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)

2012 Objectives:

- ❑ Comfort Model Enhancement and Validation
- ❑ Finalize distributed TE devices design and testing on mule vehicle
- ❑ Climate system efficiency metrics
- ❑ Develop efficient coolant TE heater for the Chevy Volt's cabin and windshield defrosting system

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 Watts.
- 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 for personalized comfort than traditional HVAC heat exchangers, and thereby overcoming the above performance constraints.

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, new 2012

GM R&D

TE Material Research
CAE Modeling
Project Management

Intrepid

TE/System Software/Hardware Control Support, new 2012

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 UCBerkeley (UCB) environmental test chamber and mule vehicle in Delphi Climatic Tunnel to perform human subject testing
  - Update UCB'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
  - 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 UCB, Delphi and GM

Milestones – Technical Accomplishments

Through Quarter 3, 2012

- DOE Milestone: Completed specification of the interface between Delphi/GM controllers – Dec. 16, 2011
- Complete build of mule vehicle with TE devices for thermal comfort evaluation – Jun. 26, 2012
  - TE assembly qualification test and report from Marlow – May 1, 2012
  - Distributed TE assembly installation on mule vehicle with CFD analysis – May 17, 2012
  - Delphi TE interface circuit and wiring harness fab with control hardware/software development – Jun. 22, 2012
  - Strategy and method to control distributed climate control system – Jun. 26, 2012

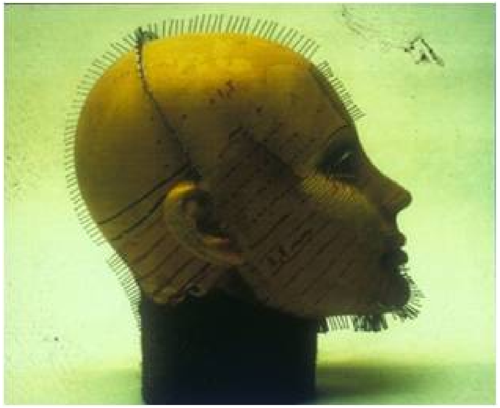
Milestones – Technical Accomplishments (cont.)

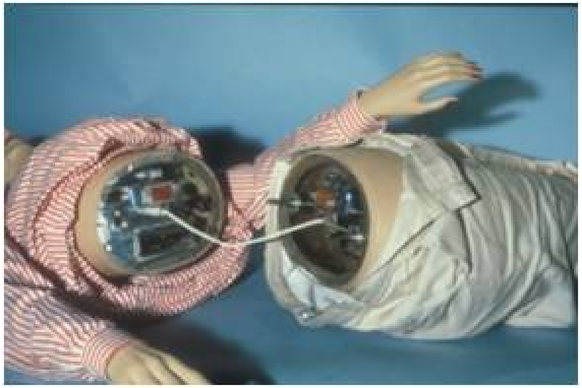
Through Quarter 3, 2012

- ❑ Complete climatic wind tunnel tests for occupant comfort evaluation with distributed TE devices – Sep. 28, 2012
  - Spot cooling – Jul. 31, 2012
  - Spot heating – Aug. 31, 2012
  - Spot cooling power consumption testing – Sep. 28, 2012

Technical Accomplishments and Progress (cont.)

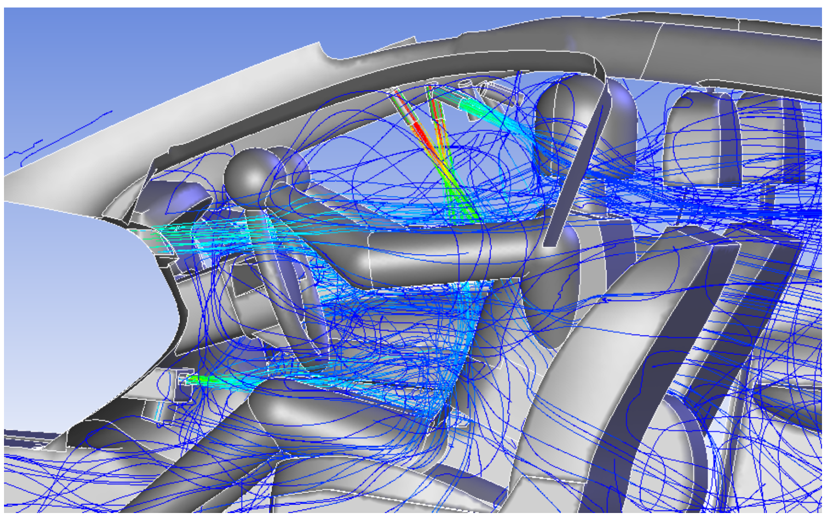
- All phases of testing benefit from UC Berkeley thermal manikin evaluation; providing detailed localized comfort measurement with an absence of psychological influence

