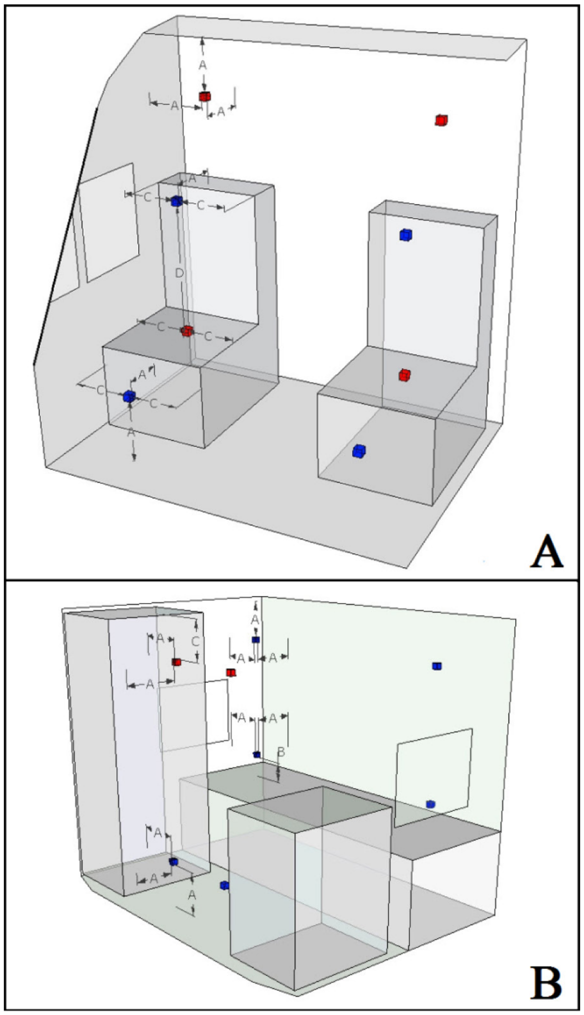

Figure 2. Cab (A) and sleeper (B) thermocouple locations, blue - Technology and Maintenance Council's standard [12], red - NREL added, dimensions A = 12,″ B = 6,″ C = 18″

For the evaluation of paint color, black, blue, a color-matched solar reflective blue, and white paints were selected. The paint was applied with a primer, basecoat, and clear coat process. Both the blue and solar reflective blue basecoats were applied to a white basecoat adding an additional paint layer for those configurations. While there are different approaches to formulating coatings for increased IR reflection, the blue color used was made with pigmentation that would impart a very similar color in the visible spectrum but has increased transparency to wavelengths in the IR region. This prevents the energy in the IR spectrum from being absorbed in the blue color layer and it is reflected by the white layer underneath. Both test and control bucks were initially painted a standard white color. For evaluation of black, blue, and solar reflective blue paints, the test buck was painted and compared to the white control buck. In order to compare blue and solar reflective blue test results, a calibration correction was first applied to the control buck. The ratio of corrected control buck results obtained during blue and solar reflective blue tests were then used to scale the blue test results to that of the solar reflective blue test results.

Results

Phase I: Baseline Testing and Model Development

Phase I research focused on the installation, instrumentation, and baseline testing of the two bucks supplied by Volvo Trucks and the NREL-owned test truck. To confirm the bucks were accurate representations of a complete truck, average sleeper and cab air temperatures were compared between the control buck and test truck baseline data. The average air temperature between the control buck and test truck differed by less than 7°C for the cab air space and 5°C for the sleeper air space. The temperature differences observed may be largely explained by differences in manufacturer, geometry, and components. The temperature difference between the buck and truck prior to calibration was highly repeatable with a standard error of less than ± 0.17°C. For the test buck and control buck, cab air temperature agreed to within 1.6°C and sleeper air temperature was within 0.9°C prior to calibration.

