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Assessment of the Thermal Performance of Tinted Vehicles Cabin and Its Implication for Energy Efficiency and Climate Change Mitigation

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Abstract

Solar radiation penetrating vehicle cabins significantly increases interior temperatures, resulting in thermal discomfort, increased cooling demand, and higher greenhouse gas emissions from vehicle air-conditioning systems. This study assesses the thermal characteristics of tinted and untinted vehicles and examines the implication of vehicle window tinting for energy consumption and climate change mitigation. An experimental approach was adopted in which cabin temperatures of vehicles with different window tint conditions were measured under identical environmental conditions. Temperature measurements were conducted for five days using a Generic HTC-2 digital thermometer on vehicles parked under direct solar radiation between 12:00 pm and 2:00 pm with engines turned off, windows closed, and no air-conditioning in operation. The collected data were analyzed using descriptive statistics. Results show that untinted vehicles recorded the highest average cabin temperature of approximately 60°C. In contrast, vehicles fitted with dyed, carbon, and ceramic tint films recorded significantly lower temperatures of 52°C, 48°C, and 42°C respectively. This represents an average temperature reduction of about 18°C across tinted conditions, demonstrating the effectiveness of window tinting in limiting solar heat penetration. Cooling time analysis further revealed that untinted vehicles required longer air-conditioning operation (6.8 minutes) compared with tinted vehicles (3.2 minutes), representing a reduction of approximately 53% in cooling time. These findings indicate that window tinting substantially improves vehicle thermal performance and reduces cooling energy demand. Reduced air-conditioning operation translates into lower fuel consumption and decreased greenhouse gas emissions. Consequently, widespread adoption of heat-reducing window technologies has the potential to reduce greenhouse gas emissions through reduced fuel consumption, contribute to climate change mitigation, energy efficiency, and improved thermal comfort. The study highlights the need for innovative vehicle glazing technologies capable of minimizing cabin heat gain while addressing regulatory concerns associated with window tinting in Nigeria.

Keywords: Vehicle thermal management; solar radiation; window tinting; fuel consumption; greenhouse gas emissions; climate change mitigation.

Introduction

Car owners in Nigeria often install window films popularly known as tint for beautification and reducing the intensity of sunrays that penetrate their vehicles. The intensity of solar irradiance penetrating into vehicle cabins contributes to thermal discomfort of occupants and heat strokes due to elevated ambient temperature of vehicle cabin. According to Hingane (2018) heat stroke is the leading cause of deaths in vehicles (excluding crashes) for children 14 years old and younger. Vehicle cabins act as heat traps due to solar radiation. Increased temperature leads to higher air-conditioning usage, resulting in fuel consumption and emissions (Smith, 2020). When an automobile is closed, the dash, upholstery, steering wheel, and other interior components heat up rapidly in the sun. The situation replicates the greenhouse effect. The air within the car becomes hotter as a result of those components radiating heat into it. The heat from such components radiating into the air, raises the temperature inside the vehicle. The raised temperature then becomes detrimental to the materials used for the steering wheel, dashboard, armrest and other components inside the automobile made up of leather or plastic. The effect extends not just to the materials used for the automobile interior but also to occupants of the vehicle. Therefore, necessitating the need for the increased use of vehicle cooling systems.

Vehicle cooling systems contribute significantly to global greenhouse gas emissions, with vehicle energy consumption driven partly by thermal loads. Solar radiation entering vehicle cabins increases internal temperatures, necessitating higher use of air conditioning (AC), which in turn increases fuel consumption and emissions. The transportation sector contributes roughly 15% of anthropogenic greenhouse gas (GHG) emissions and 23% of global energy-related emissions, making even incremental efficiency gains relevant for climate mitigation (Ferrer and Thome, 2023). Reducing thermal loads via improved glazing, tinting, and reflective coatings is therefore of dual importance: enhancing comfort and safety in a warming climate, and lowering energy use and GHG emissions.

Study by Parrino et al. (2004), found that the most effective way to reduce initial vehicle temperature is by applying appropriate shielding of the windscreen when parked in the sun. The temperature can increase up to 40ºC in just 5 minutes, making pre-cooling of the vehicle cabin to be insignificant.

Manning and Ewing (2009) showed that sunshade application to a vehicle is insignificant for the first one hour with only 1.4ºC differences and 4.7ºC cooler after 5 hours of soaking period. However, Al-Kayiem, Sidik and Munusammy (2010), differs with Manning that the usage of sunshade was found to be 25ºC lower than other vehicles without any shades.

