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Energy Efficiency Impact of Localized Cooling/Heating for Electric Vehicle

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Abstract

The present paper reports on a study of the HVAC energy usage for an EREV (extended range electric vehicle) implementation of a localized cooling/heating system. Components in the localized system use thermoelectric (TE) devices to target the occupant's chest, face, lap and foot areas. A novel contact TE seat was integrated into the system. Human subject comfort rides and a thermal manikin in the tunnel were used to establish equivalent comfort for the baseline and localized system. The tunnel test results indicate that, with the localized system, HVAC energy savings of 37% are achieved for cooling conditions (ambient conditions greater than 10 °C) and 38% for heating conditions (ambient conditions less than 10 °C), respectively based on an annualized ambient and vehicle occupancy weighted method. The driving range extension for an electric vehicle was also estimated based on the HVAC energy saving.

Introduction

The HVAC system imposes the largest accessory load on an electric vehicle to meet occupant comfort heating and cooling needs. Thus the HVAC energy consumption has a major impact on the driving range of a pure electric vehicle (EV) or an extended range electric vehicle (EREV such as Chevy Volt). Traditionally, the vehicular HVAC system is designed to cool and heat the entire cabin to provide occupant comfort. Localized cooling and heating, on the other hand, focus on keeping the occupants comfortable by creating a micro climate around the passenger. Such a system can easily adapt to the number of occupants in the car and enables zonal control. The net impact of the localized cooling and heating system is that equivalent comfort can be achieved at a reduced HVAC energy consumption.

In the previous papers [1, 2, 3], the effect of localized cooling and heating HVAC system was studied. A fundamental study of spot cooling was reported in which localized cooling streams were

experimentally investigated for its impact on human thermal comfort [1]. The individual cooling streams were evaluated by human comfort for effectiveness and limitations. Based on the local cooling studies, combination local cooling strategies were then created and evaluated. An earlier paper by Ghosh et al. [2] reported on a CFD study of a vehicle cabin with local cooling streams to design and develop micro-cooling strategy in the vehicle and evaluate the potential for good comfort. Wang et al. [3] has reported the design, fabrication and in-vehicle testing of the thermoelectric modules for distributed cooling and heating, otherwise referred to as spot cooling and heating. A TE module, is a self-contained unit with thermoelectric devices, air fins, coolant jackets, connectors, and air flow nozzles packaged within a plastic casing to fulfill the function of an air stream and directing the air stream toward a specific occupant body part or a group of body parts to satisfy their thermal comfort requirements. Several TE modules were designed to meet the thermal comfort requirements of the different body parts.

Similar to the TE HVAC system designed and fabricated for the Buick LaCrosse as reported in [3], a significant amount of work was carried out to retrofit the system in [3] into the Volt. This includes TE modules with a coolant conditioning system and a control system to coordinate and supervise the operation of the TE modules. The coolant conditioning system is composed of coolant pumps, valves, CHCM (Cabin Heating Coolant Module) or coolant PTC heater, air blowers, lines and hoses, etc. The control system is composed of hardware and software capable of monitoring the operating states of the TE devices, driving the operation of the TE module fans and the coolant pumps, controlling the operation of the TE waste heat removal cooling blower, communicating with the vehicle bus for obtaining and providing operational parameters, and finally, supporting data logging for both sensor generated data streams and control system generated data streams. One new TE item unique to the Volt vehicle is the contact TE seats installed on the driver and

front passenger. This is different from the ventilation TE seats used in [3]. The comfort aspect for both types of TE seats will be briefly mentioned later in the paper.

For a gas powered vehicle, it was reported that the energy saving impact by the localized TE HVAC system was about 29% over the baseline vehicle for the cooling operation only [3]. However, the heating saving efficiency was not reported since it is irrelevant to compare the TE operation with the baseline gas powered vehicle with free waste heat.

The primary focus of the present paper is to investigate the energy impact of the TE HVAC system for the heating operation during winter driving that has proven to be one of the largest range reduction factor for EVs and EREVs. Also based on the HVAC energy savings achieved for both cooling and heating conditions, the driving range extension will be estimated. The paper is outlined as follows: (1) The TE components installed in the vehicle are described first, (2) Human subject road test to establish equivalent comfort for baseline and TE system, (3) The tunnel test to verify EHT (Equivalent Homogeneous Temperature) by a thermal manikin and (4) tunnel power consumption analysis and report energy saving results.

Thermoelectric Cooling and Heating Module

In the present paper, only a brief description of the TE modules installed in the Volt is provided. Interested readers should refer to Wang et al. [3] in which detailed design, fabrication, test and performance of each individual module, as well as the waste heat removal supporting system, and overall system integration and control are documented. The TE modules and control design in the Volt are directly derived from the Lacrosse components in [3]. The face/chest TE module and lap/foot module were chosen to be modified and fitted into Volt due to their effectiveness for the comfort. Also, same as in the Lacrosse, TE seats were installed for the driver and front passenger. However, contact TE elements were chosen for the Volt seats, instead of the ventilation TE type used for the Lacrosse. Another noticeable design change is that the heat exchange loop utilizes the CHCM heater to warm up the TE coolant in EV mode for TE spot heating operation since waste heat is not available during engine off operation.

Face/Chest TE Module

Figure 1 shows the face/chest TE module discharge nozzles for both the driver and the front passenger. The TE cooling/heating unit is hidden inside the roof liner. The TE air inlets are on the roof behind the B-pillar (see Figure 1).

