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Experimental Investigation of Local Thermal Sensation of Vehicle Passengers During Cooldown

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Abstract: This paper aims to investigate thermal sensations of vehicle passengers near face, chest and feet during cooling period in a stationary car cabin. Probit regression analysis was applied for predicting localised air temperature variation corresponding to local thermal sensation of vehicle passengers that is based on nine-point thermal sensation scales. Our results show that the maximum limit of air temperature recommended to achieve a thermal neutrality is approximately 34°C, 30°C and 29°C for face, chest and feet, respectively. We also found that facial thermal sensation had a stronger relationship with local air temperature.

Keywords: thermal sensation; cooldown; experiment; probit regression analysis

1. Introduction

The role of heating, ventilation, and air conditioning (HVAC) systems is crucial in ensuring the comfort of individuals within enclosed spaces¹. Conditions that are too hot or too cold can contribute to the discomfort of occupants. However, HVAC systems are known to use a lot of energy to operate, which is considered to be one of the major contributing factors to global warming². While many has concentrated the efforts in reducing the environmental impact of air conditioning by developing new refrigerants³, minimizing heat entering the space⁴, and optimizing HVAC duct configurations⁵, it is also imperative to understand the relationship between thermal environment and how it affects human thermal comfort/sensation in order to design an effective air conditioning system.

The use of HVAC in vehicle environments is especially important to provide thermal comfort to passengers as fast as possible⁶ because of the extreme temperature when the car is soaked under direct solar radiation⁷. However, vehicular air conditioning is one of the biggest contributor to greenhouse gas emission⁸ compared to other categories of air conditioning systems. One study had found that the air conditioning consumed about 90% more fuel than without air conditioning during idling condition⁹. Therefore, the ability to predict the desired thermal comfort/sensation of passengers could optimize energy

consumption while achieving thermal comfort for passengers.

A considerable body of literature has reported on thermal sensation model and its application in vehicle environments. Many researchers have adopted Fanger's Predicted Mean Vote (PMV) model¹⁰ to evaluate passenger thermal comfort inside vehicles including Alahmer et al.¹¹, Chotave et al.¹², Yan et al.¹³. This model considers environmental factors, metabolic rate, and clothing insulation, designed specifically for indoor thermal comfort assessment.

To accurately predict thermal comfort in the dynamic and non-uniform environment of a car cabin, Nilsson¹⁴ proposes the use of equivalent temperature, evaluated through special equipment such as thermal manikins. In general, the equivalent temperature is determined by measuring the amount of heat loss on one or more parts of the sensors during exposure to a conditioned climate. The local and overall thermal comfort is then estimated by referring to comfort zone diagram.

It is worth noting that the PMV model is only effective under steady-state and homogeneous environments, which is much different when compared to a typical car cabin. Recently, Danca et al.¹⁵ compared the PMV model against the thermal sensation vote collected from questionnaires where they found the PMV values are far from the actual value. On the contrary, more sophisticated instruments are required to account for heat exchange

between sensors and the car cabin environment for the evaluation of equivalent temperature.

Alternative thermal sensation models that are more robust and directly correlated to the thermal environment have also been developed by many. Most of the models were developed empirically using multiple regression model (see Hagino and Hara¹⁶, Shimizu and Jindo¹⁷, Yamashita et al.¹⁸, Yun et al.¹⁹). Apart from thermal environment, few other researchers have explored human thermoregulation as a predictive factor for anticipating thermal sensation and comfort. Qi et al.²⁰, for instance, examined human skin temperature as a predictor to forecast local thermal sensation within a car cabin, revealing a strong linear correlation. Zhou et al.²¹ have considered cabin thermal environment and human skin temperature to compare thermal comfort predictions under real driving conditions. The study revealed differences in the thermal sensation of the driver under outdoor driving conditions compared to when the vehicle was parked.

