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Sleeper Cab Climate Control Load Reduction for Long-Haul Truck Rest Period Idling

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Abstract

Annual fuel use for long-haul truck rest period idling is estimated at 667 million gallons in the United States. The U.S. Department of Energy's National Renewable Energy Laboratory's CoolCab project aims to reduce heating, ventilating, and air conditioning (HVAC) loads and resulting fuel use from rest period idling by working closely with industry to design efficient long-haul truck climate control systems while maintaining occupant comfort. Enhancing the thermal performance of cab/sleepers will enable smaller, lighter, and more cost-effective idle reduction solutions. In order for candidate idle reduction technologies to be implemented at the original equipment manufacturer and fleet level, their effectiveness must be quantified.

To address this need, a number of promising candidate technologies were evaluated through experimentation and modeling to determine their effectiveness in reducing rest period HVAC loads. For this study, load reduction strategies were grouped into the focus areas of solar envelope, occupant environment, and conductive pathways. The technologies selected for a complete-cab package of technologies were “ultra-white” paint, advanced insulation, and advanced curtains. To measure the impact of these technologies, a nationally-averaged solar-weighted reflectivity long-haul truck paint color was determined and applied to the baseline test vehicle. Using the complete-cab package of technologies, electrical energy consumption for long-haul truck daytime rest period air conditioning was reduced by at least 35% for summer weather conditions in Colorado. The National Renewable Energy Laboratory's CoolCalc model was then used to extrapolate the performance of the thermal load reduction technologies nationally for 161 major U.S. cities using typical weather conditions for each location over an entire year.

Introduction

Sleeper cab climate control is one of the primary reasons for operating the main engine in a long-haul truck during driver rest periods. In the United States, long-haul trucks (trucks that travel more than 500 miles per day) use approximately 667 million gallons of fuel annually for rest period idling [1]. This rest period idling is approximately 6.8% of the total long-haul truck fuel use and 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 incentives to reduce truck idling. One example is the idle reduction technology credit in the Heavy-Duty Greenhouse Gas Emissions Standards, effective starting 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 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 three aspects: reducing the thermal loads, efficient delivery of climate control for occupant thermal comfort, and maximizing equipment efficiency. By reducing

thermal loads, the occupant's climate control needs are reduced, and reduced capacity equipment can then provide the conditioning. 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. To reduce thermal and resulting idle loads in long-haul trucks, NREL has identified four thermal load reduction technology focus areas: (1) conductive pathways, (2) the solar envelope, (3) the occupant environment, and (4) efficient equipment. Working closely with industry partners, NREL applied modeling tools and experimental methods to identify and evaluate promising complete-cab heating, ventilating, and air conditioning (HVAC) load reduction solutions comprised of technologies in each of these focus areas. The goal of the complete-cab solutions was to exceed the project's 30% air conditioning (A/C) load reduction goal.

Approach

NREL collaborates with original equipment manufacturers (OEMs) and suppliers to develop and implement a strategic approach capable of producing commercially viable solutions to enable idle reduction systems. NREL first conducts baseline testing of vehicles to quantify their thermal behavior. This information is then used to build and validate CoolCalc and other models. CoolCalc is NREL's rapid HVAC load estimation tool [6]. CoolCalc thermal models are used in conjunction with experimental screening tests to identify promising thermal load reduction technologies. The most promising technologies are then experimentally evaluated for their impact on climate control loads. Experimental results are also used to inform model improvement as needed and gain further confidence in the models. The validated models are then used to understand the national impact of the climate control load reduction technologies on thermal performance, climate control loads, and fuel consumption, spanning the wide range of use and environmental conditions that occur in the United States.

Technology Focus Areas

NREL has identified four key climate control load technology focus areas: conductive pathways, the solar envelope, occupant environment, and efficient equipment. The first three of these technologies impact the cab's heat transfer and resulting thermal loads and are the focus of this paper. The efficient equipment focus area translates the thermal loads into mechanical or electrical loads. The four technical focus areas are described below.

