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Interior Temperature Dynamics and Its Implications for Heatstroke Risk: Designing an IoT-Based Vehicular Heatstroke Sensor Device

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ABSTRACT

Vehicular heatstroke incidents involving children represent a critical issue with potentially severe consequences. To address this problem, this research presents an IoT-based Child Safety System (CSS) designed to prevent and mitigate heatstroke incidents in vehicles. This article focuses on the development and evaluation of the system, taking a user-centric approach to ensure its effectiveness and user acceptance. The study begins with a comprehensive survey conducted to gather user requirements and preferences regarding CSSs. The survey data provides valuable insights into the design and functionality expectations of potential system users, enabling the development of a solution that aligns with their needs. Subsequently, an experiment is conducted to evaluate the performance of the proposed IoT-based CSS. The experiment involves the installation of temperature sensors in a fleet of vehicles, with data collected to monitor and analyze the temperature variations inside the vehicles during different conditions. Consequently, the acquired temperature data assesses the system's ability to detect potentially dangerous situations and provide timely alerts to caregivers. Preliminary results indicate a positive response from the survey participants, with a high level of interest in and willingness to adopt the IoT-based CSS. Moreover, the temperature data collected during the experiment demonstrates the system's capability to effectively monitor the in-vehicle temperature and promptly notify caregivers when potentially hazardous conditions arise. This article presents a preliminary investigation, laying the foundation for further research and development in the field of CSSs. Future studies could focus on refining the system's design, incorporating additional features to enhance its functionality, and conducting larger-scale trials to evaluate its effectiveness in real-world scenarios. Overall, this research contributes to the ongoing efforts to combat vehicular heatstroke incidents involving children. By emphasizing a user-centric approach and leveraging IoT technology, the proposed CSS shows promising potential in preventing tragic incidents and safeguarding the well-being of children in vehicles.

Keywords:
Child heatstroke; IoT; Vehicular Heatstroke Sensor Device (VHSD); ASEAN NCAP; carbon monoxide

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1. Introduction

Child heatstroke incidents resulting from negligence or unintentional actions by parents or caregivers continue to threaten children's safety significantly. The alarming statistics surrounding child heatstroke deaths necessitate urgent measures to enhance child safety in vehicles [1-3]. In response to this pressing issue, this paper presents a comprehensive study on enhancing child safety by designing and developing an IoT-based Vehicular Heatstroke Sensor Device (VHSD). By leveraging the capabilities of IoT technology, the VHSD integrates advanced sensors, real-time monitoring, and cloud connectivity to provide an effective solution for detecting and addressing the dangers of vehicular heatstroke incidents [4,5]. Research findings indicate that approximately 10% of child deaths are attributed to heatstroke caused by parental or caretaker negligence [6]. This issue is particularly critical for toddlers more susceptible to heat-related risks due to their physiological and behavioral characteristics. Hence, the urgency to address this problem is highlighted by the average of 38 child heatstroke deaths per year reported between 1998 and 2014 in the United States alone [7]. Further data from the Malaysian Institute of Road Safety Research (MIROS) reveals a concerning number of child deaths in parked vehicles during 2018 [8].

The occurrence of child heatstroke incidents is closely associated with the condition known as vehicle hyperthermia, where the interior temperature of a parked car can rise rapidly. Studies have revealed that the temperature inside a vehicle can increase by 16°C within just twenty minutes [9]. This temperature rise elevates the child's core body temperature, leading to severe medical complications when it surpasses 40°C, including coma, brain damage, and even sudden death [10]. Additionally, the presence of Carbon Monoxide (CO) gases inside the car further exacerbates the risks. CO, commonly used in air conditioning compressors, can block the blood system, severely damaging the brain and heart [11]. To address this pressing issue and enhance child safety, the New Car Assessment Program for Southeast Asian Countries (ASEAN NCAP) has introduced a roadmap emphasizing child presence detection in vehicles as a key criterion for vehicle safety ratings [12]. This initiative encourages manufacturers to take responsibility for the safety of children traveling in their vehicles. The assessment includes a reminder system that prompts the driver to check the back seat at the end of each journey, with compliance contributing to the overall vehicle rating.

With the growing concern for child safety in vehicles, particularly during hot weather conditions, researchers have been exploring the potential of IoT-based children heatstroke sensor devices in cars. These devices aim to monitor and detect the temperature inside a car in real-time, alerting parents or caregivers if it reaches dangerous levels that could potentially lead to heatstroke. This research takes into consideration the vulnerable population, including children, patients, and the elderly, who are at a higher risk of heatstroke when left behind in a vehicle. By integrating various sensors, such as temperature and humidity sensors, the IoT-based heatstroke sensor device continuously monitors the car's interior environment. If the temperature inside the car exceeds a certain threshold, the device will trigger an alert message to the parents or caregivers, as well as to emergency services, ensuring prompt action can be taken to prevent any potential casualties [13-16]. Furthermore, researchers are exploring the possibility of enhancing the device by integrating it with other electrical control units inside the vehicle through an in-vehicle communication network. This would further improve vehicle safety and enable smart communication between various systems, such as rolling down the windows or starting the engine and turning on the air conditioner, to create a safer environment for children and vulnerable individuals left in cars [17-20].

