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Evaluation of Advanced Automotive Seats to Improve Thermal Comfort and Fuel Economy

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ABSTRACT

Automotive ancillary loads have a significant impact on the fuel economy of both conventional and advanced vehicles. Improving the delivery methods for conditioned air is an effective way to increase thermal comfort at little energy cost, resulting in reduced air-conditioning needs and fuel use. Automotive seats are well suited for effective delivery of conditioned air due to their large contact area with and close proximity to the occupants. Normally a seat acts as a thermal insulator, increasing skin temperatures and reducing evaporative cooling of sweat. Ventilating a seat has low energy costs and eliminates this insulating effect while increasing evaporative cooling. The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) has applied a combination of experimental testing and modeling to quantify improved thermal comfort and potential fuel savings by using a ventilated seat. The thermal comfort improvement can be used to reduce the A/C heat capacity by 4%, resulting in a predicted A/C fuel use reduction of 2.8% on an EPA highway cycle and 4.5% on an EPA city cycle. This is a 0.3%-0.5% reduction in total vehicle fuel use when the A/C system is on; while modest for an individual car, the potential fuel savings is significant on a national level.

INTRODUCTION

An operating air-conditioning (A/C) system is currently the largest ancillary load on automobile engines, negatively impacting both fuel economy and tailpipe emissions. In a conventional vehicle, A/C use can decrease vehicle fuel economy by 21%-24% over a Unified Cycle (California ARB inventory test cycle). Vehicle tests, over the Unified Drive Cycle, indicate oxides of nitrogen (NO_X) and carbon monoxide (CO) increases of 13%-66% and 60%-120% respectively [1]. These effects are even larger for advanced high efficiency vehicles. On a national level, the impact of air-conditioning fuel use is immense. A recent study estimates that the United States uses 26.4 billion liters (7.0 billion gallons) of gasoline for automotive air-conditioning; equivalent to 9.5% of U.S. imported crude oil [2].

NREL supports a three-part approach to A/C fuel use reduction: reducing the thermal load, improving delivery of conditioned air to enhance thermal comfort, and increasing the efficiency of equipment. This paper focuses on efficient delivery through the use of advanced automotive seat concepts. Improving the delivery methods for conditioned air is an effective way to increase thermal comfort with little energy cost. This reduces air-conditioning needs, and thus fuel use. In order to evaluate climate control delivery methods, the Vehicle Climate Control Laboratory (VCCL) was developed to allow rapid and repeatable evaluation of occupant thermal comfort response to advanced climate control systems in a controlled, asymmetrical, thermal environment; allowing researchers to estimate impacts on thermal comfort and fuel economy.

Automotive seats are well suited for effective delivery of conditioned air due to their large contact area with and close proximity to the occupants. Normally a seat acts as a thermal insulator, increasing skin temperatures and reducing evaporative cooling of sweat. Ventilating a seat has low energy costs and eliminates this insulating effect while increasing evaporative cooling. Mesh seats use no additional energy and have similar benefits. Both of these technologies were evaluated.

Increasing local heat loss and better targeting of body segments with large contributions to thermal comfort can offset the effects of higher cabin temperature. When efficient delivery methods result in equivalent thermal comfort at higher cabin temperature, the air-conditioning load is reduced, and fuel savings can be achieved.

A combination of experimentation and modeling was used to estimate the potential impact of these advanced automotive seat technologies on thermal comfort and fuel economy.

EXPERIMENTAL METHODS

OVERVIEW

The Vehicle Climate Control Laboratory (VCCL) at the National Renewable Energy Laboratory (NREL) was developed to simulate the soak and cool-down of a vehicle passenger compartment (Figure 1). The passenger compartment from a compact car, A to C pillar, was heat soaked using a 963 W/m^2 ± 23% full spectrum solar simulator for 3.5 hours. During this time, the average room environment was controlled to 31.6°C ± 0.4°C and 30% ± 5% RH. The subject entered the heat soaked room, stood for 30 seconds, and then did step exercises for one minute to simulate walking to the car. The subject entered the heat soaked car and took a pre-cool-down thermal comfort and sensation vote. The air-conditioning system was started 45 seconds after the subject entered the vehicle, at which time the first cool-down vote was taken. Thermal comfort and sensation votes followed every two minutes for the duration of the test. Surface and air temperatures, solar irradiance, humidity, and A/C inlet velocity through the cowl were measured during the test.