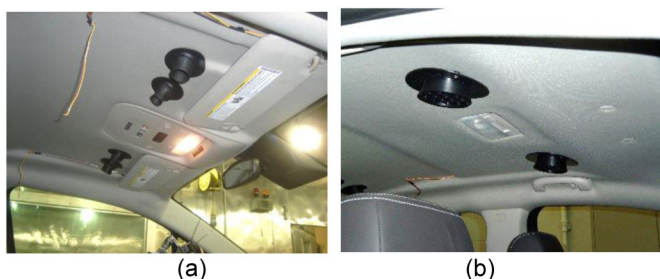


Figure 1. (a) Face/chest nozzles and (b) TE air inlet vents in the Volt.

Lap/Foot TE Module

Figure 2 shows the lap/foot TE nozzles in the front passenger side. The lap nozzle is designed to aim to cool and warm the upper leg and lower abdomen area. The driver side lap TE nozzle is similar to the passenger side except that it was split into two on either side of the steering column.

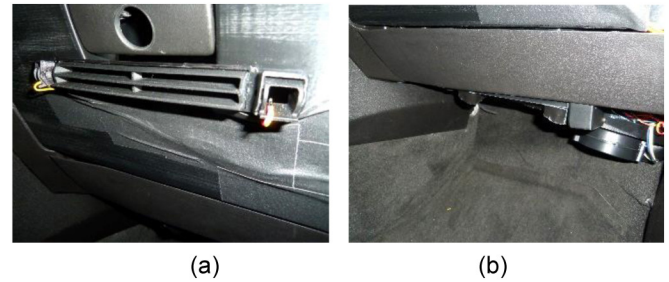


Figure 2. (a) Lap TE nozzles and (b) Foot TE nozzle in the front passenger side.

The air flow rate and temperature differential across the TE devices are shown in Table 1. Comparing to the cooling, the air flow rate for the heating is designed to be much smaller to avoid generating too much unfavorable convective “cooling” sensation during the spot heating operation.

Table 1. Air flow and ΔT across TE devices and the corresponding COP.

	Cooling operation			Heating operation		
	Airflow(CFM)	$\Delta T(C)$	COP	Airflow(CFM)	$\Delta T(C)$	COP
Chest/face TEDs	13	5.1	1.4	8	15.3	2.5
Lap/foot TEDs	15	5	1.7	5	14	2.7

TE System Control

The TE devices need to be controlled in a coordinated way to provide cooling or heating to the passengers in the car to maintain comfort and provide energy saving. From the functional point of view, the control system needs to support communication with the vehicle CAN bus to gain access to the operating parameters in the vehicle, including those of the powertrain and the climate control system so that operating decisions for the TE devices can be made. It needs to provide a Human Machine Interface (HMI, or control panel) to allow the passengers to give control input to the controller to optimize the operation of the TE devices. The coolant loop, composed of two pumps, three linear valves, waste heat exchanger airflow blower, needs to operate to get rid of the waste heat from the TE devices and simultaneously ensure that the TE devices do not get over-heated. On the processed air side whereby cooled or heated air is generated and delivered to the passengers through a TE air conditioning module, the power supply to the TE devices and the individual fans need to be controlled for sustained operation. Additional control requirements for the TE system come from the need to calibrate the various operating parameters so that the TE HVAC system can be optimized for performance and energy efficiency. Lastly, the control system needs to support data logging for system debugging and performance evaluation. Data streams from the vehicle CAN bus and those from the various controller of the TE system need to be collated and recorded into a single data file with unified time stamp and sampling rate. More details in TE control can be found in [3]. Figure 3 shows the HMI for the TE face/chest and lap/foot modules in the Volt. A separate control panel for the two front seats will be described later.



Figure 3. HMI in the center console of the Volt for auto TE control.

Contact TE Seat for Front Passengers

Both front seats are equipped with plume air delivery system. The air supply comes from the conditioned air from the main HVAC source. To effectively manage the air supply, booster fans are selected and fitted into the available space under the IP. Two booster fans were installed under the center IP area to draw the conditioned air from the main source. A schematic of the plume air is shown in Figure 4, where air streams exit from vents on both sides of the bolster and openings under the headrest.



Figure 4. Plume air delivery showing air directions.

For the Volt demonstration vehicle, a contact-based TE design is used for the seats. This is different from the more conventional ventilation-based TE design. In the ventilation TE design, air is blown across the TE surface (hot or cold) and exchanges heat with the TE before exiting through the vents. In the contact TE design, the TE surface (hot or cold) is in direct contact with the human body to improve the effectiveness of the heat transfer and to speed up attainment of the hot/cold sensation and comfort. It is even more important to use contact TE design in seating components since a large portion of human body is in contact with the seating surface and the majority of the contact body surfaces are closer to the core region of human body. The prototype contact TE seat performance was evaluated in a thermal chamber prior to the installation into the Volt. Figure 5 shows the performance of the contact TE seat in terms of “time to sensation” (TTS) and “time to comfort” (TTC). The TTS and TTC were counted from the initial soak condition at 50 °C to the time of the 1st sensible cool sensation and the time to

feel comfort. It demonstrates the contact TE seat is twice faster to reach both TTS and TTC than the ventilated TE seat and three times quicker to reach TTS than the ventilation seat. The TTS and TTC data are not available for the cold soaking although it is expected that similar performance can be achieved.