After calibrating the modified buck and test truck with the control buck, calibration accuracy was checked using validation test data. Thermal soak calibration was shown to be within ±0.4°C for the test cab and within ± 0.6°C for the test truck between the peak solar loading time of 11:00 a.m. and 1:00 p.m. MST. The results of the calibration applied to a validation dataset for the test truck sleeper air temperature are shown in Figure 3. For the validation dataset, sleeper air temperature prediction agreed to within ±0.4°C for the test truck and ±0.2°C for the test buck.

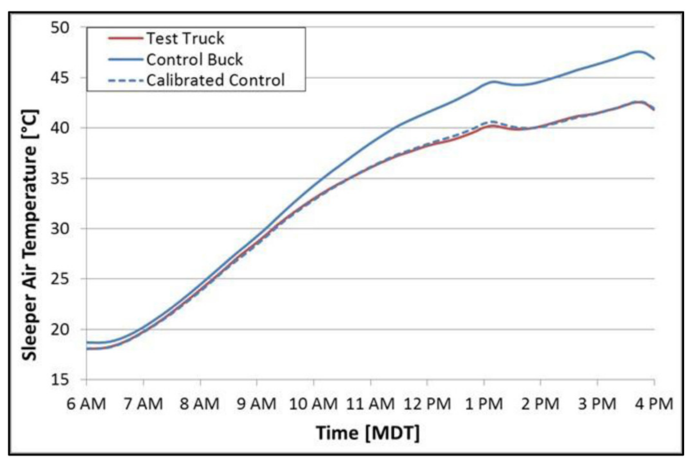

Figure 3. Average sleeper interior air temperature validation day

Baseline A/C testing of the test and control bucks showed repeatable differences between the two configurations. The calibration data for A/C baseline testing is shown in Figure 4, which includes both calibration days and additional test days. The additional test days were collected but are excluded from the calibration dataset because the solar load throughout these days was not consistent due to partially cloudy weather. The additional test days confirm the strong linear correlation between the two test configurations. The additional test data also indicate that the correlation between test and control buck A/C power consumption is somewhat insensitive to minor solar load variations.

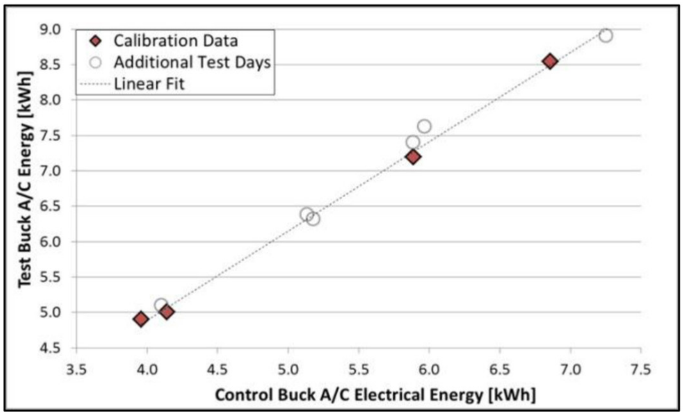

Figure 4. Daily A/C energy calibration data for test and control bucks

After completing baseline testing, a CoolCalc model of a Volvo test “buck” (shown in Figure 5) 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 (Figure 10) undergoing thermal testing at the VTIF. Test bucks were used in place of complete vehicles to reduce cost and improve adaptability.

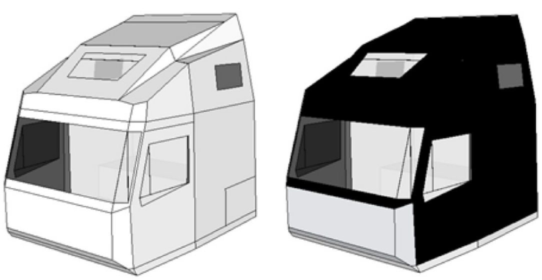

Figure 5. CoolCalc model of a Volvo test buck, white baseline and black paint configuration shown

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 6) 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 7, between model and test results demonstrate that the model accurately captures the effect of solar position and vehicle orientation.

