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Thermal Load Reduction of Truck Tractor Sleeper Cabins

Kenneth Proc, Lawrence Chaney
National Renewable Energy Laboratory

Eric Sailor
International Truck and Engine Corp.

ABSTRACT

Several configurations of truck tractor sleeper cabs were tested and modeled to investigate the potential to reduce heating and cooling loads. Two trucks were tested outdoors and a third was used as a control. Data from the testing were used to validate a computational fluid dynamics (CFD) model and this model was used to predict reductions in cooling loads during daytime rest periods. The test configurations included the application of standard-equipped sleeper privacy curtain and window shades, an optional insulated or arctic sleeper curtain, and insulated window coverings. The standard curtain reduced sleeper area heating load by 21% in one test truck, while the arctic curtain decreased it by 26%. Insulated window coverings reduced the heating load by 16% in the other test truck and lowered daytime solar temperature gain by 8˚C. The lowered temperature resulted in a predicted 34% reduction in cooling load from the model. Modeling also predicted doubling cab insulation could reduce cooling load by 35% and up to 54% with the sleeper curtain closed. Infrared images of the truck cabs identified other potential areas to reduce heat loss that included areas around window and door seals, at body and structural seams, and areas where insulation may be lacking around air circulation ducts.

INTRODUCTION

The trucking industry is faced with increased costs from rising fuel prices, higher maintenance costs, and driver turnover. In addition, excessive idling has been identified as a source of wasted fuel and an unnecessary cost. Survey estimates report sleeper trucks idle an average of more than 1,400 hours annually [1]. Engine idling consumes more than 800 million gallons of fuel annually in long-haul (>500 miles/day) trucks [2]. Trucks typically idle to run cabin climate control (heating, cooling, and dehumidification) during driver rest periods and to provide electric power for other amenities. Reducing the amount of truck engine idling can significantly reduce fuel consumption, save money, and reduce tailpipe emissions.

The U.S. Department of Energy's (DOE) Advanced Vehicle Testing Activity (AVTA) initiated a study of diesel truck engine idle reduction technologies in 2002 [3]. This study consisted of several projects that evaluated existing on-board idle reduction technologies, including diesel-fired and electric heaters, electric air conditioning systems, and an auxiliary cab cooler using phase change material. This evaluation demonstrated measured idle reduction and fuel savings with some of the technologies but identified the following issues in meeting driver and operator requirements:

- Energy storage capacity: Battery powered and other stored energy cooling systems lacked capacity to meet mandatory driver rest periods in warm ambient temperatures (above 85˚F).
- Driver comfort: Drivers noted areas within the truck cab where excessive heat penetrated the cabin walls from the environment and the engine exhaust system.
- Cost: Some of the technologies tested required significant installation time to retrofit an existing truck. This installation cost, in addition to the hardware cost, was too high to provide sufficient technology payback to the fleets.

To the address the identified cost issue, DOE solicited proposals for cost-shared projects to integrate an on-board idle reduction technology at a truck original equipment manufacturer (OEM) [3]. International Truck and Engine Corp. was awarded a contract, and the design and factory installation work is currently underway. This work, however, is not addressed in this report.

To address the capacity and comfort issues identified, DOE, through the National Renewable Energy

Laboratory (NREL), launched the CoolCab project, which conducted a qualitative study of truck tractor cabins to identify potential areas for improvement. Working with Schneider National, two tractors were analyzed using infrared images to investigate heat loss [4]. This exploratory work noted several areas for improvement in the truck cab insulation, including driver and passenger footwells, sunroof and ceiling pad areas, and the rear of the upper bunk (Figure 1).