By leveraging IoT technology, researchers are developing an intelligent life monitoring system for vehicles that includes interior environment monitoring and emergency management mechanisms. This system utilizes various sensors to collect data on the car's interior environment and analyzes it in real-time. Based on the collected data, the system can determine if the conditions inside the car pose a risk of heatstroke for any occupants and take appropriate actions to prevent any potential harm. These actions may include sending alert messages to parents and emergency services, as well as activating features such as rolling down windows or turning on the air conditioner [21-25]. In response to these challenges, this study focuses on designing and developing an IoT-based VHSD. By leveraging the power of IoT technology, the VHSD integrates multiple sensors to detect and measure crucial parameters such as CO levels, humidity, interior temperature, and environmental temperature within the vehicle. The collected sensor data is transmitted to the cloud, enabling real-time monitoring and analysis. Furthermore, the Blynk-IoT platform is a robust framework for data visualization and smartphone integration to facilitate seamless communication and control. By integrating advanced sensors, cloud connectivity, and real-time monitoring capabilities, the proposed device aims to analyze the interior temperature of a Perodua Axia car over a period of five days and examine the relationship between outdoor temperature and interior temperature. It seeks to identify patterns or trends in interior temperature fluctuations and assess the effectiveness of the car's insulation and air conditioning system in maintaining a stable interior temperature. It also provides insights and recommendations for optimizing the car's interior temperature management for passenger comfort and safety. This study lays the foundation for future advancements in protecting the lives of vulnerable children by enhancing child safety in vehicles.

2. Methodology

This study encompasses three key components: software and hardware development, as well as computer software analysis to identify the optimal design techniques and methods necessary for the successful completion of the project.

2.1 Design Survey

The survey design methodology employed in this study places the user at the forefront of product development and design. This approach offers several advantages, including gaining insights into users' comprehension of designs and requirements, facilitating design iteration and evaluation, and ultimately ensuring the product's utility and usability [26]. To gather feedback and requirements for the development of the VHSD, a survey was conducted. The survey consisted of two sections. The first section collected demographic data, including age, gender, vehicle ownership, and experience with unintentionally leaving children in the vehicle. The second section focused on users' requirements, needs, and preferences regarding the system. This section contained nine sets of questions, each using a five-point rating scale to assess the importance of various specifications. It includes battery life, design, aesthetics, durability, gas carbon dioxide sensor, radiation for sensor, safety, temperature, and user-friendliness. Subsequently, the survey was distributed to 120 respondents through social media platforms such as WhatsApp and Facebook.

2.2 System Structure

The main objective of this study is to develop a monitoring device that prevents parents from inadvertently leaving their children in vehicles. The device incorporates Arduino IDE, a Temperature and humidity sensor, a CO sensor, and the Blynk Application, connecting Arduino with the Blynk application. Arduino serves as a bridge between the hardware components and the Blynk application. When parents unintentionally leave their children in the vehicle, the device alerts them about the temperature, humidity, and CO levels inside the vehicle. Additionally, the device automatically connects to the home Wi-Fi network, preventing hyperthermia in children. Once the system is set up, it sends email notifications to the parents. Consequently, it provides alerts through the application by vibrating and displaying pop-up messages on the smartphone's lock screen.

2.3 Hardware and Software Development

The VHSD proposed in this study integrates hardware, software, and communication into a comprehensive solution to optimize the Child Safety System (CSS) design through IoT implementation. The hardware component of the system includes an Arduino UNO microcontroller, which is integrated with a multi-sensor setup to measure and monitor the condition of children left inside the vehicle. Figure 1 illustrates the system's flow chart. Upon activation, the device connects to the internet via a Wi-Fi module (ESP8266). Consequently, the sensors collect readings: the DHT22 temperature sensor measures temperature and humidity, while the MQ-7 gas sensor module detects the presence of combustion gas. Note that the Wi-Fi shield module facilitates the IoT connection. At each sensor stage, parents receive warning notifications on their smartphones through the IoT platform if an abnormal condition is detected. Real-time monitoring is facilitated through the Blynk application on the smartphone, while Light Emitting Diode (LED) indicators on the prototype provide visual feedback. All embedded sensors adhere to the child presence detection criteria specified in the ASEAN NCAP standard [27]. The normal readings for outdoor temperature, in-cabin temperature, humidity, and CO gas level are set at 39℃ to 42℃, 27℃ to 33℃, 40% to 80% Relative Humidity (RH), and 10 (Rs/Ro), respectively. Furthermore, the software components employed in this project include the Arduino IDE software and the Blynk application. The Arduino IDE supports programming languages such as C and C++ and provides a platform for writing and uploading programs to Arduino-compatible boards. On the other hand, Blynk is an app available for iOS and Android that enables users to create interfaces for controlling and monitoring hardware projects efficiently [14]. By utilizing widgets within the Blynk application, users can interact with the sensor outputs. Moreover, Blynk supports a wide range of platforms, including Arduino boards, Raspberry Pi models, ESP8266, Particle Core, and other popular microcontrollers.

