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Thermal energy storage to increase the range of electric vehicles under cold conditions

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Abstract

In the last decade, the electric vehicle technology has been establishing and shows a great potential to become predominant in mobility sector. One of the critical problems of current technology is a limited vehicle range compared to extended charging times. Energy consumption of HVAC unit, especially in winter season, can remarkably affect the range. This work evaluates the benefits of introducing a thermal energy storage able to recover the regenerative braking energy excess, in terms of range extension of a light duty commercial vehicle. A detailed digital twin model of the vehicle has been implemented into the Matlab/Simulink platform to this aim. Results show potential benefits up to 10% of increase in vehicle range under winter conditions. Thermal Energy Storage has been then confirming a viable and effective mean to increase the EV range especially under cold ambient conditions.

Keywords: electric vehicle; thermal enegy storage; digital twin; driving range; electric heating

1. Introduction

Maximization of driving range is one of the more critical problems in supporting the massive implementation of electromobility concepts. With such regard, the energy consumption of the vehicle auxiliary systems, such as the Heating, Ventilation and Air Conditioning (HVAC) system and the Battery Thermal Management system (BTMS), remarkably affects the range, necessitating the development of specific solutions.

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Thermal management of an Electric Vehicle (EV) is, in fact, a key performance parameter. Maintaining a high vehicle energy efficiency while ensuring cabin temperature comfort conditions (Lajunen et al., 2020), requires design, operational, and control strategies that are quite different from those used in conventional vehicles. Due to the greater efficiency compared with Internal Combustion Engines (ICEs), EVs have a limited amount of waste heat that can be used to meet comfort and cabin heating needs (Lajunen et al., 2018). As a result, they require additional electric heaters. Positive Temperature Coefficient (PTC) heaters are standard solutions to provide the cabin heat demand but are highly energy-intensive. This problem may become even more critical under extremely cold climatic conditions when the driving range of an electric vehicle may reduce up to 50% (Horrein et al., 2017).

A thermal model of the cabin and of the HVAC system is needed to assess or predict electricity consumption under different operating conditions. Authors in (Marcos et al., 2014) developed a cabin thermal model to estimate the variations in the behavior and the fuel consumption of a vehicle due to the use of an HVAC system. Numerical results are compared with the cabin air temperature of a vehicle under different conditions, demonstrating a rather good accuracy. Other papers proposed the integration of a priori information on the HVAC consumption with the navigation system to increase driver awareness about energy consumption (Valentina et al., 2014).

The efficiency of the cabin HVAC system is key, especially in cold ambient conditions (Delos Reyes et al., 2016). Different solutions regarding conventional technologies have been investigated so far, considering Heat Pumps (HPs) (Al Haddad et al., 2020). These studies have worked on optimizing the vehicle control strategy to achieve high Coefficient of Performance (COP) operating conditions for the HP over the driving cycle. By operating the HP under such conditions, energy consumptions may be reduced by a fraction up to 39%, depending on ambient temperature conditions. In (De Nunzio et al., 2018), the optimization between two HP operating modes resulted in a reduction of energy consumption while still maintaining the thermal response needed to reach comfort conditions within about 20 minutes. Experimental evaluations conducted in (Jeffers et al., 2016) demonstrated a reduction of up to 28.5% in the cabin heating energy requited over a 20-minutes warm-up period.

Through vehicle simulations during various driving cycles, researchers found that implementing promising zonal heating management led to an improvement in the EV range of up to 18.7% compared to the baseline heating strategy. In (Lajunen, 2017), more sophisticated technological solutions have been discussed, including HP, waste heat recovery, and PTC heater, which improved the driving range by 6 to 22%. However, it was noted that the HP does not significantly affect the HVAC system performance under -10°C. An alternative technology studied in (Leighton, 2015), is the Combined Fluid Loop (CFL), which demonstrated a 22.5% improvement over the baseline, with the HP system being effective only above an ambient temperature of 12°C.

