Climate Control Load Reduction Strategies for Electric Drive Vehicles in Cold Weather

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Climate Control Load Reduction Strategies for Electric Drive Vehicles in Cold Weather

Abstract

When operated, the cabin climate control system is the largest auxiliary load on a vehicle. This load has significant impact on fuel economy for conventional and hybrid vehicles, and it drastically reduces the driving range of all-electric vehicles (EVs). Heating is even more detrimental to EV range than cooling because no engine waste heat is available. Reducing the thermal loads on the vehicle climate control system will extend driving range and increase the market penetration of EVs.

Researchers at the National Renewable Energy Laboratory have evaluated strategies for vehicle climate control load reduction with special attention toward grid-connected electric vehicles. Outdoor vehicle thermal testing and computational modeling were used to assess potential strategies for improved thermal management and to evaluate the effectiveness of thermal load reduction technologies. A human physiology model was also used to evaluate the impact on occupant thermal comfort. Experimental evaluations of zonal heating strategies demonstrated a 5.5% to 28.5% reduction in cabin heating energy over a 20-minute warm-up. Vehicle simulations over various drive cycles show a 6.9% to 18.7% improvement in EV range over baseline heating using the most promising zonal heating strategy investigated. A national-level analysis was conducted to determine the overall national impact. If all vehicles used the best zonal strategy, the range would be improved by 7.1% over the baseline heating range. This is a 33% reduction in the range penalty for heating.

Introduction

As in conventional vehicles, electric vehicles (EVs) require cabin climate control for passenger thermal comfort and safety. Heating and cooling can have a large negative impact on a vehicle's energy efficiency. For conventional vehicles this results in lower fuel economy and higher per-mile travel costs, but for EVs this means a reduction in the vehicle's maximum driving range. According to tests conducted at Argonne National Laboratory's Advanced Powertrain Research Facility, cabin heating at 20°F ambient can reduce EV range by 20%–59% compared to no heating, as shown in Figure 1 [1]. This presents a major challenge for many drivers and a barrier to widespread adoption of EVs.

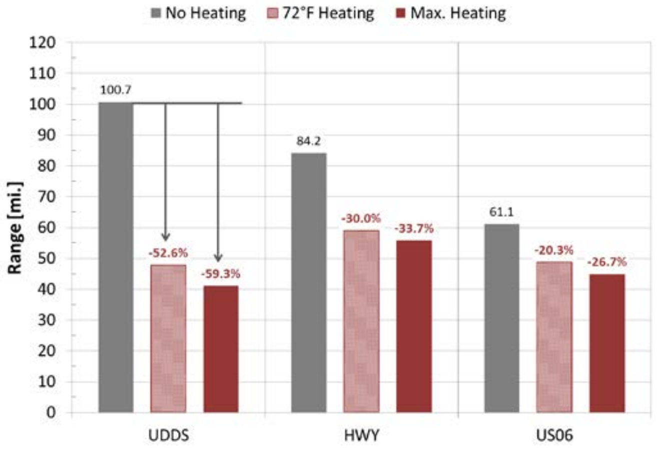

Figure 1: Impact of cabin heating on EV driving range in 20°F ambient

The negative impact of cabin heating is a relatively new challenge for automobile manufacturers because conventional vehicles traditionally used abundant waste heat from the engine. EVs do not have sufficient waste heat to fulfill cabin heating requirements. Using electric resistance heaters for cabin conditioning takes valuable battery energy away from propulsion, reducing electric driving range. Oversizing traction batteries to overcome range limitations is too costly to be a viable solution. Therefore, it is critical to minimize climate control loads in EVs to maximize vehicle range.

The objective of this research was to minimize climate control energy requirements to increase in-use EV driving range by 10% during operation of the climate control system while maintaining occupant thermal comfort. This range improvement is expected to increase customer acceptance of EVs, thereby improving adoption of EVs into the national vehicle fleet.

Approach

Experimental and analytical techniques were used in conjunction to investigate thermal load reduction strategies for EVs in cold weather. Outdoor vehicle tests conducted at the National Renewable Energy Laboratory (NREL) consisted of a cold thermal soak and cabin warm-up to establish baseline performance and to assess the impact of zonal heating strategies on heating, ventilating, and air conditioning (HVAC) energy consumption. A thermal model of a Ford Focus EV, including a virtual manikin, was also developed to investigate thermal load reduction strategies and to simulate an occupant's thermal comfort response. Vehicle simulations and analysis were used to expand experimental results to a national-level EV impact estimate.

