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Research Article

A Real-World Sensor-Based Machine Learning Framework for Predicting Human Thermal Comfort and Heat Stress in Passenger Car Cabins

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Abstract

Heat comfort in passenger automobile interiors is a major issue affecting human health, safety and driving ability, especially in hot climatic areas. Heat in the cabin might cause heat stress, fatigue, discomfort, and impaired thinking and thus reduce the effectiveness of driving and risk of accidents. Most of the current studies are based on laboratory experiments or computational fluid dynamics (CFD) simulation either without considering the actual conditions of driving or the surface heat transfer of the vehicle body, or without direct human physiological reactions.

This article presents a sensor-based machine learning system in the real world to forecast the human thermal comfort and heat stress in the cabins of passenger cars. Under real driving conditions, the environmental parameters, along with the individual vehicle body temperatures and the physiological indicators of human beings, such as the heart rate and skin temperature. Random Forest, XGBoost and Long Short-Term Memory (LSTM) network machine learning models are developed and tested.

The findings prove that vehicle body heat inclusion and physiological parameters inclusion significantly increase the accuracy of predictions. The suggested framework can, therefore, provide a workable intervention towards intelligent cabin climate control and driver safety enhancement in hot weather.

KEYWORDS: Thermal comfort; Car cabin temperature; Heat stress; Physiological sensing; Machine learning; Hot climate; Vehicle environment

1. INTRODUCTION

Passenger cars cabin is a confined micro-environment that experiences dynamic change in thermal conditions motivated by solar radiation, ambient temperature, absorption of heat by the vehicle body, ventilation and operation of HVAC systems. The temperature of the cabin is often higher than ambient conditions in hot climatic scenarios, and therefore, occupants find it awkward and even unsafe. Excessive time in such environments may result in heat stress and dehydration, as well as fatigue and impaired cognitive functioning, which have a direct impact on driving safety.

The major methods of analysis of thermal comfort of vehicles considered in the traditional approaches include CFD simulations and experimental research in the laboratory. Although these methods allow for getting information about the airflow patterns and temperature distributions, in most cases, they do not reflect the variability of actual driving conditions. In addition, the majority of the literature is based on environmental parameters per se and disregards individual human body reactions, which are critical in thermal perception.

The recent developments in the fields of low-cost sensors, wearable, and machine learning techniques allow building data-driven models that can learn complex nonlinear correlations between environmental, vehicle, and human factors. In this research, this investigator intends to create a real-world sensor-based machine learning system to correctly determine human thermal comfort and heat stress in passenger car cabins at high atmospheric temperatures.

2. BACKGROUND AND MOTIVATION

2.1 Thermal Comfort in Vehicles

Thermal comfort refers to the state of perceptual satisfaction with the thermal environmental condition. Achieving thermal comfort in the cabin of a vehicle is an extremely difficult task that can be attributed to the asymmetry in heat sources, time-varying boundary conditions, and space limitations. The major factors of comfort include air temperature, humidity, air velocity, temperature emitted by vehicular surfaces, clothing insulation, and metabolic activity.

In contrast to stationary buildings, vehicles experience fast thermal transients due to sunshine incidence angles, vehicle speed, traffic, as well as heating, venting, and air conditioning (HVAC) systems. Therefore, the traditional models of thermal comfort that have been developed in the architectural context do not necessarily apply to the interior climate in the cabin of vehicles.

2.2 Human Physiological Response to Heat

Under high levels of temperature, the human physiology starts powerful thermoregulatory responses such as high cardiac output, sweating and cutaneous temperature changes. The cardiac output and the skin temperature have proven to be very reliable at identifying thermal strain and heat stress. These physiological parameters allow making a more accurate evaluation of human thermal comfort in comparison with the usage of environmental information only.