1. The conductive pathways focus area addresses the heat transfer through walls and other surfaces of the cab/sleeper. While heat transfer for this focus area is largely conduction through solid bodies, it also includes convection and radiation through air gaps in the composite wall and glass structures of the cab. Technologies in this area include insulation, advanced materials, and glass.
2. The solar envelope describes the interaction of surfaces with radiant energy from the sun and the surrounding environment. It is predominantly driven by radiant heat transfer and is most relevant during daytime operation; however, nighttime radiation to the sky is also included. This focus area includes the study of opaque and transparent surface properties of paints and glass, respectively. It also includes devices to modify these properties, such as window shades.
3. The occupant environment includes the volume of conditioned air, occupant heat exchange with the surroundings, and human factors such as thermal sensation/comfort. Designing the thermal environment to make every occupant comfortable rather than to meet the traditional temperature based metric has a significant impact on design. Technologies in this area include sleeper curtains and control of the microenvironment.
4. The use of efficient equipment impacts conversion of thermal loads to mechanical, electrical, or chemical loads. A range of technology options and design considerations fall into this category. These include battery electric A/C, fuel fired heaters, and auxiliary power units. For the purposes of this study, battery electric idle-off systems were used; however, the idle thermal load reduction technologies applied to the cab/sleeper are largely independent of the equipment used.

Experimental Test Setup

The test program was conducted at NREL's Vehicle Testing and Integration Facility, 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, a current model Volvo control 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, and the other was modified.

For the experimental setup, the test truck, control truck, test buck, and control buck 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.

Figure 1. NREL's Vehicle Testing and Integration Facility

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. Among the four vehicles, more than 200 calibrated type K thermocouples were used for a variety of surface and air temperatures. An isothermal bath and reference probe were used for thermocouple calibration, achieving a U95 uncertainty of ±0.32°C in accordance with American Society of Mechanical Engineers standards [7]. Air temperature sensors were equipped with a double concentric cylindrical radiation shield to prevent errors due to direct solar radiation.

Weather data were collected from both NREL's Solar Radiation Research Laboratory and NREL's Vehicle Testing and Integration Facility [8] weather station, which together feature more than 160 instruments dedicated to high-quality measurements of solar radiation and other meteorological parameters.

The impact of cab climate control load reduction technologies was quantified for daily rest period A/C tests. These tests used 2,050-W (7,000-Btu/hr) electric no-idle A/C systems provided by Dometic Environmental Corporation [9] which were installed in the sleeper compartment of each vehicle. For the A/C experimentation, unless noted otherwise, the sleeper curtain and all four shades were utilized on the vehicles. All curtains and shades 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.

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 [10], as shown in Figure 2A. Similarly, the 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 average air temperature measurement by more accurately capturing the air temperature distribution. During testing, it was determined that the two temperature measurements made in the cab footwell air space 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.

Air conditioning electrical power consumption was measured using a Load Controls Incorporated model UPC adjustable capacity power sensor. The power sensor was calibrated to ±15 W. A/C systems were controlled to a target sleeper air temperature of 22.2°C (72°F). Calibration of the modified vehicle A/C system was performed by collecting multiple days of baseline data. The daily clearness index was calculated as the daily total ratio of direct normal irradiance to extraterrestrial direct normal irradiance. If the daily clearness index exceeded 0.525, the day was identified as a high solar test day. Due to limited high solar test days, the test procedure was expanded when appropriate to accommodate lower clearness index days. The expanded range of weather is expected to provide a conservative quantification of technologies compared to days with a high clearness index.