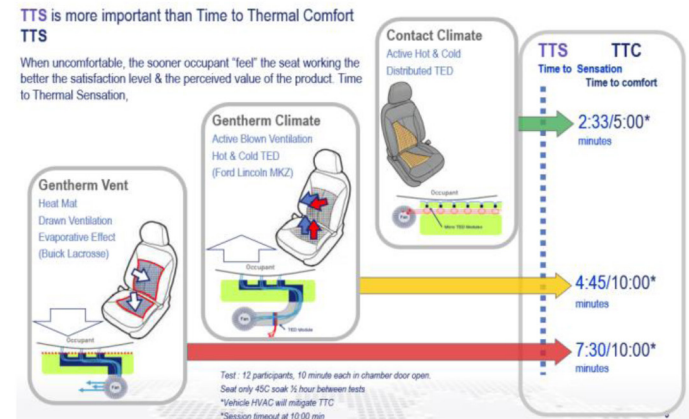


Figure 5. Comparison of the TTS and TTC of the contact TE seat to the ventilated TE and vent seats.



Figure 6. HMI in the center console for the contact TE seats.

Figure 6 shows the control HMI for the seats installed in the center console, one for the driver and one for the front passenger. The control of the contact TE seats were not integrated into the TE auto control system which includes both the face/chest and lap/foot TE modules as described before. The TE power setting for the seats were later calibrated through the human subject road tests for thermal comfort and the same setting was used in the tunnel for power consumption analysis and for manikin's EHT calculation.

Equivalent Thermal Comfort Establishment for the Integrated Volt Vehicle

Thermal Sensation and Thermal Comfort Rating

Subjective comfort rides were used to evaluate the capability of the TE HVAC system and the baseline HVAC. During the subjective comfort rides, a custom-designed survey tool for comfort evaluation was used to log the riders' evaluation of their comfort. The survey

employs two indices: thermal sensation and thermal Comfort [4, 5, 6, 7, 8, 9]. The rider's thermal sensation is his perception of the environmental temperature. The rider may feel cold if the temperature is low and he/she may feel hot if the temperature is high. From cold to hot, there are 9 gradations from -4 through 0 to +4, with -4 being the coldest and +4 the hottest. Similar to the thermal sensation scale, the thermal comfort scale also runs from -4 to +4, with -4 being most uncomfortable and +4 most comfortable. The thermal comfort rating describes the comfort state of the rider.

Open Road Test Ride

Road tests were conducted in Southeastern Michigan for 11 days during the winter time of 2014. Six human subjects participated during the tests for the ambient temperatures varying between 4 °F (-15 °C) and 40 °F (+4 °C). Each test started with the vehicle soaking in the open parking space for at least three hours. The focus of the road tests was to establish the ACC (automatic climate control) set temperature for the baseline HVAC and TE spot heating modes to reach equivalent thermal comfort at steady state. Each test ride lasts for one hour. Both the thermal sensation and comfort were recorded for both the driver and the front passenger during the one-hour long ride. The ridership during each ride was alternated between the driver and the front passenger position so that the final average values for the sensation and comfort were not biased toward individual or sitting location.

For the Volt, there are at least three HVAC climate control modes: (1) *Comfort mode*, where the priority is to provide excellent passenger comfort in the car; (2) *Economy mode (Eco mode)*, where the priority is to provide acceptable comfort at reduced battery power consumption; and finally, (3) *Ventilation mode* where the priority is to maximize driving range with minimal comfort. For the comfort evaluation on the road and also in the tunnel test, the Baseline was defined as turning on the main HVAC without TE devices by choosing the *Comfort mode*. The TE Eco mode was defined by turning on all the TE devices and using the *Eco mode*. The HVAC ACC control was used for both the Baseline and TE Eco modes. In the Volt HVAC control system, the *Eco mode* delivers at 50% of the air flow and the maximum heating power is kept at 50% of the *Comfort mode* to save battery energy.

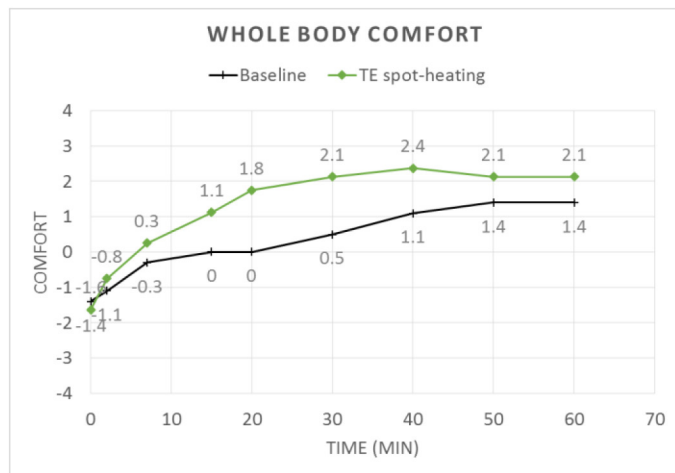


Figure 7. Transient whole body comfort for the Baseline and TE system.

Based on the early comfort test result in the tunnel for the Volt, the comfort for the Baseline can be achieved by setting the HVAC ACC temperature at 74 °F with *Comfort mode* in 0 °C ambient environment. This set temperature for the Baseline was then used on the road test. To match the comfort ride with the Baseline, the TE Eco mode with set temperature at 72 °F was tested.

