PMV-Based Thermal Comfort Assessment Methodology Using Driving Data from xEV Vehicles

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***Abstract*— With the rapid adoption of electric vehicles (xEVs), the importance of maintaining thermal comfort in vehicles has become more critical. Unlike internal combustion engine vehicles, xEVs require optimized energy efficiency, which is closely related to the operation of HVAC (Heating, Ventilation, and Air Conditioning) systems. This study utilizes the Predicted Mean Vote (PMV) model to quantitatively evaluate in-vehicle thermal comfort based on real-time driving data, including temperature, humidity, and airflow velocity, collected during summer and winter. Using Python's pythermalcomfort module, PMV values were successfully calculated, demonstrating their applicability in dynamic vehicle environments. The results showed that approximately 70% of summer data and 85% of winter data fell within the ISO 7730 comfort range (-0.5 ≤ PMV ≤ +0.5), validating the PMV model as an effective tool for assessing in-vehicle thermal comfort. Additionally, the study identifies areas for improvement in HVAC system operation and suggests potential future directions for personalized comfort evaluation and system optimization.**

Keywords*— *Electric Vehicles(xEVs), Thermal Comfort, HVAC Systems, Predicted Mean Vote (PMV), pythermalcomfort

I. Introduction

With the widespread adoption of electric vehicles (xEVs), the importance of managing in-vehicle thermal comfort has become increasingly significant. Unlike internal combustion engine vehicles, xEVs require maximized energy efficiency, which is closely tied to the operation of HVAC (Heating, Ventilation, and Air Conditioning) systems. In particular, the driving range and performance of xEVs are greatly influenced by the energy consumption of HVAC systems. Against this backdrop, the need for a scientifically validated method to evaluate in-vehicle thermal comfort has emerged, enabling the development of systems that maintain energy efficiency while ensuring passenger comfort.

The in-vehicle environment is determined by various factors such as temperature, humidity, and airflow, which influence the passengers' perceived temperature and overall comfort. To effectively adjust interior conditions amidst dynamic external environments during driving, a quantitative model for evaluating in-vehicle thermal comfort is essential. Such evaluations can guide the design of vehicles and the optimization of HVAC systems, thereby enhancing passenger satisfaction and improving energy efficiency.

This study adopts the Predicted Mean Vote (PMV) model as a methodology for evaluating in-vehicle thermal comfort using real-world driving data [1]. The PMV model is a widely recognized index for quantifying human thermal comfort in various environments, integrating multiple environmental factors. In this paper, we calculate PMV values based on temperature, humidity, and airflow data collected during xEV driving. Furthermore, we present a case study evaluating in-vehicle thermal comfort using PMV and discuss how this approach contributes to research on vehicle environments while proposing possibilities for future studies.

II. Review of Comfort Models and Selection of the PMV Model

A. Literature Review and Comfort Models

Various comfort evaluation models, including the Discomfort Index, Perceived Temperature, Effective Temperature, and PMV (Predicted Mean Vote), reflect factors such as temperature, humidity, and airflow to quantify thermal comfort.

Previous studies highlighted the limitations of the PMV model in dynamic environments like vehicles, as it was originally designed for static indoor conditions [1][2]. To address these limitations, Kim (2017) evaluated thermal comfort using physiological data [2], while Yun et al. (2018) developed the HMC model, which incorporates the unique characteristics of Korean passengers to assess localized comfort within vehicles [3].

Although these studies proposed various ways to overcome the PMV model's limitations, real-time collection of physiological or localized data in actual driving environments remains constrained by technical and financial limitations. Therefore, this study adopts the PMV model as the primary approach to comprehensively evaluate in-vehicle thermal comfort

B. PMV Model: Selection and Advantages

The PMV (Predicted Mean Vote) model integrates factors such as temperature, humidity, airflow, and clothing insulation to evaluate thermal comfort and provides reliable results across diverse environments. Recognized in ISO 7730 as a standard metric for indoor thermal comfort assessment, PMV is also applicable to constrained environments like vehicles [1].

The PMV is calculated using the following fundamental formula:

$$PMV = \left(0.303e^{(-0.036)} + 0.028\right) \times [(M - W) - H - EC - CRES - Eres \quad (1)$$

Where:

- M: Metabolic rate depending on activity level (w/m^2)
- W: External work rate (w/m^2)
- H: Heat loss by radiation and convection
- Ec: Heat exchange by skin evaporation
- Cres: Heat exchange by sensible respiration
- Eres: Heat exchange by latent respiration

Details on PMV calculations are elaborated in ISO 7730. In this study, we implemented PMV calculations using the pythermalcomfort Python module [5]. Thermal comfort evaluation based on PMV offers a quantitative measure of passenger comfort derived from simple environmental variables, making it suitable for identifying improvement opportunities in HVAC system design within vehicles.

III. Data Collection and PMV Calculation

A. Data Collection During Driving

In this study, real-time data collected during xEV driving was used to calculate PMV values. Data were obtained via CAN communication in a Hyundai Kona EV and included the following variables:

- Temperature data: Collected from eight locations (driver's seat, passenger seat, rear seats, front and rear roof).
- Humidity data: Measured using a single sensor inside the vehicle.
- Airflow data: Collected from four air outlets (driver/passenger sides, footwell, seat direction).
- Additional data: External variables such as vehicle speed, solar radiation, and external temperature.

B. Data Mapping for PMV Calculations

The collected data were mapped to PMV input variables as follows:

- Metabolic rate (M): Set to 70 (w/m^2) for driving activity.
- External work (W): Set to 0, as no additional work was performed inside the vehicle.
- Air temperature (t_a): Driver's seat temperature was used as the representative value.
- Mean radiant temperature (t_r): Calculated as the average of temperatures from eight locations.
- Air velocity (v): Mean velocity of airflow from four air outlets.
- Relative humidity (rh): Measured inside the vehicle.
- Clothing insulation (I_d): Adjusted based on seasonal variations:
  - Summer: 0.5 clo
  - Winter: 1.0 clo

PMV values were calculated using the pythermalcomfort Python module [5].