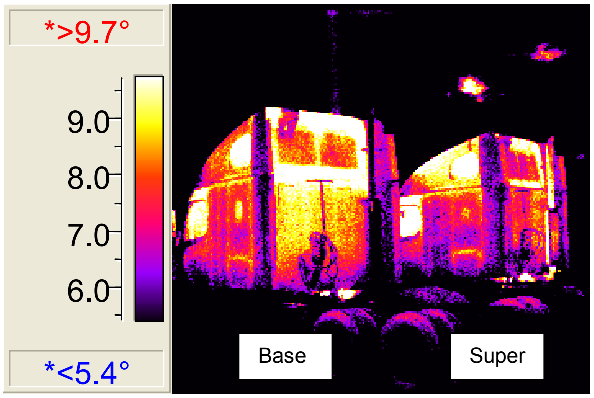

Figure 1. Upper Sleeper Bunk Infrared Image

The CoolCab project continues to quantify truck cab heat loss and further investigate reducing the thermal load of the truck heating, ventilating, and air conditioning (HVAC) system during driver rest periods. Working with truck OEMs Volvo and International, CoolCab tested and analyzed two trucks at NREL's outdoor test facility; this work is the focus of this paper.

OBJECTIVE

The main objective of the CoolCab project is to identify design opportunities to reduce the thermal load inside truck tractor cabs. Reducing the heating or cooling load is the first step in improving system efficiency to reduce fuel consumption. Reducing this load will enable existing idle reduction technologies and allow more efficient technologies to keep truck drivers comfortable during rest periods.

A secondary objective of reducing cabin thermal load is to decrease heating and cooling loads while a truck or other vehicle is traveling. This load reduction may provide further gains in reducing fuel consumption and improving fuel economy. In addition, with a trend toward hybrid powertrains in vehicles, energy required for HVAC and other accessories will be at a premium. Load reduction will help reduce these energy demands and help extend vehicle range and efficiency in both light and heavy vehicles.

APPROACH

TRUCK TESTING

Truck testing was conducted outdoors at NREL's test facility. Two trucks were tested with a third truck tractor used as a control for comparison and baseline data (Figure 2). All trucks were fully instrumented and subjected to a series of four tests to help measure heat transfer and identify high heat loss areas: Co-heat tests, solar soak, air exchange, and infrared (IR) imaging.

Figure 2. Test Truck and Control Truck Parked for Testing

<u>Co-Heat Tests</u>

Testing began with establishing a baseline for truck cab insulation. By measuring the amount of heat required to maintain a given temperature, an overall heat transfer coefficient, or UA, for the cabin can be calculated from the expression

$$Q = UA\Delta T$$, where Q is the heat transfer rate.

From UA, an 'R-value' can be derived from a known area for the truck cab from the equations

$$R = 1/U \text{ and } U = UA/A$$, where A is the truck cabin interior surface area.

UA tests were performed to quantify the heat transfer rate in both the test and control trucks. By using a control truck but only modifying the test trucks, it was possible to quantify changes in performance under variable conditions encountered at the outdoor test site. A correction factor was applied to the test data based on data obtained from the control truck (which was not modified). Once the baseline testing of the trucks was completed, simple modifications (insulating windows, applying a sleeper isolation curtain, etc.) were made to the test tractors to help understand heat loss paths.

<u>Solar Soak</u>

Testing also included daytime heat soak tests to help quantify solar gains. Interior temperatures were measured in both test trucks with and without window insulation to understand the effects of the glass areas. Once again, the control truck was used to obtain correction factors for variable conditions. The data obtained in the daytime heat soak tests were also used to validate the accuracy of a Fluent Inc. model of the cab previously developed by NREL and International.

Air Exchange

An air exchange test was also conducted on the trucks by measuring the decay rate of a known gas injected into the cab interiors. This test provided data on the amount of overall air leakage in the truck cab relative to other vehicles.

IR Imaging

Additionally, infrared images of both the interiors and exteriors of the trucks were used to identify higher heat loss areas (hot spots) in the truck cabs. The images provided more insight to areas that could be improved to reduce measured heat loss.

