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Vehicle cabin heat build-up analysis based on dimensional differences under direct sunlight parking

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Abstract

Prolonged parking of vehicles under direct sunlight leads to significant cabin heat build-up, reducing thermal comfort, accelerating interior material degradation, and increasing health risks associated with elevated temperatures. This study experimentally investigates the influence of vehicle dimensional differences on cabin temperature rise during outdoor parking under tropical conditions. Two passenger vehicles with contrasting cabin volumes the Toyota Avanza 1.3 G (2010) and Toyota Innova 2.0 G (2010) were exposed to direct sunlight for eight hours (08:20-16:20 WIB). Cabin temperatures were recorded using a multi-point measurement system consisting of four Type-K thermocouples connected to a data logger, while ambient temperature was monitored simultaneously. The results show that both vehicles experienced substantial cabin heat accumulation relative to ambient conditions, with the highest temperatures consistently observed in the front cabin region (dashboard and front-seat areas). The Avanza exhibited a higher average cabin temperature increase of 15.78 °C (45.25%) compared to 9.06 °C (24%) for the Innova, indicating faster heat accumulation in vehicles with smaller cabin volumes. These findings confirm that vehicle dimensional characteristics significantly influence passive cabin thermal behaviour during parking under direct sunlight. The study provides experimental evidence to support the consideration of cabin size, glazing characteristics, and interior layout in the development of effective thermal risk mitigation strategies for vehicles operating in tropical environments.

Keywords

Cabin temperature, Vehicle dimensions, Solar heat gain, Thermal comfort, Carbon monoxide exposure

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Introduction

The rapid growth of motorized vehicles in developing countries, including Indonesia, has significantly increased the demand for parking facilities, particularly in dense urban environments. Unfortunately, the expansion of shaded or climate-controlled parking infrastructure has not kept pace with vehicle ownership growth, resulting in many vehicles being routinely parked under direct solar radiation. Under such conditions, solar heat gain becomes the dominant factor governing cabin temperature rise, leading to severe thermal discomfort and safety risks for vehicle occupants [1].

When a vehicle is exposed to direct sunlight with closed windows, short-wave solar radiation penetrates the glazing surfaces and is absorbed by interior components such as dashboards, seats, and trim panels. The absorbed energy is then re-emitted as long-wave radiation, which is partially trapped inside the cabin, producing a greenhouse effect. Numerous experimental studies have reported that cabin air temperature can exceed ambient conditions by 20-30 °C within a short duration of parking, particularly in tropical climates [2], [3]. Such extreme thermal environments not only reduce passenger comfort but also accelerate material degradation and increase the cooling load once the vehicle is reoccupied.

Beyond thermal discomfort, elevated cabin temperatures pose serious health and safety concerns. Prolonged exposure to high temperatures promotes the emission of hazardous gases from interior materials through evaporation and thermal decomposition. Carbon monoxide (CO) accumulation in enclosed vehicle cabins poses significant health risks due to its strong affinity for haemoglobin, potentially leading to hypoxia and neurological impairment [4]. In addition, ammonia (NH_3) and other volatile compounds released from polymer-based interior components may cause respiratory irritation at elevated concentrations [5].

Vehicle design characteristics strongly influence the rate and magnitude of cabin heat build-up. Key parameters include overall vehicle dimensions, cabin volume, glazing area, glass orientation, and interior material properties. Vehicles with larger window surface areas and higher solar transmittance tend to absorb greater amounts of radiant energy, while cabin volume and geometric configuration govern heat storage capacity and internal air circulation patterns [6].

Existing research on vehicle cabin thermal behaviour has primarily focused on mitigation strategies, such as reflective window films, solar-powered ventilation systems, and active cooling approaches. Comparatively limited attention has been devoted to direct experimental comparisons of cabin temperature behaviour based on vehicle dimensional differences under real outdoor parking conditions. This gap is particularly evident for commonly used passenger vehicles in tropical environments.

Accordingly, this study aims to experimentally analyse and compare cabin temperature profiles of two passenger vehicles with distinct dimensional characteristics Toyota Avanza 1.3 G and Toyota Innova 2.0 G when parked under direct sunlight. Multi-point temperature measurements and continuous data logging are employed to capture spatial and temporal thermal variations within the cabin, providing insights into the influence of vehicle dimensions on heat build-up behaviour.

