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# The Study of Thermal Comfort in a Common Commercial Car Cabin: Looking at Malaysia's Perspective

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ABSTRACT

*Assessing thermal comfort in vehicles poses unique challenges compared to buildings. The in-car environment is characterized by specific factors such as sunlight exposure, poor clothing insulation, non-uniform average radiant temperature, and limited time to establish comfort parameters. To address these challenges, this study aims to evaluate thermal comfort in different branded car cabins by analyzing temperature distribution, air velocity, relative humidity, and dew point temperature. A comprehensive review of literature was conducted, focusing on various aspects including airflow regimes, factors influencing thermal comfort, measuring instruments, and comfort indices. Understanding these factors is crucial for developing comprehensive methodologies to assess thermal comfort and indoor air quality in vehicle cabins. The results of the study indicate that MPV cars offer superior comfort levels within the optimal range of -1 to +1, surpassing sedans and compact cars. These findings are instrumental in guiding design and engineering decisions to improve passenger comfort in vehicles. Tailoring the design of different car types to meet the specific comfort requirements can lead to enhanced overall comfort and satisfaction. In conclusion, this study provides valuable insights into assessing thermal comfort and indoor air quality in vehicle cabins. By addressing the unique challenges posed by the in-car environment, it offers guidance for designing and engineering vehicles that prioritize passenger comfort and well-being.*

*Keywords: Thermal comfort; Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD)*

## INTRODUCTION

Based on information from the Malaysian Meteorology Department, Malaysia's climate is characterized by uniform temperatures, high humidity, and abundant rainfall. Conversely, wind conditions tend to be generally weak. Despite the equatorial location, clear skies are uncommon due to persistent precipitation. Additionally, Malaysia experiences few days without direct sunlight, except during the northeast monsoon season. The average ambient temperature in Malaysia is 27 °C, with a recommended range of 23 °C to 25 °C for achieving individual comfort. Meanwhile relative humidity is arround 75% to 95%. Moreover, the recommended air velocity for comfort is 0.25 m/s (Idris et al., 2016).

Energy conservation is now a prominent topic in society, with energy savings often associated with the use of renewable energy. However, it is important to note that energy saving is not solely reliant on renewable energy; reducing energy consumption itself can be considered a form of energy saving (Abdul Rahman & Kannan, 1996). While renewable energy technologies are a future solution, they are not yet fully matured. Thus, for the present, it is essential to focus on energy saving through reduced consumption. This can be achieved by optimizing controllable parameters, such as employing air conditioners that open at lower temperatures and do not operate unnecessarily. Optimization can also be achieved by setting the air conditioner temperature with consideration for thermal comfort, as excessively cold temperatures can cause discomfort to occupants (Junaedi & Akbar, 2018).

In this progressive era, comfort holds significant importance as human beings strive for an enhanced quality of life through technological advancements. Among various forms of comfort, thermal comfort is highly desirable, as nobody wishes to endure a consistently sweaty state. Therefore, air conditioning systems have been developed to meet human needs (Sabri et al., 2014). Additionally, Husin et al. (2018) examine the energy consumption patterns associated with retrofitted air-conditioning systems. Their study investigates the energy efficiency of such systems and provides insights into potential measures for energy conservation.

Vehicles serve as important tools of convenience, facilitating transportation for various purposes. Thermal perception and comfort within vehicles are influenced by several factors, including ambient temperature, humidity, air velocity, clothing insulation, and metabolic rate. Various studies have examined the impact of these factors on thermal sensation, comfort, and preference in different vehicle types and climatic conditions (Lu et al., 2017). Accurately assessing thermal comfort in vehicles necessitates the use of appropriate measurement techniques. There is various approaches, such as subjective assessments through questionnaires and interviews, objective measurements using thermal manikins, and physiological measurements like skin temperature and heart rate monitoring (Chan et al., 2019 & Yusof 2020). These techniques enable researchers to gather quantitative and qualitative data to evaluate occupants' thermal experiences and comfort levels.

Different modeling approaches have been utilized, including the Predicted Mean Vote (PMV) and Adaptive Thermal Comfort (ATC) models, which consider the interaction between occupants, the environment, and HVAC systems (Mandal et al., 2020). These models aid in designing and evaluating heating, ventilation, and air conditioning (HVAC) systems, thereby improving thermal comfort in vehicles. Numerous strategies have been proposed, such as optimizing HVAC system design, incorporating personalized climate control, utilizing seat heating/cooling, and implementing advanced sensing and control technologies (Ploetz et al., 2021). Research efforts focus on evaluating the effectiveness of these strategies through experiments, simulations, and field studies, aiming to provide practical solutions for improving thermal comfort in vehicles.