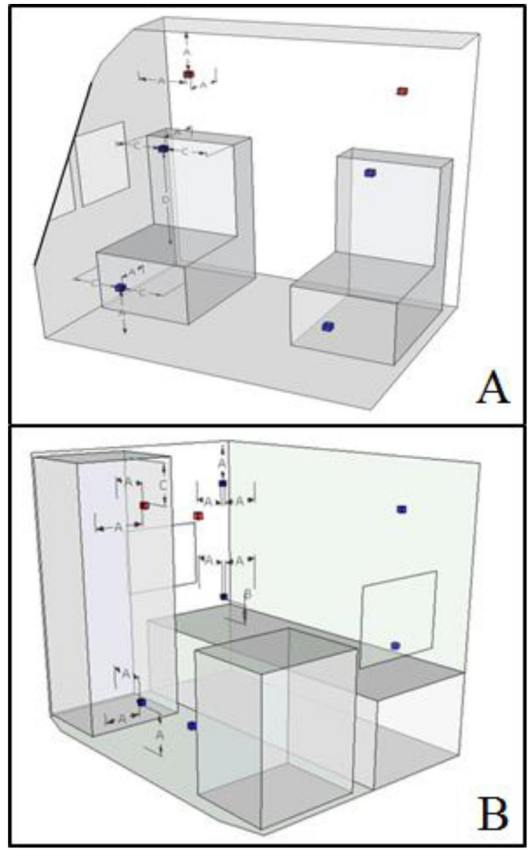

Figure 2. (A) Cab and (B) sleeper thermocouple locations. Dimensions: A = 12″, B = 6″, C = 18″. Blue: TMC standard [10]; red: NREL added

Technology Identification

A test plan was developed based on prior experimental screening of individual technologies and CoolCalc modeling of combined packages to identify a complete-cab package for rest-period load reduction. To determine a complete-cab package, prior work at NREL identified insulation, paint color, and privacy curtains as promising technologies. Prior work on insulation has shown significant reductions in both cooling and heating tests compared to a baseline insulation package [11]. In addition, paint color has shown reductions in daily A/C load for black to white paint and blue to solar reflective blue paint [11]. An idealized sleeper curtain test identified advanced curtains as a candidate technology for A/C load reduction [13]. In addition, an idealized white film test identified advanced privacy shades as a promising technology [13].

To estimate the impact of the proposed complete-cab solution on cooling and heating thermal loads at the national level, CoolCalc modeling was performed using a design of experiments, analysis of variance method [14] to determine the contributions of each technology and its interaction effects for load reduction. Two levels were used for curtains and paint and three levels for insulation. For paint, a midtone solar-weighted reflectivity midway between black and white was estimated as a baseline color. A full factorial matrix of simulations was run for 144 cities throughout the United States for analysis.

The main effects of the national 95th percentile daily loads for each design variable are calculated for every level by holding the factor level constant and averaging all the values with this factor level. This is then compared against the grand mean, the average of all the

response variable values. The main effect plot, represented as a percent change for both heating and cooling from their respective grand means, is show in Figure 3. The results of the sensitivity study suggested that the combination of insulation, paint, and advanced curtains and shades provides a complete package for A/C load reduction that exceeded 30% at the national level. It should be noted that in heating mode, the slope for paint is positive. This shows the small detrimental effect lighter color has on the solar heating and thus increased sleeper climate control system heat demand during the winter. It should also be noted that black paint would show much larger impacts if it were included in the study.

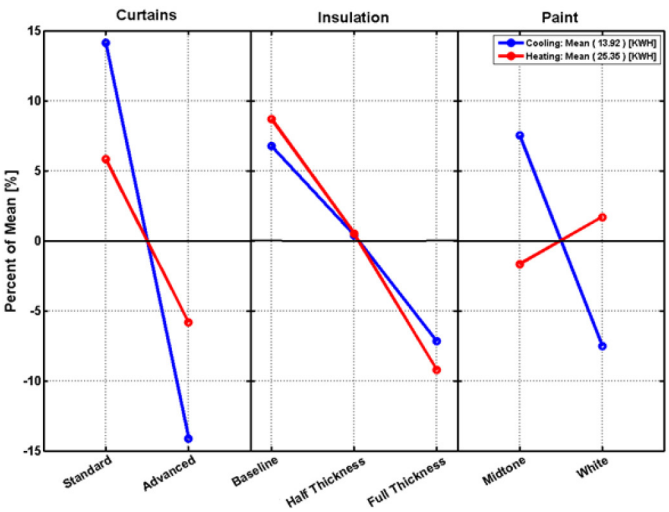

Figure 3. Main effects plot for national 95th percentile daily load showing relative impact of individual technologies for both cooling and heating thermal loads

An analysis of the interactive effects showed that paint and insulation have some interaction, although much smaller than the main effects. As expected, adding insulation was found to result in some reduction in the sensitivity to paint. While these technologies are not completely additive for load reduction, the interactive effect is significantly smaller than the primary effect.

