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Vehicle and Systems Simulation and Testing

VEHICLE TECHNOLOGIES OFFICE

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annual progress report

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

IV.O. CoolCalc HVAC Tool

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IV.O.1. Abstract

Objectives

- Demonstrate at least a 30% reduction in long-haul truck idle climate control loads with a three-year or better payback period by 2015
- Help industry overcome barriers to the adoption of market-viable and efficient thermal management systems that keep the cab comfortable without the need for engine idling
- Investigate opportunities to reduce truck cab thermal loads through modeling and simulation to reduce the 838 million gallons of fuel used for truck rest period idling

Approach

- Develop analytical tools to evaluate the impact of technologies that reduce thermal loads, improve climate control efficiency, and reduce vehicle fuel consumption
- Work closely with industry partners to evaluate and improve modeling and analysis tools that are relevant and beneficial to both original equipment manufacturers and suppliers
- Use validated CoolCalc models to identify promising technologies for further investigation with outdoor testing
- Utilize CoolCalc simulations to extend test results to a wide variety of climate and time-use conditions to more thoroughly evaluate technology performance and estimate fuel savings

Major Accomplishments

- Validated model of Volvo test buck to within 0.89°C of sleeper air temperature at peak solar load
- Applied Volvo model to guide CoolCab outdoor testing, predicting average interior air temperature reductions of:
  - 7.3°C (β=35.9%) from black to white paint
  - 2.8°C (β=15.6%) from blue to an estimated solar-reflective blue paint
- Developed and incorporated vehicle-specific interior convection models
- Improved functionality and reliability; released latest version to industry partners for evaluation

Future Activities

- Improve and apply CoolCalc's rapid parametric analysis tools to help industry estimate design impacts on fuel use and payback period across a broad range of weather and operating conditions
- Continue validation of CoolCalc models, including heavy-duty vehicle heating and cooling systems
- Begin development, validation, and application of medium- and light-duty vehicle models
- Improve integration of CoolCalc with NREL's air conditioning model (CoolSim) and with Autonomie

IV.O.2. Technical Discussion

Background

Heating and air conditioning are two of the primary reasons for long-haul truck main engine operation when the vehicle is parked. In the United States, 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 efficiency, there is a great opportunity to reduce the fuel used and emissions created by idling. Enhancing the thermal performance of cab/sleepers will enable cost-effective idle reduction solutions. If the fuel savings from new technologies can provide a one- to three-year payback period, fleet owners will be economically motivated to incorporate them. This provides a pathway to rapid adoption of effective thermal and idle load reduction solutions.

The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory's (NREL's) CoolCab project is researching efficient thermal management strategies that keep the vehicle occupants comfortable without the need for engine idling. To achieve this goal, NREL is developing tools and test methods to assess idle reduction technologies. The heavy-duty truck industry needs a high-level analysis tool to predict thermal loads, evaluate load-reduction technologies, and calculate their impact on climate control fuel use.

To meet this need, NREL has developed CoolCalc, a software tool to assist industry in reducing climate control loads for heavy-duty vehicles (HDV). CoolCalc is enables rapid exploration of idle reduction design options for a range of climates.

Introduction

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 (CAE) 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 CAE tools by first exploring the design space to identify promising technologies and specific parameters that require deeper investigation.

CoolCalc, described in more detail in [3], was originally built on NREL's OpenStudio platform as a plug-in extension for Google's 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.

CoolCalc is filling an important role in the CoolCab project's suite of experimental and analytical tools, as well as equipping industry partners with a valuable and cost-effective research and design tool.

Approach

The goals of the CoolCab research project are to reduce thermal loads, improve occupant thermal comfort, and maximize equipment efficiency to eliminate the need for rest period engine idling. To accomplish these goals, NREL is closely collaborating with original equipment manufacturers (OEMs) and suppliers to develop and implement commercially viable thermal management solutions.

The CoolCab project employs a strategic, three-phase approach to evaluating commercially available and advanced vehicle thermal management and idle-reduction technologies. The three phases are (I) baseline characterization and model development, (II) thermal performance enhancement, and (III) idle reduction. Each phase features applications of NREL's suite of thermal testing and analysis tools. CoolCalc is applied throughout the entire research process to complement the evaluation of idle-reduction strategies through outdoor testing and more detailed CAE modeling.

In Phase I, CoolCalc models of the test vehicles are built, starting from computer-aided design (CAD) models and other information provided by OEMs and suppliers. The models are validated against test data collected at NREL's Vehicle

Testing and Integration Facility (VTIF). Local weather data logged at the VTIF's new weather station are fed into the CoolCalc simulation to ensure that the model behaves similarly to the test vehicle under the same weather conditions.