Figure 7 shows the transient whole body comfort for the Baseline at 74 °F and TE Eco mode at 72 °F. The TE spot heating was very effective in quickly bringing up the whole body comfort index above 0 after 6 minutes, while the Baseline took 15 minutes to cross the zero threshold. In general, TE Eco mode at 72 °F exceeded the baseline in comfort. At the end of 60 minutes, the whole body comfort value for the TE Eco mode is 0.7 higher than the Baseline. Local sensation and comfort values for some selected body parts are shown in Figures 8 and 9 to highlight the effectiveness of the TEDs. The face and lap TE nozzles and contact TE seats all show better comfort (0.5 to 1 index higher) and warmer sensation (1 index higher) than the Baseline. Figures 10 and 11 show the sensation and comfort, respectively at steady state for all body parts. With the TE localized heating devices on, the comfort level at steady state is higher than the Baseline, especially for the back, gluteal and the lap, where the TE seats and lap nozzles are very effective in providing comfort.

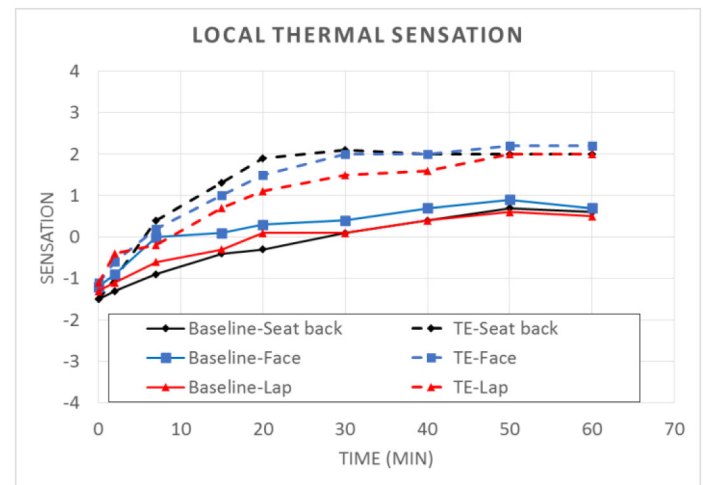


Figure 8. Transient local sensation for the Baseline and TE system.

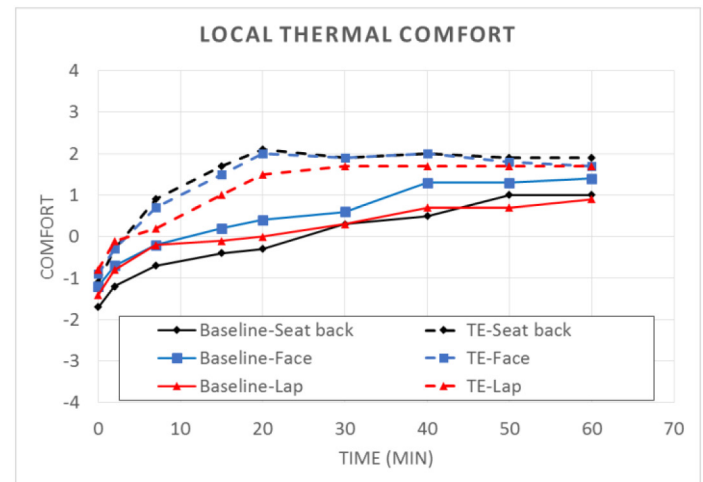


Figure 9. Transient local comfort for the Baseline and TE system.

The results shown are based on the average survey values for all road tests with ambient temperatures ranging from 4 °F (-15 °C) to 40 °F (+4 °C). Our conclusion during the road test was that the equivalent comfort can be established with Baseline at 74 °F and the TE Eco at 72 °F, with slightly more comfort toward the TE Eco side. The road test gave a subjective guideline before going into the climatic wind tunnel test for a more objective manikin comfort evaluation.

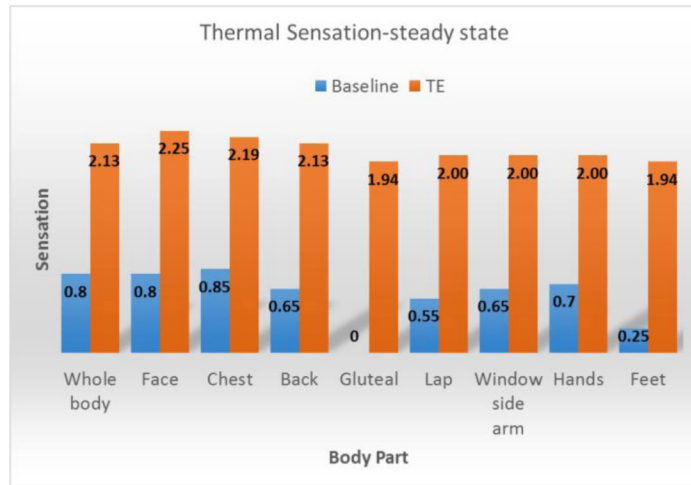


Figure 10. Steady state whole body sensation for the baseline (74 °F) and TE system (72 °F).