To quantify the impact of paint color for the complete-cab solution, an analysis was performed to estimate the national average solar-color paint. For this study, the national average solar-color paint is defined as a paint color with radiative properties that match that of the theoretical count weighted average of paint colors throughout the United States for long-haul trucks. For this analysis, truck stops were randomly selected throughout the country, and Google satellite images of the truck stops were collected. Color groupings were defined based on identifying colors that had similar radiative properties. Next, long-haul trucks for each color category were counted at each truck stop location using the satellite images. The percent of each color category was determined after classifying more than 2,600 trucks. The cumulative totals of each color category with the addition of incremental truck stop data are shown in Figure 4. Using the CoolColors database developed at Lawrence Berkeley National Laboratory [15], average radiative properties for each color group were calculated, and the national average solar-weighted reflectivity was determined to 0.37. Through collaboration with PPG Industries, a heavy-duty truck paint color was experimentally identified with radiative properties that closely approximated that of the national average solar-color. This national average solar-color paint was used for experimental quantification of the baseline paint configuration. Paint properties were measured using a combination of ultra-violet, visible, and infrared spectrometers.

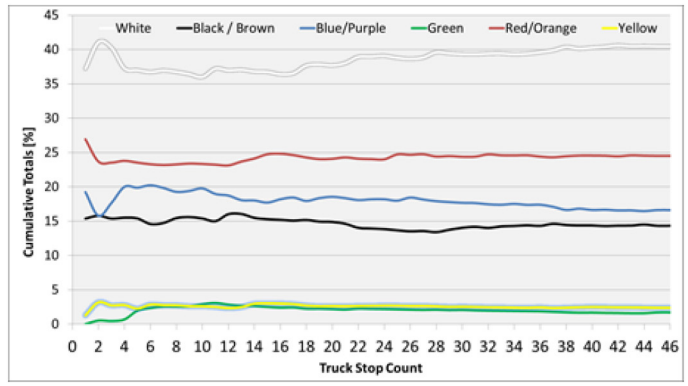

Figure 4. Cumulative totals of long-haul truck paint colors for the incremental addition of truck stop data

The baseline experimental configuration for the test cab contained blanket insulation as part of the vehicles stock insulation configuration. The stock insulation was affixed to portions of select upholstery panels that composed the sleeper compartment. In comparison, for the advanced insulation package, prefabricated insulation panels were installed throughout the sleeper compartment to occupy the void space between the upholstery panels and exterior frame wherever possible. The advanced insulation package consisted of Thinsulate automotive acoustic insulation provided by Aearo Technologies. The areas of the cab insulated included the rear sleeper wall, sleeper ceiling and portions of the cab ceiling, and sleeper side walls. The installed insulation package contained a combination of one and two inch-thick blanket insulation with a nominal thermal conductivity of between 0.03 and 0.05 W/m-K.

The standard vehicle curtains and shades were used for the baseline configuration. Using Thinsulate insulation, NREL designed and fabricated an advanced prototype curtain and shade configuration for testing.

Results

Baseline Testing

For the complete-cab solution experimental evaluation, an A/C system calibration was completed for the test and control bucks using the baseline configuration for the test buck. The baseline configuration consisted of the national average solar-color for paint, the standard OEM insulation package, and standard sleeper and privacy curtains. Calibration data for the complete-cab solution A/C baseline are shown in Figure 5. The figure contains daily A/C baseline data for both variable weather test days and high solar test days that exceeded the daily clearness index of 0.525. Due to the limited number of high solar test days, the entire data set was used for baseline calibration and shows a strong linear correlation with a coefficient of determination (R2) of 0.983.

The linear regression line shown in Figure 5 was used to calculate a calibration correction for the baseline test buck daily A/C energy for a given test day.