Method

This study employed an experimental field-based research design to evaluate the influence of vehicle dimensional differences on cabin heat build-up under direct solar exposure. An experimental approach was selected to enable controlled comparison between vehicles subjected to identical environmental conditions while allowing continuous monitoring of thermal responses over time [9].

Two passenger vehicles with contrasting dimensional characteristics were selected as test objects: a Toyota Avanza 1.3 G (2010) and a Toyota Innova 2.0 G (2010). These vehicles represent commonly used multi-purpose vehicles in Indonesia and differ substantially in cabin volume, body size, and glazing area. Both vehicles were maintained in original factory condition, without modifications to windows, ventilation systems, or interior materials, to ensure experimental consistency. The research pattern can be seen in Figure 1.

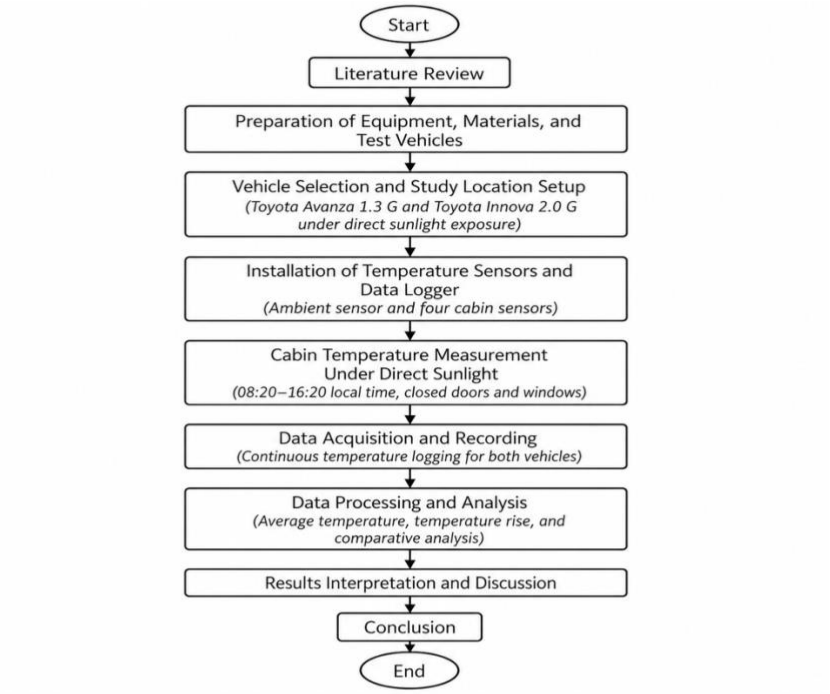

Figure 1. Research flowchart

The experiment was conducted in an open parking area at Universitas Negeri Padang, Indonesia. The location was selected to ensure unobstructed exposure to direct sunlight throughout the measurement period. Data collection was carried out from 08:20 to 16:20 local time, covering the full diurnal variation of solar radiation and ambient temperature.

Cabin temperature measurements were obtained using Type-K thermocouples connected to a digital data logger capable of continuous recording. An additional thermocouple was positioned outside the vehicles to measure ambient air temperature. Type-K thermocouples were selected due to their reliability, wide operating temperature range, and suitability for outdoor thermal measurements [7].

Inside each vehicle, four thermocouples were installed at representative locations to capture spatial temperature distribution: (1) the center of the front dashboard, (2) the front seat area, (3) the middle-seat area, and (4) the rear-seat area. This sensor configuration follows established practices in vehicle cabin thermal studies and ensures coverage of key occupant zones [8]. The placement of the temperature sensor in the cabin can be seen in Figure 2.

Figure 2. Placement of the temperature sensor in the cabin

Prior to testing, both vehicles were parked under direct sunlight with all doors and windows fully closed to simulate typical parking conditions. The thermocouples were securely mounted, and the data logger was activated to record temperature data at regular intervals throughout the eight-hour exposure period. During the experiment, the vehicles remained stationary and were not shaded or ventilated to prevent external interference. To ensure data reliability, the experimental procedure was repeated three times on separate days with similar weather conditions. At the end of each test, the recorded temperature data were downloaded and organized into structured datasets for further analysis.