Vehicle Thermal Testing

Cold Weather Testing Approach

Through a cooperative research and development agreement, the Ford Motor Co. provided two Ford Focus Electric vehicles for outdoor thermal testing at NREL. The same vehicles and test setup as described in [2] for warm weather testing were used for cold weather thermal load reduction evaluation. The test vehicles each contained over 40 calibrated thermocouples to measure interior and exterior air and surface temperatures. The cabin air temperature was calculated as the average of eight interior air temperature measurements: one breath-level thermocouple and one foot-level thermocouple at each of the four primary passenger seats. The instrumentation on the vehicles also included measurement of the climate control power and data acquisition from select channels on the vehicle controller area network (CAN) bus. Environmental conditions—including air temperature and relative humidity, wind speed and direction, and solar irradiance—were recorded by the onsite weather station at the Vehicle Testing and Integration Facility.

Throughout the testing, one of the two vehicles remained unmodified to serve as a control vehicle while the other vehicle was modified for each test configuration that was evaluated. Testing the vehicles side by side under the same weather conditions allowed a direct comparison of thermal performance of each load reduction strategy.

The cold weather test procedure included an overnight thermal soak period during which the vehicles remained closed and undisturbed, followed by a stationary transient warm up beginning at 5:30 a.m. mountain standard time (MST). Tests were conducted on days when the overnight ambient temperature was near 0°C. All tests had a warm-up duration of 20 minutes and were completed before sunrise to avoid any impact of solar heating. Auto 72°F settings were used for the onboard climate control systems during warm up. This provided the same warm-up rate as the vehicles' maximum heat setting but allowed the HVAC system to control to a temperature set point after warm up to avoid overheating the cabin. The timing, duration, and climate control settings for the warm-up procedure were selected to represent an early morning commute during winter months.

Zonal Heating Configurations

Four zonal heating configurations were evaluated during cold weather testing. They are depicted in Figure 2, listed in order of increasing zonal heating effect. For Zonal Configuration #1, all passenger air vents were closed and only the driver air vents were used to supply warm air to the cabin. This configuration required no major modifications to the vehicle's air ducts or HVAC blower. It provided a higher flow rate of warm air to the driver while lowering the total HVAC air flow rate. Zonal Configuration #2 used the existing driver air vents as well as a lap vent that was added near the center console to deliver warm air to the driver's arms, lap, and lower torso. This improved the convective heating in the driver air space. Zonal Configuration #3 consisted of the zonal air vents from Zonal Configuration #2 and a heated driver seat. The heated seat was operated at the maximum heating setting for the duration of the warm-up test. Lastly, Zonal Configuration #4 included the zonal air vents and the heated seat from the previous configuration, and incorporated a heated steering wheel (42 W average) and a custom-built heated floor mat (129 W average).


Zonal Configuration #1
Zonal Configuration #2
Zonal Configuration #3
Zonal Configuration #4

Figure 2: Zonal heating test configurations

These four configurations provided increasing levels of zonal heating for the driver by focusing air flow on the occupant and by providing direct heating through contact surfaces. With each incremental improvement, the overall HVAC heating load was reduced while maintaining or improving driver thermal sensation. This reduction in heating energy was accomplished by reducing the total air flow rate of the HVAC system from the measured baseline value for subsequent zonal configurations, as shown in Figure 3.

