Enhancing EV Range and Thermal Comfort in Cold Climates: Optimized PTC/Heat Pump System Coupling

Lorenzo Bartolucci[1], Edoardo Cennamo[1], Stefano Cordiner[1], Marco Donnini[1], Davide Frezza[1], Federico Grattarola[1], Vincenzo Mulone[1]

[1] *federico.grattarola@uniroma2.it Department of Industriale Engineering, Tor Vergata University of Rome, via del Politecnico 1, 00133, Rome, Italy*

Research field: ☐ Economics, x Technology, ☐ Politics, ☐ Social Aspects
Preferred Presentation Type: x Oral ☐ Poster

Abstract

Electric Vehicles (EVs) play a crucial role in the transition toward sustainable mobility, but their range is often limited by high HVAC energy consumption, particularly during winter. Cabin heating typically relies on Positive Temperature Coefficient (PTC) thermistors, which are inefficient, or Heat Pumps (HPs), whose performance drops at very low temperatures. This study explores a hybrid approach, coupling PTC and HP systems to optimize their thermal power split, maintaining high HP efficiency while extending PTC's operating range. Using a validated digital twin of a light-duty commercial vehicle modeled in Matlab/Simulink, the results reveal that the PTC/HP system reduces energy consumption by up to 50% compared to PTC-only systems while maintaining similar thermal comfort. Additionally, it extends the operating range down to -10°C and accelerates cabin heating to setpoint temperature. This approach offers a practical solution for enhancing EV range in cold climates.

Introduction and Motivation

Sustainability has become a strategic priority across various sectors, particularly in transportation. Electric Vehicles (EVs) are increasingly viewed as a high-potential solution for reducing carbon emissions by replacing traditional gasoline and diesel vehicles, thereby mitigating greenhouse gas emissions and pollution [1]. However, the limited driving range of EVs remains a significant barrier to widespread adoption [2], compounded by long charging times [3]. Among the factors influencing range, the energy consumption of HVAC units is particularly impactful, especially during the winter season [4]. Cabin heating primarily relies on PTC thermistors, which are simple but inefficient, or heat pumps, which offer higher COP but are less effective at lower temperatures [5]. This study investigates the coupling of PTC and HP systems, optimizing the thermal power split to enhance efficiency and extend operational temperature limits, addressing a critical challenge in improving EV performance.

Applied Method

A light-duty commercial vehicle model was developed in the Matlab/Simulink environment, utilizing Simscape libraries for multidomain physical modeling to accurately describe the behavior of each vehicle subsystem, including a detailed HVAC system representation. The model was previously validated against experimental data for each component, achieving a total energy consumption error of approximately 3% during a WLTP cycle [6]. This study focuses on coupling map-based PTC and HP systems, optimizing their thermal power split using a loss function. The optimization ensures that the total power output matches that of the PTC-only system, allowing the supplier's thermal management strategy to remain unchanged.

Results

The results demonstrate that using the coupled HP/PTC system while maintaining the same thermal management strategy as the PTC-based HVAC—i.e., preserving the same internal blower command and thermal power requirements—reduces total energy consumption by 30% to 50% as the external temperature increases, all while maintaining identical cabin thermal behavior. Additionally, the system extends the operating temperature range down to -10°C compared to the HP-based HVAC, effectively compensating for the limitations of the HP system. Furthermore, when the thermal management of the coupled system is adjusted to maximize heating power, the results indicate a reduction in the total heating phase duration, from ambient to setpoint temperature, of up to 15% under colder conditions.

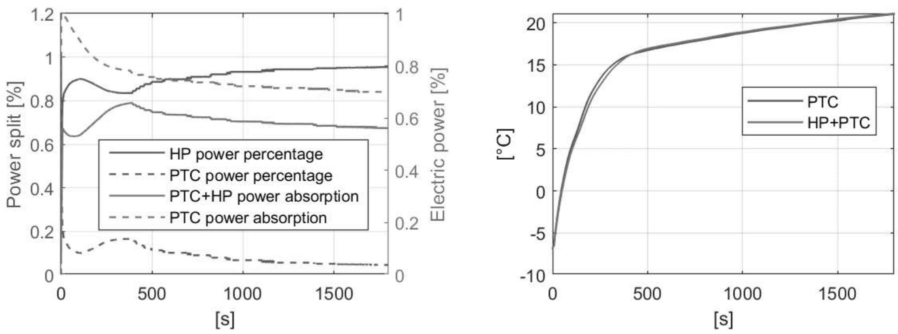

Fig.1 - Power split between PTC & HP and electric power (left) Cabin temperature (right)

Conclusions

In conclusion, this study examined the impact of coupling the two most commonly used heating systems in electric vehicles: PTC and HP. Simulations were conducted using a digital twin of a light-duty vehicle, previously validated with experimental data, and implemented in the Matlab/Simulink environment. The key findings indicate that coupling these systems reduces total HVAC energy consumption, achieving savings of up to 50% while maintaining the same thermal performance. Additionally, by adjusting the thermal management strategy, the coupled system can decrease the time required to reach the setpoint temperature by up to 15%.

References

[1] Bi-Hai J., Chao-Chung H., Nai-Wei S. Chun-Cheng L., *A review of modern electric vehicles innovations for energy transition*, Energies 2024, 17 (12), 2906, https://doi.org/10.3390/en17122906

[2] H. Zhang, M. Irfan, F. Ai, K. M. Al-Aiban, S. Abbas, *Analyzing barriers to the adoption and development of electric vehicles: a roadmap towards sustainable transportation system*, Renewable Energy 233 (2024) 121136

[3] A. Pamidimukkala, S. Kermanshachi, J. M. Rosenberger, G. Hladik, *Barriers and motivators to the adoption of electric vehicles: a global review*, Green energy and intelligent transportation 3 (2024) 100153

[4] L. Bartolucci, E. Cennamo, S. Cordiner, V. Mulone, F. Pasqualini, M. Aimo Boot, *Digital twin of a hydrogen fuel cell hybrid electric vehicle: effect of the control strategy on energy efficiency*, International journal of hydrogen energy, Colume 48, Issue 54, 29 June 2023, Pages 20971-20985

[5] B. Torregrosa-Jaime, J. Payà, J. M. Corberan, *Design of efficient air-conditioning systems for electric vehicles*, SAE international journal of alternative powertrains, may 2023

[6] L. Bartolucci, E. Cennamo, S. Cordiner, F. Grattarola, V. Mulone, S. Pasquale, F. Pasqualini, M. Aimo Boot, G. Giraudo, *Thermal energy storage to increase the range of electric vehicles under cold conditions*, 8th International electric vehicle conference, Transportation research procedia 70 (2023) 414-422