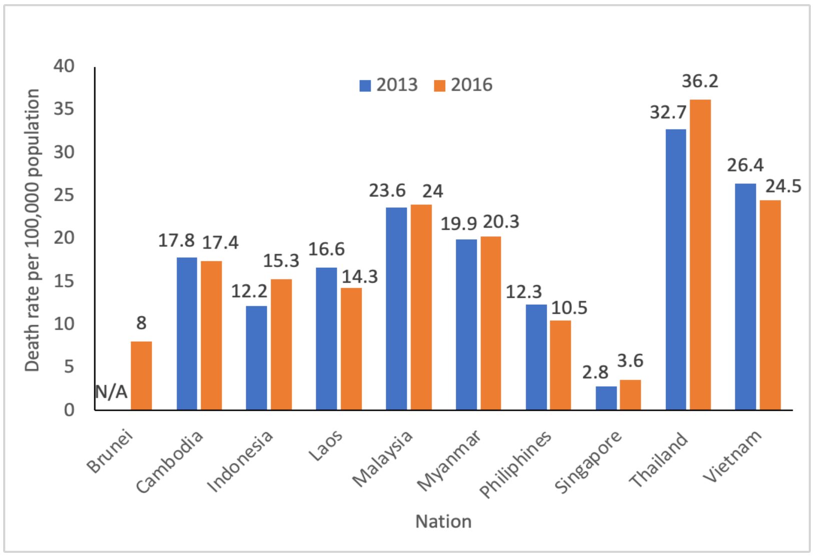


FIGURE 1. Estimated road mortality rate per 1 million population of Asean countries

Apart from its societal importance, vehicles also have a negative impact, such as the potential to cause road accidents when drivers experience discomfort (Alahmer et al., 2011). The Global Status Report on Road Safety 2018, released by the WHO in December 2018, reveals that the annual number of road traffic deaths has reached 1.35 million, as depicted in Figure 1.

Malaysia has the third-highest death rate from road accidents in ASEAN, following Thailand and Vietnam (Chin, 2019). Since 2007, there has been no significant change in the number of fatalities resulting from road accidents in Malaysia. From 1990 to 2011, the country experienced a continuous increase in both overall deaths and deaths specifically related to road accidents, with the latter rising by 70%. According to the report by the Bukit Aman Traffic Police Chief, Malaysia witnesses an average of 19 deaths per day caused by road accidents on flat roads, as illustrated in Table 1. This sharp increase in fatalities presents a highly unfavorable situation for developing nation like Malaysia.

TABLE 1. Statistics of road accidents in Malaysia from 1997 to 2014

| Year | Registered Vehicles | Population | Road Crashes | Road Deaths |
|---|---|---|---|---|
| 1997 | 8,550,469 | 21,665,600 | 215,632 | 6302 |
| 1998 | 9,141,357 | 22,179,500 | 211,037 | 5340 |
| 1999 | 9,929,951 | 22,711,900 | 223,166 | 5,794 |
| 2000 | 10,598,804 | 23,263,600 | 250,429 | 6,035 |
| 2001 | 11,302,545 | 23,795,300 | 265,175 | 5,849 |
| 2002 | 12,068,144 | 24,526,500 | 279,711 | 5,891 |
| 2003 | 12,819,248 | 25,048,300 | 298,653 | 6,286 |
| 2004 | 13,828,889 | 25,580,000 | 326,815 | 6,228 |
| 2005 | 15,026,660 | 26,130,000 | 328,264 | 6,200 |
| 2006 | 15,790,73.2 | 26,640,000 | 341,252 | 6,287 |
| 2007 | 16,813,943 | 27,170,000 | 363,319 | 6,282 |
| 2008 | 17,971,901 | 27,730,000 | 373,001 | 6,527 |
| 2009 | 19,016,782 | 28,310,000 | 397,330 | 6,745 |
| 2010 | 20,188,565 | 28,910,000 | 414,421 | 6,872 |
| 2011 | 21,401,269 | 29,000,000 | 449,040 | 6,877 |
| 2012 | 22,702,221 | 29,300,000 | 462,423 | 6,917 |
| 2013 | 23,819,256 | 29,947,600 | 477,204 | 6,915 |
| 2014 | 25,101,192 | 30,300,000 | 476,196 | 6,674 |

For individuals who spend significant time on the road, the requirement for thermal comfort within the car cabin is of utmost importance, as it directly impacts their level of concentration during driving. Studies have shown that excessively high temperatures inside car cabins can impair driver performance and increase the risk of accidents. Heat stress, thermal discomfort, and decreased alertness are commonly observed in drivers exposed to extreme heat conditions (Ploetz et al., 2021). This research aims to study and test the thermal comfort in the cabins of various car brands. To ensure the success of this study, several objectives have been established as guidelines. The first objective is to obtain the temperature distribution, air velocity, relative humidity, and dew point temperature in three different car models, namely the Perodua Myvi, Toyota Vios, and Toyota Vellfire, using the Sensirion EK-H4 measuring device and SHT71 sensor. The second objective is to compare the levels of thermal comfort among the three car models by using Fanger's model.

## METHODOLOGY

This study consisted of two phases. The first phase involved conducting experiments using the Sensirion EK-H4 measuring device and SHT71 sensor, which were installed in the cars to collect data on air velocity, temperature, relative humidity, and dew point temperature. The test was conducted at an outside temperature ranging from 30°C to 35°C and a relative humidity ranging from 65% to 75%. Three specific locations were selected as measurement points, and three different car brands were used for the study. The experiments were conducted when the car park during the sunlight on separate days, with each test lasting 30 minutes from 3 pm to 3:30 pm. Total days taken for data collection were nine days. This approach allowed for the collection of average data to minimize experimental error.

In the second phase, the recorded data was transferred to Microsoft Excel and organized in tabular format. Graphs were then generated to illustrate the relationship between air temperature and time, relative humidity and time, and dew point and time. Additionally, average data for each measurement point in the three cars were calculated to create a graph depicting the Predicted Mean Vote (PMV) versus Predicted Percentage of Dissatisfied (PPD). Figure 2 provides an overview of the study's flow chart, outlining the research methodology employed to ensure its success.