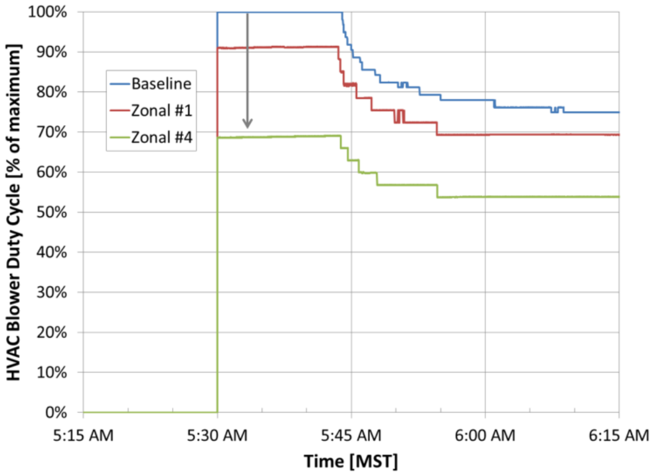

Figure 3: HVAC blower duty cycle profiles

Zonal Heating Test Results

The results of the heating tests are shown in Figure 4. The zonal heating strategies were evaluated in terms of the reduction in cumulative heating energy during the 20-minute warm up for the modified vehicle compared to the unmodified control vehicle. Engineering evaluations were used to assess driver thermal sensation for the baseline and zonal heating tests to ensure the driver's thermal sensation was not compromised. During the baseline warm-up test, it took 12 minutes for the occupant to reach neutral overall thermal sensation. The energy savings for each zonal case were the result of the decreased total air flow rate of the HVAC system. The energy savings are shown as the percent decrease for the modified vehicle compared to the control vehicle and were adjusted to account for minor day-to-day weather variation.

Zonal Configuration #1 resulted in a 5.5% decrease in energy consumption with a warm-up time of 8 minutes. This configuration used the vehicle's existing air ducts and vents and simply restricted air flow to the driver only. Zonal Configuration #2 increased the convective heating for the driver's air space by adding a lap vent near the center console area. This led to a 9.4% reduction in heating energy and a slightly faster time to neutral thermal sensation than the baseline warm up. Zonal Configuration #3 incorporated the Focus Electric's heated seat with the zonal air vents, achieving a 13.6% energy reduction and equivalent warm-up time. Finally, Zonal Configuration #4, which combined convective and conductive heating for the driver, demonstrated 28.5% energy savings and a slightly faster warm-up time. This highlights the importance of heating an occupant's extremities during a warm up from cold soak. As expected, the heated steering wheel had a large and immediate impact on the driver's thermal sensation due to direct contact with the driver's bare hands. The thermal benefit of the heated floor mat was smaller but still noticeable. It was noted that the evaluator's feet did not feel as cold with the heated floor mat as they did during the baseline test without it, especially toward the end of the warm up. Thus, the floor mat prevented some of the discomfort caused by cold feet. The hands and feet are major drivers of overall thermal sensation and comfort in cold weather and can have a large impact on the potential energy savings of heating strategies.

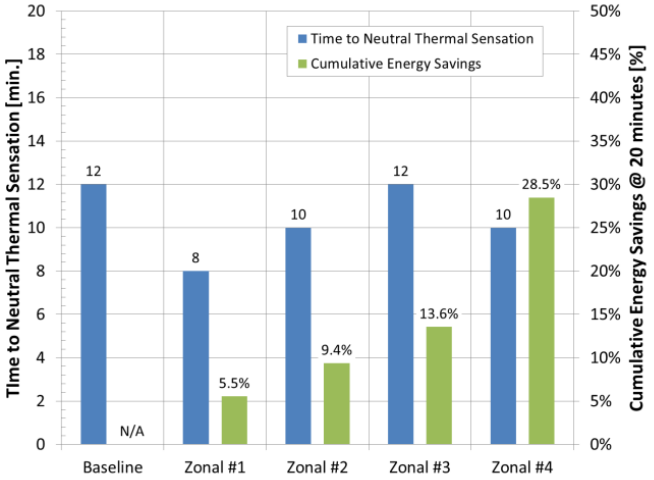

Figure 4: Zonal heating test results

Zonal heating is expected to have greater benefit during transient heating than during steady-state heating, so the potential reduction in heating energy would be less for drive profiles longer than 20 minutes. However, short-duration drives are more common for EVs than for conventional or hybrid electric vehicles. It should be emphasized that these warm-up tests were conducted with stationary vehicles. A moving vehicle would have greater heat loss to the cold ambient environment than a stationary vehicle at the same temperature. Increased exterior convection on a moving vehicle would increase the steady-state heating rate for all test cases, including the baseline. However, the difference in cabin heating rate between a stationary and a moving vehicle during a 20-minute transient warm up from a cold soak is very small. Lastly, the thermal sensation results were intended as a test-to-test reference point to produce equivalent warm-up times; they do not necessarily represent the average thermal response of the national driving population.

