An Experimental Investigation of Two Locations for Representing Vehicle's Cabin Air Temperature

A.A. Lahimer
Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
e-mail: salsale3@yahoo.com

M.A. Alghoul
Center of Research Excellence in Renewable Energy, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia
Energy and Building Research Center,
Kuwait Institute for Scientific Research, P.O. Box (24885), Safat 13109, Kuwait
e-mail: dr.alghoul@gmail.com

K. Sopian
Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
e-mail: ksopian@ukm.edu.my

M. H Ruslan
Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
e-mail: hafidzruslan@gmail.com

N. G. Khrit
Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
e-mail: nassrjak@hotmail.com

Abstract— **Vehicle's cabin air temperature has a substantial role in the enhancement of passenger safety and comfort, fuel economy and tailpipe emission. Equipping the cabin with dozens of thermocouples to measure the interior air temperatures at different heights and locations for obtaining the bulk cabin air temperature is a time/effort consuming and adding unnecessarily cost, especially when dealing with the evaluation of no-flow temperature reduction techniques. The aim of this study is to compare the temperature of the most two common locations used in representing the bulk cabin air temperature. The experimental results revealed that the temperatures at the driver and midpoint were matched well in their trends for both days. Also, both average differences were negligible about 0.45ºC and 0.078ºC for day 1&2, respectively although the tests were conducted under different date, time period and climatic conditions. According to the observation and the comparison results of this study, it can be concluded that middle or driver locations can represent the average value of the cabin air temperature during thermal soak and can be taken as an index for investigation or evaluation of non-flow climate control load reduction strategies for passengers and driver thermal comfort upon entry. In addition, the cabin air temperature and other parameters can confidently be assumed to be uniformly distributed inside the entire of the cabin.**

Keywords— parked vehicle cabin soaked under the sun; breath level air temperature; thermal comfort;

I. INTRODUCTION

The temperature of the air inside the cabin enclosure which surrounding the occupants is called as the cabin air temperature. It can determine the net heat flow between the human body and its environment via convection [1]. Also, its value can give a quick indication for the conditions of occupant's thermal comfort inside the vehicle cabin and can be used to evaluate the effectiveness of any strategies in reducing the cabin soak temperature for AC load reduction and improving the level of comfort upon occupants' entry. In addition, it is an essential parameter for thermal load calculation to determine cooling capacity for AC sizing and to find out the hot soak pull-down time (cool down period) to reach thermal comfort. Furthermore, it is an important parameter of interest to many other sectors for example, in promoting public awareness [2], forecasting hazardous conditions, estimating past cabin temperatures for use in forensic analyses [3] and market competition among car makers where low initial temperature can add values to their cars to meet the needs of customers for comfort upon entry (achieving quickly thermal comfort with less amount of fuel consume).

It was agreed that reducing the air temperature of the hot-soaked vehicle cabin (initial thermal solar loads) is essential to reduce occupants exposure time to the high temperature, thereby reducing their thermal stress and anxiety upon entry in return achieving human comfort quickly, decrease the cooling peak load and lower the cooling capacity, which yield to improve the fuel economy, and reduce the tailpipe emissions [4-6]. From the above, it can be said that cabin air temperature is a sensitive and interest parameter for representing human thermal sensation and comfort. Therefore, it was convenient to adopt it as an index for any strategy evaluation. However, during surveying and scrutiny the literature, it was found that investigating the difference between driver and middle cabin locations to use one of them to represent the cabin air temperature instead of equipping the cabin with dozen of sensors for reduction strategies evaluation has not been reported in the existing literature. Some researchers used the term cabin interior air temperature in general without specifying where. On the other hand, others where specified for example, [7] used driver air temperature at breath level as a reflection for driver thermal sensation and for the evaluation of the impact of their approach on occupant sensation and HVAC energy use. As a result, this motivates the current research whose main objective is to study cabin interior temperatures under the influence of prolonged solar irradiation in order to feasibly evaluate any reduction approach.

