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Localized Cooling for Human Comfort

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ABSTRACT

Traditional vehicle air conditioning systems condition the entire cabin to a comfortable range of temperature and humidity regardless of the number of passengers in the vehicle. The A/C system is designed to have enough capacity to provide comfort for transient periods when cooling down a soaked car. Similarly for heating, the entire cabin is typically warmed up to achieve comfort.

Localized heating and cooling, on the other hand, focuses on keeping the passenger comfortable by forming a micro climate around the passenger. This is more energy efficient since the system only needs to cool the person instead of the entire cabin space and cabin thermal mass. It also provides accelerated comfort for the passenger during the cooling down periods of soaked cars. Additionally, the system adapts to the number of passengers in the car, so as to not purposely condition areas that are not occupied.

The present paper reports on a fundamental study of localized cooling to achieve comfort in a vehicle environment. The individual cooling streams are evaluated by human comfort riders for effectiveness and limitations. Based on the local cooling studies, combination local cooling strategies are then created and evaluated by riders.

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INTRODUCTION

Air conditioning systems impose the largest accessory load on a vehicle. It has a fairly significant impact on the fuel economy of the vehicle. According to Rugh [1] and Johnson [2], the United States uses 7.0 billion gallons (26.4 billion liters) of fuel a year for vehicle air conditioning, equivalent to 5.5% of the total national fuel use and 9.5% of the imported crude oil. Proportionally, the air conditioning systems contribute to the direct and indirect Green House Gas emissions from the vehicle. With the proposed regulation that will mandate 54.5 mpg vehicle fuel economy by 2025, every vehicle subsystem, including the air conditioning system, will need to be examined to reduce its energy consumption to be able to achieve the fuel economy target.

The effort to improve air conditioning system energy efficiency thus far has mainly been focused on component and control optimization. New air conditioning systems designed with energy efficiency in mind likely have an electrical compressor

or electronic variable compressor, a Thermal Expansion Valve (TXV) for the expansion device, and possibly with brushless motors for the HVAC blower and engine cooling fan. Other systems may use PWM controlled DC motors to gain energy efficiency. From the systems control point of view, modern air conditioning systems, especially those on Hybrid Electrical Vehicles (HEV) and Plug-In Hybrid Electrical Vehicles (PHEV), inevitably use some level of compressor control point elevation in the form of evaporator air out temperature, or some degree of air recirculation in the passenger compartment. Both of these control measures are designed to reduce the loading on the compressor while still maintaining uncompromised passenger comfort in the cabin. For air conditioning systems with fixed displacement compressors and pneumatic variable compressors, similar load reduction control measures have been taken to gain energy efficiency [3].

Other cabin thermal load reduction methodologies have also been explored. These include advanced thermal insulation for the cabin, double pane glass windows, solar reflective glazing, solar reflective paint, electro-chromatic films, low mass seats, cabin preconditioning through ventilation, etc. [4, 5, 6].

In general, the existing measures to gain energy efficiency have been directed at either the refrigeration system optimization or thermal load reduction from the cabin as a whole. Progress in technologies such as thermoelectric modules and human thermal comfort modeling now provides a new possibility of load reduction through localized cooling. Basically, local cooling, via a dedicated local nozzle, targets a specific body part with a diffusing stream of air to provide direct comfort for the body part [7]. Use of multiple streams allows efficient coverage of the key, thermally sensitive body parts to ensure thermal comfort of the passenger. Consequently, the general thermal environment in the cabin may be stratified

without impacting the comfort of the body due to the isolation effect of the local cooling. The thermal load reduction may be further enhanced with passenger presence sensors to perform zonal cooling management. The combined energy expenditure by the air conditioning system operating at a reduced level and by the local cooling streams is expected to be lower than the traditional method of thermal comfort maintenance in which the entire cabin is cooled regardless of the number of passengers in the car.

The present investigation attempts to provide the fundamental understanding of localized cooling in its ability to maintain human thermal comfort by experimentally studying the impact of individual or combined local cooling streams on passenger comfort. The study uses Thermal Comfort rating as well as Thermal Sensation rating to record passenger comfort feedback while subjected to local cooling streams at various flow rates and temperatures in the vehicle environment.

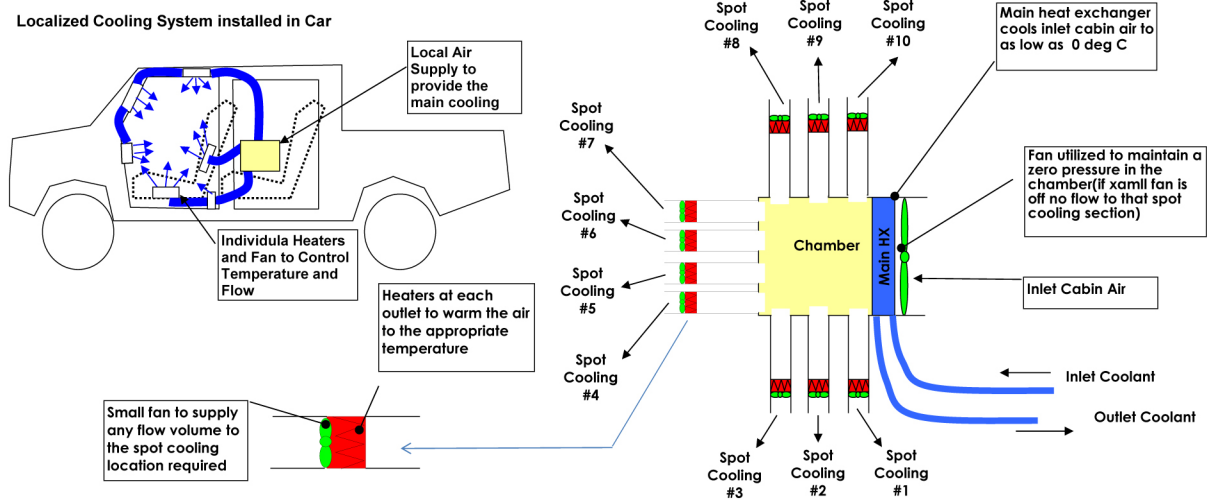


Figure 1. Local Cooling Air Supply



(A)



(B)

Figure 2. Air Supply System and Overhead Nozzles

AIR SUPPLY SYSTEM AND DATA ACQUISITION

Local Cooling Air Supply System

For the local cooling studies, a crossover vehicle is used as the test vehicle. A local cooling air supply system is designed to provide the local cooling streams at specified flow rates and temperatures. As illustrated in [Figure 1](#), the local air supply system has a build-in chiller heat exchanger to provide chilled air that is sent through six hoses leading to the local cooling nozzles. At the connection point for each hose, an electrical heater is installed to re-heat the air to a specified discharge temperature. The discharge temperature is controlled to a thermocouple reading at the exit of the local cooling nozzle to ensure that the desired discharge temperature is achieved. Within each hose, a small fan is installed to propel the air through the discharging nozzle. Behind the chiller, an air balance fan is installed to ensure that the air pressure downstream of the chiller is balanced to the cabin interior pressure. The purpose is to allow air flow measurement using the local cooling fan PWM control signal, which has been correlated to air flow rate prior to the environmental tunnel testing in an airflow laboratory. Two of these local air supply systems were built, one for the driver side and one for the passenger side.

[Figure 2-\(A\)](#) shows the two rows of hose connections out of the Local Cooling Air Systems for a total of 12 hoses connecting to the local cooling nozzles. The straight portion wrapped in insulation tapes are the electrical heaters used to control the discharge air temperature at the local cooling nozzles. Imbedded within the hoses are small electrical PWM fans to supply air flow to each local cooling nozzle.

[Figure 2-\(B\)](#) shows the overhead local cooling nozzles. For the passenger side with the manikin in place, four nozzles are trained at the manikin. The inside two nozzles are aimed at the face of the manikin and the outside two nozzles are aimed at the chest of the manikin. Similar arrangement of nozzles is made for the driver. Not shown in [Figure 2-\(B\)](#) are the lap cooling, the steering cooling, and neck cooling nozzles. The lap cooling nozzles are mounted under the steering wheel column on the driver side and under the glove compartment on the passenger side. The steering wheel cooling nozzles are mounted behind the steering wheel on the steering column. The neck cooling nozzles are mounted under the head rest on the seatback.

Data Acquisition

In the environmental tunnel testing, three types of data were taken. The first was the standard HVAC system development data. The vehicle was instrumented with thermocouples, coolant and refrigerant flow meters, pressure transducers for the refrigeration system, and HVAC module air static pressure measurement. These provide the objective data for monitoring

the vehicle state in the passenger compartment and the refrigeration system. The data were logged with two Campbell scientific data loggers located in the trunk of the vehicle.

