Thesis

Industrial Technology Engineering

Numerical study of passive HVAC solutions

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ETSEIB

MEMORY

Summary

English

The aim of this project is to identify and study different passivesolutions (conventional and innovative) for car cabin Heating Ventilation and Air Conditioning (HVAC).
A car cabin thermal model will be numerically developed altogether with different HVAC solutions using lumped and one-dimensional system-level simulation techniques.

Subsequently, a thermal study will be made in order to study the temperature difference over time when a car is parked under a solar radiation exposure $I_T = 1105\ W/m^2$ and an exterior ambient temperature T_{ext}= 45ºC. With this analysis, it will be possible to analyze which of the methods are useful to implement to a HVAC car cabin and how temperature evolves over time.

Among all passive HVAC solutions explained, window tint, exterior color, thermal insulation, low emissivity material and phase change material are studied. All solutions have been studied together, obtaining a final interior cabin temperature difference of 9,984ºC, which directly reflects on car energy consumption and car occupant comfort, especially when energy saving and environment preservation are becoming a crucial factor for the planet.

Castellano

El objetivo de este proyecto es identificar y estudiar diferentes soluciones pasivas (convencionales e innovadoras) para la calefacción, ventilación y aire acondicionado (HVAC) de la cabina del automóvil. Un modelo térmico de cabina de automóvil se desarrollará numéricamente en conjunto con diferentes soluciones de HVAC utilizando técnicas de simulación a nivel de sistema agrupadas y unidimensionales.

Posteriormente, se realizará un estudio térmico para estudiar la diferencia de temperatura a lo largo del tiempo cuando un coche está estacionado bajo una exposición a la radiación solar $I_T = 1105\ W/m^2$ y una temperatura ambiente exterior T_{ext} = 45ºC. Con este análisis, será posible analizar cuáles de los métodos son útiles para implementar en una cabina de automóvil HVAC y cómo evoluciona la temperatura con el tiempo.

Entre todas las soluciones pasivas de HVAC explicadas, se estudian el tinte de la ventana, el color exterior, el aislamiento térmico, el material de baja emisividad y el material de cambio de fase. Todas las soluciones se han estudiado conjuntamente, obteniendo una diferencia final de temperatura interior de la cabina de 9,984ºC, que se refleja directamente en el consumo de energía del automóvil y en el confort de los ocupantes del automóvil, especialmente cuando el ahorro de energía y la preservación del medio ambiente se están convirtiendo en un factor crucial para el planeta.

Català

L'objectiu d'aquest projecte és identificar i estudiar diferents solucions passives (convencionals i innovadores) per a la cabina de l'automòbil Ventilació i Climatització de la Calefacció (climatització). Es desenvoluparà numèricament un model tèrmic de cabina de cotxe juntament amb diferents solucions de climatització mitjançant tècniques de simulació a nivell de sistema monodimensionals i unidimensionals.

Posteriorment, es realitzarà un estudi tèrmic per tal d'estudiar la diferència de temperatura al llarg del temps quan un cotxe està estacionat sota una exposició a la radiació solar $I_T = 1105\ W/m^2$ i una temperatura ambient exterior T_{ext} = 45ºC. Amb aquesta anàlisi, serà possible analitzar quins dels mètodes són útils per implementar a una cabina de cotxes de climatització i com evoluciona la temperatura amb el pas del temps.

Entre totes les solucions passives de climatització explicades, s'estudia la tonalitat de les finestres, el color exterior, l'aïllament tèrmic, el material de baixa emissivitat i el material de canvi de fase. Totes les solucions s'han estudiat conjuntament, obtenint una diferència final de temperatura interior de cabina de 9,984ºC, que reflecteix directament el consum d'energia del cotxe i el confort dels ocupants dels cotxes, especialment quan l'estalvi energètic i la preservació del medi ambient s'estan convertint en un factor crucial pel planeta.

Content

1. Glossary

All terms and abbreviations will be written and explained below:

Term / abbreviation	Explanation
AAC	Automotive air conditioning
BOE	Official State Gazette
CFD	Computational fluid dynamics
EV	Electric vehicle
GWP	Global warming potential
HVAC	Heating, ventilation and air conditioning
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
PHEV	Plug-in hybrid electric vehicle
RH	Relative humidity
ODP	Ozone depleting potential
PCM	Phase change materials
VCC	Variable capacity compressor
VCRS	Vapor compression refrigeration system

2. Introduction

2.1. Project Objectives

The aim of this project is to identify and study different passivesolutions (conventional and innovative) for car cabin Heating Ventilation and Air Conditioning (HVAC).

A car cabin thermal model will be numerically developed together with different HVAC solutions using lumped and one-dimensional system-level simulation techniques.

Subsequently, a comparison will be made in order to study the difference of temperature over time when the HVAC is switched on after the car has been exposed to negative conditions. With this analysis, it will be possible to analyze which of the methods are useful to implement to a HVAC car cabin. Furthermore, all solutions will be compared in terms of energy, economics and environmental impact.

2.2. Project range

The topic of this project arose by talking to the tutor of the final degree project, Roser Capdevila, about the possible applications or implementations of a material that allows radiative cooling. The idea that appeared in mind was the possibility of implementing this material in a car cabin, since I had often found myself in an uncomfortable situation due to the car cabin's high temperature. This situation occurred specially in summertime, when taking the car from the parking lot where I am currently carrying out an internship program.

The initial idea evolved into the possibility of implementing new methods or even improving the HVAC passive systems to reduce the interior temperature.

An interior temperature reduction is thought to be beneficial for driver and companions’ comfort and health, for the conservation of the interior finishes of the vehicle and specially for energy saving.

In addition to this, the scope of the project includes both budget and time spent limits.

As the project will consist of a thermal study using lumped and one-dimensional system-level simulation techniques, no budget will be needed as long as the program license is complimentary. For this reason and for possible unforeseen events, it has been self-established not to exceed a total of € 100.

For time spent limits, it will be established not to exceed the total number of hours according to 12 credits (a credit equals 25 hours), so the total time spent might not exceed a total of 300h.

The resources available for the project are the knowledge, documentation and notes acquired last year when studying thermotechnics, as well as the knowledge of my final degree project director, Roser Capdevila.

In addition to this, information and knowledge can be taken from SEAT S.A., the company where I am carrying out my internship.

Regarding the deadlines, and based on the last year timing guide, the following points show where (Aplicació TFE) and when have to be transacted:

- Partial evaluation: from 11 to 18 November
- Digital deposit: from 18 to 25 January
- Director validation: from 18 to 26 January
- Defense: 4 to 23 February

It is necessary, in every project, to specify the tasks for the project and when they must be accomplished through Figure 1:

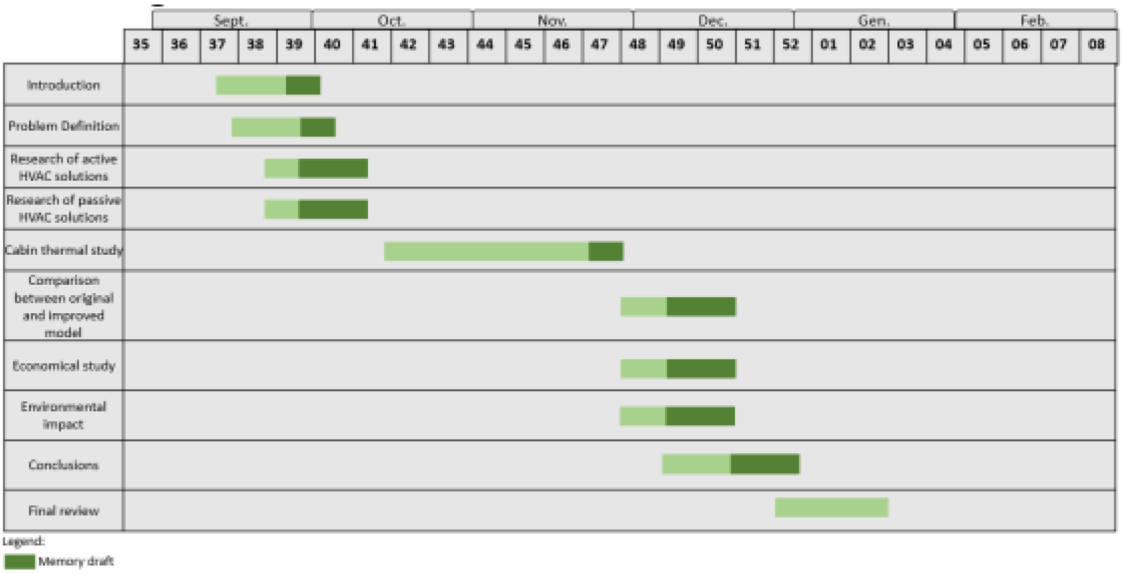


Figure 1. Timing tasks

The main out of range element is the weak knowledge of 1 D numerical simulation, so the cabin thermal study will be the densest part of the project. For this reason, it will be necessary to learn about the finite element program chosen for the project.

2.3. Methodology

The next point to proceed with the project is to analyze the problem and the actual situation, explaining the actual status of the electric vehicle, the greenhouse effect and the factors that cause car cabin heating linking it with possible HVAC system solutions in order to improve the car cabin cooling.

The second and third points will be researching passive HVAC solutions respectively, talking about the existing methods and how they can be improved. Related with the passive HVAC solutions, phase change materials and radiation cooling materials will be introduced.

Once the theoretical knowledge has been acquired, the fourth point will consist of cabin thermal study, deciding which interior geometry design fits and optimizing the model for proper cooling. Following the cabin thermal study, it is necessary to establish certain boundary conditions such as location, sun inclination, hour, etc. Finally, carrying out a 1D numerical study.

After the numerical model, a comparison between the original and improved car cabin model will be carried out. All improvements must be based on the previous research of passive HVAC solutions.

The thermal study will consist of the analysis of the factors that might improve car cabin cooling (such as interior volume, seats, window inclination, exterior paint and insulators), setting the boundary conditions for the cabin thermal study (such as the number of passengers, sun exposure and location).

