Scientific Research Publishing

Open Journal of Energy Efficiency, 2024, 13, 88-99
https://www.scirp.org/journal/ojee
ISSN Online: 2169-2645
ISSN Print: 2169-2637

Reducing Electrical Consumption in Stationary Long-Haul Trucks

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How to cite this paper: Sheth, K., Patel, D. and Swami, G. (2024) Reducing Electrical Consumption in Stationary Long-Haul Trucks. *Open Journal of Energy Efficiency*, **13**, 88-99.
https://doi.org/10.4236/ojee.2024.133006

Received: July 23, 2024
Accepted: August 25, 2024
Published: August 28, 2024

Abstract

On average, long-haul trucks in the U.S. use approximately 667 million gallons of fuel each year just for idling. This idling primarily facilitates climate control operations during driver rest periods. To mitigate this, our study explored ways to diminish the electrical consumption of climate control systems in class 8 trucks through innovative load reduction technologies. We utilized the CoolCalc software, developed by the National Renewable Energy Laboratory (NREL), which integrates heat transfer principles with extensive weather data from across the U.S. to mimic the environmental conditions trucks face year-round. The analysis of the CoolCalc simulations was performed using MATLAB. We assessed the impact of various technologies, including white paint, advanced curtains, and Thinsulate insulation on reducing electrical demand compared to standard conditions. Our findings indicate that trucks operating in the eastern U.S. could see electrical load reductions of up to 40%, while those in the western regions could achieve reductions as high as 55%. Such significant decreases in energy consumption mean that a 10 kWh battery system could sufficiently manage the HVAC needs of these trucks throughout the year without idling. Given that many long-haul trucks are equipped with battery systems of around 800 Ah (9.6 kWh), implementing these advanced technologies could substantially curtail the necessity for idling to power air conditioning systems.

Keywords

Long-Haul Trucks, Electricity Consumption, Idling Reduction, HVAC Systems, Climate Control, Energy Efficiency

1. Introduction

The Department of Energy (DOE) encourages industry-laboratory collaboration to reduce national carbon emissions. The CoolCab project at the National Renewable Energy Laboratory (NREL) researched cost-effective thermal reduction technologies' impact on heavy-duty vehicle climate control systems and occupancy comfort. Thus, CoolCab's focus on reducing fuel use and associated emissions aligns with DOE goals and has led to strong partnerships with Volvo and other industry partners.

Several incentives to develop idling load reduction technologies motivated the industry-laboratory collaboration. Idling represents an operating cost that, if reduced, could improve the competitiveness of long-haul fleets. Furthermore, truck trailer businesses are required to meet stringent idling regulations in all 50 states [1]. Most long-haul trucks have an ownership cycle of only four years; therefore, fleet owners will be economically motivated to adopt idle reduction technologies if the payback period is under three years [2].

Improved fuel efficiency during rest-idle periods could significantly cut transportation costs and reduce carbon dioxide emissions. Large line-haul trucks idle overnight to keep fuel and the engine warm, power cab appliances, and maintain comfortable cab temperatures during driver rest periods. Additionally, trucks idle during the workday at ports, busy delivery sites, border crossings, and loading zones. Fuel accounts for 38% of the total long-haul truck operational costs and is the second largest cost per mile [3]. On average, long-haul trucks in the United States consume 667 million gallons of fuel annually during rest period idling, accounting for 6.8% of the total long-haul truck fuel use [4].

The recent advancements in passenger vehicle technologies reflect a broader trend towards improved fuel efficiency and reduced carbon emissions, which is also relevant for heavy-duty vehicles. Predictive modeling and efficiency forecasting based on extensive datasets from the U.S. Department of Energy have illuminated significant trends in miles-per-gallon performance and tailpipe CO_2 emissions over the years [5]. These insights can guide the development of more energy-efficient long-haul trucks, leveraging similar technological improvements and consumer choice dynamics to reduce their environmental impact.

The reliability of photovoltaic systems as alternative power sources for long-haul trucks, especially in powering auxiliary systems such as HVAC, can vary significantly with climatic conditions. The performance of solar panels across different North American climates shows that geographic and environmental factors must be carefully considered in system design to ensure efficiency and reliability. This insight supports the use of solar-powered systems in trucks, potentially reducing the need for traditional fuel consumption during idle periods [6].