While multiple regression analysis is a common method to relate thermal comfort to thermal environments, it is challenging to model ordered category responses like thermal sensation using ordinary linear regression. This is because the dependent variable in linear regression is considered as continuous, which implies the underlying assumption of equality of distances between the categories. In this regard, the ordinal probit models is the most appropriate method and have been widely used for indoor thermal comfort evaluation (see Indraganti and Boussaa²², Rijal et al.²³).

The focus of this paper is to analyze the localized heat sensations felt by passengers within a stationary car cabin as the car cabin undergoes a cooling period. Field surveys were conducted in the open field; taking into account the air temperature at various positions and a questionnaire to the occupants. Based on the data obtained, the local thermal sensations votes (TSV) of the occupants were analyzed and developed using ordinal probit regression.

2. Methodology

Due to the potential for high outdoor air temperature and intense solar radiation causing significant thermal discomfort to vehicle occupants, these experiments were designed to simulate the HVAC cooldown period from occupants entering a parked vehicle from an outdoor hot environment. The tests were performed over a four-day period in March 2020 without cloud cover and with outdoor air temperatures exceeding 30 °C. For this study, 7 male subjects, all local Proton staff with an average age of 42.3 (standard deviation=8.5), were recruited to assess thermal comfort in a car. All subjects wear short sleeve shirt, long trousers, men's briefs, socks and sport shoes with clo value of approximately 0.56²⁴. The experiments were performed using a B-segment sedan automobile, namely Proton Persona 2014 model positioned at open field (there is no tall structures/objects in 50 m radius)

facing East. The experiment was conducted under stationary in order to keep the same sun orientation for all test period and for the safety of occupants to fill out the thermal comfort surveys.

Both exterior/interior environments as well as subjective thermal response are collected throughout the experimental trials. In order to account for the large temperature variation in the car cabin during cooldown period, a 9-point thermal sensation was adopted to evaluate subjective thermal response. The nine-point thermal sensation categories are divided into two distinct thermal sensations. For the hot sensation, the most extreme is Very hot (+4), followed by Hot (+3), Warm (+2), and Slightly warm (+1). In contrast, for the cold sensation, the less extreme is Slightly cool (−1), gradually increasing to Cool (−2), Cold (−3), and Very cold (−4). Both sensations are centered around the 'neutral' mark at zero on the thermal scale. Subjects were instructed to provide local thermal sensation votes (face, chest, and feet) during cooldown period. For exterior environment, a pyranometer (EKO model MS-602, accuracy of $\pm 2\%$) was used to measure solar irradiation while a standard thermocouple (K-type, accuracy of $\pm 0.75\%$) was used to measure ambient air temperature. These sensors were mounted on top of the car rooftop (see Fig. 1a). For interior environments, a total of 13 K-type thermocouples were placed at all seats, namely front right (FR), front left (FL), rear right (RR) and rear left (RL) at three heights (face, chest and feet) including one at center cabin. Another 5 K-type thermocouples were placed at supply/return vents (see Fig. 1b). All sensor junctions were connected to a datalogger (GL820; GRAPHTEC) where signals were recorded at 5-s intervals.

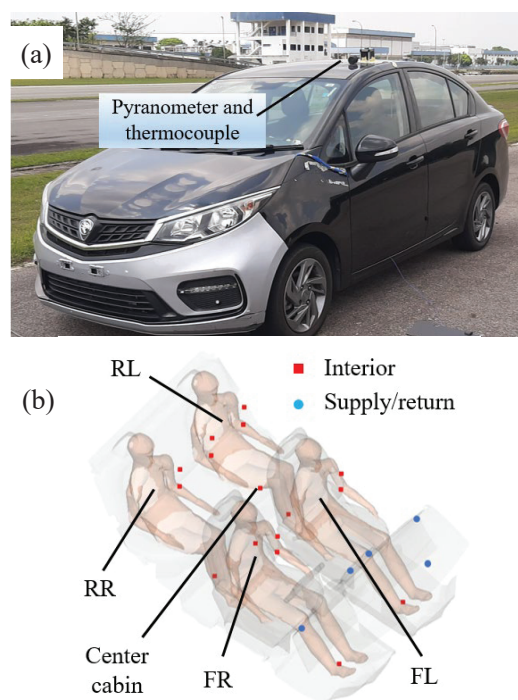


Fig. 1: Sensor placements: (a) sensors outside cabin (b) thermocouples inside cabin.