Thermal Analysis

Computational Fluid Dynamics/RadTherm

Fluent/RadTherm Co-Simulation Methodology

Thermal analysis tools were used to complement outdoor vehicle testing in evaluating thermal load reduction strategies. The analysis tools and simulation methodology are detailed in [2]. Computer-aided design (CAD) geometry of the Focus Electric was provided by Ford and used to develop RadTherm and computational fluid dynamics (CFD) meshes for the vehicle model. The thermal modeling tool RadTherm, developed by ThermoAnalytics, Inc., was used to calculate the heat transfer between the vehicle interior and the environment. Fluent was used to perform CFD simulations of the cabin interior air. During co-simulation of the model, surface temperatures calculated by RadTherm and fluid temperatures and heat transfer coefficients calculated by Fluent were continually exchanged as boundary conditions between the two simulation tools. A virtual manikin included in the driver seat of the model enabled human thermal comfort analysis using the human physiology model in RadTherm's human thermal comfort plugin.

Baseline Model Validation: Cold Thermal Soak and Warm-up

In addition to the warm weather simulations used to validate the model previously [2], simulations were performed to validate the model in cold weather. A steady-state soak simulation was performed using weather data from the baseline test day of January 13, 2015. The analysis was performed both to check the accuracy of the model and to obtain an initial state for the warm-up simulation.

The steady-state soak temperatures from simulation at 5:30 a.m. MST were compared to soak test data averaged over 15 minutes, from 5:15 a.m. to 5:30 a.m. MST. The baseline simulation soak temperatures compared favorably to the test data. The most important locations (breath-level air, instrument panel, windshield, and driver's seat) matched within 1°C. The simulated foot-level temperatures had the greatest difference from the data, but even those differences were less than 3°C.

The next step was to perform a transient warm-up analysis and compare the model results to the data. Experimental data from the same day were used, and the simulation was compared to data for the first 20 minutes of the warm-up beginning at 5:30 a.m. MST January 13, 2015. The simulation used the same conditions as the warm-up test: auto 72°F heating and 100% recirculation. The model used vent flow splits obtained from Ford, and the vent air velocities were validated by measurement. The transient vent temperatures were obtained from test data.

Figure 5 shows the comparison of the average cabin air temperature predicted by the simulation to test data from the warm-up test. The simulated average air temperature initially increased slightly faster than the test data with a maximum deviation of 3.5°C, but after 10 minutes was within 1.6°C for the remainder of the simulation. Although not shown, the predicted interior surfaces compared well to test data. Because the transient simulation performance was reasonable and the steady-state temperatures matched well, the model can be used to predict the thermal conditions during soak and warm-up trade studies.

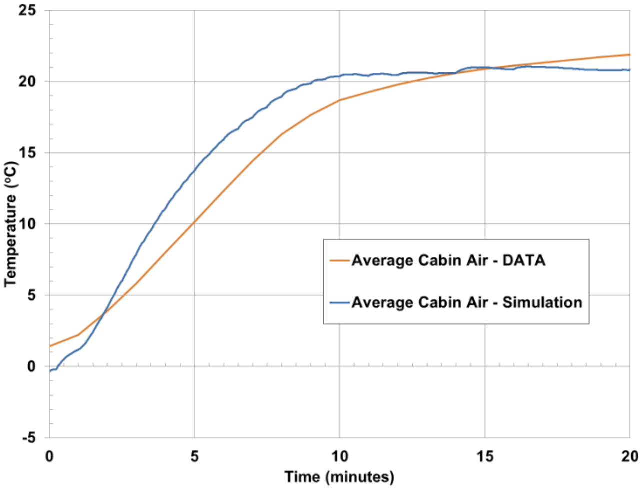

Figure 5: Comparison of simulated cabin air temperature to experimental data for baseline warm up

Zonal Heating Analysis

A zonal heating analysis was conducted to verify that a zonal testing approach would maintain or improve driver thermal comfort compared to the baseline. The baseline model boundary conditions were modified to reflect the test setup. This included no air flow to the passenger vents and adding flow to the driver lap vent. Due to the zonal strategy focusing on the driver, the analysis was run with a 50% reduction in total air flow compared to the baseline to maintain thermal comfort. The zonal analysis was performed both with and without a heated steering wheel and heated seat to understand the effect of those heated surfaces on thermal comfort.

Figure 6 shows the driver sensation for Zonal Configuration #4 is very similar to the baseline case. Without the heated surfaces, the driver is predicted to be colder than baseline. This means the heated surfaces are required or the heater air flow would need to be increased to maintain the same thermal comfort as the baseline. This analysis confirms the test approach that measured lower energy consumption by using zonal air flow and heated surfaces while maintaining human thermal comfort.