In the context of long-haul trucking, the strategic placement of service stations equipped with advanced energy-saving technologies is crucial. Drawing parallels from study on the strategic placement of EV charging stations, similar considerations can be applied to the trucking industry [7]. Their approach to optimizing the location of infrastructure to maximize accessibility and minimize redundancy offers a valuable framework for planning truck stop placements that could facilitate the widespread use of energy-efficient technologies among long-haul trucks.

Improving the cab's thermal performance has the largest idle load reduction potential. The cab's thermal performance refers to its ability to control heat transfer between outside ambient air and the interior air. A high-performing cab design will reduce the need to run the climate control system. During idling, the main engine is run to power the truck's heating, ventilation, and air conditioning (HVAC) system. Improving thermal performance will reduce the HVAC electrical load to maintain a constant temperature, thereby improving idling efficiency.

The project used CoolCalc, a modeling software developed at NREL; to simulate the temperatures a long-haul truck cab would experience throughout the year. CoolCalc combines heat transfer principles with weather data collected at 161 cities across the United States, allowing researchers to quickly model idle load reduction technologies and show the effects on a national scale. CoolCalc was used to conduct two studies intended to meet the required payback period. The first study investigated if orienting a long-haul truck north during rest periods reduces HVAC loads and interior temperatures. The second study examined the change in thermal load when several paint colors, curtain designs, and insulation thickness were applied to a truck cab. The results presented will help inform the industry as they consider different fuel-saving technologies for their long-haul truck fleets.

2. Process

2.1. Materials

Simulation-based assessment of truck cab thermal performance was evaluated using NREL's CoolCalc program. The physics-based modeling software is a relatively easy to use and cost-effective means to estimate technological impacts at a national scale. CoolCalc is a plug-in extension to Trimble SketchUp's three-dimensional modeling environment. CoolCalc links the computational domain of EnergyPlus to SkethUp, allowing energy simulation to be performed on three-dimensional vehicle models. By utilizing weather data in the form of Typical Meteorological Year (TMY) data files, CoolCalc can simulate the cab's internal temperature and rapidly test HVAC loads. Both studies described below were modeled using CoolCalc version 2.4.149 beta, SketchUpMake v.13, and EnergyPlus v.8.1.0. For these studies, simulations were evaluated at 161 locations throughout the 48 contiguous United States. The simulation process and modeling parameters are described further by Lustbader *et al.* [8]. All post-processing of simulation results were completed using MATLAB numerical computation and visualization packages. Extensive time was devoted to improving existing code, analysis accuracy, and documentation. Furthermore, MATLAB functions were developed to enable mapping between thermal and electrical loads.

2.2. Simulation Studies

The results described below pertain to post processing two cab studies: the axis sweep study and the full cab solution study.

The axis sweep study evaluated if truck orientation impacted the cab's internal air temperature. A class 8 truck cab was modeled in CoolCalc and rotated in 22.5-degree increments until the cab made a full 360-degree sweep; thus, the truck was oriented in 16 different directions. Days in which the internal temperature exceeded 25˚C were considered cooling degree days. Conversely, days that saw internal temperatures fall below 20˚C were denoted as heating degree days. The terms heating and cooling degree days serve as indicators of the amount of heating and cooling energy required to maintain a set point temperature. Since cab paint color can impact solar and thermal absorbance, a standard color was needed as a reference color to compare against. Previous work by Lustbader, et. al. used statistical analysis on data collected from fleets nationwide to determine national solar average paint properties [9]. The properties were applied to the simulated cab's exterior. Since the study's purpose was to gauge internal temperature variations as a function of truck orientation, the simulated truck's HVAC system was disengaged.

The full cab solution study evaluated the impact of three idle load reduction technologies on the truck's HVAC electrical loads at a national level. The technologies tested can be separated into three groups: paint color, curtain type, and insulation thickness. In each group, several levels were applied to the simulated cab. **Tables 1-3** list the properties programmed into CoolCalc normalized to properties of the standard combination: standard curtains, national solar average paint, and baseline insulation. The cab's HVAC load was calculated using twenty-four combinations of the group parameters at each geographic location. Because 161 cities were evaluated and thermal data was saved each minute over an entire year, the simulation demanded the computational power of a high-performance computer.

After the models were configured, they were simulated using NREL's Windows High Performance Computer (WINHPC). The WINHPC used its 96 cores in parallel to process each study in 14 hours. The results, which can exceed 500 GB in memory, are populated into a large CSV (comma-separated values) data structure. In this format, directly comparing the results of multiple simulations requires more physical memory than available to current personal computers. Consequently, data from WINHPC was imported into MATLAB to create a compressed data structure that allowed easier analysis of the simulation results.

