Ford AZTECS Vehicle - Thermal Testing

Cooperative Research and Development Final Report

CRADA Number: CRD-09-340

NREL Technical Contact: Jason Lustbader

NREL is a national laboratory of the U.S. Department of Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-76889
June 2020

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Cooperative Research and Development Final Report

Report Date: April 15, 2020

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Ford Motor Company

CRADA Number: CRD-09-340

CRADA Title: Ford AZTECS Vehicle - Thermal Testing

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
First 6 months	$105,937.20
7-18 months	$238,379.98
19-30 months	$61,094.32
31-36 months	$37,720.50
Modification #1	$443,132.00
Modification #4	$883,132.00
Modification #6	$983,132.00
TOTALS	$1,283,132.00

Abstract of CRADA Work:

Investigation of a parked car ventilation strategy using the duct system that is part of a thermoelectric Heating, Ventilation and Air Conditioning (HVAC) system.

Summary of Research Results:

At the time this report was prepared, the PIs for the CRADA were no longer with NREL so this report was prepared by others, who despite best efforts, were only able to find limited information on the results from the CRADA. The following is a summary of the research results from the CRADA based on that information.

The original 5 tasks of this CRADA were part of a joint U.S. Department of Energy and the California Energy Commission award under U.S. Department of Energy Award Numbers DE-EE00000014 and DE-EE0000020. For this project NREL was a sub recipient with Ford leading the project. As such NREL reported results to Ford and the project team, which in turn reported to DOE. The final report for this project describes the full scope of the project and The National Renewable Energy Laboratory's role of providing expertise in the area of vehicle occupant thermal comfort and HVAC load reduction technologies [1]. NREL successfully supported this project and met CRADA agreements. As a subrecipient reporting was coordinated through the project team and results of this work were reported to the project sponsors through Ford's progress reports and publications on the topic [1]–[4]. Below is a brief summary of NREL's contributions to this team project for each of the original 5 CRADA tasks.

TASK 1.0: Original, Date Accepted February 25, 2010; Develop System Architecture for Reducing the Thermal Load

- Leverage NREL's Vehicle Ancillary Load Research to support vehicle architecture development that minimizes the power budget required for cabin HV AC. Identify strategies to reduce the beating and cooling loads. Objective is to optimize the system architecture and minimize the electrical energy required.
- Deliverable: Contribute sections to the team's report documenting the selection of system architecture if required.
- Support Role: Phase 1, SOPO Task 1.3.1
- Phase I Execution+ 10 months

NREL supported the team, applying its knowledge of vehicle ancillary loads to help develop the vehicle architecture. NREL applied a system-level approach to HVAC efficiency. The first step is to reduce the load into the vehicle. Then the conditioning (heating or cooling) needs to be delivery efficiently to occupants for comfort. Once the HVAC system load is minimized, then the efficient thermal electric system is used to provide the climate control required. This is illustrated in Figure 1.

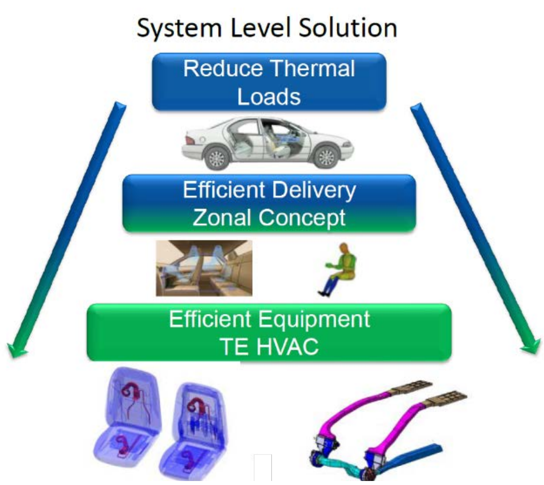

Figure 1: System-Level Approach to Minimize Energy Use

TASK 2.0: Original, Date Accepted February 25, 2010; Assess and Enhance Thermal Comfort Tools

- Assist in the definition of thermal comfort metrics.
- Support the application of human physiological models and thermal comfort models in CAE analysis of proposed system architecture.
- Assist Ford/Visteon to determine if changes to current NREL and Visteon thermal comfort models can meet the program analysis needs. Assess alternative thermal comfort models if required.
- Coordinate with Visteon to link the selected thermal comfort model with CFD software and/or existing Visteon analysis tools
- Deliverable: Report detailing existing thermal comfort modeling capability of the team members, alternative options if required, recommended approach for the project, and implementation of the recommended thermal comfort modeling approach.
- Lead Role: Phase I, SOPO Task 1.1.4
- Support Role: Phase I, SOPO Tasks 1.1.2, 1.1.3, 1.1.5, 1.1.6
- Phase I Execution + 10 month

NREL supported the selection of thermal comfort metrics, selecting a University of California Berkeley (UCB) thermal sensation and comfort methodology [5]–[7] . NREL then supported the application of the selected human physiological models and comfort models in a computer aided engineering environment (CAE), using AcuSim and Radtherm as shown in Figure 2. NREL worked the with team to determine that these models were sufficient for the purposes of the project.