MODELING

A numerical model of the International sleeper cab was developed using Fluent CFD software and RadTherm thermal analysis software. The volume and surface mesh file of the sleeper cab interior geometry was provided by International. The model volume mesh is approximately 4.4 million cells; the surface mesh in RadTherm was approximately 105,000 elements. RadTherm models the solar load on the vehicle, convection losses on the interior and exterior surfaces, and conduction through the surfaces. Fluent CFD software was used to model the convective heat transfer and fluid flow in the cabin. During the analysis, RadTherm and Fluent interacted in the following way: RadTherm provided surface temperature boundary conditions to Fluent, and Fluent provided heat transfer coefficients and fluid temperatures to RadTherm. Several exchanges between RadTherm and Fluent were needed to achieve a consistent solution. Figure 3 shows Fluent-predicted air temperatures on a centerline of the cabin. Figure 4 shows RadTherm-predicted surface temperatures. Both figures show a baseline cool down configuration with a curtain partitioning the cabin.

Figure 3. Fluent Predicted Air Temperature (˚C)

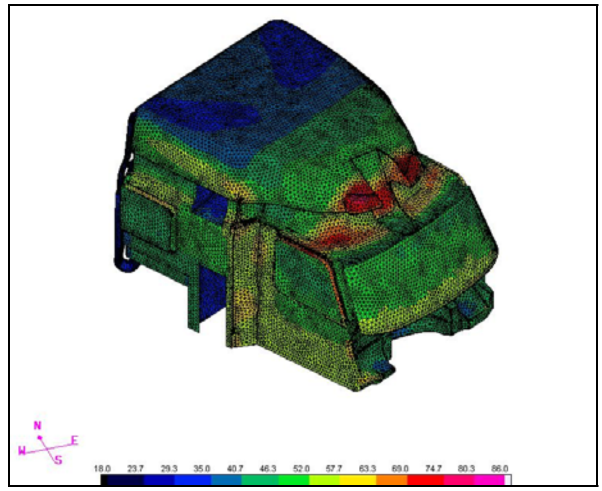

Figure 4. RadTherm Predicted Surface Temperatures (˚C)

The model was first validated against quasi steady state soak data from several days of soak tests. The soak tests represented several configurations of the cabin; for example, some tests were with a curtain and others were without. Figure 5 shows a comparison of the average cabin air temperatures predicted by the model to test data for the sleeper cab. Figure 6 shows a comparison of the average surface temperatures predicted by the model to test data for the sleeper cab. In both Figures 5 and 6, ambient temperature is also shown for reference. Several factors, such as uncertainty in temperature measurement locations, material properties, and vehicle orientation, could have contributed to the differences between measured temperatures and the model-predicted temperatures. Overall, the results show agreement within 3˚C to 4˚C. The validated model was then used to simulate the vehicle cool down.