2.3. Post Processing Methods

The importing process combined all simulation CSV files related to the same city, into a single MAT file (standard output file for MATLAB). Thus, data was accessed by location and loaded into the MATLAB workspace. Each location MAT file contained the variable combinations applied in addition to columns of

Table 1. Curtain properties evaluated in the full cab solution study normalized to standard curtain.

	Standard	Advanced
Solar Reflectance	0	0.95
Infrared Emissivity	1.00	0.056
Thickness	1.00	12.70

Table 2. Paint properties evaluated in the full cab solution study normalized to the national solar average paint color.

	White	National Solar Avg.	Midtone	Black
Solar Absorptance	0.59	1.00	1.05	1.51
Thermal Absorptance	1.10	1.00	1.10	1.10

Table 3. Insulation properties evaluated in the full cab solution study normalized to baseline insulation.

	Baseline	Half-Thinsulate	Thinsulate
Thickness	1.00	1.79	2.42
Conductivity	1.00	1.30	1.30

HVAC load, ambient air temperature, and internal cab temperature data. Substantial time was dedicated to improving existing analysis code and developing new scripts to expand post-processing capabilities. Scripts and functions were coded in a generic format to allow for use in future studies. Furthermore, the code encompasses three broad processes: ANOVA analysis, load analysis, and plotting.

The analysis functions serve as an initial screening and compilation. Each location file contained 525,000 values per variable combination. Given the full cab solution study utilized 24 variable groups, the amount of data had to be integrated and compiled for a single computer to handle. The analysis functions used weighted averages between each data column, integration, and confidence interval screening to compile the raw data into 365 values for each location and variable combination.

Load analysis functions were developed to determine the amount of electrical energy used by the truck's HVAC system. Currently, directly assessing the applied technology's impact on fuel consumption is outside the scope of this project. Using linear interpolation of existing HVAC performance tables, the project stepped closer to mapping electrical load directly to idling fuel consumption.

The plotting functions provided a graphical interpretation of the processed data. The functions were generically coded and utilized to plot MAT files generated by both ANOVA analysis and load analysis script. Cumulative distribution functions, scatter plots, and contoured maps of each study's data were generated to visually assess the results.

3. Results & Discussion

3.1. Rotational Study

The first study investigated the impact truck orientation had on solar radiation absorbed by the cab. For the thermal soak simulation results, sleeper zone and cab zone weighted mean air temperature was used to calculate cumulative cooling and heating degree days. The resulting degree day metric was derived by integrating weighted mean air temperature (T_{WMAT}) difference from a reference temperature (T_{Ref}) over each day.

Reference temperatures of 25˚C and 20˚C were used to calculate cooling and heating degree days, respectively. Using Equations (1) and (2), cooling degree days (*CDD*) and heating degree days (*HDD*) were calculated using trapezoidal numerical integration.

$$CDD = \frac{1}{1440} \int_0^{1440\,\text{min}} \begin{cases} T_{WMAT} - T_{Ref} & \text{if } T_{WMAT} > T_{Ref} \\ 0 & \text{if } T_{WMAT} \le T_{Ref} \end{cases} \tag{1}$$

$$HDD = \frac{1}{1440} \int_0^{1440\,\text{min}} \begin{cases} T_{Ref} - T_{WMAT} & \text{if } T_{WMAT} < T_{Ref} \\ 0 & \text{if } T_{WMAT} \ge T_{Ref} \end{cases} \tag{2}$$

These equations represent the integration of the delta values from T_{Ref} for one day (1440 minutes) divided by the number of minutes in a day to get the units of degree day. The degree day values were summed over the entire year to give a cumulative degree day value for each location and each rotational angle. The cumulative degree days for each direction at a location were then normalized by the south cumulative degree days for that location.

The plots of cooling degree days and heating degree days versus rotation angle are shown in **Figure 1** and **Figure 2**, respectively. In both figures, the normalized degree day for each location is marked by a red diamond. At each orientation angle, the degree day mean and the range for two standard deviations are shown in blue. The results show that for cooling conditions, a 23.7% decrease in the mean cooling degree days can be achieved by facing the cab north while idling compared to pointing it south. For heating conditions, an 8.7% increase in the mean heating degree days was calculated when facing north rather than south.