The second type of data was provided by a thermal manikin. The thermal manikin has internal heat generation control via an embedded PC to simulate a warm body. The manikin body interacts with the incar environment through the clothing layers and arrives at a particular temperature and heat flux for the skin of each body part. These body parts temperatures and heat fluxes were recorded by an external control computer and translated later on into the Equivalent Homogeneous Temperatures (EHT) [8] to indicate the degree of comfort for those parts.

Lastly, human subjective comfort ride data were taken. Comfort riders were recruited to participate in vehicle rides in the environmental tunnel. Individual local cooling locations and combination local cooling locations were evaluated using established test procedures by the comfort riders and rated for their acceptability.

LOCAL COOLING DEVELOPMENT

Development Environment and Comfort Evaluation Method

The local comfort cooling study was carried out with the objective of reducing total energy consumption for passenger comfort maintenance. The local cooling, capable of being turned off when a seat is empty to save energy, also enables the vehicle air conditioning system to work less hard by maintaining an elevated general incar thermal environment. The 29 °C EHT incar temperature was selected as the optimal elevation level due to the fact that, if any lower, it will not provide meaningful energy saving to the HVAC system by way of compressor, and if any higher, it will surpass the capability of the present day thermoelectric devices to provide local cooling.

The local cooling development went through two phases. Phase I development studied the working of individual local cooling nozzles to determine their effectiveness. Phase II development evaluated and optimized the combination of the selected individual cooling nozzles to ensure that they work together coherently to provide optimal passenger comfort in a passenger compartment with elevated EHT. The majority of the local cooling studies were conducted under the warm ambient condition of 29.4°C×55%×500W/m². Higher and lower tunnel ambient temperatures were used for verification purposes. In addition to the two major phases of studies, a set of baseline comfort rides were conducted for the 29 °C EHT incar condition. These baseline tests were completed to gauge passenger discomfort when local cooling is not instituted.

Most development tests were performed under the steady state test conditions to improve the fidelity of data. Given the environmental tunnel ambient and incar automatic climate control system set point, the vehicle was run for an extended

period at the road speed of 50 kph to achieve steady state in-car thermal conditions. When the vehicle became ready for comfort ride, two riders would enter the environmental tunnel to get acclimated for 5 minutes before entering the vehicle. Each condition as defined by the local cooling stream flow rate and discharge temperature was repeated with different pair of riders. The same test condition was repeated one more time with the manikin in the passenger seat to take objective data for the calculation of body parts EHT temperatures.



Figure 3. Scale of Thermal Sensation and Thermal Comfort

During the subjective comfort rides, a custom-designed software tool for comfort evaluation was used to log the riders' evaluation of their comfort. The software employs two indices: Thermal Sensation and Thermal Comfort [9, 10, 11, 12, 13]. The rider's Thermal Sensation is his perception of the environmental temperature. The rider may feel cold if the temperature is low and he 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 (see Figure 3). 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. For example, during winter, a slightly warm Thermal Sensation provides the best Thermal Comfort rating, while during summer, a slightly cool Thermal Sensation gives the best Thermal Comfort rating. Under steady state conditions it is expected that a Thermal Comfort index of 2 is the upper limit. Ratings beyond 2 are achieved during transient thermal processes, such as when a cold-soaked passenger is exposed to a warm environment.

Baseline Comfort at 29 °C EHT

The standard cabin condition of the 29 °C EHT is used for most of the evaluations of the individual or combined local cooling strategies. In order to understand the impact by the local cooling streams, it is necessary to establish the baseline comfort state at 29 °C EHT temperature in the cabin. Comfort riders were employed in the environmental tunnel to provide subjective rating for the baseline comfort state.

Figure 4 shows the Thermal Sensation rating during the 29 °C EHT rides without local cooling. There are five body parts rated during the rides: Face, Back, Gluteal, Right Hand, and Chest.

Additionally, the whole body Thermal Sensation is also rated. The chart shows consistent warm rating for the in-car environment from all riders. Each of the body parts registered warm to hot sensation, along with the whole body. The "whole-body" Thermal Sensation on average is rated at 1.4.

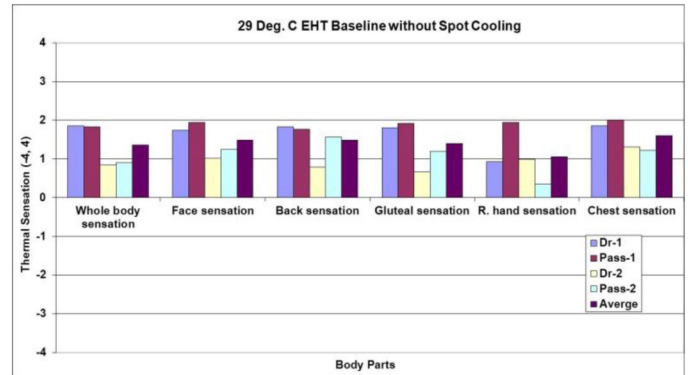


Figure 4. Baseline Thermal Sensation at 29 °C EHT without Local Cooling

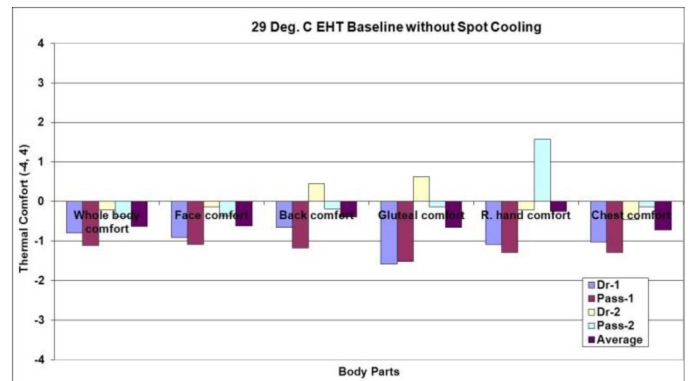


Figure 5. Baseline Thermal Comfort at 29 °C EHT without Local Cooling

Figure 5 shows the corresponding Thermal Comfort rating for the 29 °C EHT rides without local cooling. Most riders rated the riding experience "just uncomfortable", with the average "whole-body" Thermal Comfort at -0.7. For steady state comfort, a Thermal Comfort rating of close to +2 is expected. Thus there exists a significant thermal comfort gap.

Individual Local Cooling Studies

A total of six local cooling locations were examined for their impact on body parts comfort. A local cooling location refers to the physical location in the car where an airflow nozzle was installed, as well as the targeted body part if it is not self-evident. These locations include the following:

- Seat (seat back + seat bottom)
- Rear Face/Neck (installed under headrest, toward rear face and neck area)
- Headliner Face (from headliner toward face)
- Headliner Chest (from headliner toward chest)
- Steering Wheel (fixed on steering column, toward hands)
- Lap (from knee bolster toward lap)

As shown in [Table 1](#), each of the local cooling locations was examined under two airflows and two discharge temperatures that were estimated to contain the optimal parameters. The incar condition was controlled by the automatic climate control system to 29 °C EHT or 31 °C EHT. The ambient condition used was 29.4°C×55%×500W/m². Comfort riders and manikin were employed to assess the effectiveness of the local cooling and to optimize the delivery of local cooling airflow and discharge temperature.

Table 1. Airflow and Temperature Matrix for Individual Locations (“L” and “H” represent “Low” and “High”, “F” represents “Flow” and “T” represents “Temperature”. Footnotes represent body parts)

	Rear Face/ Neck	Seat	Head-liner Face	Head-liner Chest	Lap	Steering Wheel
Airflow Rate (CFM)	LF _{nk} HF _{nk}	LF _{st} HF _{st}	LF _f MF _f HF _f	LF _{ch} HF _{ch}	LF _{lp} HF _{lp}	LF _{str} HF _{str}
Dischg Temp (°C)	LT _{nk} HT _{nk}	LT _{st} HT _{st}	LT _f HT _f	LT _{ch} HT _{ch}	LT _{lp} HT _{lp}	LT _{str} HT _{str}
Cabin EHT (°C)	29	29	29	29, 31	29, 31	29

Seat Cooling

The crossover vehicle used in the study was equipped with ventilated and heated front seats. In the present study, the internal air distribution ducts were disconnected and reconnected to Local Cooling Air Supply System so that local cooling for the seat can be tested. Two airflow rates, LF_{st} and HF_{st}, and two discharge temperatures, LT_{st}, and HT_{st} were used in the study. The same flow rates and temperatures were applied to both the seat back and seat bottom. In [Figure 6](#) the body part and whole body EHT’s for each airflow and discharge temperature combination are plotted along with the baseline body part EHT from the baseline test. It can be seen that the Left Thigh, Right Thigh, Pelvis, Head, both Hands, and the back are impacted by the seat cooling air discharge. The EHT temperatures of the Thigh, Pelvis, and Back are significantly impacted by the seat cooling discharge and are sensitive to the changes in discharge parameters in terms of the airflow rate and temperature.