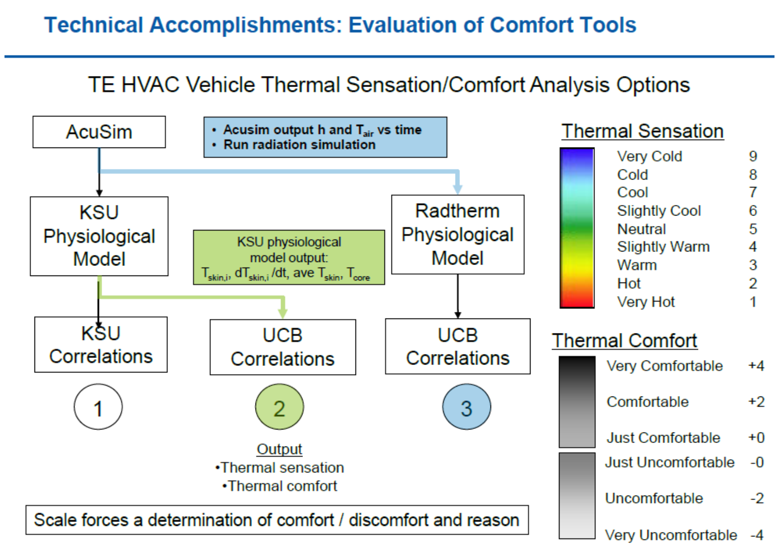

Figure 2: Thermal Comfort Tools

TASK 3.0: Original, Date Accepted February 25, 2010; NREL Task 3.0 Strategic Vent Placement

Subtask 3.1: Develop and Apply Methodology to Determine Vent Location

- Support Visteon CAE and Comfort modeling. Assist in refining the thermal comfort tool from Task 2 as required.
- By test and/or analysis, develop objective process to assess the relative cooling performance of TE air conditioning system options and vent locations. Use this process to determine optimum vent placement to minimize cooling capacity required
- Deliverable: Contribute sections to the overall project milestone report as required.
- Support Role: Phase 2, SOPO 2.1.2, 2.1.3 and 2.3.1
- Phase II Execution+ 9 months

NREL supported the team to develop a process, to assess the relative cooling performance the air conditioning system options and vent locations. Figure 3 shows an example configuration analysis using the thermal comfort tools in a CAE environment. The results are compared against evaluator responses for validation.

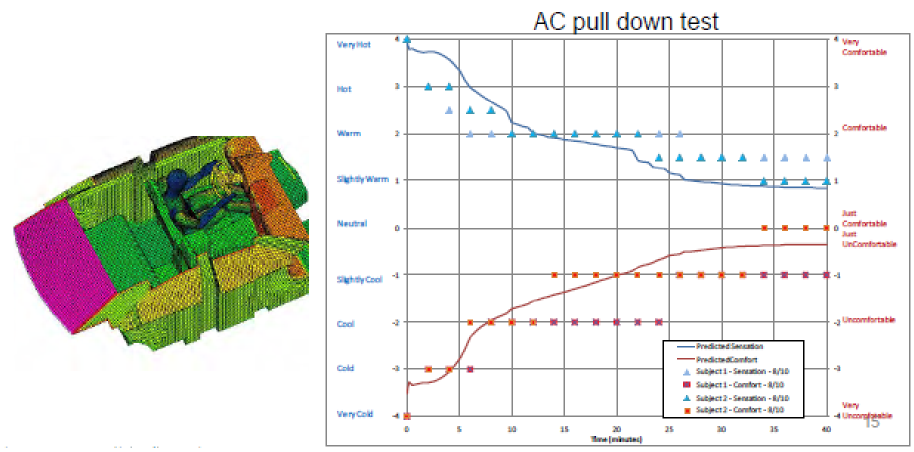

Figure 3: Example configuration analysis and confirmation testing

Subtask 3.2: Original, Date Accepted February 25, 2010; Evaluate Most Promising Vent Locations in Vehicle Test Buck

- Test proposed vent location options in NREL's Vehicle Climate Control Lab using the thermal manikin ADAM. TE devices or substitute equipment shall be provided by Ford.
- Deliverable: Report summarizing test procedure, results, and vent location recommendation.
- Lead Role: Phase 2, SOPO 2.3.3
- Phase II Execution+ 9 months

NREL worked with the team to develop a test method leveraging both a thermal manikin and analysis tools as shown in Figure 4. The team choose to use the next generation of thermal manikin, named Newton. Newton improved upon the innovations achieved with NREL’s older Advanced Automotive Manikin (ADAM). Good correlation between the manikin and test subjects was achieved and vent locations selected [8].

