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Control Techniques for Greenhouse Phenomena in Car Cabins to Enhance Fuel Consumption, Emission Reduction, and Air Quality: A Review

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Abstract

This review paper examines various technologies that aimed at reducing the interior temperature of car cabins when parked under direct sunlight. The key technologies explored include solar ventilation, phase change materials (PCM), electric glazing, car covers, heat pipes, car color selection, and insulation. These technologies are designed with several critical objectives in mind. Firstly, they aim to enhance air quality within car cabins, a concern of growing importance as rising cabin temperatures have been shown to increase emissions of volatile organic compounds (VOCs) from interior materials by 3 to 36 times. Secondly, they address a significant safety issue: vehicular heatstroke, which tragically results in the death of approximately 40 children annually in the USA, with similar figures reported globally. Furthermore, these technologies contribute to preserving the integrity of car cabin materials, improving fuel efficiency, and reducing pollutants. For instance, studies indicate that the use of solar ventilation systems can lead to a 38% reduction in fuel consumption and a 36% decrease in CO_2 emissions during idle states. The review also delves into the phenomenon of cabin hot soaking, where car interiors can exceed ambient temperatures by 20 to 30 °C, with peak temperatures surpassing 80 °C. It highlights the effectiveness of certain methods, such as solar ventilation, PCM, reflecting glass, and car covers, in reducing cabin temperatures by over 15 °C. On the other hand, technologies like solar chimneys, heat pipes, and heat exchangers face practical challenges due to their size and weight, limiting their widespread application. Additionally, methods like insulation, cracked windows, and sunroofs are found to be less effective, typically achieving reductions of no more than 5 °C. The methodology of this review includes setting inclusion and exclusion criteria, gathering data from various sources, identifying relevant information, and conducting data extraction along with rigorous evaluation. Our review stands out by comprehensively analyzing multiple critical aspects. Beyond examining the impact of greenhouse phenomena on cabin temperature and fuel consumption, our focus extends to air quality, a crucial health consideration, particularly in enclosed spaces like car cabins, where volatile organic compounds (VOCs) can pose significant risks. This approach offers a unique synthesis across various dimensions of vehicle cabin environment management, providing valuable insights into the interactions between greenhouse effects, fuel efficiency, and human health.

Keywords: Cabin temperature, Air quality, Energy consumption, Emissions.

Nomenclature

AC	Air Conditioning
BC	Black Carbon
BEVs	Battery Electric Vehicles
CO_2	Carbon Dioxide
CO	Carbon Monoxide
g	Total Energy Transmission, W/m^2
HC	Hydrocarbons
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
ICE	Internal Combustion Engine
IP	Instrument Panels
IRR	Infrared Reflective
ISO	International Organization of Standardization
NOx	Nitrogen Oxides
PCM	Phase Change Materials
PHEVs	Plug-in Hybrid Electric
PM	Particulate Matter
q_a	Absorbed Energy, W/m^2
q_i	Internal Re-radiation , W/m^2
RBS	Radiant Barrier System
R_e	Reflected Energy , W/m^2
RH	Relative Humidity, %
SHGC	Solar Heat Gain Coefficient
SO_2	Sulfur Dioxide
SRC	Sun Reflecting Coating
SRF	Sun Reflecting Film
SRG	Sun Reflecting Glass
SRP	Sun Reflecting Paint

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SUVs	Sport Utility Vehicles
SVOCs	Semi-Volatile Organic Compounds
Ta	Ambient Temperature , °C
T_c	Cabin Air Temperature , °C
T_e	Transmitted Energy , W/m^2
TVOCs	Total Volatile Organic Compounds
UV	Ultraviolet
VLT	Visible Light Transmission
VOCs	Volatile Organic Compounds , ppm
WHO	World Health Organization

1. Introduction

Vehicles play a crucial role in the transportation sector of our society. However, the consumption of fossil fuels presents significant drawbacks, such as smog emissions and global warming. These issues necessitate urgent attention from the automotive industry to develop alternative energy sources[1], [2], [3], [4], [5], [6].

In modern cars, air conditioning is now seen as essential rather than a luxury. Health, as defined by the WHO, includes complete physical, mental, and social well-being, influenced by our environment, temperature being a key factor. Poor car interiors can increase driver fatigue and reduce cognitive function. The automotive industry prioritizes occupant thermal comfort, but challenges remain, including real-time comfort assessment, intelligent automation, and optimizing HVAC systems for fuel efficiency in varying weather conditions. Accurate measurement of thermal comfort is complex due to the subjective nature of physiological and psychological factors and the uneven conditions inside a vehicle, requiring further research [7].

Vehicles carry several disadvantages, including their tendency to consume high amounts of fuel, emit pollutants, and contribute to the ongoing challenges of global climate change [8], [9], [10].

The phrase "climatic analysis of the cabin" involves calculating heat transfer by considering conduction, convection, and radiation between the passengers and the cabin's components. Figure 1 illustrates the main mechanisms that affect heat gains or losses[11], [12], [13].

Numerous studies have shown that cooling the cabin negatively impacts energy consumption in battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and traditional internal combustion engine (ICE) cars. Climate control systems can significantly decrease a vehicle's energy efficiency and, consequently, its effective driving range. To improve the efficiency of climate control systems, it is crucial to accurately evaluate both the energy savings and thermal comfort provided by new heating and cooling technologies[14].The use of AC in cars is estimated to increase CO emissions by 0.99 g/km, raise NOx emissions by 0.12 g/km, and decrease fuel economy by 2.0 km/L[15].If the air conditioning power were reduced to 70% of its baseline and emissions were also reduced, each car could save an average of 41.6 liters. When sizing an air conditioner for a car, two key factors must be considered: the unit's ability to sufficiently cool the interior, maintain the desired temperature, and rapidly stabilize the cabin temperature [16]. Using the air conditioning system can affect emissions and fuel economy by approximately 80% for NOx, 70% for CO, and 20% for fuel economy[17].

Auxiliary devices in a car, such air conditioning, heating, lights, and electric systems, have an impact on the engine load. The air conditioning specifically causes a greater auxiliary load on the engine since it requires a higher driving torque than other devices [18].

Cars that are exposed to the hot sun can quickly overheat, with the interior air temperature rising by as much as 20 to 30 °C relative to the outside temperature as shown in Figure 2[19], [20], [21]. An increase in interior car cabin temperature has several detrimental effects, including increased fuel consumption, emission levels, and reduce thermal comfort [22], [23]. Parking your car under the sun for an extended period elevates the interior temperature, leading to discomfort for the driver and passengers upon re-entering the vehicle. To counter this, drivers often crank up the air conditioning to maximum upon getting in. However, this strains the vehicle's air conditioning system, resulting in increased fuel consumption due to the added thermal load[24], [25], [26], [27], [28].

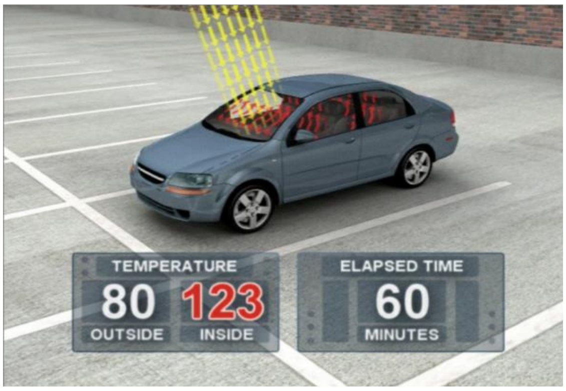

Figure 2. Shows the rapid rise in temperature within the cabin [12].