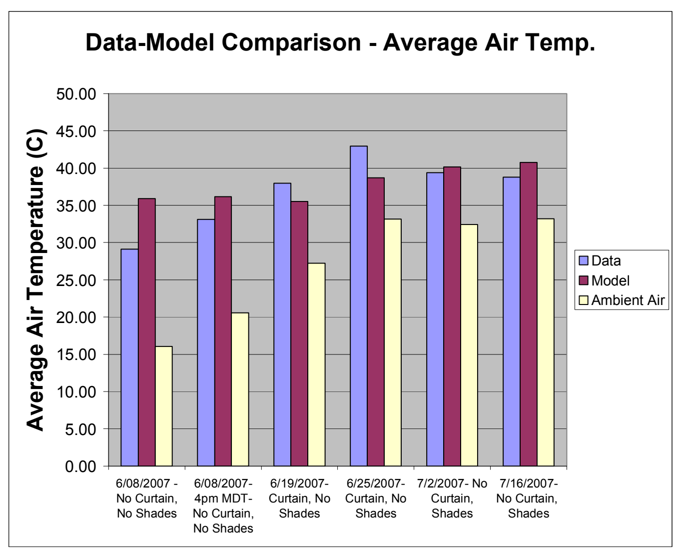

Figure 5. Model Air Temperatures Compared to Test Data

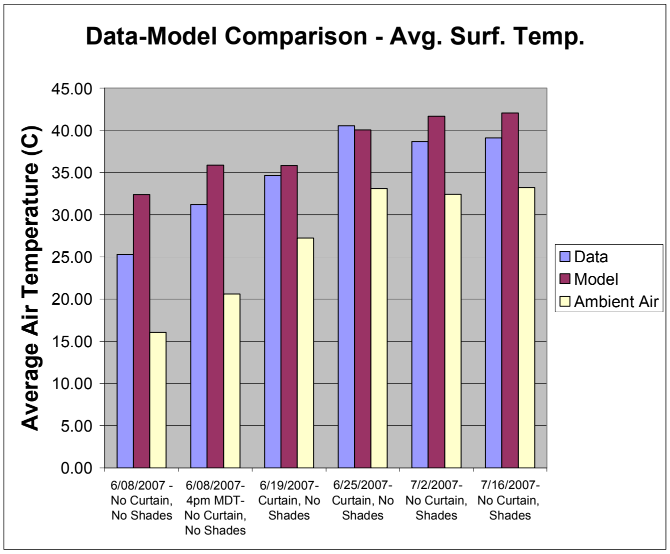

Figure 6. Model Surface Temperatures Compared to Test Data

RESULTS

CO-HEAT TESTS

The co-heat tests were run with two electric heaters installed in the sleeper bunk area of the truck tractor cab. Truck interiors were heated to 40˚C to simulate a typical cab temperature differential in a test ambient of about 15˚C. Truck interiors were temperature-soaked overnight (about six hours) to stabilize temperatures (±0.5˚C of set point) before logging data. To calculate the UA value, power usage (logged voltage and current to the heaters) was recorded to determine the heat transfer rate.

Figure 7 shows interior and exterior (ambient) temperatures of the control truck during a typical co-heat test. Temperatures were very stable during the data recording period from 3 a.m. to 5 a.m.

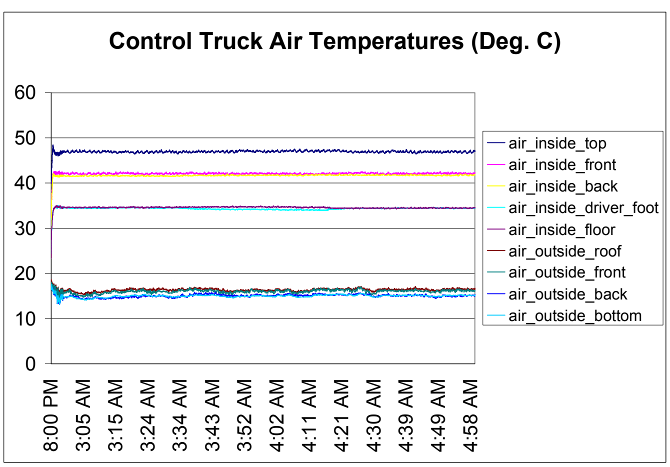

Figure 7. Measured Inside and Outside Truck Air Temperatures

Typically five runs of each configuration were conducted to obtain three valid runs (stable temperatures and little or no wind). Three valid runs were averaged to calculate the UA value for each configuration. Simple modifications were made to the test trucks to help understand heat loss paths. The different configurations for the UA test were the base case (no modifications), sleeper curtain closed and window shades applied, and windows insulated. The sleeper curtain configuration applied the factory-supplied snap-in window shades and sleeper privacy curtain during testing to measure the effects of isolating the sleeper compartment. The windows-insulated configuration included the application of foiled bubble insulation on the inside of the cab windows to estimate the amount of heat lost through the window glass (Figure 8). The factory sleeper curtain and shades were not applied in this configuration. A fourth configuration was also tested in the second test vehicle, which replaced the standard curtain with a foam-insulated or arctic curtain in the closed position (standard window shades applied).