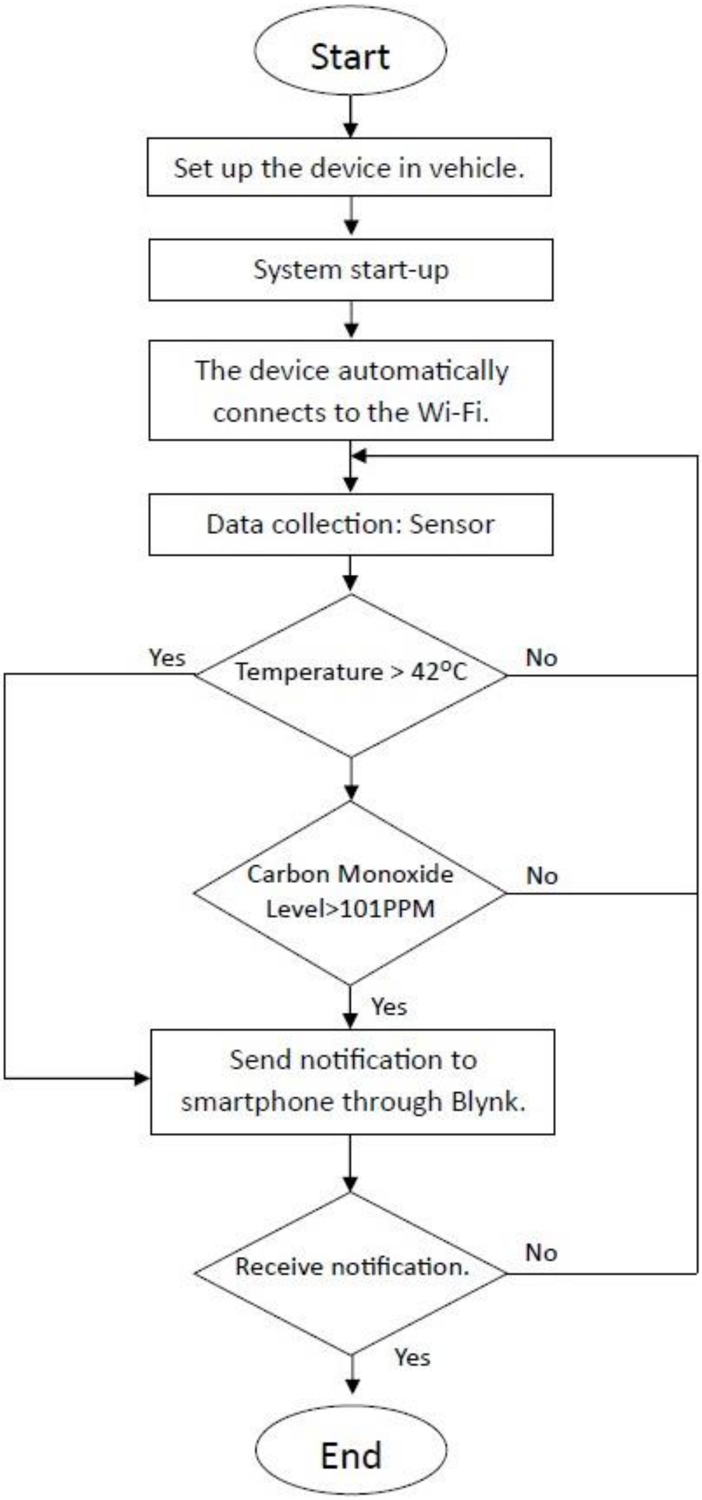

Fig. 1. Logic flow chart of the system

2.4 Experiment Setup

The experiment conducted in this study aimed to measure interior vehicle temperature, ambient temperature, humidity, and CO levels in two different types of vehicles: sedan and compact vehicles. These vehicle types were selected based on their representation of different sizes, vehicle categories, and exterior colours. The Perodua Axia was selected as the compact vehicle type, while the Proton Persona represented the sedan type. The experiments were conducted over a period of five consecutive days in August 2022, specifically at a parking lot in Melaka, Malaysia, between 10:00 a.m. and 4:00 p.m. The VHSD placement within the vehicles is illustrated in Figure 2. Throughout the experiment, no individuals were present inside the vehicles. The data recording interval of the device was set to 5 minutes, the windows were kept fully closed during data collection, and the engine remained turned off.