3.2. Full Cab Solution Study

In order to spatially relate thermal load patterns to geographic coordinates, the HVAC heating and cooling electrical loads for the full cab solution study are presented as a contour map in **Figure 3**, **Figure 4**. The full cab study simulated HVAC loading at 161 locations over an entire year. The annual data was integrated into an average daily power usage at each location and interpolated to produce the contour plots below. Even though 24 combinations of curtain type, insulation thickness, and paint color were evaluated, only the combination with

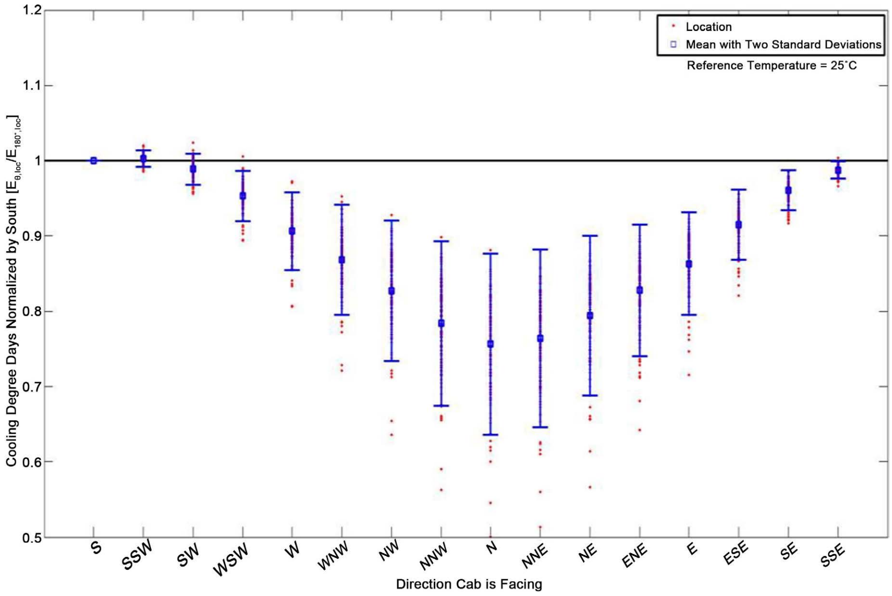

Figure 1. Cooling degree days as a function of cab orientation normalized to south.

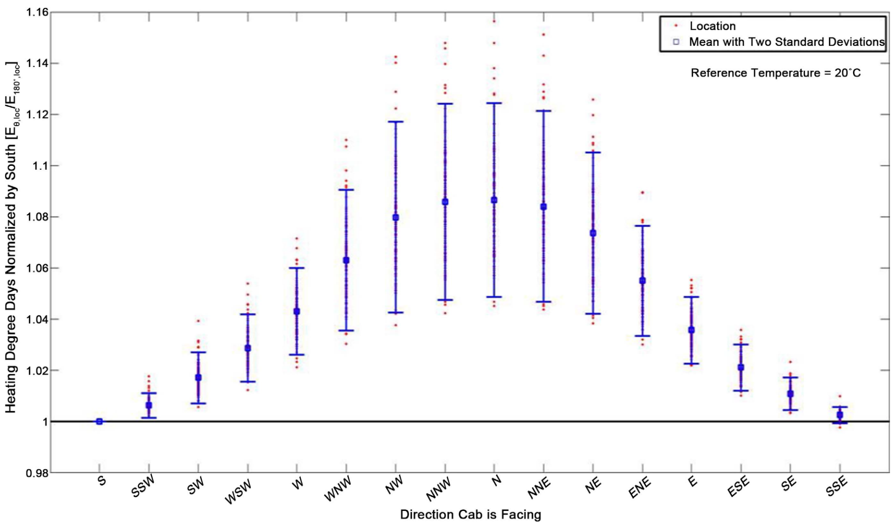

Figure 2. Heating degree days as a function of cab orientation normalized to south.

the largest impact on idle load reduction is presented in this report: advanced curtains, Thinsulate insulation, and white paint. In both figures, the advanced combination is compared to the power usage under standard conditions: standard curtains, baseline insulation, and national solar average. The geographic locations corresponding to processed TMY3 data are marked by blue asterisks. The colors overlaying both maps represent daily thermal demands on the HVAC system in units of kWh. Using the color bars, Figure 3 indicates cabs using advanced idle load reduction technologies consumed a daily 5 - 13 kWh compared to the daily 14 - 27 kWh required if standard conditions were applied. Figure 4 represents the thermal load required to heat the cab. During heating days, cabs applied with the advanced combination will use up to 45 kWh while operating in the northern half of the nation compared to energy demands of up to 60 kWh using baseline combinations. As expected, the map indicates truck operators with routes in northern states with harsh winters use more energy to heat the cab than in milder southern states. From **Figure 4**, we can also infer that applying the advanced combination results in a smaller load reduction during heating compared to the reduction seen while cooling the cab.