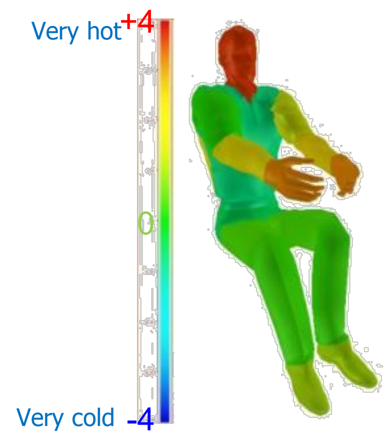




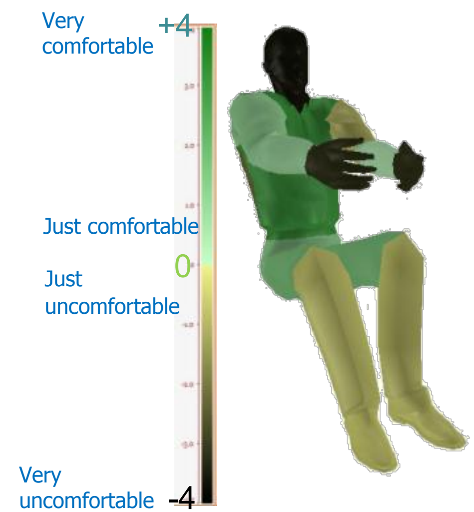
Technical Accomplishments and Progress (cont.)

- 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





Sensation scale



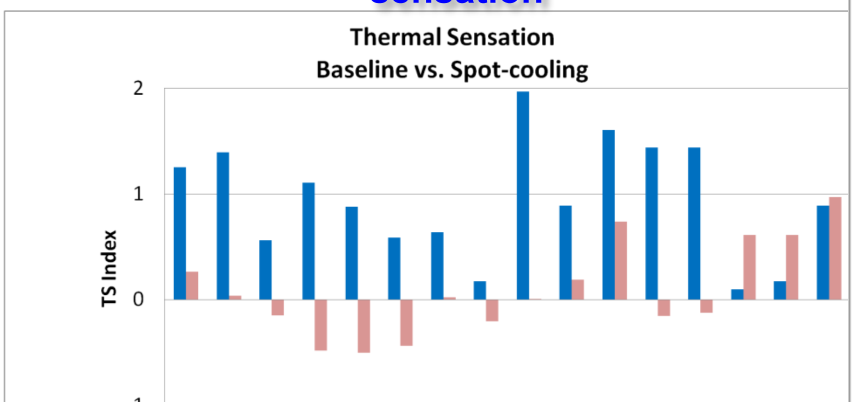
Comfort scale

Technical Accomplishments and Progress (cont.)

- ❑ Thermal comfort human subject test data (2011) from Delphi CWT were used for VTCE tool validation.