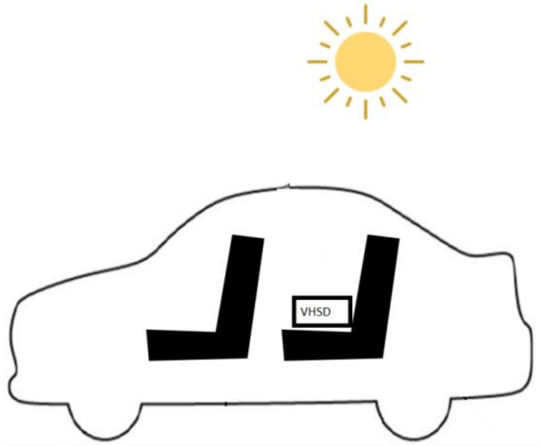

Fig. 2. Placement of experiment in the vehicle

3. Results

3.1 Demographic and Product Specification

The survey conducted in this study provided valuable insights into the respondents' demographic data and their preferences regarding the VHSD. Figure 3 illustrates the age distribution of the respondents, revealing that the majority (76.7%) fall within the age range of 20 to 29 years. When considering accident experience, it was discovered that 73% of the respondents did not have any previous accident-related incidents in Figure 4. On the other hand, Figure 5 displays the vehicle ownership status of the respondents, indicating that 68.3% of them own a vehicle while 31.7% do not. In terms of gender distribution in Figure 6, 70.8% of the respondents were male, while 29.2% were female. Furthermore, the survey examined the respondents' preferences and requirements for the VHSD system. Figure 7 presents the percentage of respondents who rated each specification as important for the system. The results demonstrate that most respondents prioritized safety (94.2%) as a crucial specification. Other significant specifications included temperature sensor (92.5%), durability (90.8%), radiation sensor (87.5%), battery life (89.2%), user-friendliness (87.5%), gas sensor (81.7%), price (78.3%), and aesthetics (70%). Notably, safety received the highest percentage, indicating that respondents strongly emphasized the safety features of the VHSD. In contrast, aesthetics received the lowest percentage, suggesting that respondents valued safety over visual design. Overall, the survey results shed light on the demographic characteristics of the respondents and their preferences regarding the VHSD system. These findings provide valuable insights for developing and designing an effective and user-centric VHSD.