The cabin thermal study will conclude with the numerical 1 D study between the original and an improved car cabin. The study will consist of switching on the HVAC system after a long sun exposure.

After the numerical model is done, a temperature analysis will be carried out comparing both original and improved car cabin after switching on the HVAC system.

The comparison enables the possibility to carry out an economical study and analyze the environmental impact.

Finally, a conclusion of the whole project and possible and viable solutions will be exposed.

3. Problem definition

3.1. Current problematic

The use of the automobile is one of the most important methods of traveling. Entire urbanistic plans are based on the use of the vehicle. This fact obligates citizens to purchase a car and make use, not only on our day-to-day tasks but also for vacation and free time.

A total of 1billion cars are used today. Therefore, it is important to take into account not only the pollution produced, but also the energy expenditure involved. The use of air conditioning is the second largest energy expenditure after the engine, increasing ICE vehicle's fuel consumption in a 30%. The United States itself consumes a total of 32.3 billion liters of gasoline per year for AC systems [1].

Car electrification implies the same importance in terms of energy use and savings, and how it directly affects its autonomy. For this reason, it is essential to have a correct use of the energy supplied and a major importance to the car battery.

The fact of establishing a temperature set in the air conditioning system causes a high consumption of energy and therefore of electricity, affecting the vehicle's autonomy. For this reason, finding passive systems in order to reduce the car cabin temperature becomes a necessity, especially when the vehicle has been exposed to the sun for a long period of time.

Apart from reducing electricity consumption, temperature decrease might help the conservation of car upholstery and plastics. In addition to this, a temperature decrease reduces the possibility of eradicating negative climate conditions inside the car. This fact might be crucial in terms of health, especially when pets or even newborns are trapped inside the car cabin, as temperature can reach a maximum of 70ºC and dashboard temperature can approach 100ºC when the vehicle is parked outside with no shade [2].

3.2. Heat factor and greenhouse effect

Numerous factors provoke the heating of a car cabin. Both interior and exterior properties of the vehicle cause a temperature increment. Such properties can be analyzing exterior paint, interior surface colors and capacity as well as shape, size and angle of the windows. All properties are directly related to their response to sun radiation, which is the main factor in elevating the vehicle's interior temperature.

There are three mechanisms of heat transfer: conduction, convection and radiation. Radiation enables the heat transfer between surfaces through the void or a participating medium, and originates in a system due to its own temperature.

Thermal radiation is considered between a wavelength λ [0,1;1000] µm, which can be divided into:

- Ultraviolet light [0,1;0,38] µm
- Visible light [0,38;0,76] µm
- Infrared light [0,76;1000] µm

Glass transmissivity can be directly related to the effect of ultraviolet, visible and infrared waves through Figure 2 and applied to the study of car cabin greenhouse effect.

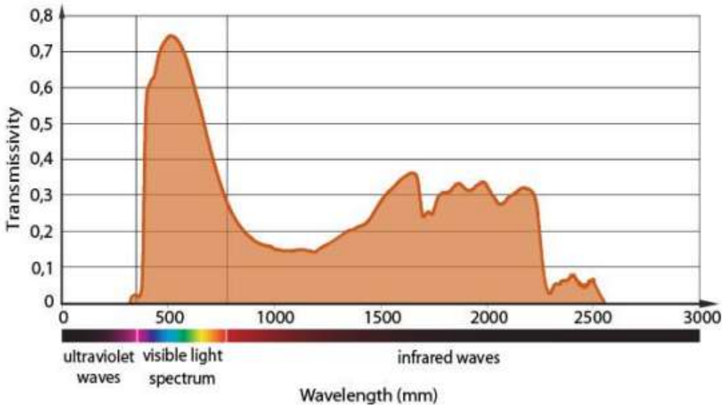


*Figure 2. Spectrum wavelength transmittance of conventional glass (*SCHOOL OF DESIGN MSc,2016).

Long wavelength radiation in a car cabin is the principal cause of heat increase in interior objects and air, which provokes a higher resultant interior temperature [3].

In addition, it is clear that ultraviolet waves have no transmissivity through glass, while the visible light spectrum has an important transmissivity value.

The effect of Sun radiation through windshields can be schematized (Figure 3) showing all UV rays are rejected, while a percentage of infrared and visible light pass through the glass.

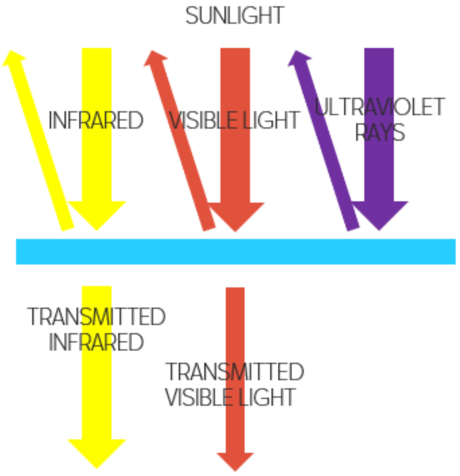


Figure 3. Scheme of Sun radiation through windshield.

Transmitted infrared and visible light are the cause of cabin heating and the reason why HVAC is strictly necessary.

3.3 Thermal comfort

Human thermal comfort is considered according to a series of variables: temperature, enthalpy and specific humidity are the 3 main factors to take into consideration in a car cabin as shown in figure 4.

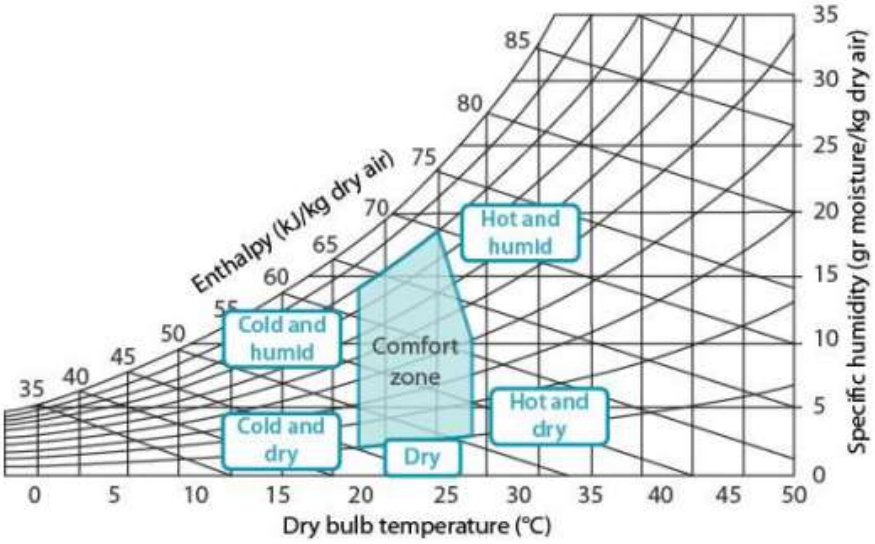


Figure 4. Comfort zone limits (SCHOOL OF DESIGN MSc in Design and Engineering).

Humidity plays an important role in human comfort, the amount of water vapor in the air is influenced by the human body's sweat, especially in a warm temperature. For this reason, it is necessary to have a proper relative humidity

(RH) control, recommended between 30% and 70%, with a comprehension of both humidity and temperature.

4. Research of passive HVAC solutions

The exposed parts of the vehicle HUT absorb solar load, especially roof, windows and body panels. The proportion of solar load absorbed directly depends on the thermal conductivity of each material. This effect leads to the increase of interior temperature of the car cabin and objects. A temperature reduction can be accomplished if a surrounding insulation is installed between the interior car cabin and the exterior surrounding, considering each part that is affected differently.

4.1. Phase change materials

Phase change materials (PCM) are able to absorb the heat and store it within the material itself, this is due to the fact of changing phase from solid to liquid the heat is absorbed and later released when changing from liquid to solid.

PCM are becoming more attractive due to their efficiency and effectiveness when collecting high amounts of thermal load in a high range of temperatures and different climatic situations, being able to store between 5 and 14 times more heat per unit volume than traditional materials used.

Starting from an initial solid state, the material absorbs heat energy due to an increase in temperature. When the material reaches the phase change state (which is specific depending on the material used), heat is stored in the material from the beginning to the end of the phase change. The beginning occurs when the melting starts until the material is totally converted into liquid. Thanks to PCM the temperature remains constant and reduces car cabin heating. When the temperature lowers again, the material performs the phase change in reverse, shown in equation 1.

$$(Q) = m\,L \qquad \text{Eq. 1}$$

There are several known and developed PCM such as eutectics (inorganic compounds), hygroscopic (natural building materials), organic (paraffins and fatty acids) and inorganic (salt hydrates). Each of them can be used depending on the temperature requirements and necessities, shown in figure 8 [16].

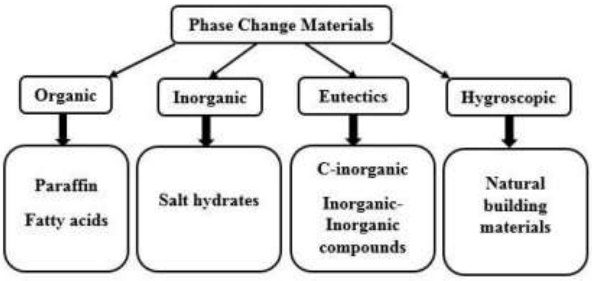


Figure 8. PCM classification (R. Family and M. P. Mengüç, "Materials for Radiative Cooling: A Review,").

Implementing PCM in roofs can show the true potential of the material in terms of car cabin thermal insulation, and becoming a great success when it is referred to as energy saving and thermal comfort.

A study carried out in 2017 showed that an integrated layer of PCM (1-dodecanol) into a normal roof structure shows the true potential compared to a non-insulated roof. The PCM keeps heat load and enables a considerable temperature decrease [17].

The PCM material (1-dodecanol) used in the experiment has a phase change between 24°C and 27°C, and has a maximum effectiveness up to 259°C, superior to a maximum temperature reached in the interior of a car cabin, results are shown in figure 9.