VTCE Prediction

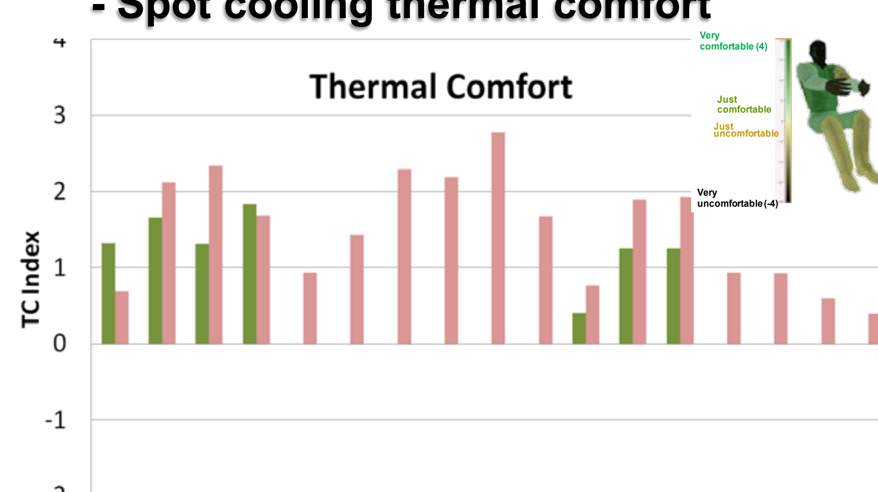
- Effectiveness of the spot cooling on therma sensation



	Over all	Head	Chest	Back	Pelvis	Left upper arm	Right upper arm	Left lower arm	Right lower arm	Left hand	Right hand	Left thigh	Right thigh	Left leg	Right leg	Left foot
Baseline	1.254	1.392	0.563	1.104	0.879	0.587	0.636	0.174	1.967	0.887	1.606	1.441	1.441	0.097	0.174	0.892
Spot-cooling	0.262	0.034	-0.15	-0.48	-0.5	-0.44	0.02	-0.2	0.006	0.19	0.736	-0.16	-0.13	0.609	0.614	0.97

Validation

- Spot cooling thermal comfort



	Over all	Head	Chest	Back	Pelvis	Left upper arm	Right upper arm	Left lower arm	Right lower arm	Left hand	Right hand	Left thigh	Right thigh	Left leg	Right leg	Left foot	Right foot
Test - SpotCooling	1.32	1.65	1.31	1.84							0.4	1.25	1.25				
Prediction	0.695	2.118	2.335	1.679	0.932	1.425	2.296	2.189	2.771	1.673	0.759	1.894	1.922	0.939	0.932	0.598	0.394

Baseline – main AC only without spot cooling
Spot cooling – with “chest/face/lap/seat” cooling

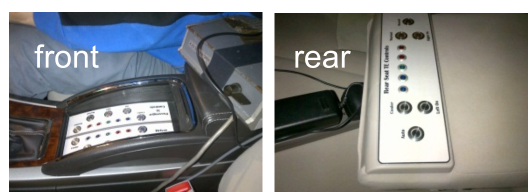
Test – Delphi CWT test with “chest/face/lap/seat” spot cooling
Prediction – GM VTCE Tool

Technical Accomplishments and Progress (cont.)

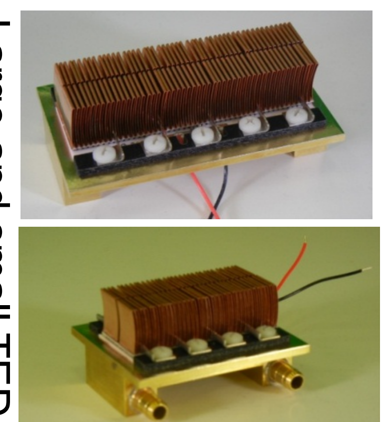
Manikin on the front passenger seat

TED heat exchanger/controller/data logger in the trunk of LaCrosse

- Delphi's climatic wind tunnel testing used for TE local spot cooling/heating (Jul-Sep, 2012)
- Thermal manikin and human subjects for comfort evaluation
- Conditioned air supply source installed in test vehicle, manifold distribution for rapid thermal variation and reconfiguration
- Separate front and rear TED controller