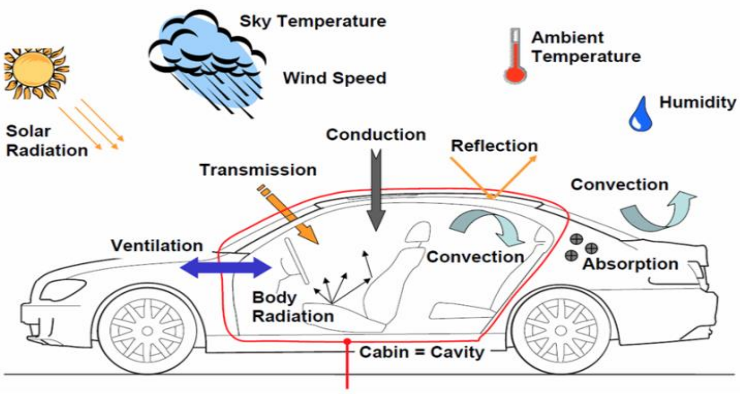

Figure 1. The main mechanisms that affect heat gains or losses[11].

Researchers recommend raising public awareness about the greenhouse effect inside cars to reduce hyperthermia-related deaths caused by leaving individuals in closed, parked vehicles exposed to the sun, and to enhance the safety of child passengers [29]. A very significant factor in health is air quality. However, there are instances in which people are exposed to air that is poisonous and contains a lot of volatile organic compounds (VOC), especially in enclosed spaces like car cabins [30]. Asthma, headaches, eye irritation, sneezing, lethargy, and other serious health consequences can be brought on by poor indoor air quality in microenvironments like vehicles. Such a condition could impact the driver's health and ability to drive safely. Volatile organic compounds (VOCs), which are toxic to humans, are frequently correlated with vehicle indoor air quality [31]. The International Organization of Standardization (ISO) approves measuring standard ISO 12219-1:2012, which is a method for figuring out what kinds and amounts of volatile organic compounds (VOCs) are in the air inside cars. Indoor air often has a higher concentration of VOCs than outdoor air [31].Controlling the interior temperature of the car is one factor that affects the air quality within the vehicle. The internal temperature impacts the concentration of TVOCs inside the vehicle [32].

Interior surfaces like the steering wheel, dashboards, and seats will notice a sharp increase in temperature. The concentration of TVOCs generated by material emissions will therefore rise correspondingly [33]. The World Health Organization views the air inside cars as a severe hazard to people's health because of the high concentration of VOCs and other substances. The air within the car's cabin contained 242 organic chemicals in total. Due to multiple factors, their concentrations may vary from one car to another [30]. After several minutes or hours of parking the car under the sun's rays, a hot cabin interior compelled the driver to wait until the temperature dropped. The increase in cabin temperature caused degradation of the interior materials and heat stroke in human beings [8], [34]. VOCs are the main air pollutants found within the new car; most of these pollutants are emitted into the cabin air by plastics. Polypropylene, polyamide, polyester, polystyrene, polyethylene, and acrylonitrile-butadiene-styrene are among the plastics. Rubber and leather, whether synthetic or natural, are the second sources of volatile organic compounds (VOCs) [33], [35]. The issue of air pollution from vehicles has become a major public health concern on a global scale, especially with regard to the volatile organic compounds (VOCs) that are emitted from within vehicles. Although research has shown that VOC production is temperature-dependent, it is unclear how sun radiation affects the distribution of VOCs in confined spaces like cars [31], [36].

To improve fuel efficiency, reduce emissions, and enhance cabin air quality, various temperature reduction technologies have been developed. Their success, however, depends significantly on user behavior and preferences. Drivers' comfort needs and ease of use impact their acceptance of these technologies. For example, those who prioritize comfort might avoid systems requiring frequent adjustments. Adoption rates vary: drivers who actively engage with climate control are more likely to embrace new technologies, while those who prefer minimal interaction may resist. Additionally, the effectiveness of these technologies is influenced by user awareness and education. If users are not aware of or educated about the benefits and optimal use of these systems, their potential for fuel savings and emission reductions could be diminished. Ensuring users are informed and engaged is crucial for maximizing the effectiveness of temperature reduction technologies.

Lack of critical review studies has collected the majority of the available data on cabin hot soaking temperature and its reduction strategies into one publication. This paper aims to combine every relevant detail regarding the subject matter of the articles into one document in order to present an up-to-date, comprehensive review as well as to look into and assess the most popular temperature reduction techniques' potential, features, limitations, and most current advancements in order to increase comfort, safety, and energy consumption. This paper will also provide important findings that could be beneficial to researchers in the future.

The rest of this paper is organized as follows: In Section 2, an overview of how the greenhouse affects the temperature inside the car is provided, including the cause of the high temperature inside the car, the heat sources, the time it takes for the temperature inside the car to reach its maximum, the factors that influence the cabin temperature, the impact on human beings, the quality of the air, fuel consumption, and emissions. Then Section 3 presents an in-depth review of the potential of the most popular methods currently in use for decreasing car interior soak temperature, together with a summary of their drawbacks, to assess how efficient they are at addressing a high cabin temperature, as well as a categorization of temperature reduction techniques according to the energy they supply and the technology they employ. Finally, the study's conclusions are presented in Section4

2. Greenhouse phenomena in a car cabin

The issue arose when the car was parked in the summer sun without shade. As shown in Figure 3, short waves pass through the car's windows and are absorbed by the interior, including the dashboard, seats, floor, and steering wheel. These components, with higher thermal capacities, release long-wave energy that can't escape through the windows, leading to a gradual increase in the car's interior temperature [36][37], [38].

As previously stated, the temperature rises by over 80% in the first 15 to 30 minutes [29]. In the case of an unshaded stationary car cabin, the internal cabin soak air temperatures are generally estimated to be 20 to 30°C more than the out cabin temperature[39]. On hot summer days, the highest measured temperature of soaked cabin air was 83 °C[33].It was determined that decreasing the temperature in an overheated car cabin is crucial for quickly achieving human comfort. This also lowers the cooling capacity and peak load, which enhances gasoline consumption and lowers emissions [24], [33], [40].

There are different factors affecting the greenhouse phenomenon inside a car cabin. The most important factors are mentioned in below table.

Table 1. Factors influencing the cabin temperature.

Item	Factors	Reference
1.	Solar Radiation	[15], [39], [41], [42], [43], [44]
2.	Ambient temperature	[29], [45]
3.	Car orientation	[33], [46], [47]
4.	Wind Speed	[42], [48]

2.1. Harmful impacts of this phenomenon on the car cabin

This section discusses the effects of the sock temperature in the car cabin on human and pets left inside cabin, the impact on the car cabin's air quality, in addition to the emissions and use of fuel.