The test car is first parked outdoor in the morning and let to be soaked under the sun for at least two hours. The cooldown experiment begins in the afternoon when the center cabin temperature has reached more than 60 °C. Four subjects arrived at the site by another car and stood outside of the test car for at least two minutes to precondition their body with the ambient environment. Then, subjects are instructed to promptly and simultaneously embark upon entering the car, with the purpose of minimizing any potential heat loss. The engine and A/C system is not switch on until the air temperature at center cabin has reached 60°C. Once the air temperature at center cabin has reached a desired level, the car engine and A/C system with recirculation mode are turned on upon which the subjects votes every two minutes for 10 minutes before the vote frequency is increased to every five minutes for another 20 minutes. During the test, subjects are not allowed to adjust the air-conditioning to their preferences. Instead, all vent outlets are directed normal to the dashboard with maximum blower speed and lowest temperature settings. The main reason for the vent outlets to be directed normal is to avoid direct cooling towards specific passenger and/or body parts; which can possibly causes bias subjective votes due to unbalance cooling distribution.

3. Results and Discussion

Figure 2 shows the ambient environmental parameters based on average, maximum, and minimum values, representing alterations in meteorological data across all experiments. The average solar radiation was 500 W/m² while the average ambient temperature was 34°C. The ambient environmental parameters were found to be consistent because the cooldown experiment were performed under clear sky with direct solar radiation onto the car throughout the experiment period. The car was left exposed to direct solar radiation since morning to increase heat accumulation in the car cabin before the cooldown test began around noon.

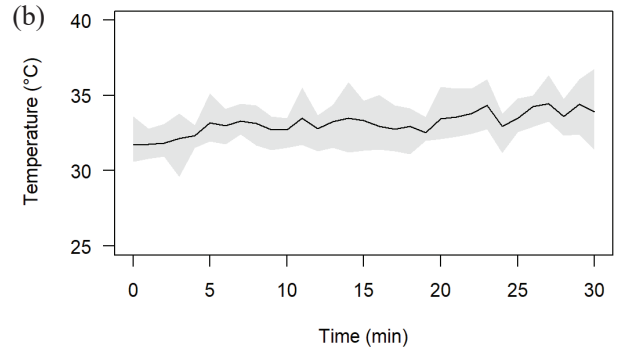
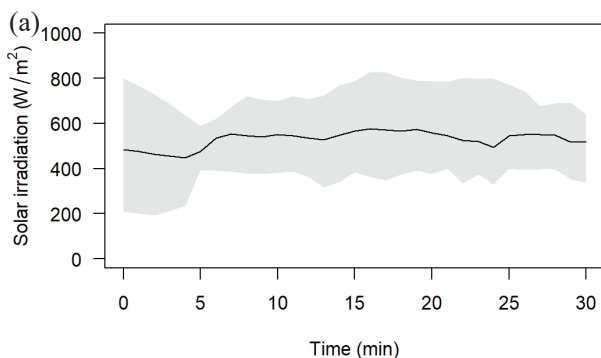


Fig. 2: One-minute averaged ambient environmental parameters: (a) solar irradiation (b) air temperature.

The supply air temperatures reduces rapidly during the initial five minutes period (see Fig. 3). On the other hand, the return air temperature is about 15 to 18 °C higher than the vent outlets for all test period. In all tests, the air temperature variation was found to be small (around 1 to 2 °C) indicating the stability of A/C performance.

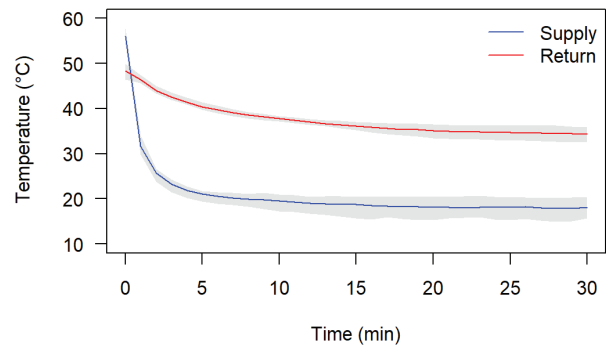


Fig. 3: One-minute averaged of supply and return air temperature.

