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PHYSIOLOGICAL RESPONSES OF THE DRIVER IN A SOLAR HEATED CAR CABIN

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ABSTRACT

The aim of this study was to evaluate the physiological responses of the driver when he or she enters the vehicle cabin for the first time after the vehicle was in a parking lot. Eight healthy male students underwent tests in vehicle cabins that had been parked for two hours without any shade. Immediately after they entered the cabin, they ran one of the test conditions: (1) all windows in the cabin were fully lowered and the air conditioning (AC) system was off (CON); (2) all windows were closed and the AC was set at the first speed level (AC 1); or (3) all windows were closed and the AC was set at the second speed level (AC 2). The attempt to decrease the air temperature in the cabin by opening all the windows did not provide a significant impact on the participants' physiological responses. Decreasing the air temperature by turning the vehicle air conditioning on lowered mean skin temperature and heart rate, but not core body temperature. However, using the first or second speed of the AC did not make any significant difference in the physiological responses of the volunteers.

Keywords: Physiological responses; Vehicle air conditioning system; Vehicle cabin

1. INTRODUCTION

Nowadays, the existence of an air conditioning unit in a car is not just as an accessory. In Indonesia and other tropical countries, air conditioning is designed only to cool the hot air trapped in a cabin. The air conditioning is important to provide comfort for the driver and passengers. Air conditioning regulates the temperature as well as the humidity in the cabin. In Indonesia, the average highest air temperatures (T_a) can reach 38^{o}C with 87% relative humidity (RH). The temperature increases to almost double when air is trapped inside the cabin of a vehicle in a parking lot during the day without any shade from the sun (Al-Kayiem et al., 2010; Basar et al., 2013; Saidur et al., 2009). Data shows that mean annual solar irradiation in Indonesia is 4–5.5 kWh/m^2 per day (Morrison & Sudjito, 1992; Rahim et al., 2010; Rumbayan & Nagasaka, 2012) with average mid-day irradiation at 1000W/m^2 (Jacob, 2010) (Figure 1). These radiation intensities are almost equivalent to the solar intensities in Middle East countries that have 4.5 to 6.1 kWh/m^2 intensity per day (Sudhir & Al Dhali, 2015).

Heat trapped inside a vehicle cabin is an accumulation of the heat propagation of the vehicle's panel body (65%), the engine system (20%), and the latent heat of the highway (15%) (Gilles, 2015). Besides that, a vehicle's speed and the number of passengers can also influence cabin's temperature (Mezrhab & Bouzidi, 2006). For that reason, having a thermally comfortable cabin is very important. However, evaluating and analyzing the thermal comfort in a vehicle cabin is

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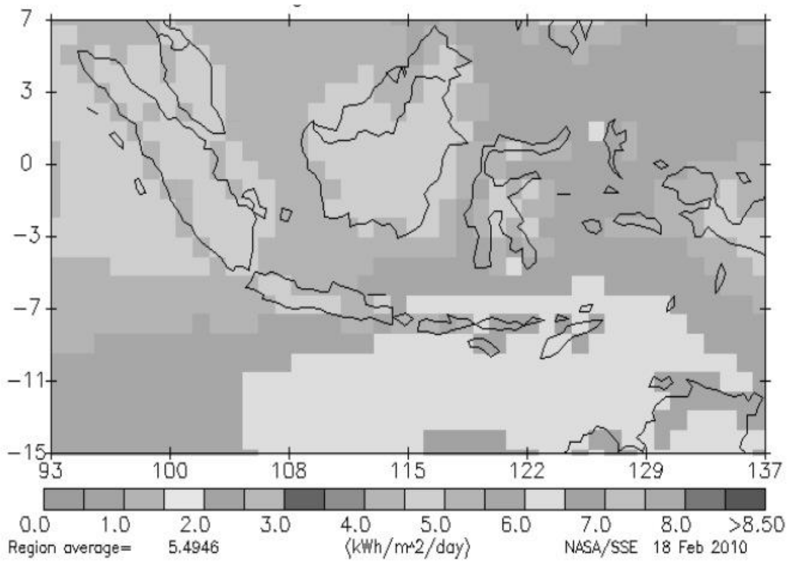

Figure 1 Mean annual solar irradiation in Indonesia 1993-2012 (Jacob, 2010)

complex work that involves several variables (Brooks & Parsons, 1999; Cengiz & Babalık, 2006). The microclimate inside the vehicle cabin is very dynamic and non-symmetrical. As a result, a bad microclimate condition can influence the passengers and the performance of the driver (Norin & Wyon, 1992).

