

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

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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.

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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.

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.

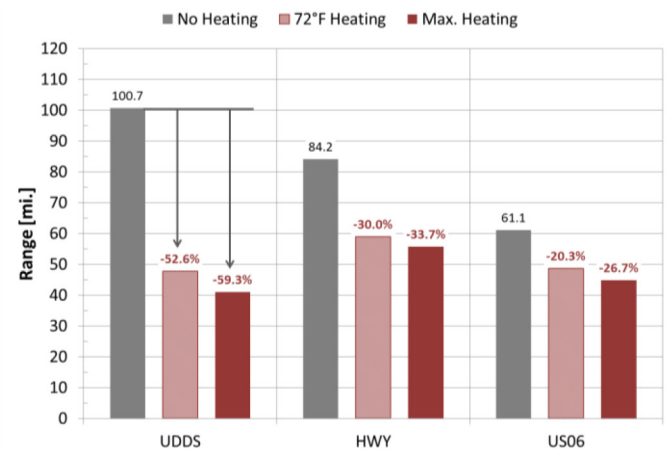


Figure 1. Impact of cabin heating on EV driving range in 20°F ambient

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

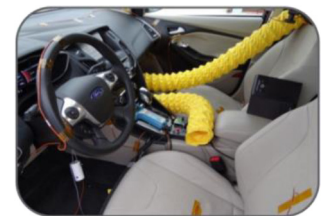
warm up to avoid overheating the cabin. The timing, duration, and climate control settings for the warm-up procedure were selected to represent an early morning commute during winter months.

Zonal Heating Configurations

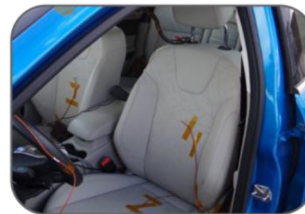
Four zonal heating configurations were evaluated during cold weather testing. They are depicted in Figure 2, listed in order of increasing zonal heating effect. For Zonal Configuration #1, all passenger air vents were closed and only the driver air vents were used to supply warm air to the cabin. This 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.

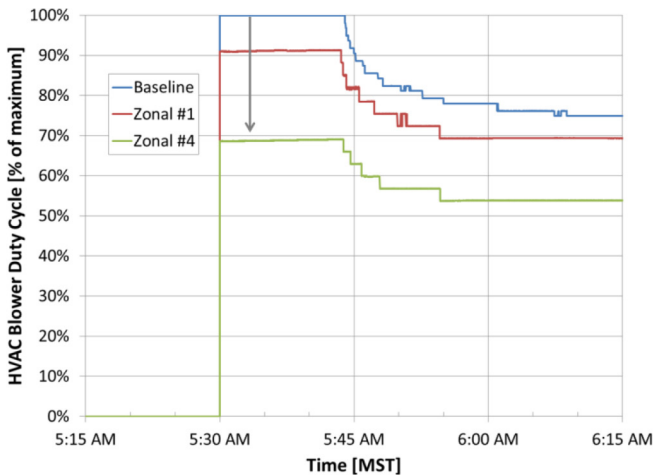


Figure 3. HVAC blower duty cycle profiles

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.

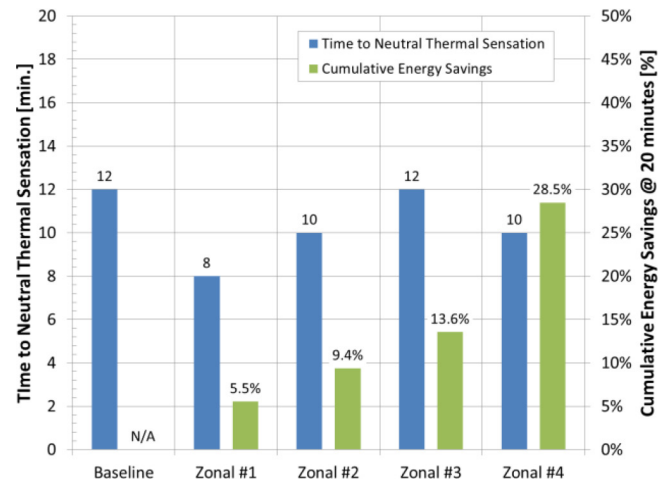


Figure 4. Zonal heating test results

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.