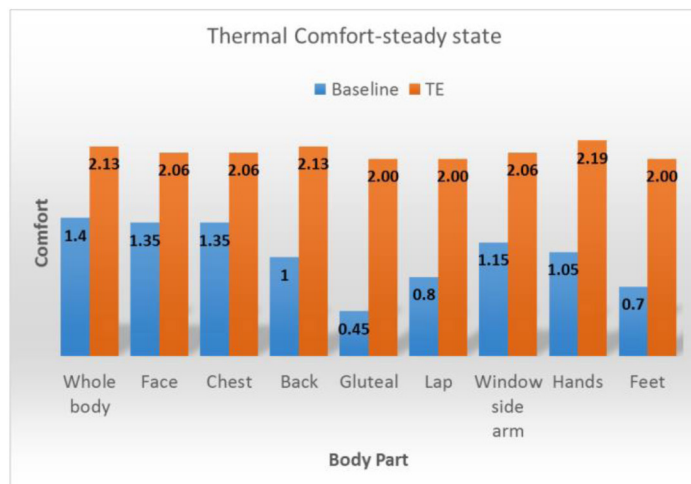


Figure 11. Steady state whole body comfort for the baseline (74 °F) and TE system (72 °F).

Climatic Wind Tunnel Test

The thermal manikin can provide an objective evaluation of the thermal comfort by measuring the Equivalent Homogeneous Temperature (EHT) in a well-controlled tunnel environment. The thermal manikin, Monika, provided by the University of California at Berkeley was used in GM's climatic wind tunnel to measure the EHT for the Baseline and TE Eco modes. Guided by the above mentioned human subject comfort rides, we were able to experiment several ACC set temperatures for both the Baseline and TE Eco modes to reach objective EHTs. Three ambient conditions were used in the tunnel test throughout the current evaluation. They are -10 °C × 80% RH, 0 °C × 80% RH and +10 °C × 20% RH. The vehicle speed was set at 50 kph. The tunnel tests were focused on the “cold” environment for the heating condition and the Volt was operated at EV (Electric Vehicle) mode exclusively for the energy saving

evaluation. At the EV mode, the cabin HVAC heating was solely provided by the CHCM only in the Volt. For the EV mode operation, since there is no engine waste heat, the spot heating provided by the TEDs can be more effective in maintaining equivalent thermal comfort while consuming less CHCM power. The thermal manikin is an objective tool to confirm the subjective road test comfort data and establish a clear equivalent comfort for energy evaluation. [Figure 12](#) shows the Volt in GM's CWT and EHT data collection.

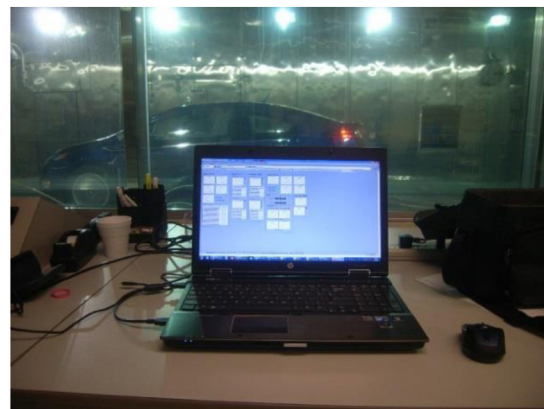


Figure 12. The Volt in GM's Climate Wind Tunnel and EHT data collection in the control room.

EHT Data from Thermal Manikin in the Tunnel

[Figure 13](#) shows Monika positioned in the front passenger position of the Volt with the proper winter clothing. She was equipped with heating elements under the skin and thermocouples for 16 body segments to calculate the EHT for each body segment and whole body. [Figure 14](#) shows the whole body EHT for various set temperatures for the Baseline with *Comfort mode* and *Eco mode*. Also the TE Eco mode at 71 °F is shown. The trend of the EHT's dependency on the set temperature and mode of HVAC operation can be clearly identified in [Figure 14](#). For the Baseline, the EHT shows a linear relationship with the set temperature. The slope with the *Comfort mode* is slightly higher than the *Eco mode*. It also clearly indicates that 71 °F TE Eco mode and the 74 °F Baseline reach the same whole body EHT of about 24 °C. Furthermore, the local EHTs for 16 body segments for both the 74 °F Baseline and 71 °F TE Eco mode are shown in [Figure 15](#), where higher EHTs on back, pelvis and thighs are the contribution from the contact TE seats and lap TE nozzles. The EHTs on the foot and lower leg areas are lower for the TE Eco mode comparing to the Baseline is due the fact that 50%

reduction of the air flow from the main HVAC and 50% energy cap from the CHCM heater in the *Eco mode*. However, with the addition of the local TE heating from the TE seats and lap TE nozzles, the resulting whole body EHT for the TE Eco mode is 24.05 °C which is very close to the 23.95 °C reported for the Baseline at 74 °F set temperature. The conclusion of the manikin test is that a clear equivalent EHT of 24 °C was established for the Baseline at 74 °F and TE Eco at 71 °F in the tunnel.

From the road test, we have shown that the 72 °F TE Eco mode is more comfort (0.7 index higher) and warmer than the 74 °F Baseline as seen in [Figures 7 and 11](#). The Monika's EHT data reconfirmed this and is consistent with the subjective road test. Therefore, based on the subjective comfort tests on the road and the objective thermal manikin data in the tunnel, we have clearly established the equivalent thermal comfort for the Volt demonstration vehicle for the spot heating condition in winter driving. The energy saving calculation for the winter driving will be based on the 74 °F Baseline comfort mode and the 71 °F TE Eco mode.