The average and percentiles values of air temperature and thermal sensation for the face, chest and feet are shown in Fig. 4a, 5a, and 6a, respectively. The boxplot indicates the first and third quartiles of the data while the blue lines indicate the mean values. The initial average air temperatures near the face, chest, and feet were approximately 57.7°C, 55.6°C, and 40.8°C, respectively. The vertical temperature difference at the beginning is almost 17°C, which clearly proves the inhomogenous temperature inside the car cabin. In this case, the air temperature is higher near the ceiling and lower near the floor. Although the vertical temperature difference in the cabin is initially high during the cooling period, it decreases over time due to heat transfers and air movements facilitated by the air-conditioning system. At 30 minute, the difference in air temperature between head and feet are negligibly small, though it still dependent on seating positions (not shown).

The effects of cooling in the car cabin on human thermal sensation on the face, chest and feet are presented in Fig. 4b, 5b and 6b, respectively. At the initial period of cooling, most subjects have voted “very hot” with mean value of about 3.7 for the face and chest but slightly lower

average values for the feet of about 3.4 due to the higher air temperatures at initial time and the higher air temperature near the face as compared to near the feet. The thermal sensation of the subjects has gradually improved as the overall air temperature within the cabin decreases over time. At the end of the experiment period, most subjects have voted neutral for the face and chest (with an average votes of -0.5 and -0.1 , respectively), except for the feet with an average value of 0.7 . A peculiar trend was observed in the case of feet where the thermal sensation votes are strongly varied throughout the duration of the experiment although the air temperature variations are relatively small as compared to the temperature variations recorded near face and chest.

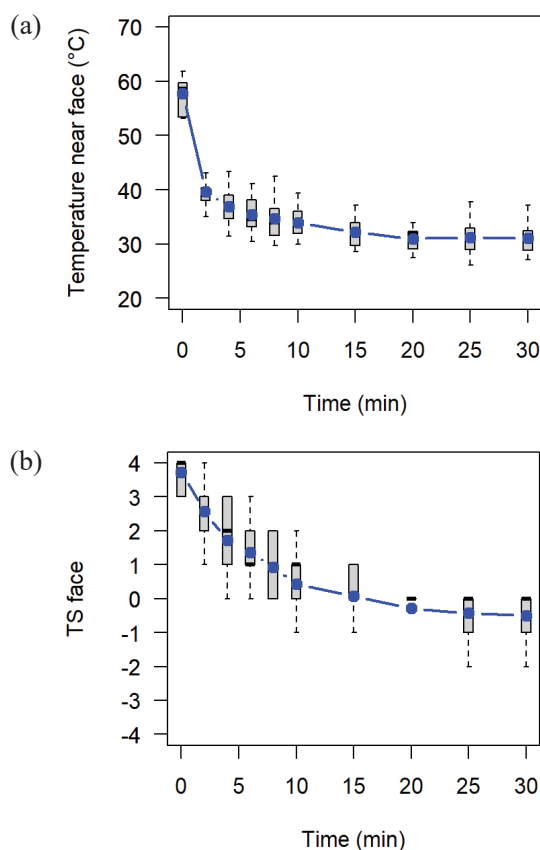


Fig. 4: Box plots and average values (blue dots and lines) of (a) air temperature and (b) thermal sensation votes near face.