Recently, the use of a Thermal Energy Storage (TES) system on-board EVs has emerged as a very promising approach for vehicle thermal control. Indeed, it may allow decoupling of the cabin and battery heat management from instantaneous operating conditions of the battery and electric motor. By adopting the power-to-heat (P2H) concept, it becomes possible to increase the energy storage capacity of the EV itself with relatively low marginal costs compared to the baseline design solution. Additionally, the TES's tolerance to current absorption regardless of its State of Charge (SOC) and its greater durability compared to electrochemical storages make it a viable solution to optimize the EV design, particularly under extreme ambient conditions.

The design and control of TES are key for their effective implementation in electric vehicles. In (Campos ‑ Celador et al., 2020), a design method has been developed for stationary applications using both direct- and indirect-contact, sensible and latent TES systems. Phase Change Materials (PCM) may also help optimize thermal system management (Kim et al., 2019). In (Lajunen et al., 2017), numerical results have been shown considering PCM technologies to increase driving range by close to 25%, with the best results obtained at -20°C ambient temperature. In (Wang et al., 2016), an innovative control of the PCM system has been demonstrated, storing energy during the battery charging process, and obtaining an increase in the range of 20% using a 2.7 kWh TES, implementing a P2H approach for the integration of energy production from renewables. In (Dreißigacker & Belik, 2019), a similar method was applied to a solid SiC TES, electrically heated with a PTC. The system was designed to allow bypassing and mixing with the main flow to maintain a target cabin temperature. The values of the design parameters for the energy stored and the thermal power requirement were, respectively, 2.5 kWh and 5 kW. Design implications were also considered important to optimize the trade-off between convective heat transfer effectiveness and friction losses, and the most promising designs presented specific surfaces in the order of 300 m2/m3. Furthermore, the size limitations of the thermal insulation are studied in (Dreißigacker, 2020), where an alternative version of the bypass flow control is proposed by direct integration into the insulating layer, with a thickness reduction.

The thermal characterization of TES systems depends on material and design: hybrid 1D-3D modeling approaches are discussed in (Vigneshwaran et al., 2019), considering air-concrete systems. The model, validated in comparison with experiments, highlights the role of the inlet air temperature. Different works show an overall improvement in EV range under winter conditions, especially with extreme cold ambient temperatures compared to HPs, regardless of the type of TES used. High-temperature solid-media TESs are able to reach an energy density up to 140Wh/kg at far less cost comparable to the batteries one. The lower battery utilization at the same distance also results in a decrease in the ageing of the battery itself.

All of the above-mentioned works considered recharging the TES during the battery charging phase; this results in an increase in the charging cost. TES implementation also introduces complexities of layout and insulation, increasing energy storage without increasing vehicle overall efficiency. To improve the overall efficiency of the electric vehicle, it is required to act on the control and management of the regenerative braking system. The amount of regenerative braking energy that can be recovered is limited by the SOC of the battery and the maximum energy flux allowed. Accordingly, braking generates more energy than the battery can handle. Wagner et al. (Wagner et al., 2019) discuss the possibilities of adding a secondary battery-independent regenerative braking to directly power auxiliaries, and HVAC unit, in order to recover more energy compared to the one that the primary battery could handle. In (Zhang & Tong, 2022) is proposed the use of regenerative braking energy to directly power EV's auxiliaries and HVAC unit in order to reduce charging/discharging battery cycle using a MPC methodology. The results show a reduction of overall energy consumption of approximately 3.4% and 29% in the ageing of the battery cycling.

According to (Xie et al., 2022), adopting a system-level design approach is crucial for maximizing the advantages of TES devices in EVs. Integrating TES devices with EV thermal management systems calls for further innovation and optimization. These versatile TES devices can be seamlessly integrated with the vehicle's battery thermal management system, heat recovery system, and heat pump. They can serve as the primary heat source for EV heating or serve as auxiliary heat sources, supporting the EV heat pump in enhancing its efficiency or facilitating battery warming in subzero temperatures. In order to evaluate the economic feasibility and energy consumption of these novel solutions throughout their entire lifecycle, system-level simulations become invaluable tools. Through such simulations, researchers gain a comprehensive understanding of the overall performance and impact of incorporating TES devices into EVs, thus enabling well-informed decisions about their implementation.