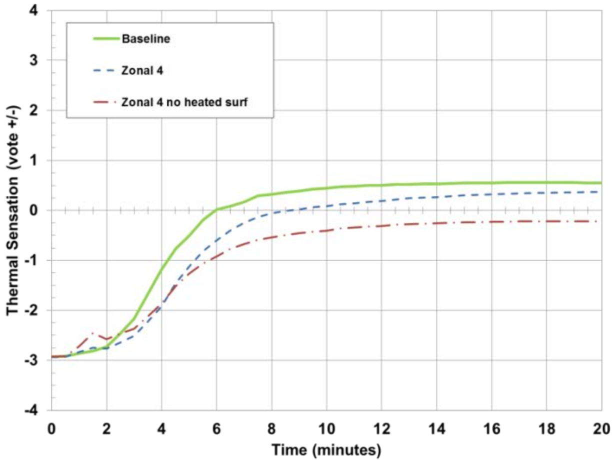

Figure 6: Predicted thermal sensation for baseline and zonal heating

CoolCalc Thermal Modeling

Model Development

CoolCalc is a rapid HVAC load estimation tool built as a plugin to SketchUp drawing software. CoolCalc was developed at NREL from an early version of the U.S. Department of Energy's OpenStudio energy modeling tool and it uses EnergyPlus as the heat transfer solver. More detailed background information about the CoolCalc modeling tool is provided in [3] and [4]. CoolCalc was used to assess thermal load reduction technologies applied to the cabin shell to reduce the steady-state heating load.

A CoolCalc thermal model of the Ford Focus Electric was developed using CAD files of the vehicle geometry and other vehicle information provided by Ford, along with measurements made at NREL. This included information on surface and material properties, cabin thermal mass, air infiltration rates, and HVAC system specifications. All model properties were specified to most closely match the Focus Electric vehicle tested at NREL, including orientation to solar loads. Figure 7 shows an image of the CoolCalc model geometry next to a photo of the test vehicle. A simplified HVAC system was added to the model to provide cabin climate control. The simplified system delivers the thermal load necessary to meet cabin temperature set points, within the capacity and air flow rate limits imposed on the system.

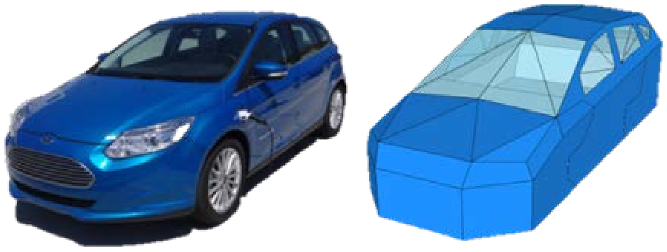

Figure 7: Ford Focus Electric test vehicle and CoolCalc thermal model

Model Validation

The CoolCalc model of the Focus Electric was validated against experimental data from baseline warm- and cold-weather vehicle tests. The simulations were set up to match the conditions of the stationary outdoor vehicle tests, including vehicle configuration and HVAC system settings. Actual weather data recorded from the outdoor tests were supplied to the model as environmental boundary conditions. These conditions included ambient temperature and relative humidity, wind speed and direction, and solar irradiance. Warm and cold thermal soak simulations were performed to verify that the passive thermal behavior of the model matched the diurnal trends from the vehicle tests. The model results were in very close agreement with the test data for both warm and cold weather thermal soak conditions, as shown in Figure 8. Transient warm-up simulations were also performed to verify the inputs to the simplified HVAC system. The average cabin air temperature recorded from the baseline test was input as a control set point for the model. The required heater power was calculated by the model and the energy consumption was compared to the measured energy consumption from the test. Heating energy from the simulation matched test data within 3.8%. This validated model was used as the baseline configuration for the following load reduction simulations.