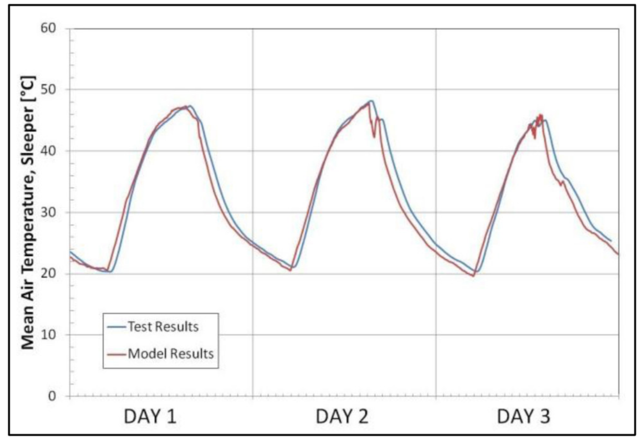

Figure 6. Volvo test buck CoolCalc model validation - sleeper compartment mean air temperatures

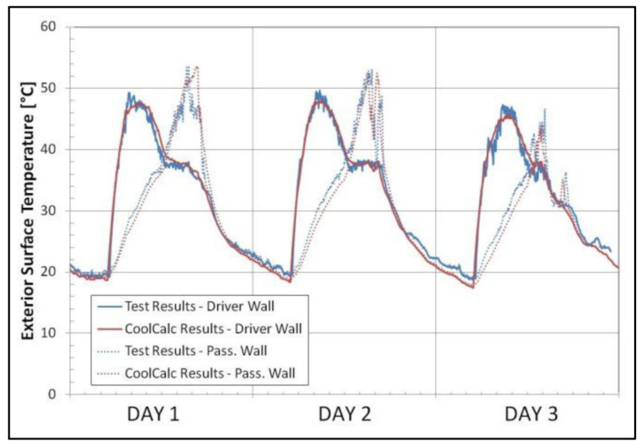

Figure 7. Volvo test buck CoolCalc model validation - exterior side wall temperatures for both driver and passenger sides

After validating the model with test data, the CoolCalc model was used to help guide testing efforts by identifying opportunities to reduce long-haul truck thermal loads.

Phase II: Thermal Load Reduction

Phase II research investigated the significance of vehicle color on thermal loads, using interior air temperature as an indicator of trends. The validated CoolCalc model was used to quantify the impact of paint colors on vehicle air temperatures. Figure 8 shows the predicted interior air temperatures from each of the simulations using estimated paint properties. The percentage of maximum possible temperature reduction, β, was calculated from the average air temperatures during the peak solar time of day (11 a.m. −1 p.m. MST). The model predicts β = 35.4% changing from black to white paint, and β = 14.6% from blue to solar reflective blue paint. Based on the promising modeling results obtained, NREL worked with industry partners to experimentally measure the potential impact of paint properties on engine-off thermal soak air temperature reduction for heavy-duty trucks.

The radiative properties of the paints provided by PPG for experimental testing were measured at NREL. Figure 9 shows the reflectance spectra in the ultraviolet, visible, and infrared regions. The reflectance spectrum of blue and solar reflective blue show very similar behavior throughout the visible spectrum (380-750 nm) followed by a sharp increase in reflectance for solar reflective blue in the infrared region. Table 1 summarizes the measured solar-weighted radiative properties. The initial estimated properties for solar reflective blue were based on exploratory information, and the actual solar reflective blue properties showed less but still significant change from the reference blue paint.