CoolCalc is leveraged in Phase II to identify opportunities to reduce thermal loads via rapid simulation of technologies and thermal management strategies. Top candidates from the parametric simulations are selected for further investigation through outdoor testing.

Testing results from Phase II serve as a launching point for CoolCalc simulations to analyze performance and estimate fuel use savings across a wide variety of weather and time-use distributions. For each set of conditions, CoolCalc supplies thermal loads to CoolCab's air-conditioning (A/C) model, which calculates required compressor power. The model is then coupled with Autonomie to predict fuel use for the weather and use conditions. This fulfills the end goal of providing decision makers with the necessary information to adopt solutions that reduce or prevent engine idling and save fuel.

Results

COOLCALC IMPROVEMENTS AND NEW FEATURES

Many enhancements were made to the CoolCalc HVAC load estimation tool to improve functionality and usability:

- Several minor and major bugs were corrected, and a CoolCalc bug tracker was developed to report software issues and to suggest new features. The bug tracker was only used internally, but will be available to the public in future CoolCalc releases.
- CoolCalc source code was restructured to a "project-based" format, permitting the use of more modular components and building a strong foundation for future model improvements. This change also gives users more control over individual portions of CoolCalc models while still allowing importing and exporting of EnergyPlus input file format.
- The graphical user interface (GUI) of the Object Browser was expanded to include dynamically generated interfaces for all available EnergyPlus objects. An exclusion list was developed to hide all objects that do not apply to vehicle modeling. When available, EnergyPlus Class and Field notes are displayed to the user.
- A Parametric Variables GUI was developed that enables users to define multiple values for individual model parameters. The GUI allows simulations to be run parametrically. For example, all defined values of a material property such as insulation thickness can be programmatically evaluated. The parametric variables can be implemented at the field level and, in the future, at the object level, providing greater flexibility to the model for parametric analyses. This feature also applies to weather files, which can be grouped (for example, by geographic region) and defined as a single parametric variable.
- The overall model development process was extended beyond vehicle geometry and basic component definitions to incorporate a more flexible vehicle climate control system setup. The user can now more easily add a default HVAC system to a vehicle model and modify system settings through a graphical interface, as shown in Figure 1.

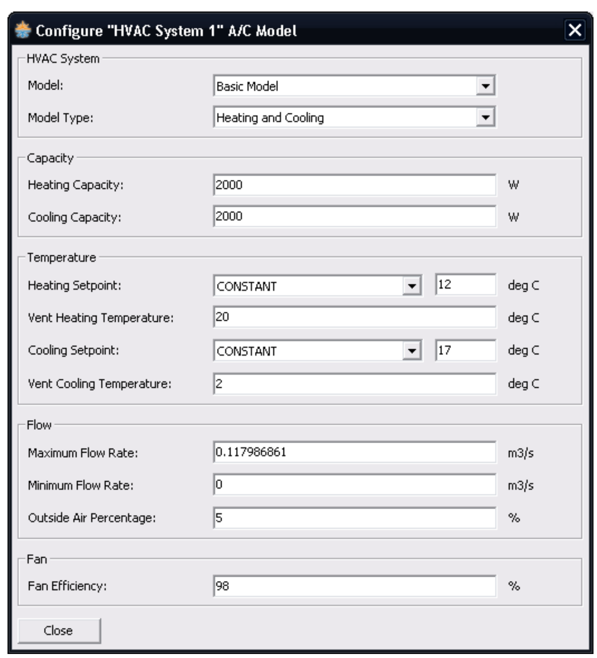

Figure 1. CoolCalc HVAC system GUI.

- The Run Simulation GUI was overhauled to provide much greater simulation control. With the new GUI, the user can select which design days to evaluate, which output variables to report, and which output files to create and display upon simulation completion. The user can also create and select multiple simulation periods (opposed to only one, previously) when using weather files. The Run Simulation GUI displays all parametric variables defined in the model, including weather files. The GUI also allows the user to configure variable combinations for simulation up to a full factorial analysis. Sequential simulations are automatically executed, saving user setup time and allowing simulations to be run unattended.
- Documentation of code was improved. HTML documentation of the classes and a diagram of the general system architecture were added. This improved code readability and facilitates future development.

The CoolCalc user guide will be updated to reflect all of the recent improvements, and expanded to include sections for troubleshooting common errors and for advanced users. The latest version of CoolCalc was released to industry partners in September.