Figure 8. Insulated Windows on Test Truck

The measured UA for the first test truck in the base configuration was 65 W/K. Therefore, in a typical overnight cab heating case with an ambient of 0˚C, heating the cab to 20˚C would require 1,300 W ($Q = UA\Delta T$). Closing the sleeper curtain and applying the window shades lowered the UA to 54 W/K for the sleeper area, a 16% reduction from the base case. The sleeper-curtain-closed configuration yielded a 21% reduction in the second test truck. Insulating the windows reduced the UA 16% in the first test vehicle from the base case and 14% in the second. Insulated window shades could further reduce heat loss when used in conjunction with the sleeper curtain, but this configuration was not tested. Although the 16% or 21% reduction from insulating the windows is significant, it is important to note that a large portion of the heat loss was through the cabin walls and other heat loss paths (door seals, vents, etc.) and was investigated through modeling and other testing detailed in this report. The results of UA tests are summarized in Table 1.

Table 1. Summary of UA Test Results (Reductions from Base)

	Base or Unmodified Case	Sleeper Curtain Closed	Arctic Curtain Closed	Windows Insulated
UA Test Truck 1	65 W/K	-16%	N/A	-16%
UA Test Truck 2	51 W/K	-21%	-26%	-14%

Table 2. Summary of Solar Soak Test Results (Reductions from Base)

	Base or Unmodified Case	Sleeper Curtain Closed	Arctic Curtain Closed	Windows Insulated
Soak Test Truck 1	ΔT = 13˚C	N/A	N/A	-8˚C
Soak Test Truck 2	ΔT = 11˚C	-1˚C	-3˚C	-4˚C

SOLAR SOAK

Testing also included daytime heat soak tests to help quantify solar gains. Interior temperatures were measured in both trucks with and without window insulation to understand the effects of the glass areas. Once again, a control truck was used to obtain any correction factors for variable conditions. The data obtained in the daytime heat soak tests were also used to validate the accuracy of a Fluent model of the cab previously developed by NREL and International.

The soak tests were run in a similar manner to the co-heat tests, using the same temperature data acquisition set-up but not using electric heaters. Trucks were faced south to maximize sun exposure with soak temperatures recorded to capture peak sun intensity from about noon to 2 p.m. The truck interior air temperatures and the outside ambient temperatures were used to calculate an average interior cab temperature above ambient. Three valid runs (stable solar irradiance and little or no wind) were averaged to calculate the average temperature rise above ambient for the same configurations as the co-heat tests.

The interior temperature rose 13˚C above ambient on average for the first test truck and 11˚C for the second test truck. For the second test truck, closing the standard sleeper curtain and installing the window shades reduced the temperature rise above ambient by about 1˚C and 3˚C with the arctic curtain. Covering the windows with foil insulation (windows-insulated configuration) reduced the temperature rise in the truck cab by 8˚C in the first test truck, 4˚C in the second truck. The results of the soak testing are summarized in Table 2. The greater reduction in temperature rise in the windows-insulated configuration (and the greater ΔT in the base case) for the first test truck can be attributed to a larger glass area that included a sunroof (no sunroof in the second test truck).

AIR EXCHANGE

To calculate the air exchange of the truck tractor cabins, the decay rate of a known gas in the cab was measured. Sulfur hexafluoride (SF_6) gas was injected into the truck cab and a tracer gas analyzer was used to record the decay data. From the measured concentration over a given period, the air exchange rate was calculated in air changes per hour (ACH).

The first test truck averaged 0.8 ACH over the test period, while the second truck averaged 0.7 ACH. Figure 9 shows the results of the air exchange testing. Both truck cabins were less than one air change per hour and were considered relatively well sealed. No additional investigation on air leakage as a source of thermal load reduction was considered.