Data analysis was conducted by calculating the average cabin temperature at each sensor location for both vehicles. Temperature rise relative to ambient conditions was determined to quantify heat accumulation within the cabin. Comparative analysis between the two vehicles was then performed to evaluate the influence of dimensional differences on thermal behaviour. The results were presented in graphical and descriptive forms to illustrate temporal and spatial temperature variations. This study did not involve human or animal subjects. All experimental procedures complied with standard safety guidelines for outdoor measurements and electronic instrumentation handling.

Results

The experimental results demonstrate a significant increase in cabin temperature for both vehicles during parking under direct sunlight, accompanied by clear spatial variations across the four sensor locations. The measured temperature and humidity data for the Toyota Avanza 1.3 G and Toyota Innova 2.0 G are summarized in Tables 1 and 2, respectively. Graph of avanza temperature test results show in Figure 3.

Table 1. Results of the avanza temperature and humidity tests

No	Time	Outside Temp. (°C)	Average Cabin Temperature (°C)				Average Cabin Humidity (%)			
			Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 2	Sensor 3	Sensor 4
1	08.20	27.37	34.67	32.33	30.67	32	69.33	79.00	81.00	73.00
2	09.20	31.67	45.33	42.67	38.67	41	45.67	58.67	62.33	59.00
3	10.20	34.20	52	50.67	47.33	48	40.67	42.67	43.33	42.67
4	11.20	35.43	58.67	58.67	53.67	57.67	23.33	30.33	36.67	28.00
5	12.20	37.30	60	59.67	56.67	58	24.67	28.67	28.00	26.33
6	13.20	39.93	61	59	56	56	30.00	25.33	31.67	29.67
7	14.20	40.53	55.33	54.67	52.33	53.67	33.67	29.33	36.67	33.67
8	15.20	35.50	55.33	54.33	50.33	52.33	32.33	31.00	44.33	35.00
9	16.20	31.83	53.33	52.67	48	50.33	33.33	34.67	47.00	37.67
Average		34.86	52.85	51.63	48.19	49.89	32	39.96	45.67	40.56

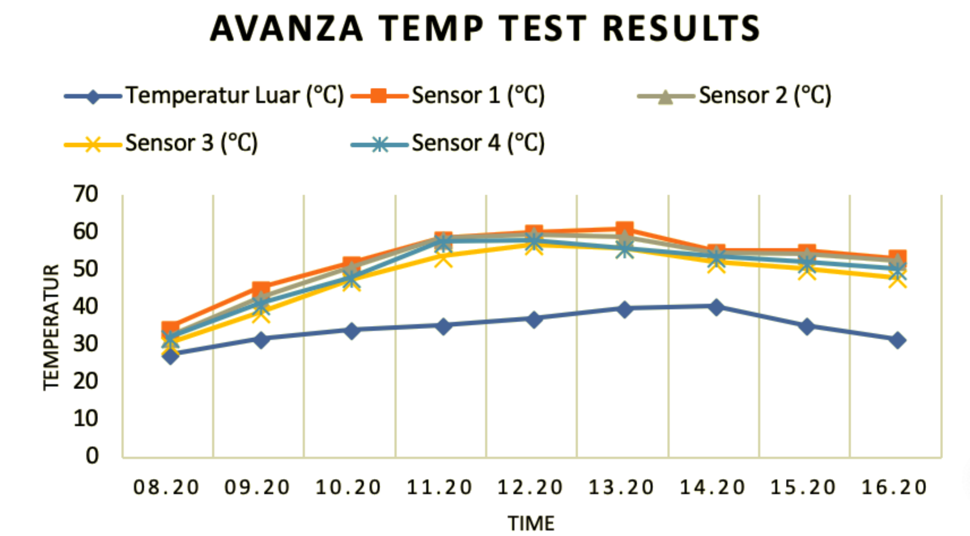

Figure 3. Graph of avanza temperature test results

For the Toyota Avanza, the average ambient temperature during the testing period was 34.86 °C. The highest cabin temperatures were consistently recorded at Sensor 1 (dashboard region), reaching a peak value of 61 °C. The average cabin temperatures at Sensors 1 to 4 were 52.85 °C, 51.63 °C, 48.19 °C, and 49.89 °C, respectively. These results indicate a substantial temperature rise relative to ambient conditions, particularly in the front cabin area. A general decrease in relative humidity was observed as cabin temperature increased, with average values ranging from 37% to 46%. The temporal trend of temperature rise for the Avanza is illustrated in Figure 3.

