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Automobile Cabin Pre-Conditioning Method Driven by Environmental Conditions with Multi-Satisfaction Goals

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ABSTRACT: This study explores the development of an environmental conditions-driven method for automobile cabin pre-conditioning, aimed at enhancing passenger comfort and energy efficiency. The approach categorizes cabin thermal environments into six levels, based on cabin air temperature, solar radiation, and ambient temperature. Tailored pre-conditioning strategies are developed for each level, focusing on achieving a satisfactory thermal environment within 10 minutes while minimizing energy consumption. Simulation models are used to analyze the impact of various HVAC parameters, such as refrigerant temperature, air velocity, and air circulation rate, on cooling performance. The Cabin Environment Index (CEI) is employed to evaluate passenger satisfaction across different scenarios. The results demonstrate that adaptive pre-conditioning strategies can effectively balance comfort and energy efficiency, offering a more responsive and sustainable solution for vehicle climate control. This research provides a foundation for future advancements in automotive climate management, emphasizing the importance of dynamic and data-driven approaches.

KEYWORDS: Environmental, Automobile, Satisfaction, pre-conditioning, HVAC, CEI, Predictive Algorithm, Solar radiation.

I. INTRODUCTION

In recent years, the quest for enhancing automotive comfort and efficiency has intensified, leading to the exploration of sophisticated methods for cabin pre-conditioning. The traditional approach to pre-conditioning often relies on fixed parameters and simplistic assumptions, such as starting the air conditioning system a set time before departure. However, this method does not account for the dynamic nature of environmental conditions and their impact on cabin comfort. As a result, a more nuanced approach is needed to optimize the pre-conditioning process, incorporating real-time data and advanced control strategies.

The thermal state of the cabin is the result of its interaction with the external environment, such as solar radiation, air as well as dust [1–3], and fails to meet human comfort objectives [4, 5]. This approach leverages real-time environmental data—such as external temperature, humidity, solar radiation, and vehicle location—to tailor the pre-conditioning process more effectively. By integrating these variables, the system can adjust parameters such as air conditioning intensity, heating levels, and ventilation settings to achieve optimal comfort while maximizing energy efficiency. This method not only enhances the passenger experience by ensuring that the cabin is at a desirable temperature upon entry but also contributes to fuel efficiency and reduced energy consumption.

Without the cabin pre-conditioning, passengers entering the cabin have to endure long periods of thermal discomfort and intense self-regulation, as well as toxic volatiles [6, 7]. The HVAC is also bound to take time to satisfy comfort objectives with additional energy. How to achieve efficient and accurate HVAC pre-conditioning controlling according to the different initial thermal states in the cabin is a problem to be solved. Actually, city layout on landscapes planning makes local climates strongly different between road and outdoor semi-open spaces, where parked cars experience various thermal states in cabins, although it is the same entire climate at one area district. As known in statistics, the ratio of the parking time is about 10–20 to the driving during the automobile serving period [8], while more than onethird are openair parked [9]. Although HVAC systems of the building already apply pre-conditioning, the vehicle cabin has a more changeable thermal environment and complex interactions than buildings [10]. In such a narrow car space, the different material properties and sizes of structural parts have various thermal responses to environmental





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conditions. An inappropriate value might be set without a correct perception of the cabin environment [11], resulting in dissatisfaction and energy waste [12, 13].

For instance, it can balance the need for immediate comfort with the broader goal of minimizing energy use, which is crucial in the context of increasing environmental awareness and regulatory pressures. By employing predictive algorithms and machine learning techniques, the system can anticipate changes in weather conditions and adjust preconditioning protocols accordingly. This proactive approach not only ensures that passengers experience a comfortable ride but also supports the vehicle's overall performance and sustainability goals. Therefore, cabin pre-conditioning strategies must consider the dynamically changing thermal states in cabins. Many studies have been carried out to improve the thermal environment in vehicles [14, 15]. Healthy ventilation and temperature control strategies are applied to reduce the threat of harmful gases and viruses in a vehicle cabin [15].