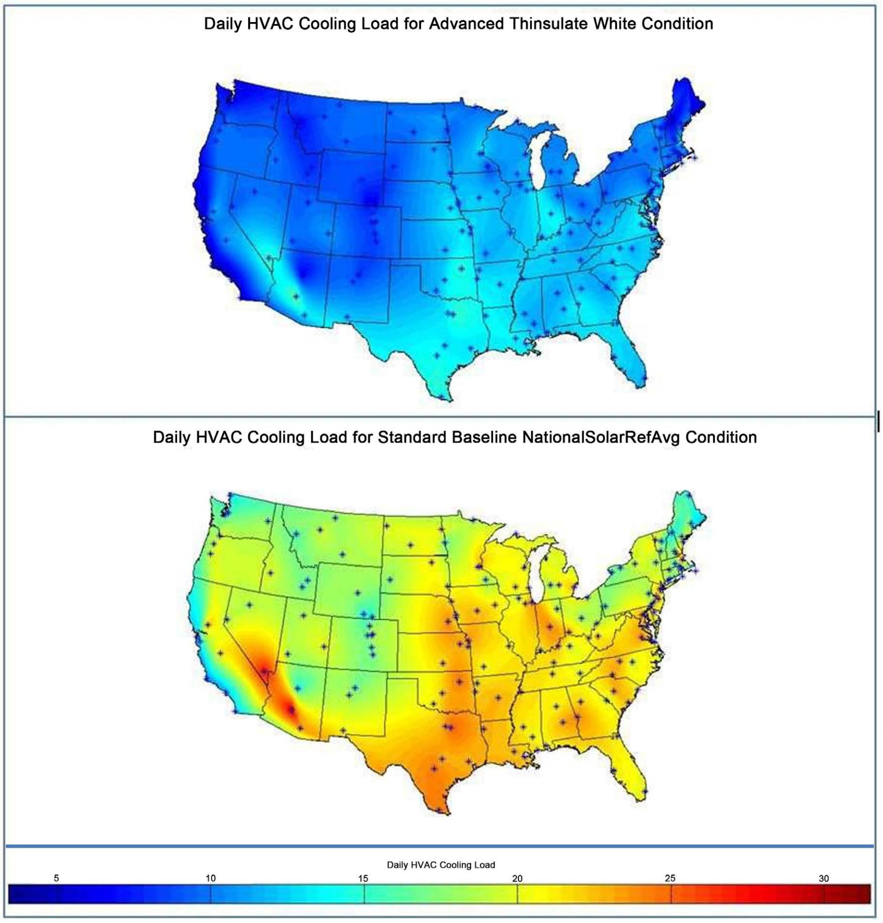

Figure 3. Comparing cooling thermal loads using advanced and standard combinations.

To investigate the reduction in thermal load, HVAC data was interpolated on contour maps of the United States, see **Figure 5**, **Figure 6**. As indicated by the color bars, the contour overlaying both maps represents the HVAC load percent reduction using advanced conditions compared to power usage under standard conditions. The geographic locations corresponding to processed TMY3 data are marked by blue asterisks. **Figure 5** suggests truck fleets operating in the nation's eastern half can reduce cooling loads in the range of 35% - 40% and those functioning in the western half will use an approximate 50% - 55% less energy. This trend could be the result of denser cloud cover over the eastern half, which would decrease solar radiation's impact on thermal loads. **Figure 6** shows fleets operating in the northern half of the U.S. will reduce energy consumption by 25% - 35% and fleets in the southern half experience reductions ranging 5% - 26%.