II. MATERIALS AND METHOD

The objective of this study is to experimentally compare the temperature of two locations inside vehicle cabin parked under the sun to represent the bulk cabin air temperature. First of all, it is worthy to mention that, based on the deep study and detailed analysis carried out on the previous works, this research argued that the driver or middle of the cabin location can be used as a proxy for the cabin air temperature to evaluate any reduction technique and thermal sensation of a parked vehicle. Also, the authors expected that there will be a negligible difference in the temperature measurements between the two locations (driver and middle) at breath level, since the interior space of the mid-size sedan car cabin is very small compared with other transportation sectors such as bus, train, and airplane. Accordingly, the cabin air temperature and other parameters can be assumed to be uniformly distributed inside the cabin. The outdoor thermal hot soaking tests were planned to be conducted during the peak and steady time period due to the fact that, climatic parameters can be considered in the steady condition (solar radiation and ambient temperature) and with minimum inconsistency. In addition, the sun is most of the period is normal to the roof, therefore, direct solar radiation incidence on the sensors can be avoided so, there is no need to equip the thermocouples with a radiation shield (thermocouple inside cardboard tubing covered with white tape) or using a double concentric cylindrical or wrap Aluminum foil around them or any other type of radiation shields as many researchers did. In addition, the increase in the apparent cabin air temperature can be avoided as well. However, according to the literature [4, 8-10], time between 11:00 and 15:00 is the hottest portion of the day [5] and most likely to be in the steady state conditions as assured the maximum irradiation will be recorded in this period.

In order to prove the above argument, several outdoor thermal hot soaking tests have been conducted on the selected vehicle to investigate the temperature different between the two locations for representing the cabin air temperature. Once the temperatures measured and compared after each thermal soak test then, the results can be analyzed and discussed thoroughly. However, only the measurement results of two different days (May 26, and June 6, 2017) were selected because they were having completely different climatic conditions, table 1. In this stage, the vehicle has to be prepared and equipped with specific instrumentations and a proper procedure has to be developed for the thermal soaking test.

TABLE.1 SUMMARY OF TESTED DAYS DURING SOAKING TRIALS UNDER AVERAGE ENVIRONMENTAL CONDITIONS

Date	Soaking period	Orientation	Sky condition	Ambient temperature °C	Solar irradiance W/m^2
May 26, 2017	11:46-15:46	South-east	Partly cloudy	32.6	725
June 6, 2017	10:06-15:18	South-east	Mostly Sunny	34.5	767

The experiments were not performed on a full daylight because it was found from the previous thermal soaking tests that solar radiation between 11:00 to 15:00 is in the peak value which is adequate to rapidly rise the cabin temperatures to their maximum values. In addition, it was also found that during this peak period, orientation has insignificant influenced on the cabin temperatures. Moreover, the weather in Malaysia was fluctuating from raining to overcast before and after this period.

A. Experimental Setup

A Proton Iswara compact sedan with its original factory conditions has been available for conducting several thermal soak tests at the National University of Malaysia (latitude of 2.9° N and longitude of 101.78° E), Fig. 1.

Fig. 1. Proton Iswara compact sedan vehicle at UKM

The instruments used for the experimental works will be selected to be robust and set up outdoor to combat the harsh climatic conditions. The data acquisition systems, portable Data Logger (Datataker DT80, fig.2) will be capable for measuring the research interest parameters such as: surface and air temperatures, air velocity and the global horizontal solar irradiance. The vehicle was instrumented with thermocouple wires type K connected to the Datataker DT80 to measure and record the interest locations (at breath-level height for middle of the cabin and for driver at the midway between the front seat headrest and steering wheel), the ambient air temperatures and the solar irradiance via SP-110: self-powered silicon-cell pyranometer as shown in Fig.3. The Logger was sheltered on a table and located about 1m above the ground and the ambient air temperature was recorded at a height about 63cm above the ground. The pyranometer was oriented parallel to the horizontal plane, so the values of solar irradiance monitored in this study indicate the global radiation on a south facing horizontal flat surface. The data acquisition system was recorded the measured data every 60sec step interval throughout the test and the sky conditions throughout the experiment were observed. However, the other channels were used to measure other parameters for future studies.