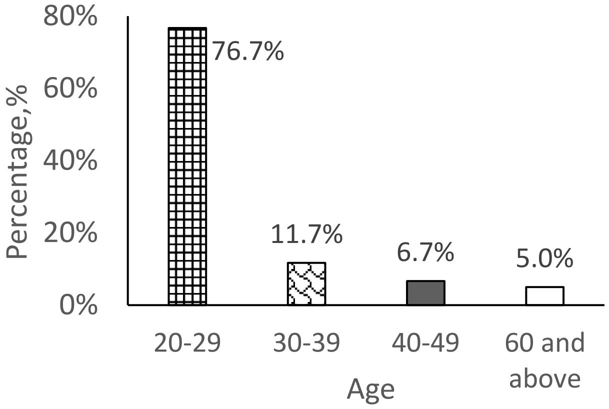

Fig. 3. Age

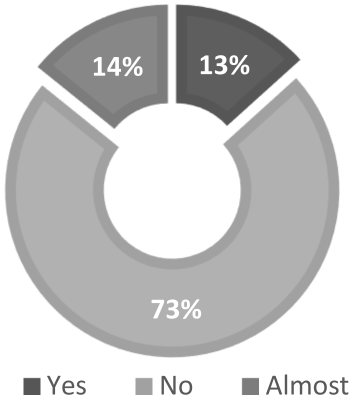

Fig. 4. Accident experience

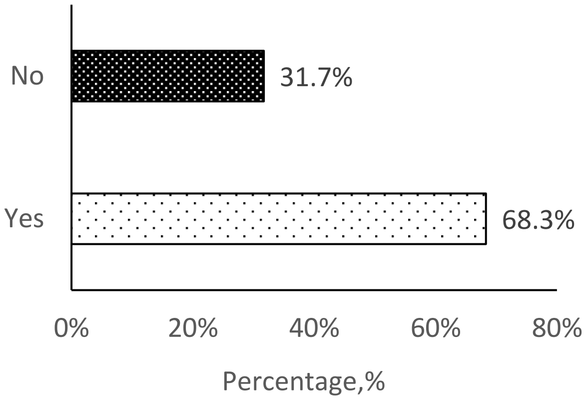

Fig. 5. Own a vehicle

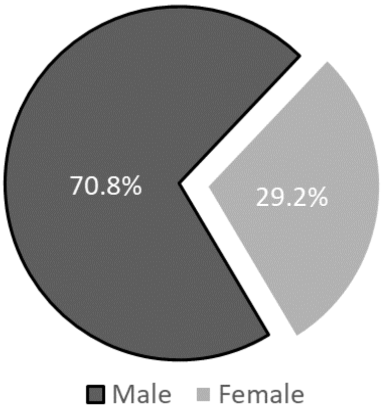

Fig. 6. Gender

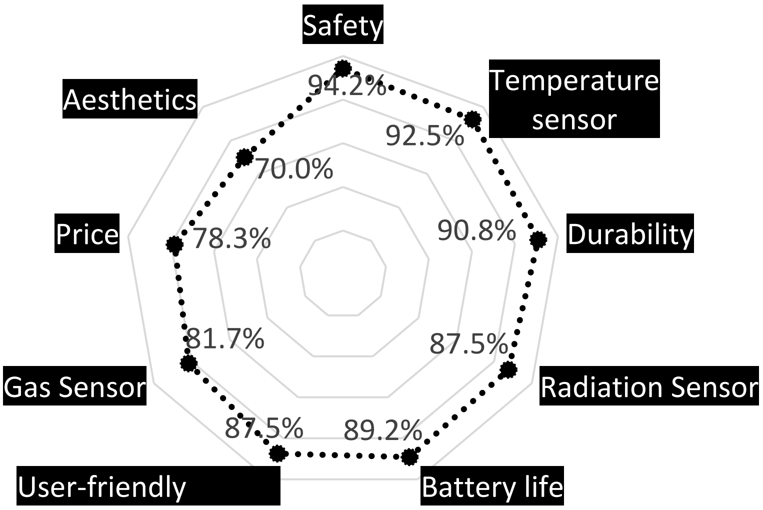

Fig. 7. Respondent specification

3.1.1 Experiment result

Understanding the indoor temperature dynamics within a car is crucial for ensuring occupant comfort and reducing heatstroke risk. This study examines the interior and outdoor temperature data collected from Perodua Axia and Proton Persona cars over five consecutive days. Note that the interior temperature data and the corresponding outdoor temperatures were collected at specific time intervals. The objective is to understand the relationship between outdoor and interior temperatures and identify any patterns or trends that may exist. Data on outdoor and interior temperatures over a span of five days were recorded at different time intervals, as displayed in Figure 8. The outdoor temperature readings were taken at 10-minute intervals from 10:00 a.m. to 3:00 p.m., while the corresponding interior temperature readings were also recorded. The purpose of this analysis is to examine the relationship between outdoor and interior temperatures and evaluate any trends or patterns that may emerge. Based on observation, the outdoor temperature fluctuates throughout the day, ranging from a minimum of 29.8℃ to a maximum of 41.6℃. Similarly, the interior temperature varies between 41.1℃ and 50.98℃. According to the Department of Standard Malaysia, the recommended interior air temperature range for a standard interior environment in Malaysia is between 23℃ and 26℃ [28-30]. It is important to note that the interior temperature consistently remains higher than the outdoor temperature, which can be attributed to factors such as insulation, solar gain, and internal heat sources. Further data analysis reveals a clear positive correlation between interior and exterior temperatures. As the outdoor temperature increases, the interior temperature also tends to rise, and vice versa. This correlation is expected as heat transfers from higher-temperature to lower-temperature regions. Therefore, as the outdoor temperature increases, more heat is transferred into the interior space, resulting in an elevated interior temperature. The time of the day also plays a role in temperature fluctuations. During the morning hours, both outdoor and interior temperatures are relatively lower. As the day progresses, temperatures rise, peaking around noon and gradually decreasing in the afternoon. This pattern aligns with the diurnal temperature variation commonly observed in outdoor environments. The data also suggests a delay in the response of interior temperature to changes in outdoor temperature. Note that this delay can be attributed to thermal inertia, causing a time lag in heat transfer. Additionally, the building materials and thermal mass of the interior space influence this time lag. As a result, the interior temperature may not immediately reflect changes in the outdoor temperature but instead exhibit a lagged response.