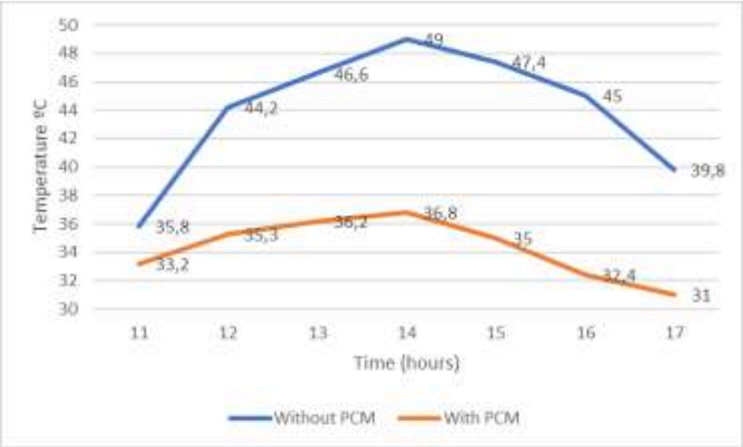


Figure 9. Temperature comparison.

The experiment was carried out with an exterior ambient temperature between 22 and 27ºC, with clear sky. Thanks to the PCM heat absorbing capacity, it can be assured that the maximum difference is about 12,2ºC around 14:00h, time where the Sun has the highest incidence. In addition to this, a smooth line along time can be observed in the insulated PCM car cabin compared to the non-insulated roof.

Each PCM has different properties, performance and therefore, different applications. Depending on the characteristics and necessities, prices might vary, starting from 9€/kg up to 1000€/kg.

A better thermal performance, according to the 1-dodecanol could save up to 30% energy for the HVAC system, without taking windy and car motion conditions into consideration [18].

4.2. Radiative cooling materials

Implementing radiative cooling materials enable the possibility to reduce car cabin temperature. This is due to the fact that radiative cooling materials emit more energy than they gain from the atmosphere thanks to a high emissivity in a wavelength range of 8 to 13 µm (known as transparency window for electromagnetic waves). For this reason, radiation emitted by earth escapes to space with no absorption within the atmosphere.

Especially during daytime when solar absorption occurs and affects the car cabin, radiative cooling materials can be useful to reduce interior temperature down to 5ºC, when the interior has been exposed to a high-temperature source [19].

Through an energy balance, the net radiative cooling power can be expressed as follows in figure 10 [20].

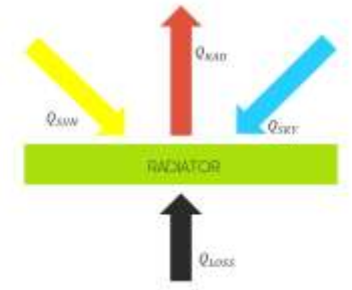


Figure 10. Schematic heat balance.

The following equations show the balance from figure 10, and how to calculate radiative heat.

$$q_{net-cooling} = q_{rad}(T_r) - q_{sky} - q_{sun} - q_{loss} \qquad \text{Eq. 2}$$

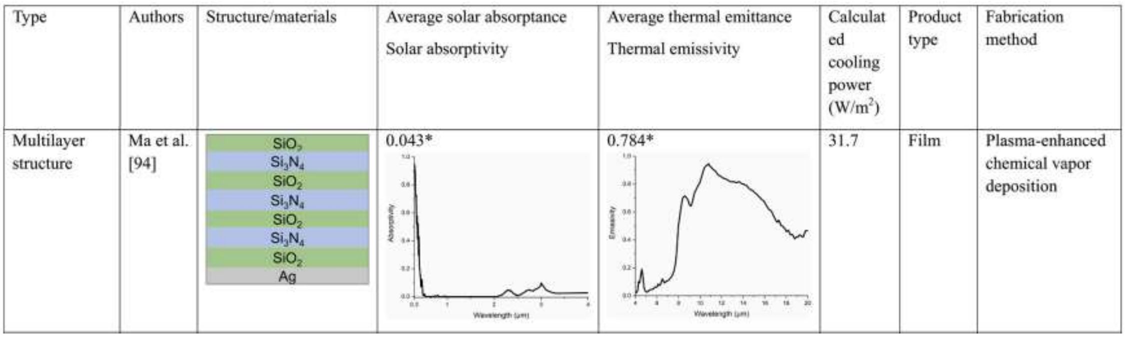
Where qrad is the radiative power of the radiative cooling material, which can be calculated by:

$$q_{rad} = 2\pi \int_0^{\infty} \int_0^{\frac{\pi}{2}} \varepsilon(\lambda, \theta) I_b(\lambda, T) sin\theta cos\theta d\theta d\lambda \qquad \text{Eq. 3}$$

Where the emissivity can be calculated by:

$$\varepsilon_s(\lambda, \theta) = \begin{cases} 1 & (\lambda < 8 \ \ \mu\text{m}, \ \lambda > 13 \ \ \mu\text{m}) \\ 1 - [1 - \varepsilon_s(0)]^{1/cos(\theta)} & (8 \ \ \mu\,\text{m} < \lambda < 13 \ \ \mu\text{m}) \end{cases} \qquad \text{Eq. 4}$$

Radiative cooling materials can be obtained by the combination of several substances. An example that can be implemented, among other materials, is a multilayer structure obtained by plasma-enhanced chemical vapor deposition [21], consisting of a thin film with a thermal emissivity of 0,784 and a solar absorptivity of 0,043. Properties are shown in figure 11.



Type	Authors	Structure/materials	Average solar absorptance Solar absorptivity	Average thermal emittance Thermal emissivity	Calculated cooling power (W/m^2)	Product type	Fabrication method
Multilayer structure	Ma et al. [94]	SiO_2 Si_3N_4 SiO_2 Si_3N_4 SiO_2 Si_3N_4 SiO_2 Ag	0.043*	0.784*	31.7	Film	Plasma-enhanced chemical vapor deposition

Figure 11. Radiative cooling material properties (X. Yu, J. Chan, and C. Chen, "Review of radiative cooling materials).

4.3. Thermal insulation

The amount of absorbed heat energy from the roof varies from 20% up to 95% depending on insulation and heating reduction methods. One of the basic and most commonly used are thermal insulation products such as polyurethane, polystyrene and polystyrol. Which are used as refrigerator, buildings, campers, yachts and mobile homes insulators.

Thickness is directly related to the insulation level. As thicker the better insulation level is offered. The fact of not being flexible and the necessity to accomplish a certain thickness do not fit to implement inside a car cabin. For this reason, aluminum foil layers, polyethylene/polyester-based foams are one of the most effective and suitable materials for automobile interior insulators.

4.4. Low emissivity material

Low emissivity materials such as aluminum foils are used as a thermal barrier for computer hardware, electric parts, cooking or even as a blanket for extreme weather conditions due to its high insulation capacity.

Absorbed heat from the hot aluminum is distracted into the air and decreases its temperature. For this reason, some car manufacturers like Nissan are already implementing this method, enabling interior temperature conservation becoming an affordable solution.

This method consists in attaching a thin aluminum layer to the car roof and a 25 mm air layer space, leading into a temperature stabilization (losing/gaining cold/warm loads from the outside environment becomes harder), which reflects in less frequent and more effective usage of the HVAC, leading into a fuel consumption diminish. The thermal analysis is demonstrated below, following the thermal radiation equation of parallel layers, for equations from 5 to 8.

$q_{high} = \frac{\sigma \cdot (T_2^4 - T_1^4)}{\frac{1-\varepsilon_1}{A_1 \cdot \varepsilon_1} + \frac{1-\varepsilon_2}{A_2 \cdot \varepsilon_2} + \frac{1}{A_1}}$; Being $\varepsilon_2 = 0.85$ and $A_1 = A_2 = A$ Eq. 5

For a high emissivity foil, emissivity for surface 1: $\varepsilon_1 = 0.8$

$$\frac{q}{A_{high}} = \frac{\sigma \cdot (T_2^4 - T_1^4)}{1{,}42} \qquad \text{Eq. 6}$$

For a low emissivity foil, emissivity for surface 1: $\varepsilon_1 = 0.05$

$$\frac{q}{A_{low}} = \frac{\sigma \cdot (T_2^4 - T_1^4)}{20{,}17} \qquad \text{Eq. 7}$$

If we equal equations, the result is:

$$14{,}2 \cdot \frac{q}{A_{low}} = \frac{q}{A_{high}} \qquad \text{Eq. 8}$$

Thanks to low emissivity material, heat is diminished a 14,2 compared to $\frac{q}{A_{high}}$, which directly affects interior temperature.

4.5. Exterior color

It is known that color surfaces have different thermal absorption of solar energy due to their reflectance and thermal radiation of every color. For this reason, dark surfaces from both interior (door trims, steering wheel, seats, control panels) and exterior (painting) vehicles receive a greater heat than other colors when being at the same solar exposure conditions.

Black surfaces absorb up to 90% of incident sunlight, which is directly converted into heat, therefore the vehicle interior reaches a higher temperature in a less time exposure compared to a white exterior painting, which absorbs only up to 25% of sunlight, staying cooler.

Studies show that the biggest temperature difference between a black and silver painted car is observed at the roof, reaching a temperature up to 24ºC warmer than the silver car. It can be explained because of the difference of their solar reflectance and thermal radiation respectively:

- 0,05 and 0,83 for exterior black paint.
- 0,58 and 0,79 for exterior silver paint.

The biggest interior surface temperature occurs at the ceiling, with a peak of 11°C between black and silver interior, leading to a 6°C difference in the average cabin breath temperature. Fuel consumption is directly related to temperature, leading to a HVAC consumption of around 24% decrease between black and silver paint [22].

4.6. Window tinting

Window tinting has a direct effect on visibility, comfort, privacy and security, as well as becoming another method for car cabin heating prevention. Tinted windshields and windows block infrared waves and therefore, a cabin heating reduction occurs.

Current windows applied in cars nowadays are known as laminated glass, which consist on a union of two tempered glasses (glass that has been under several heating and cooling phases, allowing a hardness increase) and a transparent polymer between them, becoming together with the seat belt, one of the main safety measures implemented in a car.