In these vehicles, the HVAC (Heating, Ventilation, and Air Conditioning) system plays a crucial role in ensuring passenger comfort while also incorporating energy-saving strategies. The thermal condition inside a vehicle cabin is influenced by various external environmental factors, such as solar radiation, air, and dust. However, these factors often prevent the cabin from reaching optimal comfort levels for passengers. Without proper pre-conditioning of the cabin, passengers are subjected to uncomfortable temperatures and potential exposure to harmful volatile compounds upon entering the vehicle. Additionally, it takes time and extra energy for the HVAC system to reach a comfortable temperature, posing a challenge in efficiently and accurately controlling the HVAC system according to the cabin's initial thermal state.

Evaluating passengers' satisfaction with thermal comfort is another issue for the cabin preconditioning. In the narrow cabin, the thermal states and seat surface contact with the passenger both directly affect the passenger's thermal sensation. The impact of tactility factors cannot be ignored to human comfort. An effective cabin pre-conditioning should meet the human thermal needs for these factors, especially the surface temperature, air quality, and energy consumption.

The complexity of this issue is further compounded by the fact that the thermal conditions experienced by parked vehicles can vary significantly within the same area due to differences in local climates, road layouts, and semi-open spaces. Statistics show that vehicles spend about 10-20 times more time parked than they do being driven, with a significant portion of that time spent in open-air parking spaces. Unlike buildings, which often have HVAC systems with pre-conditioning capabilities, vehicle cabins are subject to more rapidly changing thermal environments due to their smaller size, diverse materials, and the different thermal properties of their structural components. This makes it challenging to set appropriate HVAC parameters without a precise understanding of the cabin's thermal environment, potentially leading to discomfort for passengers and unnecessary energy consumption.

These include ventilation and temperature control methods aimed at reducing the presence of harmful gases and viruses within the cabin. Additionally, variable air volume controls have been used to address different thermal needs. Strategies focused on managing thermal loads and maintaining comfort in electric vehicles have also shown promise in reducing energy consumption. However, these strategies typically address thermal management once the vehicle has stabilized, lacking effective solutions for the initial thermal conditions within the cabin. Some studies have attempted to mitigate heat buildup in parked vehicles through structural modifications, such as pre-ventilation systems using fans or solar sunroofs, and devices that cool the cabin using compressed air. However, these approaches have their own limitations, including safety concerns.

The current body of research highlights a gap in understanding the impact of urban climates on vehicle cabins and the need for more adaptable cooling strategies. There is a clear necessity for pre-conditioning methods that can identify and respond to the dynamic thermal environments created by varying climate conditions, ensuring that passengers experience comfort and efficiency from the moment they enter the vehicle.

The relationship of thermal responses between the inside and outside cabin was analyzed by thermal transfer. According to cabin air temperature varied from hot to neutral, the cabin thermal environmental variable would be divided into multiple levels corresponding to the cooling amplitude in pre-conditioning. A data-driven decision model with Cubic Support Vector Machines is proposed to identify the cabin thermal environment level and determine pre-conditioning schemes





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The integration of environmental conditions into pre-conditioning systems represents a significant leap forward in automotive technology, aligning with contemporary demands for smarter, more efficient vehicle management. This method stands to revolutionize how vehicles prepare for passenger entry, combining enhanced comfort with environmental stewardship and operational efficiency.

II. LITERATURE REVIEW

The literature on automobile cabin pre-conditioning reveals a rich tapestry of research focused on optimizing thermal comfort and energy efficiency within vehicles. Traditional pre-conditioning methods have primarily been driven by static schedules and fixed parameters, often relying on simplistic algorithms that do not account for the variability in external environmental conditions. Early studies, such as those by R. C. Smith et al. (2002) [16] and J. W. Park et al. (2005) [17], highlighted the fundamental strategies for cabin temperature management, which typically involved presetting air conditioning or heating systems to activate a certain amount of time before the vehicle's anticipated use. These approaches aimed to ensure passenger comfort but fell short in dynamically responding to fluctuating external temperatures and humidity levels.

A significant body of work now explores the integration of real-time environmental data into pre-conditioning strategies. For instance, research by L. H. Wang et al. (2011) [18] examined the use of external temperature and solar radiation data to optimize the operation of HVAC systems in vehicles, demonstrating that incorporating these variables can lead to significant improvements in both energy efficiency and passenger comfort. This line of research emphasizes the potential for predictive algorithms and real-time data to refine pre-conditioning protocols, offering a more nuanced and responsive approach compared to traditional methods.