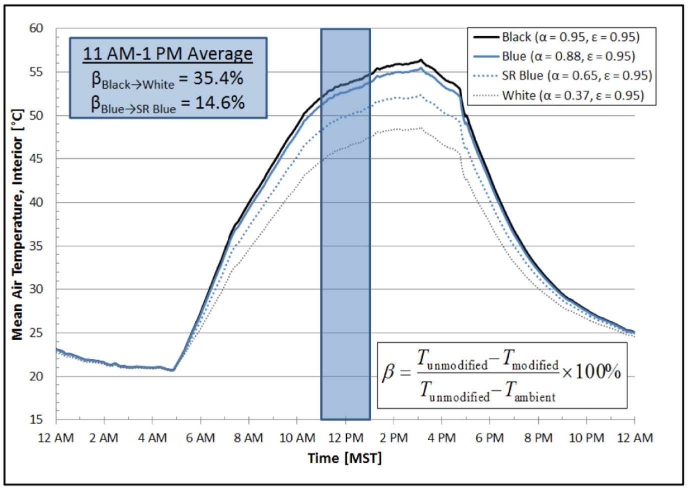

Figure 8. CoolCalc surface absorptivity screening study with estimated solar reflective blue properties

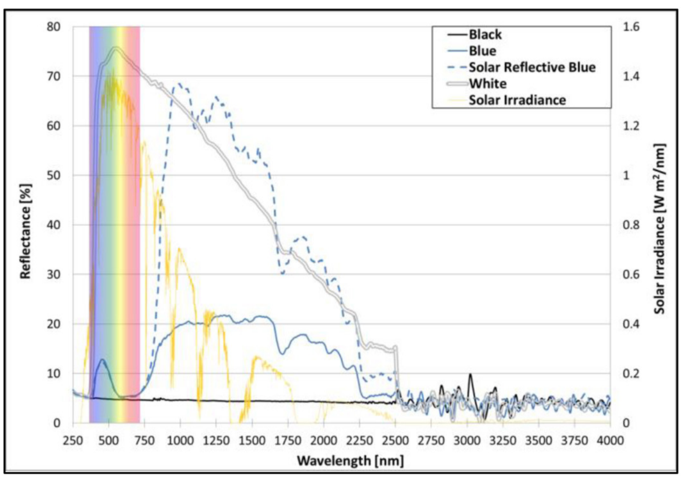

Figure 9. Measured reflectance spectrum for paint colors used in testing

Table 1. Solar-weighted radiative properties of paint test samples

Paint Color	Absorptance [%]	Emissivity
White	37.2	0.953
Black	95.3	0.951
Blue	88.0	0.951
SR Blue	74.2	0.948
SR Blue Estimated	65.0*	0.950*

*Estimated values used in CoolCalc prediction study

The test bucks were painted and thermal soak tests were conducted, Figure 10. In addition, the measured weather data was used to simulate the same conditions in the CoolCalc model. Figure 11 shows the experimental and CoolCalc model average interior air temperatures over the daytime thermal soak test for both black and white paint. The figure also shows both experimental and model results for the percent of maximum possible reduction in interior air temperature rise above ambient, β, at peak solar load between 11:00 a.m. and 1:00 p.m. MST. The CoolCalc model accurately captures air temperature with time for both black- and white-painted cabs and shows close agreement with experimental results obtained for the percent of maximum possible reduction in interior air temperature rise above ambient, with β = 31.1% for experiment and β = 32.5% for the CoolCalc model.

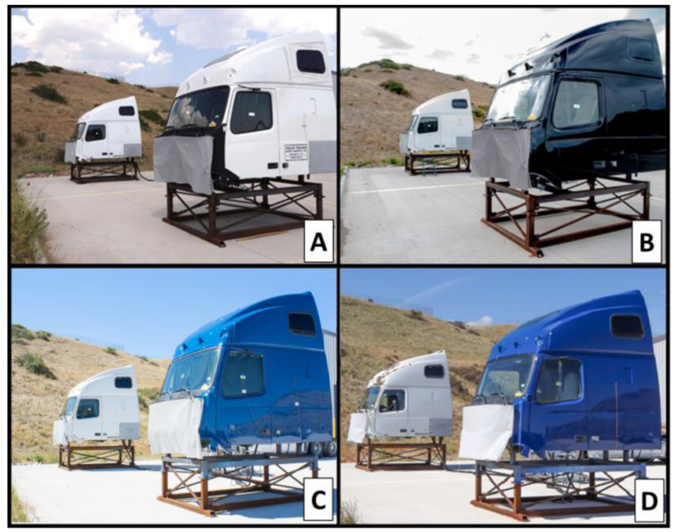

Figure 10. Cab experimental configurations: Test buck painted white (A), black (B), blue (C), and solar reflective blue (D)

