EMAS Engineering Modelling, Analysis & Simulation THE NAFEMS JOURNAL
NAFEMS
Vol. 2, Issue 1, 2025

Numerical analysis of the energy efficiency measures for improving the truck cabin thermal performance

Imre Gellai[a,1], Mirza Popovac[a], Milan Kardos[a], Dragan Simic[a]

[a]AIT - Austrian Institute of Technology, Electric Vehicle Technologies, Center for Low-Emission Transport, Giefinggasse 2, 1020 Vienna, Austria

Abstract

This paper presents the numerical analysis of the thermal performance of a truck cabin. The results obtained for a standard truck cabin setup are compared to the configurations with energy saving measures implemented. As a very promising energy efficiency measure, the application of the infrared panels is considered. Based on the radiative heat transfer mechanism, the infrared panels influence directly all inner cabin surfaces. This includes also the truck cabin occupants, whose perception of the indoor comfort reaches neutral values much faster and at lower ambient air temperatures. As a result, there is much lower energy demand for the cabin heating, required for maintaining the desired indoor comfort. The preliminary numerical analysis indicates the energy saving potential of around 30% for this innovative cabin thermal concept, as compared to the original energy demand for the traditional cabin heating configuration.

Keywords

System simulation, Indoor comfort, Cabin air conditioning, Infrared panels, HVAC

1 Introduction

Rising global CO2 emissions and the related climate change ask for a swift decarbonization of our economies and lifestyles. To face the related demands, massive human and financial resources are mobilized with the aim to achieve full carbon neutrality across all social and economic areas [1]. Given that in EU approximately 27% of the CO2 emissions can be allocated to the transport sector [2], the electro-mobility is seen as an important mean for reaching CO2 targets. The work presented in this paper is dealing with e-trucks, where the tackling issue is not any more to demonstrate the potential of the zero-emission technologies, but to improve their performance while cutting their production and operational costs, as that will make them attractive competitor against the traditional solutions.

The air conditioning systems in e-trucks (similar to their internal combustion predecessors) are typically oversized in order to be able to compensate the variability of the effects related to the thermal comfort within the cabin (in particular due to a poor cabin thermal insulation). Hence, by reducing the required energy and/or improving the energy efficiency of the e-truck (including the cabin), the maximum driving range can be extended given that the energy used from the battery of an e-truck goes directly on the cost of the vehicle driving range. In addition to the straightforward measures for improving cabin energy efficiency (such as better cabin insulation), a very promising one for the cabin thermal comfort regulation are the infrared (IR) heating panels. These panels affect the surface temperatures, acting swiftly to attain the desired thermal comfort level. Thus, they can ensure optimal indoor thermal comfort at lower cabin air temperatures, and that can lead to a considerable opportunity for energy savings.

[1]Corresponding author.
E-mail address: imre.gellai@ait.ac.at (I. Gellai)
https://doi.org/10.59972/tmsa26ss

This paper presents the numerical analysis of the aforementioned energy efficiency measures on the truck cabin thermal performance. Following this introductory section, the central part of this paper is Section 2 where the thermal model of the truck cabin is presented: the model components are explained in Section 2.1, while the thermal analysis is described in Section 2.2. The numerical analysis of the truck cabin energy demand is given in Section 3, which compares the results obtained for the standard cabin setup and that with the energy efficiency measures applied. Finally, the discussion of the presented work is given in Section 4, together with the related conclusions.

2 Materials and Methods

For the thermal analysis of an innovative cabin concept, the model for the thermal performance of the cabin has been developed such that it mirrors the structure typically found in the truck cabins. To obtain the thermal characteristics of the cabin (indoor temperature and humidity depending on the cabin energy losses, inlet air properties, solar radiation and heating panels operation), the physical model is developed in Modelica/Dymola simulation framework [3], [4] to replicate the heat transfer mechanisms involved. This model can be used in a stand-alone mode or exported as the Functional Mockup Unit (FMU) it can be combined with other simulation tools.