Fig. 2. Datataker DT80 during field measurements

Accuracy, measurement ranges, software and other details can be found via supplier's website (www.datataker.com).

Fig. 3. Pyranometer for solar radiation measurement

B. Experimental Procedure

The procedure adopted in this study were similar for day 1 (may 26, 2017) and day 2 (June 6, 2017) and will assure to simulate the real parking scenario of the selected days. Summary of date, soaking period, instrumentation, orientation, sky condition and climatic parameters are detailed in table 1.

On the morning, the car was parked under a shadow to shield it from direct solar radiation and to protect the researchers from sunstroke as they installing thermocouples inside the cabin for the air temperature measurements and recording. During the preparation for the experiment, the seats were adjusted to the same position and all doors were opened until the cabin attaining equilibrium with the ambient, interior air temperature was as same as the ambient air temperature. After that, the car was then parked outdoor at the designated location (open car park, the ground surface was a typical asphalt surfaced) oriented facing South-east, fig.1 and then exposed to direct solar radiation normal to the cabin roof without interruption and shadow interference during thermal soaking test. The car remained stationary throughout the thermal soak tests with all windows and doors closed and with engine and AC OFF and HVAC system was in maximum (100%) recirculation mode. Simultaneously, all doors and windows were remained closed throughout the test and the cabin measurements are ON and the data were recorded every minute throughout the test and the soaking intervals were closely synchronized.

- *Thermocouples locations*

For monitoring and recording the air temperatures of the selected locations, in this study, the cabin breath level is considered as a perfect location to obtain the measurements of cabin interior parameters because it is the only location where all human sensations are close to each other and mostly uncovered. It is found to be about 25cm from the ceiling. As a result, the driver air thermocouple will be dangled downward in the air space in front of the seat headrest at the breath level, while the middle cabin air thermocouple also will be dangled downward midway the front seat headrests at the breath level, fig.4. The temperature sensors used for measuring the air temperatures were not fitted with radiation shields as the sun was overhead and the errors will be cancelled out when the temperatures are subtracted.

Fig. 4. Thermocouples located at breath-level of driver (DR) & middle cabin location (Mid)

Lastly, there will be one thermocouple mounted and shaded beneath a table and 63cm above the ground near the vehicle for monitoring the ambient air temperature.

III. RESULTS AND DICUSSION

In this section, the experimental data of the comparison between temperatures measured at middle and driver breath level during hot thermal soak trials are shown in figures 6&8 and going to be discussed and analyzed.

A. Soaking Test of Day 1, (May 26, 2017)

This experiment was conducted for 4h of period of time from 11:46 till 15:46 in partly cloudy sky condition. Fig.5 shown that the trend of the average global horizontal solar irradiance which measured on a horizontal surface was increased with time even it varied during the measurement due to the sky conditions (partly cloudy weather). The maximum recorded irradiance was 1241W/m^2 and the average solar irradiance was 725W/m^2.

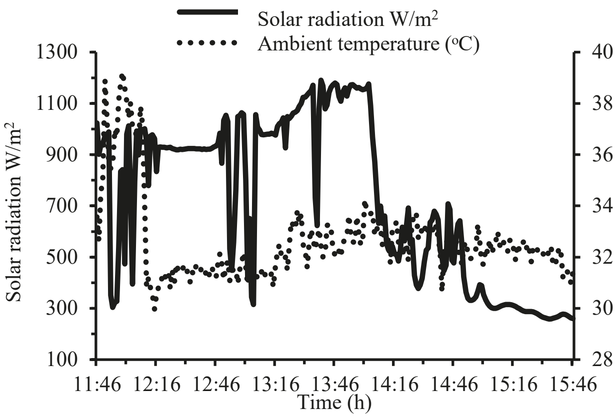

Fig. 5. Solar irradiance and ambient air temperature measurements, Day 1

Also, Fig.5 shows the average ambient air temperature trend during the time of the experiment. The influence of the solar irradiance on the ambient air temperature can be seen clearly in this figure. Where the variation of the ambient air temperature pattern during the parking condition is following the variation of the solar irradiance, with a certain time lag. However, the average ambient temperature was 32.6^{o}C.