Figure 13. The thermal manikin, Monika, is positioned in the front passenger seat.

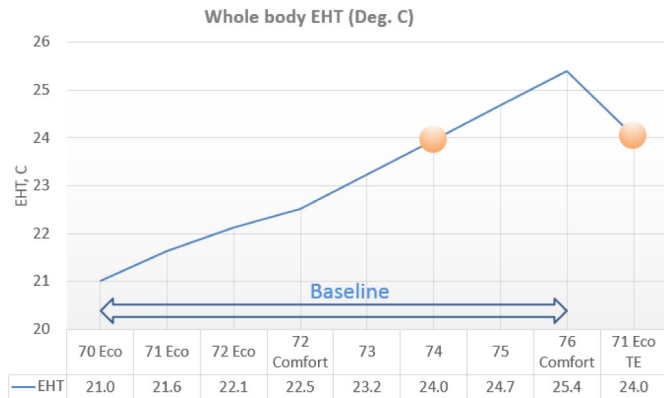


Figure 14. Whole body EHT for various comfort and Eco modes.

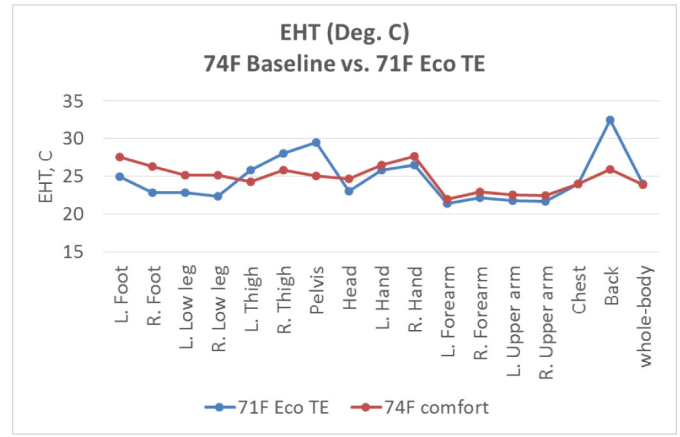


Figure 15. Whole body and local EHTs for the 74 °F Baseline and 71 °F TE Eco mode.

TE HVAC System Energy Efficiency

Power Consumption Test and Analysis Method

A focused effort has been made to provide the initial energy efficiency assessment of the TE HVAC System in comparison with the Baseline HVAC system of the Volt vehicle. Generally speaking, the energy efficiency assessment is based on the steady state tunnel test data. It is understood that energy saving is available during the transient operations of the vehicle, however, due to the complexity of test protocols, drive cycle variation and concerns about repeatability, presently only the steady state energy saving is examined.

Since the Volt is an Extended Range Electric Vehicle (EREV), it relies on the on-board battery to provide power to heat and cool the cabin in an EV mode. In our previous study for the traditional gas powered vehicle [1, 2, 3], the TE HVAC system's energy impact has been demonstrated for the Lacrosse for cooling conditions with an annualized occupancy weighted saving of 29% over the Baseline HVAC system. However, the energy saving impact of TE HVAC system in heating mode could not be demonstrated in Lacrosse because the main heating source came from the waste heat of the IC engine. Therefore for the Volt, the tunnel test and power consumption measurement were focused on the heating condition for the vehicle operating under the pure EV mode, where the heating was provided by a 5 KW electric heater (CHCM). The primary interest in energy efficiency assessment is in the area of reducing the CHCM power usage while maintaining thermal comfort. For the cooling energy calculation, the energy saving reported for the Lacrosse vehicle [3] was used for the Volt with a correction factor of the AC compressor power based on the cabin volume and the window glass area exposure to solar load between the two vehicles. This was justified based on the fact that the TEDs used in the Volt demonstration vehicle are identical to the Lacrosse except the front seats where contact TE seats are used in the Volt in contrast to the ventilated TE seat used in Lacrosse.

To distinguish the energy impact of the TE HVAC system on the heating for the Volt, two power consumption numbers, one for the heating and the other for the cooling are reported. They are defined based on the following ambient temperature:

1. Heating operation calculation: 10 °C and below for the ambient temperature
2. Cooling operation calculation: 10 °C and above for the ambient temperature

For the EV heating mode, the Baseline power consumption for the HVAC system includes the CHCM and the HVAC blower power. For the TE HVAC system power consumption, the power use by the TE modules is included. The TE module power use is broken down to component power use by the TE devices, TE module fans, the coolant pumps, contact TE seats (and TE seat fan) and CHCM power for the TE coolant. These power uses are subsequently added to the HVAC system power use to obtain the TE HVAC system power use and is to be compared with the Baseline HVAC system power use.

For both the Baseline and the TE HVAC system, miscellaneous power use by the Campbell data logger and the TE HVAC controller are not included.

The total TE system power consumptions are further allocated to each passenger in the vehicle. Due to the capability to be turned off, unoccupied seats do not consume any power. For the front seats, which share the same coolant pump, power consumption by the pump is divided between the two front seats. It is expected that when there is only the driver in the seat, coolant pump flow rate may be halved to reduce pump power consumption.