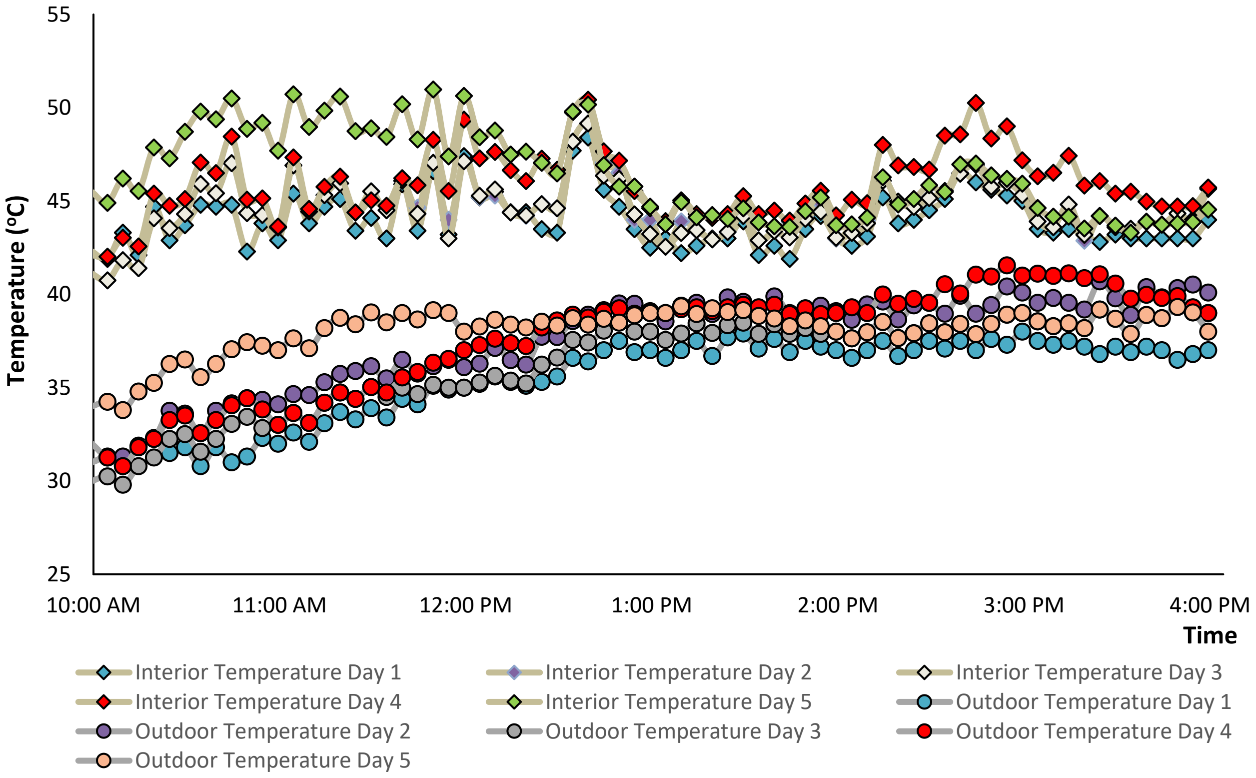

Fig. 8. Outside temperature and interior temperature in Axia

Similar to Perodua Axia, the data recorded in Proton Persona for the temperatures were recorded every five minutes from 10:00 a.m. to 2:00 p.m., as illustrated in Figure 9. The data collected provides insights into the thermal behaviors of the car's interior under varying outdoor conditions. The results (Persona) demonstrate a range of indoor temperatures between 36.10℃ and 49.49℃, reflecting the influence of external weather conditions on the car's thermal environment. The observed indoor temperature range within the Proton Persona car reveals its sensitivity to external weather conditions. The car's thermal behavior is influenced by factors such as solar radiation, ambient temperature, and the efficiency of its air conditioning system. During the study period, the outdoor temperatures varied between 30.80℃ and 47.20℃, while the indoor temperatures ranged from 36.10℃ to 49.49℃. The recorded temperatures indicate that the car's interior tends to be slightly warmer than outdoors, consistent with the greenhouse effect often experienced inside vehicles. The greenhouse effect occurs due to the absorption of solar radiation by the car's windows and the subsequent trapping of heat inside. Additionally, factors like insulation, ventilation, and the number of occupants can affect the overall thermal balance within the car's cabin. It is worth noting that the highest recorded indoor temperature of 49.49℃ suggests the possibility of discomfort for passengers, particularly in hot weather conditions. Such high temperatures may also impact the efficiency and performance of electronic devices inside the car. Therefore, it is important to consider measures to mitigate excessive heat buildup, such as sunshades, tinted windows, or proper ventilation systems [31-34]. Conversely, the lowest recorded indoor temperature of 36.10℃ indicates that the car's interior can still provide a cooler environment than the outdoor conditions under certain circumstances. Hence, this finding could be advantageous during hot weather conditions as the car's cabin may act as a refuge from the external heat, offering a relatively lower temperature.