### DETERMINATION OF PERSONAL FACTORS

Before conducting measurement experiments for environmental parameters, it is essential to determine three personal factors: metabolic rate, effective mechanical work, and thermal insulation of clothing. These factors need to be known as they are included in the Predicted Mean Vote (PMV) equation. According to the metabolic rate table from ISO Standard 7730 for Malaysia, the typical metabolic rate for drivers is 70 W/m2. In terms of effective mechanical

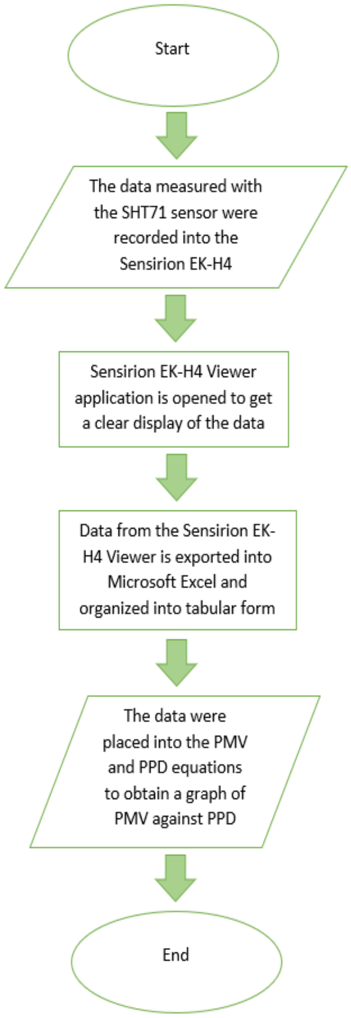


FIGURE 2. The overall flow chart of this stu

work, it is considered as 0 since no physically demanding tasks are typically performed while driving. Considering studies and observations on the road, it is observed that drivers commonly wear regular work attire during summer, such as collared t-shirts, long pants, socks, and closed-toe shoes. Based on the ISO 7730 Standard, the appropriate value for garment insulation factor, measured in Clo units, is 0.7.

## METHODS OF CONDUCTING THE EXPERIMENT

The experiment took place in the parking lot of Kolej Ungku Omar (KUO), Universiti Kebangsaan Malaysia (UKM). This location is characterized by its open and spacious layout, with full exposure to sunlight. Figure 3 illustrates the specific experimental site used in this study.


FIGURE 3. Parking lot of KUO, UKM

The parameters to be measured in the car for this study include air velocity, relative humidity, temperature, and dew point temperature. In the experimental phase, an anemometer, as shown in Figure 4, was employed to manually measure air velocity every 30 seconds. The collected data for air velocity showed an average reading of approximately 1.0 m/s across all nine conducted experiments. Furthermore, the Sensirion EK-H4 device, along with the SHT71 sensor, was set up and installed in the car. The wire connections on the Sensirion EK-H4 device are illustrated in Figure 5. Three different car brands were used in this study: the Perodua Myvi (compact car), Toyota Vios (sedan car), and Toyota Vellfire (MPV). All the cars had bright colors, such as white, and even the interior of the cabin was designed with dark colors, such as black and dark brown.

FIGURE 4. GM816 Digital Anemometer

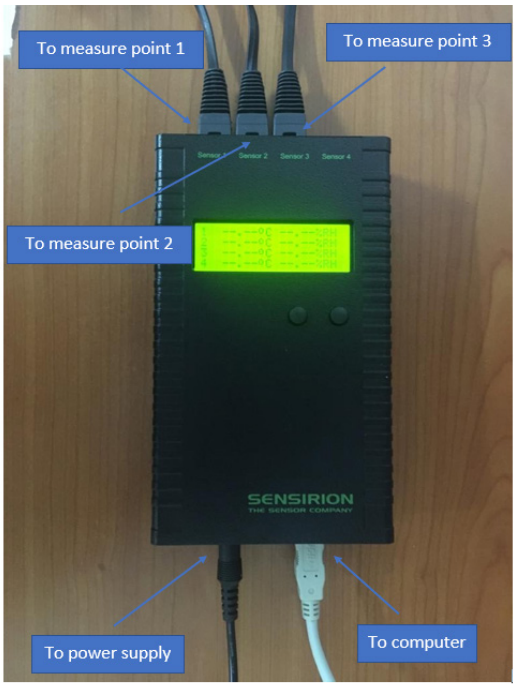


FIGURE 5. Wires connection on Sensirion EK-H4

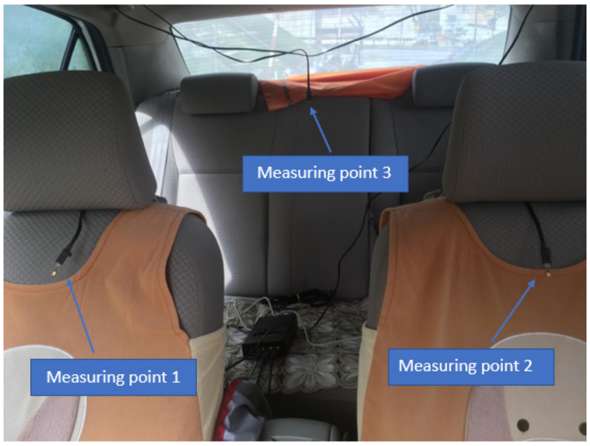


FIGURE 6. Three different measuring points in the car

The SHT71 sensor was installed in three specific locations: measurement point 1 (driver's seat), measurement point 2 (passenger seat), and measurement point 3 (middle of the back seat) as depicted in Figure 6. The same setup was repeated for the remaining two cars. The experiments were conducted on three different days for each car, with each session lasting 30 minutes from 3 pm to 3:30 pm. By conducting multiple experiments, average data could be obtained, thereby reducing experimental errors. To investigate the natural ventilation conditions, the experiments were conducted without the use of a fan or the activation of the car's air conditioner and the engine turned off. Only the windows were opened to allow for airflow. It should be noted that due to the Full Movement Control Order (FMCO) in Malaysia at the time of the experiment, it was not possible to conduct the study throughout the entire day. The experiment was conducted from 1st June until 9th of June 2021.