VEHICLE INTERIOR CONVECTION MODELS

An important component of any vehicle thermal model is the convection model used for the interior surfaces. The EnergyPlus heat transfer coefficient model is appropriate for the natural convection under soak conditions. Interior forced convection that occurs when using vehicle HVAC systems is not properly captured by the default convection models available in EnergyPlus. To improve the accuracy of forced convection modeling on interior surfaces, vehicle-specific convection correlations have been implemented in CoolCalc. Leveraging previous computational fluid dynamics (CFD) simulations of vehicles, these correlations were developed to relate the interior surface convection coefficients to the HVAC air exchange rate of the vehicle. Correlations were developed for heavy- and light-duty models, for four primary surface types: ceiling, floor, walls, and windows. For the HDV correlations, CFD simulations were conducted with air flow rates varying between 0.005 and 0.119 m^3/s, and the resulting convection coefficient data were fitted with a third-order polynomial curve, as shown in Figure 2.

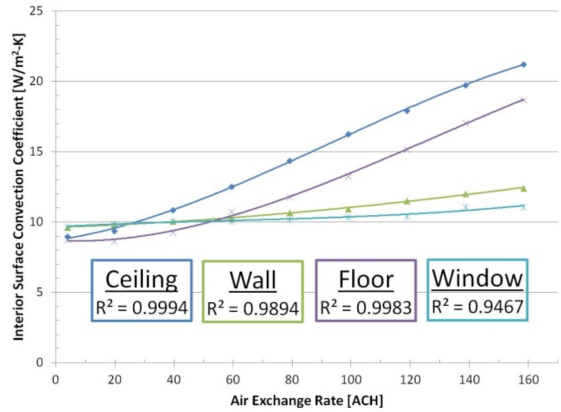

Figure 2. HDV interior surface convection correlations.

In future work, these convection correlations will continue to be refined, validated and extended to a variety of different vehicles and air-distribution configurations.

VOLVO COOLCALC MODEL VALIDATION

A CoolCalc model of a Volvo test "buck" (shown in Figure 3, below) was built from CAD 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 defined to most closely match the configuration of the actual Volvo test bucks (Figure 4) undergoing thermal testing at the VTIF. Test bucks were used in place of complete vehicles to reduce cost and improve adaptability.

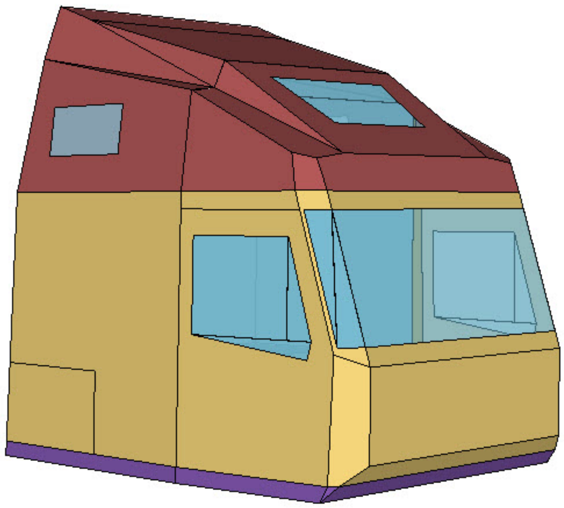

Figure 3. CoolCalc model of a Volvo test buck.

Figure 4. Volvo test bucks at NREL's VTIF.

A custom weather file was created from data collected at NREL's VTIF and Solar Radiation Research Laboratory weather stations. The Volvo model simulation 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 5) 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 6, between model and test results demonstrate that the model accurately captures the effect of solar position.

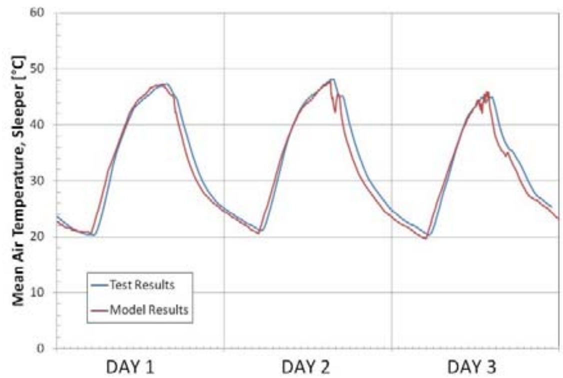

Figure 5. Volvo test buck CoolCalc model validation – sleeper compartment mean air temperatures