Four methods are commonly used in the evaluation of thermal comfort in a vehicle cabin: (1) a theoretical numerical method using computer simulation (Alahmer et al., 2011; Prek, 2006; Tseng et al., 2014); (2) testing the vehicle on a public road or parking lot using humans as test subjects (Jasni & Nasir, 2012; Saidur et al., 2009; Vishweshwara & Al Dhali, 2013); (3) a laboratory test using a thermal manikin (Mayer & Schwab, 1999; Snycerski & Wasiak, 2002; Tanabe et al., 1994); and (4) a laboratory test using humans as test subjects. Studies have used these methods mainly to explore the microclimate conditions inside vehicle cabins, but no previous studies have evaluated the impact of the microclimate on the physiological and subjective sensation responses of the driver or passengers. The aim of this study was to evaluate the physiological responses of the driver when he or she enters the vehicle cabin for the first time after the vehicle was in a parking lot without any shade.

2. METHODOLOGY

2.1. Volunteers

Eight healthy male students participated in this study (Table 1). To avoid partial heat acclimation due to the prevailing ambient conditions during testing, the experiment was balanced across subjects according to the Latin square design. Before participating in the study, the volunteers completed a health status questionnaire and signed a written informed consent form.

Table 1 Characteristics of the participants

Characteristics	Average	Standard Deviation
Age (y)	21	1.0
Body Weight (kg)	65	10.7
Body Height (cm)	170	5.8
Body Mass Index	22	3.1
% Fat Ratio	19	6.5

2.2. Experimental Design and Procedures

Before the experiments with the volunteers were performed, an experiment was conducted to determine the best time period to take the physiological and subjective sensation data in the vehicle cabin. A test vehicle (three rows of seats for six passengers) was parked without shade from 10:00 AM until 4:00 PM for seven consecutive days with all windows closed. Figure 2 shows the average temperature in the vehicle cabin. Based on this data, it was decided that for the main experiments, the test vehicle must be parked from 11:00 AM until 1:00 PM.

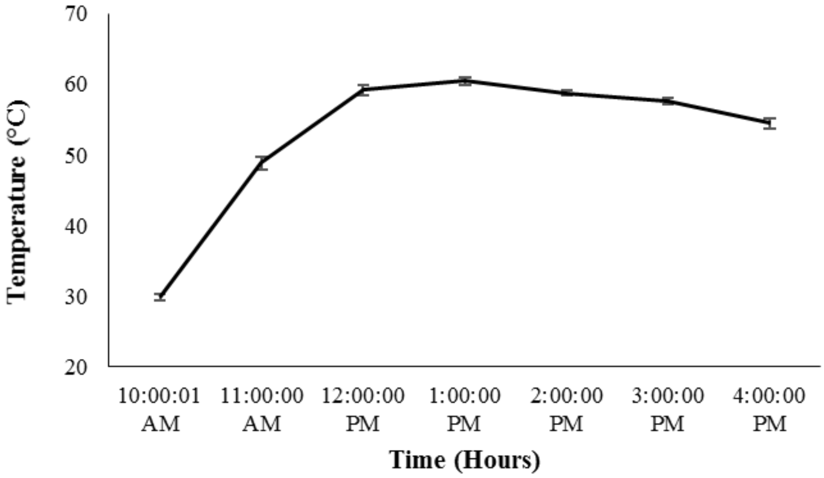

Figure 2 Average cabin temperature

One volunteer was tested each day. On the day that the volunteer was assigned to, he had to be in the preparation chamber about 30 minutes before 1:00 PM. Just after the volunteer arrived in the preparation room, he was asked to remove his clothes and wear shorts only to allow the sensors to be put on specific places on his body. After that, the volunteer donned a round-neck T-shirt, short sleeve shirt, short pants, long pants, socks, and running shoes with overall insulation about 1 clo (0.115 m^2K/W). Five minutes before 1:00 PM, the volunteer was escorted to the test vehicle. At 1:00 PM, the volunteer entered the vehicle cabin, started the vehicle's engine, and initiated one of the following test conditions: (1) all windows in the cabin were fully lowered and AC was off (CON); (2) all windows were closed and AC was set at the first speed level (AC 1); or (3) all windows were closed and AC was set at the second speed level (AC 2). After applying one of the test conditions, the volunteer then drove the vehicle for 15 minutes at approximately 30 to 40 km/h on a specific route that had been determined earlier. At minute 15, the vehicle was pulled over and the engine was stopped at exactly 20 minutes.