## METHODS OF PREDICTING COMFORT LEVELS

Once the personal factors have been established and the physical parameters have been measured, it becomes possible to predict the overall thermal sensation of the body by calculating the Predicted Mean Vote (PMV). Additionally, the value of the Predicted Percentage of Dissatisfied (PPD) can be determined using the corresponding equation in Excel.The PMV aligns with the prediction methodology recommended by ISO 7730. ASHRAE has defined a 7-point thermal sensation scale for evaluating the encountered thermal environment. Table 2 displays the average expected values of the PMV index for a large group of individuals.

TABLE 2. Comfort scale of PMV

| Scale | PMV Index |
|---|---|
| Very hot | +3 |
| Hot | +2 |
| Slightly hot | +1 |
| Neutral | 0 |
| Slightly cold | -1 |
| Cold | -2 |
| Very cold | -3 |

*Source*: (ASHRAE Handbook)

To maintain thermal comfort, two conditions must be satisfied. Firstly, the combination of skin temperature and core body temperature should create a sensation of thermal neutrality. Secondly, the body needs to maintain an energy balance, where the heat produced by metabolism equals the heat lost through conduction, convection, evaporation, and respiration. These two conditions are combined into a single equation known as the comfort equation. The equation incorporates the heat transfer due to evaporation on the skin, assuming the person is in a state of thermal neutrality. This is expressed as equation (1) for the body's energy balance, as illustrated below:

$$M - W = H + E + C_{res} + E_{res} \tag{1}$$

Fanger introduced modifications to the comfort equation and published a revised version known as Fanger's comfort equation. However, as the equation still does not fully account for the thermal sensation of individuals who are less satisfied, the Predicted Mean Vote (PMV) equation was developed (Abdullah et al., 2012). According to ISO 7730, the PMV equation can be expressed as follows:

$$PMV = (0.303 \times e^{-0.036M} + 0.028)$$

$$\left[\begin{array}{l} (M - W) - 3.05x10^{-3}[5733 - 6.99(M - W) - p_a] - 0.42[(M - W) - 58.15] - 1.7x10^{-5}M \\ (5867 - p_a) - 0.0014(34 - t_a) - 0.0014M(34 - t_a) - 3.96\times10^{-8} f_{cl} [(t_{cl} + 273)^4 - (t_r - \\ 273)^4] - f_{cl} h_c(t_{cl} - t_a) \end{array}\right] \tag{2}$$

Equation (2) allows for the calculation of the Predicted Mean Vote (PMV) by considering various factors such as metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity, and relative humidity (Xia & Guo). The PMV index is typically used for steady-state conditions but can also serve as a reasonable approximation for situations where variables exhibit minimal instability.

The PMV index provides an estimation of the average rating for a group of individuals exposed to the same environment. However, it is important to note that the PMV ratings are primarily applicable to the majority of individuals, disregarding the satisfaction levels of those who may be less satisfied.

Fanger has further modified the PMV index to incorporate the Predicted Percentage of Dissatisfied (PPD). This modification enables the PPD to reflect the percentage of individuals who are less satisfied with the thermal environment and assigns a level of discomfort to them. The value of PPD is expressed as a function of PMV, as shown in equation (3) below:

$$PPD = 100 - 95exp - (0.3353PMV^4 + 0.2719PMV^2)\text{x} \tag{3}$$

Figure 8 illustrates the graphical representation of the relationship between PMV and PPD, based on equation (3). It provides a visual depiction of how the PMV index relates to the corresponding PPD values, allowing for a better understanding of the discomfort levels experienced by individuals in relation to the thermal environment.

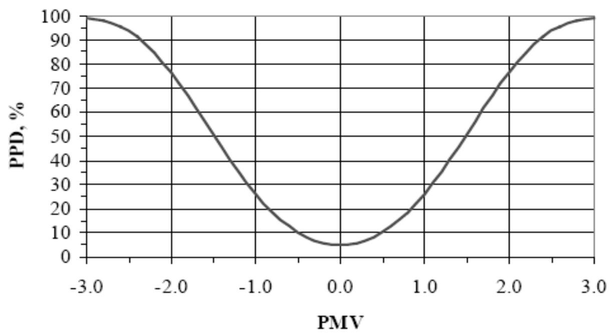


FIGURE 7. PPD as a function of PMV (ASHRAE, 20XX)

One of the features of the PPD index is that its value will not fall to a level less than 5% for any PMV value, as shown in Figure 7. The real factor contributing to this is that there are differences in thermal sensation between each individual, and thermal neutrality for different people is achieved by unequal environmental factors.