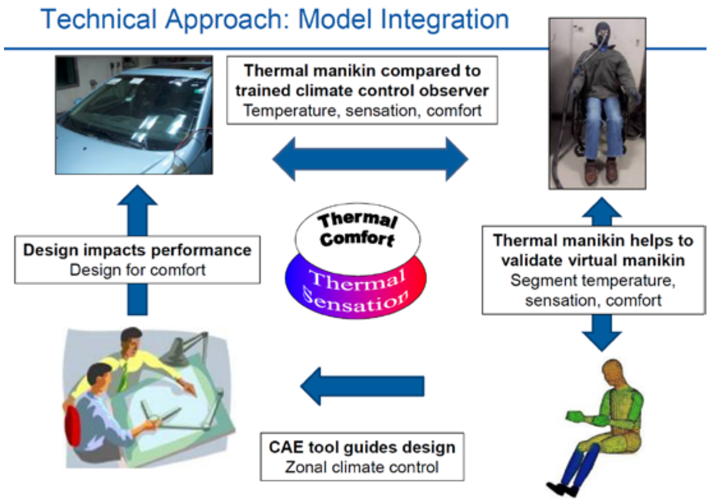

Figure 4: Model and thermal manikin test integration for comfort evaluation

TASK 4.0: Original, Date Accepted February 25, 2010; NREL Task 4.0 Optimize Strategy for Reducing Cabin Thermal Loads

- Leverage NREL's Vehicle Ancillary Load Research to identify additional technologies and strategies for optimizing system costs, reducing the heating and cooling power requirements, and maintaining occupant comfort.
- Deliverable: Report on vehicle thermal load reduction strategies
- Lead Role: Phase 3, SOPO 3.4.5
- Phase Ill Execution + 11 months

NREL worked with the project team to consider additional ancillary load reduction technologies such as glazing (infrared reflective or absorptive), instrument panel mass (low mass or infrared reflective), body insulation, parked car ventilation, and heat seats or other surfaces [3].

TASK 5.0: Original, Date Accepted February 25, 2010; Conduct Vehicle Level TE HVAC System Test

- Use ADAM in Ford climate control chamber to test the TE HVAC system in a vehicle
- Deliverable: Report summarizing test results and recommendations.
- Lead Role: Phase 4, SOPO 4.3.12
- Phase IV Execution+ 6 months

NREL assisted the project team with evaluation of the system under various conditions, helping to complete trade-off studies, optimize design, and evaluate performance, Figure 5.

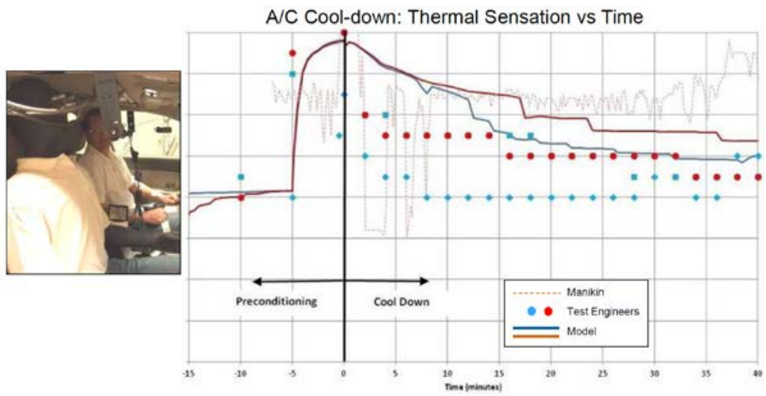

Figure 5: Evaluation of advanced climate control system

EXECUTED MODIFICATION NO. 1 to CRADA No. CRD-09-340

This modification adds $582,500 in agreement value and 13 months to the period of performance.

TASK 6 Mod 1, Date 4/5/12; Electric Drive Vehicle Climate Control Load Reduction

Research and develop techniques which will reduce cooling and heating loads on ED Vs to improve range. The following areas will be considered:

- Thermal load reduction technologies
- Occupant thermal comfort optimization
- Zonal approach to climate control
- Intelligent HVAC control to minimize energy use
- Advanced seating concepts
- Unique EDV thermal needs of the battery and power electronics
- Secondary fluid loop options

<u>Summary of Research Results:</u>

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. Tests conducted at Argonne National Laboratory's Advanced Powertrain Research Facility showed a range reduction of up to 53.7% due to air conditioning (A/C) and 59.3% due to heating over the Urban Dynamometer Driving Schedule (UDDS) drive cycle [9]. This presents a major challenge for many drivers and a barrier to widespread adoption of EVs. To investigate solutions to this problem, outdoor vehicle thermal testing was conducted on two 2012 Ford Focus Electric vehicles to for both hot weather and cold weather conditions to evaluate thermal load reduction technologies, occupant thermal comfort optimization, zonal climate control, intelligent HVAC control, and advanced seating concepts.

Hot weather, A/C evaluation summary, documented in detail in an SAE technical paper [10]: For this task, outdoor vehicle thermal testing was conducted to evaluate thermal management strategies for warm weather. Thermal load reduction technologies for cabin pre-ventilation and solar load reduction we investigated. Three different time-based pre-ventilation strategies were investigated, continuous, just-in-time (JIT) 30 minutes before drive and JIT 15 minutes before drive. These were also compared to a ventilation strategy that turned on when the interior soak temperature of the cabin was 15 °C above ambient. These results can be seen in Figure 6. The JIT 15 minute and JIT 30 minute, achieving much of the benefit of the continuous ventilation with significantly less energy use. The temperature control ventilation (T-ctrl. Vent.) was also effective but used more energy than the JIT strategies.