Table 2. Results of innova temperature and humidity tests

No	Time	Outside Temp. (°C)	Average Cabin Temperature (°C)				Average Cabin Humidity (%)			
			Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 2	Sensor 3	Sensor 4
1	08.20	30.7	31	30.67	29.67	29.33	79.33	80.00	83.33	85.67
2	09.20	32.87	36.67	35.33	34.33	34.67	69.33	69.67	70.00	72.67
3	10.20	36.57	49.33	47.33	46.33	45	43.67	48.67	44.00	48.33
4	11.20	42.37	52.67	51.33	49.67	48.67	33.33	41.33	40.67	46.00
5	12.20	44.07	53	51.33	49.67	47.67	38.00	37.67	37.00	42.33
6	13.20	44.87	58	55.67	54	53.33	30.67	34.67	33.67	33.33
7	14.20	43.77	59	57.33	55.33	53.67	25.33	29.67	33.00	33.00
8	15.20	32.93	51	50.33	49	47.33	35.67	44.00	39.33	47.33
9	16.20	30.37	46.67	47.33	44.67	43.33	39.67	45.33	51.00	55.67
Average		37.61	48.59	47.41	45.85	44.78	43.89	47.89	48.00	51.59

In contrast, the Toyota Innova exhibited lower cabin temperature values despite a higher average ambient temperature of 37.61 °C. The average cabin temperatures recorded at Sensors 1 to 4 were 48.59 °C, 47.41 °C, 45.85 °C, and 44.78 °C, respectively, with a maximum temperature of 59 °C at Sensor 1. Compared to the Avanza, the Innova showed slower heat accumulation and relatively higher humidity levels, suggesting a different thermal response of the cabin. The corresponding temperature distribution is presented in Figure 4.

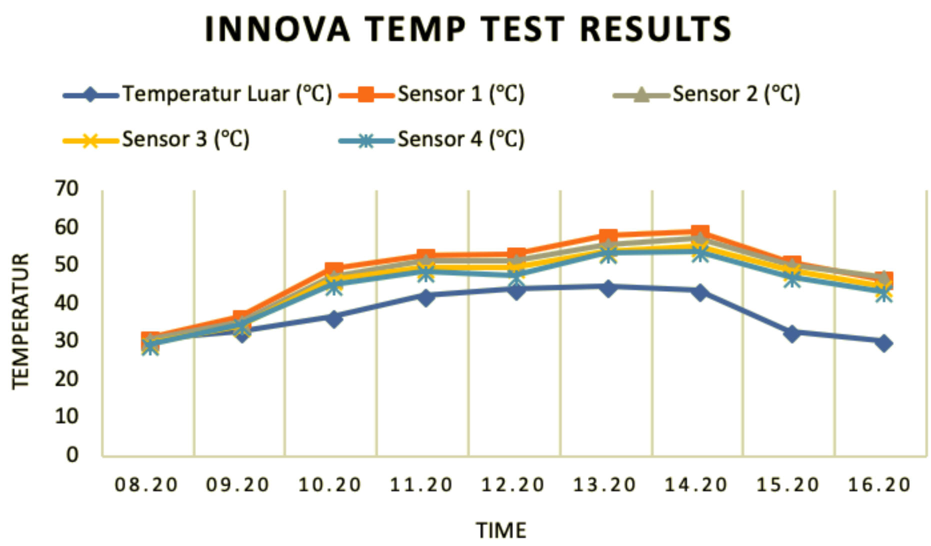

Figure 4. Graph of innova temperature test results

Overall, both vehicles experienced pronounced cabin heat build-up under direct solar exposure, with the highest temperatures consistently occurring in the front cabin region. A direct comparison of the average cabin temperature rise for both vehicles is provided in Figure 5.