2.1 Model components

Aiming at the truck cabin thermal performance analysis, the core elements of the cabin thermal modelling include the model for the Heating, Ventilation and Air Conditioning system (HVAC) and the indoor thermal comfort model. This modelling approach enables on the one hand side to simulate the occupants' comfort in the cabin, and to assess the cabin energy efficiency on the other. As sketched in Figure 1, typically the cabin thermal setup combines the following: the ambient air enters the HVAC module after the heat recovery (HR) air-to-air heat exchanger. Subsequently, in HVAC the thermal energy is transferred between different flow streams, to either heat or cool the cabin air. Finally, IR panels provide the optimal cabin thermal comfort regulation, as they can act swiftly to attain the desired thermal comfort level.

The purpose of the thermal system is to provide optimal thermal conditions for the occupants inside the cabin. In that view, the cabin thermal simulation includes the Linear Comfort Model to evaluate the indoor comfort parameters. The Predicted Mean Vote (PMV) is widely accepted indicator of the indoor thermal comfort, which is based on the cabin air temperature and the surface temperature [5]. The linear PMV model efficiently employs a linear comfort map which approximates various parameters to gauge occupants' perceived comfort levels.

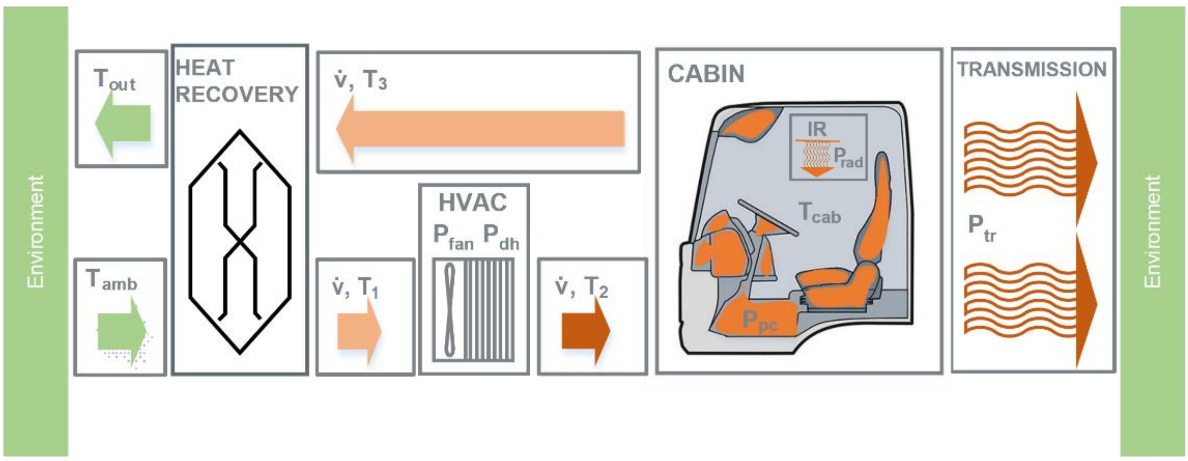

Figure 1. The schematic representation of the cabin thermal system.

The heat recovery unit facilitates the pre-treatment of the incoming ambient air. This can be combined with the air mixing and recirculating the cabin air (including filtering) in order to reach the air quality control. If HR is not part of the thermal system, the ambient temperature T_{amb} will be the HVAC inflow temperature T_1 (Figure 1). The HVAC delivers the temperature of supply air to the cabin T_2, which determines the occupants' sensation of the thermal comfort. However, IR panels can ensure optimal indoor thermal comfort even at lower cabin air temperatures since they are affecting directly the surface temperatures. The temperature of the air evacuated from the cabin is T_3, which is the same as the outflow temperature from the thermal system T_{out} if HR is not present. This rejected heat, together with the dissipation of the heat transmitted through the cabin walls, represents a significant heat loss -- therefore, this is the target spot for energy savings with regard to the cabin thermal system.