[Figure 7](#) shows the body part sensation from the seat cooling test. It shows that both the Back and the Gluteal were cooled down nicely. The Thermal Sensation rating for the two body parts were quite a bit below neutral sensation, while the uncooled body parts continue to show Thermal Sensation ratings on the warmer side. [Figure 8](#) shows that the overall comfort of the surveyed body parts were all improved over the baseline comfort of [Figure 5](#). However, the direct contact body parts, the Back and Gluteal, did not show the amount of comfort improvement expected. Verbal feedback from the riders indicated that for all the flow rates and discharge

temperatures, the direct contact body parts were overcooled, and thus the neutral comfort rating instead of the expected positive Thermal Comfort rating. It is to be noted that, for each testing condition, each Thermal Sensation and Thermal Comfort bar in [Figure 7](#) and [Figure 8](#) is an average of ratings from four riders (two passengers per ride and each condition has a repeat ride).

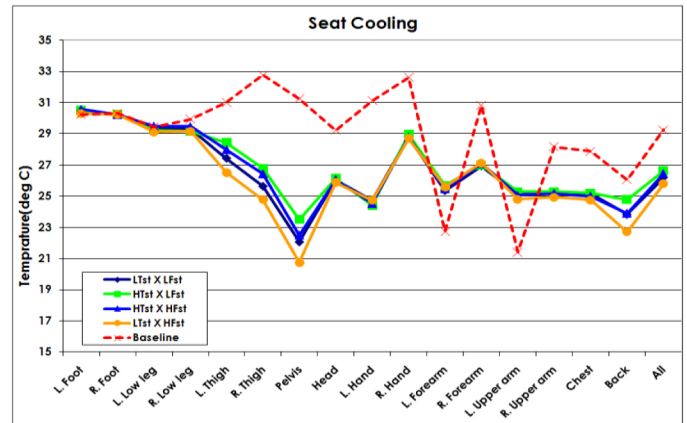


Figure 6. Body Part EHT Temperature Change due to Seat Cooling

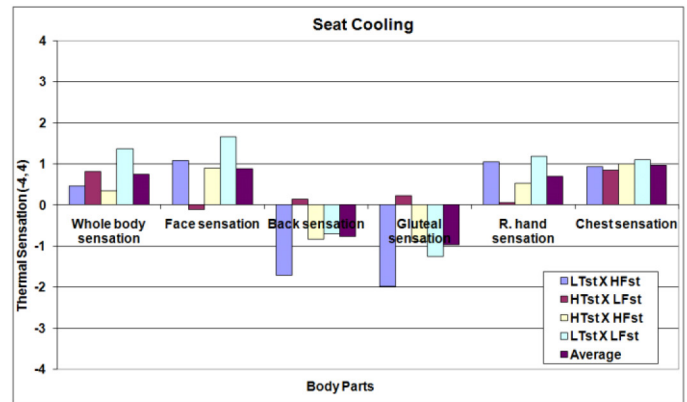


Figure 7. Thermal Sensation with Seat Cooling

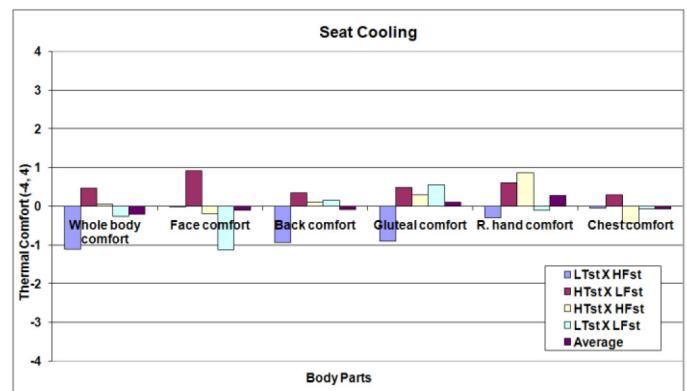


Figure 8. Thermal Comfort with Seat Cooling

Headliner Chest Cooling

The Headliner Chest nozzle was mounted overhead in the headliner area. Two nozzles were used to provide symmetric airflow toward the chest. Both of the two nozzles were fed by a

single hose from the Local Cooling Air Supply System. The airflows used in the Chest Cooling tests were LF_{ch} and HF_{ch} . The discharge temperatures were at LT_{ch} and HT_{ch} .

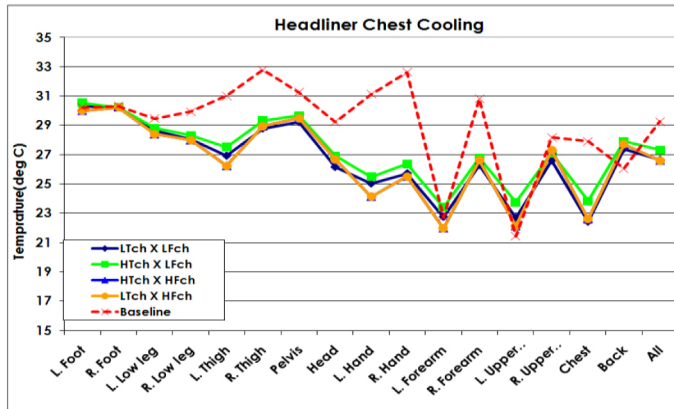


Figure 9. Body Part EHT Temperature Change due to Chest Cooling

Figure 9 shows EHT temperatures calculated from the data provided by the manikin. The four discharge conditions formed from two air flows and two temperatures are plotted along with the baseline manikin measurement at 29 °C EHT. The manikin EHT data shows significant cooling effect at the thighs, pelvis, head, hands, left forearm, and chest. Since the nozzles are directed from above downward toward the chest, the airflow from the nozzles provides a large coverage area. It can be seen that, as expected, the larger airflow and lower discharge temperature gives better cooling than the lower flow rate and higher discharge temperature condition.

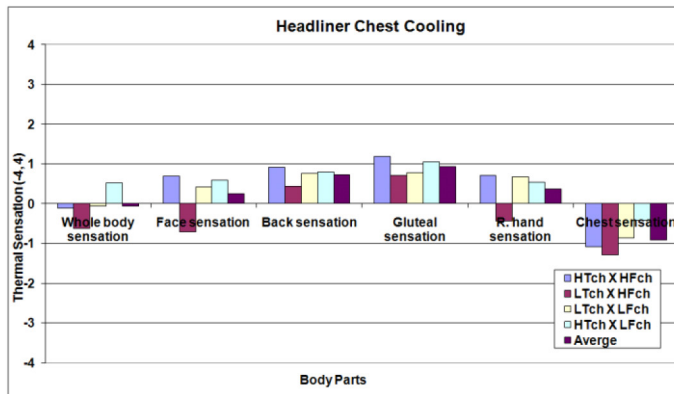


Figure 10. Thermal Sensation with Chest Cooling

Figure 10 shows the chest Thermal Sensation rating from riders' subjective rating. The chest was cooled effectively to a rating of -1, whereas other untargeted body parts are between 0 and 1, with the face and right hand Sensation below the other warmer body parts. The whole body Thermal Sensation was cooled to neutral. The Thermal Comfort rating (Figure 11) was also significantly improved for the chest. It was elevated from the baseline average level of -0.7 (Figure 5) to the new chest average of 1.9. Other body parts, such as the hands and the face, also showed good improvement in Thermal Comfort rating.

From the cooling point of view, the chest nozzle was rated the most effective local cooling location due to its broad coverage. It appears from the ratings in Figure 11 that one can get by with moderate comfort simply from the cooling supplied by the Headliner Chest nozzles. However, the parameters tested are by no means optimal. Verbal feedback from the comfort riders indicates that the airflow is too strong for long range driving and needs to be adjusted down.

