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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

HEAVY DUTY MODELING AND SIMULATION

IV.N. CoolCab Truck Thermal Load & Idle Reduction

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IV.N.1. Abstract

Objectives

- Demonstrate at least a 30% reduction in long-haul truck idle climate control loads with a 3-year or better payback period by 2015.
- Collaborate with industry partners in the development and application of commercially viable climate control solutions targeted at minimizing long-haul truck rest period idling.
- Reduce the 838 million gallons of fuel used annually for rest period idling to increase national energy security and sustainability.

Approach

- Evaluate commercially available and advanced technologies using a three-phase approach consisting of baseline testing and model development, thermal load reduction, and idle reduction.
- Implement cost-effective and readily modified cab sections as representative replacement test bucks for full trucks in the evaluation of idle load reduction technologies.
- Quantify the effects of thermal load reduction technologies such as films, paints, or radiant barriers and idle reduction technologies using engine-off soak and daytime rest period air conditioning (A/C) test procedures.

Major Accomplishments

- Demonstrated a 20.8% reduction in daily electric A/C system energy consumption in Colorado outside environment test conditions when switching from a black colored cab to white.
- A 16.7% reduction in A/C battery capacity and weight reduction of 22 kg (48lb) was achieved at little or no additional cost through the selection of cab paint color.
- Demonstrated a 31.1% of maximum possible interior air temperature reduction during peak solar loading soak conditions when switching from a black colored cab to white.
- Demonstrated a 21.8% of maximum possible sleeper air temperature reduction during peak solar loading soak conditions using all privacy curtains.

Future Activities

- Further evaluation of commercially available advanced thermal management and idle reduction technologies such as advanced paints, films, glazing materials, glazing treatments, and insulation.
- Research innovative technologies that may include air distribution, zonal control, comfort based control, and active ventilation systems.
- Development of test methodology for direct quantification of cab climate conditioning energy demands.
- Implement tools for quantifying the impacts of climate control solutions on fuel use and payback period.

IV.N.2. Technical Discussion

Background

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, long-haul trucks (trucks that travel more than 500 miles per day) use 838 million gallons of fuel annually for rest period idling [1]. Including workday idling, over 2 billion gallons of fuel are used annually for truck idling [2]. By reducing thermal loads and improving the efficiency of climate control systems, there is a great opportunity to reduce fuel use and emissions associated with idling. 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, fleet owners will be economically motivated to incorporate them. Therefore, financial incentives provide a pathway to rapid adoption of effective thermal load and idle reduction solutions.

Introduction

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.

Approach

NREL is closely collaborating with original equipment manufacturers (OEMs) and suppliers to develop and implement a strategic approach capable of producing commercially viable results to enable idle reduction systems. This strategic, three-phased approach was developed to evaluate commercially available and advanced vehicle thermal management and idle reduction technologies. The three phases, illustrated in Figure 1, are: Baseline Testing and Model Development, Thermal Load Reduction, and Idle Reduction. Each phase features applications of NREL's suite of thermal testing and analysis tools.

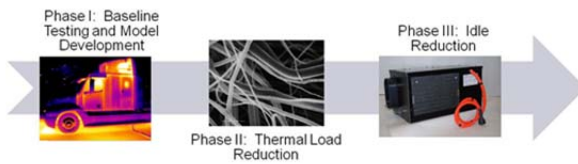

Figure 1. NREL's three-phase approach

In Phase I, Baseline Testing and Model Development, thermal data are collected on a test vehicle and on a control vehicle simultaneously. Several days of data are collected for each test procedure under varying weather conditions. These data are 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 are 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. After calibration verification, the test vehicle is modified with technologies for Phase II evaluation. Baseline performance data of the test vehicles is also used for the development and validation of CoolCalc [3] models.

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.

In order to experimentally characterize the impacts of the technologies being studied, thermal test procedures are conducted in each phase of the project. Throughout the project, the following test procedures are used for technology evaluation: thermal soak, overall heat transfer (UA), daytime rest period A/C, infiltration rate, and infrared imaging. For the technology evaluation in FY 2012, thermal soak and daytime rest period A/C testing were utilized.

For FY 2012, application of the CoolCalc analysis tool applied to a Volvo cab model identified a reduction in the truck cab rise over ambient temperature by as much as 35.9% through the application of films, paints, or radiant barriers to the exterior opaque surfaces. In addition, experimental results in previous work by Rugh and Farrington [4] on light-duty vehicles showed that a reflective roof film reduced breath air temperature by 12% of the maximum possible temperature reduction and determined that a theoretical maximum of 28% was possible with treatment of all opaque surfaces. Work done by Levinson et al. on light-duty vehicles showed a 4°C–6°C reduction in cabin air temperature with a silver car compared to a black car [5]. It was expected that application of films, paints, or radiant barriers to the exterior opaque surfaces of heavy-duty vehicles would have a larger impact on thermal load reduction due to the increased ratio of opaque to glazing surface areas compared to light-duty vehicles. Experimental tests were completed to quantify the impacts on thermal and idle load reduction.