2.2 Thermal analysis

The thermal dynamic behaviour of the cabin can be expressed through the temporal variation of the average cabin temperature T_{cab}. The model for this dynamic behaviour is obtained by balancing the heat power input P_{in} (delivered either by means of the convection or radiation) on the one hand side, and the heat losses P_{loss} on the other:

$$m \cdot c_p \cdot \frac{\partial T_{cab}}{\partial t} = P_{in} - P_{loss} \tag{1}$$

where m and c_p are the mass and heat capacity of the air inside the cabin respectively.

As depicted in Figure 1, P_{loss} comprises the exhaust air loss (the air evacuated from the cabin) and the transmission loss calculated using the heat transmission coefficient G. The transmission loss depends on the cabin geometry and includes the cabin wall insulation properties: $G = G(d_{cwi})$, where d_{cwi} is the thickness of the cabin wall insulation. In a general case of the cabin thermal system, the power of the cabin pre-conditioning P_{pc}, which involves heating or cooling the heat capacities, can be included, and as well as the dehumidification operation P_{dh} in the HVAC model for the cabin cooling.

Contributing to P_{in} is the air heating provided by the HVAC system, together with the power of the fan power P_{fan} needed to drive the air flow (Figure 1). Particularly important for the present analysis is the power of radiation heat P_{rad} provided by IR panels. It is treated explicitly, depending on the cabin surface area covered with IR panels: $P_{rad} = P_{rad}(S_{IR})$, where S_{IR} is the IR panel coverage of the cabin inner surface. For improved energy efficiency, HR can be implemented, with its heat exchanger efficiency coefficient η. Finally, the balance terms from Eq. (1) read:

$$\begin{aligned} P_{in} &= \dot{V}\rho c_p(T_2 - T_1) + \eta\dot{V}\rho c_p(T_3 - T_{amb}) + P_{fan} + P_{rad} \\ P_{loss} &= G(T_{cab} - T_{amb}) + P_{pc} + P_{dh} \end{aligned} \tag{2}$$

where T_{amb} is the ambient temperature, $\dot{V}$ and ρ are the volumetric flow rate and the density of the incoming air respectively, while T_1, T_2 and T_3 are the inflow and outflow temperatures from HVAC and/or cabin (Figure 1).

The temperature prediction, obtained by combining Eq. (1) and Eq. (2), is coupled to the PMV calculation in order to drive the cabin parameters towards the optimum indoor comfort. In the linear PMV model, represented with the diagram given in Figure 2, two factors are the most influential: the cabin air temperature and the temperature of the cabin surfaces. The cabin air temperature is calculated by solving the equation in the cabin and HVAC model. The cabin surface temperature is determined using the cabin model where the ambient air and the cabin air are connected through a row of heat capacities and resistances. Due to the heat capacities, a delayed temperature of the cabin air was used as the average surface temperature in the PMV model. The surface temperature can be influenced by heat panels, which cover a portion of the surface. The cabin surface temperature for the remaining area is calculated using the model.

The optimum comfort point, as determined by the linear PMV model, is 20°C for both air and surface temperature: this point serves as a reference for maintaining an ideal thermal environment within the cabin. It is important to note, however, the variation in the individual comfort perception when exposed to a range of temperature values: although the linear PMV model provides valuable insights, there are individual preferences to be considered and to flexibly adapt the cabin thermal conditions accordingly.

With the IR panels switched on, the surface temperatures within the cabin are immediately affected. In this way the optimum indoor thermal comfort (PMV=0) can be achieved more rapidly, even at non-favourable ambient conditions. This is indicated by the evolution of the PMV value, presented in Figure 2 by the lines with stars for the no-IR case (S_{IR}=0), and the lines with circles for the IR case ($S_{\neq}0$). Starting from the cold ambient conditions, the IR case rises quickly to the desired comfort state through the change in the surface temperature. In the no-IR case, however, the surface temperature (and correspondingly PMV) increases gradually over time. This temporal development can be quantified from the graphs given in Figure 3.