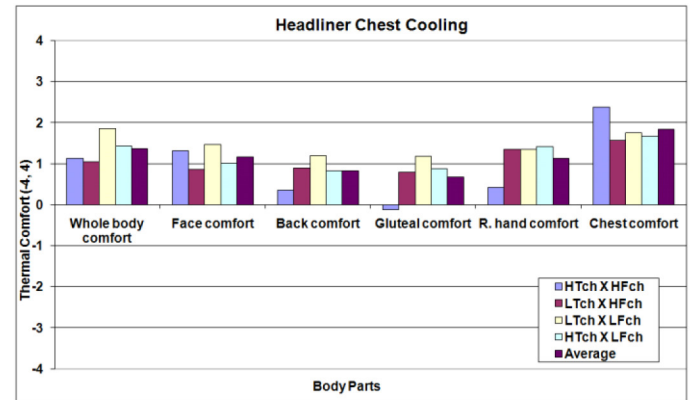


Figure 11. Thermal Comfort with Chest Cooling

Individual Local Cooling Summary

The remaining local cooling locations, including the Rear Face/ Neck, Lap, Headliner Face, Steering Wheel, were similarly tested and rated. Both objective data in the form manikin measurements and subjective ratings were obtained from these tests.

Table 2 summarizes the Whole Body EHT impact by the 5 major cooling locations except the steering wheel location due to the difficulty of sitting the manikin on the driver seat. The EHT whole body impact was not the sole criterion for the selection of individual cooling location for further combination cooling development, however, the ranking from the table does coincide with the final selected locations. The "circle" in Table 5 denotes recommended, the "triangle" "marginal", and the "X" "not recommended". The Headliner Chest is ranked the highest in impact, followed by the Seat. The Headliner Face and Lap locations had moderate impact, with both being better than the Rear Face/Neck location, which is not recommended.

Table 2. Effectiveness of Individual Local cooling Measured by Whole-Body EHT

Local Cooling Location	Whole Body EHT	Rating
Baseline	29.7	
Rear Face / Neck	28.7	X
Lap	27.5	Δ
Headliner Face	27.7	Δ
Seat	26.7	O
Headliner Chest	26.8	O

Table 3. Local cooling Locations Summary

Locations	Rear Face/ Neck	Seat	Headliner Face	Headliner Chest	Lap	Steering Wheel
Findings	Low Acceptance, airflow too harsh	Too cold	Dry eye harshness	Good but too much airflow	Good but too much airflow	Works when hands are in stream. Too limiting
Selection Decision	Not selected for cooling development	Use HT_{st} discharge temp. Use lower of the airflows	Use lowest airflow	Use lower of the airflows	Use lower of airflows	Not selected for further development

The individual local cooling location study revealed that, generally, the airflow rates used were too high, causing harsh airflow perception. As presented in Table 3, it was found that the Rear Face/Neck nozzle was not well received due to airflow sensitivity of the neck. The Steering Wheel nozzle provides limited impact on overall comfort. It did provide hand cooling when the hands were within the air cone of the nozzle. However, positional limitation on the hands reduced the overall effectiveness of the nozzle.

The seat cooling was found to be effective but too cold. Moderation of airflow and discharge temperature was needed. Face airflow was too high causing dry eyes and perception of harshness. The Chest nozzle provides good comfort but the airflow was too high. And, similarly, the Lap nozzle was acceptable but with too much airflow.

Combination Cooling Strategy Development

Based on the individual local cooling development results, nozzle locations were selected to form a combination strategy for comfort maintenance. The combination strategy went through optimization development so that the most effective comfort cooling delivery may be achieved.

Tri-Combination Strategy Development

The Tri-Combination strategy was composed of the three most effective nozzles: Seat, Headliner Chest and Lap. The airflow rates selected for these nozzles are the lower of the two airflow rates used during the individual local cooling studies, as is defined in Table 1. The seat nozzles were supplied with LF_{st} , the Chest nozzle was supplied with LF_{ch} , and the Lap nozzle was supplied with LF_{lp} . The discharge temperatures were initially set at a uniform temperature for all nozzles at the HT_{ch} level. This combination strategy was first tested under the ambient condition of $29.4^{\circ}\text{C} \times 55\% \times 500\text{W}/\text{m}^2$ and the incar condition at 29°C EHT.

Figure 12 shows the Thermal Sensation of the Seat-Chest-Lap combination with the initial air flow and uniform discharge temperature. In comparison with the baseline case of Figure 4 where most riders rated the incar as being too warm, the Tri-Combination cooling strategy at the same incar EHT of 29°C significantly improved the passenger comfort. As shown in Figure 12, the Thermal Sensation in general is cooler than neutral. Average whole-body thermal sensation is -0.8 , close to "slightly cool" (-1 , Figure 3).

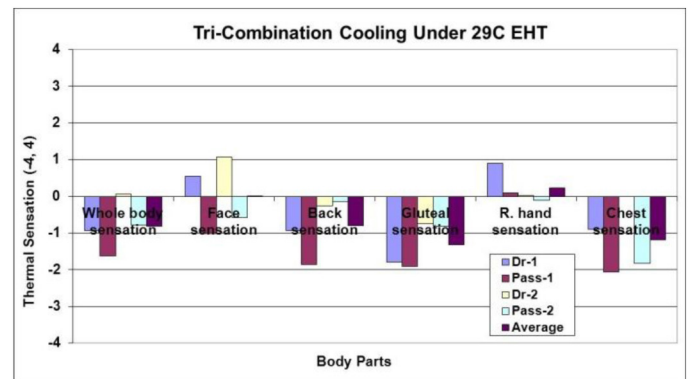


Figure 12. Thermal Sensation for Tri-Combination under 29°C EHT Cabin

The complaint from these tests was that the seat was too cold, which accounted for both the Back and Gluteal thermal sensation. Some riders complained that the forehead, being close to the headliner, were too warm. For the Chest, the complaint was that the comfort was good but there was too much airflow which caused the perceived harshness in the air delivery.

Figure 13 shows the Thermal Comfort rating from the same car rides. For the face, the somewhat lower comfort rating from some riders was due to the head being too warm from the hot roof and lack of airflow. In contrast, the other body parts, such as the Gluteal and the Back suffered from being too cold and received low comfort ratings from some riders. Overall, the whole body comfort rating attained an average rating of greater

than 2.3. In comparison with the baseline rides, where the Thermal Comfort rating averaged -0.6, the thermal comfort improvement was dramatic.

The same Tri-Combination strategy was re-evaluated at the incar temperature of 31 °C EHT. Figure 14 shows that the degree of over-cooling is reduced in the hotter incar environment as compared with Figure 12. Similarly, as shown in Figure 15, the whole body Thermal Comfort rating is at 1.4, still a reasonably comfortable environment.

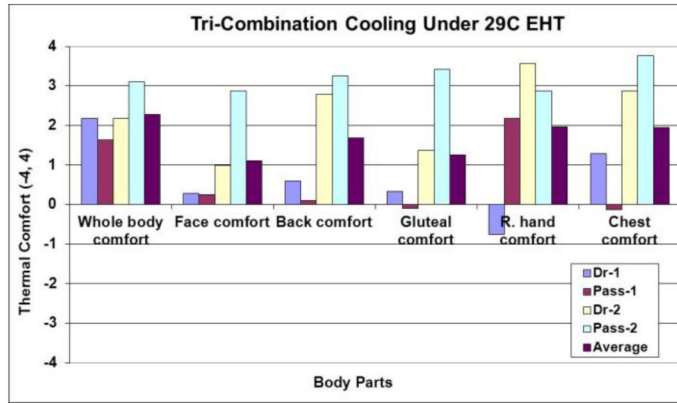


Figure 13. Thermal Comfort for Tri-Combination under 29 °C EHT Cabin

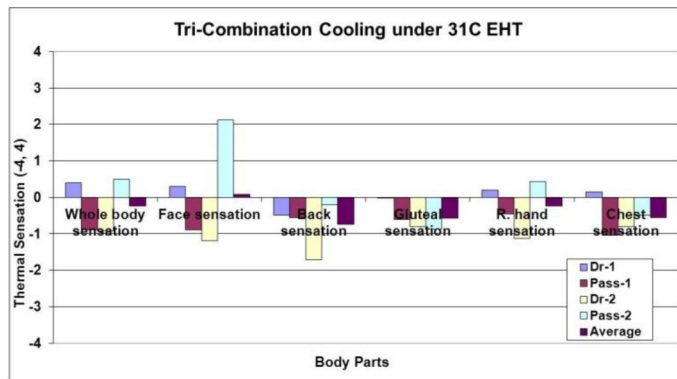


Figure 14. Thermal Sensation for Tri-Combination under 31 °C EHT Cabin

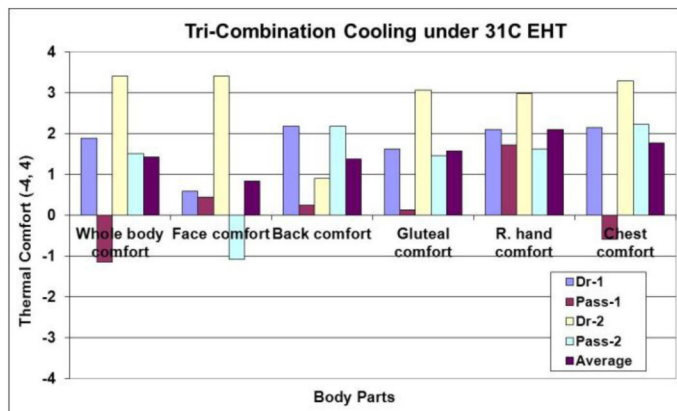


Figure 15. Thermal Comfort for Tri-Combination under 31 °C EHT Cabin

Tri-Combination Strategy with Improved Airflow Delivery

After the Tri-Combination strategy was tested and evaluated, improvement to the airflow delivery and discharge temperature was made to fine-tune the cooling. To reduce over-cooling by the seat, the airflow rate to the seat was reduced from LF_{st} by 43% (for seat back and bottom each), with the discharge temperature unchanged at HT_{st} . The air delivery to the Chest and Lap nozzles were reduced by 41% and 25% respectively. To compensate for the airflow reduction, the discharge temperature for the Chest and Lap nozzles were lowered to LT_{ch} and LT_{lp} .