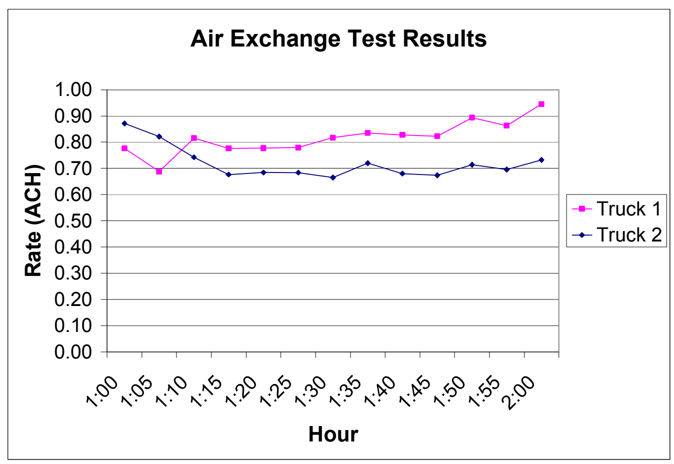

Figure 9. Results of Air Exchange Testing

INFRARED IMAGING

Infrared images were taken of the test trucks to help identify potential sources of high heat loss. An infrared radiometer was used to capture images while truck interiors were heated during the co-heat tests. The nighttime images revealed expected heat loss around door and window seals in both trucks as well as at the seam joining the roof to the lower cab (Figure 10). Some heat loss was also noted at the roof structural members where insulation may have been lacking. The higher exterior temperatures in the image indicated the areas of higher heat loss than the surrounding areas.

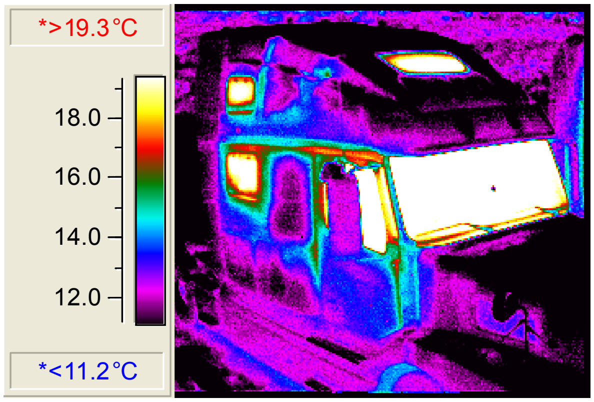

Figure 10. Infrared Image of Test Truck 1

Infrared images of the second test truck revealed higher temperature areas in the upper left and right corners at the rear of the truck cab (Figure 11). This heat loss could be the result of lacking or missing insulation in air duct areas at the rear corners of the cab.

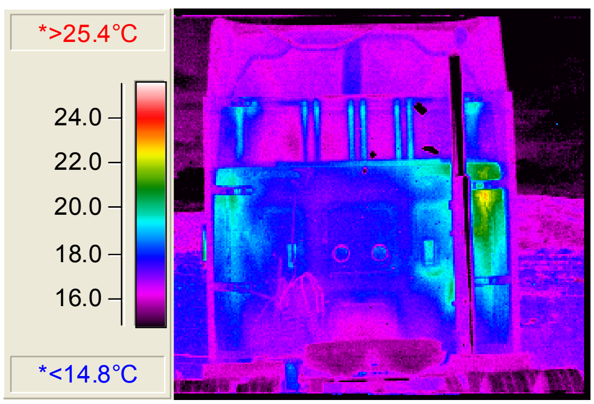

Figure 11. Infrared Image of Test Truck 2

MODELING

For the cool-down model only the rear air-conditioning (A/C) unit was simulated with a fixed airflow of 0.156 kg/s (264 cfm). As a worst-case scenario, daytime ambient and solar conditions were chosen to be an August day in Phoenix. The temperature of the air inlet to the cabin was adjusted to achieve equal cabin volume average air temperature. For the configurations without a divider curtain, the average air temperature of the entire cabin was compared. For the configurations with a divider curtain, only the sleeper portion of the cabin was considered. The duty of the A/C unit was then calculated as the sensible heat gain of the air being circulated through the A/C system. Recirculation of cabin air and moisture removal was not considered and would affect the size and duty of the A/C system. The heat due to cabin occupants and cabin equipment, such as electronics, was also not considered. The duty or heat gain of the air circulating in the A/C system was then compared to judge the effectiveness of the various configurations.