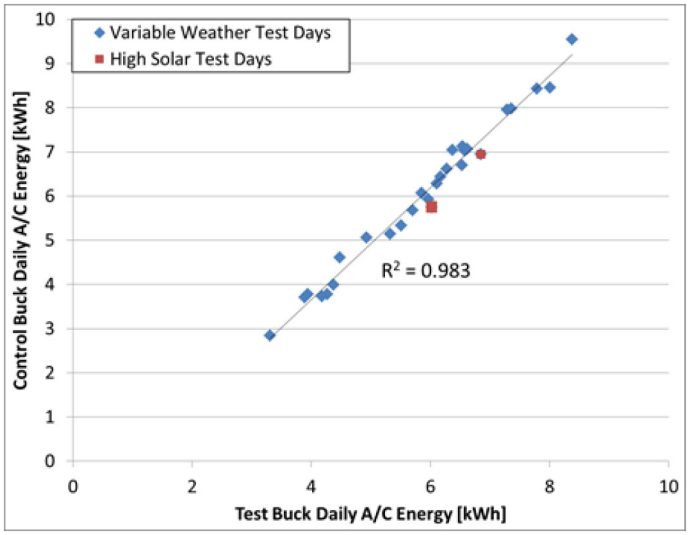

Figure 5. Daily A/C energy calibration data for test and control bucks

Paint Property Characterization

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 table summarizes the measured solar-weighted radiative properties. Initial paint samples of the national average solar color paint matched the target value of 0.37; however, the final paint coat applied to the test buck was under the target value with a solar-weighted reflectivity of 0.27. While the cause of the shift in reflectivity from the sample to the vehicle application is not known, it could be due to variations in the painting process. Because the reflectivity is lower than the target, the experimental results somewhat overestimate the impact of paint color from the national average.

Paint Color	Black	National Average Solar-Color	White	Ultra-White
Total Hemispherical Emittance @ 20°C	0.951	0.949	0.953	0.935
Solar Weighted Reflectivity	0.047	0.269	0.628	0.857
Solar Weighted Absorptivity	0.953	0.731	0.372	0.143

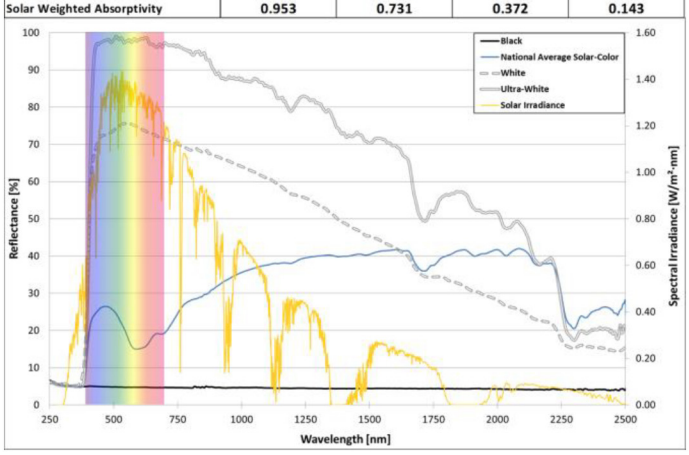

Figure 6. Measured reflectance spectrum for paint colors used in testing

Complete Cab Solution Evaluation

To quantify the impact of a complete-cab solution on rest-period load reduction, the test buck was painted the "ultra-white" color provided by PPG Industries, advanced privacy shades and sleeper curtains designed by NREL were deployed, and a truck insulation package provided by Aearo Technologies was installed. A comparison between the complete-cab solution and baseline configurations is provided in Table 1.