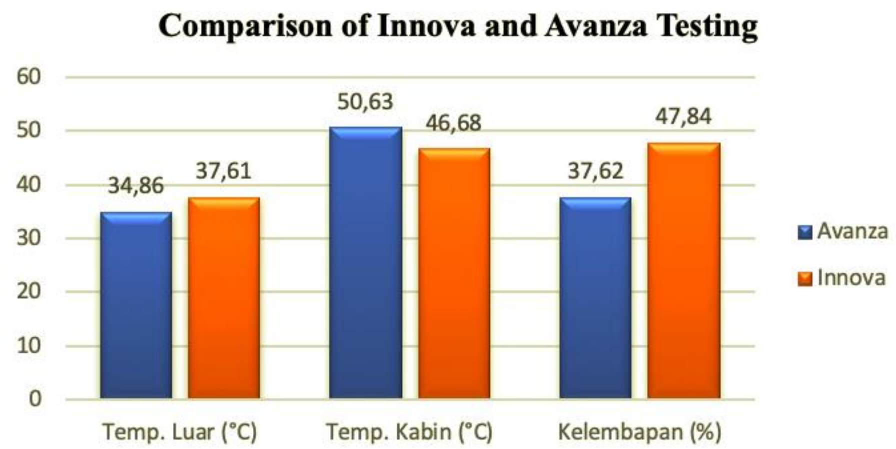

Figure 5. Comparison of test results on avanza and innova

Discussion

The observed increase in cabin temperature in both vehicles can be primarily attributed to solar radiation-induced heat gain and the greenhouse effect occurring within an enclosed cabin. Short-wave solar radiation entering through the windshield and side windows is absorbed by interior surfaces such as the dashboard and seats. This absorbed energy is subsequently re-emitted as long-wave radiation, which becomes trapped inside the cabin due to limited air exchange, leading to rapid temperature escalation.

The spatial temperature distribution clearly indicates that Sensors 1 and 2 recorded higher temperatures than Sensors 3 and 4 in both vehicles. This pattern confirms that the front cabin region experiences more intense heat accumulation as it is directly exposed to incoming solar radiation through the windshield. Heat absorbed in this region accumulates initially in the dashboard and front-seat area before gradually propagating toward the middle and rear cabin through conduction and natural convection. Consequently, the rear cabin regions exhibit lower temperatures and slower heating rates.

A comparison between the two vehicles highlights the significant influence of dimensional and design characteristics on cabin thermal behavior. Despite similar exposure conditions, the Toyota Avanza experienced a higher maximum temperature rise relative to ambient conditions (17.99 °C) compared to the Toyota Innova (10.98 °C). This difference suggests that the smaller cabin volume of the Avanza promotes faster heat accumulation and reduces the thermal buffering capacity of the cabin air.

In addition to cabin volume, glazing properties and interior material characteristics likely contributed to the observed differences. The Innova benefits from a larger cabin volume and glazing with improved ultraviolet attenuation, which reduces solar energy transmission into the cabin. Moreover, lighter interior materials and enhanced thermal insulation in the Innova may limit radiant heat absorption and delay temperature rise.

Conversely, darker interior materials in the Avanza are more effective at absorbing radiant energy, thereby intensifying heat build-up.

These findings confirm that vehicle dimensional differences play a critical role in determining cabin heat build-up during parking under direct sunlight. Vehicles with smaller cabin volumes and higher effective solar absorption are more susceptible to rapid and severe temperature increases, which can exacerbate thermal discomfort and elevate health risks. The results emphasize the importance of passive thermal design considerations such as cabin geometry, glazing characteristics, and interior material selection in mitigating heat-related hazards in parked vehicles, particularly in tropical climates.

Conclusion

This study experimentally investigated the effect of vehicle dimensional differences on cabin heat build-up during parking under direct sunlight using two representative passenger vehicles. The results confirm that a significant temperature rise occurs inside vehicle cabins relative to ambient conditions, with pronounced spatial variation across sensor locations. In both vehicles, the highest temperatures were consistently observed in the front cabin region, particularly at the dashboard and front-seat areas, indicating the dominant role of direct solar radiation through the windshield.

A comparative analysis revealed that the Toyota Avanza exhibited a higher average cabin temperature increase than the Toyota Innova, with an average rise of approximately 15.78 °C (45.25%) compared to 9.06 °C (24%). This finding demonstrates that vehicles with smaller cabin volumes are more susceptible to rapid heat accumulation due to reduced thermal buffering capacity. In contrast, the larger cabin volume and glazing characteristics of the Innova contributed to a lower temperature rise under similar exposure conditions.

Overall, the findings highlight that vehicle dimensional characteristics significantly influence cabin thermal behavior during outdoor parking. This work contributes fundamental experimental evidence to the understanding of passive cabin heat build-up in tropical environments and underscores the importance of considering cabin size, glazing properties, and interior layout in vehicle design and thermal risk mitigation strategies. Future studies may extend this work by incorporating a broader range of vehicle types, material properties, and environmental conditions to support the development of effective passive and active thermal management solutions.

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