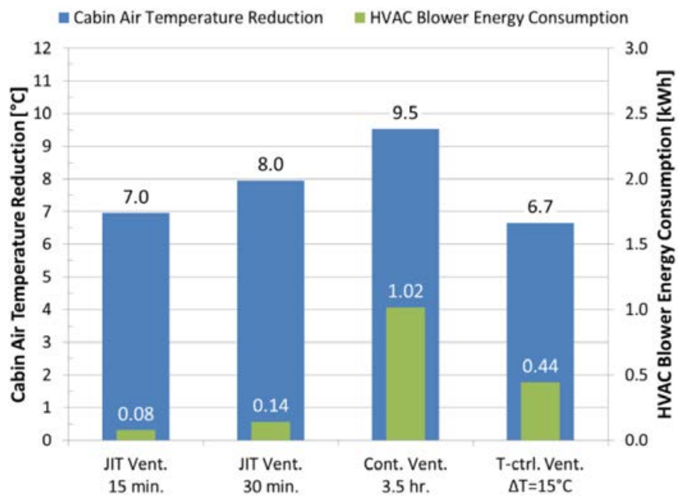

Figure 6: Soak temperature reduction and HVAC blower energy consumption for pre-ventilation test cases

The solar load reduction configurations that were evaluated are displayed in Figure 18 and include (clockwise from top left): 1) a shading canopy, 2) white glazing film, 3) solar-reflective glazing film, and 4) an infrared-reflective (IRR) windshield. The shading canopy blocks all direct solar energy from the entire EV (glazing and opaque surfaces) during thermal soak. This was intended to represent the maximum solar load reduction possible by parking under a carport or large tree, for example. The visibly opaque white glazing film was applied to all vehicle glazing and was used to represent the solar load reduction potential of exterior glazing shades that could be used while a vehicle is parked. The solar-reflective glazing film was also applied to all glazing, to approximate the realistic application of advanced solar-reflective glazing technology. This film can meet visible light transmission requirements when laminated in an OEM-installed glazing. Lastly, the IRR windshield is an advanced, production-quality windshield that meets automotive safety standards but transmits less solar energy than standard windshields. The IRR windshield configuration used standard automotive glass for all other glazing locations.

Figure 7: Solar load reduction test configurations

Results the solar load reduction tests are shown in Figure 8, and compared against the JIT 15min pre-ventilation.

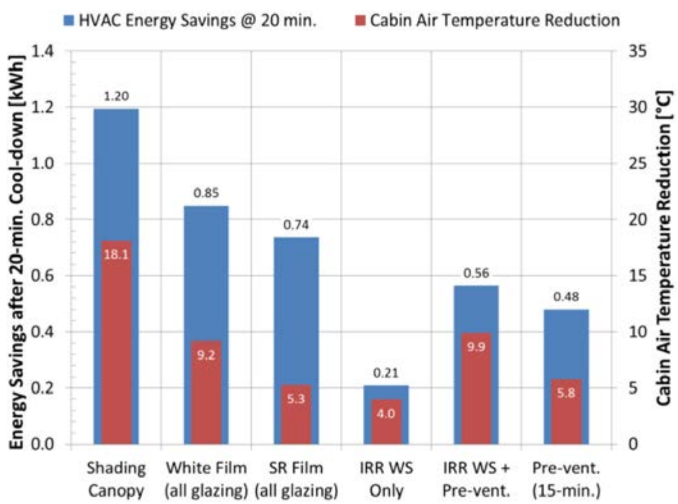

Figure 8: Thermal load reduction test results

Zonal Cooling, occupant thermal comfort optimization, and intelligent HVAC control were investigating using an advanced thermal test manikin. An overhead A/C and combined zonal configuration (overhead A/C with load reduction strategies, glazing and pre-ventilation) were evaluated. The combined configuration cooling concept tested at NREL demonstrated the potential for up to 0.92 kWh (66.5%) energy savings for a 20-minute cool-down after hot thermal soak. The test results were then used with a vehicle model to simulate the potential impacts on range, results are shown in Figure 9. The combined solution was estimated to increase EV driving range by 11%-33%. Energy savings from HVAC load reduction solutions translate directly into increased energy for vehicle propulsion, which improves driving range for EVs and can lead to wider EV adoption.

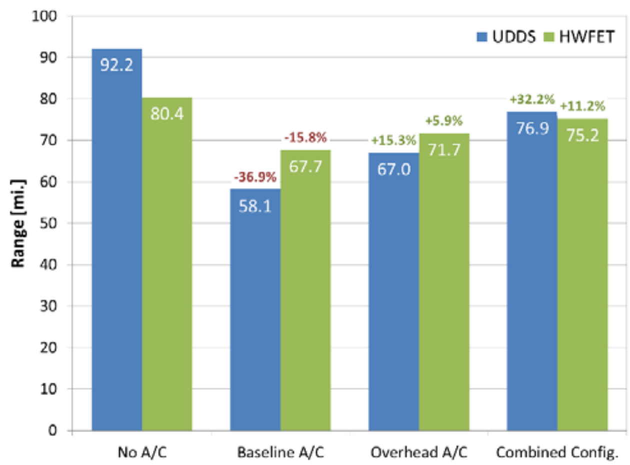

Figure 9: Estimated range impacts using a combination of test results and vehicle simulation. Note that impacts are weather and drive cycle dependent and range improvement for moderate environmental conditions and longer trip lengths will be less

Cold weather, heating evaluation summary, work is documented in detail in an SAE journal paper [11]: Outdoor vehicle tests and thermal modeling were used to assess strategies for reducing vehicle cabin heating loads through zonal control and advanced seating for and comfort optimization. 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. Shown in Figure 10, 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%.