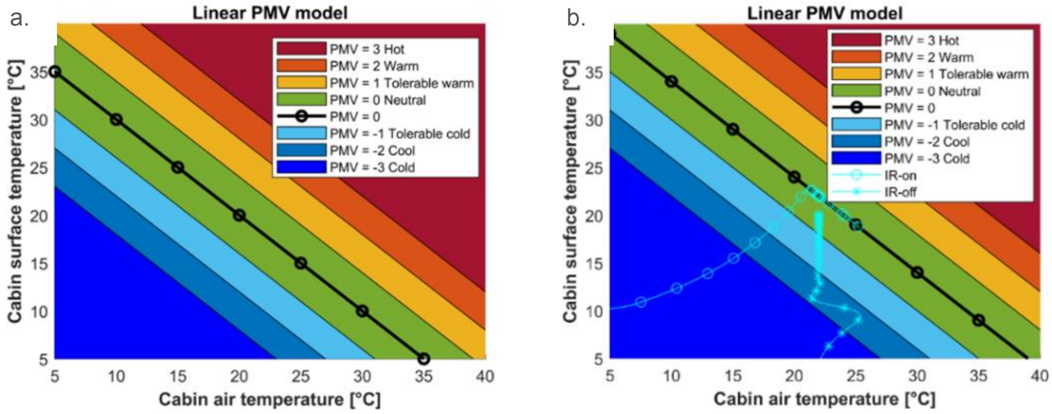

Figure 2.a. The diagram of the linear PMV model neutral thermal comfort -- black circles, b. the evolution of PMV prediction: with IR panels -- blue circles, without IR panels -- blue stars.

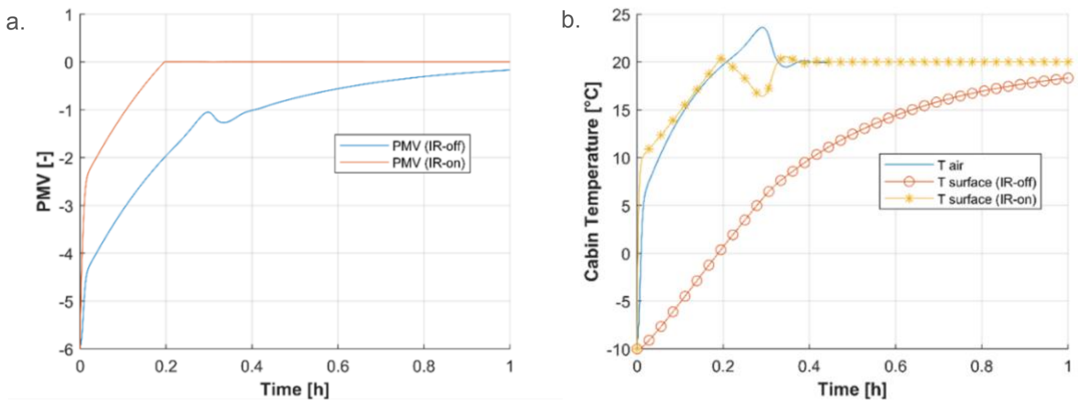

Figure 3.a. The influence of the IR panels: temporal development of PMV, b. the temperature of cabin air and inner surface during the cabin heating phase.

3 Results and Discussion

To quantify the cabin thermal energy saving potential by implementing the energy efficiency measures, the presented numerical modelling approach is used for the analysis of the exemplary truck cabin thermal performance. As a part of the NextETRUCK project, the thermal energy demand in two characteristic operating conditions (winter and summer) is compared between the standard cabin configuration and the one with energy efficiency measures implemented. For the winter case the IR panels are adopted for improved indoor comfort, and for the summer case better cabin insulation is used to prevent the cabin overheating. In both cases the aim is to reach and maintain the optimal indoor comfort, while reducing the thermal energy demand.