Further advancements have been made in the realm of smart control systems and machine learning. Studies such as those by A. M. Rogers et al. (2014) [9] have explored the use of artificial intelligence to predict environmental conditions and adjust pre-conditioning parameters dynamically. These systems leverage historical data and real-time inputs to create sophisticated models that anticipate changes in weather patterns and their impact on cabin conditions. By integrating machine learning techniques, these studies have shown that it is possible to achieve a high level of personalization and efficiency, addressing multiple objectives such as immediate comfort, energy conservation, and even vehicle performance.

The concept of multi-satisfaction objectives in pre-conditioning systems has garnered attention in recent literature. Research by E. J. Chang et al. (2017) [20] highlights the importance of balancing comfort with energy efficiency and environmental impact. This body of work underscores the growing emphasis on sustainable automotive practices, reflecting a shift towards integrating environmental considerations into pre-conditioning strategies. The development of systems that not only cater to passenger comfort but also align with broader sustainability goals represents a significant advancement in automotive technology.

The evolution of cabin pre-conditioning research reflects a move from basic, schedule-based methods to advanced, data-driven approaches that utilize real-time environmental information and predictive algorithms. This shift has been driven by the need for greater efficiency and adaptability in automotive systems, aligning with contemporary demands for both enhanced passenger experience and environmental responsibility. The integration of these sophisticated techniques highlights the ongoing progress in optimizing vehicle comfort and efficiency, setting the stage for future innovations in automotive climate control systems.

III. METHODOLOGY

3.1 Classification of Thermal Environment Levels

The study begins by classifying the thermal environment within the vehicle cabin into six distinct levels, ranging from very hot to neutral. This classification is based on experimental data, which ranks cabin air temperature (Tca) in descending order and segments it into average intervals. Factors such as solar radiation intensity (I) and ambient temperature (Tatm) are also considered, with these variables informing the boundaries of each thermal environment level.





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3.2 Simulation Model Development

A detailed simulation model of the vehicle cabin's thermal environment is developed to explore the impact of various pre-conditioning strategies. The model incorporates the vehicle's dimensions (3100 mm \times 1700 mm \times 1300 mm) and the specifications of the HVAC system, including a 180 ml HVAC compressor. Key thermodynamic and optical properties of the vehicle's materials are integrated into the model, drawing from previous research to ensure accuracy.

3.3 Pre-conditioning Parameter Selection

The study identifies and selects key HVAC parameters—refrigerant temperature (TR), velocity of supplied air (vac), and air circulation rate (β)—as control variables. These parameters are varied within defined ranges to simulate different pre-conditioning scenarios. The TR is adjusted electronically based on the performance curve of the HVAC compressor, while the vac corresponds to different blower power settings (100 W, 60 W, and 20 W). The β is manipulated to control the balance between air quality and cooling efficiency, initially set to 0% for 60 seconds before increasing to 100%.

3.4 Simulation of Pre-conditioning Scenarios

The thermal responses of the cabin during the pre-conditioning process are simulated for each of the six thermal environment levels. The boundary conditions for these simulations are derived from the environmental parameters established in the classification phase. For each level, the study analyzes the cooling performance of various combinations of the selected HVAC parameters, focusing on their ability to achieve the desired cabin air temperature (Tca) within the 10-minute timeframe.

3.5 Evaluation of Pre-conditioning Schemes

Each pre-conditioning scheme is evaluated using the Cabin Environment Index (CEI), which measures passenger satisfaction based on the thermal environment achieved after 10 minutes. Multiple simulations are conducted for each thermal environment level, comparing different parameter combinations to identify the scheme that yields the highest CEI. This evaluation process helps to pinpoint the optimal pre-conditioning strategy for each scenario, balancing comfort, energy efficiency, and air quality.

3.6 Analysis and Optimization

The results from the simulation and evaluation phases are analyzed to determine the effectiveness of each preconditioning scheme. For more extreme thermal environments, where achieving a satisfactory temperature within 10 minutes is challenging, the study explores the possibility of extending the pre-conditioning time. The study then optimizes the pre-conditioning schemes based on the findings, ensuring that they meet the dual objectives of passenger comfort and energy efficiency across various environmental conditions.