2.1.1. Impact on humans and pets

On sunny days, cabin temperatures can rise to 67°C within 15 minutes, posing serious risks of thermal burns and hyperthermia to unsupervised children, people with disabilities, and pets.[29], [33].Despite research, the auto industry has largely prioritized market expansion, comfort, and fuel efficiency over addressing high cabin temperatures, recently focusing on faster passenger thermal comfort[48]. The impact on humans is under-researched, with National Safety Council data showing an average of 40 child deaths per year from 1998 to 2023. This underscores the need for more focused research.

2.1.2. Impact on cabin air quality

A very significant factor in health is air quality. However, there are instances in which people are exposed to air that is poisonous and contains a lot of volatile organic compounds (VOC), especially in enclosed spaces like car cabins [30]. Poor air quality in vehicles can cause asthma, headaches, eye irritation, and other health issues, affecting driver safety. Volatile organic compounds (VOCs) are often linked to these problems[49], [50], [51].

Controlling a car's interior temperature affects air quality, as higher temperatures increase total VOCs. VOC levels rise by 42.7% between 30-40°C and 58.5% between 40-50°C. Car interiors can reach temperatures up to 76°C, exceeding the surrounding temperature by over 20°C [32], [45], [52]. The primary factor thought to contribute to a rise in interior temperature is solar radiation entering the car through the windshield or windscreen [40][53]. Interior surfaces like the steering wheel, dashboards, and seats will notice a sharp increase in temperature. The concentration of TVOCs generated by material emissions will therefore rise correspondingly[54]. The World Health Organization considers car cabin air a serious health hazard due to high VOC levels, with 242 different organic chemicals present. Concentrations can vary between vehicles [30]. After parking under the sun, a hot cabin forces drivers to wait for temperatures to drop. High heat can degrade interior materials and cause heat stroke[8], [34].

In new cars, VOCs mainly come from plastics like polypropylene and polyamide, and from rubber and leather. These materials are used in components such as dashboards, floor mats, seats, and upholstery [35], [55].Vehicle air pollution, particularly VOCs, is a major global health concern. While VOCs increase with temperature, the impact of sun radiation on VOC distribution in confined spaces like cars remains unclear [31], [36], [56].The car interior can harbor hazardous pollutants from materials, fuel leaks, and outside air. Different cabin designs and ventilation systems lead to varying pollutant levels. New cars often have high pollutant levels due to high temperatures and poor air exchange. See Figure 4 for details on pollutants and their sources[57].

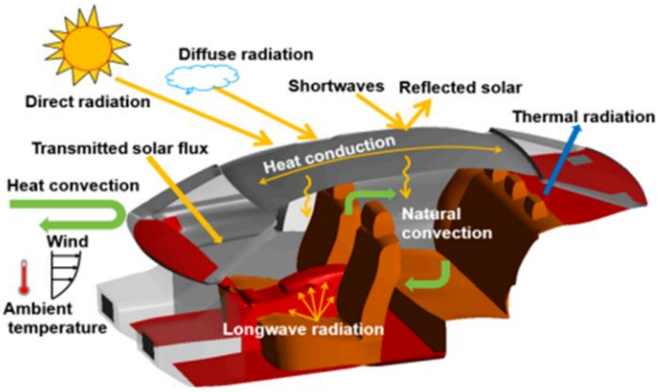

Figure 3. Greenhouse effect inside the car cabin [36].

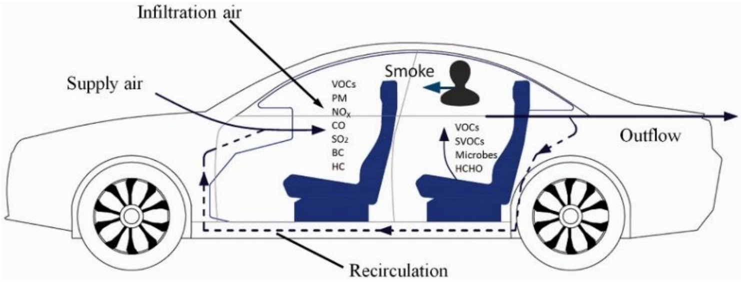

Figure 4. Diagram of air pollutant sources and movements inside the cabin [57].

Car cabin air quality significantly affects driver and passenger comfort, safety, and health. Poor indoor air quality (IAQ) is common in many cars, with high levels of VOCs and other pollutants posing serious health risks, according to the World Health Organization.

Table 2. Summary of the greenhouse impact on the cabin temperature.

Location / Year	Main Result	Reference
USA / 1988	Cabin air temperature reach up to 82 °C and dashboard reach 120 °C	[42]
China / 1998	Cabin air temperature reach up to 83 °C.	[58]
USA / 2000	Cabin air temperature reach up to 50 °C.	[59]
France / 2006	Cabin air temperature reach up to 20–30 °C more than the ambient.	[43]
Malaysia / 2009	Cabin air temperature reach up to 50 °C.	[40]
Jordan / 2021	Cabin air temperature reach up to 65 °C.	[8]
Jordan / 2023	Cabin reach up to 66 °C.	[34]

2.1.3. Impact on tail pipe emissions and fuel consumption

Cabin temperature, or "sock temperature," impacts fuel efficiency and emissions. High temperatures increase AC demand, leading to higher fuel consumption and emissions. Managing interior heat effectively is key to reducing fuel use and environmental impact.

In summer, high cabin temperatures force drivers to use air conditioning, which is a major factor in increased fuel consumption[34].Yet, owing to its substantial energy requirements, the air conditioning system stands as the primary auxiliary load in vehicles equipped with internal combustion engines [48]. Two to four times the steady cooling demand can be the AC system's peak need[59]. Moreover, a medium-sized vehicle's engine needs between 5 and 7.3 kW to run the AC compressor, which uses the same amount of energy as a small single-family house air conditioner [44]. After the electric motor, the AC load is the system that uses the most energy [60].Reducing AC load to 70% of the normal could potentially result in lower emissions, conserving 11 gallons per vehicle annually [16]. Resizing the AC system's compressor without compromising thermal comfort has been an area of research [61]. The action encourages the auto industry to decrease the size of car air conditioners, lower tailpipe emissions, and install more energy-efficient AC systems [33].Maximizing cabin temperature is key in designing air conditioning systems. Reducing peak cabin temperature can significantly lower energy use by the AC compressor[62]. Sun-reflecting film (SRF) reduces cabin temperature by 4.6°C, cutting cooling time by 3.75 minutes and lowering AC compressor power usage by 19%, which in turn reduces fuel consumption. It enhances occupant comfort and shortens cooling periods[63]. Air conditioning is the largest auxiliary load in vehicles, impacting air quality and fuel efficiency. It can reduce emissions by 20% for CO, 70% for fuel economy, and 80% for NOx[41]. The fuel consumption at idle state can reduce by 38% and emissions by 36% when the cabin temperature decreased by almost 11 °C [34].

3. Techniques for regulating interior car cabin temperature

Maximizing interior comfort remains essential in automotive design. Efficient temperature regulation enhances driving satisfaction, vehicle performance, energy efficiency, emissions, and safety. This section explores various methods for maintaining optimal cabin temperatures.