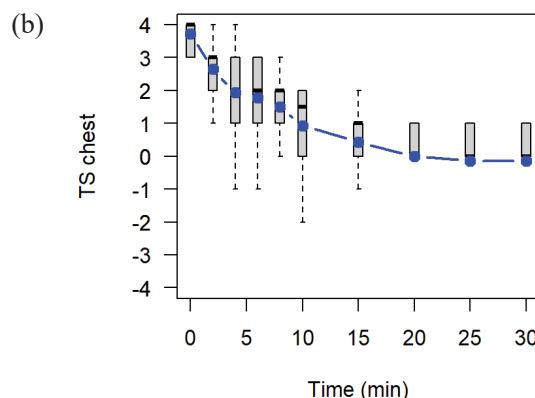
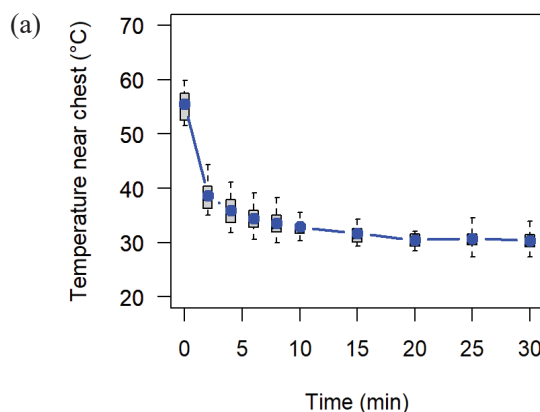


Fig. 5: Box plots and average values (blue dots and lines) of (a) air temperature and (b) thermal sensation votes near chest.

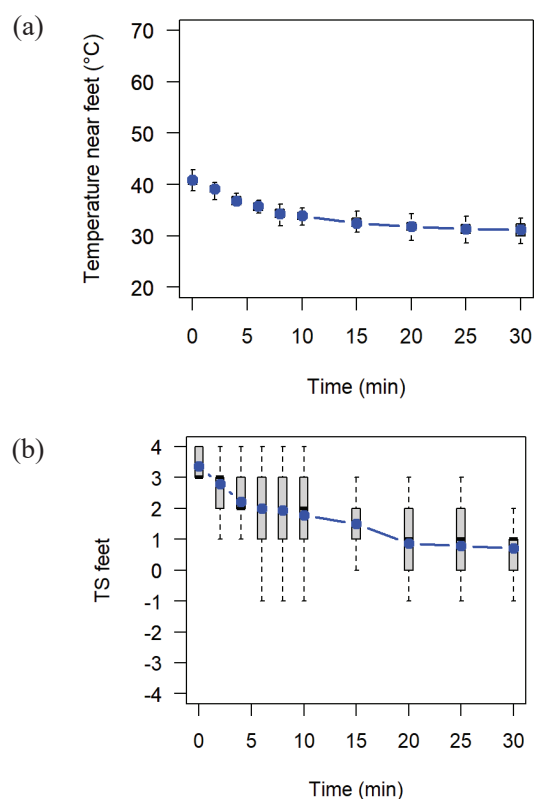


Fig. 6: Box plots and average values (blue dots and lines) of (a) air temperature and (b) thermal sensation votes near feet.

The ordinal probit regression model was used in this study to predict an ordinal dependent variable. Presented in Table 1 are the outcomes of the probit analysis, where the analysis considers the air temperature near the local body parts of subjects as the manipulated variable, and the local thermal sensation votes of the subjects as the respond variable. The analyses were executed using R program version 4.1.1 and RStudio version 1.4.17172. The calculation for the temperature corresponding to the median response involves dividing the constant by the regression coefficient, exemplified as $10/0.193 = 52$ °C. The categories of TSV; “very cold” (-4) and “Cold” (-3) were not included in the evaluation due to unavailability of votes in these categories.

Table 1. Local thermal sensation and air temperature after probit analysis.