In this perspective, based on the literature review proposed, the main contribution of this work lies in the assessment of the benefits that can arise from implementing a TES into an EV operated under winter conditions. The TES is designed to exploit the excess energy from the regenerative braking and use it to warm up the cabin when needed. To achieve this, a Digital Twin platform is utilized, which has been previously validated with experimental tests and used in previous work to simulate FCHEV (Bartolucci, Cennamo, Cordiner, Mulone, Pasqualini, & Boot, 2022). A comprehensive model of the vehicle, including the cabin thermal model, has been developed in MATLAB/Simulink and verified with experimental data. The baseline model of the HVAC system is implemented with a 7.5 kW PTC heater to meet the cabin thermal needs. The benefits of introducing solid media TES are then evaluated in terms of vehicle energy efficiency and extended driving range features.

2. Light duty electrical commercial vehicle digital twin

A model has been implemented with Matlab-Simulink, employing multidomain physical modelling Simscape libraries to describe the behaviour of a commercial electric vehicle. In the literature, several works have utilized the Simscape toolbox for the physical thermal modelling of vehicles, demonstrating satisfactory results in terms of temperature distribution (Bartolucci, Cennamo, Cordiner, Mulone, Pasqualini, & Aimo Boot, 2022). The electric vehicle model developed for this study, depicted in **Error! Reference source not found.**, provides a comprehensive representation of the main components of the powertrain and thermal system. This includesthe radiator for electric motor and battery cooling, the chiller for battery cooling, and the HVAC system for cabin heating and cooling.

Each color of the connection lines between the components in the model represents a different simulated physical domain. The powertrain is modeled using a system-level motor and drive component, whose efficiency and heat disposal have been validated by comparing with experimental data. The electric motor is exclusively cooled down by the radiator, which can exchange heat with the ambient based on the control of the electric fan. The manufacturer provided tabulated values to represent the main performance data in this regard. The modeling of the electric pumps for the circulation of the coolant and the electric fan for air circulation has been done using the manufacturer pump and system datasheet under different operating conditions. The head losses were modeled based on experimentally acquired values. Different experimental tests were performed under different flowrate and head losses trhough the pipes have been recorded and imposed into the model using a tabulated approach.

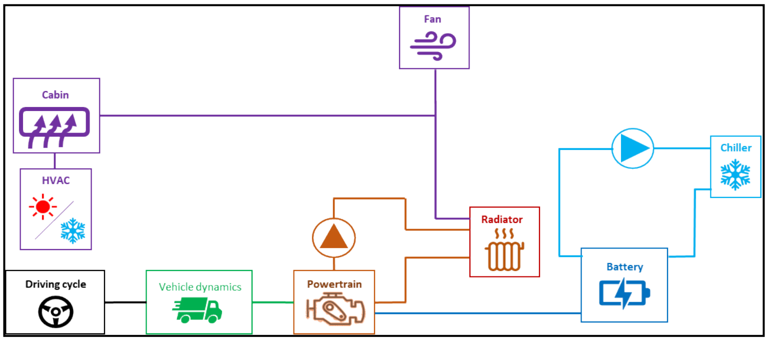

Fig. 1. Electrical light duty commercial vehicle layout.

The modeling of the chiller and the HVAC cooling system has been carried out by mapping the operating points obtained from an off-line simulation of the refrigeration cycle. This approach allows having a realistic energy consumption estimation of auxiliary systems while maintaining affordable computational requirements and favorable numerical stability characteristics.

The battery has been modeled based on the electric and thermal parameters. Moreover, the heat disposal characteristics of the battery have been calibrated based on the measurements of the temperature distribution fields of the cell, refrigerant, and cooling plate supplied by the manufacturer. The heat exchange surfaces have been modeled based on the actual internal geometry of the van cabin, assuming a simplified geometry as also reported in (Fayazbakhsh & Bahrami, 2013).

The Worldwide harmonized Light vehicles Test Cycle WLTC has been considered as the standard driving cycle reference for the simulations in this work. Within the vehicle dynamics subsystem, all the parameters of a commercial electric van are included.

For the sake of brevity only the results of the PTC consumption validation for HVAC needs are reported in the following. As shown in Fig. 2 (values normalized due to copyright), both the electrical power of the PTC and the thermal dynamics of the cabin match well with the results of the experimental tests. In general, the light duty commercial vehicle digital twin is able to accurately simulate the main sub-system of the vehicle, both from the thermal and energy point of view, underestimating the overall battery energy demand with a maximum error of about 4% (**Error! Reference source not found.**).