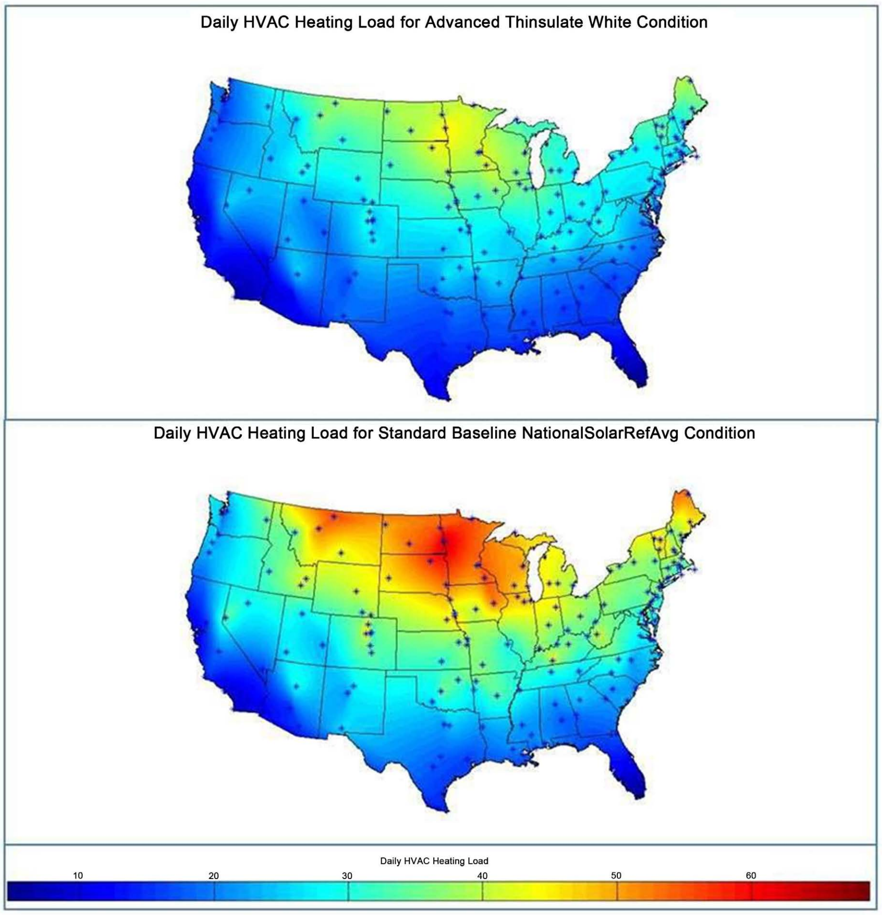

Figure 4. Comparing heating thermal loads using advanced and standard combinations.

Figure 5, **Figure 6** suggest applying the selected idle load reduction technologies under cooling conditions may reduce thermal loads—16 kWh and under heating conditions approximately 7 - 14 with the same technologies applied.

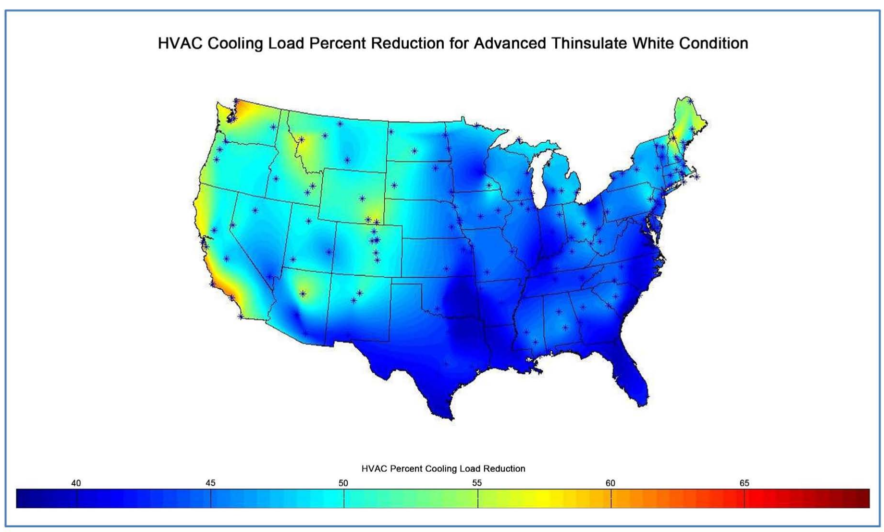

Figure 5. Comparing heating thermal loads using advanced and standard combinations.