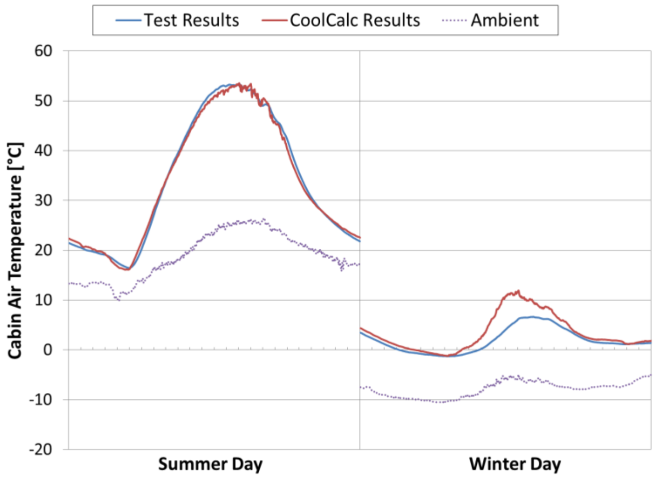

Figure 8: Results of model validation to test data for summer and winter days

Model Application

The validated CoolCalc model was applied to evaluate the potential impact of polycarbonate glazing on steady-state heating loads. For this analysis, the conductivity of the window material was reduced from 0.9 W/mK to 0.2 W/mK to simulate a polycarbonate glazing. Simulations were performed with no solar loads during heating, so the solar spectral properties of the glazing would not have an impact. The ambient air temperature was -5°C, and the cabin air temperature was maintained at 22°C. Ambient air speed and direction were fixed to simulate a vehicle speed of 30 miles per hour.

Polycarbonate was evaluated in place of automotive glass for three configurations: 1) the rear (fixed) glazing only; 2) the rear glazing and all sidelites (i.e., door windows); and 3) all glazing, including the windshield. The baseline configuration used standard automotive glass for all window locations. Figure 9 shows these simulation results in terms of the average thermal power for steady-state heating for each configuration and the percent reduction from baseline. Heating power was reduced by 0.79%–3.27% for the three polycarbonate configurations. Automobile manufacturers face challenges implementing polycarbonate for movable glazing and windshields. Using polycarbonate for the fixed glazing is the most feasible configuration, but produced only a 0.79% reduction in steady-state heating power.

The CoolCalc model was also used to evaluate the impact of increased insulation in the cabin body panels. A uniform layer of ½-inch thick foam insulation was included in the material construction for various cabin surfaces. The thermal conductivity of the insulation was 0.04 W/mK. The four configurations evaluated were: 1) door surfaces only; 2) roof surface only; 3) door and roof surfaces; and 4) all cabin surfaces, which included the doors, roof, floor, and firewall surfaces. All other vehicle surface constructions matched the baseline case. These simulation results are also shown in Figure 9. The steady-state heating power was reduced by 3.8%–18.3%. Insulating all the surfaces listed in the fourth configuration with an average thickness of ½-inch may be difficult for vehicle manufacturers due to space limitations and other design constraints. Improving insulation in the roof and/or door surfaces is more feasible and can provide significant thermal benefit.

Reducing thermal conductivity of the cabin shell (with polycarbonate glazing and/or increased insulation) will have the greatest load reduction benefit after the cabin is warmed up. Little or no benefit is expected during transient warm up from a cold soak. Given the short duration of typical EV trips, heating load reduction may not be realized from these strategies without thermal preconditioning of EVs in cold weather.

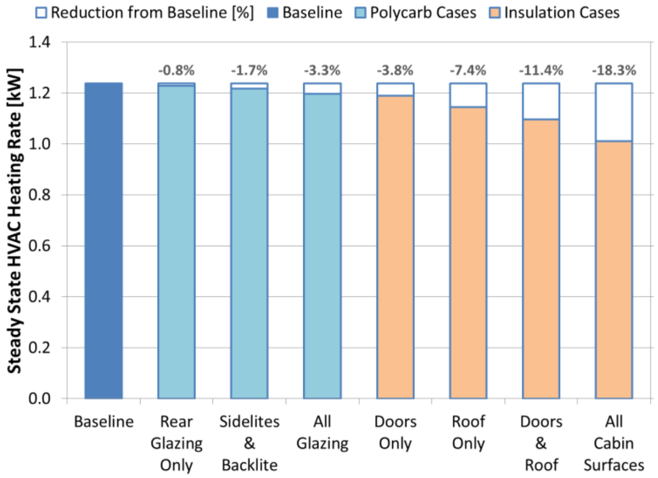

Figure 9: CoolCalc analysis results for polycarbonate glazing and improved cabin insulation

Vehicle Range Impact Analysis

Drive Cycle Simulations

The vehicle simulation tool Autonomie was used to calculate the impact of cabin heating on EV driving range. A model of the Ford Focus Electric provided by Argonne National Laboratory was used for the simulations along with experimental measurements of the heating power for the baseline and Zonal Configuration #4 cases, including power for heated surfaces.