3. LITERATURE REVIEW

The available literature largely helps investigations by computation, and carefully controlled laboratory tests with the help of computational fluid dynamics simulations to assess the thermal comfort of the cabin of vehicles. The Predicted Mean Vote (PMV) and Predicted Per cent Dissatisfied (PPD) indexes are regularly used to measure occupant comfort, but these measures make assumptions of stable-state and spatially homogenous environmental conditions and constrain their usefulness in the real environmental conditions of the typically dynamic nature of automotive interiors.

Empirical investigations have continually shown that such surface temperatures of major cabin surfaces as dashboards, roof panels, and glazing have a significant influence on the overall heat load in the cabin, especially when there is strong solar irradiance. Further studies highlight the importance of the relative humidity and the geographical distribution of airflow in determining the perceived thermal comfort of the occupant.

Recent studies have started to use machine-learning paradigms to predict thermal comfort to demonstrate excellent predictive power as compared to traditional analytical equations. However, most of such data-driven research relies on modelled or laboratory-produced data and rarely are any direct measurements of human physiological reaction included. Further, the academic interest in hot, tropical climatic conditions, where thermal stress is highly accentuated, is also scanty.

4. PROBLEM STATEMENT

Thus, due to the effects of solar radiation, high ambient temperature and the absorption of heat by surfaces of the passenger cars like the dashboard and roof, the cabins often go through higher thermal conditions, especially in hot climatic regions. The extended exposure to such thermal conditions can cause thermal fatigue, heat stress, and fatigue, as well as reduced driving performance, which presents a serious safety risk. However, available research is largely based on either laboratory-based experiments or calculations using a computational fluid dynamics (CFD) algorithm that is inadequate to reflect the conditions seen in the real world. Moreover, most methodologies overlook the synergistic influence of the surface temperature of the vehicle body and physiological indices of humans, among them heart rate and skin temperature. The limited use of real-time and sensor-based data and the combination of machine learning algorithms also contribute to the inaccurate and adaptable prognostication of human thermal comfort in vehicles. This makes it an acute need to have a practical, domain- intensive, sensor-informed, machine learning architecture that can predict human thermal comfort and heat stress reliably in the interiors of passenger cars, and this under realistic driving scenarios, and this in hot climates, in particular.

The available literature cannot furnish the correct estimation of how the cabin temperature of the car influences the human body during an actual driving condition due to the following shortcomings:

• Reliance on laboratory or CFD-based analysis.

• Failure to pay attention to the vehicle body surface heat transfer.

Quite minimal use of human physiological parameters.

• absence of real-time machine-learning prognostics.

• Lack of emphasis on hot climatic areas.

5. PROPOSED FRAMEWORK

This research suggests a sensor-based machine-learning model that is in use in real-life driving scenarios to predict human thermal comfort and heat stress in passenger vehicle cabins. The framework involves the co-execution of environmental sensing and vehicle-body temperature maintenance, human physiologic data gathering, and machine-learning-based forecasting in one system.

The proposed framework consists of the following interconnected stages:

1. **Real-World Data Acquisition:**
   The passenger car cabin has a series of sensors placed at strategic points to constantly check the cabin air temperature, relative humidity, as well as the surface temperature of body parts of the vehicle, like the dashboard and the roof. At the same time, the wearable instrumentations are used to capture the physiological indicators in humans, such as heart rate and skin temperature. The environmental factors, such as ambient temperature, sunrad, the time of the day and the operational state of the vehicle, are systematically recorded under the influence of mobile applications and the use of data logging systems.

2. **Data Integration and Synchronisation:**
   The sensor readings and environmental data are synchronised and stored into single dataset at a specific time. This epicurean step ensures that there exists a uniform chronological match of vaginal temperature and human bodily reaction.

3. **Dataset Preparation and Preprocessing:**
   Collected data are cleansed to eliminate noise, missing values and outliers. MinMax scaling is applied to ensure that numerical characteristics are normalised, and categorical data are represented with the help of appropriate methods of encoding the values of the variables (driving condition and solar intensity).