Following the defined aims, in the simulation the operating parameters (such as the air flow rate and the supply air characteristics) are adjusted to drive the system towards reaching a neutral PMV. The model parameters regarding the cabin geometry, heat capacity and thermal resistance are obtained from the preliminary cabin test or estimated based on the available reference data. The main cabin characteristics that are used in the simulations are summarized in Table 1. The performed simulations do not to cover the truck operation in full complexity: e.g. the realistic profiles of driving and environment conditions are not included, but rather assumed constant.

Table 1. Estimated truck cabin parameters.

Quantity	Value	Unit
Surface area of cabin	12	m^2
Volume of cabin	2.4	m^3
Heat capacity of cabin interior	65000	J/K
Heat capacity of cabin walls	21000	J/K
Heat capacity of air channels	1040	J/K
Heat resistance of cabin walls	1/310	K/W

In the winter case simulations, the ambient temperature was set to -10°C, and two cabin setups have been investigated. The first setup is the original configuration (S_{IR}=0), serving as the baseline to which the IR modifications will be compared. The second setup represents the proposed cabin concept with IR panels implemented, by taking S_{IR} = 10%, 20% and 30% IR panel coverage of the cabin inner surface. The adopted IR panels are very flexible and therefore relatively easy to implement (Figure 4.a). It is estimated to be covering up to one third of the cabin surface area. Although the surface temperatures of these panels can reach about 50-60°C (Figure 4.b), there is no risk of burning sensation or discomfort for occupants due to the presence of a protective cover. The ambient temperature in the summer case is set to 35°C, and HVAC system is used to reduce and maintain this temperature in the cabin at the neutral level of indoor comfort. For this case the energy efficiency measure selected for investigation is the cabin wall insulation. Namely, in the original configuration $d0_{cwi}$=0.5 cm was taken as the thickness of the insulating material, and for improved energy efficiency this thickness was increased 150%, 200% and 300% (clearly, the original value is denoted with 100%). Although it might seem like an oversimplified modification of the thermal system, this choice was deliberately taken in order to make a transparent comparison: if any of the HVAC system parameters would have been changed for the summer conditions, that would not hold for the winter conditions, and thus the comparison between these two cases would not be straightforward.

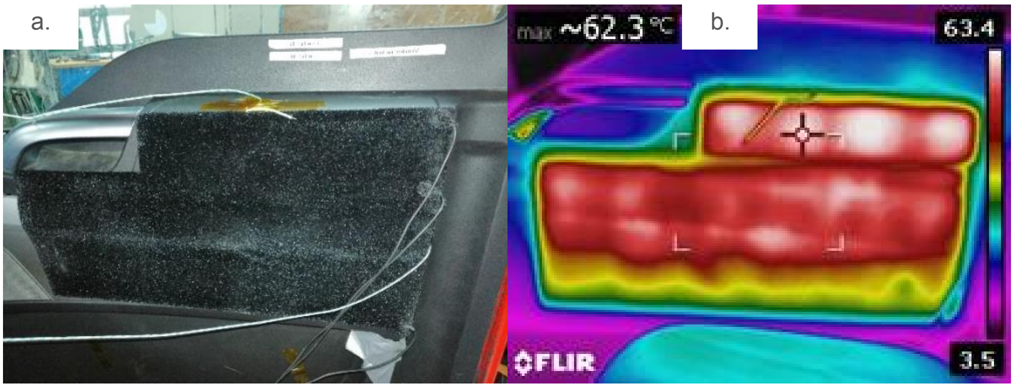

Figure 4.a. IR panel implemented on the cabin door, b. the thermo-camera view of the IR panel in the heating mode.