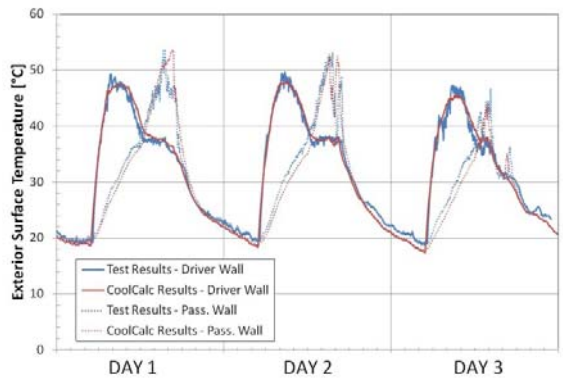

Figure 6. Volvo test buck CoolCalc model validation – exterior side wall temperatures.

COOLCALC ABSORPTIVITY STUDY

After validating the model with test data, the CoolCalc model of the Volvo test buck was used to identify opportunities to reduce long-haul truck thermal loads and help guide testing efforts. The FY 2012 focus was on the solar envelope of the vehicle, including opaque and glazing surfaces. A CoolCalc analysis was performed to evaluate the impact of different vehicle paints, including those with solar-reflective properties. PPG supplied samples of traditional (OEM) paints to support CoolCab research activities. Samples of black, white, and blue paint were tested at NREL to determine their solar spectral properties, which are shown in Table 1. Properties for solar-reflective (SR) blue paint were estimated from [4] and are also listed in Table 1. These four paints were applied to the validated CoolCalc model to evaluate the impact of surface absorptivity on the thermal load of the vehicle.

Table 1. Solar-weighted optical 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	65.0*	0.950*
*estimated value		

Figure 7 shows the predicted interior air temperatures from each of the simulations. The percentage of maximum possible temperature reduction, β, (described in more detail in the CoolCab section of this report) 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 = 35.9% changing from black to white paint, and β = 14.6% from blue to solar-reflective blue paint. These estimates predict the potential impact of paint properties on engine-off thermal soak air temperature reduction for heavy-duty trucks.

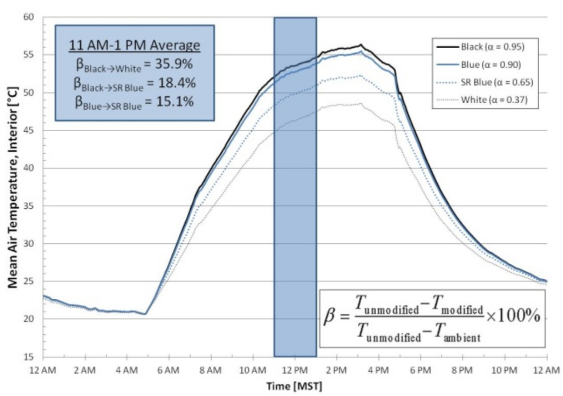

Figure 7. CoolCalc surface absorptivity study.

CoolCalc will continue to be used in conjunction with outdoor testing to estimate the impact of polycarbonate and chromogenic (switchable) glazings.

Conclusions

The CoolCalc model predicted an interior air temperature reduction of 7.3°C changing from black to white paint at peak solar load. This corresponds to β = 35.9%, which is a measure of the maximum temperature reduction possible. These results are in good agreement with CoolCab test results provided in the CoolCab section of this annual report. Switching from blue to the estimated solar-reflective blue, an air temperature reduction of 2.8°C was predicted, with β = 15.6%.

CoolCalc's recent improvements have added significant modeling capability and made the modeling environment much easier to use. Reducing the user learning curve allows for much quicker adoption and implementation of the tool by industry partners.

CoolCalc continues to be used effectively to guide testing efforts through preliminary technology performance evaluation. Methods and tools are currently being developed to improve CoolCab vehicle fuel use estimation through testing and the application of CoolCalc modeling. The next step is to apply CoolCalc across a wide variety of weather and time-use conditions. Quantifying fuel savings and payback periods is vital to the adoption and implementation of idle-reduction solutions in long-haul truck fleets.

CoolCalc was used to assist partners on both DOE- and industry-funded projects, including Volvo Trucks, Daimler Trucks, E-A-R Thermal Acoustic Systems, PPG Industries, Oshkosh, and The Aerospace Corporation. By working with industry partners to develop and apply commercially viable solutions to reduce idling fuel use, both national energy security and sustainability will be improved.

IV.O.3. Products

Tools & Data

CoolCalc version 2.0.0 is currently available to industry and laboratory partners.

1. CoolCalc 2.0.0 – long-haul truck thermal load estimation tool

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