Improving Energy Efficiency by Developing Components for Distributed Cooling and Heating Based on Thermal Comfort Modeling [Thermoelectric (TE) HVAC]

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Objectives - Relevance

Project Primary Goal: Integrate TE technology in a distributed cooling/ heating climate control system

- Reduce fuel used for occupant comfort by 30% by localized use of TE technology
- Develop components $COP_{cooling} > 1.3$ and $COP_{heating} > 2.3$
- Integrate & test as a system in 5-passenger demonstration vehicle
- Integrate & test an extended range electric vehicle (Chevrolet Volt)
- Develop a model to predict occupant physiological response to transient localized heating and cooling

Objectives - Relevance

Project Secondary Goal: improve TE generators

- Develop TE materials for engine waste heat recovery applications (to provide power TE HVAC climate loads)

2011 Objectives:

- Comfort Model Enhancement and Validation
- Climate System Efficiency metrics
- Powertrain Mode operation impacts

Overview – The Challenge

TE devices in a traditional internal combustion engine vehicle utilize power at a cost of 0.3 mpg per 100 alternator watts, whereas a traditional AC compressor utilizes crankshaft power at 0.2 mpg per 100 crankshaft W.

Electric vehicles, in comparison, do not have a crankshaft advantage for Climate Control Power delivery

TE devices in cooling mode obtain an average COP of 1.3 whereas a traditional AC compressor typically attains a COP greater than 2.0.

TE devices can be integrated into the vehicle more effectively than traditional HVAC heat exchangers, and thereby overcoming the above performance constraints.

Milestones – Technical Accomplishments

Through Quarter 3 2011

- Completed identification of initial set of components for distributed heating and cooling development – Mar. 31, 2010
- Complete build of mule vehicle with simulated TE devices for Thermal Comfort evaluation – Aug. 31, 2010
- Complete Design of Experiments for phase 1 testing of Mule and virtual vehicle – Nov 16, 2010
- Climatic Wind Tunnel tests for warm ambient occupant comfort evaluation demonstrate occupant preference for reduced localized airflow velocity – Dec 16, 2010
- Strategy and method to control distributed climate control system identified – March 10, 2011

GM

Team Composition

GM GVE GLOBAL VEHICLE ENGINEERING

Vehicle Integration
System Controls

DELPHI

TE Component Design
Climatic Tunnel Testing
Vehicle Instrumentation

faurecia

Modify Seating to Optimize Thermal Comfort
Optimize Interior surfaces

GM R&D

TE Material Research
CAE Modeling
Project Management

Berkeley UNIVERSITY OF CALIFORNIA

Human Subject Testing
Comfort Model Enhancement

UNLV

TE Material Research
Computational Research

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

Funding
Project Oversight

The California ENERGY COMMISSION

Funding
Project Oversight

Approach/Strategy

- **Applied Research – Phase 1**: Develop Thermal Comfort model of human responses to potential locations for distributed heating & cooling
  - Identified potential locations for distributed HVAC components and measured their physiological and psychological effectiveness
  - Used automotive mockup in the UC-Berkeley environmental test chamber and mule vehicle in Delphi Climatic Tunnel to perform human subject testing
  - Update UC-Berkeley's Thermal Comfort model as the "key component" of the Virtual Thermal Comfort Engineering (VTCE) computer-aided engineering (CAE) tool used by GM and Delphi Thermal Systems
- **Exploratory Development – Phase 2**: Develop the initial prototype HVAC components and evaluate on bench & mule vehicle
  - CFD and vehicle Design of Experiments (DoE) analysis
  - Functional intent component manufacturing and vehicle integration
  - Define control strategies and algorithms
  - Build eAssist LaCrosse with design intent localized TE components

Approach/Strategy (cont.)