3.1 Winter case

The obtained winter case temperature variation inside the cabin air, given in Figure 5 shows how the proposed IR concept reduces significantly the time needed to reach the optimal indoor comfort (Figure 5.a). In the original configuration, on the other hand, warming up the entire cabin to reach the desired indoor comfort takes much more time. Furthermore, for maintaining the required thermal conditions, higher power inputs are needed in the original configuration, given that with IR the optimal indoor comfort is obtained on lower cabin temperatures (Figure 5.b).

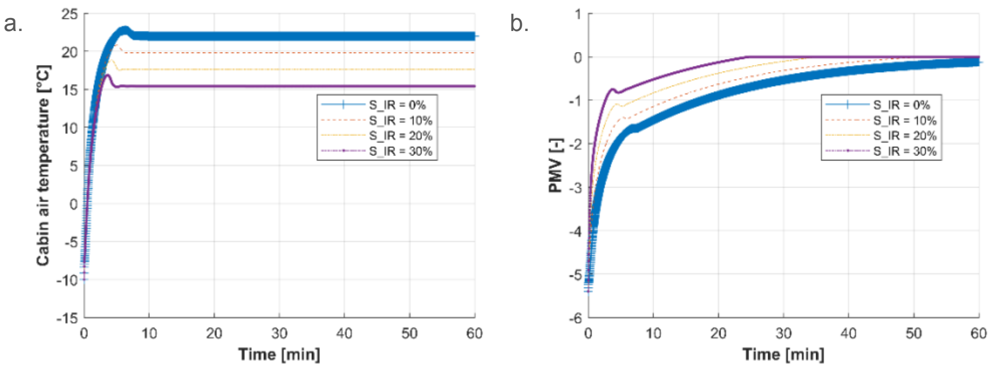

Figure 5.a. The temporal evolution of temperature, b. PMV for the standard and improved cabin concepts at ambient temperature -10°C.

From the results shown in Figure 6 one can see the advance in time (until the steady state is reached) of the power used for the cabin thermal conditioning. As expected, in the original configuration (S_{IR}=0) the total heat load is high because of the higher thermal level (Figure 6). On the other hand, in the proposed IR concept the heating power increases strongly in the initial phase (Figure 6.b). However, as the IR panels increase the surface temperature, the power needed to maintain the target thermal condition reduces significantly. The power used for IR panels (Figure 6.a) starts to drop once the required PMV is reached (Figure 5.b). The heating panels heat the interior air directly. When the power of the heating panels decreases, the less efficient air heating system compensates for this, causing the total consumption to increase slightly (Figure 6.b).

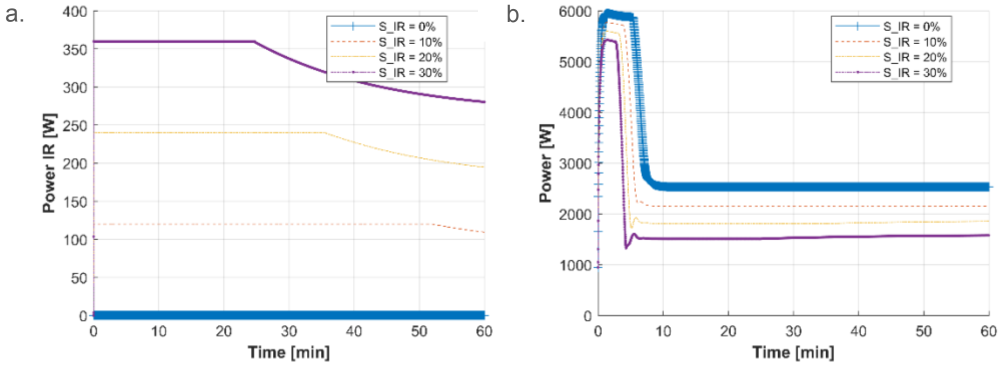

Figure 6.a. The IR panels power, b. total heating power for the simulated cabin configurations at ambient temperature -10°C.