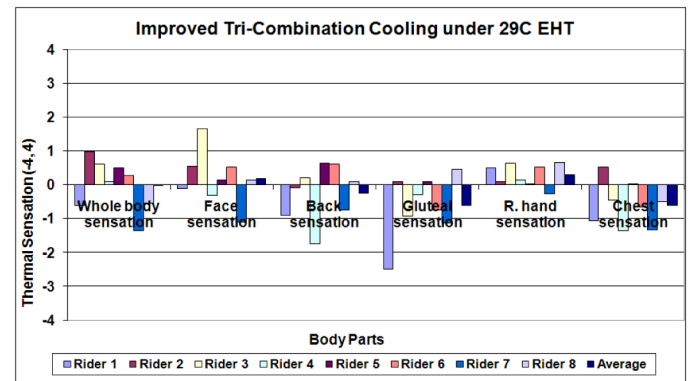


Figure 16. Thermal Sensation - Improved Airflow and Discharge Temperature for the Tri-Combination Strategy

The improved delivery settings were tested with another round of vehicle rides. As is shown in Figure 16 the Thermal Sensation did move toward neutral for every body part. On average the whole body Thermal Sensation is exactly at neutral. Without airflow delivery to the forehead, the “warm forehead” complaint persisted.

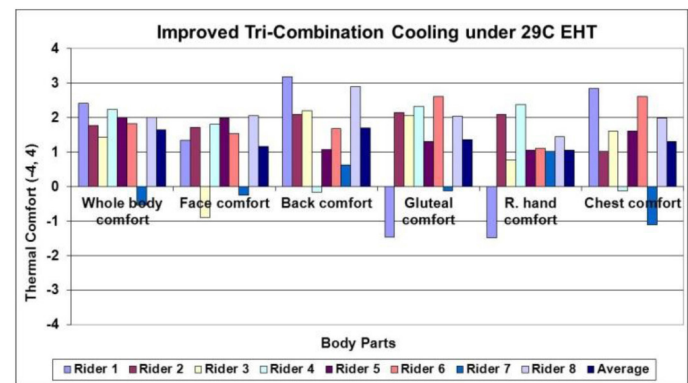


Figure 17. Thermal Comfort - Improved Airflow and Discharge Temperature for the Tri-Combination Strategy

Interestingly, the whole body Thermal Comfort rating (Figure 17) did not improve from the previous testing. The average whole body comfort rating was rated at 1.6. This may indicate that the Tri-Combination strategy with the original airflow delivery is harsh and the seat temperature was too cold, but the whole body thermal comfort is actually better, whereas with the improved airflow delivery and discharge temperature, the

objectionable harshness and overcooling were removed but the overall whole body thermal comfort actually declined. Thus the improved delivery may be a compromise solution.

Quad-Combination Strategy

During the development rides, it became clear that face cooling must be added to address the “warm forehead”. Without face cooling, the “warm forehead” has been a consistent subtraction from the overall occupant thermal comfort. The initial judgment made against the face nozzle was the harshness of the face airflow and the potential for eye dryness. To make the face flow acceptable to the riders, low face airflow was adopted.

The face airflow was optimized at 50% of LF_f through iterative testing. Figure 18 and Figure 19 show the comfort ride data for Thermal Sensation and Thermal Comfort at the low face airflow rate. The Quad-Combination with low face airflow was further evaluated through comfort rides at the 31°C EHT incar condition. The overall comfort was acceptable (Figure 20 and Figure 21). From both rides, it can be seen that the face comfort was rated at a high level similar to the other body parts.

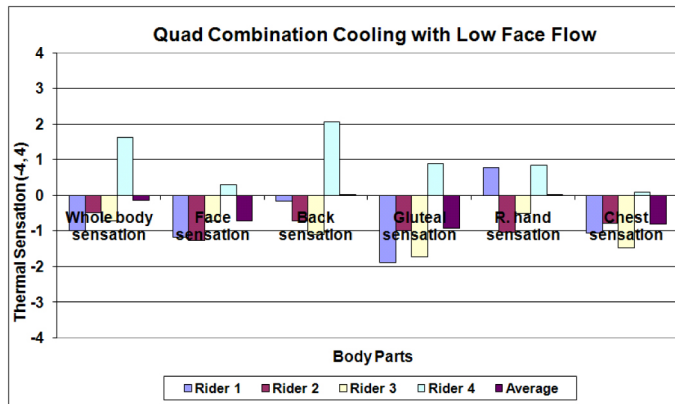


Figure 18. Thermal Sensation Rating for Quad-Combination Cooling

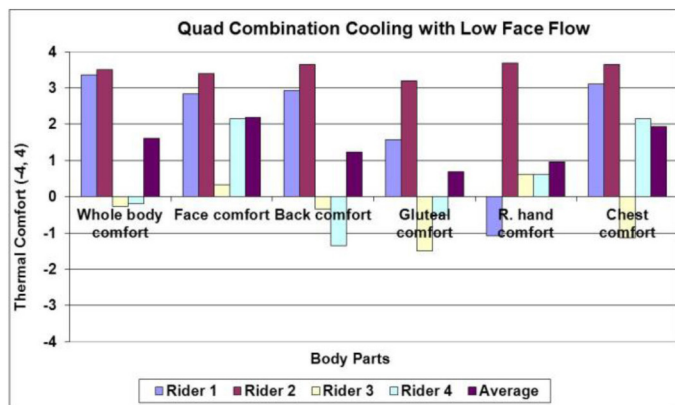


Figure 19. Thermal Comfort Rating for Quad-Combination Cooling

Evaluating the comfort data in Figure 19 and Figure 21, it is clear that individuals have differing comfort requirements due to age, gender, body fat ratio, day to day health condition variation, weather preconditioning, etc. The subjective data from the comfort rides reflect all this variation. It was

recognized during development testing that a single combination strategy would be taxed to provide uniformly satisfactory comfort to everyone, just as in the case of Automatic Climate Control, where a set point temperature dial is provided to address comfort requirement variations. Subsequently, a multi-tiered combination strategy was devised and tested.

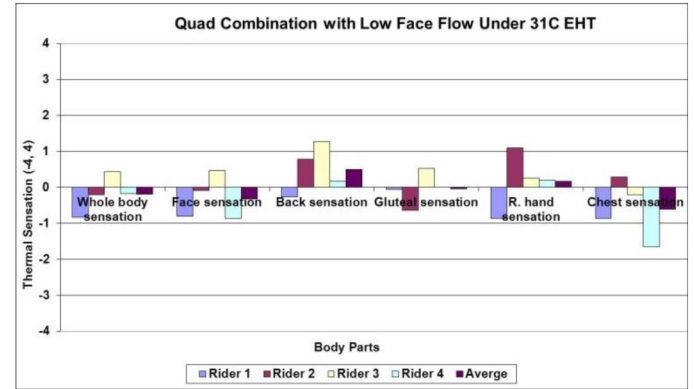


Figure 20. Thermal Sensation Rating for Quad-Combination Cooling at 31°C EHT

Table 4 shows the combination strategies with four levels of cooling capacity: Extra-High, High, Medium, and Low. The Extra-High capacity local cooling has all the four nozzles turned on, with the seat discharge temperature at HT_{st} , and the face discharge at $(LT_f - 1)^\circ C$. The High capacity local cooling increased the face discharge temperature to HT_f . The Medium cooling capacity raised the seat discharge temperature to $(HT_{st} + 2)^\circ C$. The Low cooling capacity shut off the face airflow discharge. With these multi-tiered capacity local cooling, most people found their comfort satisfied with one of the four discharge levels.