Temperatures were taken at over 80 locations, measuring both room and passenger cabin conditions. Concentric cylinder radiation shields were used for passenger compartment air temperature measurements. Eight thermocouples were sewn to the surface of the driver seat to measure the contact temperature between it and the occupant. Surface temperature probes were attached using thermal epoxy, and large thermal gradients near the point of contact were minimized. The cabin interior velocities and A/C inlet velocity profile into the cowl were characterized for the setup after the cool-down tests were completed and assumed to be constant for the test.

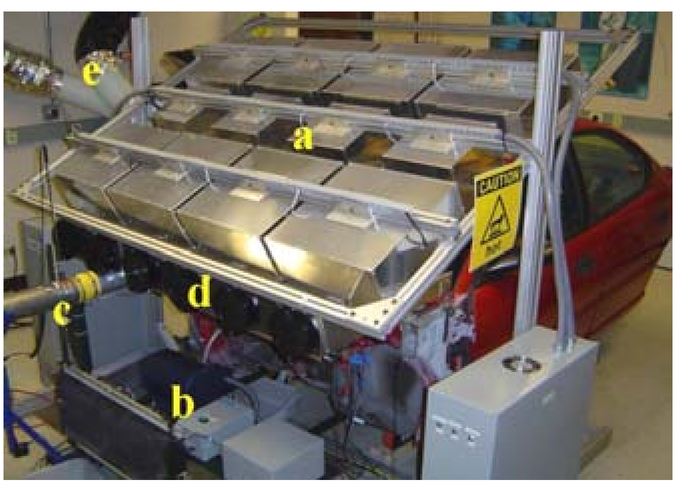

Figure 1: Vehicle Climate Control Laboratory (VCCL)

LABORATORY COMPONENTS

The solar simulator, "a" in Figure 1, has a mean irradiance of 963 W/m^2 ± 23% as shown in Figure 2.

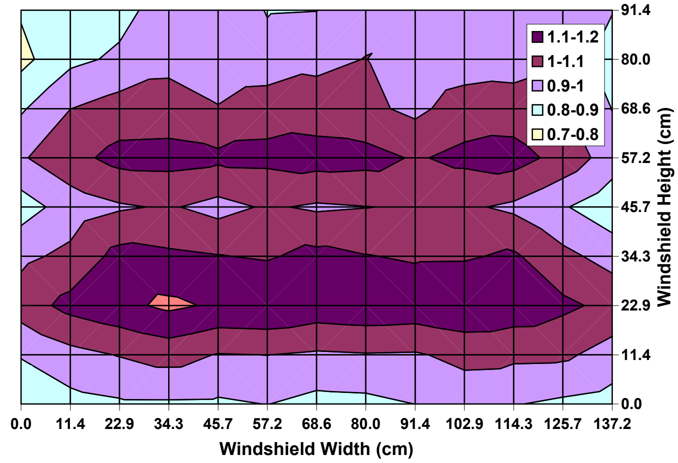

Figure 2: Solar Simulator Normalized Irradiance = 963 W/m^2 ±23%

The mean irradiance was determined from an ASTM standard for solar spectral irradiance [3, 4]. Metal halide lamps were used to approximate the solar spectrum shown in Figure 3. Although not as accurate as xenon lamps, complexity and cost issues made metal halide lamps the best choice.