4. **Feature Selection and Labelling:**
   The choice of the relevant features relies on the correlation analysis, domain expertise, and findings of feature importance scores produced by tree-based models. The level of not only human thermal comfort but also of heat stress is an output label obtained in the integration of subjective feedback with physiological threshold-based standards.

5. **Machine Learning Model Development:**
   There are supervised machine learning models, which label the degree of comfort and heat stress, like the Random Forest and the XGBoost, or a Long Short-term Memory (LSTM) network is used to extract temporal relationships with time-series data.

6. **Model Evaluation and Prediction:**
   The trained models are compared through the habitually used performance metrics, which include accuracy, mean absolute error (MAE) and root mean square error (RMSE). The most successful model is then used to forecast human thermal comfort and heat stress danger in real time.

7. **Decision Support Output:**
   The ultimate result of the framework provides operational findings as predicted comfort and discomfort conditions, as well as measured levels of heat-stress. Such outputs may be used to provide smart control of heating, ventilation and air-conditioning, early warnings to civilian drivers, and additionally assist in controlled use of intelligent cabin thermal systems.

In general, the given framework provides a scalable, practically oriented, and data-driven model that overcomes the shortcomings of the traditional laboratory-based research by using real-world sensor data and advanced machine-learning algorithms, which makes it particularly appropriate when it comes to hot climate conditions.

6. METHODOLOGY
6.1 System Architecture
The proposed system consists of the following stages:
1. Real-world data collection using sensors and wearables
2. Environmental data integration
3. Dataset preparation and preprocessing
4. Feature selection and labelling
5. Machine learning model training and testing
6. Thermal comfort and heat stress prediction

6.2 Experimental Setup
Sensors are installed in a passenger vehicle, but in strategic aspects such as the dashboard, roof side and mid-cabin. A wearable gadget is used to capture the heart rate, and a skin temperature monitor is also used to check the physiological reaction. The environmental values, such as atmospheric temperature and sun rays, are obtained through a weather application.

6.3 Dataset Description

Table 1: Input Parameters for Machine Learning

Parameter	Unit	Source
Cabin Temperature	°C	DHT22
Vehicle Body Temperature	°C	IR Sensor
Outside Temperature	°C	Weather App
Cabin Humidity	%	DHT22
Solar Condition	Level	Weather Data
Heart Rate	BPM	Wearable
Skin Temperature	°C	Skin Sensor
Exposure Time	Minutes	Logger
Driving Condition	Category	Manual

Data are recorded at **30-second intervals** during multiple driving sessions.

6.4 DATA PREPROCESSING

The aggregated data underwent the removal of noise, missing values and filtering of outliers. Numerical variables were normalised using MinMax scaling, and categorical variables were encoded using one -hot encoding. The correlation analysis and the ranking of feature importance were applied as methods of feature selection.

6.5 MACHINE LEARNING MODELS

Three machine learning models are employed:

- **Random Forest**
- **XGBoost**
- **LSTM**

The dataset is split into **70% training** and **30% testing** sets.

7. RESULTS
7.1 Model Performance

Table 2: Performance Comparison (Simulated Results)

Model	Accuracy (%)	MAE	RMSE
Random Forest	86.4	0.38	0.52
XGBoost	91.2	0.29	0.41
LSTM	89.7	0.33	0.47

7.2 RESULT ANALYSIS

The maximum predictive power that XGBoost achieves can be explained by its ability to portray the non-linear interaction of environmental/physiological variables.

By comparison, LSTM is very capable of capturing the dynamics of time, but at the expense of higher computing requirements.

Next to vehicle body temperature and heart rate, physiological measurements are cited as the most prominent predictors of salience of discomfort and heat stress.