This laminated glass is a composed material, created by exposing these three layers into high temperatures in order to obtain greater properties and mechanical characteristics such as hardness and resistance (thanks to the tempered glass) as well as flexibility (due to the polymer) [23].

The laminated glass offers several properties that reduce car cabin heating, with properties similar to low-E glasses, used for housing construction. The transmissivity values in function of the wavelength are obtained in figure 12, considering the Sun as a blackbody at a temperature of 5800K, producing an irradiation of 1100 W/m2 into the glass [24].

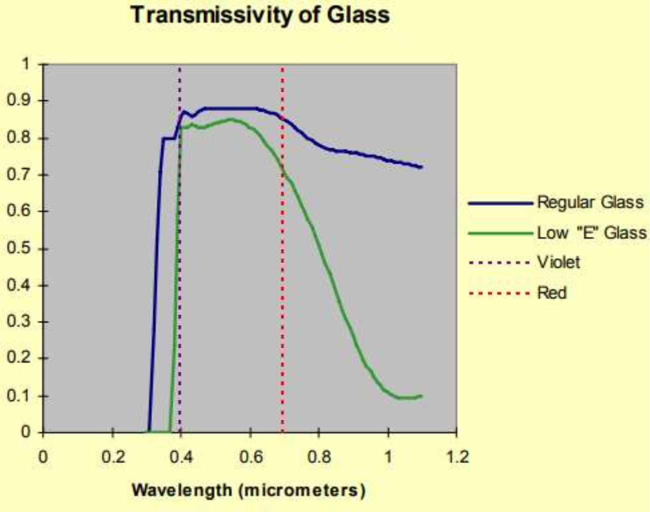


Figure 12. Transmissivity values for glass (Transmissivity of Glass - Heat Transfer Today).

Whereas window tinting consists in applying a solar reflective film into the tempered or laminated glass made of an adhesive tinted PET or polyester to the glass window, which enables reducing the amount of infrared, visible light and ultraviolet (UV) radiation. It has been demonstrated that temperature can be reduced from 1,8ºC up to 4,6ºC in car cabin interior ambient air by using solar reflective films [25].

Through figure 13 can be observed that tinted windows are an effective method to reduce car cabin ambient temperature, having a similar temperature effect to ventilation method. The study was carried out from 10:00h to 15:00h, the maximum temperature observed was held at 14:00h and the temperature difference between tinted and standard windows is approximately 5ºC [26].

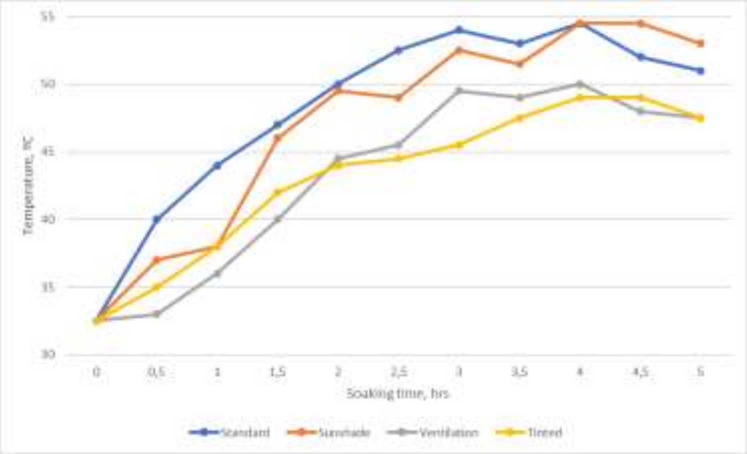


Figure 13. Average car cabin temperature by window tinting.

Nonetheless, Spanish legislation establishes that only rear windows can be tinted, so that the pilot's visibility is not affected due to his/her security while driving. For this reason, the pilot's visibility must not be affected in a 180º angle vision.

In addition, price viability enables the possibility to implement window tint for a reasonable price and, as observed in figure 12, favors temperature cabin reduction.

5. Passive methods table consideration

In order to decide which passive measures are chosen to analyze on the one-dimensional numerical study, a table consideration has been thought to be a proper way of considering all variables: thermal analysis viability, potential and effectiveness, personal knowledge, environmental viability and economic viability.

All variables are tabulated from 1 to 2, in table 1 meaning:

1: Feasible	**2: Viable**

	Thermal modelization complexity	Interior temperature reduction	Implementation viability	Environmental viability	Economic viability	**TOTAL**
Phase change materials	2	2	2	1	1	8
Radiative cooling materials	1	2	1	1	1	6
Thermal insulation	1	2	2	1	2	8
Low emissivity material	2	2	1	1	2	8
Exterior color	2	2	2	2	2	10
Window tinting	2	2	2	2	2	10

Table 1. Table consideration.

Each viability has been taken into consideration, assigning the same value ponderation for each of them: thermal modelization complexity, implementation viablility, implementation viability, environmental viability and economic viability.

It has been established to rank or classify passive solutions from 1 to 2, so the total maximum value can reach 10.

Thermal modelization complexity comprises the complexity when introducing it with modelica language, clearly radiative cooling material supposes a major complexity when dividing radiation into more than two bands.

Interior temperature reduction shows the effectiveness of each passive HVAC solution, in which none of them differentiates.

Implementation viability implies the possibility of adapting these measures into the cabin car, where radiative cooling materials show a difference compared to the other solutions.

Environmental viability has to be considered, if it has a major impact when obtaining raw materials as well as implementation, it is shown in the chart.

Finally, economic viability is directly related to implementation viability and the costs of acquiring materials, as well as introducing the solution or method into the car cabin.

Having seen the comparative chart, radiative cooling materials have been discarded for car cabin thermal improvement.

6. Cabin mathematical study

For thermal analysis, all car parts must be considered with their thermal properties and dimensional characteristics. Being defined as:

- A: Area (m^2)
- δ: Thickness (mm^2)
- V: Volume (m^3)
- ε: Thermal emissivity
- τ: Thermal transmissivity
- ε^*: Thermal emissivity
- τ^*: Thermal transmissivity
- c_p: Heat capacity (J/kg.K**)**
- ρ: Density (kg/m^3)
- λ: Thermal conductivity (W/m.K)

Considering the following table properties in table 2.

Material	A	δ	V	ε_b^a	τ	$\varepsilon^{*a}_{\ b}$	τ^*	c_p	ρ	λ
Glass	8	$5 \cdot 10^{-3}$	0,04	0,1	0,8	0,1	0.8	830	2500	0,78
				0,1		0,1				
Steel	15	$2 \cdot 10^{-3}$	0,03	0,95	0,03	0,95	0.03	400	7600	25
				0,5		0,5				
Insulator (Polystyrene)	15	$5 \cdot 10^{-2}$	0,75	-	-	-	-	1800	80	0,3
Seats	15	10^{-1}	1,5	0,6	-	-	-	1400	40	50
Carpet	8	$5 \cdot 10^{-2}$	0,4	0,5	-	0,4	-	1200	40	2
Air	-	-	2,5	-	-	-	-	1003	1,2	-

Table 2. Material properties

Car cabin model has been simplified into 3 surfaces to facilitate calculus and dimensions. In addition, thermal heats have been added to schematize and shown how car cabin is heated during the practice.

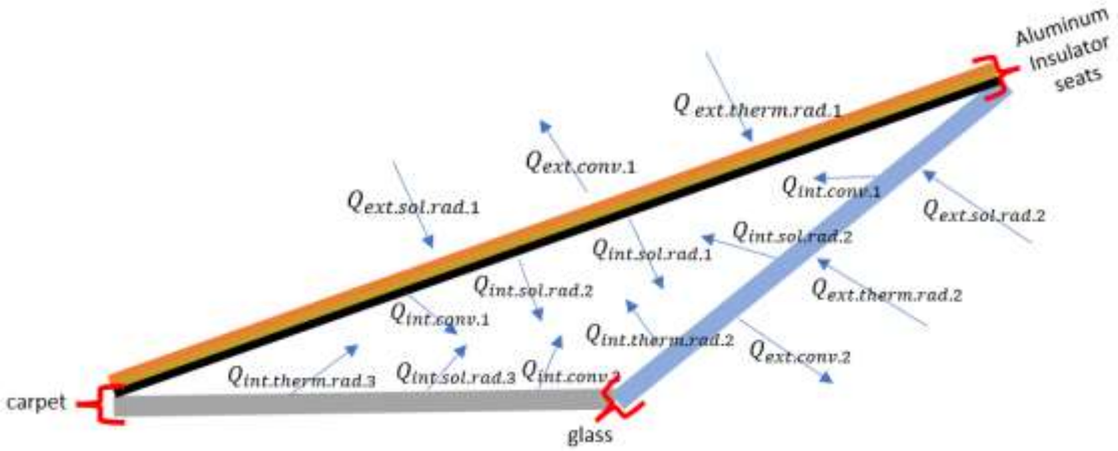


Figure 14. Car cabin schematic layout.

The 3 surfaces have been simplified to plane surfaces, as well as considering three materials together: aluminum, insulator and seats as a “sandwich”. Carpet layer does not have contact with the exterior, so exterior solar and thermal radiation and exterior convections haven’t been added, unlike the other two areas.