A number of researchers are interested in using different techniques to lower the temperature inside automobile cabins. A wide range of methods for lowering the interior temperature of an automobile were investigated and assessed, which include: Thermoelectric cooling device [64], car color and sun-reflective paint [24], [43], [65], [66], [67], shades [37], [38] ,solar chimney [68], solar-powered air ventilators or cooling system[24], [34], [40], [69], [70]. Solar reflective film [38], [43], [59], enhanced glazing [24], [71].

3.1. Techniques for blocking sun radiation

There are various methods for preventing solar radiation from entering the car's glass and heating the interior of a parked car in an open field. Setting the stage for a discussion of the advantages and drawbacks of these techniques for protecting automobile interiors and improving comfort on hot days is this section

3.1.1. Shaded area and car cover

Car covers have been developed to reduce the sun's heat and UV radiation, acting like sunscreen to lower cabin temperatures and prevent photo degradation. Numerous companies have attempted to produce a suitable car cover, but most designs still require the cover to be draped over the vehicle and then adjusted to fit properly. This adjustment process, especially under direct sunlight, can be time-consuming and inconvenient. Additionally, users often need to fold the cover neatly before storing it, which can be bothersome. To address these issues, it is advisable to use a car cover that offers effective heat insulation, is easy to install on the car's roof, reflects a substantial portion of solar rays, and can be securely fastened to the vehicle[33], [72].

A car's interior receives between 50 and 75 percent of its thermal energy from sun radiation that gets through the glass. Reducing the quantity of radiation that enters via the windows is essential to lowering the increased cabin temperature when parking [44], [73]. Automobile shades can be inconvenient to use regularly, leading many owners to avoid them. However, they can be installed inside or outside the car. Research shows that on sunny days, a radiant barrier system (RBS) or low-emissivity shade behind the windshield can reduce interior temperatures by up to 12°C [33].In hot climates like Cape Canaveral, Florida, unshaded parked cars can reach interior temperatures of 150°F, with dashboards nearing 200°F. A standard cardboard car shade can lower interior air temperatures by 15°F and dashboard temperatures by 40°F. Radiant Barrier System (RBS) shades, with their low-emissivity foil backing, offer additional benefits, reducing interior temperatures by another 3–5°F and dashboard temperatures by 6–11°F. While window venting slightly lessens the effectiveness of RBS shades, they still significantly reduce dashboard temperatures by around 8°F. RBS shades improve passenger comfort, protect interior components, and reduce the initial load on the air conditioning system. For optimal performance, RBS shades should have a light, high-emissivity exterior, with light blue, green, or yellow decorative elements preferred. Further research is needed to fully evaluate the thermal performance of automobiles [42]. Additionally, A parasol in front of the glass was proven to dramatically lower temperatures, with the maximum air temperature dropping by 27% and the temperature of the surface of dashboard reducing 26% [37]. A study found that a sun reflector cover on the roof and windows of the in-cabin temperature decrease 17.7ºC. Figure 5 shows two identical cars parked under intense sunlight, one with and one without a solar reflecting cover [74].

Figure 5. Two identical cars parked in the sun, with/ without a solar reflecting cover.[74].

Testing showed that using sunshades on all windows is the best way to passively lower cabin temperature, reducing the dashboard temperature by 18°C by blocking sunlight through the windshield.[38].Rising windshield temperatures affect cabin air. Blocking heat sources like the dashboard helps regulate interior temperature. Reflective window shades can lower cabin temperature by 20%, reduce instrument panel heat by 43%, and decrease breath air and seat temperatures by 4°C and 5°C[61].The study tested aluminum foil on the exterior to lower cabin temperature. Covering all surfaces with aluminum foil reduced cabin temperature by 93% at an outside temperature of 30°C. Using foil only on windows reduced it by 65%, and on doors and roof by 28.3% [16]. A car shade made from sewn cardboard pieces covered the windows and roof. This setup kept the cabin temperature just 3°C above the outside, with interior air, dashboard, steering wheel, and seat temperatures 70% lower than without the shade [75]. An aluminum cover blocks sunlight from entering the cabin when the car is parked, helping the car cool faster, reducing AC fuel use, and providing greater comfort for passengers entering a hot vehicle [48].

Despite their benefits in reducing cabin temperatures and reliance on air conditioning, several practical issues impede the widespread adoption of greenhouse control technologies in car cabins. As the number of vehicles on the road increases daily, drivers often struggle to find indoor or shaded parking, particularly during peak hours. Vehicles are the only convenient and important mode of transportation for many people due to limited public transport facilities, leading to a high density of private passenger vehicles and a significant shortage of parking space. This shortage is especially pronounced at government offices, universities, colleges, and shopping malls, where shaded parking spaces are insufficient to meet demand. Consequently, many drivers are left with no choice but to park in open spaces, as illustrated in Figure 6[76].

Figure 6. Cars left under the blazing sun[76].

However, since shaded parking spaces are hard to find due to the explosion in vehicle population or are avoided due to their high cost, car cabins are subjected to moderate temperatures and high levels of solar radiation for extended periods. This scenario is exacerbated when vehicle users engage in short-interval activities such as having lunch, paying utilities, or quick shopping, which can accelerate interior temperatures at a rapid rate. Finding shaded parking spots can be challenging, but improving urban infrastructure and encouraging shaded parking solutions could help. The installation and maintenance of these technologies can also be cumbersome, so simplifying these processes and offering user-friendly products are essential. High initial costs pose another barrier, which could be mitigated by highlighting long-term savings and offering financial incentives. Limited user awareness of the benefits and operation of these technologies affects their adoption; thus, educational campaigns and clear information are needed. Additionally, ensuring compatibility with various vehicle models through collaboration with automotive manufacturers can facilitate smoother integration. Addressing these practical challenges is crucial for maximizing the benefits of these technologies in enhancing fuel consumption, emission reduction, and air quality[33], [76].

3.2. Glazing Methods

3.2.1. Solar-reflective and electrochromic glass

The study examined electrochromic windows in cars, finding they significantly improve passenger comfort and fuel efficiency by reducing solar energy transmission by 2.5 times, lowering electricity consumption compared to conventional glass [77].Sun-reflecting glass is designed to reflect 50-75% of sunlight entering the cabin, reducing cooling loads and influencing the size of the car's air conditioner.[16], [61]. Considering that the sun's infrared spectrum generates the most solar energy, As a result, Using SRG might decrease the inner mass's absorption of solar rays[24], [62]. A sunlight-reflective coating with insulating layers and silver was applied to a car, resulting in the cabin and instrument panel being 2.7°C and 7.6°C cooler, respectively. The windshield alone reduced breath temperature by 2.2°C. This cooling effect could decrease AC load by 11%, improving fuel economy and lowering emissions[63]. They estimated a 4.1% reduction in AC compressor power for each 1°C drop in cabin temperature. The modified windshield reduced solar radiation by 14% compared to standard glazing, highlighting the impact of glass properties on a vehicle's solar load [59], [78].