Table 1. Technology Configurations for Baseline and Complete-Cab Package Experimental Evaluations

	Baseline	Complete-Cab Package
Paint	National Average Solar-Color	Ultra-White
Curtains	Stock OEM	Advanced
Insulation	Stock OEM	Advanced Package

For the complete-cab evaluation, daily A/C energy was quantified under a range of environmental conditions. The percent reduction in daily A/C energy was calculated for the complete-cab solution configuration in comparison to the baseline configuration. A plot of the percent improvement in daily electric A/C energy for the complete-cab solution for varying daily loads is shown in Figure 7. For the days tested, an improvement of at least 35.7% was obtained for the complete-cab solution. Figure 7 shows an increase in the percent improvement for the complete-cab solution as daily A/C energy decreased. This trend is due to seasonal variation in the results, and as the daily A/C energy was reduced for the baseline condition, the percent improvement was expected to approach 100%. At 100% load reduction, the baseline case requires use of the A/C while it is not used for the modified case. The percent improvement trend was consistent with modeling results and is expected to level out at high load conditions. Under these higher load conditions, the improvement is mostly dependent on power reduction during A/C system operation and less on system on-time reduction. The trend in the final two high-load data points in the figure suggests that the improvement measured is expected to be consistent with additional increases in daily load.

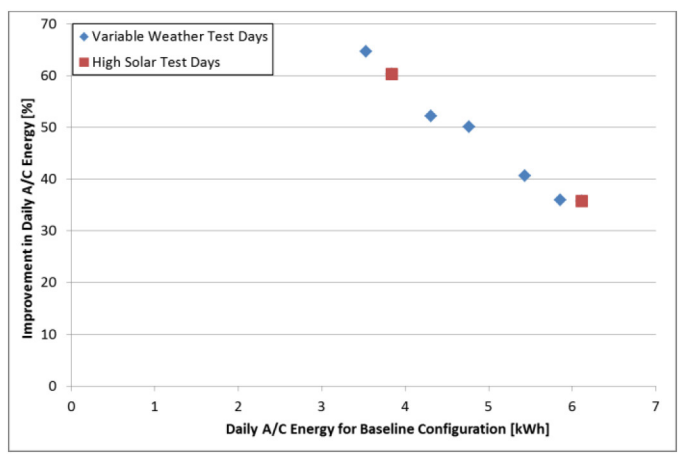

Figure 7. Percent improvement in daily A/C energy for the complete-cab solution for varying A/C loads and weather conditions

Figure 8 shows the hourly electrical A/C load for the maximum load condition test. The data are therefore the detailed hourly results from the last point on the graph in Figure 7. The hourly results show a significant reduction in A/C system load throughout the day, with continuous system operation for both configurations throughout the entire test period.

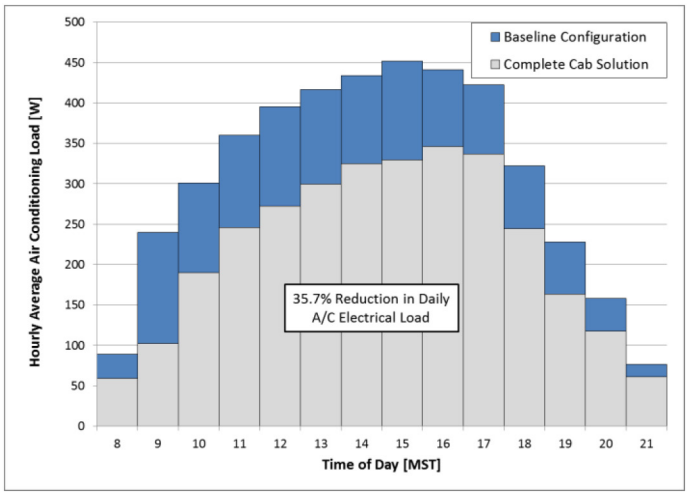

Figure 8. Hourly electrical A/C load for maximum tested daily load condition

In addition to the complete-cab solution, the combined impact of ultra-white paint and the advanced insulation package was evaluated with both the stock OEM curtains and a configuration without curtains. For the configuration with stock OEM curtains, a three-day average was used for percent improvement over baseline. For the configuration without curtains, one day of data was collected. All test days for the comparison had a daily clearness index greater than 0.525. The effect of advanced, stock, and no curtain configurations on improvement in daily A/C load with ultra-white paint and advanced insulation is shown in Table 2. The results indicate that ultra-white paint and insulation combined with stock curtains provide a 21.1% improvement over baseline conditions. In addition, ultra-white paint and insulation are effective even when curtains are not used, showing an 11.6% improvement over the baseline. Finally, the results indicate that a significant improvement is obtained from the advanced curtains themselves over stock OEM curtains in the complete-cab solution, with a change in percent improvement from 21.1% to 35.7%.