For exterior solar radiation:

Both glass and steel receive exterior solar radiation, shown in equation 9. Being $I_T = 1105\ W/m^2$.

$$G_i^* = I_T \cdot A_i \qquad \text{Eq.9}$$

For interior solar radiation:

Three surfaces exchange solar radiation through the following equations, being surfaces of glass, carpet and seats respectively, shown in equations from 10 to 15:

$$J_1 = A_1 \cdot \varepsilon_1^* \cdot \sigma \cdot T_1^4 + \rho_1 \cdot G_1 + \tau_1 \cdot G_1^* \qquad \text{Eq.10}$$

$$G_1 = F_{11} \cdot J_1 + F_{12} \cdot J_2 + F_{13} \cdot J_3 \qquad \text{Eq.11}$$

$$J_2 = A_2 \cdot \varepsilon_2^* \cdot \sigma \cdot T_2^4 + \rho_2 \cdot G_2 + \tau_2 \cdot G_2^* \qquad \text{Eq.12}$$

$$G_2 = F_{21} \cdot J_1 + F_{22} \cdot J_2 + F_{23} \cdot J_3 \qquad \text{Eq.13}$$

$$J_3 = A_3 \cdot \varepsilon_3^* \cdot \sigma \cdot T_3^4 + \rho_3 \cdot G_3 \qquad \text{Eq.14}$$

$$G_3 = F_{31} \cdot J_1 + F_{32} \cdot J_2 + F_{33} \cdot J_3 \qquad \text{Eq.15}$$

Knowing that view factors equations are:

$$1 = F_{11} + F_{12} + F_{13} \qquad \text{Eq.16}$$

$$1 = F_{21} + F_{22} + F_{23} \qquad \text{Eq.17}$$

$$1 = F_{31} + F_{32} + F_{33} \qquad \text{Eq.18}$$

$$F_{12} \cdot A_1 = F_{21} \cdot A_2 \qquad \text{Eq.19}$$

$$F_{13} \cdot A_1 = F_{31} \cdot A_3 \qquad \text{Eq.20}$$

$$F_{23} \cdot A_2 = F_{32} \cdot A_3 \qquad \text{Eq.21}$$

Considering the schematic layout in figure 14 and the surface value of each material ($A_1 = 15\, m^2, A_2 = 8\, m^2,\ A_3 = 8\, m^2$), view factors have been calculated with equations 16 to 21.

Having plane surfaces, $F_{11}, F_{22}\ and\ F_{33}$ equal to zero, so the result is the following for the other view factors:

$$F_{12} = 0{,}5 \qquad F_{13} = 0{,}5$$

$$F_{21} = 0{,}9375 \qquad F_{23} = 0{,}0625$$

$$F_{31} = 0{,}9375 \qquad F_{32} = 0{,}0625$$

For exterior convection:

Both glass and aluminum have convection with the ambient, shown in equation 16:

$$Q_{ext.conv\ i} = h_{ext} \cdot A_i \cdot (T_i - T_{ext}) \qquad \text{Eq.16}$$

Being: $h_{ext} = 25 \frac{W}{K \cdot m^2}$ & $T_{ext} = 318\, K$

For exterior thermal radiation:

Both glass and aluminum have exterior thermal radiation, represented by equation 17:

$$Q_{therm.rad.\ i} = \sigma \cdot A_i \cdot \varepsilon_i \cdot (T_i^4 - T_{sky}^4) \qquad \text{Eq.17}$$

Being: $T_{sky} = 0.0552 \cdot T_{ext}^{1.5} = 313\, K$

For interior convection:

Glass, seats and carpet have interior convection with the ambient, in equation 18

$$Q_{int.conv\ i} = h_{int} \cdot A_i \cdot (T_i - T_{int}) \qquad \text{Eq.18}$$

Being: $h_{int} = 30\ \frac{W}{K \cdot m^2}$

Interior thermal radiation:

There is a thermal radiation exchange between seats, glass and carpet, shown from equation 19 to 24.

$$Q_{12} = F_{12} \cdot \sigma \cdot A_1 \cdot \varepsilon_1 \cdot (T_1^4 - T_2^4) \qquad \text{Eq.19}$$

$$Q_{21} = F_{21} \cdot \sigma \cdot A_2 \cdot \varepsilon_2 \cdot (T_2^4 - T_1^4) \qquad \text{Eq.20}$$

$$Q_{13} = F_{13} \cdot \sigma \cdot A_1 \cdot \varepsilon_1 \cdot (T_1^4 - T_3^4) \qquad \text{Eq.21}$$

$$Q_{31} = F_{31} \cdot \sigma \cdot A_3 \cdot \varepsilon_3 \cdot (T_3^4 - T_1^4) \qquad \text{Eq.22}$$

$$Q_{23} = F_{23} \cdot \sigma \cdot A_2 \cdot \varepsilon_2 \cdot (T_2^4 - T_3^4) \qquad \text{Eq.23}$$

$$Q_{32} = F_{32} \cdot \sigma \cdot A_3 \cdot \varepsilon_3 \cdot (T_3^4 - T_2^4) \qquad \text{Eq.24}$$

Insulators thermal conduction:

Noise and thermal insulator and seats have thermal conduction from point a and b of their surfaces, in equation 25.

$$Q_{cond.\ i\ a \to b} = \frac{\lambda_i \cdot A_i}{L_i} \cdot (T_{i\ a} - T_{i\ b}) \qquad \text{Eq.25}$$

Heat capacity:

All components shown in the previous table (glass, aluminum, insulator, seats and air) have a heat capacity, which enables the possibility to start a transitory analysis setting an initial temperature on each surface. Through iteration, the problem reaches a thermal balance at a certain time t. An initial temperature $T_{i_t} = 20\ ºC$ is set for all surfaces with a heat capacitor.

The equation 16 by which it is governed is:

$$Q_{TOTAL\ i} = C_{pi} \cdot m_i \cdot (T_{i_{t+1}} - T_{i_t}) \qquad \text{Eq.26}$$

7. Cabin thermal study

7.1. Software research

It was necessary to find the proper software to obtain the temperature analysis based on the mathematical model explained in point 7.

Firstly, it was thought to use Matlab Simulink because it was a programming language that had already been explained and taught at university, data was easily comparable and already had a license to program. The problem was that Matlab Simulink does not have a specific library for thermal analysis, which would have required adaptation into an electric circuit. For this reason, it was discarded.

Secondly, Ansys was thought to be a proper programming software to proceed for calculus and data obtention. It had already been taught and was familiar from other projects and already had a license, but it implied a car cabin modelization (exterior and interior), which supposed detailing material and modeling complexity through Solidworks.

Theseus was thought to be the best option because it only required introducing the data and not programming by myself. Consisted on setting the number of passengers, car cabin volume, car location, time and day, which was directly related to sun radiation and exterior ambient temperature. The program would have allowed to reduce time dedication by using a car manufacturer software. The main issue was that programs with this complexity are not for free use.

Finally, Open Modelica was chosen as the best option, an open-source modeling and simulation environment intended for industrial and academic usage. It required no previous purchasing and disposed of a specific thermal library called Modelica buildings among other libraries. Therefore, the biggest drawback was that there was no previous knowledge as no subject taught at university used this software for modeling. Hence, not only required time dedication, and reading, but also self-learning by trying simple thermal cases, checking if they worked properly and then increasing their thermal complexity. This learning process is explained below at point 8.2.

7.2. Open Modelica language learning

Through the Modelica library, the first goal was to reproduce a conduction model, setting a temperature in both surfaces of a material and check if the result was coherent.

Conduction

Knowing that conduction equation is shown in Eq. 25, figure 15 shows the Modelica representation with a conductance that has two temperatures on both sides of surface. Enabling the calculus of the heat transmitted from both points, setting a value G in conductance, shown in equation 27 in which:

$$G_i = \frac{\lambda_i \cdot A_i}{L_i} \qquad \text{Eq. 27}$$

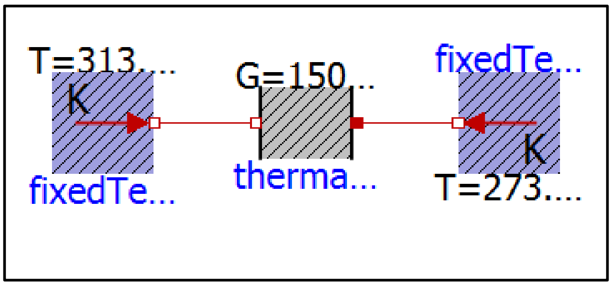


Figure 15. Open Modelica conduction calculus.

Convection layer

Once conduction is finished, convection is set in one of the thermal conductance layers, shown in figure 16, knowing that convection equation is shown in Eq. 16. The convection block needs a heat transfer area and convection coefficient

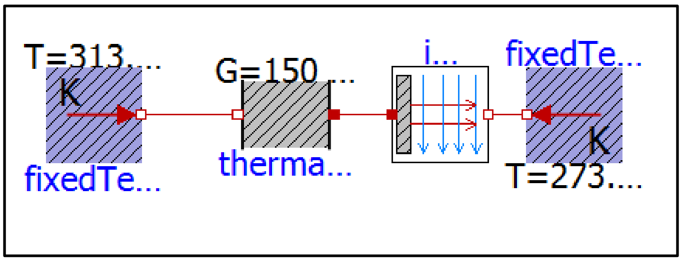


Figure 16. Convection calculus in a conductance layer.

Thermal radiation

Knowing that radiation through two surfaces equation is shown in Eq. 19, figure 17 shows how to modelize the third case in which a surface temperature is set on both surfaces and radiation is calculated from point a to point b by setting the value Gr, in which it is shown in equation 28:

$$Grij = F_{ij} \cdot A_i \cdot \varepsilon_i \qquad \text{Eq. 28}$$

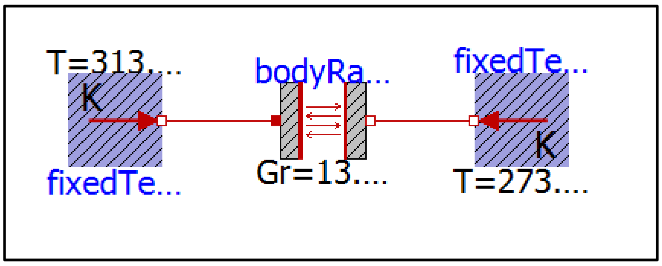


Figure 16. Radiation calculus between two surfaces.

Radiation between two surfaces

For solar radiation it was set to check how two surfaces exchanged it between them, setting a temperature, absorptivity and reflectivity value, equations shown in Eq. 14 and 15 for both surfaces. Temperature values are set on each surface, as well as area and absorptivity value.