Local Body Part	TSV	Probit Regression Line	Median
Face	$P(\leq 3)$	$0.193T_{\text{face}} + 10.0$	52.0
	$P(\leq 2)$	$0.193T_{\text{face}} + 8.3$	43.1
	$P(\leq 1)$	$0.193T_{\text{face}} + 7.5$	38.7
	$P(\leq 0)$	$0.193T_{\text{face}} + 6.6$	34.2
	$P(\leq -1)$	$0.193T_{\text{face}} + 5.1$	26.5
	$P(\leq -2)$	$0.193T_{\text{face}} + 4.6$	23.9
Chest	$P(\leq 3)$	$0.155T_{\text{chest}} + 7.7$	49.4
	$P(\leq 2)$	$0.155T_{\text{chest}} + 6.3$	40.3
	$P(\leq 1)$	$0.155T_{\text{chest}} + 5.5$	35.1
	$P(\leq 0)$	$0.155T_{\text{chest}} + 4.7$	30.0
	$P(\leq -1)$	$0.155T_{\text{chest}} + 4.0$	25.8
	$P(\leq -2)$	$0.155T_{\text{chest}} + 3.7$	23.9
Feet	$P(\leq 3)$	$0.192T_{\text{feet}} + 8.2$	42.6
	$P(\leq 2)$	$0.192T_{\text{feet}} + 7.0$	36.7
	$P(\leq 1)$	$0.192T_{\text{feet}} + 6.4$	33.2
	$P(\leq 0)$	$0.192T_{\text{feet}} + 5.6$	29.3
	$P(\leq -1)$	$0.192T_{\text{feet}} + 5.0$	26.0

Note: The probability $P(\leq 3)$ represents the likelihood of voting 3 or lower, while $P(\leq 2)$ signifies the probability of voting 2 or lower, and so forth. All regression coefficients hold significance with a p-value less than 0.001.

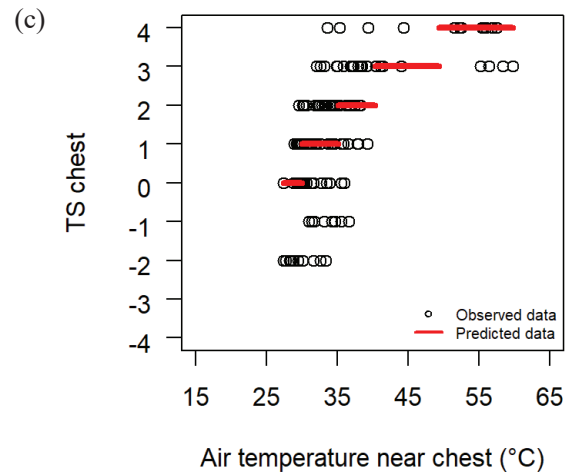
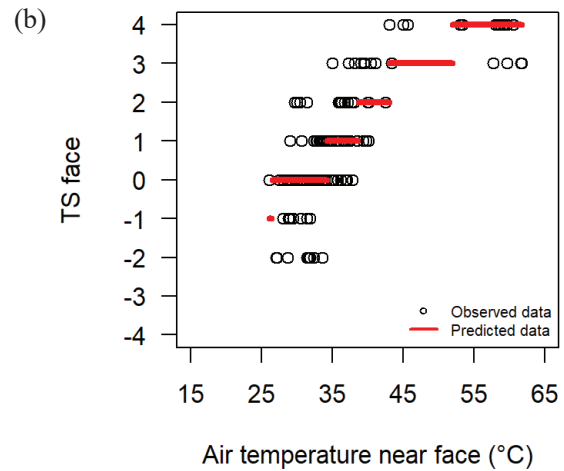
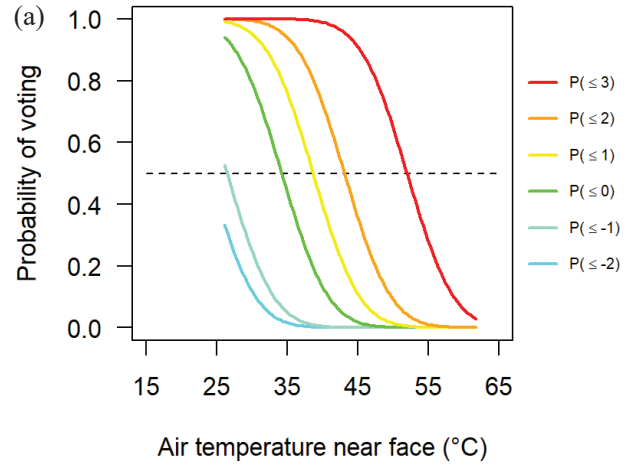
Probit analysis provides ranges of air temperatures for each thermal sensation category. Based on the data obtained in this study, we proposed that the air temperature near face shall be between 26.5 to 34.2°C, near chest shall be between 25.8 to 30°C and near feet shall be between 26 to 29.3°C for the local thermal sensation at the respective body parts to be at neutral state. It is important to note that the prediction accuracy of the model varied between body parts. Based on R^2 and RMSE as shown in Table 2, the probit data correlates well with the near face followed by chest and feet. The poor correlation for near feet has been mentioned earlier (see Fig. 6) where the variation of thermal sensation is highly varied even with small variations in air temperature. The insignificant effect of air temperature near the feet with feet thermal sensation may be due to other environmental factors that may play a role or lack of foot thermal sensitivity to air temperature.