A numerical model studied thermal comfort, solar radiation, glazing, and car color. Results showed that reflective glazing reduced cabin temperature by 10°C due to its low absorption and transmittance. White car color reduced the temperature by 7°C compared to gray [43]. The study enhanced solar reflective glass and interior paint to better reflect solar radiation. Combined with a solar ventilation system, these improvements reduced breath temperature by 12°C, seat temperature by 11°C, windshield by 20.4°C, and instrument panel by 16.8°C[24].The study found that laminated windshields with solar control PVB interlayers reduced breath-level temperature by 1.2°C, lowered AC load by up to 4%, and improved energy savings by 0.7-1.5%[79].The study explored energy-saving methods for conventional, electric, and hybrid cars by reducing sun impact on the cabin. Effective strategies included IRR windshields, shading canopies, and pre-ventilation before AC use, significantly reducing HVAC load. Results are in Table 3[48].Siglasol glass allows 77% of visible light while blocking most infrared and UV rays, transmitting only 50% of solar energy. Figure 7 illustrates its function[11].

3.2.2. Sun-reflective film and absorbing glass

By utilizing absorbing glazing, which possesses higher absorptivity compared to reflecting glazing, the cabin temperature can be reduced by 2.2 degrees Celsius. This allows solar energy to be conveyed into the cabin through convection and thermal infrared radiation [43]. However, this approach is not frequently used as an approach to the issue due to its limited effect on lowering cabin temperatures [62]. Solar-reflective window tinting is a popular method for reducing car cabin temperature. Applied to interior glass, it reflects visible, UV, and infrared radiation, lowering the solar load inside the cabin[63], [80]. Using solar reflecting film on all of the windows while they are closed was one of the techniques they investigated. Through the duration of the soak test, they observed that this method successfully cooled the cabin by 9 °C [63]. The study tested a metal-free solar reflecting film (SRF) on two small cars and two SUVs. The SRF, which reflects infrared radiation while allowing visible light, reduced average breath temperature by 4.6°C when applied to all glass, and by 2.5°C on just the windshield. This reduced the time needed to reach thermal comfort by 3.75 minutes [59]. Researchers used a numerical model to study how solar radiation, glass type, car color, and material properties affect thermal comfort and AC energy use. Tinted glass with low transmissivity and absorptivity reduced cabin air temperature by up to 10°C[43]. A study tested solar-reflective coating on a car's roof and found that, despite a 6.7°C drop in roof temperature, it had no noticeable effect on interior temperatures. Similar results are expected with solar-reflective paint [24]. The application of window tinting reduced each area's average highest temperature of the car by a minimum of 5.6%, establishing it as most efficient method for reducing the interior cabin temperature[80]. Research on electric cars showed that solar-reflective and white coatings on windows reduced interior temperatures by 5.3°C and 9.2°C, respectively. An opaque white glazing film effectively reduced solar load during parking, serving as a prototype for external glazing covers [48].

Although advancements in glazing technologies have significantly reduced the amount of solar radiation entering automobile interiors, these technologies still face limitations related to cost, weight, durability, optical clarity, and regulatory compliance, adaptability to various climates, aesthetics, and design. Key factors in managing cooling loads through glazing design include the Solar Heat Gain Coefficient (SHGC), which measures the amount of solar radiation that passes through the glazing and impacts energy efficiency and indoor comfort. In warm climates, a lower SHGC is preferable to minimize heat gain and reduce the cooling load. However, Visible Light Transmission (VLT), which reflects the percentage of visible light that can pass through the glazing, must be balanced with SHGC to ensure adequate daylight while minimizing unwanted heat gain. Additionally, the U-Factor, which measures the rate of heat transfer through the glazing, is also crucial. Addressing these constraints through further research and development is imperative to advancing glazing technologies, optimizing their efficiency in reducing solar radiation, and enhancing overall performance in automobile interiors [81].

Table 3. The reduction in thermal load in the car cabin using different methods [48].

Method	Reduction in Temperature	Energy Saving kWh/20 min	Energy Saving (%)
Pre ventilation and IRR windshield	9.9	0.56	44.2
Pre-ventilation (15min)	5.8	0.48	31.2
IRR windshield	4	0.21	21
Glazing with SR film	5.3	0.74	49
Glazing with white film	9.2	0.85	57
Canopy	18.1	1.2	75

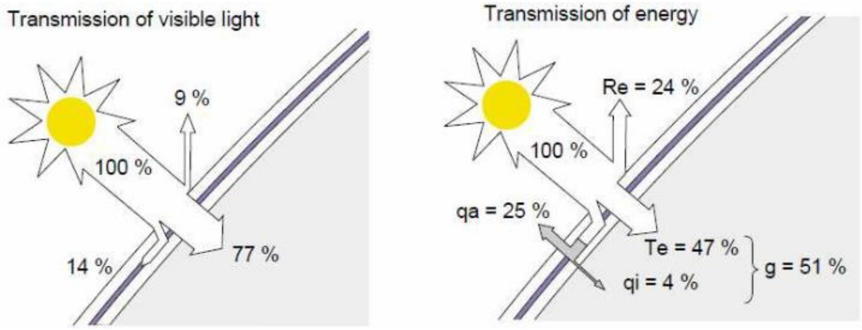

Figure 7. Shows the function of the Siglasol glass [11].

3.2.3. Sun-reflective film and absorbing glass

By utilizing absorbing glazing, which possesses higher absorptivity compared to reflecting glazing, the cabin temperature can be reduced by 2.2 degrees Celsius. This allows solar energy to be conveyed into the cabin through convection and thermal infrared radiation [43]. However, this approach is not frequently used as an approach to the issue due to its limited effect on lowering cabin temperatures [62]. Solar-reflective window tinting is a popular method for reducing car cabin temperature. Applied to interior glass, it reflects visible, UV, and infrared radiation, lowering the solar load inside the cabin[63], [80]. Using solar reflecting film on all of the windows while they are closed was one of the techniques they investigated. Through the duration of the soak test, they observed that this method successfully cooled the cabin by 9 °C [63]. The study tested a metal-free solar reflecting film (SRF) on two small cars and two SUVs. The SRF, which reflects infrared radiation while allowing visible light, reduced average breath temperature by 4.6°C when applied to all glass, and by 2.5°C on just the windshield. This reduced the time needed to reach thermal comfort by 3.75 minutes [59]. Researchers used a numerical model to study how solar radiation, glass type, car color, and material properties affect thermal comfort and AC energy use. Tinted glass with low transmissivity and absorptivity reduced cabin air temperature by up to 10°C[43]. A study tested solar-reflective coating on a car's roof and found that, despite a 6.7°C drop in roof temperature, it had no noticeable effect on interior temperatures. Similar results are expected with solar-reflective paint [24]. The application of window tinting reduced each area's average highest temperature of the car by a minimum of 5.6%, establishing it as most efficient method for reducing the interior cabin temperature[80]. Research on electric cars showed that solar-reflective and white coatings on windows reduced interior temperatures by 5.3°C and 9.2°C, respectively. An opaque white glazing film effectively reduced solar load during parking, serving as a prototype for external glazing covers [48].

Although advancements in glazing technologies have significantly reduced the amount of solar radiation entering automobile interiors, these technologies still face limitations related to cost, weight, durability, optical clarity, and regulatory compliance, adaptability to various climates, aesthetics, and design. Key factors in managing cooling loads through glazing design include the Solar Heat Gain Coefficient (SHGC), which measures the amount of solar radiation that passes through the glazing and impacts energy efficiency and indoor comfort. In warm climates, a lower SHGC is preferable to minimize heat gain and reduce the cooling load. However, Visible Light Transmission (VLT), which reflects the percentage of visible light that can pass through the glazing, must be balanced with SHGC to ensure adequate daylight while minimizing unwanted heat gain. Additionally, the U-Factor, which measures the rate of heat transfer through the glazing, is also crucial. Addressing these constraints through further research and development is imperative to advancing glazing technologies, optimizing their efficiency in reducing solar radiation, and enhancing overall performance in automobile interiors [81].