## RESULTS AND DISCUSSION

### ANALYSIS OF CAR PARK CONDITIONS AT KUO

The parking lot of KUO is situated in the vicinity of the cafeteria at UKM. This location was selected for conducting the research experiment due to the limited availability of suitable places caused by the prevailing FMCO in

Malaysia. Throughout the 9 days of the experiment, the average air temperature recorded during the time frame of 3:00 to 3:30 p.m. was approximately 32 °C. For each vehicle, data were collected over a period of 3 days to ensure accurate averages. Therefore, a total of 9 days were required to complete measurements for all 3 vehicles.

## ANALYSIS OF DATA FROM SENSIRION EK-H4

The following graphs shows data for relative humidity, air temperature, and dew point temperature, categorized according to their respective measurement points inside car cabin. The graphs clearly demonstrate an initial increasing trend followed by a gradual stabilization of air temperature over time. In contrast, the relative humidity data exhibits an inverse trend to the air temperature data, initially decreasing before reaching a stable level. The dew point temperature data follows a similar pattern to the air temperature, with an initial increase followed by a stable value.

Comparing the graphs, it is evident that the air temperature at all three measurement points is highest in the Perodua Myvi and lowest in the Toyota Vellfire. The air temperature distribution for the Toyota Vios falls between that of the Perodua Myvi and the Toyota Vellfire. In terms of relative humidity, the Perodua Myvi exhibits the lowest distribution of data, while the Toyota Vellfire shows the highest data distribution, indicating higher humidity levels inside this vehicle. Figure 8 through Figure 16 provide a visual representation of the data distribution for the three different cars at each measurement point.