C. PMV Calculation Using pythermalcomfort Module

PMV calculations were performed using the pythermalcomfort.models.pmv function [5]. The input data were processed in a Pandas DataFrame and converted into the required PMV inputs. An example of the implementation is as follows:

```
from pythermalcomfort.models import pmv

# Calculate PMV using pythermalcomfort
pmv_value = pmv(
    ta=driver_temp,           # Air temperature
    tr=mean_temp,             # Mean radiant temperature
    vel=mean_velocity,        # Air velocity
    rh=humidity,              # Relative humidity
    met=met_rate,             # Metabolic rate
    clo=clo_value,            # Clothing insulation
    standard="ISO"            # ISO standard
)
```

IV. Results and Analysis

A. Validation of PMV Calculation

This study successfully calculated PMV values based on driving data and demonstrated the applicability of PMV for evaluating thermal comfort in vehicle environments.

Histogram Analysis of PMV Distribution The histograms below illustrate the distribution of PMV values during summer and winter.

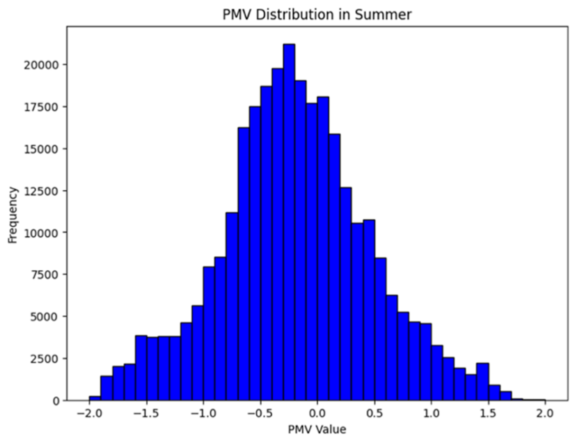

Fig. 1. PMV Value Distribution in Summer Data

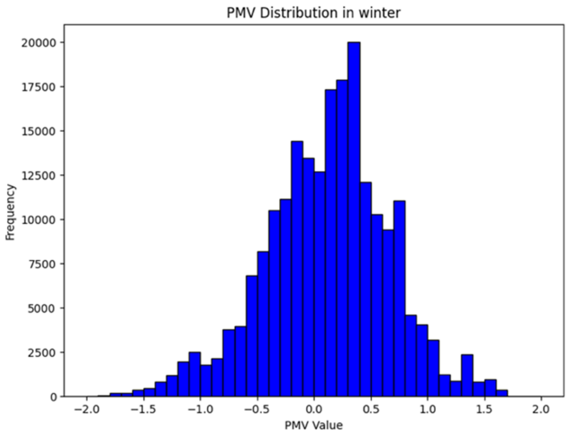

Fig. 2. PMV Value Distribution in Winter Data

Key findings include:

- Summer data:
  Approximately 70% of PMV values fell within the comfort range ($-0.5 \leq PMV \leq +0.5$), indicating mostly comfortable conditions.
- Winter data:
  About 85% of PMV values were within the comfort range, suggesting high comfort levels.

The results confirmed that most PMV values met the ISO 7730-defined comfort criteria [1], validating the PMV model as an effective tool for evaluating in-vehicle thermal comfort.

V. Conclusion and Future Work

A. Summary and Contributions

This study proposed a methodology for evaluating in-vehicle thermal comfort using the PMV model and driving data. Key contributions include:

1) Validation of PMV's applicability to dynamic and constrained environments like vehicles [1,2].

2) Establishing a foundation for evaluating HVAC system efficiency using real-time driving data.

B. Limitations and Future Directions

1) Limitations:

a) Lack of passenger-specific characteristics: PMV does not account for individual factors such as age, gender, or metabolic rate.

b) Exclusion of psychological factors: Subjective thermal comfort perceptions were not considered.

2) Future directions:

a) Develop personalized comfort models incorporating physiological and psychological data : The research will focus on developing personalized thermal comfort models that incorporate physiological data (e.g., heart rate, skin temperature) and psychological data (e.g., stress levels, individual preferences). These models will utilize wearable sensors and machine learning algorithms to evaluate in-vehicle thermal comfort with greater precision.

b) Optimize HVAC systems using real-time PMV-based control algorithms : Future work will involve designing algorithms that automatically adjust HVAC system settings such as temperature, airflow, and fan speed based on real-time PMV values. These algorithms aim to minimize energy consumption while maintaining passenger comfort. Additionally, reinforcement learning techniques will be implemented to create personalized control systems that adapt to individual preferences over time.

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References

[1] ISO, "Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria," ISO 7730, 2005.

[2] M. S. Kim, "A study on evaluation and application of thermal comfort sensibility considering psychological and physiological response of automobile drivers," Ph.D. dissertation, Hanyang University, Seoul, Korea, 2017.

[3] S. Y. Yun, J. Y. Kwak, J. Y. Jeon, H. W. Yeom, J. S. Park, S. W. Seo, et al., "Development of HMC comfort model to validate comfort prediction," in Proc. Spring Conf. Korean Soc. Automot. Eng., 2018, pp. 1323–1330.

[4] P. O. Fanger, Thermal comfort: Analysis and applications in environmental engineering. New York, NY, USA: McGraw-Hill, 1970.

[5] pythermalcomfort Documentation. [Online]. Available: https://pythermalcomfort.readthedocs.io/