2.3. Measurements

Cabin temperature was continuously measured every second throughout the trial using a logger (LT-8A, Gram Corporation, Japan) and a temperature probe (LT-ST08-00, Gram Corporation, Japan; resolution of 0.01°C). The probes were placed on the ceiling of the cabin at eight sites (driver's seat, front left seat, right middle seat, middle seat, left middle seat, right rear seat, middle rear seat, and left rear seat). T_{cab} is the simple average of the T_{cab} from each site. RH was also measured every second using a thermo recorder (ESPEC RS-12).

The volunteer's core temperature was measured every second from the tympanic canal of his left ear using a tympanic probe (NiproCE) and a logger (Nipro) and was defined as the tympanic temperature (Tty). Skin temperature was measured with the same logger and probe used in the cabin temperature measurement. The probes were attached to eight sites (head, chest, abdomen, back, forearm, upper arm, thigh, and calf) and measurements were taken every second. The weighted mean skin temperature (T̅sk) was calculated according to a modified version of Hardy and DuBois' (1938) 7-point formula. Heart rate (HR) was monitored every second throughout the experiment using an HR monitor (RS400, Polar Electro, Finland).

2.4. Statistics

All quantitative data are expressed as the mean for the last three minutes of each hours and the standard deviation (mean ± SD). A repeated Analysis of Variance (ANOVA) was used to identify differences in the physiological responses of the volunteer. All statistical analyses were performed with the SPSS v. 17.0 statistical package (SPSS Inc., Chicago IL, USA). Significance was set at $P < 0.05$.

3. RESULTS

There was a narrow gap variation in the temperature inside the vehicle cabin. After being parked for one hour, the cabin temperature rose from 29.85 ± 0.5°C to 56.44 ± 0.88°C; the highest cabin temperature was 60.47 ± 0.37°C at 1:00 PM (Figure 3).