The test program was conducted at NREL's Vehicle Testing and Integration Facility, shown in Figure 2, during the months of May through October. 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. For the study, bucks were utilized in place of complete vehicles because they provided a representative and cost-effective model that was adaptable for test configurations and evaluation of potential thermal and idle load reduction technologies.

For the experimental setup, the modified 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.

Figure 2. 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 one-minute intervals. Among the three vehicles, a total of 140 calibrated type K thermocouples were utilized. 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 [6]. 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 the Vehicle Testing and Integration Facility weather station, 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 technologies in an engine-off solar loading condition. This test procedure was used to characterize technology impacts on interior air temperatures in a test truck or buck ($\overline{T}_{modified}$) compared to interior air temperatures in the baseline buck ($\overline{T}_{baseline}$). 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 ($\overline{T}_{ambient}$), 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.

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

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 type K thermocouples with four located in accordance with the American Trucking Association Technology Maintenance Council's recommended practice RP422A [7], as shown in Figure 3A. Similarly, average sleeper air temperature was calculated by averaging eight type K thermocouples with six located in accordance with RP422A. 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, illustrated in Figure 3B. 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.

For the thermal soak testing, data were collected for a time interval from 6:00 a.m. to 4:00 p.m. MDT. During baseline thermal soak measurements, all privacy curtains were removed. The thermal soak performance of the bucks in their baseline conditions were used to characterize and calibrate the inherent differences between the two bucks and between the control buck and the test truck. 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 and between the control buck and test truck. Solar load intensity peaked at approximately 1:00 p.m. daily during thermal soak testing. In addition, peak differential temperatures were found to occur within the 12:00 p.m. to 2:00 p.m. MDT time interval corresponding to this peak solar load. Therefore, interior air and ambient temperatures from 12:00 p.m. to 2:00 p.m. MDT were used for the calculation of β.

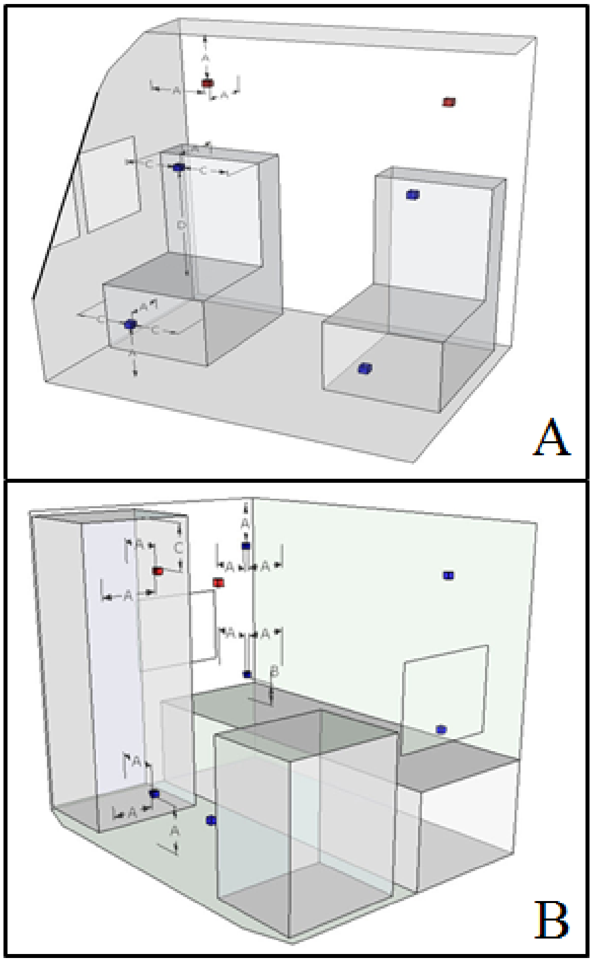

Figure 3. Cab (A) and Sleeper (B) thermocouple locations, dimension A = 12", B = 6", C = 18", blue – TMC standard [5], red – NREL added.

Daytime rest period A/C tests were conducted to characterize thermal management technology impacts on an electric no idle A/C system. A 2,050 W (7,000 BTU/hr) Dometic electric A/C system [5] was installed in the sleeper compartment of each vehicle. For A/C experimentation, all five curtains were utilized on the control buck, test buck, and test truck. 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/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. A/C systems were controlled to a target sleeper air temperature of 22.2°C (72°F) or increased to 26.7°C (80°F) if a configuration was expected to exceed the A/C capacity at the lower target temperature. Calibration of the modified buck's A/C system was performed by collecting four days of baseline data. A clear solar day with insignificant cloud cover was required for data to qualify as a baseline test day.