Jasni and Nasir (2012), proved that the application of sunshade can decrease dashboard and steering wheel temperature by 18ºC. The sunshade managed to avoid direct sunlight through the windshield, but it does not have significant effect on vehicle cabin ambient air.

Manning and Ewing (2009), have studied the effectiveness of window tinting at three different type that is T35 and T20, which 'T' refers to film's light transmittance factor. The three windows were bonded into polystyrene boxes to provide insulation and airtight seal. They found that the temperature for window with no tint rises the fastest and has highest temperature peak compared with other two windows but with advantages of faster cooling rate. Windows with tint on the other has lower temperature peak by 5°C and lower heating rate, but in the expense of lower cooling rate. This is because the tint slows down the heat exchange between the environment and vehicle cabin.

Olisa, *et al* (2019), examined the degree of temperature rise as well as the rate of rise at specific positions inside the cabin of vehicles parked under intense sun. The vehicles were parked in North-South direction under direct sunlight at the University of Nigeria Nsukka campus. Case A involved winding up the window glasses for a long period of 5 hours while in Case B, the effect of having the two front glass windows lowered with a gap of 0.04m and monitored for 5 hours was evaluated. The maximum cabin air temperatures were recorded at the dashboard, rear compartment, driver head rest and centre of back seat which gave temperatures of 72.4^{0}C, 72.4^{0}C, 62.6^{0}C, 60.2^{0}C respectively for Case A. For Case B, the maximum temperatures were 56.2^{0}C, 60.6^{0}C, 52.8^{0}C, 48.4^{0}C, respectively. It was deduced that air temperature in the cabin can increase to health threatening temperature in 8-10 minutes after parking under intense sunlight exposure. T-tail test analysis showed that there is statistically significant difference between the two considered Cases.

Although previous studies have examined vehicle cabin heating and the benefits of solar-reflective technologies, limited empirical evidence exists on the thermal performance of different window tinting conditions under Nigerian climatic conditions. The study by Olisa et al (2019), focused on temperature variations in vehicle cabins but didn't include effect of window glazing or tinting on vehicle cabin temperature characteristics. Furthermore, few studies have linked vehicle cabin thermal regulation to energy demand and climate change mitigation within the Nigerian transport sector.

This study was conducted to assess the thermal characteristics of tint and no tint vehicles under Nigerian climatic condition and further give credence to earlier findings on heat gain as a result of solar radiation. Additionally, the study will also assess cooling time of both tint and no tint vehicles cabins.

Research Objectives

The study aims to:

1. Assess cabin temperature variations in tinted and untinted vehicles.
2. Compare thermal performance among different tint types.
3. Determine air condition cooling time requirements under different tinting conditions.
4. Examine implications for climate change mitigation.

Study Area

Anambra State lies between latitude 5˚ 42′ N and 6˚ 47′N and longitude 6˚ 37′ E and 7˚ 23′E. The state has 21 local government areas. The study area lies within the tropical region, and its boundaries are formed by Delta State and Edo State to the west, Imo State and Rivers State to the south, Enugu State to the east, and Kogi State to the north. The area is influenced by two climatic seasons: the dry and wet seasons. The wet season starts around April and ends in November, with a break in August, and the average annual rainfall is about 1800 mm. The dry season lasts from November to April. The months of February and March are arguably the hottest months of the dry season. According to Onwuzuligbo, Ejikeme, Ojiako and Ezeh (2017), the temperature pattern has mean daily and annual temperatures as 28^0C and 27^0C respectively. The mean daily temperature can rise to about 32^0C during hot periods of the year usually in the month of February. This majorly informed the decision of February as the period to undertake this study.