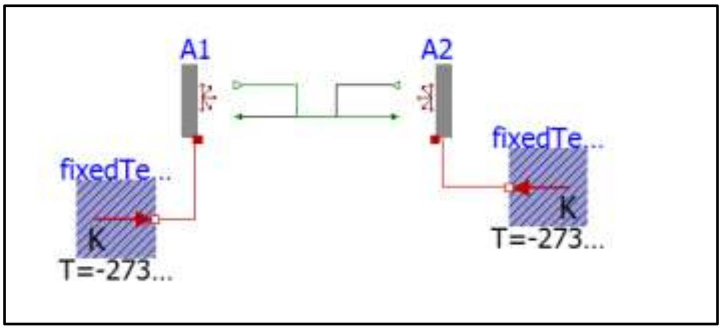


Figure 17. Solar radiation calculus between two surfaces.

Radiation between three surfaces

Radiation between three surfaces implied the introduction of view factors and having a clear knowledge of the equations. The result was implementing a gain that multiplied separately each of J_i and the total sum was the G_i of the respective surface. The result is shown in figure 18, with the equations shown in Eq 29 to 35.

$$J_1 = A_1 \cdot \varepsilon_1^* \cdot \sigma \cdot T_1^4 + \rho_1 \cdot (F_{11} \cdot J_1 + F_{12} \cdot J_2 + F_{13} \cdot J_3) \qquad \text{Eq.29}$$

$$J_2 = A_2 \cdot \varepsilon_2^* \cdot \sigma \cdot T_2^4 + \rho_2 \cdot (F_{21} \cdot J_1 + F_{22} \cdot J_2 + F_{23} \cdot J_3) \qquad \text{Eq.30}$$

$$J_3 = A_3 \cdot \varepsilon_3^* \cdot \sigma \cdot T_3^4 + \rho_3 \cdot (F_{31} \cdot J_1 + F_{32} \cdot J_2 + F_{33} \cdot J_3) \qquad \text{Eq.31}$$

Knowing that view factors equations are:

$$1 = F_{11} + F_{12} + F_{13} \qquad \text{Eq.32}$$

$$1 = F_{21} + F_{22} + F_{23} \qquad \text{Eq.33}$$

$1 = F_{31} + F_{32} + F_{33}$ Eq.34

Being plane surfaces, view factors from each surface to their selves equal to 0, as shown in equation 35

$F_{11} = F_{22} = F_{33} = 0$ Eq.35

And the relation between view factors are the areas, as shown in equations 35 to 37

$F_{12} \cdot A_1 = F_{21} \cdot A_2$ Eq.35

$F_{13} \cdot A_1 = F_{31} \cdot A_3$ Eq.36

$F_{23} \cdot A_2 = F_{32} \cdot A_3$ Eq.37

After all values are obtained from the areas above, which have been already calculated. Therefore, view factors are introduced in gain blocks, obtaining G_i and J_i for each surface.

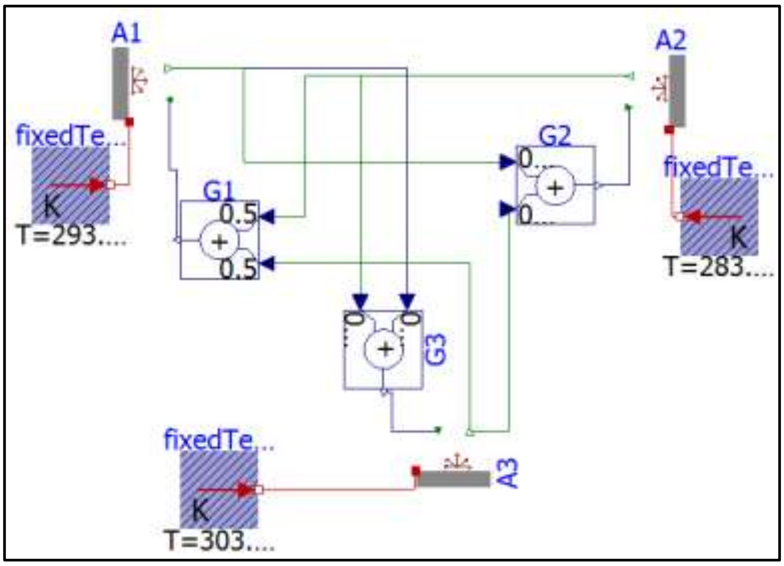


Figure 18. Radiation between three surfaces.

Transitory modeling

The next step was introducing transitory models, as all previous models were stationary. Introducing heat capacitors enabled the possibility of setting an initial temperature and starting an iteration until a constant temperature was reached. The value set at the heat capacitor was the heat capacity and the mass of the object heated, in equation 26.

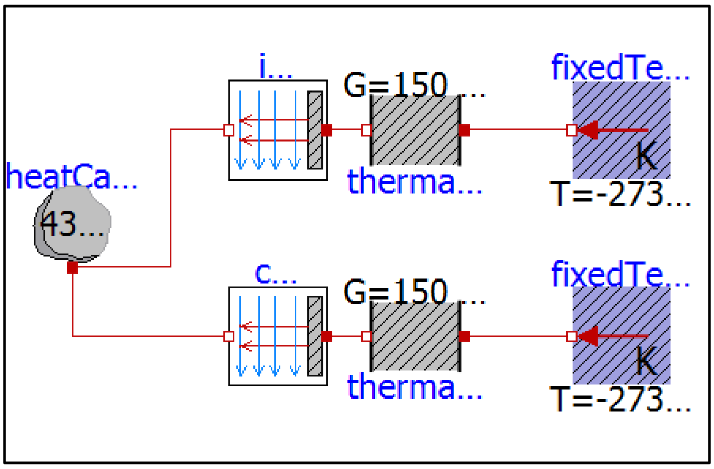


Figure 19. Transitory modeling.

Phase change material

Modifying the conductance block for another that enabled the possibility of linking it into a PCM, a new transitory model was obtained, in figure 20. PCM equation 1 shows how the material acts.

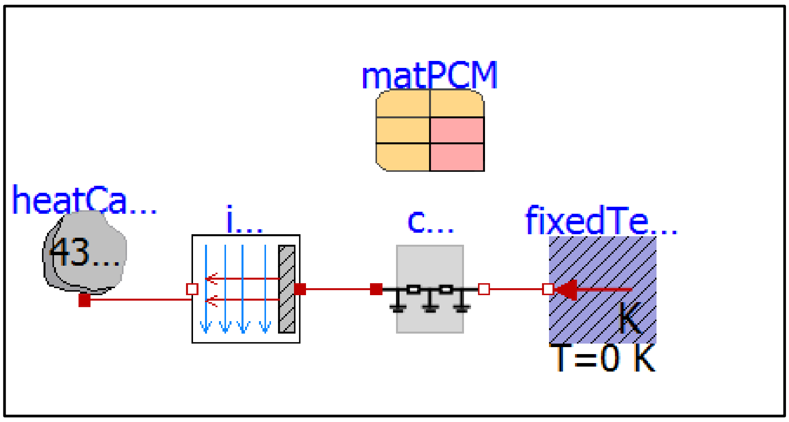


Figure 20. PCM introduction.

Radiation between three surfaces introducing windows

It can be appreciated that introducing two different windows in our model increases the complexity of variables, as it is shown below in equations

$J_1 = A_1 \cdot \varepsilon_1^* \cdot \sigma \cdot T_1^4 + \rho_1 \cdot G_1 + \tau_1 \cdot G_1^*$ Eq.38

$G_1 = F_{11} \cdot J_1 + F_{12} \cdot J_2 + F_{13} \cdot J_3$ Eq.39

$J_2 = A_2 \cdot \varepsilon_2^* \cdot \sigma \cdot T_2^4 + \rho_2 \cdot G_2 + \tau_2 \cdot G_2^*$ Eq.40

$G_2 = F_{21} \cdot J_1 + F_{22} \cdot J_2 + F_{23} \cdot J_3$ Eq.41

$$J_3 = A_3 \cdot \varepsilon_3^* \cdot \sigma \cdot T_3^4 + \rho_3 \cdot G_3 \qquad \text{Eq.42}$$

$$G_3 = F_{31} \cdot J_1 + F_{32} \cdot J_2 + F_{33} \cdot J_3 \qquad \text{Eq.43}$$

Where solar radiation is calculated by a solar factor and the surface area

$$G_i^* = I_T \cdot A_i \qquad \text{Eq.44}$$

For this reason, modeling becomes more detailed and complex, as shown in figure 21.

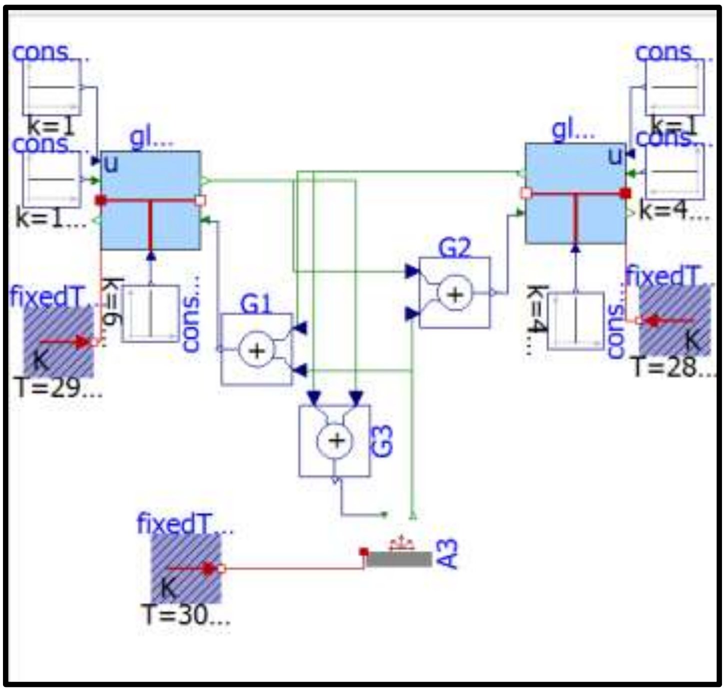


Figure 21. Radiation between three surfaces with windows.

7.3. Base case solution

After the mathematical representation and equations of each surface and numerous trials after months of checking how to apply the model, it was finally developed combining all different methods studied separately in point 8.2. Once the radiation between 3 surfaces with windows worked properly, it was now necessary to introduce thermal radiation between the surfaces, thermal radiation with the two windows (that one of them would act as the steel), interior and exterior convection and all the necessary conductance from different surfaces. After this procedure, all data from different thermal material properties was introduced in the model. The result is shown in figure 22. It is a final model that has a total number of 186 equations and variables.