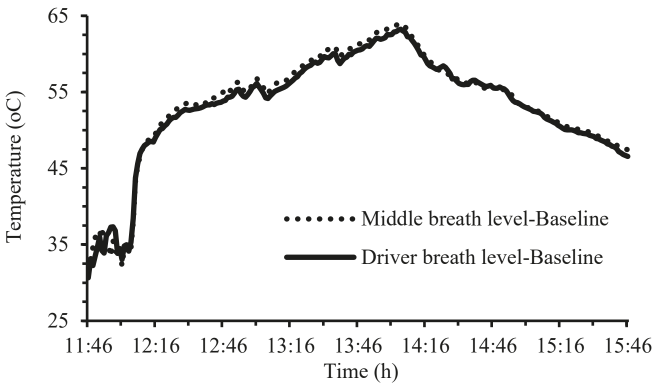

Fig. 6. Comparison between middle and driver breath level air temperatures, Day 1.

The comparison between the middle and driver breath level air temperatures for Day 1 is shown in Fig. 6. The figure shown the average soaking temperature profiles of the two locations (middle cabin location with a dashed line and the driver location with a solid line) after being soaked in the sun. The temperatures at both locations were matched well in their trends (almost identical). The middle cabin and driver locations reached their maximum of 63.97^{o}C and 63.24^{o}C, respectively at the same time (14:05) and their average were 53.6^{o}C and 53.14^{o}C, respectively. It was found that the average air temperature difference between the two locations at the breath-level was 0.45^{o}C.

B. Soaking Test Day 2, (June 6, 2017)

This test was conducted over quite a long period of time than the previous one. The climate conditions were as the following:

- Average ambient air temperature was 34.5^{o}C and the maximum recorded value was 37.8^{o}C corresponding to 13:46 and solar irradiance was 934W/m^2.
- Average solar radiation was 767W/m^2 and the max solar radiation was 994W/m^2 recorded at 12:10.

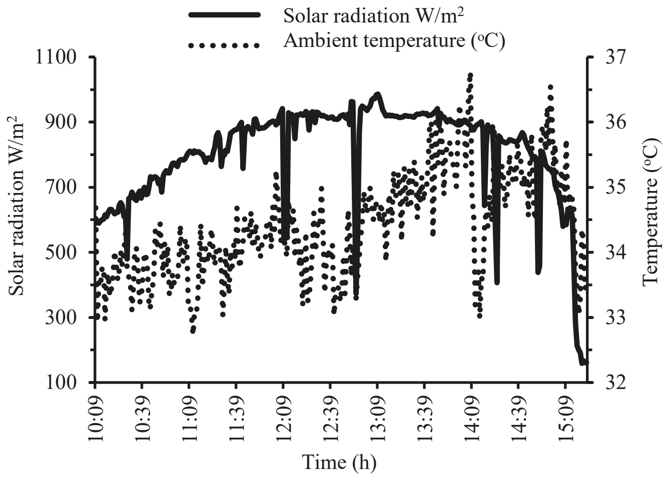

Fig. 7. Solar irradiance and ambient air temperature measurements, Day 2

Fig.7 shows the average measurements of the solar irradiance and ambient air temperature of Day 2. In this test, the average global solar irradiance was measured between 10:09 and 15:09. The figure shown that the solar irradiance trend increased with time and it was almost consistent due to the weather condition at that day (mostly sunny).