The electrical power consumed for each passenger location is then combined with the CHCM and HVAC blower power to form three different occupancy scenarios: driver only, driver and front passenger, and four passengers. It is noted that to account for the TE power use for the four passengers, the TE power from the two front passengers were added to form the total TE power use for four passengers despite the fact that there was no TEDs used for the rear passengers in the Volt.

From the test point of view, no separate tests were performed for each of the occupancy scenarios. For a given ambient condition, the vehicle is tested with all front TE seats switched on. The power consumption scenarios of one, two and four occupants are based on the allocated power to each occupant. For example, for the driver only case, the allocated power to the driver is added to the CHCM and HVAC blower power use to achieve the total TE HVAC system power, with the power allocated to the other seats ignored.

The tunnel tests for the Volt were conducted at three ambient temperatures at -10 °C, 0 °C and 10 °C, respectively for heating operation to measure the energy usage for 74 °F Baseline and 71 °F TE Eco mode.

Power Saving Projection

Based on the tunnel energy data measurement for the heating condition (below 10 °C) for the ambient temperature at -10 °C, 0 °C and 10 °C for the Volt and the cooling energy calculation (above 10 °C) from the Lacrosse's data with proper AC power scaling for the Volt, the power consumption for the entire ambient sweep is shown in [Figure 16](#) under equivalent comfort standard.

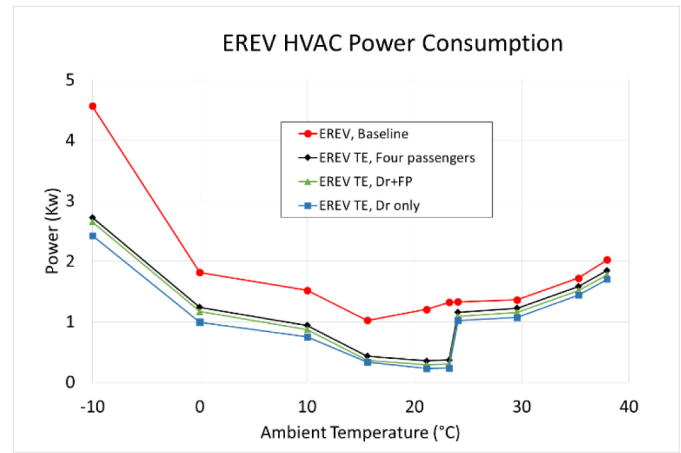


Figure 16. Volt power consumption for Baseline and TE Eco mode with three occupancy configurations.

The TE HVAC system power consumptions were further categorized into driver only, driver and front passenger, and a fully occupied vehicle with four passengers. It is seen that the Baseline vehicle has the highest power consumption. Next in the sequence is the TE HVAC system with four passengers, followed by driver and front passenger, and the lowest amount of power consumption is obtained when the car has the driver only.

In order to provide an energy saving estimate for the whole season of the A/C operation for the cooling (ambient temperature greater than 10 °C) in a single year, the A/C usage data in [Figure 17](#) is used to generate a weighted average of the A/C power use [3]. This weighting was based on the SAE GREEN-MAC-LCCP [10] climatic weighting. Similarly, [Figure 18](#) shows the weighted average of the heater power usage during heating operation according to the statistics in Chicago area.

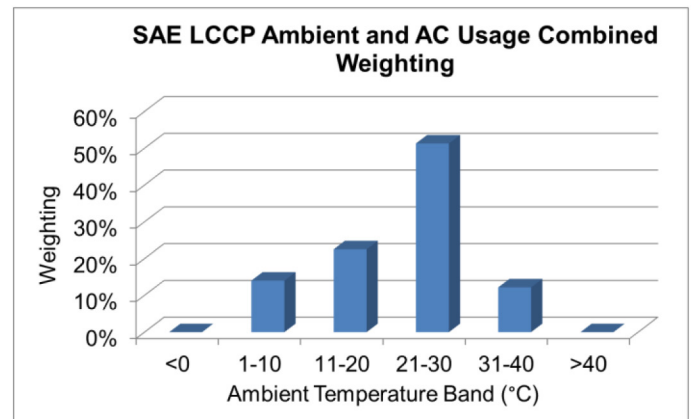


Figure 17. Ambient weighting factors used to calculate annualized cooling energy savings (ambient temperature > 10 °C).

Additional weighting of the power usage data was based on vehicle occupancy. The vehicle occupancy weight represents the probability of a car having one, two, three, or four passengers when it goes out on a trip. [Figure 19](#) shows the data based on a report submitted to the City of Lincoln, Nebraska by the Schemmer Associates in 2005 [11]. It shows that up to 70% of the time a car was observed to have one occupant - the driver only. 20% of the time there were the driver and an additional passenger in the car. Only 10% or less of the vehicles came with more than three passengers in the car.

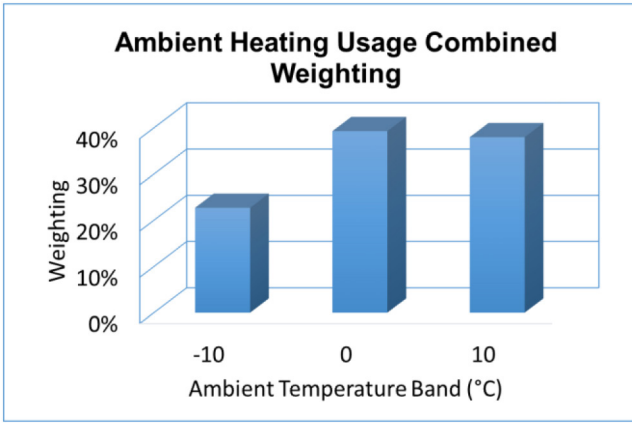


Figure 18. Ambient weighting factors used to calculate annualized heating energy savings (ambient temperature < 10 °C).