3.3. Heat pipe and solar chimney

Researchers created a passenger cabin mock-up to study cooling the instrument panel, which can reach nearly 100ºC when a car is parked, affecting passenger comfort [61]. Under long-term vehicle thermal soak circumstances, the instrument panel's surface temperature decreased up to 20 - 30 °C and the air cabin temperature by 4–10 °C, respectively, as a result of using heat pipes to cool it [61]. While a drop in surface temperatures could benefit the IP electronic components and the AC ducts' decreased heat pickup [62]. The primary barriers to including heat pipes in the IP were the additional cost of the pipes, the system's size, and its position, Figure 8. Shows passenger compartment mockup for heat-pipe IP cooling testing[61].The research showed that heat pipe systems, using common components, lowered cabin temperature by 5°C and instrument panel temperature by 6°C in just 64 seconds. Distilled water in copper heat pipes was effective, with the internal mesh providing adequate capillary pressure, confirming heat pipes' effectiveness for car cooling[82].

Figure 8. Passenger compartment mockup for heat-pipe IP cooling testing [61].

According to experts, the most important source of heat for the interior air is the panel of instruments of the cabin. It absorbs a lot of heat and can reach 100–121 °C [62], [63]. Because of its high temperature, the interior air temperature reach 82 °C [59]. Thereby affecting the thermal comfort and cooling efficiency of occupants [62]. A recent study suggested using a solar chimney on a car's roof to lower cabin temperature. This technology created natural convection airflow, reducing the cabin temperature by 20.5°C during inactivity, as shown in Figure 9[68].Solar chimneys use solar energy to enhance natural ventilation and cooling, but their size and weight can limit practicality. A heat pipe system was tested to cool the cabin without running the engine, achieving a 5°C temperature drop. While promising, further optimization is needed[33].

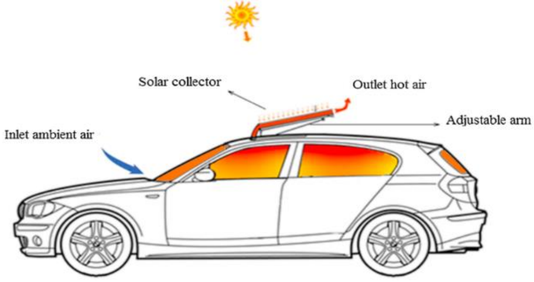

Figure 9. Shows the schematic of the solar chimney mounted on the vehicle cabin [68].

Solar chimney and heat pipe systems can effectively cool sun-exposed car cabins, but they have limitations like limited capacity, cost, and design challenges. Their effectiveness varies and may not be suitable in all situations.

3.4. Insulation and car body color

Insulating the roof might seem logical to reduce solar gain, but research shows that it could increase cabin temperature by retaining more heat during temperature rises [59]. The study found that increasing roof insulation only reduced cabin temperature by 0.2°C and could make the cabin hotter on hot days. A 6.5°C difference was noted between white and dark cars under 36°C conditions. A white car's roof was 11°C cooler than a dark blue car's, showing that exterior color significantly affects interior temperature.[33]. The temperature drop for cars with white exteriors was about 7°C when compared to cars with gray tungsten exteriors [43]. On hot summer days, black cars' interior temperatures were usually 5 °C higher than those of white cars. These results imply that a car's body color significantly influences the cabin's temperature, probably because different colors have different absorptivity's [65]. The experiments showed that for every 0.1 increase in the solar reflectance of the cabin coatings, the temperature within the cabin dropped by 1 °C[61].

Insulation helps reduce heat transfer, but its effectiveness in controlling cabin temperature is limited. It may trap heat, raising interior temperatures in direct sunlight. The study also highlights that lighter car colors reflect more heat, keeping interiors cooler than darker colors.

3.4.1. Phase change material (PCM)

The selection of a PCM is determined by the specific temperature control needs, as different PCMs exhibit a range of thermos-physical properties, including melting range, density, volume expansion, thermal conductivity, specific heat capacity, and latent heat of fusion [83], [84], [85].

Researchers explored using PCM in car systems to improve passenger comfort. During tests, they found cabin temperatures were 22°C higher than outside temperatures on hot summer days. Adding 6 kg of PCM near the ceiling reduced the cabin temperature by an average of 8°C[24]. The study compared interior temperature reductions using PCM versus AC alone. Without PCM or AC, the cabin reached 40°C. With AC only, it dropped to 33°C, and with PCM alone, it fell to 27°C. PCM cooling was 6°C more effective than AC, showing it can maintain comfort without air conditioning [67]. Employing ANSYS 13, a little wooden box of 0.15 m in thickness and 0.30 m in length was modelled to examine its thermal processing. According to the simulation results, PCM might be able to drop the interior temperature by about 20% [86].The study proposed a solar-powered cooling system using phase change materials (PCM). Key components include solar panels, a PCM cooling module, and a storage unit. Experiments showed a 30°C temperature drop. Figure 10 illustrates the system's schematic [87].

Phase change materials (PCMs) have great potential to reduce car cabin temperatures when left in the sun, there are certain obstacles to their use. PCMs are used because of their capacity to both absorb and release thermal energy during phase transitions, which helps to moderate temperature variations in the cabin.

3.5. Ventilation techniques

3.5.1. Natural ventilation through cracking the windows and sunroof

Cracking windows and the sunroof naturally cools a car's cabin by allowing airflow to dissipate heat. This simple method improves comfort without using mechanical cooling. Let's explore how it works, its benefits, and practical tips.

Cracking car windows to let in fresh air does little to lower interior temperatures in a parked vehicle under the sun. Research shows that the cabin can still reach up to 57°C within an hour, regardless of whether windows are cracked or closed. Temperatures inside can soar to 57-68°C even when it's only 30°C outside. This poses serious risks, especially for children left in cars. The study highlights that cracking windows does not effectively slow the heating process or reduce peak temperatures, emphasizing the need for increased awareness about the dangers of hyperthermia in parked cars [29].

Previous studies show that rolling down windows does not effectively reduce the rate of temperature rise or lower the maximum interior temperature of a parked car [33]. A 2.5 cm window crack can reduce cabin temperature by 3–7°C, while a 5 cm crack can lower it by 6–7°C [65]. Opening a car canopy by about six cm can lower the temperature by 5.7°C[61].

Natural ventilation fails to keep cabin temperatures acceptable in extreme heat and can attract pests when windows or sunroofs are left open. It also offers less control over temperature and airflow than mechanical cooling systems.