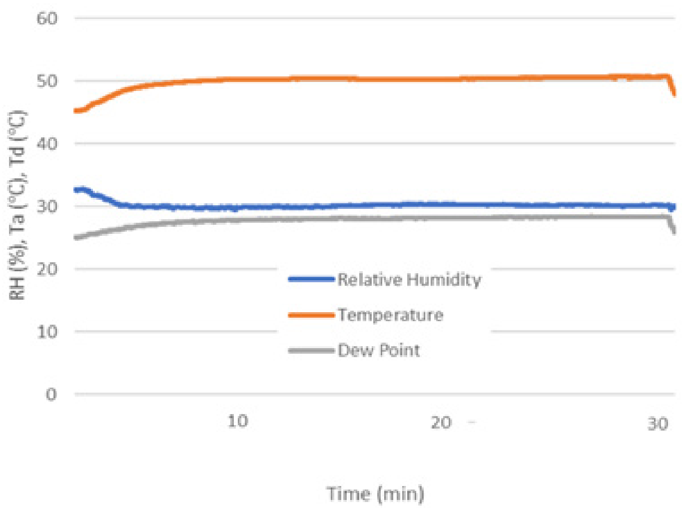


FIGURE 8. Data distribution for Perodua Myvi at measure point 1

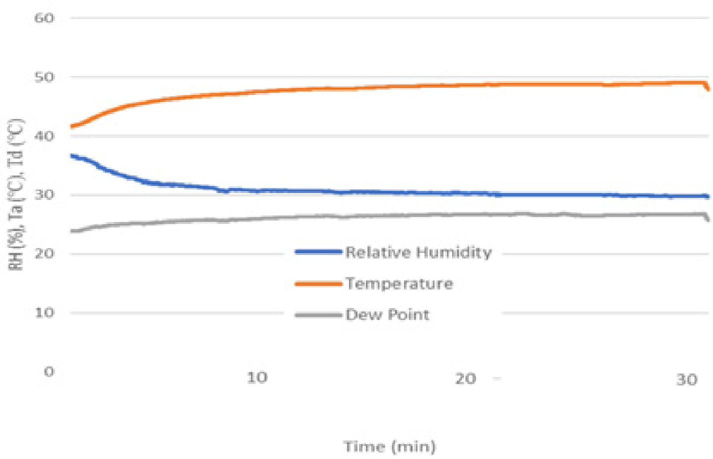


FIGURE 9. Data distribution for Toyota Vios at measure point 1

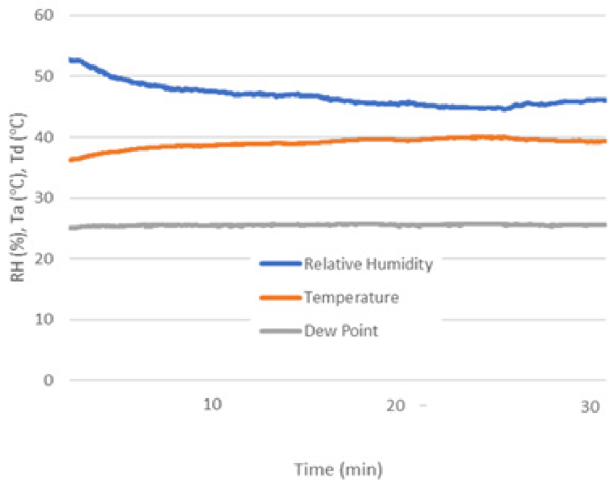


FIGURE 10. Data distribution for Toyota Vellfire at measure point 1

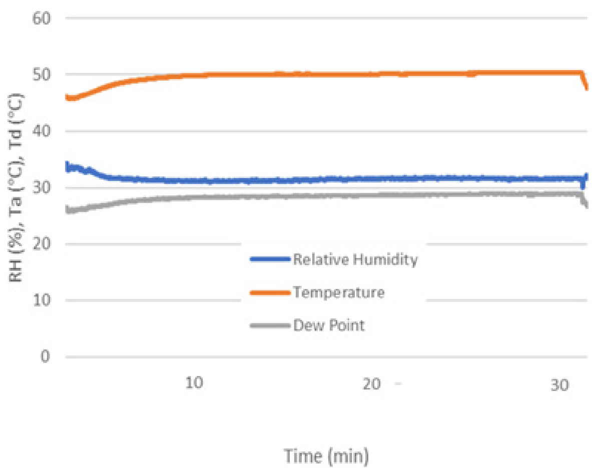


FIGURE 11. Data distribution for Perodua Myvi at measure point 2

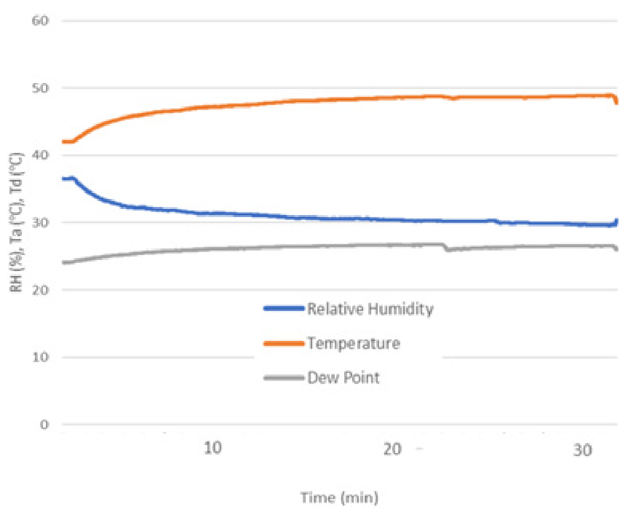


FIGURE 12. Data distribution for Toyota Vios at measure point 2

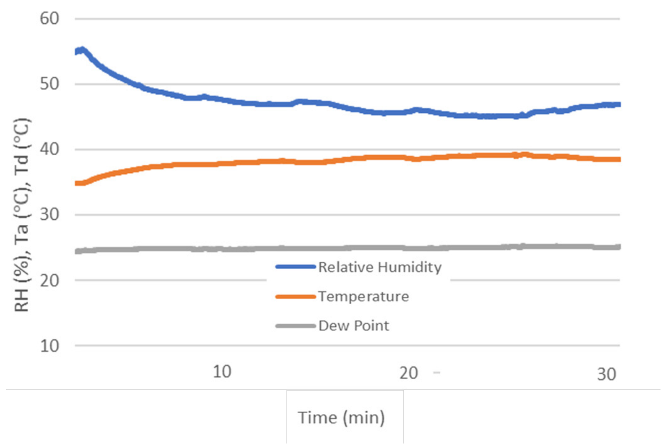


FIGURE 13. Data distribution for Toyota Vellfire at measure point 2

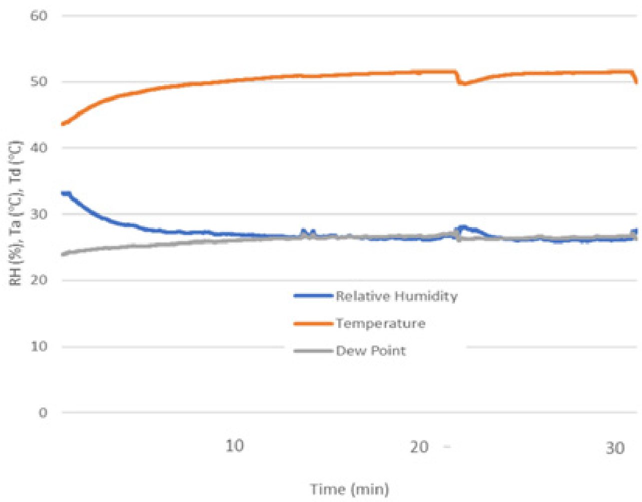


FIGURE 14. Data distribution for Perodua Myvi at measure point 3

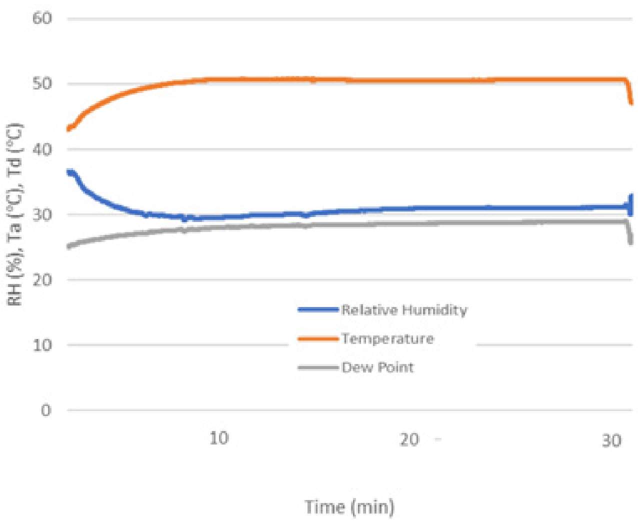


FIGURE 15. Data distribution for Toyota Vios at measure point 3

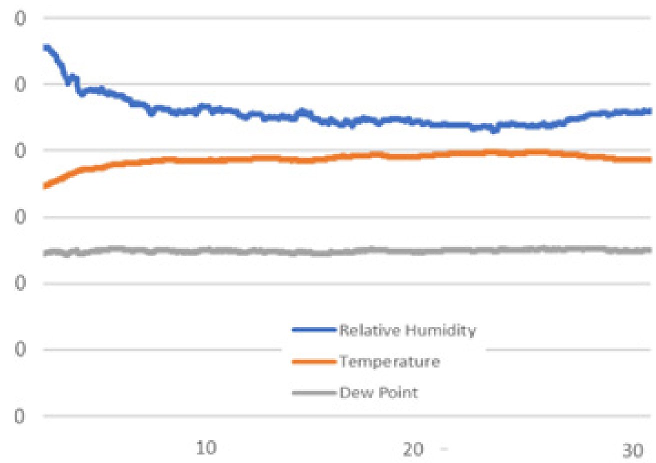


FIGURE 16. Data distribution for Toyota Vellfire at measure point 3

## ANALYSIS OF PMV AND PPD

PMV and PPD analysis was performed using equation (2) described in the methodology. These values were calculated using Microsoft Excel software, which was then analysed into the form of a graph of PMV against PPD. Before PMV and PPD values are obtained, several personal factors and parameters need to be determined, such as metabolic rate, clothing insulation factors, and effective mechanical work. The determined metabolic rate, M, is 70, which is the rate for most Malaysian drivers. Whereas, for effective mechanical work, W for driving is set to 0 because drivers do not do work that requires large amounts of body energy while driving. The value of the clothing insulation factor, Icl, was determined as 0.1085 because drivers often wear simple clothing that promotes ventilation around the body, such as collared t-shirts, long pants, and covered shoes. This PMV and PPD analysis was performed using the average data for three measurement points for each car, and then the data for every 10 seconds was used to plot the graph of PMV against PPD. These graphs for Perodua Myvi, Toyota Vios and Toyota Vellfire were shown in Figure 17, Figure 18 and Figure 19 respectively.