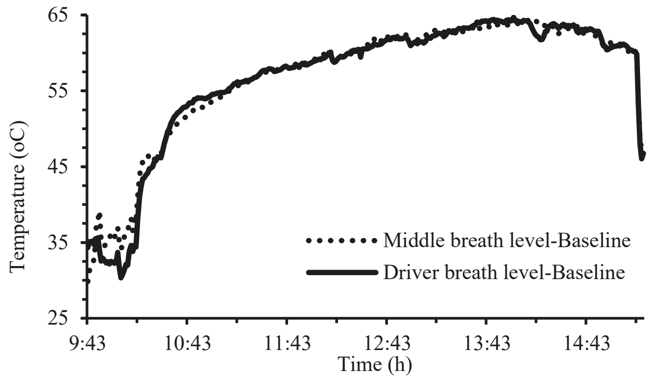

Fig. 8. Comparison between middle and driver breath level air temperatures, Day 2

Fig. 8 shows the comparison between the middle and driver breath level air temperatures for Day 2. The figure shows that the maximum difference was in the beginning before the doors closed due to proximity of the thermocouple's location to the outside air. The middle cabin and driver locations reached their maximum 64.4^{o}C at 14:11 and 64.7^{o}C at 13:59, respectively and their average were 57^{o}C and 56.7^{o}C, respectively. It was also found that the temperatures at both locations, driver and midpoint were matched well in their trends (almost identical) and the average differences between the two locations during the soaking period were negligible about 0.078ºC, considering when doors were closed.

C. Discussion (Day 1&2)

It was observed that solar irradiance is the predominant climatic factor to determine the final cabin temperature. It rises the interior temperatures of an unshaded stationary vehicle cabin soaked under the direct sun typically between 20–30ºC higher than the ambient temperature. The high temperature resulted as the conversion of incident radiant energy into thermal energy by two mechanisms; solar absorption and emission of cabin's surfaces along with the effect of greenhouse phenomenon, since cabin is well sealed. While, the impact of the ambient temperature on the cabin interior temperatures is only thermodynamically. Moreover, the variations of cabin interior soak air temperatures during the parking period are behaving similar to the pattern of the ambient temperature which generally follows the variation of solar irradiance with a certain time lag. For clear sky days with null wind speed, the solar irradiance and ambient temperature can be considered steady with minimum inconsistency during the peak solar irradiance period (11:00-15:00) and for simplicity cabin air temperature and other parameters can be assumed to be uniformly distributed inside the cabin because the space in the mid-size sedan car cabin is very small compared with other transportation systems. Thus, time between 11:00 and 15:00 is found to be very convenient when only one car is available for conducting numerous trials.

It was also observed that both locations were heated rapidly due to the large solar input through the windows which results in higher interior air temperatures rate in the beginning, while it cools in the afternoon more rapidly than does the outside air due to low solar intensity. In fact, the interior air temperatures at both locations for day (1&2) were expected to continue steady with their maximum value during the peak solar irradiance period, but the drop of the recorded temperatures can be attributed to the weather conditions as the sky became cloudy. However, it was confidently to expect that the air temperatures at the middle and driver breath-level locations of the two distinctive days will reach their maximum values almost at the same time (driver precedes middle) about 14:00 within the peak solar irradiance period (11:00-15:00) although the two experiments were conducted in different date, time, duration and climatic conditions. Because the driver location is nearer to the interior heat sources (dashboard, steering wheel, windshield and driver seat) than the middle location. This gap of time indicated that the heat transfer within the cabin is in the natural convection mode as a result of no openings were provided and the infiltration was negligible. This observation was agreed with [10, 11] who observed that the interior hot air was close to the front top roof and rear windshield. In addition to that, those sources received more radiation than the rear of the cabin as the car was oriented toward north-east during the test. But on Day 1 the driver location reached its maximum value as same as the middle location did. This is due to the inconsistency of the solar irradiance.