Results

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 12:00 and 2:00 p.m. The results of the calibration applied to a validation dataset for the test truck sleeper air temperature is shown in Figure 4. 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.

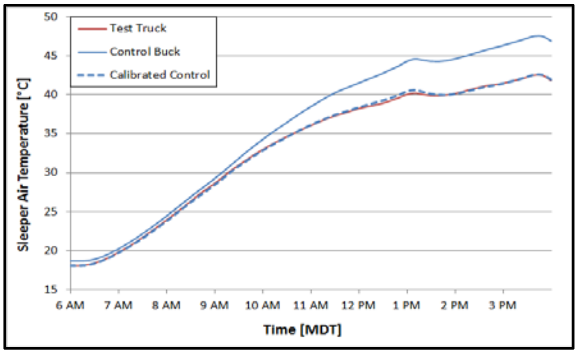

Figure 4. Average sleeper interior air temperature validation day

Baseline A/C testing of the test and control bucks showed repeatable differences between the two configurations. The calibration curve for A/C baseline testing is shown in Figure 5, 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.

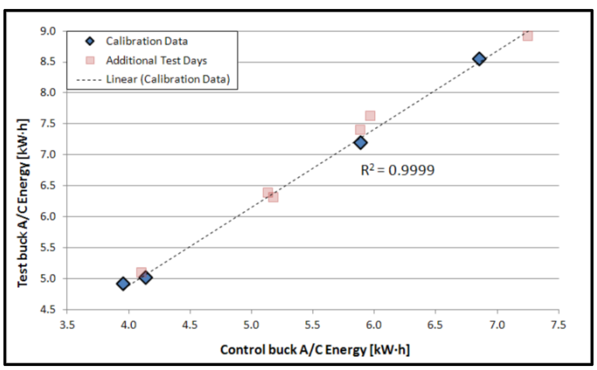

Figure 5. Daily A/C energy calibration data for test and control bucks.

Phase II research focused on the identification and quantification of thermal load reduction strategies. To study the effect of paint on cab air temperatures in thermal soak conditions, black OEM paint was provided through partnership with PPG Industries. The radiative properties of both baseline and black paint were quantified experimentally. Paint properties are given in Table 1. The test buck was painted black and compared to the calibrated white control buck as shown in Figure 6.

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

Buck model	Control	Test	Test
Color	White	White	Black
Reflectance, %	64.2	62.2	4.7
Absorptance, %	35.8	37.8	95.3
Emissivity	0.948	0.953	0.951

Figure 6. Cab experimental configurations: Test buck painted white (left) and painted black (right)

Thermal soak testing of the black and white opaque exterior surfaces showed an average buck air temperature difference of 8.1°C during peak solar load. The temperature difference equates to a percent of maximum temperature reduction, $\beta = 31.1\%$. Figure 7 shows the average buck air temperature for black and white opaque surfaces. Thermal soak testing of additional opaque surface treatments is currently in progress.

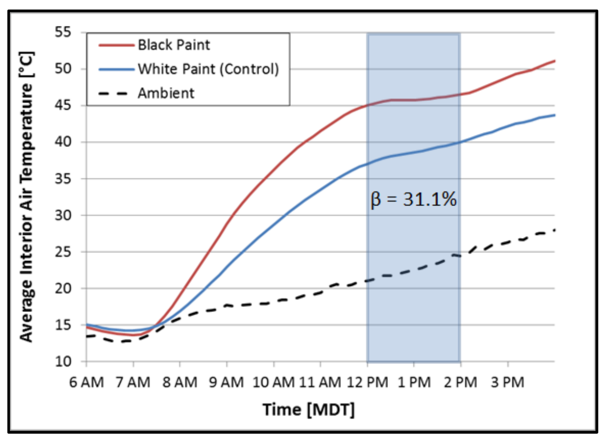

Figure 7. Thermal soak results with black and white opaque surfaces for test buck

Thermal soak testing was completed on the test truck in order to quantify the effects of OEM privacy curtains on the average sleeper air temperature. As outlined in the Approach section, all curtains were used for testing. During the peak solar load from 12:00 to 2:00 p.m., a maximum sleeper air temperature reduction of

2.4°C was measured when using all five OEM curtains on the test truck. During this time, the percent of maximum possible temperature reduction, β = 21.8%, was obtained. Figure 8 shows the average sleeper air temperature and ambient temperature for both curtains open and closed configurations. Additional test configurations to further characterize the cab thermal system for the test truck are in progress.