HMI for front and rear TE comfort testing



Large and small TED

Summary for Power Saving Estimate

- TE Distributed Cooling and Heating System implementation
  - TE cooling and heating supplemental system has been integrated into 2012 Buick LaCrosse
  - Each passenger is enveloped by a micro-environment supported by multiple TE conditioned air streams
  - Front seats: four TE locations - Chest/Face, Lap/Foot, Seat Bottom and Seat Back
  - Rear seats: three TE locations - Chest/Face, Seat Bottom, and Seat Back
  - TE cooling system development was carried out under a standard ambient condition of 85Fx55%x500 watts and evaluated under other ambient conditions (60Fx80%, 70Fx70%, 80Fx60%, 90Fx50%, 100Fx40% with corresponding solar radiation levels)
  - Tests indicate equivalent comfort was obtained
    - Baseline: T_{set} for cooling = 71F (incar breath T = 24 C)
    - TE distributed: elevated T_{set} for cooling = 76F

Comfort plot

Summary for Power Saving Estimate (cont.)

- Initial Power Saving Estimate Under Standard Test Condition (85Fx55%x500watts)
  - Compressor direct power saving at 36.5% for driver only scenario
  - TE, fan, and coolant pump add back power consumption
  - Net compressor saving after TE related power consumption is estimated at 29.5%
  - Other test conditions are being evaluated
  - For the plume seat without TE devices (sucking ventilation + targeted HVAC air stream), a slight energy efficiency improvement is expected due to elimination of TE related power consumptions
  - TE COP during the test:
    - COP ≥ 1.4 was achieved for cooling
    - COP ≥ 2.4 was achieved for heating

Technical Progress for the Volt

Through Quarter 3, 2012

- ❑ Team has finalized the design and test for the coolant TE heat exchanger.
- ❑ Test data showed the new coolant TE heater with COP = 1 for extremely low temperature (large ΔT) and achieved COP > 2.3 depending on ΔT.
- ❑ The developed TEDs for the LaCrosse are being re-examined and plan to be modified and retrofitted into Volt vehicle.

Proposed Future Work

For LaCrosse:

1. **Phase 3 activities: Oct/2012 - Apr/2013**
   - ❑ Commercialize the design of new comfort components
     - Produce/procure packaging & function intent final components
     - Test and evaluation of final comfort components
     - Component qualification and test report
   - ❑ Estimate efficiency improvements for the integrated system
2. **Phase 4 activities: Mar/2013 - Aug/2013**
   - ❑ Integrate final components into demonstration vehicle
   - ❑ Test and evaluate distributed HVAC system in vehicle
   - ❑ Calculate efficiency improvements of distributed HVAC system

3. Planned Volt Schedule

Oct. 12 | Jan.13 | Jun. 13 | Oct. 13 | Dec. 13

Phase II (Exploratory development)		Phase III (Advanced dev.)	Phase IV (Engineering dev.)
Define specs for the Volt: • Locations, flow rate, Temp for modified TED from LaCrosse • HEX (for waste removal) for TED system • Coolant heater • TE control and interface with Volt	• GM Climatic Wind Tunnel is planned for the Volt testing • Build and demonstrate function-intent components • Specify control strategies and algorithm between Volt and TED. • Integrate Initial components into Volt • Evaluate initial comfort components • Estimate energy saving and COP for the TED components	• Commercialize design of new components • Produce packaging and function-intent final components • Test and evaluate final comfort components • Estimate drive range improvement	• Integrate final components into demo Volt • Test and evaluate system • Calculate energy saving and drive range improvement • Provide demonstration Volt to DOE

2012 ⇐ ⇒ 2013

Summary – TE HVAC Project

- **Relevance** - The climate control system is the largest vehicle parasitic 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 for occupants
- **Accomplishments** – UCB Thermal manikin aids correlation, VTCE tool refined to aid in evaluation of localized heat transfer. Mule testing validated optimal locations for TE components. Initial Power saving estimated at 29.5% for standard test condition.
- **Collaboration** – UCB, Delphi and GM meet to refine daily activity. Faurecia* and Intrepid provide seat comfort and control software and hardware. The UCB comfort tool integration allows rapid optimization of distributed HVAC components.
- **Future Direction**
  - Optimized TE locations, discharge airflow and temperature for demonstration vehicles to meet DOE requirements of energy efficiency for LaCrosse and range extension for Chevy Volt.

* Faurecia contributes to the project for LaCrosse seat cooling/heating with ventilation only, not with TED.