2.1 Thermal energy storage for HVAC system: winter mode configuration

A PTC heater powered by the vehicle battery pack is a standard solution for the requirement of the cabin heat demand. Therefore, the baseline winter mode HVAC configuration consists of a PTC heater with an electric absorption up to 7.5 kW. The TES is then implemented through a by-pass valve in the ventilation circuit, with a series configuration of TES-bypass and the PTC heater. The TES airflow is regulated by a PI controller based on the difference between external air temperature and cabin temperature setpoint. The TES implemented in this work is similar to the one analyzed by (Dreißigacker, 2021). The thermo-physical properties of the thermal storage are indicated in **Error! Reference source not found.**. For charging the TES, a heating wire is integrated within the honeycomb channels, which generates the thermal power as a result of regenerative electric power supplied by electric motor during the braking process. The vehicle control unit is able to properly manage the regenerative breaking energy flows between the battery packs and the TES: established that battery packs always deserve the priority in taking the regenerative energy, the excess of that energy flow is supplied to the heating wires to heat up the TES, when the battery recharge current is limited due to high state of charge or thermal related issues.

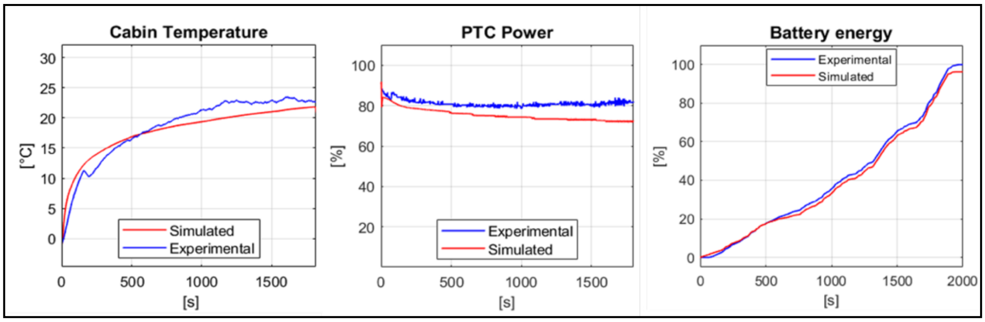

Fig. 2 Cabin temperature (*Left*), PTC electrical consumption (*Center*) and battery energy (*Right*) comparison

Table 1. Thermal energy storage physical properties.

Mass	6.8 $[kg]$
L x W x H	300 x 150 x 150 $[mm]$
Specific surface	273.4 $\frac{m^2}{m^3}$
Void fraction	62.2 %
Material	Al_2O_3 $ceramic$
Specific heat	1169 $[\frac{J}{kg\,K}]$

3. Discussion and results

In this section simulation results will be presented and analyzed. In detail, the energy performance of the new HVAC with TES will be compared to the baseline configuration for four different external ambient temperature of -10°C, -5°C, 0°C and 10°C respectively. The simulations have been carried out using WLTC reference driving cycle and setting the components initial temperature equal to the ambient conditions. For each case study we have considered the battery pack SOC equal to 100% and a starting temperature of 15°C.

3.1 Baseline HVAC performance

For the baseline case, the HVAC system uses a water-based PTC to heat up the vehicle cabin to the target temperature of about 22°C. **Error! Reference source not found.** describes the vehicle energy demand distribution for three different winter cases for