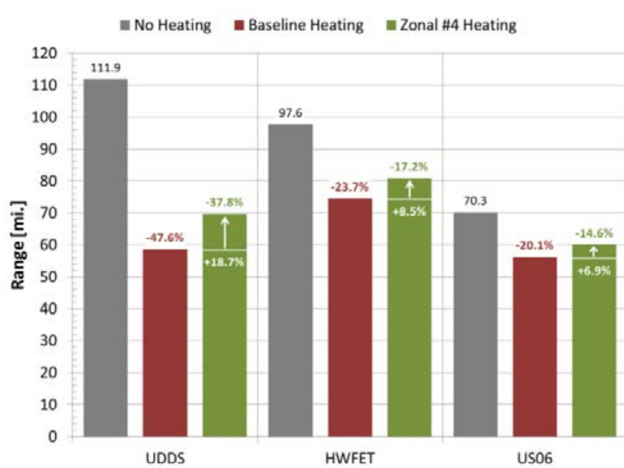

Figure 10: Calculated driving range for no heating, baseline heating, and zonal heating

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, shown in Figure 11. Low-conductivity glazing should be combined with improved cabin insulation for the most load reduction benefit during steady-state heating.

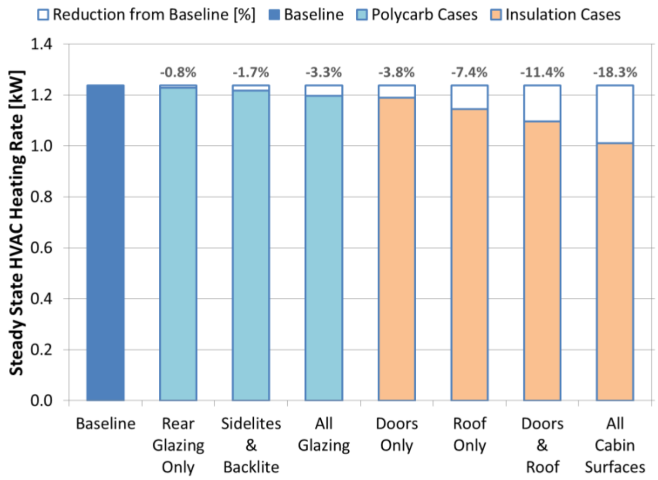

Figure 11: CoolCalc analysis results for polycarbonate glazing and improved cabin insulation

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.

Integrated electric drive vehicle thermal management to address unique EDV thermal needs, battery, and power electrics cooling through the use of secondary combined fluid loops was not done as part of the agreement and was removed from the project scope.

TASK 7.0: RESERVED, Date Accepted April 5, 2012

TASK 8.0: Mod 1, Date April 5, 2012; Hybrid Electric Vehicle (HEY) Energy Storage Investigation

- Deliverable: Converted vehicle, capable of serving as a test platform for alternative HEY energy storage systems.
- Mod execution +6 months

Summary of Research Results:

The approach and results for this task, summarized below, were documented in several reports [12]–[14]. The United States Advanced Battery Consortium (USABC) asked the National Renewable Energy Laboratory (NREL) to collaborate with its Workgroup and analyze the trade-offs between vehicle fuel economy and reducing the decade old minimum energy requirement for power assist HEVs. NREL's prior analysis showed that significant fuel savings could still be delivered from an ESS with much lower energy storage than the previous targets, which prompted USABC to issue a new set of lower-energy ESS (LEESS) targets and issue a request for proposals to support their development. To validate the fuel savings and performance of an HEV using such a LEESS device, a jointly funded activity between the U.S. Department of Energy Vehicle Technologies Office Energy Storage and Vehicle Systems Simulation and

Testing programs designed a test platform in which alternate energy storage devices can be installed and evaluated in an operating vehicle. To support this effort, this modification was added to the CRDADA with Ford Motor Company to support conversion of a Ford Fusion Hybrid into a test platform for evaluating LEESS devices. NREL subsequently acquired a 2012 Fusion Hybrid, designed the conversion, and entered into agreements with JSR Micro, Inc. to provide (at JSR Micro's expense) lithium-ion capacitor (LIC) modules as the first LEESS device to be evaluated in the vehicle. The LICs are asymmetric electrochemical energy storage devices possessing one electrode with battery type characteristics (lithiated graphite) and one with ultracapacitor-type characteristics (carbon). This LIC replacement pack was tested on a bench and compared to the production nickel metal hydride (NiMH) battery pack from the 2012 Fusion Hybrid. The LIC pack was then integrated into the Fusion Hybrid test platform Figure 12.

Figure 12: Fusion test platform and LEESS installation in the trunk space.
Top photo by John Ireland. Bottom photo by John Cosgrove.

Bench testing of the LEESS devices provided the necessary data for completing the conversion and confirmed the lower impedance level of the LEESS devices relative to traditional battery systems.