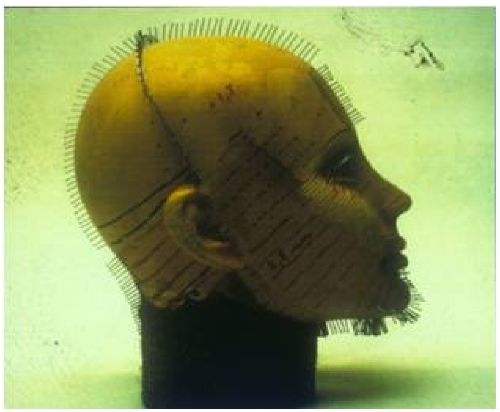
- **Advanced Development – Phase 3**: Develop final prototype HVAC components and evaluate on bench
  - Optimize control system to balance comfort and consumption (engine mode)
  - Estimate HVAC system efficiency improvements, (central system mass reduction and vehicle thermal load reduction)
  - Commercialize TE components for future production application
- **Engineering Development – Phase 4**: Integrate final local and central HVAC components into demo vehicle and optimize system performance
  - Build advanced propulsion demonstration vehicle
  - Test and evaluate distributed HVAC system
  - Calculate expected customer efficiency gain
  - Deliver vehicle and final report to DOE/CEC
- **HVAC Material/Waste Heat Recovery Research – Phase 5**: Develop new thermoelectric generator materials (concurrent with phases 1-4) to produce power for the TE HVAC climatic loads

Technical Accomplishments and Progress

- Team selection criteria lead to the Cadillac SRX for the mule demonstration, and an eAssist Buick LaCrosse for final demonstration
- Vehicles and occupants have been modeled for virtual evaluation
- Test and simulation procedures for local distribution evaluation established jointly between UC-B, Delphi and GM

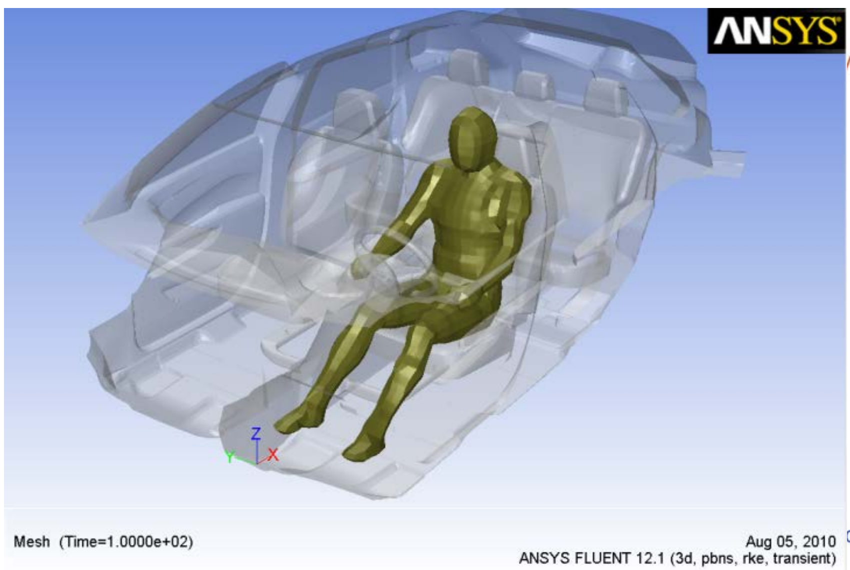
Technical Accomplishments and Progress (cont.)

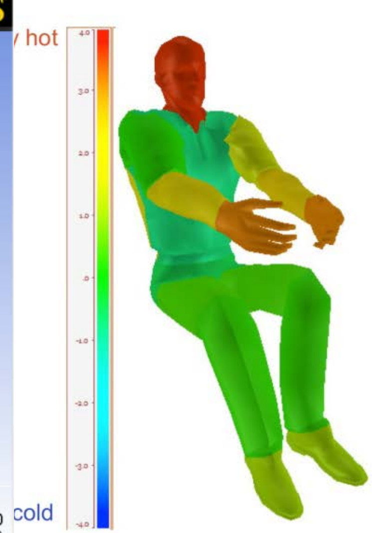
- All phases of testing benefit from UC Berkeley thermal manikin evaluation; providing detailed localized comfort measurement with an absence of psychological influence

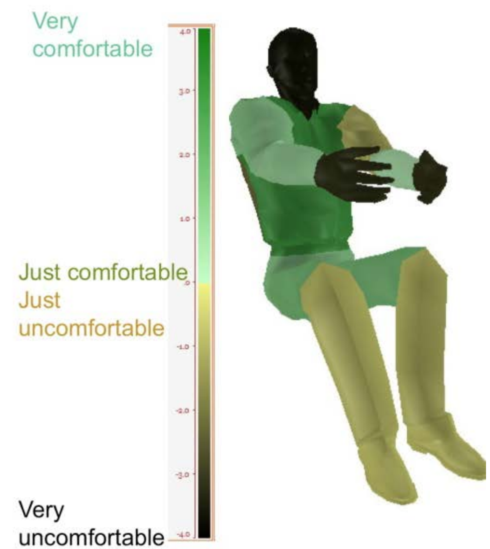


Technical Accomplishments and Progress (cont.)