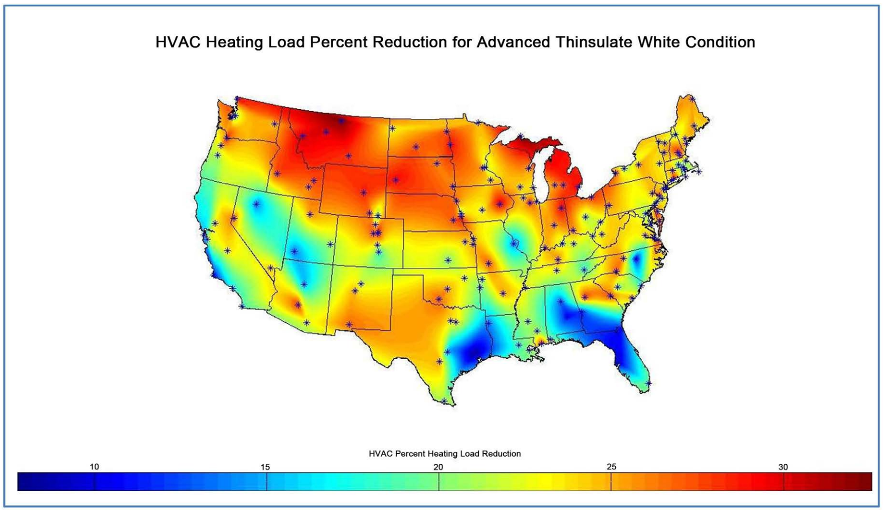

Figure 6. Heating load percent reduction using advanced technologies relative to standard combinations.

To evaluate reduction technologies at a national level, a cumulative distribution plot (**Figure 7**) presents the daily battery load at all locations as a function of time. For each day, a maximum of 10-hour window was processed. The energy utilized to maintain a cab temperature of 25˚C was cumulatively summed over each day until reaching 100% of the days (*i.e.* one year). The cooling loads observed using advanced conditions are plotted in green and the loads under standard conditions are in blue. **Figure 7** indicates a 10-kWh battery system can meet the power required throughout the entire year using advanced technologies in contrast to a standard cab demanding a 20-kWh system.

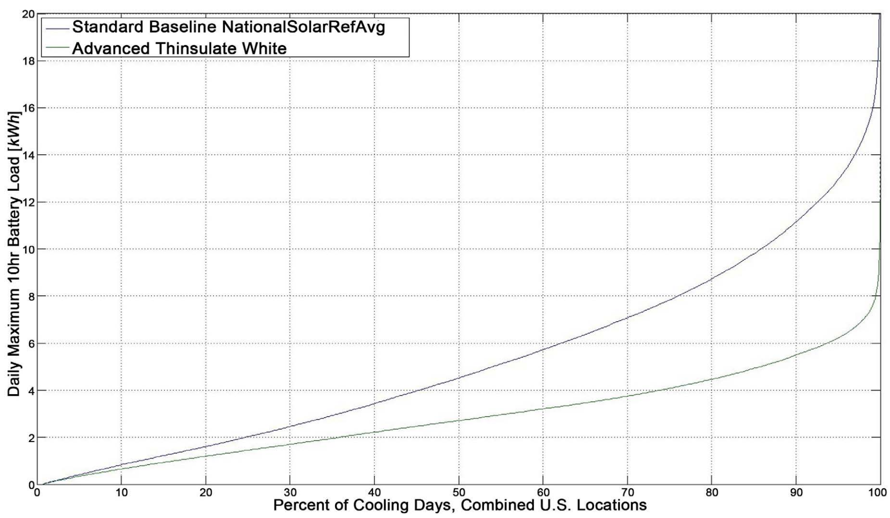

Figure 7. Cumulative sum of daily battery load requirements as a function of time.

4. Conclusion

4.1. Effects of Cab Orientation

Illustrated in **Figure 1**, there is a 13.3% decrease in mean cumulative annual cooling degree days from south-facing to north-facing. This decrease relates to a decrease in the amount of energy required to cool the truck's cab. Implementing this idle load reduction strategy would require no cost to the truck fleet or fleet operator if parking facing north is available. Illustrated in **Figure 2**, orienting the cab in a northern direction will increase the mean annual heating degree days by 4.1% relative to south facing heating degree days. The increase is a result of the selected idle load reduction technologies reducing the cab's solar radiation absorbance. Additional thermal energy is required to make up for lost solar energy, which would have helped heat the cab.