Based on the comfort range criteria, a driver would feel comfortable if the PMV data falls within the range of -1 to +1, corresponding to a PPD reading of 5% to 50%. However, from Figure 17 and Figure 18, it is evident that a significant portion of the data for these two cars falls outside the comfort range. Among the three figures, only Figure 17's PPD reading reaches 100%, indicating complete discomfort. The PPD reading for Figure 18 almost reaches 100%, while the PPD reading for Figure 19 is far from reaching 100%.

Figure 17 demonstrates that the condition throughout most of the experiment duration was uncomfortable, with only the first 10 seconds falling within the comfort zone. Towards the end of the experiment, the discomfort level reached its peak, resulting in a PPD reading of 100%. This suggests that the Perodua Myvi exhibited the highest air temperature, causing the PPD reading to consistently remain above 35%. The extremely low relative humidity, ranging from 30% to 33%, also contributed to this situation, exacerbating the extreme PPD reading.

Figure 18 displays relatively random PMV values in the early stages of the experiment, with most still falling within the comfort zone. At that time, the corresponding PPD values indicated a dissatisfaction level of less than 65%. As time progressed, the air temperature increased, leading to a decrease in comfort level. Consequently, the PMV readings moved further away from the comfort zone, approaching a value of 2. Towards the end of the experiment, the PPD reading almost reached 100%. The majority of PMV readings ranged from 1 to 2, corresponding to 50% to 100% for PPD readings. This indicates that the driver would feel uncomfortable for most of the duration, particularly during the middle and final stages of the experiment. These discomfort levels were further influenced by the relatively low relative humidity ranging from 30% to 37%.

Figure 19 exhibited slightly different behavior compared to the Perodua Myvi and Toyota Vios. The PPD reading never approached 100%. Only in the final stages of the experiment did the PMV reading slightly deviate from the comfort zone, indicating a slightly uncomfortable situation at that time. Apart from that period, the Toyota Vellfire consistently remained within the comfort zone, with PMV readings ranging from -1 to 1, and PPD readings ranging from 5% to 50%. This starkly contrasts with the Perodua Myvi and Toyota Vios, as the Toyota Vellfire provided a comfortable environment for the majority of the experiment duration, while the Perodua Myvi and Toyota Vios offered comfort for only a short period of time.