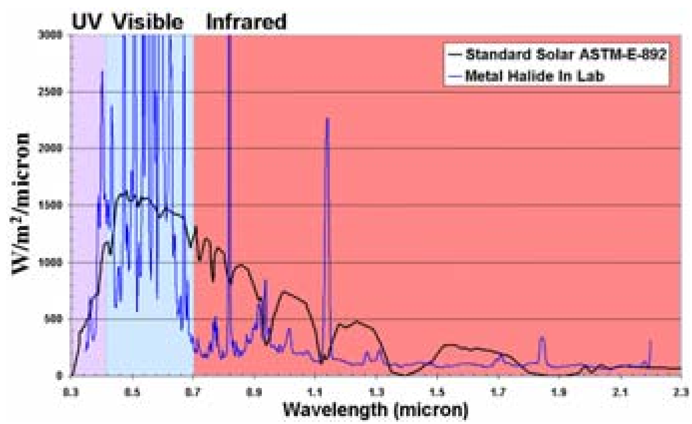

Figure 3: Metal Halide Spectral Distribution Compared to Standard Solar Spectrum

Collimation of the light was not addressed because the primary purpose of the simulator was thermal loading. The front of the car was illuminated because this was the area of primary interest for this study and it was necessary to limit cost and complexity. The solar simulator was designed by measuring the irradiance profile of one lamp and then modeled by superposition, combining multiple profiles to estimate the complete array. This allowed determination of the estimated lamp number, size, distance, and spacing. The procedure is similar to that used by Kenny and Davidson [5]. A total of eight 1000 W lamps were used, with four across the top and bottom. Four, 400 W lamps were used in the center to fill holes in the irradiance distribution. After construction, the array spacing parameters were adjusted experimentally to refine the distribution and account for lamp and bulb variations. The final array irradiance was measured with a grid spacing of 4.5-inch (11.43-cm) across both the width and height of the windshield illumination plane.

Air-conditioning was simulated using an actual system, and the belt was driven by an electric motor, “b” in Figure 1. The motor was run at a constant 2300 rpm, the approximate average engine speed of a compact car over a US06 drive cycle. The change in thermodynamic state was measured across the evaporator air side to allow calculation of heat removal as discussed in the analysis section. To prevent overcooling and freezing of the evaporator, dead-band control of the evaporator exit temperature was used, resulting in an average steady-state vent exit temperature of 8.2 ºC ± 0.4 ºC. A fabricated duct connected the cowl inlet to a 4-inch (10.16-cm) diameter tube. After an 11.5 diameter entrance length, the inlet velocity through the tube was measured transversely in both the vertical and horizontal directions in 0.5-inch (1.27-cm) increments. The hot-wire anemometer calibration is NIST traceable to ±3%, and the probe was held in place with a testing jig, “c” in Figure 1, to minimize variation.

A wind-flow simulator, “d” in Figure 1, was designed and built to blow air across the windshield, correcting for overheating due to lack of re-radiation and ambient air movement. The impact of the wind simulation on vehicle temperatures is shown in Figure 4. The re-radiation effect is an inherent short-coming of indoor testing as discussed by Rugh and Malaney [6].

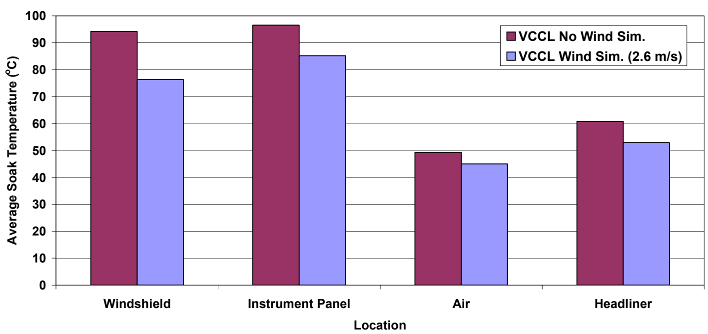

Figure 4: VCCL Wind Simulation (2.6 m/s) Compared to No Wind Simulation

The average steady-state room temperature was controlled to 31.6 ± 0.4°C. It should be noted that larger spatial variation existed in the room. The average relative humidity of the room was controlled to 30% ± 5% using PID controls. The thermocouples were calibrated to ±0.15°C using a Hart Scientific 7103 micro-bath and a reference probe calibrated through the whole data-acquisition system to NIST traceable standards. The pyranometers were calibrated by NREL’s metrology department to ±2.5%, and the humidity sensors came with a NIST traceable calibration of ±2%.

The thermal sensation and comfort scales used are similar to the ASHRAE seven-point scale and were developed at U.C. Berkeley [7]. The sensation scale used ranges from very cold (1) to very hot (9) and the comfort scale ranges from very uncomfortable (1) to very comfortable (9), as illustrated in Figure 5 below.