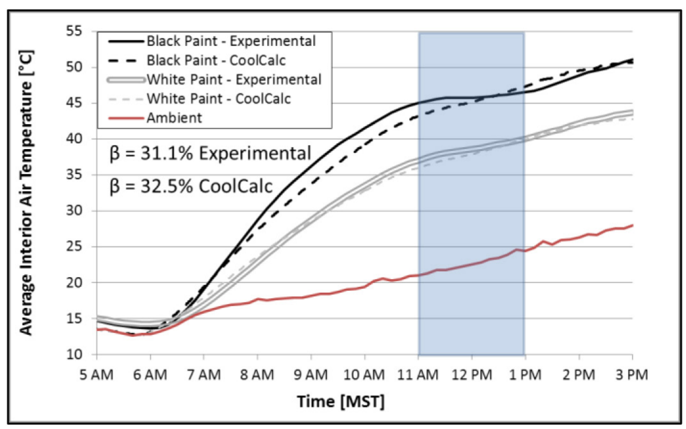

Figure 11. Thermal soak results with black and white opaque surfaces

Thermal soak testing of blue and solar reflective blue exterior surfaces showed a percent of maximum possible temperature reduction of β = 6.0% during peak solar loading from 11:00 a.m. - 1:00 p.m. MST. The average interior air temperature for blue and solar reflective blue during thermal soak conditions is shown in Figure 12A. In addition to experimental testing, CoolCalc modeling was performed using the test day's weather and measured paint properties as input. Model predicted average interior air temperatures are provided in Figure 12B. The model predicted a maximum possible temperature reduction of β = 6.2%, which closely matched experimental results.

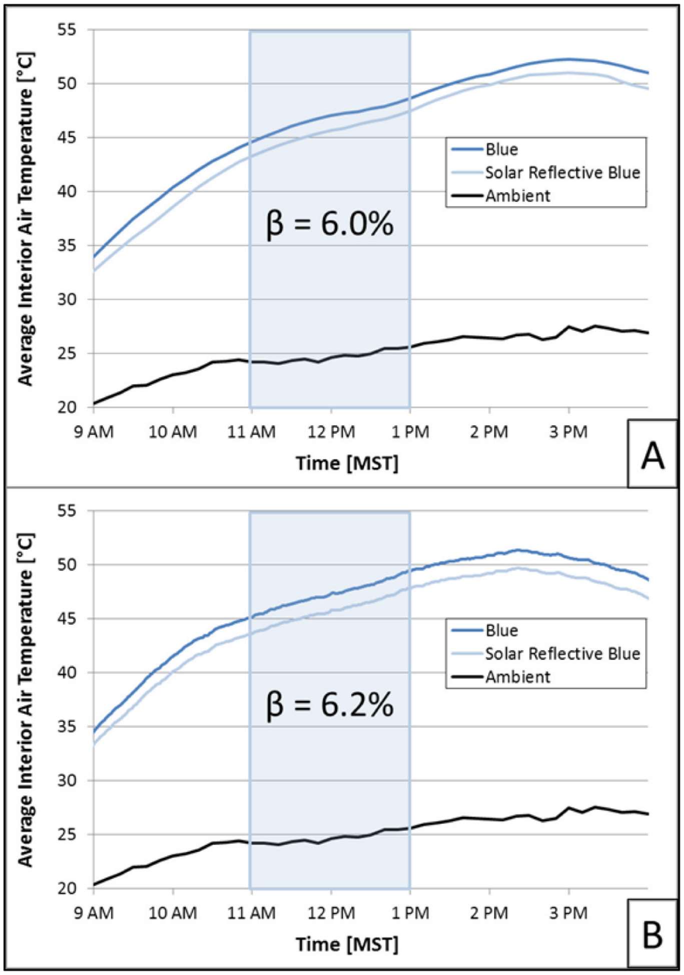

Figure 12. Thermal soak results with blue and solar reflective blue opaque surfaces. A: Experimental results, B: CoolCalc model results

Phase III: Idle Load Reduction

Phase III focused on the quantification of the impact of paint color on the A/C system electric power use in the test cab sleeper air space during engine-off daytime test conditions.