- Revisions to the Human Thermal Comfort model for localized cooling and heating correlate well with subjective and 16 segment thermal mannequin vehicle evaluations
- VTCE analysis guides localized component determination

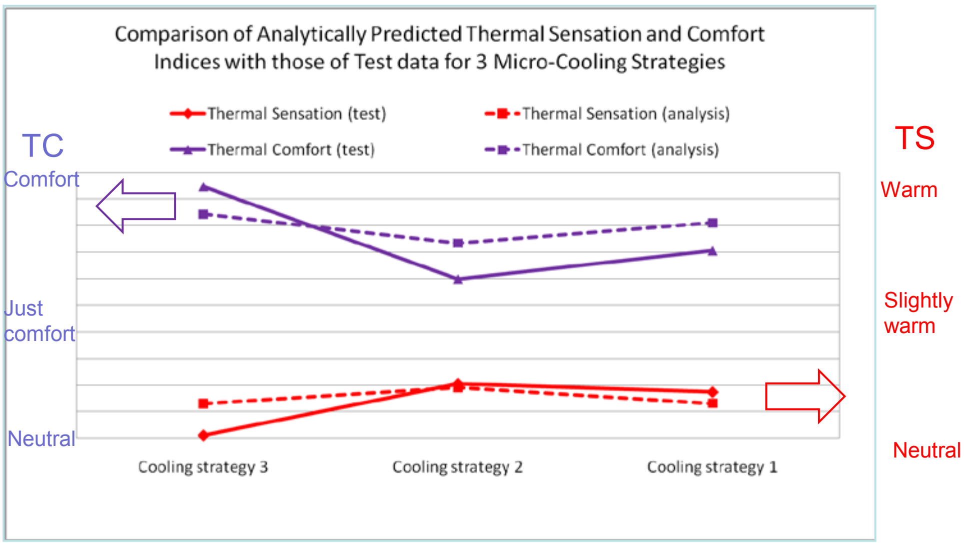


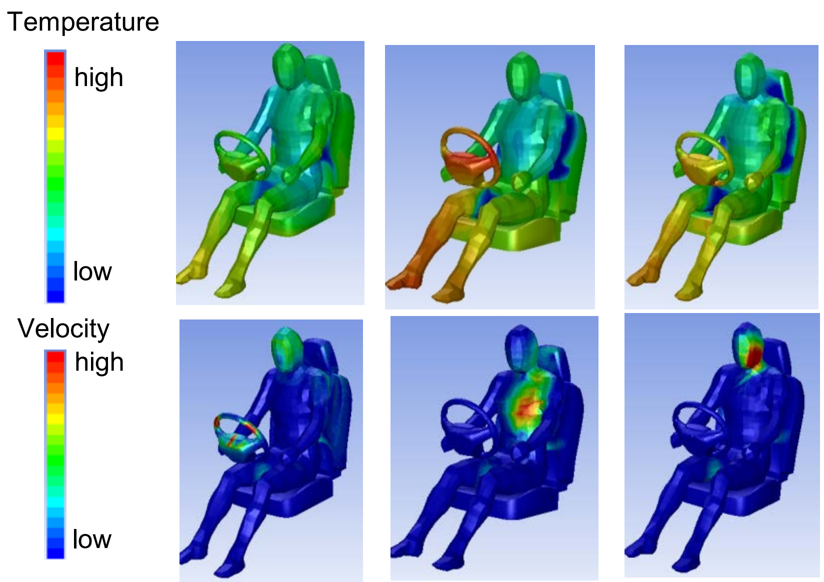




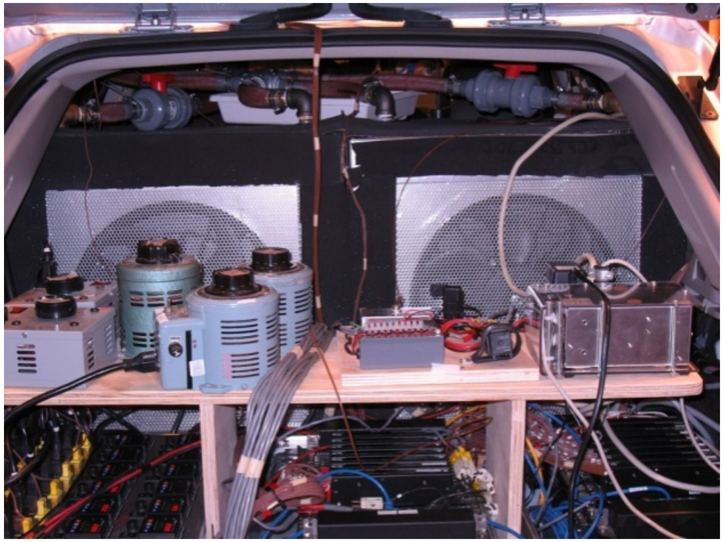
Technical Accomplishments and Progress (cont.)

- Thermal comfort human subject testing data from UC Berkeley's environmental test chamber was used for GM's VTCE tool validation.