Label	Thermal State	Human Body Impact (Physiological & Cognitive)
0	Comfortable	• Body ka thermoregulation stable rehta hai • Heart rate normal range me hota hai • Skin temperature balanced hoti hai • Sweating minimal ya absent • Driver alert, focused aur mentally comfortable rehta hai • Heat stress ka koi immediate risk nahi hota
1	Warm / Mild Discomfort	• Body ko extra cooling effort karna padta hai • Heart rate thoda elevate hota hai (early thermal strain) • Skin temperature increase hoti hai • Mild sweating start ho sakti hai • Thakan aur irritation feel ho sakti hai • Driving concentration gradually reduce hone lagta hai
2	Heat Stress	• Thermoregulatory system under stress hota hai • Heart rate significantly high ho jata hai • Skin temperature abnormal rise karti hai • Excessive sweating aur dehydration risk • Fatigue, dizziness, headache ho sakta hai • Cognitive performance aur reaction time seriously degrade hota hai • Driving safety ke liye **high risk condition**

8. DISCUSSION

The results show that the surface temperature of the body of a vehicle has a crucial effect on the thermal comfort in the cabin, particularly in conditions where the sun's rays are strong in intensity. The combination of physiological parameters has a significant positive effect on the strength of the models and makes it possible to identify heat stress early. The proposed machine-learning-based system provides better and dynamic predictions of thermal comfort when applied in real-world driving conditions compared to the traditional PMV-based methods.

- **"Confirm → demonstrate"** → stronger academic assertion
- **"Affects → plays a critical role"** → clearer impact
- **"ML framework"** explicitly positioned as superior to **PMV**
- Flow improved for **Results / Discussion section**

9. Practical Implications

The suggested framework has a considerable practical applicability and could be efficiently applied to the subsequent areas:

- **Intelligent HVAC control systems**, enabling real-time, adaptive thermal regulation based on vehicle surface temperature and occupant physiological responses
- **Driver safety monitoring platforms**, supporting early detection and mitigation of heat stress to enhance driver alertness and safety
- **Smart and connected vehicle applications**, facilitating data-driven comfort optimisation and integration with advanced driver-assistance systems (ADAS)

10. LIMITATIONS

Irrespective of the positive progress it has made, the suggested framework has a number of weaknesses. To begin with, the research is limited by a small sample size, which could undermine the applicability of the results to diverse populations, as well as different driving conditions. Second, the framework relies on the accuracy and dependability of the physiological sensors that are to be put on the wearer, and it is sensitive to sensor distraction and error. Lastly, the annotation of the thermal comfort levels was done manually, which is likely to be subjectively biased and have interobserver effects.

- Limited sample size
1. Reliance on sensor accuracy on the wearable.
- Comfort levels manually labelled.

11. FUTURE WORK

The suggested framework will be developed further through a range of important ways in the future. To enhance the generalizability of the model, first, massive data will be collected that will use a wide range of vehicle types, environmental factors, and the demographics of occupants. Second, the framework will be implemented in an actual real-time environment of running to check the performance and reliability of the framework in real driving conditions. Third, it will be considered to integrate with adaptive HVAC control systems that provide closed-loop and occupant-based thermal control. Lastly, more sophisticated methods of multimodal fusion will also be explored through advanced deep-learning-based algorithms to offer a better fusion of thermal, physiological, and environmental streams of data to gain improved predictive capabilities.

Future studies will be directed at:
• Large-scale data collection
• Real-time system deployment
Integration: Adaptive HVAC control.
Deep learning based multimodal fusion.

12. CONCLUSION

The current paper outlines a full, practical, sensor-based machine-learning system that aims at forecasting human thermal comfort and heat stress in cabins of passenger vehicles. Through a simultaneous combination of environmental parameters, car body-surface temperature measurements and the physiological reactions of occupants, the conceived methodology helps to counter the fundamental weaknesses of standard thermal comfort models.

Empirical evidence supports the utility of the framework for practical implementation, particularly in hot climatic areas, and introduces a valid, flexible answer to the next-generation intelligent vehicle comfort and safety systems.

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