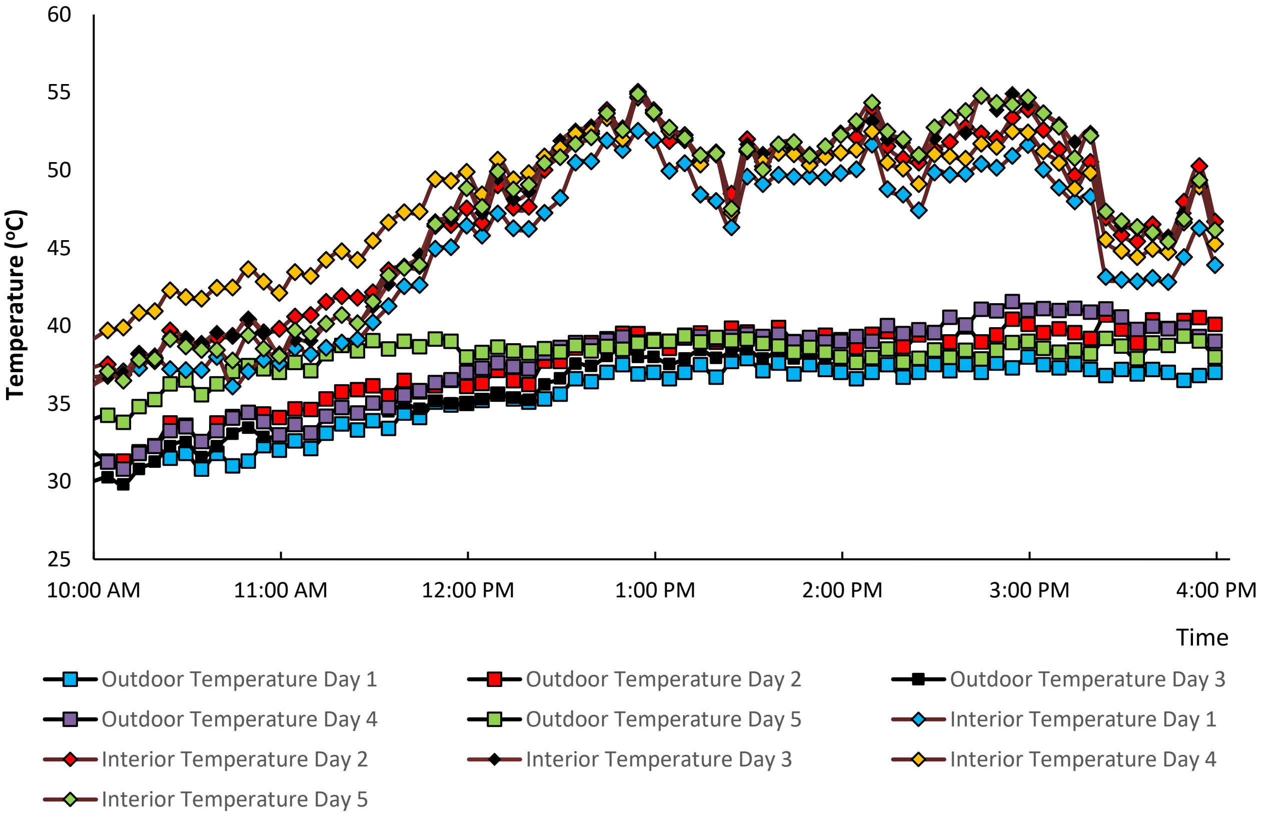

Fig. 9. Outdoor temperature and interior temperature in Persona

The analysis reveals diurnal temperature patterns, highlighting the impact of outdoor temperature on the car's interior climate. Our findings provide valuable insights for developing effective strategies to enhance in-car thermal comfort and reduce heatstroke risk. The interior temperature of a vehicle is influenced by various factors, including solar radiation, air leakage, and the surrounding outdoor environment. Understanding these dynamics is vital for optimizing occupant comfort and energy efficiency [35-37]. This study analyzes the indoor temperature variation within Perodua Axia and Proton Persona cars and explores the correlation between indoor and outdoor temperatures. The results contribute to the existing knowledge on in-car thermal behaviors, aiding in developing effective thermal management systems and reducing heatstroke risk. As portrayed in Table 1, both car models experienced a rise in interior temperature over time due to external heat sources. However, the Proton Persona consistently exhibited higher peak interior temperatures compared to the Perodua Axia. At the start of the measurements, the Proton Persona had an initial interior temperature of 32.5℃, while the Perodua Axia started at a slightly lower temperature of 31.2℃. Over the course of 60 minutes, the Proton Persona experienced a rapid increase in interior temperature, reaching a peak of 47.8℃. In contrast, the Perodua Axia reached a lower peak interior temperature of 41.5℃ during the same time. This suggests that the Proton Persona retains more heat and has a slower cooling rate than the Perodua Axia. The variations in interior temperature dynamics between the two car models can be attributed to several factors, including differences in insulation, airflow, and material properties. The Proton Persona may have less effective insulation and airflow systems, leading to a higher heat accumulation within the vehicle cabin. Conversely, the Perodua Axia appears to have better insulation and airflow mechanisms, enabling it to dissipate heat more efficiently. These findings have important implications for heatstroke risk. Higher interior temperatures and slower cooling rates increase the likelihood of occupants experiencing heat-related health issues, including heatstroke. Prolonged exposure to elevated interior temperatures can significantly elevate the risk of heatstroke. Furthermore, external factors such as prolonged sunlight exposure and inadequate ventilation can exacerbate vehicle heat buildup. These factors should be considered when assessing the risk of heatstroke and developing preventive measures.