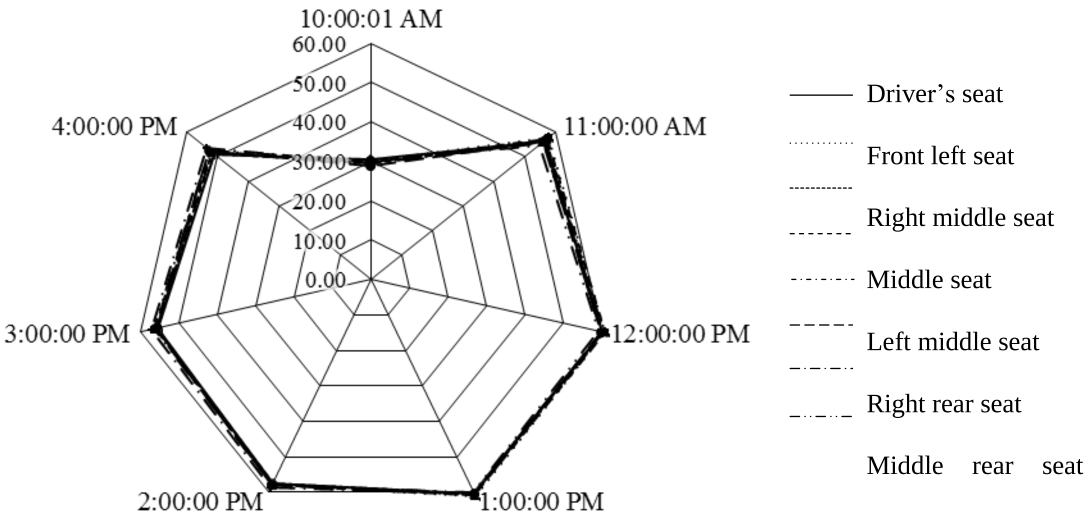

Figure 3 Distribution of temperature inside the vehicle cabin

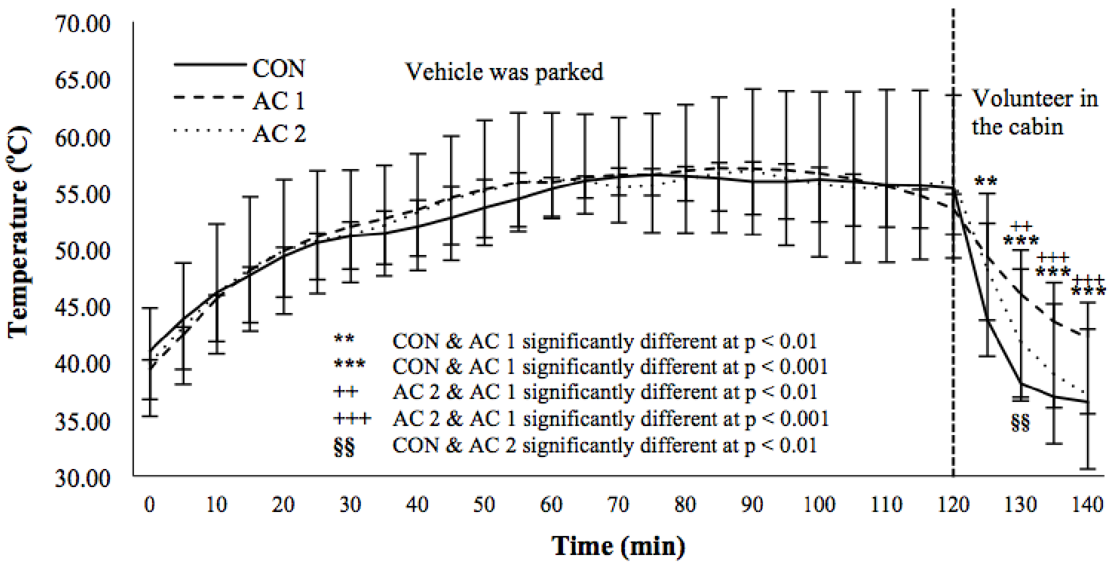

Figure 4 Time course of cabin temperature

The cabin temperature then dropped sharply when one of the test conditions was applied (Figure 4). Interestingly, when all the windows were opened without operating the AC (CON), the cabin temperature dropped more sharply than the test condition that used the air conditioning (AC 1). After 20 minutes of operation, the AC 1 test was only able to reduce the temperature by 11.33 ± 0.4°C from the initial temperature of 53.48 ± 0.5°C just before the air conditioning was turned on. On the other hand, the CON and AC 2 tests were able to suppress cabin temperature by 18.82 ± 0.3°C and 18. 85 ± 0.5°C, respectively.

In contrast, the physiological responses of the volunteers did not show a similar trend. The volunteers started the tests in the vehicle cabin with a $\overline{T}_{sk}$ of 31.11 ± 0.7°C, 31.11 ± 0.4°C, and 31.22 ± 0.5°C, for the CON, AC 1, and AC 2 tests, respectively (Figure 5). Five minutes after entering the cabin, the $\overline{T}_{sk}$ of the volunteers rose to 33.12 ± 0.3°C and 31.08 ± 0.3°C for CON and AC 1, respectively. The $\overline{T}_{sk}$ in the AC 2 test rose slightly less than the CON test to 32.90 ± 0.4°C. In the rest of the experiments, the $\overline{T}_{sk}$ of the volunteers in the CON test showed a continuous increase until minute 10 after the air conditioning was turned on and then a slight decrease to 33.38 ± 0.5°C at the end of the experiment. In the AC 1 and AC 2 tests, five minutes after the air conditioning was turned on the $\overline{T}_{sk}$ of the volunteers had already showed a decreasing trend. At the end of the experiment, the $\overline{T}_{sk}$ for tests AC 1 and AC 2 were 32.64 ± 0.5°C and 32.36 ± 0.6°C, respectively.