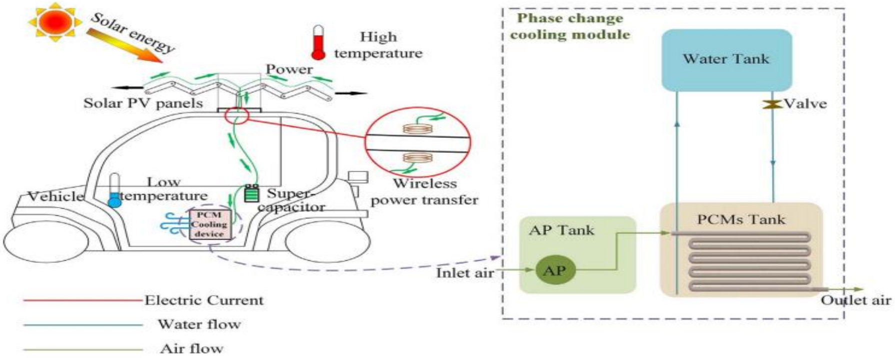

Figure 10. Schematic of the PCMs cooling system generated by photovoltaic panels [87].

3.5.2. Solar ventilation system

Solar ventilation systems use photovoltaic panels to power fans and improve cabin comfort in parked cars. They offer an eco-friendly, cost-effective alternative to traditional cooling methods. This section explores their basics, benefits, and potential uses for better temperature control and overall driving experience[88], [89], [90], [91]

Solar energy, popular for its energy-saving benefits and rising demand, enhances global energy strategies and has various applications in commercial and industrial sectors. This study proposes a solar-powered ventilator for cars, with a battery backup for when solar energy is unavailable. Equipped with a temperature sensor and controller, the system reduces cabin temperature by about 12% [92].

Figure 11 shows a modular solar system for cooling a parked car, which includes two ventilation fans, PV panels, thermostat, and battery and charge controller. This solar ventilation system reduced the temperature by 12 °C[34]. Solar-powered ventilation reduces cabin temperature by 5 to 15°C [39], [93], [94], [95], [96], [97].

In conclusion, it is worth noting that using a solar-powered ventilation system to replace the air inside a parked car is an effective method for lowering the cabin temperature and dissipating the accumulated heat. Extensive studies have shown that this approach successfully reduces cabin temperatures by leveraging convection heat loss through internal airflow.

3.5.3. Summary of the techniques for reducing cabin soak temperature

These approaches were primarily designed to reduce the cabin's elevated temperature and minimize the strain on the cars AC, leading to decreased fuel consumption while maintaining or improving thermal comfort levels.

The below Figure 12. Showed the summary of the categorization of techniques for reducing cabin soak temperature.

Below table 4 is the summary of the techniques for reducing cabin soak temperature and shows the techniques, references, location, and main results.

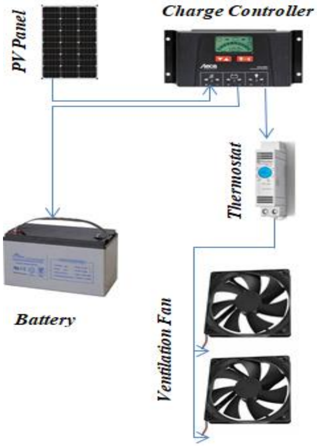

Figure 11. Solar ventilation system in car cabin [34].

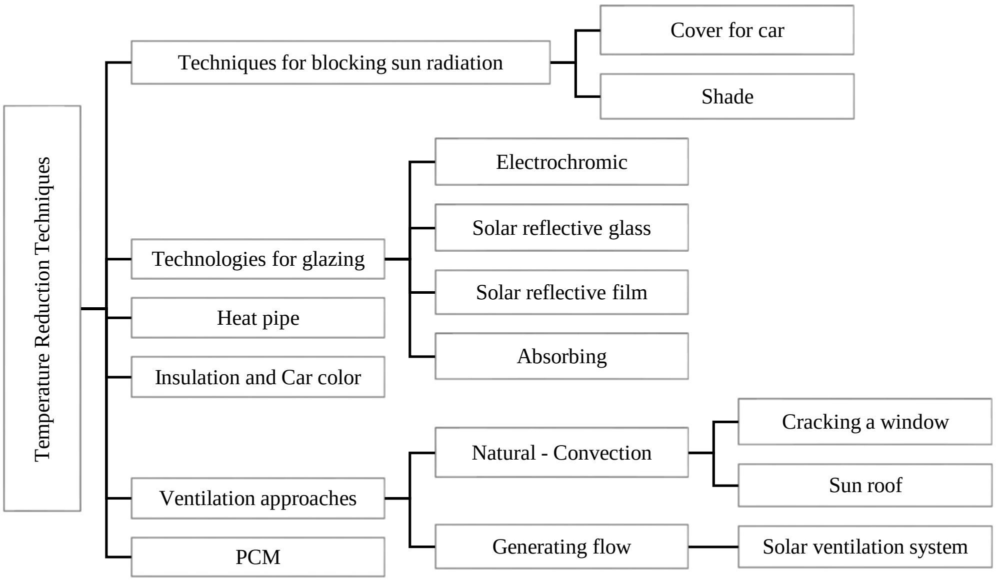

Figure 12. Categorization of techniques for reducing cabin soak temperature.

Table 4. Summary of the techniques for reducing cabin soak temperature.

Techniques	**Reference**	**Location /Year**	**Main Results**
Electric Ventilation	[59]	USA / 2000	16 ºC air temperature reduction.
	[46]	China / 2022	3-7 ºC air temperature reduction.
Portable cooling system	[76]	Malaysia/ 2013	Maintain air temperature between 25–30°C.
Techniques for blocking sun radiation / car cover or shading	[42]	USA / 1988	12 ◦C air temperature reduction.
	[16]	USA / 2004	18.6 ºC air temperature reduction.
	[61]	USA / 2008	20% average reduction in interior air temperature.
	[37]	Malaysia / 2010	26% dashboard temperature reduction and 27% maximum air temperature reduction.
	[80]	Malaysia / 2012	18 ºC dashboard temperature reduction.
	[75]	Iraq / 2015	70% cabin temperature reduction.
	[74]	Malaysia / 2018	17.7 ºC air temperature reduction.
Glass transmittance	[60]	USA / 2013	30% reduction in air conditioning use.
EC glass	[77]	USA / 2003	reduce the amount of solar energy transmitted into the vehicle by 2.5 times
Reflective glass	[63]	USA / 2001	2.2 ºC The maximum breath temperature reduction
	[11]	Romania / 2009	7 ºC air temperature reduction.
	[24]	USA / 2007	7.7 ºC air temperature reduction.
	[71]	USA / 2013	1.2 ºC air temperature reduction.
	[43]	Morocco /2006	7 °C air temperature reduction.
	[24]	USA /2007	12 °C air temperature reduction.
Absorbing glass	[43]	Morocco /2006	2.2 °C air temperature reduction.
Solar reflective film	[59]	USA / 2000	9 °C air temperature reduction.
	[63]	USA / 2001	4.6 °C air temperature reduction.
	[43]	Morocco / 2006	10 °C air temperature reduction.
	[80]	Malaysia / 2012	4.4 °C air temperature reduction.
	[48]	USA / 2015	5.3 °C air temperature reduction.
Heat pipe and heat exchanger	[44]	USA / 2008	4–10 °C surface temperature reductions
	[82]	India / 2017	5 ºC air temperature reduction.
Solar Chimney	[68]	Malaysia / 2019	20.5 ºC air temperature reduction.
Insulation and car color	[62]	USA / 2007	Increasing insulation can make the cabin hotter than those with less insulation.
	[42]	USA / 1988	The dark blue car's outside roof temperature was 11 °C higher than the white car's.
	[43]	Morocco / 2006	External white surfaces saw a 7°C reduction in temperature as compared to grey tungsten surfaces.
	[65]	Australia / 2011	Black cars' interior temperatures were usually 5 degrees Celsius higher than white cars'
Ventilation approaches / Cracking the windows and sunroof	[42]	USA / 1988	Not effective to reduce temperature
	[29]	USA / 2005	Not effective to reduce temperature
	[16]	USA / 2008	5.7 ºC air temperature reduction.
	[65]	Australia / 2011	3 ºC air temperature reduction.
	[87]	China / 2017	Not effective to reduce temperature
PCM	[66]	Iran / 2012	keep the car's inside temperature at 35 °C
	[86]	USA / 2016	20% reduction in car cabin temperature.
Combining of multiple techniques	[62]	USA / 2007	12 ºC reduction in car cabin temperature.
Solar ventilation system	[95]	Thailand/2012	Replace car cabin hot air by ambient cold fresh air.
	[96]	Malaysia/2015	15 ºC average air temperature reduction.
	[39]	China/2015	15 ºC maximum air temperature reduction.
	[93]	China/2015	5 to 10 °C cabin temperature more than ambient.
	[64]	UAE/2016	4 °C average air temperature reduction.
	[94]	Malaysia/2017	10 ºC average air temperature reduction.
	[97]	China/2017	4.2 ºC average air temperature reduction.
	[92]	Malaysia/2018	12% reduction in car cabin temperature.
	[23]	Malaysia/2022	10 ºC air temperature reduction.
	[34]	Jordan /2023	12 ºC air temperature reduction.