On-road evaluation, including standing and passing acceleration tests as well as general drive quality observation, demonstrated that most of the original vehicle performance can be maintained while operating on the lower energy devices. Under the most energy restricted configurations tested (in use energy limited to less than 70 Wh) the results indicated that high speed passing acceleration performance and overall drive quality may begin to degrade. However, it is possible that a more rigorous and production-intent controls calibration than what could be implemented for this conversion testing would be able to mitigate some if not all of this performance degradation.

Chassis dynamometer testing results, shown in Figure 13, similarly indicated that LEESS configurations could match the hybridization fuel savings achieved by the production NiMH configuration. For scenarios where artificial limitations were again imposed in order to evaluate further restricted-energy LEESS configurations, additional specific hybrid functions can become restricted (such as providing extended assist via bulk ESS depletion over certain sections of driving, or recapturing large amounts of regenerative braking energy through successive deceleration events). Even so, for all of the cycles tested even the most energy-restricted LEESS configurations experienced minimal fuel consumption impact when compared to the fuel savings offered by the HEV relative to a comparable conventional vehicle.

Photo by Jon Cosgrove, NREL

Figure 13: Dynamometer Testing

Edge cases evaluated on the chassis dynamometer included very cold testing at -10 °F, where the LEESS devices actually offered a performance advantage relative to the production NiMH battery due to their superior cold temperature tolerance. Further evaluation included 95 °F testing with air conditioning, for which the results suggested that LEESS devices could perform in an acceptable manner for consumers.

Overall, the bench, track and chassis dynamometer testing demonstrated the technical feasibility for non-traditional ESS devices to perform well in a power-assist HEV platform. Increased competition from LEESS technologies in the HEV energy storage space could be beneficial, but the onus will be on the manufacturers of these technologies to translate lower energy requirements into lower system costs before they are likely to beat out incumbent technologies in large numbers. However, if they can do so and ultimately translate these savings into an improved benefit vs. cost relationship at the vehicle level, then substantial national fuel savings benefits could be realized from aggregate increases in HEV sales.

Executed Modification No. 2 to CRADA No. CRD-09-340

This modification adds Appendix B to the CRADA.

Modification 3 to CRADA No. CRD-09-340

2/25/10 THROUGH 5/1/15 This modification adds 15 months to the period of performance.

This CRADA modification is to reflect that vehicles loaned under Appendix B of Modification 2 shall remain at NREL through 5/1/15.

Executed Modification No. 4 to CRADA No. CRD-09-340

TASK 9.0: Mod 4, Date March 20, 2014; Electric Drive Vehicle Climate Control Load Reduction

Objective:

The objective of this task is to increase in-use Electric-Drive Vehicle (EDV) range by minimizing climate control energy requirements. This may lead to increased customer acceptance of EDVs through the reduction of range anxiety. Additionally, improving thermal comfort upon entry into a hot-soaked vehicle may lead to additional motivation for drivers to adopt EDVs and improved safety through reduced driver thermal distraction.

Facilities and Equipment Used

Task	Ford	NREL
9	Ford AZTECS vehicle (Lincoln MKZ)	Vehicle Testing and Integration Facility

Summary of Research Results:

This task is summarized below and described in detail in a DOE Annual Progress Report [15]: The vehicle used to test the ventilation strategies was a silver hybrid Lincoln MKZ with black leather interior, also interchangeably referred to as the "AZTECS" vehicle. This vehicle contained modified ducting equipment from a thermoelectric element zonal cooling system previously developed under materials Department of Energy Funding Opportunity Announcement DE-EE0000020. The thermoelectric cooling system itself was not used for this work, only the modified ducting and blowers were used. The modified ducting included two identical blowers in the trunk compartment, each one drawing air from ducting that traveled up the C-pillars of the vehicle, through the headliner, and originating at low-velocity ducts positioned above the front driver and passenger seats. One blower draws air from the driver inlet duct, and the other draws air from the front passenger inlet duct. A three-dimensional computer model representing the driver side overhead duct system structure is shown in Figure 14. The second, separate duct system for the passenger side is a mirror image of the driver-side system shown.