During evaluation of the black test buck, the A/C target temperature was increased to 26.7°C (80°F) for the test buck to accommodate the increased load for this configuration. Hourly average A/C power consumption (Figure 13) shows consistent reduction in A/C electrical energy loads throughout daytime operation. The average daily A/C power consumption decreased 20.8% switching from black to white paint. The decrease corresponds to a 1,001 W·h battery energy savings over the daytime test period. A 1,001 W·h daily energy savings would correspond to a 16.7% reduction in battery capacity and 22 kg (48 lb) reduction in weight from the standard battery as described in the Approach.

During idle load reduction testing of the blue and solar reflective blue test bucks, the A/C target temperature was maintained at the recommend 22.2°C (72°F). The average daily A/C electrical load was reduced by 563 W·h, representing a 7.3% savings going from blue to solar reflective blue paint. A 563 W·h reduction in daily electrical energy would equate to a 9.4% reduction in battery capacity and 12.4 kg (27.3 lb) reduction in battery weight.

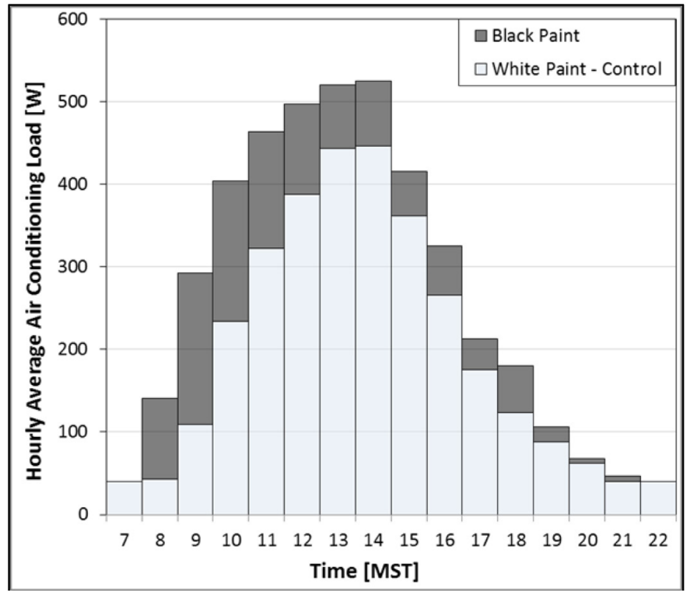

Figure 13. Hourly average test cab A/C power consumption for black and white opaque exterior surfaces

To understand the impact of exterior paint color on long-haul truck HVAC thermal loads over a wider range of conditions than those that were experimentally measured at the NREL test facility, a national-level CoolCalc analysis was conducted. To capture the weather conditions throughout the United States, the three most populous cities in each of the contiguous U.S. states were selected. For the simulation, typical meteorological year (TMY) weather data [15] for each of the 144 cities was used. TMY weather data consist of actual hourly weather information representative of typical local climatic conditions on a monthly basis concatenated into an entire year. For the evaluation, paint color was defined as a parametric variable, and the colors used for the model matched those used for experimental outdoor testing provided in Table 1 above. For the simulation, the sleeper compartment was heated when the interior air temperature dropped to 18.3°C (65°F) and cooled when the indoor air temperature increased to 23.9°C (75°F), leaving a 5.6°C (10°F) deadband between the two temperatures. The model was configured with all curtains closed and the front of the cab facing directly south. To increase the speed of simulation for large parallel runs, NREL coupled CoolCalc with a high performance computer.