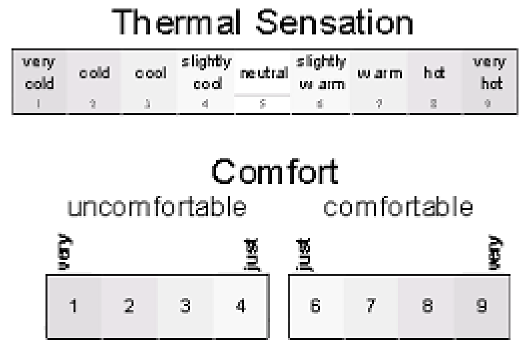

Figure 5: U.C. Berkeley Thermal Sensation and Comfort Scales [7]

The comfort scale has a break in the middle forcing subjects to be either “just uncomfortable” or “just comfortable”. It should be noted that unlike the scale used, UC Berkeley’s current scale is shifted to be centered around zero. Thermal sensation and comfort votes were taken for overall, head, chest, back, arms, legs, and feet with no distinction between right and left. Increments of 0.5 were used and subjects were not allowed to look back at previous votes. The standard test clothing consisted of a cotton short-sleeve polo shirt, kaki pants, socks, and shoes.

LABORATORY PERFORMANCE

To check the realism of passenger cabin soak temperatures, soak data was compared to previous on-site outdoor vehicle testing. The results in Figure 6 show good correlation and similar temperature distributions. It is important to note that, while similar, the identical environmental conditions were not simulated, and the vehicle geometries were significantly different.

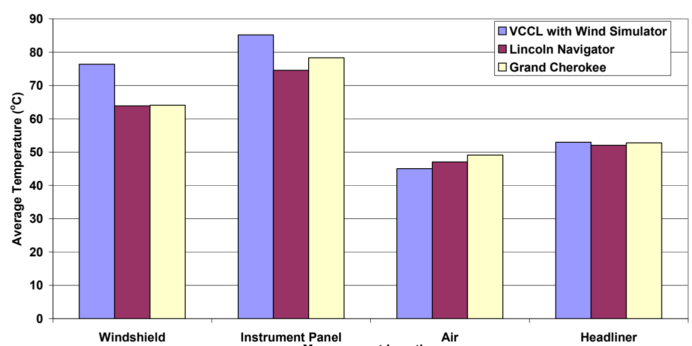

Figure 6: VCCL Baseline with Wind Simulator Compared to Outdoor Testing

In addition to realism, the repeatability of the VCCL cool-down was verified. Figure 7 shows the mean and standard deviation results for five tests using the same settings but on different days.

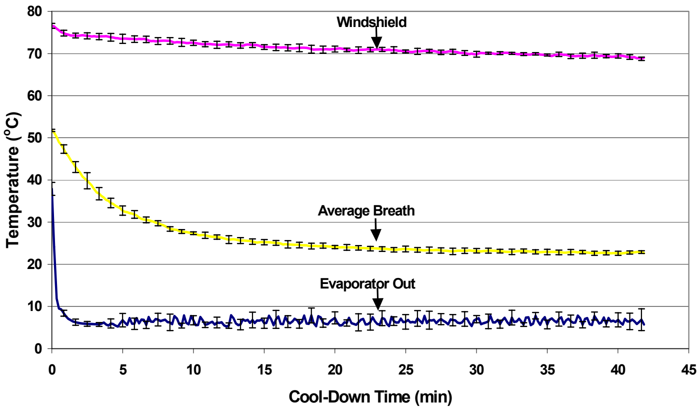

Figure 7: Sample VCCL Baseline Cool-Down Temperature, Five-Test Mean with Std. Dev. Bars for Every 5th Point

ADVANCED SEAT CONCEPTS

An existing automotive seat was modified for ventilation as shown in Figure 8. Two fans were installed in the seat back and seat bottom. A coarse spacer was used between the fan exits to prevent flow blockage and allow initial diffusion. A fine diffusion layer then further diffuses airflow, which passes through a porous seat cover. At maximum flow, the four fans together consumed 9 watts of power.

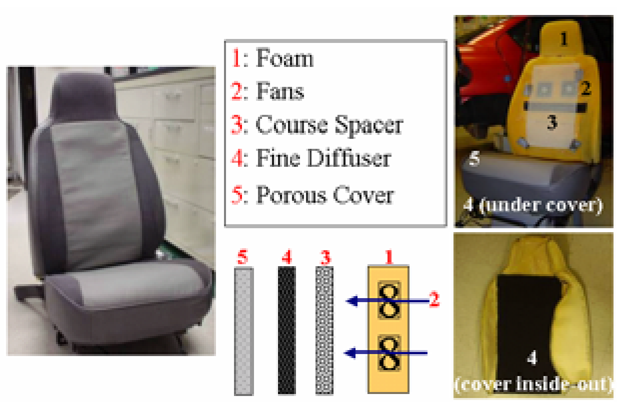

Figure 8: Ventilated Seat Schematic

The mesh back, low mass prototype test seat is from an automotive OEM. The back of the seat is constructed from a tension drawn low mass porous fabric. The bottom of the seat is similar to a standard automotive seat.