According to the observation and the comparison results of the chosen locations measurements (Fig. 6&8) it can be concluded that the cabin air temperature and other parameters can confidently be assumed to be uniformly distributed inside the entire of the cabin. As a result, one of them can represent the average value of the cabin air temperature during thermal soak and can be taken as an index for investigation or evaluation of non-flow climate control load reduction strategies for passengers and driver thermal comfort upon entry.

IV. Conclusion

Vehicle cabin is a critical segment in the early design stage of the vehicle because it influences passenger's health, safety and comfort, driver performance, fuel consumption and tailpipe emission. However, breath level is found to be as a perfect location to obtain the measurements of interior parameters such as temperature and humidity because the breath level is the only location where all human sensations are close to each other and mostly uncovered. Therefore, equipping the cabin with dozens of thermocouples at different heights and locations, such as passenger breath, feet, chest, and lap levels for both front and rear passenger locations is not necessary for calculating their average and obtaining the bulk cabin air temperature. According to the observation and the experimental results of this work, this study suggested that the middle or driver breath level locations can represent the cabin air temperature during the thermal soak test and also can be taken as an index for occupants' thermal comfort and in the evaluation of any climate control load reduction techniques for compact sedan vehicle.

Acknowledgment

We would like to express our deepest gratitude to Col. Khalil Elshebli, counsellor defense attaché office embassy of Libya in Kuala Lumpur, Malaysia for the support and standing in completion of this work.

References

[1] A. Alahmer and M. Omar, "Vehicular Cabins' Thermal Comfort Zones; Fanger and Berkley Modeling," Vehicle Engineering, vol. 1, pp. 19-32, 2013.

[2] A. Guard and S. S. Gallagher, "Heat related deaths to young children in parked cars: an analysis of 171 fatalities in the United States, 1995–2002," Injury Prevention, vol. 11, pp. 33-37, February 1, 2005 2005.

[3] A. Grundstein, V. Meentemeyer, and J. Dowd, "Maximum vehicle cabin temperatures under different meteorological conditions," International Journal of Biometeorology, vol. 53, pp. 255-261, 2009/05/01 2009.

[4] R. Saidur, H. H. Masjuki, and M. Hasanuzzaman, "Perfromance of an Improved Solar Car Ventilator," International Journal of Mechanical and Materials Engineering (IJMME), vol. 4 pp. 24 -34, 2009.

[5] N. I. Jaksic and C. Salahifar, "A feasibility study of electrochromic windows in vehicles," Solar Energy Materials and Solar Cells, vol. 79, pp. 409-423, 2003.

[6] J. P. Rugh, et al., "Reduction in Vehicle Temperatures and Fuel Use from Cabin Ventilation, Solar-Reflective Paint, and a New Solar-Reflective Glazing," presented at the SAE World Congress, Detroit, Michiga, 2007.

[7] M. A. Jeffers, L. Chaney, and J. P. Rugh, "Climate Control Load Reduction Strategies for Electric Drive Vehicles in Warm Weather," SAE Technical Paper 2015-01-0355, 2015.

[8] W. A. ABD-FADEEL and S. A. HASSANEIN, "Temperature Variations in a Parked Car Exposed To Direct Sun during Hot and Dry Climates," International Journal of Automobile Engineering Research & Development (IJAuERD), vol. 3, pp. 75-80, 2013.

[9] I. M. A. Aljubury, A. A. Farhan, and M. A. Mussa, "Experimental Study of Interior Temperature Distribution Inside Parked Automobile Cabin," Journal of Engineering, vol. 21, pp. 1-10, 2015.

[10] H. H. Al-Kayiem, M. F. B. M. Sidik, and Y. R. A. L. Munusammy, "Study on the Thermal Accumulation and Distribution Inside a Parked Car Cabin," American Journal of Applied Sciences vol. 7, pp. 784-789, 2010.

[11] A. Mezrhab and M. Bouzidi, "Computation of Thermal Comfort inside a Passenger Car Compartment," Applied Thermal Engineering, vol. 26, pp. 1697-1704, 2006.