Figure 14 shows national maps of normalized cooling and heating thermal loads simulated at each of the major U.S. cities as indicated for the four paint colors in the study. The data represent the 95th percentile for heating and cooling loads, meaning that 95% of the weather days evaluated have a lower thermal load. For the figure, cooling and heating loads were independently normalized to cooling maximum and heating maximum loads; therefore, their scales do not indicate the same magnitude. As shown in the figure, changing from black to white paint significantly reduces the cooling thermal loads and has a minimal increase in heating loads. In addition, cooling loads with black paint show a strong sensitivity to regional climate while white paint shows a much smaller sensitivity. Similarly, changing from blue to solar reflective blue paint has a measurable reduction in thermal load with no significant change in heating loads. The insensitivity of winter heating loads to paint color is due to the short days and low solar intensity in the winter, particularly in the colder northern latitudes. Unlike cooling loads, peak heating loads also occur at night and are unaffected by the solar radiative paint properties.

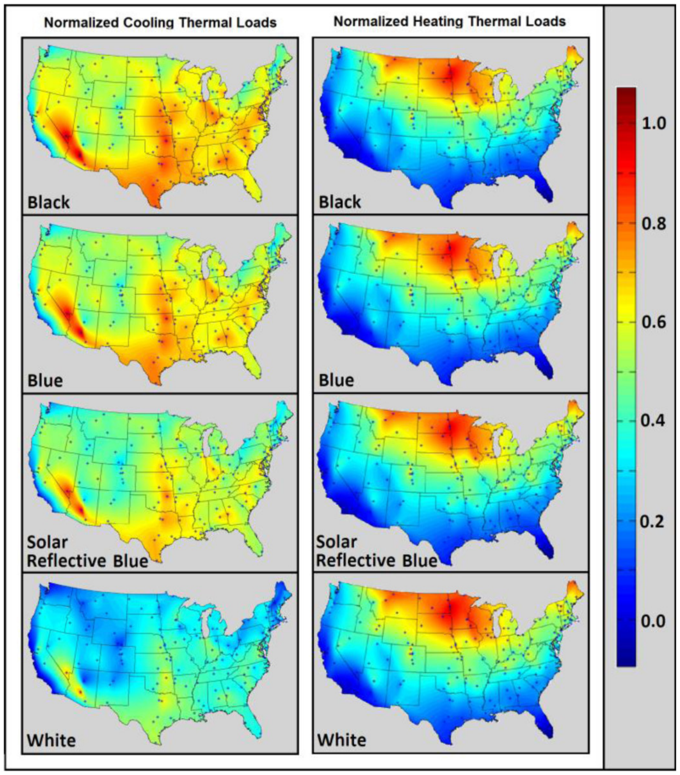

Figure 14. National daily cooling (left) and heating (right) sleeper HVAC thermal loads for the four cab paint colors of interest. Data represent 95th percentile thermal loads and are normalized based on peak load.

Summary/Conclusions

Long-haul truck rest period idling, a zero freight efficiency operating condition, consumes an estimated 6.8% of long-haul truck fuel use in the United States. Much of this idling is done to provide climate control to the cab/sleeper. To reduce loads, NREL is investigating the solar envelope, conductive pathways, and conditioned air volume management. For this study, NREL has partnered with Volvo Trucks, PPG Industries, and Dometic Environmental Corporation to investigate the impact of paint on long-haul truck climate control loads.

By switching from black to white paint, long-haul sleeper daily electrical A/C loads were reduced by as much as 20.8%. An electrical energy saving of 1,001 W·h was achieved during a daytime rest period while operating an A/C system under ambient conditions in Golden, Colorado. The electrical energy savings would correspond to a 16.7% reduction in A/C battery capacity and 22 kg (48 lb) weight reduction from the standard battery size. Selecting white paint on a new vehicle adds no additional cost and would have an immediate payback. When the choice of paint color is critical for brand recognition and/or aesthetic purposes, load reductions are obtainable through the use of advanced color-matched solar reflective paints. Switching from a blue to an advanced color-matched solar reflective blue paint resulted in a 7.3% reduction in daily electrical A/C load under the conditions tested. This 563 W·h reduction in daily electrical energy would equate to a 9.4% reduction in battery capacity and 12.4 kg (27.3 lb) reduction in battery weight.