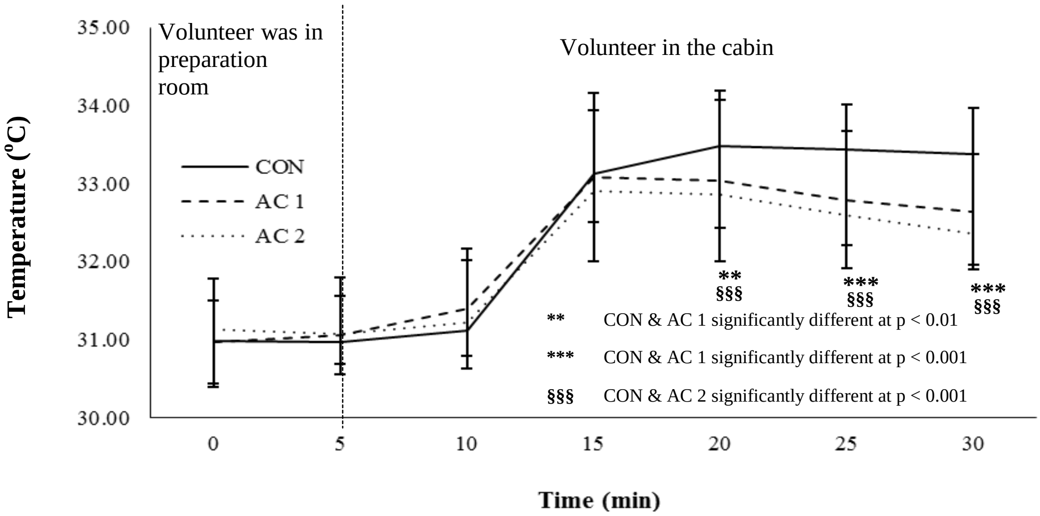

Figure 5 Mean skin temperature ($\overline{T}_{sk}$) of the participants

The tympanic temperature (T_{ty}) of the volunteer also showed an increasing trend line due to the hot air temperature inside the vehicle cabin and it was not lowered by any of the air conditioning test methods. However, there was no significant difference of T_{ty} among the test conditions (Figure 6). The initial T_{ty} of the volunteers when they entered the vehicle cabin was stable just below 37°C. At the end of the experiment, the T_{ty} were 37.66 ± 0.8°C, 37.82 ± 0.7°C, and 37.46 ± 0.5°C for the CON, AC 1, and AC 2 tests, respectively.

Apparently, the HRs were influenced by the $\overline{T}_{sk}$ of the volunteers. After a stabilization period of 10 minutes in the preparation room, the HRs of the volunteers who performed the CON and AC 2 tests were 82 ± 1 bpm, whereas the HRs of the volunteers who performed the AC 1 test were 85 ± 2 bpm. HRs peaked five minutes after the participants entered the vehicle cabin at 95 ± 3 bpm, 102 ± 4 bpm, and 98 ± 4 bpm for CON, AC 1, and AC 2 tests, respectively. After five minutes in the vehicle cabin, the HRs of the participants reached their plateau. The final HRs for each test were 96 ± 4 bpm, 98 ± 2 bpm, and 92 ± 5 bpm for CON, AC 1, and AC 2, respectively, and no significant differences were found during the entire test period among the different tests (Figure 7).