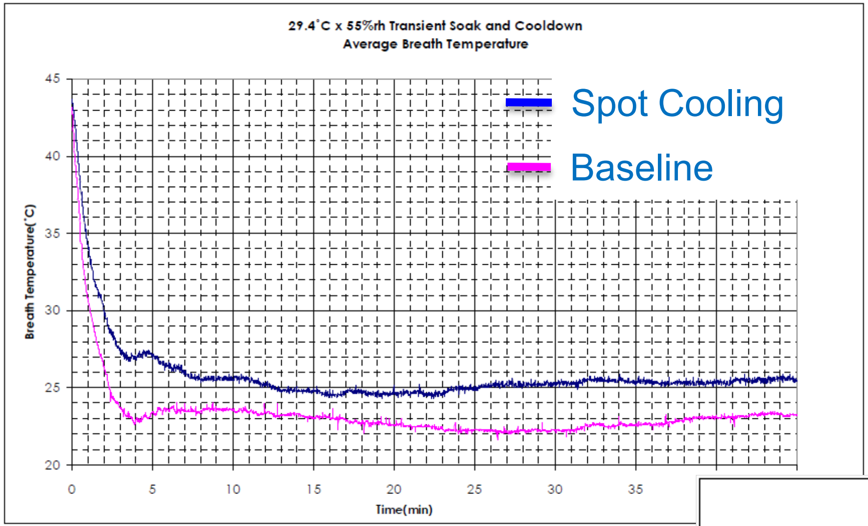
Technical Accomplishments and Progress (cont.)



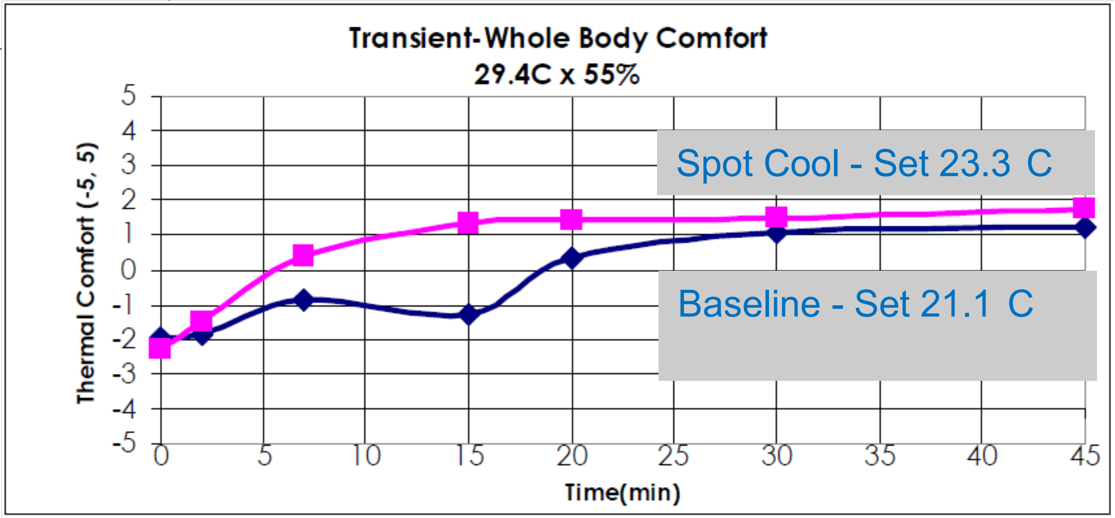
- Delphi's Climatic Wind Tunnel testing used for emulated local spot cooling (September 2010)
- Conditioned air supply source installed in test vehicle, manifold distribution for rapid thermal variation and reconfiguration
- Mule Simulation report issued October 31, 2010