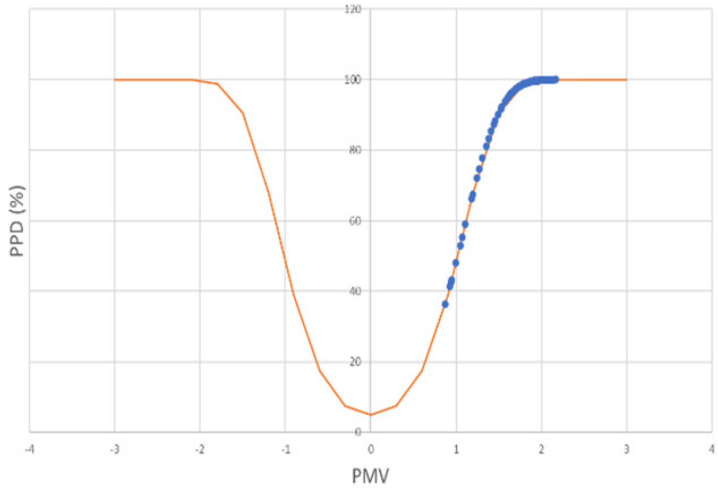


FIGURE 17. Graph of PMV against PPD for Perodua Myvi

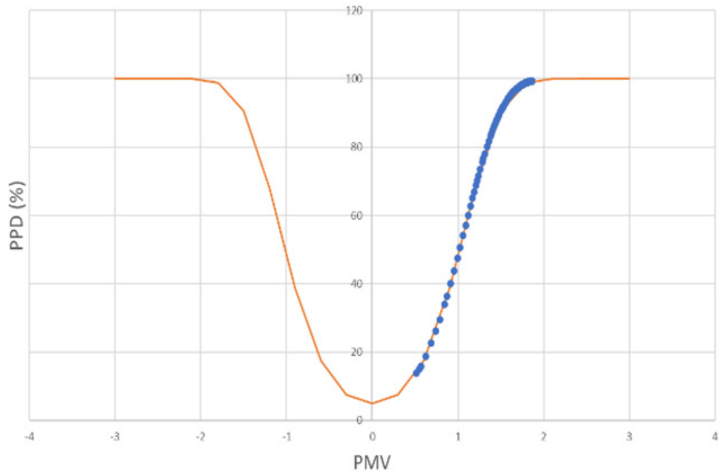


FIGURE 18. Graph of PMV against PPD for Toyota Vios

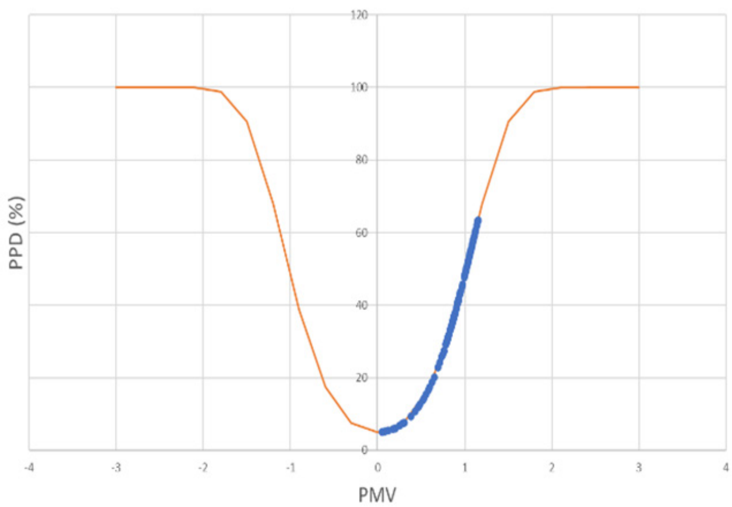


FIGURE 19. Graph of PMV against PPD for Toyota Vellfire

When comparing the cars used in this experiment, one factor contributing to the Toyota Vellfire displaying the best PMV and PPD data distribution, while the Perodua Myvi exhibited the worst, is the size difference. The Toyota Vellfire, being the largest car, features a cabin design that promotes more active air circulation between the interior and exterior of the car. Additionally, the larger car window design of the Toyota Vellfire allows for easier wind entry. The Toyota Vios, with its medium-to-large cabin size, falls between the Perodua Myvi and Toyota Vellfire in terms of data distribution. The materials used in the construction of the car's interior also influence thermal comfort. Materials with higher conduction rates absorb more heat from the sun, resulting in greater discomfort. The interior material of the Perodua Myvi has a relatively high conduction rate, leading to easy heat absorption and subsequent discomfort. Another factor is the material used for the car roof, which directly faces sunlight. It is important for the roof material to have high thermal insulation properties. In this aspect, the Toyota Vellfire excels, preventing excessive heat absorption into the car cabin. Improved roof insulation not only enhances thermal comfort but also contributes to a quieter and more peaceful driving experience by reducing external noise from wind and rain.

## CONCLUSION

Nine research experiments were conducted to fulfill the objectives of this study, and each experiment yielded distinct data distributions. The level of comfort experienced in each car varied based on its specific features. The Perodua Myvi demonstrated overall discomfort, with most PMV values falling outside the range of -1 to +1. Only the initial 10 seconds of the experiment showed a PMV value within the comfort zone. Remarkably, at the end of the experiment, the discomfort level reached an extreme point, as indicated by a PPD reading of 100%. The Toyota Vios exhibited a similar trend of discomfort throughout the experiment, although not as severe as the Perodua Myvi. Initially, the PMV values fell within the comfort zone, but as time progressed and the air temperature increased, the PMV values deviated further from the comfort zone. Ultimately, the PPD reading approached 100%. In contrast, the Toyota Vellfire displayed distinct behavior compared to the Perodua Myvi and Toyota Vios. The majority of the experiment for the Toyota Vellfire remained within the comfort zone, with only slight deviations observed in the final stages. Notably, the PPD reading never approached 100%.

Based on these findings, it can be concluded that the Toyota Vellfire is the most comfortable car, as its PMV and PPD data distributions align closest to the comfort zone compared to the other two cars. Several factors contribute to this result, including the cabin and window design, as well as the materials used for the car's interior and roof. The Toyota Vellfire boasts a spacious cabin design that facilitates active air circulation between the interior and exterior. Additionally, its larger window design allows for increased airflow. The interior materials of the Toyota Vellfire possess low thermal conductivity, preventing excessive heat absorption and maintaining a comfortable temperature within the cabin. Furthermore, the car's thermal insulation roof effectively resists heat absorption from direct sunlight exposure. This combination of factors contributes to the overall comfort experienced in the Toyota Vellfire. In conclusion, this research can be deemed successful as all two objectives have been accomplished.

## ACKNOWLEDGEMENT

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## DECLARATION OF COMPETING INTEREST

None

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