Table 2. Percent Improvement in Daily A/C Load for Varying Curtain Configurations Combined With Ultra-White Paint and Advanced Insulation Package

Curtain Configuration	Improvement [%]
Advanced Curtains	35.7%
Stock OEM	21.1%
No Curtains	11.6%

Using the calculated national average paint color with the advanced insulation and sleeper curtain models, CoolCalc simulations for the complete-cab solution were aggregated for typical meteorological year weather at 161 cities throughout the United States. National-level contour plots of normalized daily cooling thermal load at the 95th percentile are shown in Figure 9 for both baseline and complete-cab solution analyses. The results indicate a strong reduction in cooling thermal load for the complete-cab solution and a decrease in sensitivity to environmental conditions throughout the United States.

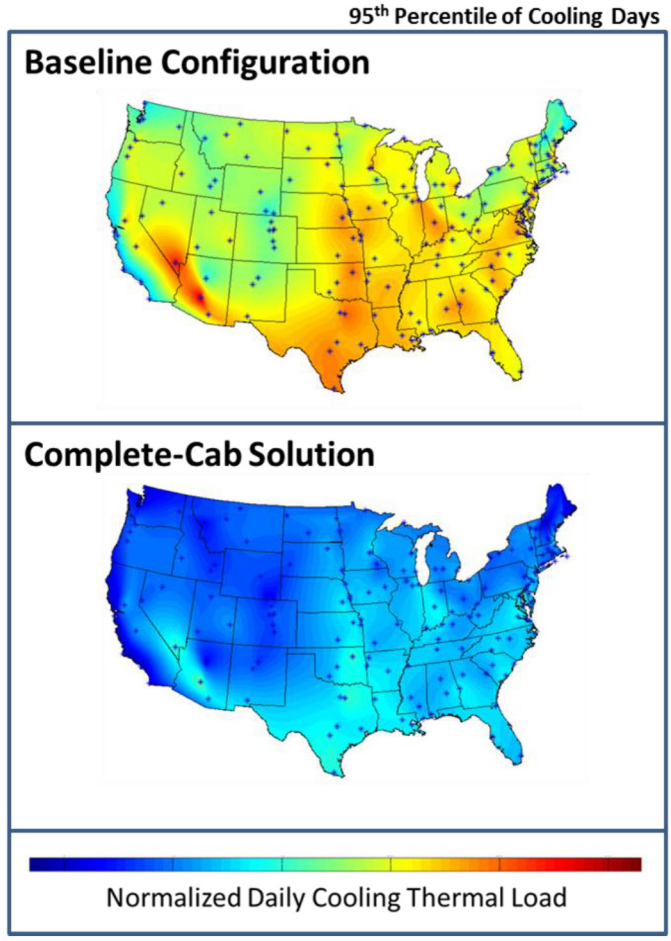

Figure 9. National contour plots of normalized daily cooling thermal load for both baseline and complete-cab solution CoolCalc analysis results

Conclusions

Through the implementation of a complete-cab package of technologies, long-haul truck daytime rest period A/C electrical energy consumption was reduced by at least 35.7% for Colorado summer environmental conditions. The complete-cab 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. For the ultra-white paint and advanced insulation package, a 21.1% reduction in daily A/C electrical energy was measured when using stock curtains. Finally, an ultra-white paint and advanced insulation package with no curtains had an 11.6% reduction compared to the baseline with stock curtains.

The complete-cab experimental results obtained exceed the CoolCab goal of a 30% reduction in long-haul truck rest-period A/C loads. The technologies implemented for the complete-cab solution were determined from previous individual technology outdoor testing and national-level CoolCalc modeling. Future work is planned to quantify further technology improvements and measure the impacts on heating. These combined technologies will then be evaluated for national-level fuel use reductions and payback period estimations.

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Definitions/Abbreviations

A/C - air conditioning

HVAC - heating, ventilating, and air conditioning

NREL - National Renewable Energy Laboratory

OEM - original equipment manufacturer

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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