Looking at the total energy consumption, the proposed IR concept can yield between 15% and 36% energy saving in comparison to the original setup (Figure 7). Clearly, better energy performance is obtained with increasing S_{IR}, equally as reaching faster the target PMV values (heating power). However, for a total picture one needs to take into the consideration also the economic aspect of this active energy efficiency measure.

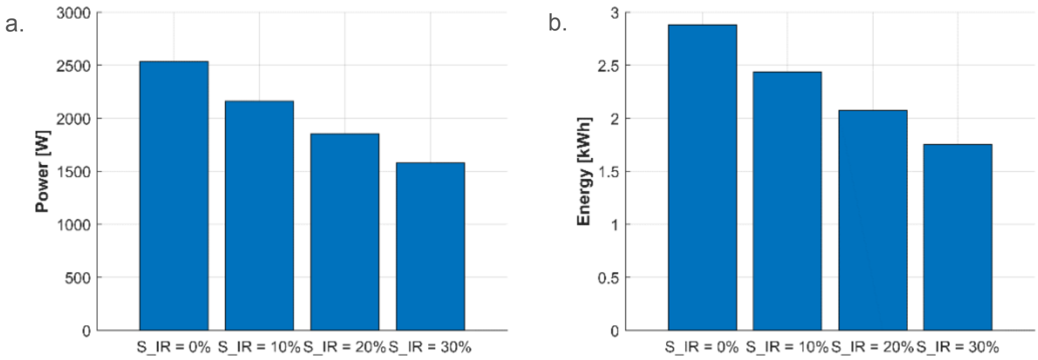

Figure 7.a. The IR panels power, b. and total heating power for the simulated cabin configurations at ambient temperature -10°C.

3.2 Summer case

Unlike in the investigated winter case, the energy efficiency measure investigated in the summer case is passive: here no energy is used for improving the thermal performance of the cabin. Typically, such measures cannot have the same level of energy saving potential like the active elements, such as IR panels used in the winter case. However, given the nature of IR panels, it is logical to consider it as a passive element that contributes to the insulation of the cabin walls.

The temporal evolution of the cabin temperature, shown in Figure 8, confirms that the neutral indoor comfort parameters (PMV under 1) can be reached faster if the cabin wall insulation is thicker: for higher d_{cwi} the cabin is better thermally isolated from the surrounding, hence it requires less time of HVAC operation to reach the required indoor conditions.

As a result, Figure 9 shows that from the same plateau of power consumption for all investigated configurations, it starts dropping sooner when this energy efficiency measure is applied. In terms of absolute values, however, the moderate energy savings are in the range between 6% and 14%.

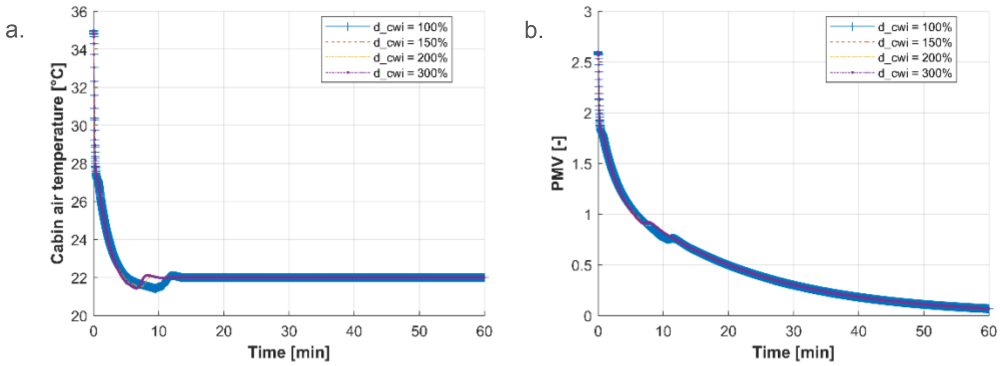

Figure 8.a. The temporal evolution of temperature, b. PMV for the standard and improved cabin concepts at ambient temperature 35°C.