A CoolCalc model of a Volvo long-haul truck sleeper cab was developed and validated, showing good agreement with test data. Over the three validation days, 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. The model also predicted the impact of paint colors well, agreeing with both trends and maximum possible reduction in rise over ambient temperature estimations. The validated model was then used to conduct a national paint impact study using TMY weather data for 144 major U.S. cities which confirmed that paints with higher solar reflectivity reduce thermal loads significantly in cooling conditions and have little to no detrimental impact on heating loads. The lower cooling loads show the potential to reduce A/C loads through the selection of paint color.

Working closely with industry partners, NREL has applied experimental and modeling tools to show that systematically combining vehicle thermal management and idle reduction technologies can reduce climate control loads needed for long-haul truck rest period idling. This can reduce cost, weight, and volume of idle reduction systems, improving payback period and increasing economic motivation for fleet owners and operators to consider idle reduction systems. Increasing idle reduction system effectiveness and adoption rates will help reduce the 667 million gallons of diesel used annually in the United States for long-haul truck rest period idling and potentially reduce truck operation costs.

The results and methods developed for this study will be used to conduct a more detailed national-level impact study. This future study will be used to understand and develop effective full vehicle thermal load reduction approaches that combine solutions for solar envelope, conductive pathway, and conditioned air volume management that reduce HVAC loads and resulting fuel use.

References

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. Fender K. and Pierce D., “ATRI Operational Costs of Trucking 2012,” American Transportation Research Institute, Atlanta, GA, 2012.
3. “Idling Regulations Compendium, American Transportation Research Institute,” http://atri-online.org/2013/02/20/idling-regulations-compendium/ Accessed on 9/16/2013.

4. “Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, Final Rule,” Federal Register 76 (15 September, 2011): 57106-57513.
5. 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.
6. Lustbader, J., Venson, T., Adelman, S., Dehart, C. et al., “Application of Sleeper Cab Thermal Management Technologies to Reduce Idle Climate Control Loads in Long-Haul Trucks,” SAE Technical Paper 2012-01-2052, 2012, doi:10.4271/2012-01-2052.
7. Rugh, J., Farrington, R. *Vehicle Ancillary Load Reduction Project Close-Out Report*, National Renewable Energy Laboratory, NREL/TP-540-42454, January 2008.
8. 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.
9. Lustbader, J., Rugh, J., Rister, B., and Venson, T., “CoolCalc: A Long-Haul Truck Thermal Load Estimation Tool,” SAE Technical Paper 2011-01-0656, 2011, doi:10.4271/2011-01-0656.
10. Dieck, R.H., Steele, W.G., and Osolsobe, G., *Test Uncertainty*. ASME PTC 19.1-2005. New York, NY. American Society of Mechanical Engineers, 2005.
11. http://www.nrel.gov/midc/vtif_rsr/.
12. “Cab Insulation Testing Methodology,” RP422A-1-9, in *Technology and Maintenance Council's Recommended Maintenance Practices Manual*, 2010-2011 edition, Arlington, VA: American Trucking Association, p. RP422A-1.
13. http://www.dometic.com/enus/Americas/USA/Truck/ Accessed on 10/18/2013.
14. “Vehicle and Systems Simulation and Testing 2012 Annual Progress Report,” DOE/EE-0834, Section IV.N. CoolCab Truck Thermal Load & Idle Reduction, pg. 284-291.
15. http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/. Accessed 9/1/2013.

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Definitions/Abbreviations

A/C - air conditioning

HVAC - Heating, Ventilation, and Air Conditioning

NREL - National Renewable Energy Laboratory

VTIF - Vehicle Testing and Integration Facility

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