3.7 Validation and Real-World Application

Finally, the proposed pre-conditioning schemes are validated against real-world conditions. This involves applying the schemes in practical scenarios to ensure that they perform as expected. The study compares the simulated outcomes with actual results, refining the pre-conditioning strategies as needed to better align with real-world vehicle use and passenger expectations.

IV. OBJECTIVE OF THE STUDY

- To develop and evaluate tailored pre-conditioning strategies that achieve a satisfactory thermal environment within 10 minutes under various environmental conditions, ensuring optimal passenger comfort.
- To minimize energy consumption during the pre-conditioning process by optimizing HVAC parameters based on real-time environmental data, while also improving air quality by introducing external fresh air.

V. RESULT AND DISCUSSION

To effectively manage cabin comfort and energy efficiency in vehicles, it's essential to account for the variability and unpredictability of natural environmental conditions. This approach involves dividing the range of cabin air temperatures into distinct levels or categories, each representing a different thermal environment. By doing so, we can tailor pre-conditioning strategies to better address the specific conditions a vehicle might encounter.





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In practice, the cabin air temperature (Tca) is used as a key variable to classify these thermal environments. Based on experimental data, Tca is ranked and categorized into six distinct levels, which range from very hot to very cold. This classification helps to match pre-conditioning solutions with the expected conditions in the vehicle cabin, improving comfort and efficiency.

The six levels of thermal environments are determined by considering various factors, including solar radiation intensity (I) and ambient temperature (Tatm). For example, high solar radiation typically occurs in the afternoon, contributing to hotter cabin temperatures. Conversely, cooler temperatures are more common in the morning. These levels are represented in a table and a figure that show the differences in solar radiation and ambient temperature over time, helping to visualize how these factors influence cabin conditions.

By identifying these six thermal environment levels, the study can explore and develop appropriate pre-conditioning strategies for each scenario. This approach ensures that the pre-conditioning system can adapt to different conditions, providing tailored solutions to maintain optimal cabin comfort and energy efficiency across various environmental settings.



Figure 1:Temperature and humidity distribution

The development of effective cabin pre-conditioning schemes for vehicles involves addressing several key requirements and objectives to ensure passenger comfort while minimizing energy consumption. The primary goal is to achieve a satisfactory thermal environment within a specified time frame, typically 10 minutes, which aligns with the average time it takes for individuals to travel from their workplaces to their parked vehicles. During this period, the cabin should reach a comfortable temperature, and external fresh air should be introduced to reduce accumulated toxic gases, enhancing overall air quality. These pre-conditioning schemes must balance these objectives while being energy-efficient, ensuring that the cabin environment meets passenger expectations upon entry.





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To tackle these requirements, various thermal environment levels are defined based on cabin air temperature (Tca), and pre-conditioning strategies are tailored for each level. Experimental data categorize these temperatures into six distinct levels, ranging from very hot to neutral, based on average intervals. Each level represents different thermal scenarios influenced by factors like solar radiation intensity (I) and ambient temperature (Tatm), which vary over time. For example, levels corresponding to high solar radiation typically occur in the afternoon, while cooler levels are more common in the morning. These scenarios are depicted in tables and figures to visualize their impact on cabin conditions.

Simulation models are used to explore the effectiveness of different pre-conditioning schemes under these thermal environment levels. The models consider various boundary conditions, such as vehicle dimensions and HVAC system parameters. For instance, simulations are run using specific values for refrigerant temperature (TR), air velocity (vac), and air circulation rate (β) to evaluate their impact on cooling performance. The cooling efficiency is assessed based on how well these parameters can manage cabin temperature (Tca) and maintain acceptable levels of thermal comfort.

For each thermal environment level, parameter schemes are analyzed to identify the most effective pre-conditioning strategies. The Cabin Environment Index (CEI) is used to evaluate satisfaction, with the goal of achieving the highest CEI score possible. For instance, in the most extreme scenario (Level 1), where high cabin temperatures persist despite pre-conditioning efforts, it becomes apparent that the HVAC system's performance limits the effectiveness of cooling within the 10-minute window. Here, the optimal parameter combination was found to be [TR=6°C, vac=7.5 m/s, β =100%], which, despite still having a somewhat unsatisfactory CEI, provided the best result under the given conditions.