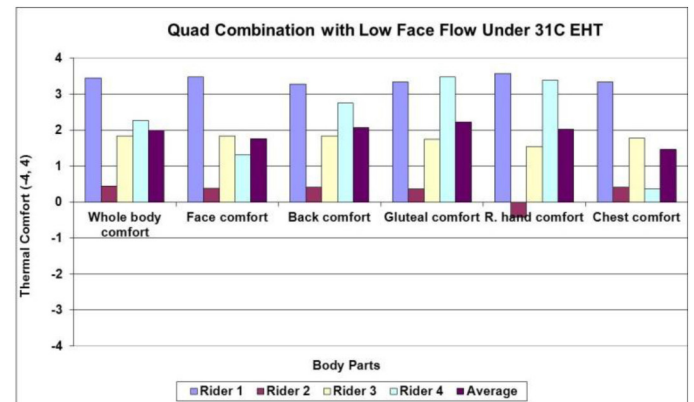


Figure 21. Thermal Comfort Rating for Quad-Combination Cooling at 31°C EHT

Table 4. Local cooling Multi-Tiered Capacity Delivery

Capacity Level	Seat (CFM, °C)	Headliner Chest (CFM, °C)	Lap (CFM, °C)	Headliner Face (CFM, °C)
Extra-High (Flow, Temp.)	57%LF _{str} , HT _{st}	59%LF _{chr} , LT _{ch}	75%LF _{lp} , HT _{lp}	50%LF _f , (LT _f - 1)
High (Flow, Temp.)	57%LF _{str} , HT _{st}	59%LF _{chr} , LT _{ch}	75%LF _{lp} , HT _{lp}	50%LF _f , HT _f
Medium (Flow, Temp.)	57%LF _{str} , (HT _{st} +2)	59%LF _{chr} , LT _{ch}	75%LF _{lp} , HT _{lp}	50%LF _f , HT _f
Low (Flow, Temp.)	57%LF _{str} , (HT _{st} +2)	59%LF _{chr} , LT _{ch}	75%LF _{lp} , HT _{lp}	0, X*

X* --- Temperature irrelevant

Figure 22 and Figure 23 show the Thermal Sensation and Thermal Comfort ratings for the multi-tiered local cooling delivery. In these tests, each comfort rider is afforded one of the four levels of local cooling listed in Table 4, or variations of it, based on their comfort preference obtained from prior subjective data and verbal comment. In comparison with Figure 19 and Figure 21, overall rider satisfaction level was improved. Similar observations were made during the repeat rides at the 37.8°C×40%RH×1000W/m² ambient condition, as shown in Figure 24 and Figure 25. As noted before, normal development was focused in the ambient condition of 29.4°C×55%×500W/m². The incar conditions are at 29 °C EHT.

make adjustment to the ACC set temperature at will per their comfort requirement?" The answer to this question is actually quite interesting!

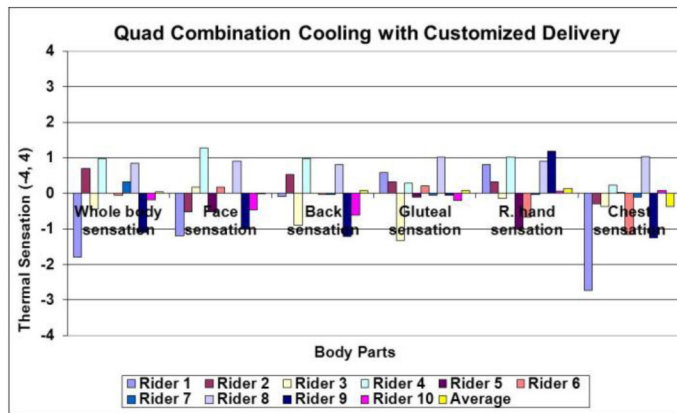


Figure 22. Thermal Sensation Rating for Customized Capacity Local Cooling at 29.4°C×55%×500W/m² Ambient and at 29°C EHT

Even though the comfort rating was in general improved and more uniform than before, the comfort rating was not as high as desired. So the question was asked: "Given the baseline Automatic Climate Control System, what kind of comfort rating should we expect to see from the riders if they are allowed to

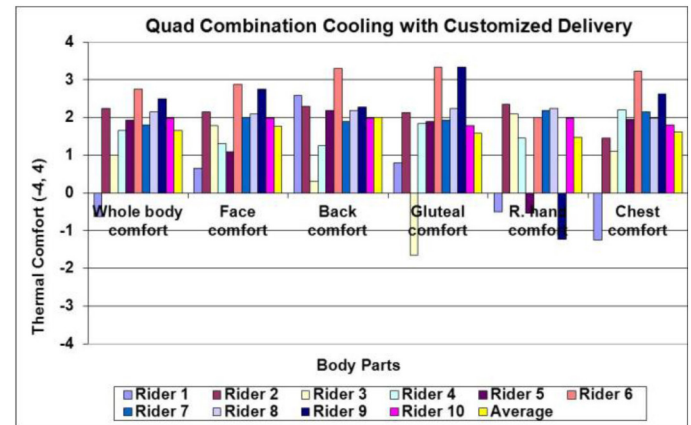


Figure 23. Thermal Comfort Rating for Customized Capacity Local Cooling at 29.4°C×55%×500W/m² Ambient and at 29°C EHT

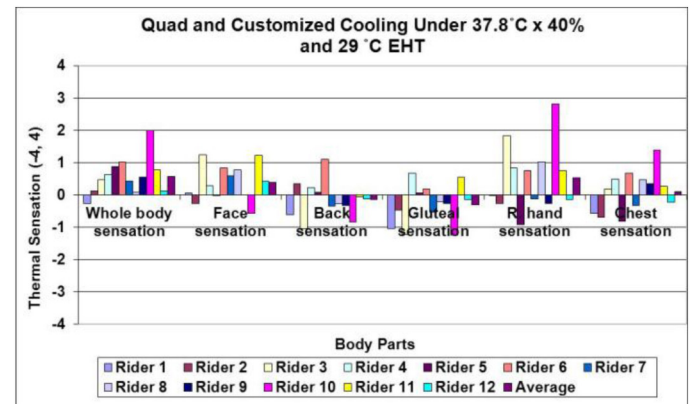


Figure 24. Thermal Sensation Rating for Customized Capacity Local Cooling at 37.8°C×40%RH×1000W/m² Ambient

Figure 26 and Figure 27 present the Thermal Sensation and Thermal Comfort of the rides where riders were allowed to maximize their comfort by adjusting the ACC temperature set point. The Thermal Sensation for the whole body may be read as “warm”. Some body parts, such as the Face, Back, and Gluteal registered “warm”, while the Chest and the Right Hand might be interpreted as “neutral”. Thermal Comfort-wise, the rating is not uniform. There is a substantial range of variation between the riders. Some rated it as highly comfortable and other rated as less desirable. It is conjectured that there are two factors at play here. On the one hand, the ACC system does not provide ideal comfort even when the set temperature can be adjusted. There is temperature stratification in the incar environment that can cause local discomfort: the body parts can be either overheated or overcooled. And secondly, given the freedom of placing a mark on the (-4, 4) comfort scale during comfort survey, different individuals will inherently place it with some variation.

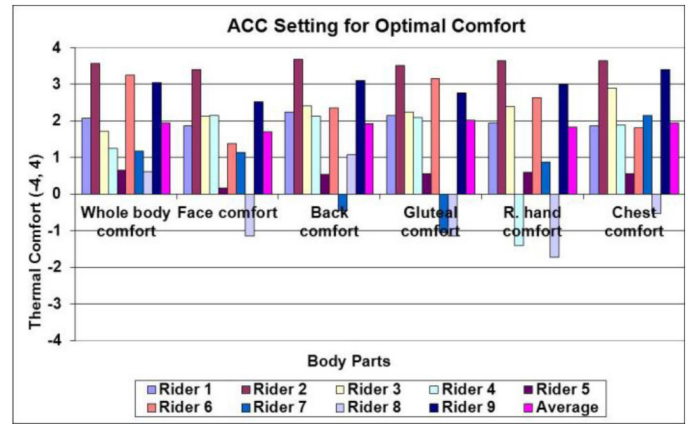


Figure 27. Thermal Comfort Rating for ACC System Where the User Is Allowed to Arbitrarily Change Set Temperature per His Comfort Requirement for the Ambient of 29.4°C×55%×500W/m²

Manikin Objective Data Analysis for Combination Cooling Strategies

Manikin data were taken during the combination cooling development. The manikin skin temperature and heat flux were converted into Equivalent Homogeneous Temperature (EHT) to indicate the comfort of the body part and whole body.