ANALYSIS

A/C POWER CALCULATION

The heat removal of the air-conditioning system was modeled as 1-D steady-flow. The dry air and water vapor were treated as ideal gases. The kinetic and potential energy changes were assumed negligible. A control surface was defined around the A/C evaporator, giving an overall energy balance [8]:

$$\dot{Q}_{ac} = \dot{m}_{air,evap}\,\Delta h_{air,evap} - \dot{m}_{water,cond}\,h_{water,cond} \quad (1)$$

Where:

$\dot{Q}_{ac}$ = heat removed from air-stream by A/C system [kW]

$\dot{m}$ = mass flow rate [kg/s]

air,evap = air flowing through the evaporator
water, cond = water condensed out of the air

The enthalpy was calculated using:

$$h = h_{air} + wh_g \text{ [kJ/kg dry air]} \quad (2)$$

$$h_{air}(T) \cong C_p T \text{ [kJ/kg]} \quad (3)$$

$$h_v(T) \cong h_g(T) \cong 2501.3 + 1.82T \text{ [kJ/kg] T in °C} \quad (4)$$

Where:

h = enthalpy

C_p = 1.005 kJ/(kg-°C)

w = specific humidity

v = water vapor

g = saturated water vapor at same temperature as v

See reference [8] for further discussion of these approximations.

The water mass balance is:

$$\dot{m}_{water,cond} = \dot{m}_{air,evap}(w_{evap,in} - w_{evap,out}) \quad (5)$$

Specific humidity was calculated using:

$$w = \frac{0.622P_v}{P - P_v} \quad (6)$$

Where:

P = Absolute atmospheric pressure [kPa]

P_v = $\phi_{in} P_{Sat,in}$ for inlet and $P_{Sat,out}$ for outlet [kPa]

ϕ = Relative humidity

The outlet humidity was not measured during the cool-down tests. It was assumed that before condensation, the outlet specific humidity equaled the inlet specific humidity. Once condensation started, the outlet specific humidity was assumed equal to the saturation specific humidity. That is to say, once condensation started, the outlet relative humidity was assumed to be at 100%. Condensation occurs when the saturation specific humidity $w_{Sat,Out}$, based on evaporator exit temperature, drops below the inlet specific humidity.

Testing of this assumption showed that the errors were small and restricted to a short time during transient cool-down. Additionally, the errors were repeatable and thus largely canceled out during comparison.

The mass flow rate was calculated from the average measured velocity and inner tube diameter. It should be noted that the hotwire anemometer used measures standard velocity; therefore, the density of air at standard conditions was used to calculate mass flow.

The air-conditioning heat removal was controlled by adjusting the flow rate of air through the evaporator.

A/C FUEL USE

The average calculated A/C power use was applied as a steady load to a vehicle in ADVISOR© software over EPA City and Highway cycles. A "composite" compact car model was chosen to appropriately match the size of the vehicle to the tested A/C system. This model was created using sales weighted average component characteristics from the top three selling US compact cars: the Civic, Focus, and Cavalier [9]. A system Coefficient of Performance (COP) of 1.8 was assumed, including compressor efficiency losses [10]. The belt efficiency and alternator efficiency (for seat power) were assumed to be 95% and 85% respectively. Power for one ventilated seat was included.

RESULTS

Cool-down tests were performed for a baseline and two reduced air-conditioning settings with the ventilated seat on. The average cool-down occupant seat contact temperatures are shown in Figure 9. At 96% heat removal capacity and with the ventilated seat on high, a multiple test average steady-state reduction in seat contact temperature of 3.5 ± 0.9°C from the baseline was seen. At 90% heat capacity, the multiple test average temperature reduction gets smaller as shown in Figure 9. The smaller temperature reduction can be attributed to reduced heat loss from the body at the elevated cabin temperature.