The Focus Electric uses a 23-kWh capacity lithium-ion battery pack. The battery utilization was assumed to be 85%; therefore, 19.55 kWh of usable energy was calculated for the battery pack [1]. Calculating the vehicle efficiency over a single short-duration drive cycle and applying it to calculate the overall range would overestimate the impact of HVAC use because the heating loads decrease when the passenger compartment temperatures attain steady state. Because the average vehicle trip duration in the United States is approximately 20 minutes [5], the average vehicle efficiency was calculated over several drive cycles each of approximately 20-minute duration. The drive cycles simulated were Urban Dynamometer Driving Schedule (UDDS) (22.8 minutes), back-to-back Highway Fuel Economy Test (HWFET) cycles (25.5 minutes), and back-to-back US06 cycles (20 minutes). The model was simulated over these drive cycles for three climate control conditions: no cabin heating, baseline HVAC heating, and Zonal Configuration #4 heating.

The results of the vehicle drive cycle simulations are shown in Figure 10. The negative impact of baseline heating using the standard HVAC system is substantial, ranging from 20.1% loss of driving range for US06 up to 47.6% range loss for the UDDS cycle. These results are in general agreement with published EV range reductions due to heating. For the same drive cycles and trip durations, the combined zonal heating strategy shows the potential to increase driving range by 6.9%–18.7% over the baseline heating case.

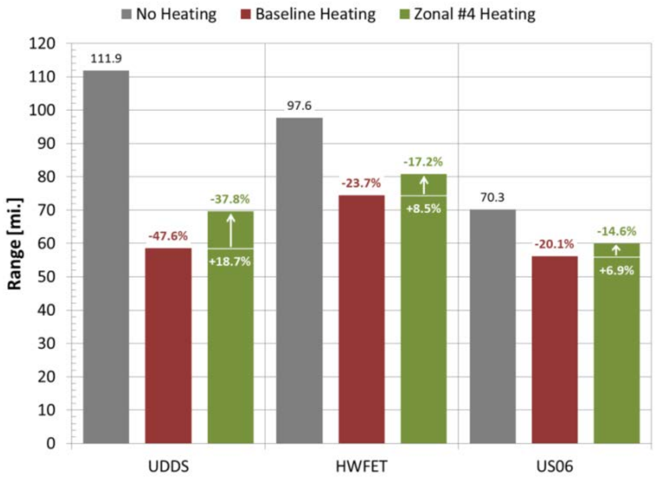

Figure 10: Calculated driving range for no heating, baseline heating, and zonal heating

National Range Impact Analysis

A national-level analysis was conducted to identify where energy-efficient heating systems will have the greatest benefit and to calculate the overall national impact. A process similar to the air conditioning fuel use analysis developed by V. Johnson was used for this analysis [6]. The bottom-up approach began with an occupant thermal comfort model to determine HVAC use based on environmental conditions, and then incorporated geographical distribution of vehicles and driving statistics. The range penalty from cabin heating was determined by the vehicle drive cycle simulations described above. Using environmental data for each state and the UDDS drive cycle to represent current usage of EVs primarily in urban locations, the per-vehicle impact of baseline heating is shown in Figure 11. This indicates the total annual range penalty for an EV based on location. The analysis assumed trips use all the available energy in the battery; therefore, these are the maximum potential range losses. As expected, there is a much larger reduction in range in colder climates.