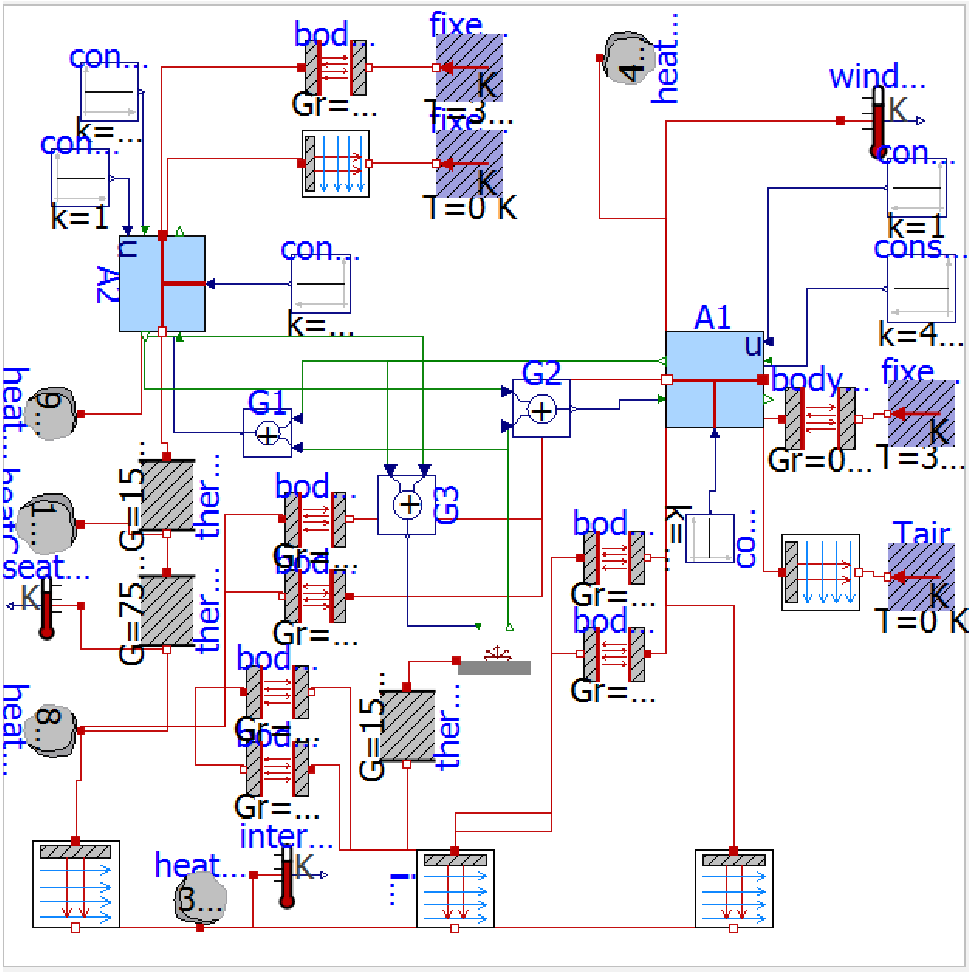


Figure 22. Open Modelica layout.

It was decided to study the temperature evolution among time of 2 surfaces: seats and interior window, and the interior ambient air, shown in figure 23.

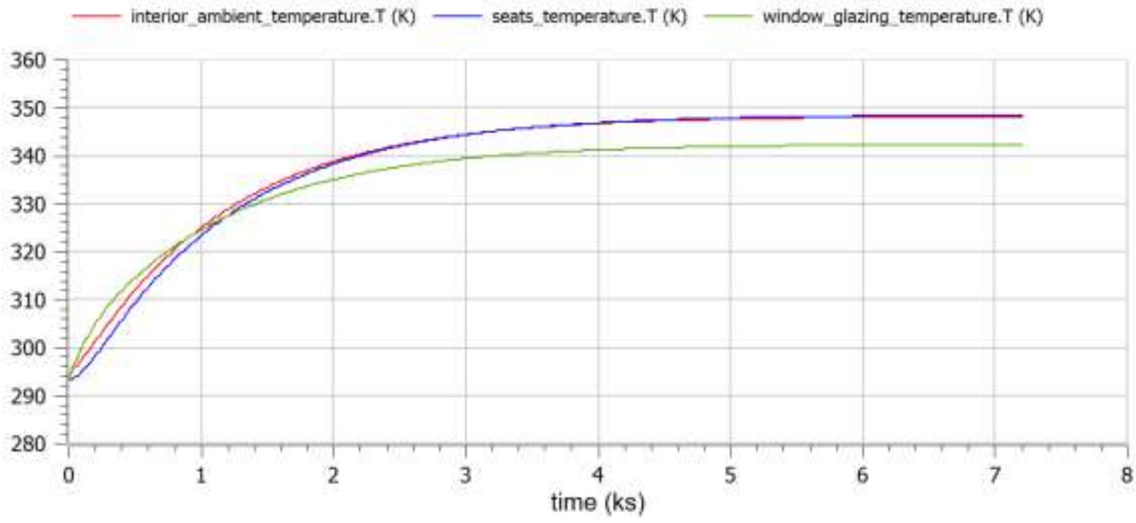


Figure 23. Base case temperature analysis.

It can be observed that interior car cabin temperature can reach a global temperature of 75ºC when it is exposed to a sun radiation of $I_T = 1105\ W/m^2$ and an exterior ambient temperature $T_{ext} = 45\ º\ C$. Through the worst-case scenario, possible solutions will be studied to reduce car cabin interior temperatures.

8. Car cabin solutions

In order to improve car cabin evolution temperature shown in point 7, both passive HVAC solutions were analyzed in order to be implemented into our car cabin. For this reason, all solutions will be thermally analyzed in the following points and how the temperature can be diminished.

Active HVAC solutions have been discarded due to thermal modelization complexity, implementation viability, environmental viability, and economic viability.

The aim is to reduce interior ambient, window glazing and seats temperature through passive HVAC solutions, the chosen ones are:

- window tinting
- exterior color
- thermal insulation
- low emissivity
- phase change material

8.1. Window tinting

Window tinting implies reducing solar transmissivity and incrementing solar reflectivity, which is a viable method to study with Open Modelica language.

Nevertheless, window tinting implies homologation premises which might have a direct effect on the implementation measure which are not going to be considered for the thesis

Considering a tint applied to the window glazing that enables a solar emissivity reduction by a factor of 10, shown in table 3.

Material	A	δ	V	ε_b^a	τ	ε^{*a}_{b}	τ^*	c_p	ρ	λ
Glass	4,2	$5 \cdot 10^{-3}$	0,021	0,1	0.8	0,01	0.8	830	2500	0,78
				0,1		0,1				

Table 3. Glass properties.

Results of the three temperatures are shown below in figure 24, where interior ambient temperature reaches 73 ºC.

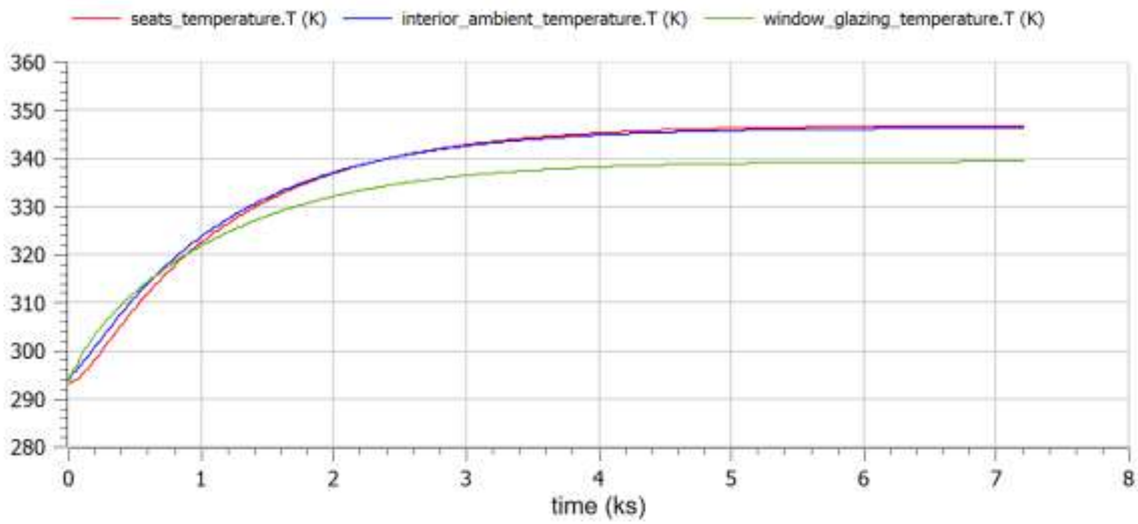


Figure 24. Window tint temperature analysis.

Window tint implementation enables a temperature reduction of 2ºC in interior temperature but also to both surfaces, seats and windows.