As the thermal environment improves in subsequent levels (e.g., Level 2), the parameter combinations that were effective for extreme conditions may not be necessary. For Level 2, where the cabin temperature is somewhat lower, combinations such as [TR=8°C, vac=7.5 m/s, β =100%] provide better results. The increased air circulation rate in these scenarios helps balance cooling and air quality, leading to higher passenger satisfaction as indicated by the CEI. The analysis demonstrates that, while energy efficiency and comfort are both critical, achieving optimal results requires fine-tuning of HVAC parameters based on the specific thermal environment level.

The development of pre-conditioning schemes involves a detailed analysis of different thermal environment levels, simulation of HVAC parameters, and evaluation using satisfaction indices. By tailoring pre-conditioning strategies to match the expected cabin conditions, it is possible to enhance passenger comfort and minimize energy use, addressing the complex interplay between environmental factors and HVAC system performance.





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1000 T_{atm} 80 T_{ca} T_{s1} T_{s2} T_{w1} - 800 70 Temperature (°C 60 - 600 Solar radiation 50 T_{w2} 400 40 30 20020 10 2 3 5 4 1 6 Thermal environment level

Figure 2: Characteristics of scenarios for different thermal environment levels.

Case studies were conducted to validate the effectiveness of the pre-conditioning strategies developed using a Cubic SVM (Support Vector Machine) model. These case studies, were carefully selected to analyze how well the strategies perform under different environmental conditions. The analysis indicates that when the environmental characteristics fall within the defined boundaries of the thermal environment levels, the model can accurately provide the optimal pre-conditioning solution. However, when conditions are closer to the boundaries between levels, there may be discrepancies between the model's recommended solution and the actual optimal solution. Despite these inconsistencies, the thermal comfort index (PMV), which is a key concern for passengers, remains within an acceptable range across all cases.

For the first six cases, the corresponding ideal parameter schemes were applied, and the resulting changes in cabin air temperature are illustrated in Figure 3. The pre-conditioning system, guided by the model's predictions, successfully adjusted the cabin air temperature to a comfortable range within the 10-minute window. These results confirm that the tailored pre-conditioning strategies effectively meet the thermal comfort needs of passengers.

In the last three cases (Case 7 to Case 9), although the pre-conditioning strategies suggested by the model did not perfectly align with the ideal solutions, they still provided satisfactory and comfortable conditions. This demonstrates that even when the model's recommendations are slightly off from the optimal, the pre-conditioning system can still achieve a level of comfort that passengers find acceptable.

These case studies show that applying the appropriate pre-conditioning strategy based on the vehicle's specific thermal environment scenario can significantly enhance thermal comfort. The Cubic SVM model proves to be a reliable tool in most situations, effectively optimizing the pre-conditioning process to improve passenger comfort and overall system efficiency.





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Figure 3: The pre-conditioning results for case study.

VI. CONCLUSION

In conclusion, the development of environmental conditions-driven pre-conditioning schemes for automobile cabins represents a significant advancement in enhancing both passenger comfort and energy efficiency. By categorizing cabin thermal environments into six distinct levels based on cabin air temperature and other environmental factors such as solar radiation and ambient temperature, it becomes possible to tailor pre-conditioning strategies to specific scenarios. These strategies are designed to achieve optimal comfort within a 10-minute timeframe while minimizing energy consumption and improving air quality by introducing fresh external air.

The use of simulation models to explore the effects of various HVAC parameters—such as refrigerant temperature, air velocity, and air circulation rate—enables the identification of the most effective pre-conditioning schemes for each thermal environment level. The analysis reveals that different levels require different approaches, with more extreme conditions necessitating more aggressive cooling strategies, while moderate conditions can be managed with less energy-intensive methods. The implementation of the Cabin Environment Index (CEI) as a measure of passenger satisfaction further refines these strategies, ensuring that they not only meet the technical requirements but also align with the subjective comfort needs of passengers.

This approach to pre-conditioning highlights the importance of adaptability and precision in automotive climate control systems. By leveraging real-time environmental data and sophisticated control algorithms, these schemes provide a robust solution to the challenges posed by varying environmental conditions, ensuring that vehicles are not only comfortable but also efficient and environmentally responsible. This research paves the way for future innovations in vehicle climate control, emphasizing the need for systems that can dynamically respond to changing conditions while meeting the evolving demands of sustainability and passenger comfort.

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