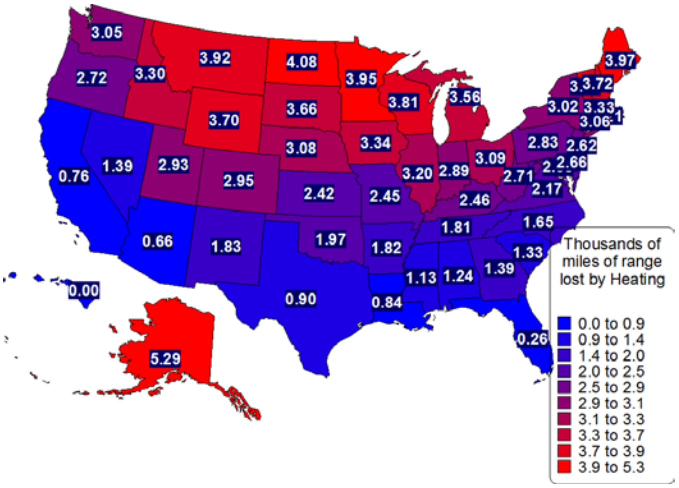

Figure 11: Reduction in range per vehicle due to cabin heating by state

To calculate the national weighted-average impact, the current EV distribution is added to the analysis. While conventional vehicles have a nearly uniform distribution with population, EVs make up a small portion of the light-duty vehicle fleet (only 192,375 EVs compared to 231.8 million conventional light-duty vehicles) and the distribution of these vehicles is driven by local incentives and regulations. Figure 12 shows the percent of EVs per state, with California having over 40 percent of the EVs in the United States. Based on this distribution and the range penalties shown above, a baseline heating load reduces the EV range by 17%. If all vehicles used Zonal Configuration #4 for heating, the range would be improved by 7.1% over the baseline heating range.

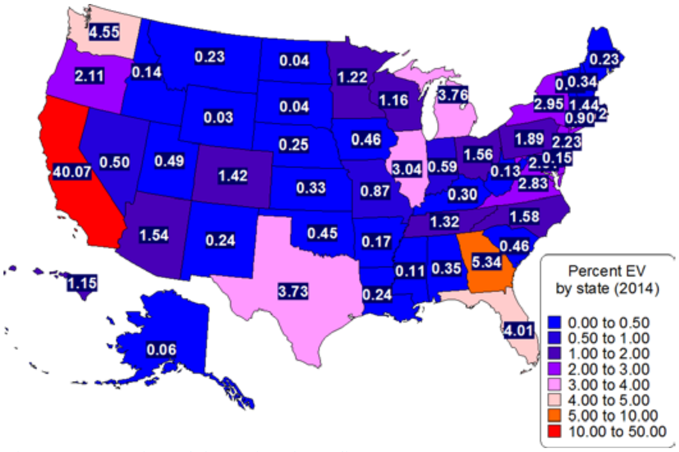

Figure 12: Fraction of the national EV fleet per state

The range improvement estimates were based on drive cycle simulations using measured weather conditions and heating power from outdoor vehicle tests at ~0°C. As noted previously, the heater power profile was more heavily weighted to a transient heater load for a 20-minute simulation. In moderate environments and for longer drive cycles, the range improvements due to zonal strategies will be lower. If vehicle use is not limited by the maximum EV range, the heater power would be inconsequential to the driver.

Summary/Conclusions

Outdoor vehicle tests and thermal modeling were used to assess strategies for reducing vehicle cabin heating loads. Testing showed that using only existing HVAC vents and focusing the conditioned air on the driver, a 5.5% reduction in heating energy can be realized. A combined heating configuration that included zonal air flow as well as heated surfaces—driver seat, steering wheel, and floor mat—reduced the heating energy by 28.5% while maintaining equivalent driver thermal sensation. Vehicle simulations showed a 7% to 19% improvement in range is achievable with zonal air and surface heating, thus reducing the national average range penalty for heating by 33%.

Analyses showed that a small reduction in heating power can be attained by using polycarbonate glazing, which has a lower thermal conductivity than glass. Increased insulation in the cabin body panels can have more significant impact, reducing steady-state heating power by 3.8%–18.3% depending on the configuration. Low-conductivity glazing should be combined with improved cabin insulation for the most load reduction benefit during steady-state heating.

Using zonal heating strategies in conjunction with reduced thermal conductivity of the vehicle shell is recommended to reduce the heating loads in EVs. Other energy efficiency improvements such as implementation of a heat pump or thermal preconditioning can be part of a combined strategy to minimize the impact of heating on EV range. Energy savings from HVAC load reduction solutions translate directly into increased energy for vehicle propulsion, which improves driving range and can lead to wider EV adoption.

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Definitions/Abbreviations

CAD	computer-aided design
CAN	controller area network
CFD	computational fluid dynamics
EV	electric vehicle
HVAC	heating, ventilating and air-conditioning
HWFET	Highway Fuel Economy Test
MST	mountain standard time
NREL	National Renewable Energy Laboratory
UDDS	Urban Dynamometer Driving Schedule