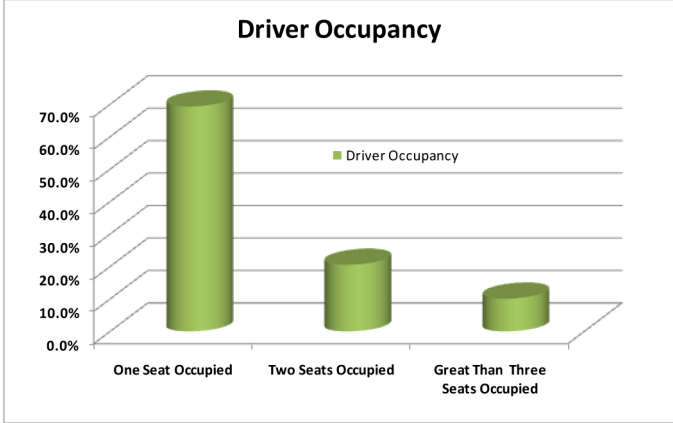


Figure 19. Weighting factors used to calculate annualized energy savings - occupancy weighting.

Similar to the annualized energy saving calculation for the Lacrosse [3], the same formula was used:

$$p = \sum_i (\sum_j P_{ij} W_a^j) W_o^i$$

Where, W_a^j represents the ambient weighting (% of occurrence) over a given set of ambient temperatures, W_o^i is the occupancy weightings, and P_{ij} represent the overall system power consumption under a given ambient and occupancy scenario. For ambient temperature between 10 °C and 23 °C, the compressor is completely shut down and all TEDs alone can maintain occupant comfort to achieve high energy efficiency except for high solar load and/or high humidity that require compressor to be restarted to ensure comfort and safety. So the compressor power saving during this ambient temperature needs to be deducted when restarting occurs. Based on one of the analysis by NREL for “Typical Meteorological Year Database V3”, 49% Restart Rate for a Climatic Average US City (Topeka, KS, or Philadelphia, PA) is adopted. So in the range of 10 °C ~ 23 °C, 51% of compressor shutdown power saving is applied in annualized power calculation.

For the Baseline HVAC system, since the power consumption does not directly depend on the number of passengers in the car, only ambient condition weighted average needs to be applied.

With the power usage data presented in Figure 16, and the weightings presented in Figures 17, 18 and 19, the steady state power consumption saving for both cooling and heating modes are as follows:

- For heating energy saving calculation (ambient temperature < 10 °C): The Baseline vehicle averaged over the operating season is 1.702 KW and 1.06 KW for the TE HVAC system. This represents an estimated saving of about 37.7%.
- For cooling energy saving calculation (ambient temperature > 10 °C): The Baseline vehicle averaged over the operating season is 1.374 KW and 0.87 KW for the TE HVAC system. This represents an estimated saving of about 36.7%.

It is expected that further system optimization should provide improved energy saving.

Summary and Conclusions

The key objective of the present paper was to explore the implementation of TE modules as heating components for an electric or an EREV operated in pure EV mode, and a TE HVAC system that utilizes these TE modules to provide spot heating or cooling. Working in conjunction with the traditional HVAC system to provide equivalent comfort, significant improvement in energy efficiency is improved with the TE HVAC system.

Vehicle testing in the climatic wind tunnel demonstrated that the TE HVAC system can supplement the traditional HVAC system to achieve the objective of “equivalent comfort” while providing energy saving. Equivalent comfort has been demonstrated for spot heating for the Volt operating in pure EV mode. The CHCM heater power saving during spot heating has been estimated to be at 37.7% and compressor power saving during spot cooling at 36.7%. It is estimated that further optimization of the TE HVAC system should provide better energy saving. Depending on the extent of the driving range loss due to HVAC usage for winter heating and summer cooling, the energy savings provided by the TE HVAC system can improve the driving range by up to 6 miles over the Baseline system.

The main challenge to commercialize the demonstrated TE HVAC system lies in the added packaging complexity and the additional cost. It is conceivable that TE spot cooling and heating systems may be first introduced into luxury vehicles to enhance passenger comfort, as has been the case with the TE heated seat technologies, and possibly into electric vehicles to help extend the battery driving range. As thermoelectric device technology improves in terms of its figure of merit, and as its manufacturing process achieves further cost reduction, TE spot cooling and heating may become more commercially competitive. In the near term, carefully considered, selective application of the TE spot cooling and heating to assist traditional HVAC system may be viable and beneficial in providing occupant comfort and energy efficiency.

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Definitions/Abbreviations

A/C - Air Conditioning
ACC - Automatic Climate Control
CFD - Computational Fluid Dynamics
CFM - Cubic Feet per Minute
CHCM - Cabin Heating and Cooling Module
EHT - Equivalent Homogeneous Temperature
HVAC - Heating Ventilation and Air Conditioning
HMI - Human-Machine Interface
Kph - Kilometer per hour
LCCP - Life Cycle Climate Performance
PWM - Pulse Width Modulation
RH - Relative Humidity
TE - Thermoelectric

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