Figure 28 summarizes the comfort impact of the multi-tiered combination strategies along with the comfort impact of two standard EHT environments. The blue curve in the chart represents comfort rating by the manikin at 29 °C EHT without local cooling. As aforementioned and shown in Figure 4 and Figure 5 with subjective Thermal Sensation and Thermal Comfort ratings, the riders were warm and uncomfortable. The lower, pink curve represents the comfort level when the incar is set at 24 °C EHT. Most people report comfort at this setting. However, the hands, forearm, and upper arm are overcooled. These two curves define the boundaries of comfort for the multi-tiered local cooling.

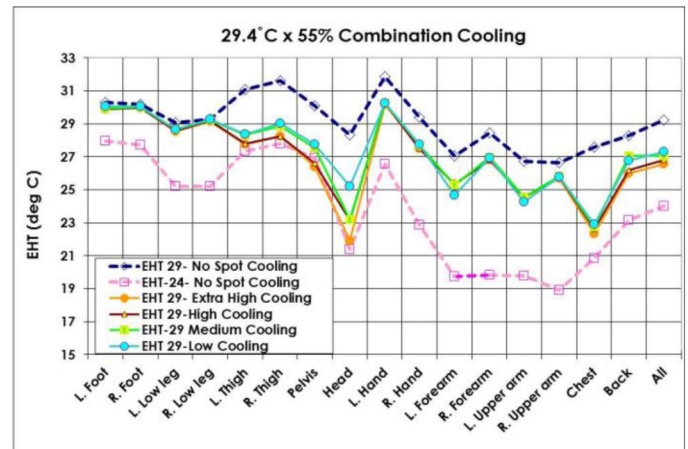


Figure 28. Manikin Study of Impact by Multi-Tiered Combination Cooling Strategies at 29.4°C × 55% RH × 500W/m²

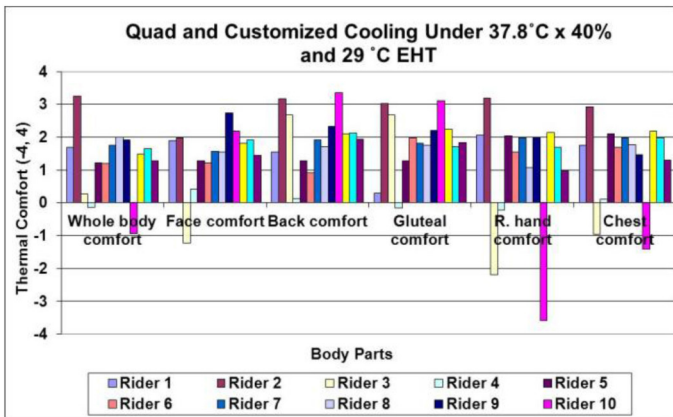


Figure 25. Thermal Comfort Rating for Customized Capacity Local Cooling at 37.8°C×40%RH×1000W/m² Ambient

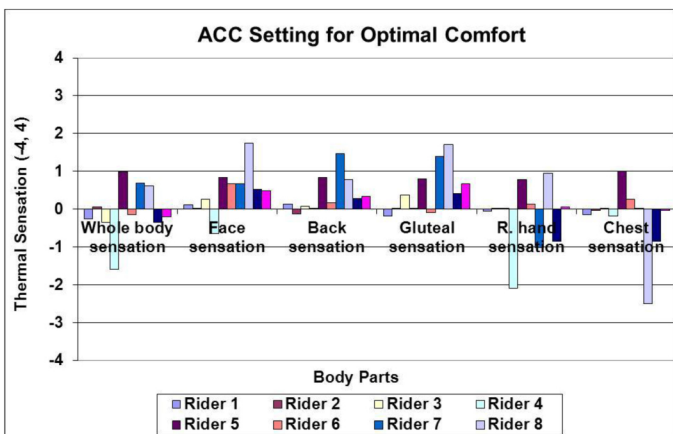


Figure 26. Thermal Sensation Rating for ACC System Where the User Is Allowed to Arbitrarily Change Set Temperature per His Comfort Requirement for the Ambient of 29.4°C×55%×500W/m²

The multi-tiered local cooling strategies were tested under the elevated incar environment of 29 °C EHT. The ambient condition was 29.4°C×55%×500W/m². With the general incar environment at 29 °C EHT, and with the combination local cooling turned on at various level of cooling capacity, **Figure 28** shows that the incar comfort was significantly improved without the side effect of hand/arm overcooling. It can be seen that the four levels of local cooling are differentiable at the Back, Thigh, Pelvis and Head. They can also be differentiated in the whole body EHT. The four levels are less differentiable at the Feet, Lower Legs, Forearms and Upper Arms, since those are the locations the local cooling did not target. There is also low differentiation in the Chest since the multi-tiered local cooling does not change the cooling delivery for those nozzles.

Figure 29 shows the impact of the ambient condition on the incar occupant comfort. For both of the ambient conditions (23.8°C ×65%×300W/m² and 29.4°C×55%×500W/m²), the ACC was set at 23.3 °C (74 °F) to provide a general incar thermal environment of 29 °C EHT. It can be seen that the capacity level of the local cooling made a difference in the body part comfort, but the ambient temperature change did not have any impact on the incar overall comfort. The ACC set point drives the ACC to work at an appropriate level to cancel out the ambient temperature effect on the incar environment and isolate the manikin from feeling the ambient condition change.

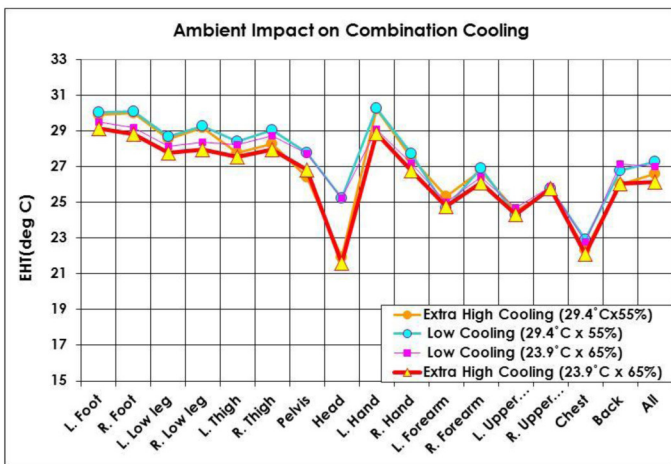


Figure 29. Impact of Ambient and Local cooling Capacity

Transient Test

The local cooling studies reported thus far have been done under steady state conditions. These include the individual local cooling and the combination local cooling. The vehicle was normally run for 60 to 90 minutes to stabilize before any local cooling studies were conducted.

In order to develop an understanding of how effective local cooling would be during the transient phase of the air conditioning operation, a series of Soak and Cool-Down tests were run with and without the local cooling for comparisons. The vehicle was set in the environmental tunnel with a selected ambient condition (29.4°C×55%×500W/m², or

37.8°C×40%×1000W/m²) and soaked for 90 minutes with 13 kph (8 mph) wind. The windows were closed so that the incar temperature could rise above the ambient temperature from the solar radiation. With the incar temperature stabilized after 90 minutes of soaking, the vehicle was started and run at 48.3 kph (30 mph) road speed and wind speed.

Two transient runs were conducted under each of the two ambient conditions aforementioned. One run is done without local cooling and with the ACC set at 25 °C EHT, and the other run is done with the local cooling and with the ACC set at 29 °C EHT. For the 29.4°C×55%×500W/m² ambient condition, the ACC set point was 70 °F (21.1 °C) for the baseline local cooling run to achieve the 25 °C EHT. For the 37.8°C×40%×1000W/m² ambient condition, the ACC set point was 68 °F (20 °C) to achieve the 25°C EHT for the baseline no local cooling run. The relative low set points were necessary to compensate for the ACC system solar sensor misreading of the tunnel solar intensity due to the solar light spectrum inaccuracy. Also, the selection of 25 °C EHT as control point for the no local cooling runs was based on the steady state development experience that it provides good comfort during steady state.

Figure 30 shows the incar average breath temperature cool-down after the vehicle start. The ambient condition was at 29.4°C×55%×500W/m². The breath temperature cooled down quickly in the first 2 to 3 minutes, and within the first 15 minutes it achieved steady state. Due to the different set temperatures for the ACC system for with and without local cooling, the breath temperatures settled to a different level to achieve the 25 and 29 °C EHT respectively.