4. Limitations and potential future research directions

While various technologies aim to reduce cabin temperatures in parked vehicles, several limitations must be considered. However, it is crucial to balance these discussions with potential benefits, ongoing advancements, and research efforts that address these challenges and enhance automotive thermal management.

High initial costs and the requirement for significant changes in vehicle design and manufacturing processes could affect affordability and add complexity. However, as consumer awareness and market demand for advanced thermal management technologies grow, further innovation and adoption are likely to follow. Although the upfront expense of these vehicles may be a hurdle, their long-term benefits, such as enhanced comfort and lower energy consumption, can justify the investment. Additionally, advancements in manufacturing technologies and materials are expected to reduce production costs over time.

Portable air conditioners and electric ventilation systems rely on electricity or batteries, which can strain a vehicle's energy resources, especially in isolated or off-grid areas. Integrating renewable energy sources like solar panels offers a sustainable solution, with recent advancements improving their efficiency for automotive use. Therefore, it's crucial for car companies and researchers to focus on incorporating renewable energy options, ensuring vehicles can operate efficiently and sustainably in diverse environments.

Passive cooling techniques, like using vehicle covers and parking in shaded areas, can reduce cabin temperatures, but have limitations. Covers can wear out or become less effective without proper maintenance, and shaded parking isn't always available. Environmental factors, such as extreme weather or sun position, can also reduce effectiveness. Relying solely on these methods may not always result in a significant temperature drop. Ongoing research into more durable, adaptive materials aims to overcome these challenges and enhance performance.

Glazing methods, such as reflective coatings and tinted windows, reduce heat transfer into vehicle cabins but depend on sunlight, temperature, and vehicle design. While advanced materials improve performance, dark tints and coatings can impact appearance, visibility, and safety, and require regular maintenance. Legal restrictions and environmental concerns also limit their use. Research is ongoing to develop more durable, reliable, and eco-friendly glazing options.

Heat pipes offer potential for efficient temperature management. Innovations in design and materials are making them more feasible for automotive applications. However, heat pipe systems can face challenges related to integration within the vehicle’s interior. Issues such as increased weight, potential for reduced vehicle performance, and complexity of installation may arise. Long-term reliability of heat pipes is also a consideration, as they may be subject to wear and tear or performance degradation over time. Research is focused on optimizing design and improving the durability of heat pipes to address these concerns.

Solar chimney systems and advanced insulation techniques offer potential benefits for managing cabin temperatures. However, solar chimneys may require regular maintenance to ensure effective operation, and their performance can vary depending on environmental conditions. Insulation materials, while crucial for thermal management, may experience degradation over time, affecting their effectiveness. Research into improved insulation materials and solar chimney designs aims to enhance durability and performance while addressing maintenance issues.

PCMs can effectively moderate cabin temperatures by absorbing and releasing thermal energy. Advances in PCM technology are improving their performance and range. However, PCMs may face limitations related to their long-term performance and durability. As PCMs undergo repeated phase changes, their effectiveness can diminish, and they may require replacement or maintenance. Research is focused on developing more durable PCM formulations and improving their efficiency under various conditions to address these challenges.

Solar ventilation systems use sunlight to enhance air circulation and reduce cabin temperatures, but their efficiency drops on cloudy days. Challenges include maintaining performance due to environmental exposure and integrating the systems into vehicle designs without affecting aerodynamics. With limited roof space, high-efficiency panels are essential. Future improvements in energy storage could allow the system to store energy for use when ventilation is not needed, further enhancing its effectiveness. Ongoing research aims to address these issues and improve both efficiency and reliability.

Future research could focus on several key areas, including advanced materials and technologies like innovative filtration systems, smart ventilation controls, and energy-efficient climate control systems for car cabins. Integrating IoT and AI for real-time cabin environment management, considering external air quality, passenger comfort, and vehicle energy efficiency, is another promising direction. Additionally, studies on the long-term impact of control techniques on fuel consumption, emissions, and cabin air quality across different driving conditions and climates would be valuable. Comprehensive economic evaluations to assess the cost-effectiveness and feasibility of these technologies could further guide decision-making and enhance sustainability in automotive transportation.

5. Conclusion

This paper reviews methods for reducing temperature increases in parked vehicles, focusing on fuel efficiency, passenger comfort, air quality, safety, and emissions reduction. It highlights the effectiveness of technologies such as solar ventilation, phase-change materials (PCMs), reflecting glass, and car covers, which can lower cabin temperatures by over 15 °C. In contrast, methods like insulation, cracked windows, and sunroofs are less effective, typically achieving reductions of no more than 5 °C. Technologies like solar chimneys, heat pipes, and heat exchangers face practical challenges due to their size and weight, limiting their widespread use. The review underscores the importance of balancing technological advancements with practical considerations such as cost, government regulations, energy sources, and consumer awareness. The rising cost of vehicles and the limited availability of these technologies pose significant barriers to widespread adoption. Therefore, future research should address these issues by exploring cost-effective solutions and enhancing public knowledge about available technologies. This review offers a valuable resource for developing and implementing effective thermal management strategies. It provides insights for creating policies that can reduce tailpipe emissions, lower energy consumption, and ensure rapid attainment of thermal comfort. Additionally, the review highlights the necessity for stringent guidelines to prevent safety hazards associated with hot vehicles. While substantial progress has been made in developing technologies to combat greenhouse phenomena in car cabins, a balanced approach that considers both advancements and limitations will be crucial in shaping future studies and implementations. By addressing these factors, stakeholders can work towards optimizing vehicle performance and enhancing overall environmental and safety outcomes.

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