Table 2: Prediction accuracy of probit analysis.

Local Body Part	R^2	RMSE	
Face	0.61	0.922	
Chest	0.50	1.282	
Feet	0.28	1.268	

Note: R^2 : Cox and Snell coefficient of determination; RMSE: root mean square error.

Probit analysis produced index values in which 50% of the respondents were on the verge of changing their vote to the next higher/lower class of thermal sensation. Transforming the probits into proportions for thermal sensation near face gives the curves shown in Fig. 7a with a 50% horizontal line. Figure 7b, 7c and 7d shows the distribution of respective thermal sensation votes as predicted using probit analysis that corresponds to air temperatures near the local body parts throughout the experiments.



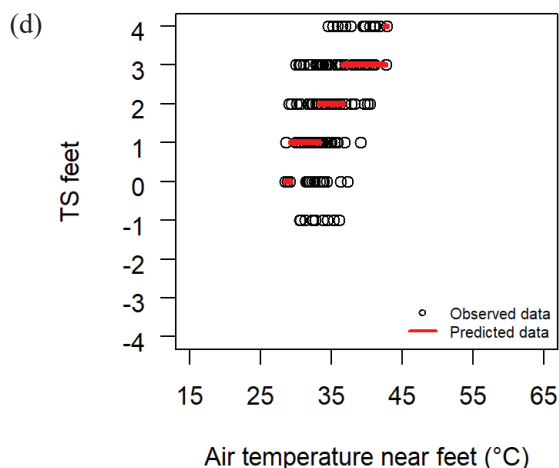


Fig. 7: Visual depiction of probit analysis: (a) Probability of voting a certain TSV corresponding to air temperature near face; (b), (c) and (d) Predicted local thermal sensation votes to that of air temperature near face, chest and feet, respectively.

4. Conclusion

In this study, in-cabin cooling of a fully occupied B-segment car was experimentally performed to investigate thermal conditions and thermal sensation votes of vehicle passengers. Over a four-day experimental duration, we gathered data on local air temperatures within the car cabin under consistent solar irradiation and clear sky. Simultaneously, we recorded the corresponding thermal sensation votes based on a nine-point thermal sensation scale.

The air temperature inside car cabin at the initial phase of cooling was found to be highly inhomogeneous, which resulted to higher thermal sensation votes by the subjects. The vertical temperature profiles at the end of 30-minute experiment was found to be small. Using probit analysis, the air temperature ranges at local sites corresponding to the local thermal sensation categories have been found. For example, we have estimated that there is a high probability that subjects' face would reached thermal neutrality when air temperature near the face is between 26.5 to 34.2°C. In addition, the air temperature near face was found to produced stronger correlation with subjects' thermal sensation near face ($R^2 = 0.6$) compared to other body parts ($R^2 = 0.5$ for chest and $R^2 = 0.28$ for feet).

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Nomenclature

<i>HVAC</i>	heating, ventilation and air conditioning
<i>PMV</i>	predicted mean vote
<i>RMSE</i>	root mean square error
<i>TS</i>	thermal sensation
<i>TSV</i>	thermal sensation vote

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