UC-B thermal maikin and human subjects used to evaluate spot cooling

Localized Spot Cooling in Tunnel Test Results – Breath temperature comparison at 25°C EHT

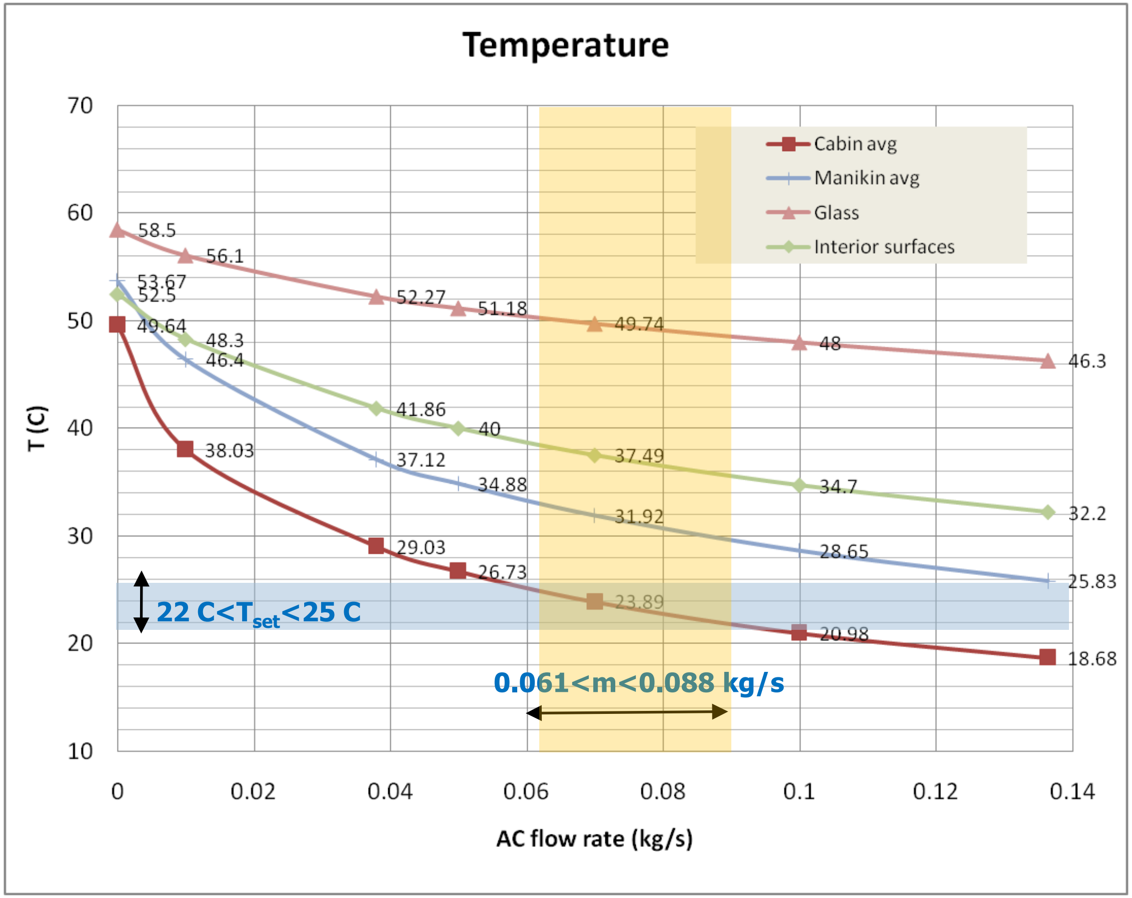


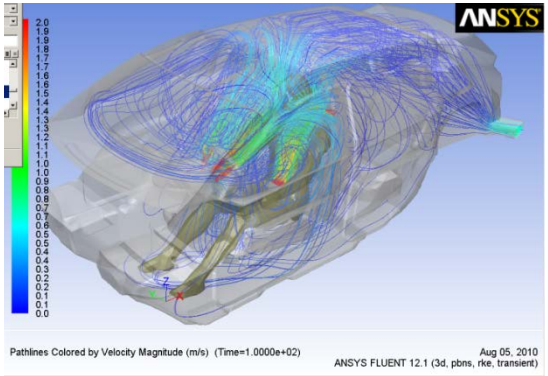
Improved comfort early in the drive cycle offers engine mode enhancement!