Table 1
Interior temperature comparison of Proton Persona and Perodua Axia cars

Time Interval	Proton Persona (°C)	Perodua Axia (°C)
0 min	32.5	31.2
15 min	38.9	35.8
30 min	42.3	37.6
45 min	45.1	39.9
60 min	47.8	41.5

Table 2 presents the results of the Independent *T*-test conducted to analyze the interior temperature differences between the Perodua Axia and Proton Persona cars at various time intervals. The *T*-test results revealed significant differences in the interior temperature readings between the two car models, confirming the existence of a statistically significant variance. At 2:20 p.m., the Perodua Axia (M = 7.0535, SD = 0.4355) exhibited a significantly lower interior temperature compared to the Proton Persona (M = 12.5620, SD = 1.6010), with a *T*-test result of t (8) = -7.4237 and a p-value of 0.0010. Similarly, at 2:35 p.m., 2:45 p.m., 2:50 p.m., 3:10 p.m., 3:15 p.m., and 3:20 p.m., the Perodua Axia consistently demonstrated significantly lower interior temperatures compared to the Proton Persona, with *T*-test results indicating strong evidence of a temperature difference ($p < 0.01$). The data from Table 1 demonstrates that the Proton Persona consistently exhibited higher interior temperatures compared to the Perodua Axia across all time intervals. Moreover, the mean interior temperature values for the Proton Persona were nearly double that of the Perodua Axia. These findings reinforce the earlier analysis and highlight the significant difference in heat accumulation potential between the two car models. The statistical significance of the *T*-test results supports the rejection of the null hypothesis, indicating that the interior temperatures of the Perodua Axia and Proton Persona are indeed significantly different. The Perodua Axia consistently maintained lower interior temperatures, suggesting better heat dissipation and insulation capabilities compared to the Proton Persona. These findings have important implications for the risk of heatstroke in vehicles. The significantly higher interior temperatures observed in the Proton Persona, coupled with slower cooling rates, increase the potential for heat-related health issues, including heatstroke. Thus, car manufacturers must consider these differences in interior temperature dynamics and implement measures to enhance heat dissipation, improve insulation, and optimize climate control systems to mitigate the risk of heat-related health hazards for vehicle occupants.

Table 2
T-Test result (significantly difference)

Time	*Perodua Axia (n=8)*		*Proton Persona (n=8)*		*T-test result for Axia vs Perodua*	
	M	SD	M	SD	t	p
2:20 p.m.	7.0535	0.4355	12.5620	1.6010	-7.4237	0.0010
2:35 p.m.	7.5236	0.5725	13.3286	2.1505	-5.8328	0.0028
2:45 p.m.	8.8795	0.5153	14.2616	2.6830	-4.4051	0.0099
2:50 p.m.	7.4058	0.6746	13.4075	2.2305	-5.7591	0.0027
3:10 p.m.	5.2979	0.8788	12.3492	2.2030	-6.6477	0.0010
3:15 p.m.	5.9312	0.4515	10.7963	2.1809	-4.8845	0.0066
3:20 p.m.	4.9956	0.8448	11.9281	2.2103	-6.5512	0.0011

4. Conclusions

In conclusion, the comparative analysis of the Proton Persona and Perodua Axia cars has provided valuable insights into their interior temperature dynamics and their implications for heat stroke risk. The study revealed significant differences in the interior temperature profiles of the two cars, with the Proton Persona exhibiting higher peak temperatures and slower cooling rates compared to the Perodua Axia. These findings indicate a higher heat accumulation potential in the Proton Persona, which could increase the risk of heat-related health issues, including heat stroke, for vehicle occupants.

To address this risk and enhance passenger safety, it is crucial for vehicle manufacturers to prioritize car design features and climate control mechanisms that minimize heat buildup, improve insulation, optimize airflow systems, and incorporate advanced temperature regulation technologies. By integrating advanced sensors, cloud connectivity, and real-time monitoring capabilities, car manufacturers can develop devices that enhance child safety in vehicles and lay the foundation for future advancements in protecting the lives of vulnerable children.

The *T*-test results provide robust evidence supporting the significant differences in interior temperatures between the Perodua Axia and Proton Persona cars. The Perodua Axia consistently maintained lower interior temperatures, demonstrating superior heat dissipation and insulation capabilities. These findings underscore the importance of effective vehicle design and climate control systems in mitigating heat accumulation and reducing the risk of heat-related health issues, such as heat stroke, for vehicle occupants.

Note that this study emphasizes the need for continuous improvement in car design, insulation, ventilation, and cooling systems to create safer and more comfortable interior environments. By optimizing these factors, the risk of heat stroke can be mitigated, ensuring the safety and well-being of vehicle occupants, particularly in regions with hot climates. Moreover, integrating advanced technologies and real-time monitoring capabilities can further enhance the effectiveness of vehicle heat management systems, providing an added layer of protection for vulnerable passengers, such as children. These advancements align with ASEAN NCAP requirements and contribute to the overall goal of reducing heat-related risks in vehicles and protecting the lives of occupants.

Acknowledgement

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