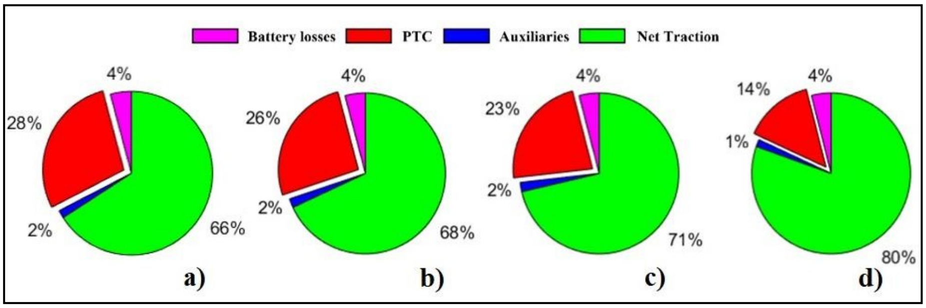

Fig. 3. Vehicle energy distribution HVAC baseline: a) T_{amb} = -10°C, b) T_{amb} = -5°C, c) T_{amb}= 0°C, d) T_{amb}=10°C

the analyzed temperatures. The net energy traction represents the difference between the electric motor energy demand and the regenerative energy recovered during the deceleration phases of the vehicle. The term battery losses takes into account the losses due to internal resistance and the charging/discharging efficiencies of the battery pack. The energy demand for cabin air conditioning significantly impacts the overall consumption of the light duty commercial vehicle, with values up to 28% for the case @ -10°C (**Error! Reference source not found.**a). Finding alternative solutions becomes essential to increase the vehicle maximum range in winter, while ensuring cabin's thermos-hygrometric comfort.

3.2 HVAC with TES integration performance

The implementation of a Thermal Energy Storage allows for recovering the energy portion derived from regenerative braking that would have been lost due to limitation on the maximum charging currents by the energy management system (EMS) to safeguard the battery's useful life or to avoid overcharge. In **Error! Reference source not found.**, it can be noted how the vehicle energy distribution changes with the implementation of TES system, considering that 100% of the pie chart represent the total energy request in the baseline configuration. The electric power consumption of the PTC is significantly reduced for all the simulated conditions, resulting in a maximum energy saving of 10% for external ambient temperature of 0°C and 10°C.

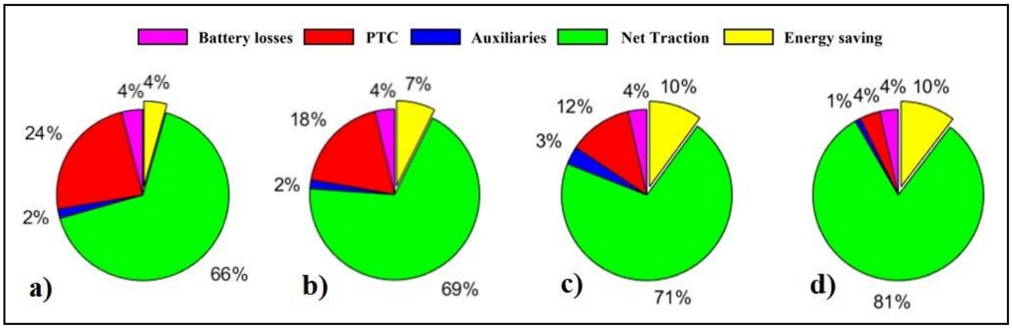

Fig. 4 Vehicle energy distribution HVAC with TES: a) T_{amb} = -10°C, b) T_{amb} = -5°C, c) T_{amb}= 0°C, d) T_{amb}=10°C

The energy recovered through regenerative braking that can be stored in the TES is shown in **Error! Reference source not found.** together with the energy recovered in the battery pack. It is worth to notice that the maximum charging current that the battery can sustain is a function of the SOC and temperature pack parameters, increasing with the decrease of the former and the increase of the latter, up to a temperature of 35°C.