DELPHI

Mass Airflow Energy for Interior Temperature Maintenance





- **AC mass flow rate can be reduced by 30.7% by raising cabin air temperature from 22 C to 25 C**

Energy Balance

$$Q_{Evp} = \dot{m}C_p\left[\left(T_{ambient} - T_{dis}\right) + 6.5\right] + Q_{condensation}$$

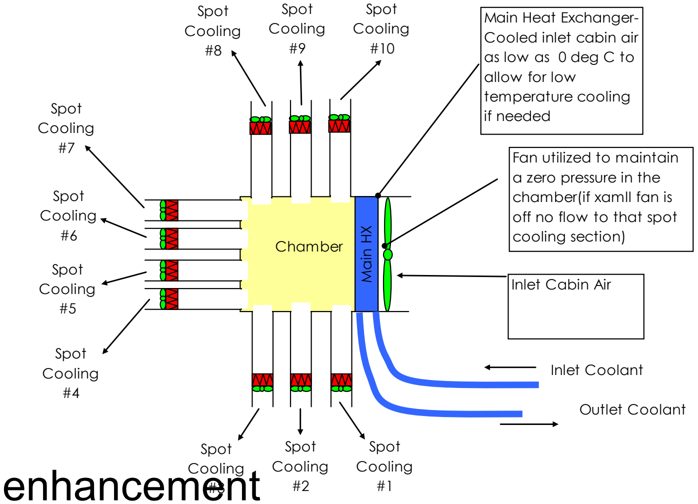
Q_{cond} = *Condensation Thermal Load*

Q_{Evp} = *Evaporator Thermal Load*

- Based on 4 kW baseline cooling load, 2.0 COP: 30% reduction in air mass flow results in 600 Watt crankshaft energy savings (1.0 mpg saving)
- Spot cooling used above requires about 70 alternator Watts (TED) per occupant at a 1.3 COP

  (0.2 mpg cost per occupant)
- Net Energy reduction assuming 2 occupants is about 460 Watts. (0.6 mpg saving net)

Collaboration and Coordination with Other Institutions



- **University of California – Berkeley:**
  Human subject testing & Thermal Comfort modeling enhancement
- **Delphi Thermal Systems:**
  HVAC component development and testing
- **University of Nevada – Las Vegas:**
  Thermoelectric materials computational research
- **GM Vehicle Engineering:**
  Vehicle requirements, system integration
- **General Motors R&D:**
  CAE tool development and TE materials research

- Human subject and Mule testing benefit from live participation between GM, Delphi and UC-B: better correlation between test phases via accurate procedure duplication and application of superior thermal comfort knowledge

Proposed Future Work

- **Phase 2 activities began in May, conclude next March**
  - CFD and vehicle Design of Experiments (DoE) analysis
  - Functional intent component manufacturing and vehicle integration
  - Metric Development for performance objectives
  - Define control strategies and algorithms to obtain integration efficiency (including engine mode)
- **Develop localized strategy for Chevrolet Volt**
  - Narrow the climate control induced variation in battery operating range between -10 to 32^{o}C (14 to 90^{o}F)

Summary – TE HVAC Project

- Relevance - The climate control system is the largest vehicle arasitic load, with strong FE and mass impact.
- Approach - Optimize localized HVAC components using a refined Thermal Comfort model. Develop TE components that provide efficient localized heating & cooling of occupants
- Accomplishments – UC-B Thermal manikin aids correlation, VTCE tool refined to aid in evaluation of localized heat transfer. Mule testing validated optimal locations for TE components
- Collaboration – UC-B, Delphi and GM meet to refine daily activity. The UC-B comfort tool integration allows rapid optimization of distributed HVAC components. UNLV TE material research is essential for the components Delphi will build in phase 2.
- Future Direction
  - Control system hardware development to regulate system output for efficient thermal comfort
  - High Watt density cabin coolant heater development for efficient defrosting performance in a Chevrolet Volt