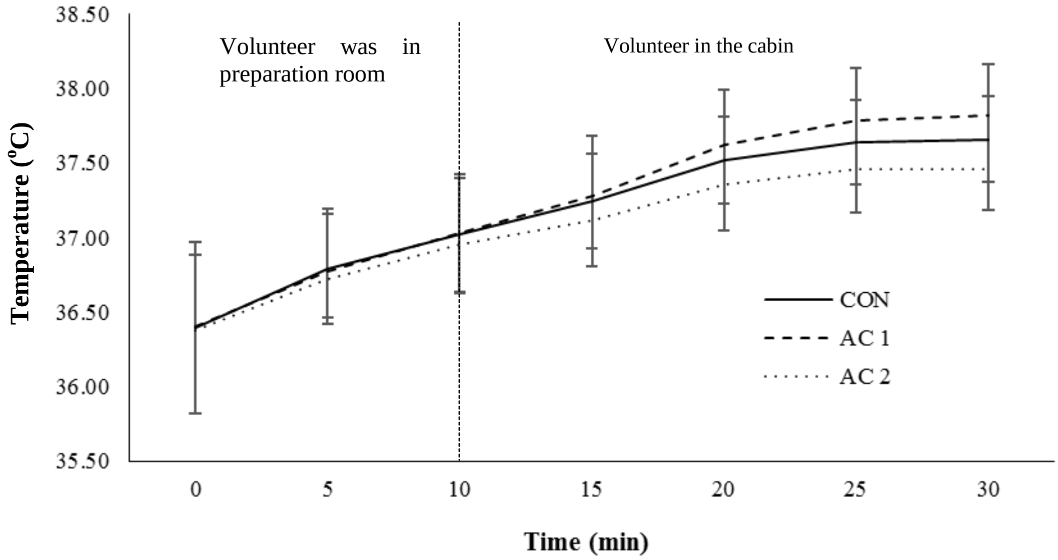

Figure 6 Average tympanic temperature (T_{ty}) of the participants

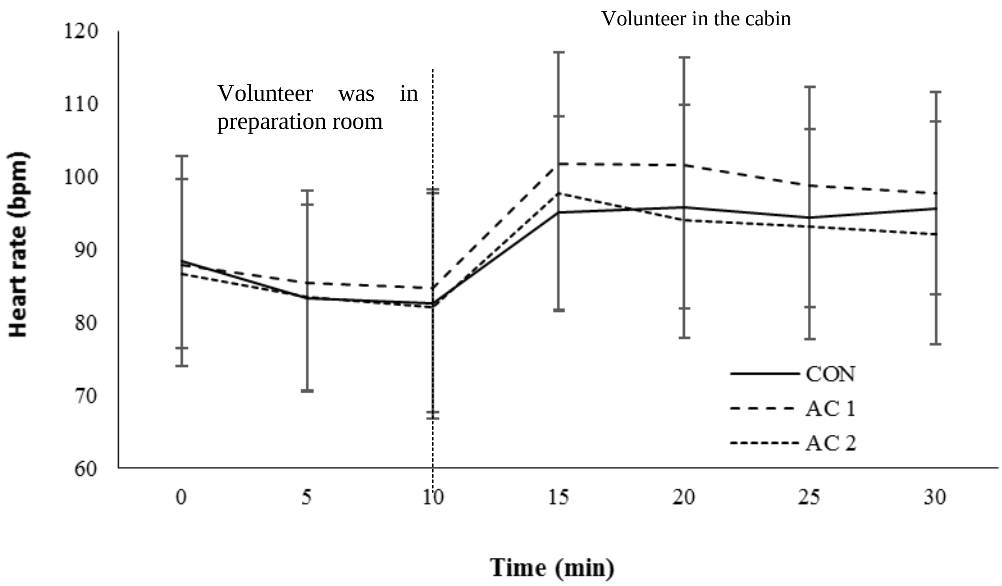

Figure 7 Average HR of the participants

4. DISCUSSION

The results of this study are very important for completing the understanding of human comfort in vehicle cabin microclimate conditions in relation to the use of the vehicle's AC system. The operation of the AC requires approximately 4000 W of additional mechanical power (McGuffin et al., 2002; Rugh et al., 2004), which leads to a high fuel consumption pattern. Reducing the cost of cooling the vehicle cabin, improving climatic control systems, lowering the solar heating load, and delivering cool air more efficiently while maintaining the required thermal comfort levels inside the vehicle are activities that can be done (Walgama et al., 2006).

The experiment's design for trapping the solar heating inside the cabin produced similar trend lines with previous studies (Jasni & Nasir, 2012; Saidur et al., 2009; Vishweshwara & Al Dhali, 2013). Figures 2 and 3 indicate that it only took two hours to double the cabin temperature from its initial temperature. Putting the AC's fan speed on the second level (and not the first level) helped to release some of the heat of the greenhouse effect in the vehicle cabin so that the cabin temperature decreased to a level similar to its initial temperature. Interestingly, a similar condition was obtained by lowering the windows in the cabin and not operating the AC system.

Depending only on the natural convection of the heat from the inside of the cabin to the ambient temperature, however, was not enough to lower the mean skin temperature of the drivers, which was the only physiological indicator that was affected by the temperature of the cabin. Figure 5 implies that to suppress the heat that hit the skin of the driver, one could choose to operate the AC system on the first level of speed and it would not be necessary to speed up the cool air circulation by putting the AC on the second level. It because the second level of AC would provide a similar effect, and the energy used to speed up the air would be higher than that used when only operating the AC on the first level.

5. CONCLUSION

The objective of this study was to evaluate the impact of hot air trapped in a vehicle cabin gained from a parking lot without any shade on the physiological indicators of the driver. After being parked for two hours, the vehicle cabin temperature exceeded 60^{o}C and increase the body peripheral (T_{sk}) and core temperatures (T_{ty}). The HR indicator also rose slightly, which might be due to the increasing of the T_{sk}. The attempt to decrease the air temperature in the cabin by opening all the windows did not significantly impact the physiological responses. Conditioning the air temperature by turning the vehicle air conditioning on, however, did suppress T_{sk} but not T_{ty} and HR. Furthermore, using the first or the second speed of the air conditioning did not make any significant difference in the physiological responses of the volunteers.

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