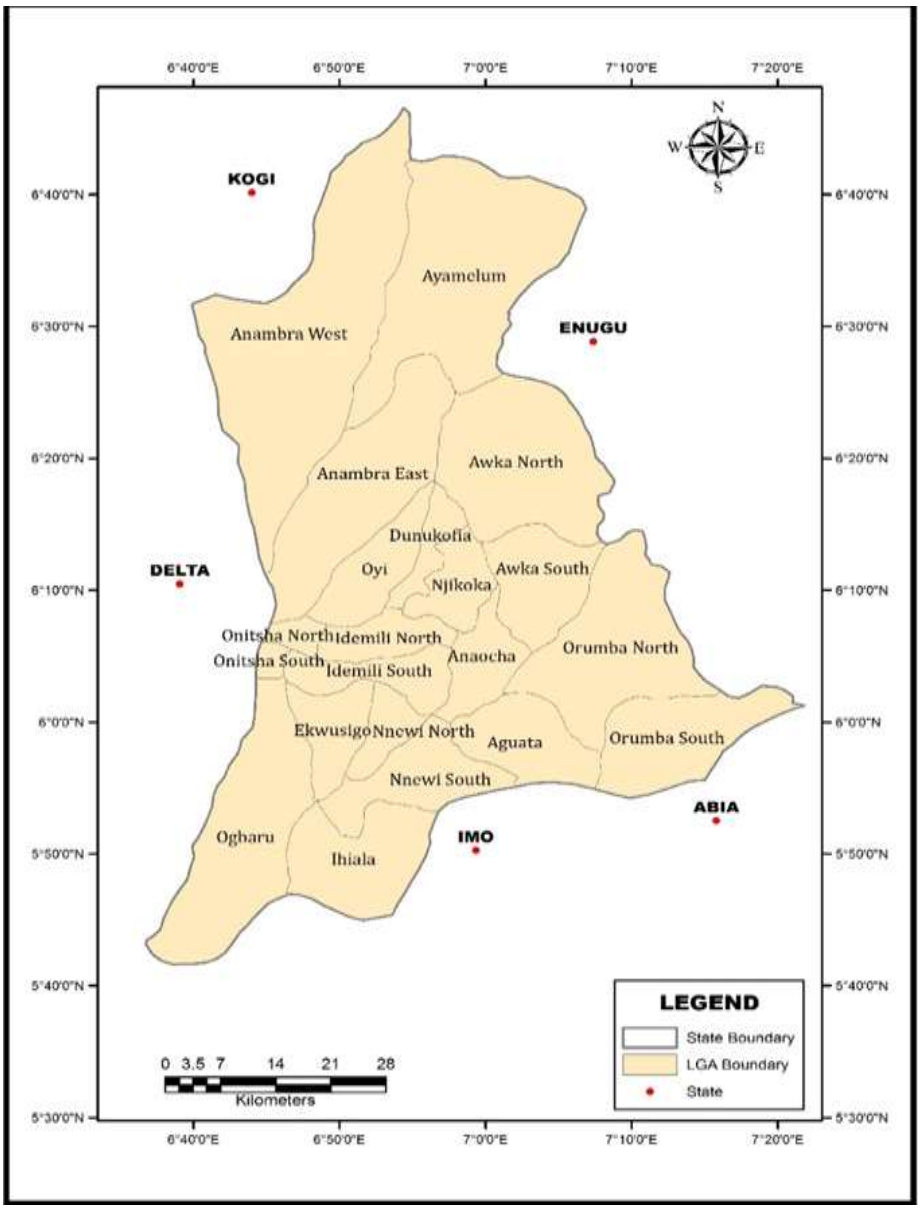


Figure 1: Map of Anambra State
Source: Geospatial Analysis Mapping and Environmental Research Solutions (2018)

Materials and Method

The study adopted an experimental approach which involved measurements of cabin temperatures of tint and no tint vehicles. Measurement of vehicle cabin temperature was done using a Generic HTC-2 digital thermometer. Four vehicles were involved in the study (2 Camry 2.2 {2000} with no-tint and ceramic tint, 1 Camry muscle also known as Spider {2010} with carbon tint, 1 Corolla {2008} with dye tint). Measurement was taken for five days (February 2024) from the vehicles parked under direct solar exposure between 12:00pm and 2:00pm with engines turned off, windows closed and no air conditioning. The collated data were analysed using means and percentage to analyze difference in thermal characteristics.

Formula as used for average cabin temperature (mean) and percentage computation:

Mean = Xn1 + Xn2 +… + Xnth/N (Eq. 1)

Where:

N = number of observations

Xn = data for individual observation

Percentage = NTT – TTT = TD/ NTT x 100 (Eq. 2)

Where:

NTT = No Tint Temperature

TTT = Tint Type Temperature

TD = Temperature Difference

Reliability Test

The HTC-2 thermometer is strictly a factory calibrated device. It therefore does not require manual calibration prior to deployment. However, its measurement uncertainty was assessed using repeated measures (n = 5). The measurement showed a precision level of ±1ºC.