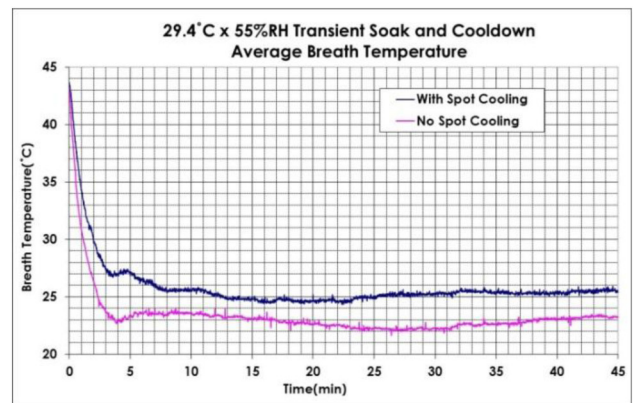


Figure 30. Breath Temperatures for Soak and Cool-Down at the Ambient Condition of 29.4°C×55%×500W/m²

Figure 31 is the Thermal Sensation comparison of local cooling with that of no local cooling for the same ambient condition. It is seen that over the entire transient cool-down process, local cooling was able to provide a cooler sensation to the rider.

Figure 32 shows the Thermal Comfort rating comparison for the same ride. It shows that local cooling provided better Thermal Comfort to the rider than the baseline that had no local cooling and was at lower ACC set point.

Figure 33 and Figure 34 are the ratings for a ride under the higher ambient condition of $37.8^{\circ}\text{C}\times 40\%\times 1000\text{W}/\text{m}^2$. Very similar comfort results was observed: local cooling in higher incar environment (29°C EHT) was able to provide better Thermal Sensation rating and Thermal Comfort rating than the baseline case of no local cooling in lower incar thermal environment (25°C EHT).

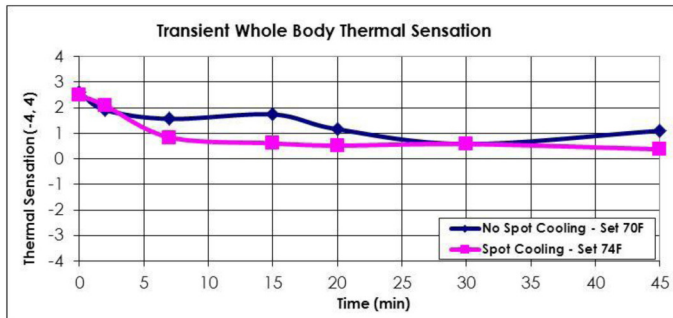


Figure 31. Whole Body Thermal Sensation Rating During Soak and Cool-Down at the Ambient Condition of $29.4^{\circ}\text{C}\times 55\%\times 500\text{W}/\text{m}^2$

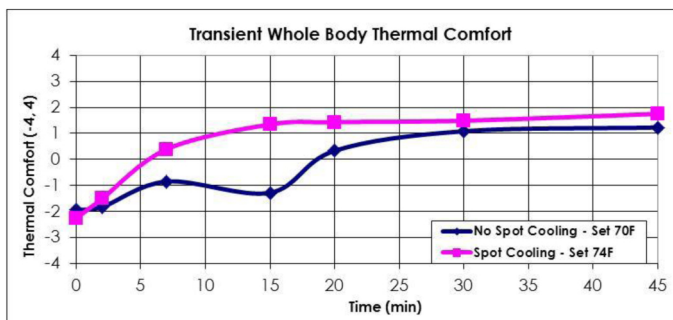


Figure 32. Thermal Comfort Rating during Soak and Cool-Down at the Ambient Condition of $29.4^{\circ}\text{C}\times 55\%\times 500\text{W}/\text{m}^2$

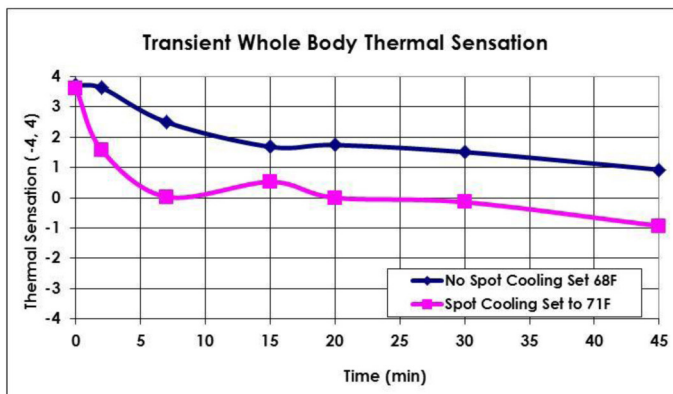


Figure 33. Whole Body Thermal Sensation Rating during Soak and Cool-Down at the Ambient Condition of $37.8^{\circ}\text{C}\times 40\%\times 1000\text{W}/\text{m}^2$

Interestingly, under both the $29.4^{\circ}\text{C}\times 55\%\times 500\text{W}/\text{m}^2$ condition and the $37.8^{\circ}\text{C}\times 40\%\times 1000\text{W}/\text{m}^2$ ambient condition, it was observed that both baseline cases never achieved comfort under the 25°C EHT setting even at the end of the vehicle rides, whereas both of the local cooling cases achieved comfort with a Comfort Rating of about 2. It is believed that the Automatic Climate Control set for 25°C EHT not able to provide comfort during these transient tests was due to the

seat mass temperature still going through its transient process, even though the air temperature has stabilized. In a truly stabilized steady state the seat mass temperature would have equilibrated with the incar air temperature.



Figure 34. Thermal Comfort Rating during Soak and Cool-Down at the Ambient Condition of $37.8^{\circ}\text{C}\times 40\%\times 1000\text{W}/\text{m}^2$

Another interesting observation was that for both ambient conditions, the rides with the local cooling had better Thermal Sensation and Thermal Comfort rating during the initial transient than the standard rides, and achieved those ratings much faster. A substantial separation was observed for the $37.8^{\circ}\text{C}\times 40\%\times 1000\text{W}/\text{m}^2$ ambient condition. It demonstrates that targeted local cooling with moderate cooling power can substantially enhance passenger comfort during the initial cool-down period. This may have application in the luxury vehicle segment to enhance initial comfort by having a supplemental local cooling system.

From Figure 32, it is clear that there is a nice benefit in comfort with local cooling from the 5 minute to 20 minutes points under the $29.4^{\circ}\text{C}\times 55\%\times 500\text{W}/\text{m}^2$ ambient condition. At the $37.8^{\circ}\text{C}\times 40\%\times 1000\text{W}/\text{m}^2$ condition, there is a large benefit associated with local cooling that occurs almost immediately after the cool-down starts (Figure 34). Interestingly, this benefit is maintained throughout the 45 minutes of the cool-down.

SUMMARY AND CONCLUSIONS

The present local cooling study indicates that targeted local cooling as a supplement to the traditional centralized HVAC system is a viable approach to maintain passenger comfort and achieve higher energy efficiency. Through on-vehicle testing of the individual local cooling concepts, it was established that Seat, Chest, and Lap cooling are very effective and without significant shortcoming. They are therefore readily accepted by the comfort evaluators. Face cooling is effective in overcoming the "warm forehead" discomfort and is beneficial to gain comfort. However, care must be taken to ensure that it does not cause dry-eye discomfort. This can be achieved by using low airflow rate through the face cooling nozzle. The steering wheel cooling location for hands is effective but limited by the positioning of the hands on the steering wheel. The Rear Face/Neck nozzle directing air at the neck or cheek was perceived by some evaluators to be objectionable. The neck is sensitive

to air velocity. It may have possible application during Soak and Cooldown. Steady state application may be perceived as harsh.

Based on the understanding gained from individual local cooling locations, a Quad-Combination cooling strategy was devised and developed for optimization. The Quad-Combination strategy includes Seat, Chest, and Lap Cooling supplemented by the Face cooling at low airflow. Airflow parameters such as the flow rate, direction, and discharge temperature have been examined and optimized for each cooling nozzle. The combination strategy was effective in providing a comfortable in-car personal environment when the overall cabin temperature was at an elevated level achieved by reducing the HVAC system power.

The combination strategy testing by comfort evaluators has also shown that a single set of airflow delivery by the combination strategy may be able to meet the comfort requirement for the majority of the passengers. However, to meet the comfort requirements from 90% or more of the driving population, a multi-tiered airflow and discharge temperature delivery to the combination of nozzles is beneficial. Through environmental tunnel optimization, a preliminary, four-tier delivery calibration has been established.

The preliminary transient test results show that the speed to cool people is faster with local cooling than traditional whole cabin cooling. The focus of local cooling on the human body parts isolates the occupants from the impact of the cabin thermal inertia effect.

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