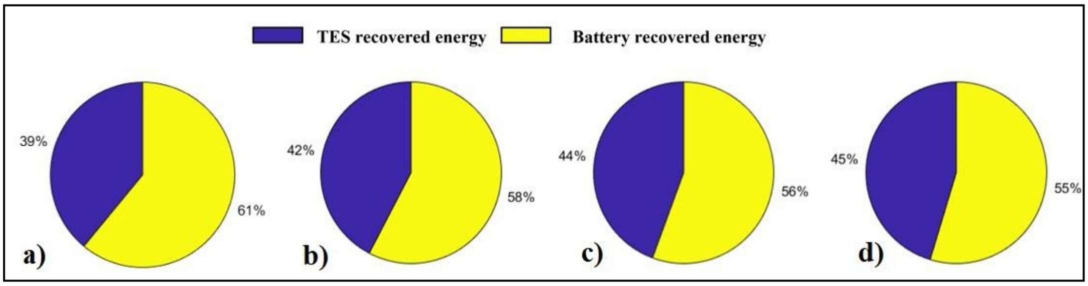

Fig. 5 Recovered energy distribution: a) Tamb = -5°C, b) Tamb= 0°C, c) Tamb=10°C

As the external ambient temperature increases, the energy required by the HVAC system to heat up the vehicle cabin decreases, which leads to a lower battery discharge and therefore greater limitation on the maximum charging current. As a result, the energy stored in TES slightly increases with the increase of the outside temperature.

To estimate the impact of TES on the overall cabin energy demand and to evaluate its thermophysical performance, the following KPIs have been defined: TES Cabin heating energy ratio (TCER) and TES utilization parameter (TUP)

$$TCER = (E_{TES_{cabin}})/(E_{TES_{cabin}} + E_{PTC_{cabin}}) \tag{1}$$

$$TUP = (E_{TES_{cabin}})/(E_{TES_{recovered}}) \tag{2}$$

where $E_{TES_{cabin}}$ and $E_{PTC_{cabin}}$ represent the energy contribution (kWh) of the TES and the PTC to cabin heating respectively and $E_{TES_{recovered}}$ (kWh) represents the excess energy recovered during braking and stored in TES. Fig. 6 shows the trends of the aforementioned KPIs. It can be noted that the TES is capable of providing up to 70%of the energy demand for cabin heating (Fig. 6b) in the case with ambient temperature of 10°C while for the other cases it contributes for about the 50% of the overall thermal demand. The TUP (Fig. 6a), on the other hand, highlights as for the cases at -5°C and 0°C, the TES almost completely use the stored energy, while in the case of 10°C, there is still some heat stored in TES available at the end of mission, which can be used later considering thegood thermal insulation of the energy storage devices.

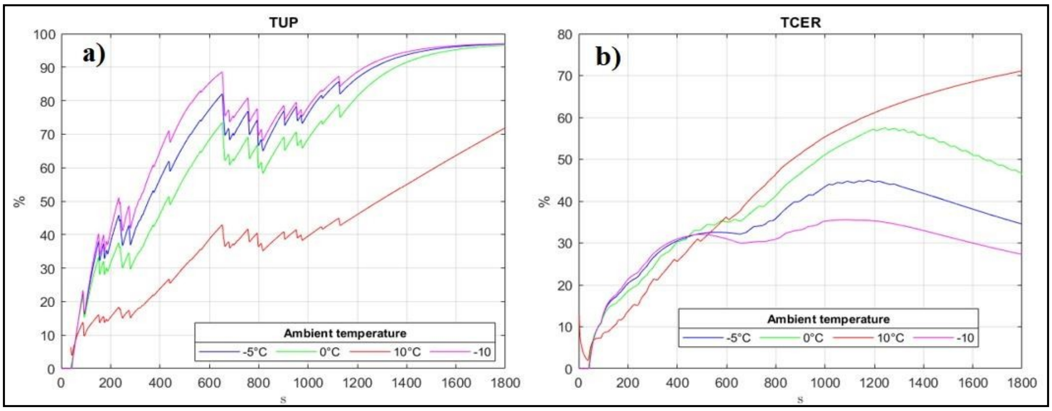

Fig. 6 TES utilization parameter (a) TES cabin heating energy ratio (b).

4. Conclusion

In conclusions, this study investigated the integration of a thermal energy storage (TES) system into a light duty commercial vehicle HVAC system to improve energy efficiency and ensure cabin comfort during winter season. The TES system was designed to recover and store the energy derived from regenerative braking that would have been lost due to battery charging limitations. The simulations were carried out using a vehicle digital twin model implemented in Matlab/Simulink and validated with experimental tests. The main results obtained show that the implementation of TES allowed for the reduction of the energy consumption of the PTC heater, resulting in a maximum energy saving of 10% for external ambient temperatures of 0°C and 10°C;. Moreover, it is shown how the TES system is capable of providing up to 70% of the energy demand for cabin heating with an external temperature of 10°C.

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