Figure 12 shows the effect of both the curtain partitioning the cabin and increasing insulation. As expected, partitioning the cabin and only cooling part of the air will take less energy. The model predicted this would decrease the duty of the A/C system by 30%. Additional insulation shows a case of decreasing returns. With the sleeper curtain open, doubling the insulation reduces the A/C duty by approximately 35%. With the curtain closed, doubling the insulation reduces duty by 25% (54% from the base configuration with no curtain). However, doubling the insulation again only resulted in approximately 6% less duty.

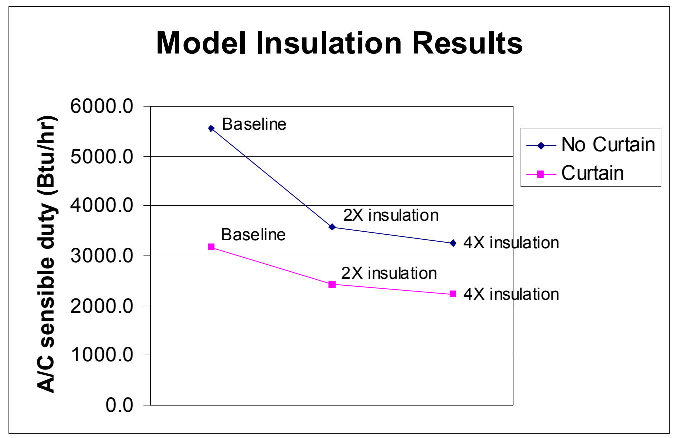

Figure 12. Effect of Increased Insulation

Covering the windows with insulated reflective shades was also simulated. The model shows that covering the windows will reduce the A/C duty by 34% with the curtain open and 14% with the curtain closed. The reduction with the curtain is much less than without it because the shades primarily keep the solar load out of the front of the cabin where most of the glass area is.

CONCLUSIONS

Through truck testing and thermal modeling, opportunities to reduce thermal load were identified and quantified. Vehicle testing demonstrated reductions in heating loads from standard configurations (sleeper curtain and window shades) as well as some optional configurations (insulated curtain and window insulation). Vehicle modeling predicted reductions in cooling loads from improved cab insulation and covered windows. The opportunities for thermal load reduction are as follows:

- Applying the standard sleeper privacy curtain and shades reduced heating load for the sleeper area by up to 21%. An insulated sleeper curtain further reduced the load to 26% over the base configuration. Covering the windows in the truck cab reduced the heating load by up to 16% over base and could further reduce heating in the sleeper curtain configurations.

- Insulating the truck cab windows also reduced daytime solar temperature gains by up to 8˚C, which reduced predicted cooling load by 34% with the sleeper curtain open. Doubling the insulation alone would reduce the cooling load by about 35% with the sleeper curtain open and a total of 54% with the sleeper curtain closed.

- Infrared images identified other potential areas to reduce heat loss, such as areas around window and door seals, at body and structural seams, and areas where insulation may be lacking around air circulation ducts.

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CONTACT

Kenneth Proc can be contacted at kenneth_proc@nrel.gov.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

ΔT: Change in temperature

A/C: Air conditioning

ACH: Air changes per hour

AVTA: Advanced Vehicle Testing Activity

CFD: Computational fluid dynamics

DOE: U.S. Department of Energy

Fluent: Flow modeling software

HVAC: Heating, ventilating, and air conditioning

IR: Infrared

OEM: Original equipment manufacturer

Q: Heat transfer rate

R: Insulation value

SF6: Sulfur hexafluoride gas

UA: Overall heat transfer coefficient