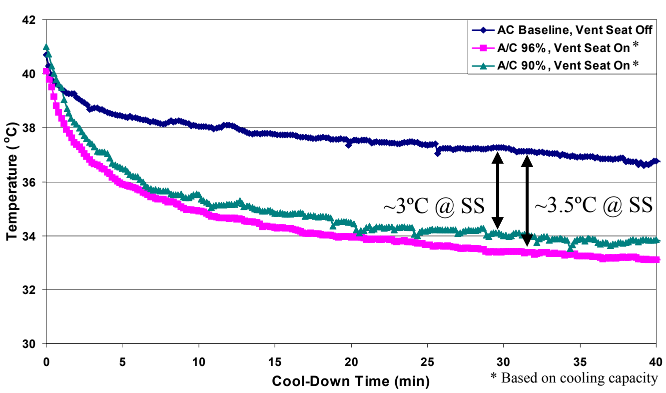

Figure 9: Reduced Average Driver Seat Contact Temperature

The decrease in back temperature resulted in a substantial improvement in back thermal comfort. Figure 10 shows decreased time to achieve a higher level of back thermal comfort when using a ventilated seat with a 96% heat capacity A/C system. Once the back thermal comfort peak is reached, the comfort level begins to fall, eventually resulting in overcooling of the back.

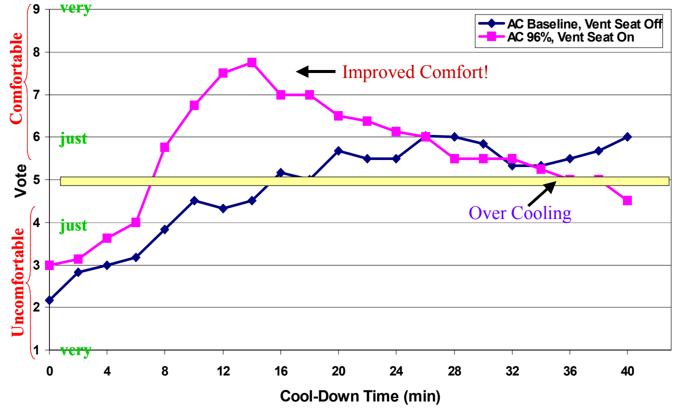

Figure 10: Improved Average Back Thermal Comfort Using a Ventilated Seat

It should be noted that the back is the fourth entry on the vote sheet, so the seat and A/C system had been on for approximately 15-20 seconds before the first cool-down vote was taken for that segment. This time lag could explain the initial vote difference.

The extent to which improvement in back thermal comfort affects the overall thermal comfort is not as clear. Figure 11 indicates approximately the same level or better thermal comfort achieved by using the ventilated seat with the A/C system heat capacity reduced by 4%. In both Figure 10 and Figure 11, a thermal comfort peak is reached and then thermal comfort begins to decrease. The first part of this decrease is due to the nature of thermal comfort. A change in thermal condition is needed to achieve responses above "just comfortable". That is to say, you need to be uncomfortable immediately before feeling "very comfortable". Once the transient change of thermal state is completed, the person returns to a "just comfortable" condition. As the person's rate of heat loss continues to increase with decreasing cabin temperatures, they begin to get over-cooled, resulting in decreasing comfort votes.

This 4% decrease in heat capacity resulting in equivalent thermal comfort when using a ventilated seat, results in a 1 ºC ± 0.7 ºC increase in average steady-state breath temperature shown in Figure 12.

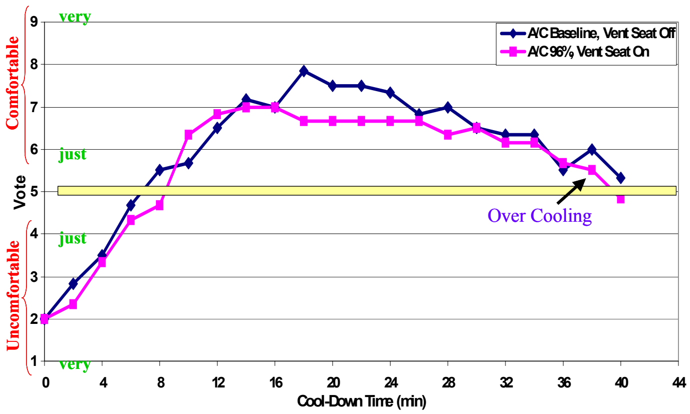

Figure 11: Maintained Overall Thermal Comfort at Reduced Load with Ventilated Seat