4.2. Effects of Full Cab Solution

Figure 3 and **Figure 4** show applying the advanced combination could reduce thermal demands to a daily 10 kWh. **Figure 5** and **Figure 6** suggest the advanced combinations can reduce national thermal loads by 35.6% - 68.7% during cooling days and 6.1% - 34.3% during heating days. The reason for larger load reductions during cooling compared to heating conditions is a result of interactions between solar radiation and load reduction technologies. A large number of cooling days occur during the summer. Applying advanced curtains reduces the transmittance of solar radiation through the cab's glazing. White paint also reflects much of the day's solar radiation, and Thinsulate insulation reduces thermal conduction between ambient and internal cab air. Coupling the effects significantly reduces the thermal energy absorbed by the cab. During the winter and nighttime periods, when many of the heating conditions occur, ambient air temperature has a stronger impact on heating loads than solar radiation. While Thinsulate insulation reduces heating loads by impeding thermal conduction between the cab air to ambient air, the paint and curtains prevent solar radiation from adding energy that would help heat the cab.

Furthermore, **Figure 7** shows a 10 kWh system could meet the annual power requirements for cooling. Vehicles with an equivalent battery system could power the AC system without the need to run the engine. Since today's battery HVAC systems typically use an 800 Ah (9.6 kWh) battery, the only cost to the fleet owner would be installing the advanced combination to the cab. If our predictions are correct and industry partners implement suggested idle reduction technologies, idling to cool the cab could help reduce the 667 million gallons of fuel used annually.

4.3. Future Research

For future research, mapping thermal loads to fuel consumption and fuel savings would help move idle reduction technologies into industry. For example, using battery sizing data to provide a cost and payback analysis of the idle reduction solutions will provide important information to the industry. Proving idle reduction combinations provide a payback period of less than three years will provide a financial incentive for fleet owners to implement the technologies. Additionally, implementing traffic flow data could provide a more accurate distribution of possible thermal energy savings. Finally, utilizing weather data for various cities could improve erroneous color map interpolation when generating national maps.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] American Transportation Research Institute (2023) Compendium of Idling Regulations. https://truckingresearch.org/wp-content/uploads/2023/04/2023-ATRI-IdlingCompendium-Mar.pdf

[2] Roeth, M., Kircher, D., Smith, J. and Swim, R. (2013) Barriers to the Increased Adoption of Fuel Efficiency Technologies in the North American On-Road Freight Sector. Report for the International Council for Clean Transportation.

[3] Fender, K.J. and Pierce, D.A. (2024) An Analysis of the Operational Costs of Trucking: 2024 Update. https://truckingresearch.org/2024/06/an-analysis-of-the-operational-costs-of-trucking-2024-update/

[4] Gaines, L., Vyas, A. and Anderson, J.L. (2006) Estimation of Fuel Use by Idling Commercial Trucks. *Transportation Research Record*: *Journal of the Transportation Research Board*, **1983**, 91-98. https://doi.org/10.1177/0361198106198300113

[5] Sheth, K., Patel, D. and Swami, G. (2024) Strategic Insights into Vehicles Fuel Consumption Patterns: Innovative Approaches for Predictive Modeling and Efficiency Forecasting. *International Journal of Engineering Research & Technology* (*IJERT*), **13**.

[6] Sheth, K. and Patel, D. (2024) Comprehensive Examination of Solar Panel Design: A Focus on Thermal Dynamics. *Smart Grid and Renewable Energy*, **15**, 15-33. https://doi.org/10.4236/sgre.2024.151002

[7] Sheth, K. and Patel, D. (2024) Strategic Placement of Charging Stations for Enhanced Electric Vehicle Adoption in San Diego, California. *Journal of Transportation Technologies*, **14**, 64-81. https://doi.org/10.4236/jtts.2024.141005

[8] Lustbader, J.A., Rugh, J.P., Rister, B.R. and Venson, T.S. (2011) CoolCalc: A Long-Haul Truck Thermal Load Estimation Tool. *SAE Technical Paper Series*, **1**, Article 0656. https://doi.org/10.4271/2011-01-0656

[9] Rugh, J.P., Chaney, L., Lustbader, J. and Meyer, J. (2007). Reduction in Vehicle Temperatures and Fuel Use from Cabin Ventilation, Solar-Reflective Paint, and a New Solar-Reflective Glazing. *SAE Technical Paper Series*, **1**, Article 1194. https://doi.org/10.4271/2007-01-1194