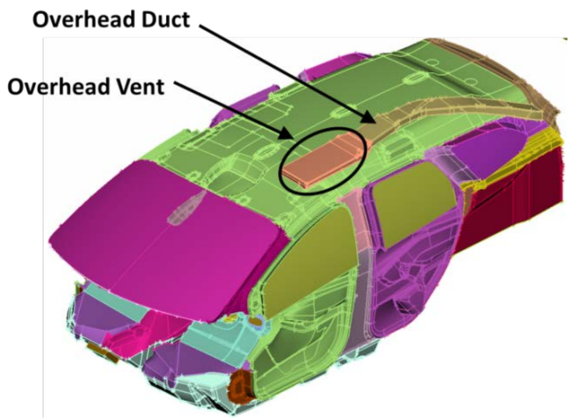

Figure 14: Overhead duct system location

Testing of the modified ducting in the Lincoln MKZ revealed that removing the ventilation air at the headliner was indeed more effective at reducing the solar soak than when using the standard HVAC system to push air through the cabin and out of the exhausters. When comparing the maximum continuous ventilation cases between using the overhead duct system or the stock HVAC blowers, the overhead ducting system showed a 55% relative improvement in the β value. The best fresh air make-up location tested for the overhead vent configuration was the foot vents, which in combination with the buoyancy-driven temperature stratification of the vehicle cabin, allowed the overhead vents to remove high temperature air from the headliner and breath level of the cabin with minimal mixing of the cabin air. It was also found that if the departure time of the vehicle is known, a short period of just-in-time ventilation will gain much of the possible benefit of pre-ventilation at a low energy cost. In fact, 15 minutes of ventilation using the overhead duct system is sufficient to achieve 62% of the maximum possible average cabin air temperature reduction realized through continuous all-day ventilation. This is a particularly important finding for the application of pre-ventilation when the vehicle is not plugged into the charger and battery energy is providing power to the blowers, a likely scenario for a vehicle hot-soaking in the sun.

Executed Modification No. 5 to CRADA No. CRD-09-340

Mod No. 5: Joint Work Statement only, 4/20/2015 **Increasing EDV Range Through Intelligent Cabin Air Handling Strategies**

1. CFD analysis of cabin airflow patterns and technologies to control the distribution of fresh air based on occupancy to increase air recirculation while maintaining cabin comfort and windshield defogging.
2. Experimental vehicle testing of promising technologies using Ford Focus BEVs to validate energy savings

Summary of Research

Task 1: Plug-in hybrid electric vehicles, battery electric vehicles (BEVs), and internal combustion engine vehicles with fuel-efficient, down-sized engines increasingly lack sufficient "free" waste heat to condition the cabin in cold weather. The lack of sufficient waste heat to fully condition the cabin means that they must resort to alternative heating systems such as electrical resistance heaters and heat pumps. These heating technologies consume additional energy for thermal management, which reduces vehicle efficiency. In BEVs this effect is particularly acute due to the complete absence of engine waste heat and the limited battery energy available for vehicle propulsion. Technologies that are able to reduce the amount of energy spent by the battery to condition the vehicle cabin will help to increase customer acceptance of electric drive vehicles (EDVs) by reducing range anxiety, which will in turn increase EDV penetration into the national vehicle fleet.

CFD simulations, Figure 15, demonstrated that continuous fractional recirculation control using standard OEM ducts and recirculation doors allows a recirculated air fraction of up to 75% before windshield fogging occurs when there are four passengers and the ambient temperature is -5°C. A 75% recirculation fraction results in a cabin heating load reduction of 50.0% relative to using full fresh air, which equates to a 50.0% energy savings for a generic heating system such as an electrical resistance heater or heat pump. This is a substantial energy savings for EDVs in cold weather at the relatively low cost of additional control logic, sensor, and potentially a redesigned recirculation actuator door. The actual EDV range increase that this energy savings would equate to would be heavily dependent on vehicle usage.

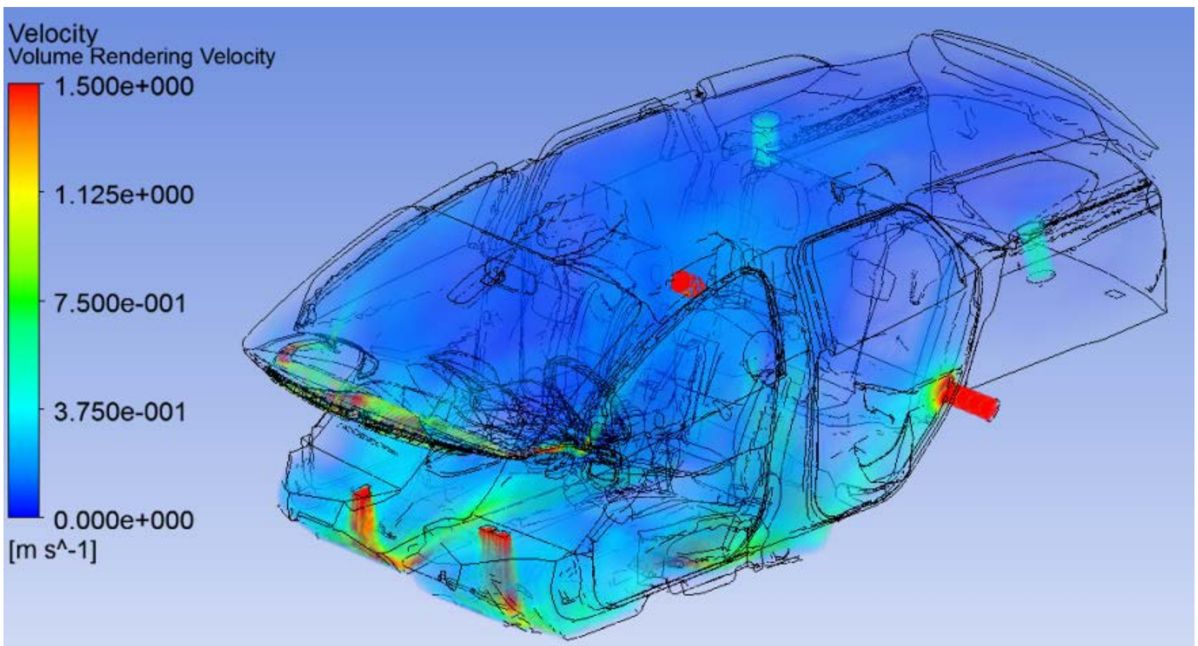

Figure 15: Cabin air velocity field of split flow case with rear split flow recirculation return ducts and exhausters at 63% recirculation