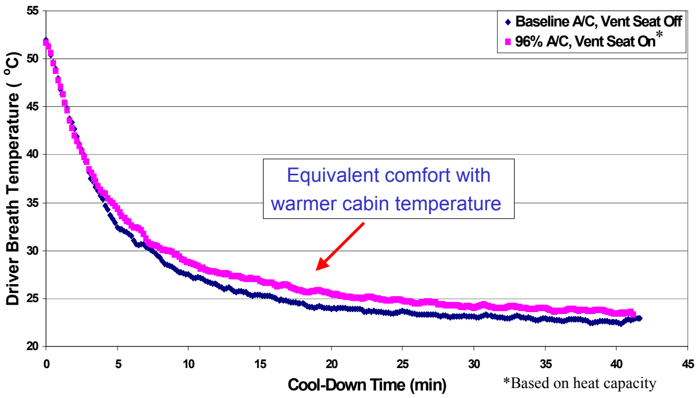

Figure 12: Equivalent Thermal Comfort with Warmer Driver Breath Temperature

The ventilated seat used in this testing, however, has not been optimized. As confidence in the overall thermal comfort impacts and the seat design improves, it is believed that a larger allowed cabin temperature will be shown.

The prototype mesh back seat also shows promising results. The mesh back seat, with a 96% heat capacity A/C system, resulted in an average steady-state reduction in seat back temperature of 4°C and seat bottom temperature of 0.6°C, giving a seat average temperature reduction of 2.3°C. Limited data did not allow for meaningful uncertainty estimation. It can be reasonably assumed that a mesh bottom would give similar results to the mesh back. In that case, much of the thermal benefit gained through the use of ventilated seats can be achieved using low mass mesh seats without any energy demands. The disadvantages of the mesh seat include: lack of control, especially during winter months, as well as mechanical comfort and safety considerations. The interface between the mesh and the supporting structure can also cause unpleasant thermal gradients.

These results show promising thermal comfort improvement trends; however, it must be noted that they are based on limited subjective data. Subjective data shows large variations between tests and people. Insufficient data is currently available for statistical analysis. The original intent of this work was to use the thermal data from experimentation to model thermal comfort and check it with subjective votes. Efforts to model the thermal comfort effects of advanced automotive seats have encountered challenges. Work is ongoing to increase confidence and improve quantification of thermal comfort and sensation impacts both through modeling and experimentation.

The thermal comfort improvement due to these advanced seat concepts can lead to significant air-conditioning fuel use reductions. Allowing the heat capacity of the air-conditioning system to decrease by 4% resulted in an estimated A/C fuel use reduction of 2.8% on an EPA highway cycle and 4.5% on an EPA city cycle. This reduction in A/C fuel use translates into a 0.3%-0.5% reduction in total vehicle fuel use when the A/C system is on. With over 213 million light duty vehicles in the United States [11], this modest individual car fuel savings would result in a substantial reduction in national fuel use. It is believed that this national fuel savings will increase even further as confidence in the overall thermal comfort impacts and the seat design are improved.

CONCLUSION

NREL has developed a Vehicle Climate Control Laboratory (VCCL) to allow rapid and repeatable evaluation of occupant thermal comfort response to advanced climate control systems in a controlled, asymmetrical, thermal environment; enabling the estimation of impacts on thermal comfort and fuel economy.

Using a combination of experimental testing and modeling, researchers quantified improved thermal comfort and potential fuel savings due to ventilated seats. The ventilated seat decreased steady-state seat contact temperature by 3.5°C ± 0.9°C and increased back thermal comfort. A low mass mesh back seat was also shown to reduce back temperature by approximately 4°C. Subjective jury data has been used to show trends. These trends show that the cooling capacity of the air-conditioning system can be reduced by 4% while maintaining thermal comfort through the use of a ventilated seat. Using ADVISOR© software, the reduction in A/C cooling capacity can be translated into a reduction of compact car A/C fuel use by 2.8% on an EPA highway cycle and 4.5% on an EPA city cycle. This is a 0.3%-0.5% reduction in vehicle fuel use when the A/C system is on. While this reduction is modest for an individual car, the potential fuel savings is significant on a national level.

This project demonstrates the potential of ventilated seats for improving delivery of conditioned air, increasing thermal comfort, and reducing air-conditioning loads. Optimizing ventilated seat design and integrating these seats with other advanced delivery methods shows promise to further reduce national A/C fuel use.

ACKNOWLEDGMENTS

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