Phase III focused on the quantification of idle load reduction strategies through collaboration with industry partners. NREL collaborated with Volvo Trucks North America, PPG Industries, and Dometic Environmental Corporation to evaluate the effect of paint on thermal load. Black OEM paint was supplied by PPG Industries and was combined with Dometic Environmental Corporation's A/C system to quantify the impact of paint color on A/C power use in the test cab sleeper air space during engine-off daytime test conditions.

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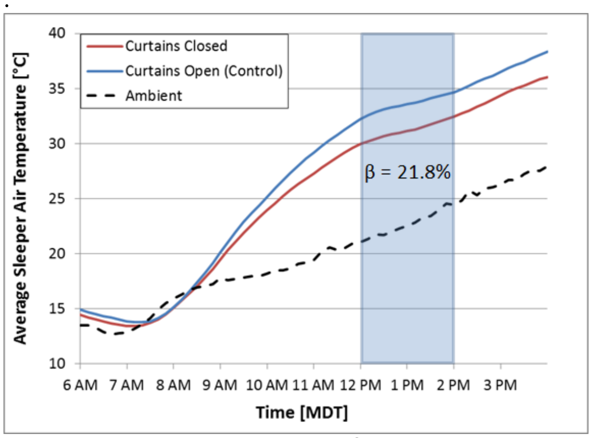

Figure 8. Thermal soak results for curtains opened and closed configurations for test truck.

During evaluation of the black test buck, the A/C target temperature was 26.7°C (80°F) for both the test buck and control buck, as discussed in the Approach section. Hourly average A/C power consumption (Figure 9) 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. The standard battery-powered A/C system uses four 1,500 W·h lead-acid batteries, weighing a total of 132 kg (291 lb). A 1,001 W·h daily energy savings corresponds to a 16.7% reduction in battery capacity and 22 kg (48 lb) reduction in weight. Daytime rest period A/C testing of additional opaque surface treatments is currently in progress.

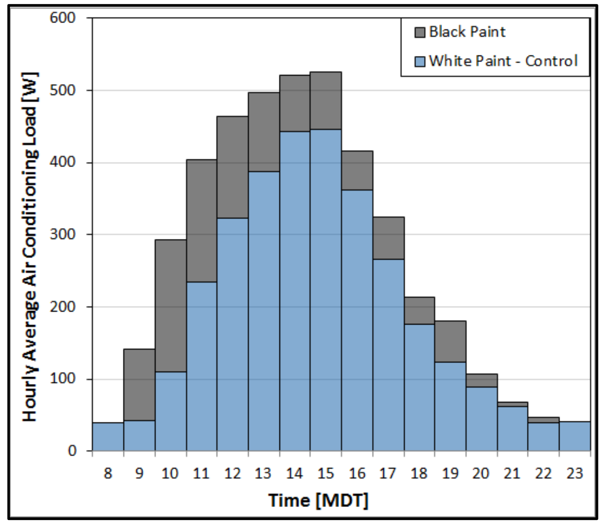

Figure 9. Hourly average test cab A/C power consumption for black and white opaque exterior surfaces.

Conclusions

Long-haul sleeper daily electrical A/C loads were reduced by as much as 20.8% by switching from black to white paint. 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 corresponds to a 16.7% reduction in A/C battery capacity and 22 kg (48 lb) weight reduction. Savings in battery capacity lead to lower purchase price and operating costs of idle reduction systems. The savings were realized with a change in paint color, which adds little to no additional cost. Although large savings were realized by using white paint compared to black, other factors such as brand recognition and aesthetics factor into the choice of paint color for heavy-duty trucks. For this reason, additional testing is in progress to characterize advanced paint colors that are dark in the visible spectrum but thermally behave similar to white paint. Future work is planned to model the impact of these technologies over a wide range of use and operating conditions.

In addition to idle load reductions, a sleeper air temperature reduction of 21.8% of maximum possible was realized during engine-off thermal soak testing by applying all vehicle curtains. This result provides insight to the effectiveness of privacy curtains in long-haul vehicles. Additional testing is in progress to fully characterize the impact and value that OEM curtains have on truck idle loads.

Working closely with industry partners and applying both modeling and testing tools, NREL has shown 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 838 million gallons used annually in the United States for long-haul truck rest period idling and potentially reduce truck operation costs.

IV.N.3. Products

Publication

1. Lustbader J., Venson, T. "Application of Sleeper Cab Thermal Management Technologies to Reduce Idle Climate Control Loads in Long-Haul Trucks," SAE Commercial Vehicle Engineering Congress, Rosemont, IL, October 2-3, 2012, Paper Number 2012-01-2052

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Tools & Data

1. CoolCalc rapid HVAC load estimation tool version 2.0.0. Only available to industry and laboratory partners at this time.

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