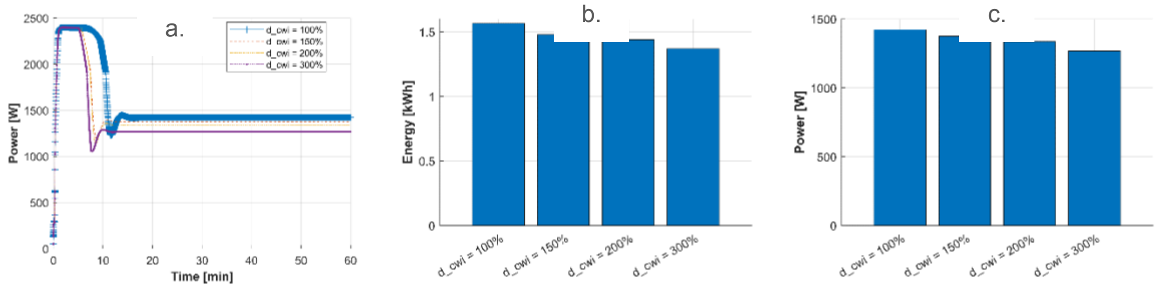

Figure 9.a. The total heating power, b. for IR panels, c. energy demand for the simulated cabin configurations at ambient temperature 35°C.

4 Conclusions

In the previous sections, the model of the thermal dynamic behaviour of a truck cabin, based on the considerations of power inputs and related losses, was developed and implemented into the Modelica/Dymola simulation framework. Using the presented model, one can analyse the truck cabin energy efficiency measures, which will lead to reduced energy demand for reaching and maintaining the required indoor comfort. In that view, one could make use of the thermal pre-conditioning of the cabin, before the truck drive starts. For the cabin heating case, one can also integrate the air-to-air heat exchanger, whereby a part of the heat from the outgoing air will be used to pre-heat the air coming into the cabin, and thus reduce the HVAC energy consumption.

The energy efficiency measure that was analysed here for the heating case is the use of IR panels, which act directly on the occupants' surface and reduces needed cabin temperature for sensing neutral indoor comfort. In addition, the surface mounted IR heating panels will increase the cabin wall insulation, which reduces the energy needed for the thermal conditioning of the cabin for the cooling case. Depending on the operating conditions and the cabin configuration, the estimated energy saving potential is between 15% and 36% of the thermal energy demand for the heating (winter case) and between 6% and 14% for cooling (summer case). For a net effect, one can assume an evenly distributed truck use throughout the year, and given the absolute values of the energy consumption, the overall saving can be estimated at around 30% per year.

Finally, the presented numerical model can be used to develop and test advanced control strategies for the cabin thermal system. Exported as the Functional Mockup Unit (FMU), the model can run either locally or as a centralized software solution, which will provide a real-time prediction used by the system controller.

5 Acknowledgement

This work was preformed within NextETRUCK project, which received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101056740.

6 References

[1] European Union, "European Green Deal," European Commission, Dec. 11, 2019. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. [Accessed: Jul. 29, 2024].

[2] European Environment Agency, "Greenhouse gas emissions from transport in Europe," EEA, 2021. [Online]. Available: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport. [Accessed: Jul. 29, 2024].

[3] Modelica Association, "Modelica Home Page," 2011. [Online]. Available: http://www.modelica.org/. [Accessed: Jul. 29, 2024].

[4] Dassault Systèmes, "Dymola 7.4," 2010. [Online]. Available: http://www.3ds.com/products/catia/portfolio/dymola. [Accessed: Jul. 29, 2024].

[5] ISO 7730, "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," 3rd ed., International Organisation for Standardisation, Geneva, 2005.

[6] Project NextETRUCK, "NextETRUCK," [Online]. Available: https://nextetruck.eu. [Accessed: Jul. 29, 2024].