Result and Discussion

Thermal Characteristics of Tint and No Tint Vehicles

The data obtained were analysed to determine the thermal characteristics of tint and no tint vehicles. The result demonstrated the ability of both tint and no tint vehicles to transmit radiation through vehicle windows. Table 1 shows average cabin temperature for the various tint types.

Table 1: Temperature Reduction Analysis

Tint Type	Avg Cabin Temp (°C)	Reduction (%)
No Tint	60°C	0%
Dyed Film	52°C	13%
Carbon Film	48°C	20%
Ceramic Film	42°C	30%

Mean reduction: 18°C across all tinted conditions.

Table 1 clearly show a progressive reduction in cabin temperature with increased tint density. Clear glass (no tint) vehicle recorded the average highest temperatures (60°C). While dark-tinted vehicles recorded substantially lower average temperatures (42–52°C). Overall, an average of 18°C temperature reduction was recorded across all categories which is substantial in thermal comfort terms. The findings of Lahimer, Alghoul, Sopian, and Khrit (2017) revealed that the maximum cabin temperature with solar reflective cover (39.6ºC) is significantly lower than that of baseline case (57.3ºC). This indicates a temperature reduction improvement of 31% and the difference between the cabin and the ambient temperature minimized by approximately 73%. The analysis of AlQahtani et al (2025), revealed significant differences in UV irradiance between vehicles, variations were attributed to factors such as vehicle model, window material, and the presence of tinting or other protective coatings. Rashid (2018), noted that volatile organic compounds increase due to high temperatures in the vehicle cabin leading to poor air quality.

Cooling Time Analysis

Following the thermal characteristics analysis, the vehicles was examined to determine cooling time, and percentage reduction in cooling time (Table 2).

Table 2: Cooling Time Analysis

Condition	AC Runtime (minutes)
Untinted	6.8
Tinted	3.2

Reduction ≈ 53% decrease in cooling time

Table 2 indicate that the vehicle without window tinting experienced longer air-conditioning runtime compared to tinted vehicles. Untinted vehicles required an average of 6.8 minutes of AC operation, while tinted vehicles only required an average of 3.2 minutes. This represents a reduction of 52.9% in AC runtime when window tinting is used. This difference suggests that tinted windows significantly reduce solar heat penetration into the vehicle cabin, thereby lowering the cooling demand placed on the air conditioning system. Since vehicle air conditioning systems draw power from the engine, longer AC operation increases engine load, which leads to greater fuel use. In a modern vehicle, an AC system can yield an auxiliary load of up to 3 kW which equals about 4 horsepower (Rashid, 2018; Farrington and Rugh, 2000). Huff, West and Thomas (2013), Lee, Kim, Park and Bae (2013), Zhang, et al (2021), Gajanayake, Bandara and Sugathapala (2023) all revealed that an AC system consumes a fair amount of power produced by the engine; of all the auxiliary power requirements, an AC system has a great impact on fuel

consumption. Using the AC can increase the fuel consumption of a conventional vehicle by up to 20%. This number depends on various factors such as cabin size, ambient temperature, the level of performance of the AC, the duration of the trip etc.

Implication for Climate Action

The United Nations Sustainable Development Goal 13 calls for immediate action to combat climate change. The action sought requires integrating climate measures into facet of life and in every sector both at individual and corporate level. Everyone can contribute by saving energy. Window tinting contributes indirectly to climate change mitigation by lowering energy demand in vehicles. When scaled across large urban vehicle populations, this effect could be substantial. Less energy demand for cooling vehicle cabins, thus translating into decreased emission of greenhouse gases. Greenhouse gases are known to encourage heat buildup. Reduced heat buildup contributes to lower urban heat accumulation.

Conclusion

This study demonstrates that car window tinting substantially improves thermal performance by reducing solar heat gain, lowering cabin temperature, and decreasing energy consumption. The broader implication is that widespread adoption of high-performance tinting may contribute to climate change mitigation through reduced cooling energy demand and fuel consumption, theoretically. However, in practice, the use of tint is strictly enforced in Nigeria for security reasons. These results reveal a significant gap in current vehicle window design, emphasizing the urgent need for innovations that provide solution to heat gain in vehicle cabins. The study recommends research and development of vehicle glazing technologies capable of minimizing solar heat gain during peak sunshine hours. This innovation will contribute to energy management, emission reduction and offer vehicle owners the freedom of choice between installation of tint or no tint window while achieving the same result of reducing heat gain.

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