The primary investigation of this CFD simulation study was to measure the effect of a split flow recirculation system. CFD results showed that having split fresh and recirculation air streams with a return duct at the rear of the vehicle allowed up to a 84.5% recirculation fraction before windshield fogging, which equates to an energy consumption reduction of 57.4% relative to full fresh air use. Although the split flow system provides significant benefit, the slight difference in energy savings of the split flow system over the fractional recirculation control system is unlikely to be justifiable due to the increased system complexity. The increased complexity is particularly apparent in the packaging challenge of running recirculation return ducts from the rear of the vehicle to the instrument panel. Also, the energy savings estimate is based on thermal load reduction and does not take into account any potential increase in HVAC blower electrical power due to the additional pressure drop of the return ducts. With that in mind a fractional recirculation control system is recommended as an effective option to reduce heating loads. In fact, Corporate Average Fuel Economy (CAFE) regulations provide off-cycle greenhouse gas credits to OEMs for implementing improved recirculation strategies, and OEMs are beginning to implement fractional recirculation controls.

Although the additional energy savings benefit of the split flow system over the fractional recirculation control system is small, an auxiliary benefit of the split flow system is potentially improved passenger thermal comfort. The split flow system provides drier air to the front windshield, which would allow a reduction of airflow through the defroster/demister vents. This is advantageous because defrost/demist flow can cause discomfort for the front passengers due to "dry eyes."

A technical report was published which describes this work in detail and meets the report deliverable for this task [16].

Task 2: Mod 5 Task 1 concluded that while there is significant benefit for the split flow system investigated, the marginal improvement over a fractional air flow control system may not justify the added complexity. For this reason, a no-go was decided for task 2, as the analysis did not show sufficient benefit to warrant a test program.

Executed Modification No. 6 to CRADA No. CRD-09-340

Mod No. 6: Joint Work Statement only, 11/9/2016

- Identify new and existing sensor technologies which can be deployable across a wide range of light-duty vehicle platforms to enable occupant comfort prediction
- Leverage existing models to develop physiological correlations for human comfort prediction in complex vehicle environments that can be deployed into HVAC system control algorithms
- Use the Focus Electric platform to demonstrate a proof-of-concept

<u>Summary of Research Results:</u>

Advanced zonal and occupant targeting climate control strategies have measured performance improvements. If advanced strategies target the occupant, so should their control systems. This provides an opportunity for integration of technologies focused on occupant thermal comfort in a way that will reduce energy consumption. An initial project roadmap was developed with 6 phases.

1. Determine information available and needed for thermal comfort prediction
2. Identify existing and new sensors
3. Develop physiological correlation for comfort prediction levering existing models
4. Build a control system framework. A schematic of this is show in Figure 16.
5. Use adaptive learning to handle difficult to capture components such as occupant clothing, time-of-year dependencies, and time-of-day dependencies. System "corrective" actions performed by occupant would be used for reinforcement learning.
6. Experimental evaluation to demonstrate functionality and quantify performance

The project roadmap was successfully reviewed with the vehicle systems analysis technical team in October 2015. Work on this project was, however, discontinued due to insufficient funding.

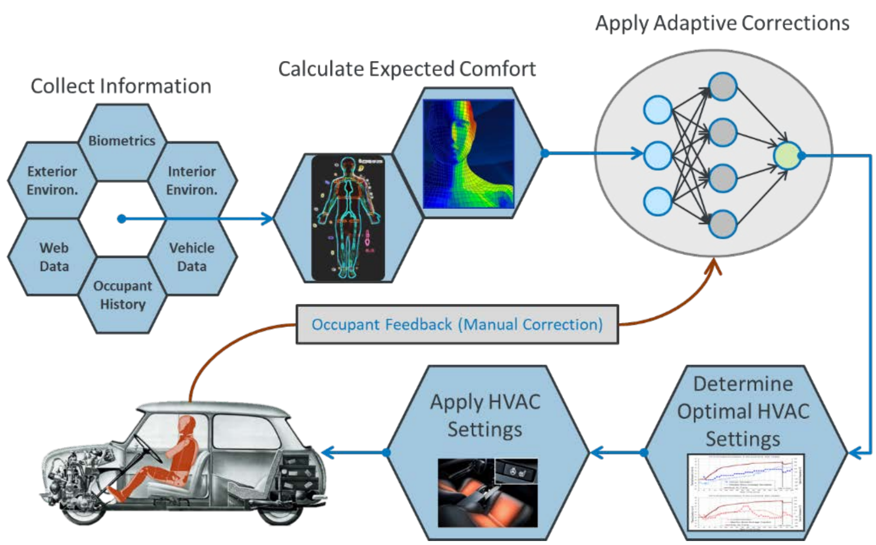

Figure 16: Occupant Based Sensing and Control System for HVAC Operation Conceptual Framework

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Subject Inventions Listing:

None

ROI #:

None

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