8.2. Exterior color

Exterior color can be an effective method to reduce interior cabin temperature, which is directly related to surface solar emissivity. The darker the color it is, the greater the absorptivity. For this reason, it is important to choose an exterior color that increases solar reflectivity. White color paint has a solar absorptivity of 0.85, while base case had a solar absorptivity of 0.95. This is directly translated into a temperature reduction, as it is shown in figure 25

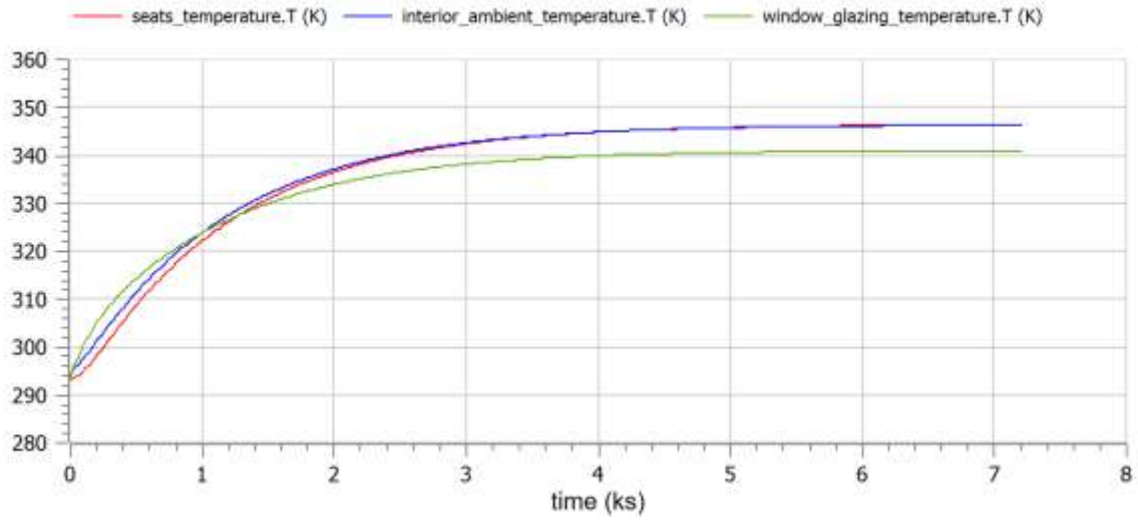


Figure 25. Exterior color temperature analysis.

Temperature evolution has a similar effect when windows are tinted, as there is a 2ºC final temperature diminish.

8.3. Thermal insulation

An insulator such as polystyrene is already being used, so thermal insulation consists on modifying material properties and analyzing temperature differences. For this reason, epotex insulator will be implemented instead, shown in table 4.

Material	A	δ	V	ε_b^a	τ	ε^{*a}_b	τ^*	c_p	ρ	λ
Polystyrene	15	$5 \cdot 10^{-2}$	0,75	-	-	-	-	1800	80	0,3
Epotex	15	$5 \cdot 10^{-2}$	0,75	-	-	-	-	1900	85	0,032

Table 4. Insulation properties.

This insulator implementation is shown in figure 26, where 2h aren't necessary to reach a constant temperature, due to different thermal properties applied instead. Interior temperature reaches a value of 69ºC after 2h exposure.

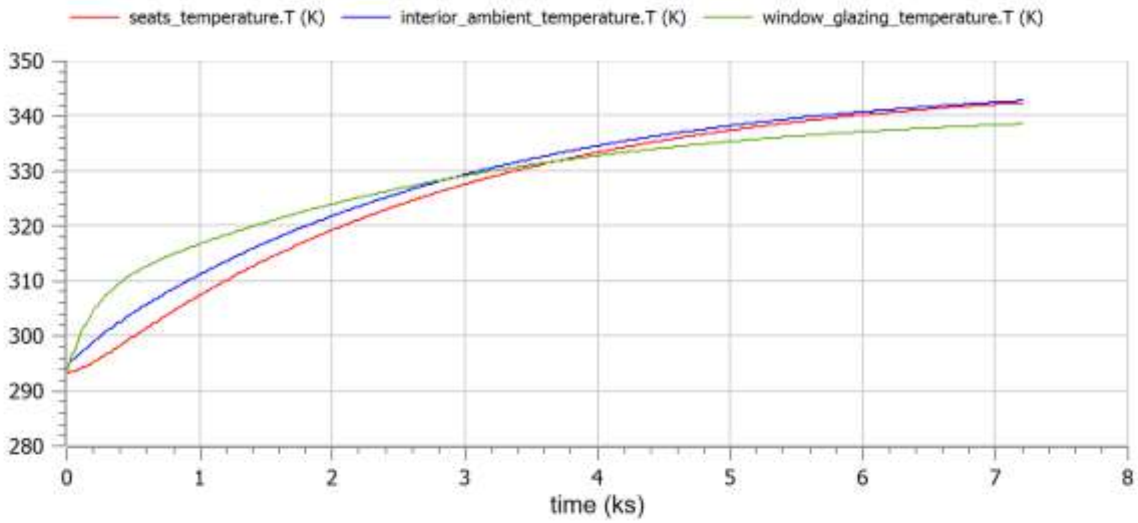


Figure 26. Thermal insulator thermal analysis

8.4. Low emissivity material

Low emissivity material consists on introducing an aluminum layer, this implementation is shown in equation 45.

$$q_{rad} = \frac{\sigma \cdot (T_2^4 - T_1^4)}{\frac{1-\varepsilon_1}{A_1 \cdot \varepsilon_1} + \frac{1-\varepsilon_2}{A_2 \cdot \varepsilon_2} + \frac{1}{A_1}} = 0.71 \cdot \sigma \cdot (T_2^4 - T_1^4) \qquad \text{Eq.45}$$

Being A1=A2= 15, E1=0.5 and E2=0.05. Aluminum properties are shown in table 5.

Material	A	δ	V	ε_b^a	τ	ε^{*a}_b	τ^*	c_p	ρ	λ

Aluminum	15	$2 \cdot 10^{-3}$	0,3	0,05	0.2	0.9	0.5	24,2	2700	237
						0,4				

Table 5. Aluminum properties.

Temperature evolution is shown below in figure 27, where 2h aren't enough to reach a constant temperature value.

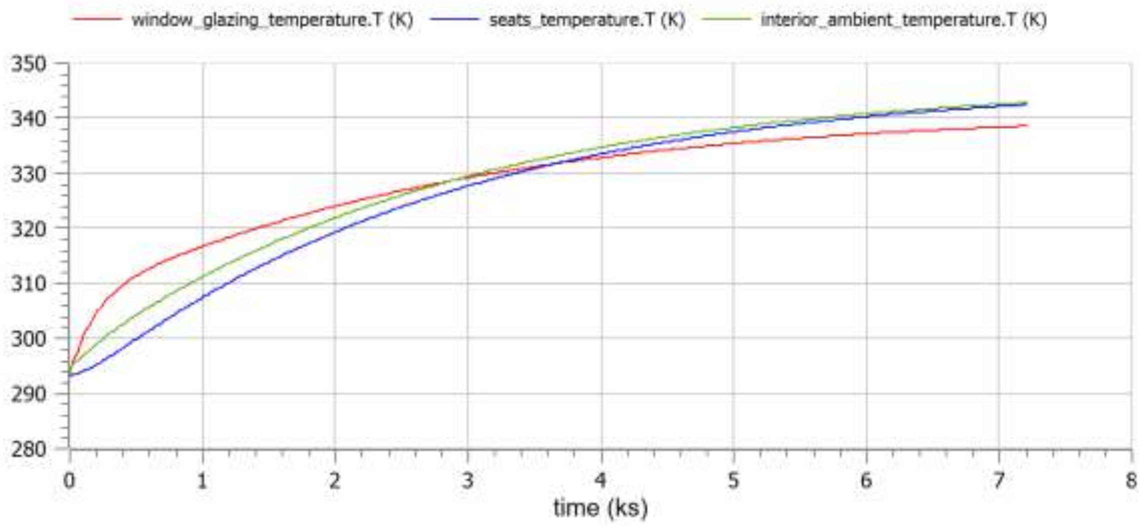


Figure 27. Low emissivity material temperature analysis

8.5. Phase change material

A phase change material is used instead of the thermal insulator. Among all PCM, organic paraffins are the viable materials to implement into the car cabin, thanks to their no toxicity and a low corrosion.

The PCM used is A28, with the properties shown below in table 6:

	Thickness (mm)	Thermal conductivity (W/m.K)	Specific heat capacity(J/kg.K)	Density (kg/m^3)	Phase change temperature (ºC)	Latent heat (J/kg)
A28	50	0,21	1800	789	28	265

Table 6. PCM properties.

Temperature evolution when phase change material is implemented is shown in figure 28, where more heat is needed to change the A28 phase from solid to liquid.

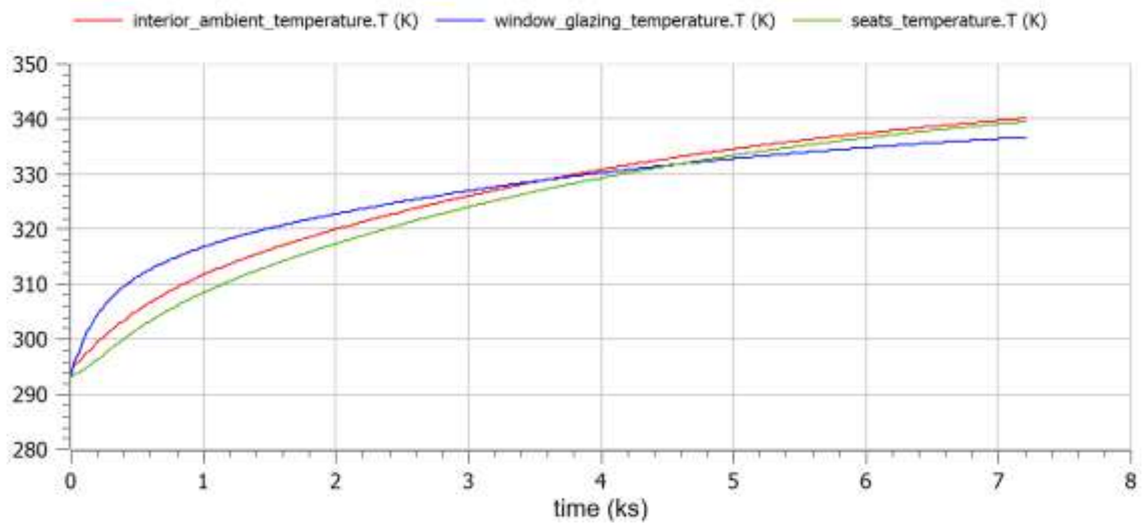


Figure 28. PCM temperature evolution

9. Final implementation

Implementing all passive HVAC solutions shown in part 8, the same analysis is performed to show how solutions affect interior, seat and window temperature but studying them separately.

Finally, figure 29 shows the Open Modelica final study, in which all HVAC passive solutions are implemented. After the mathematical representation and equations of each surface, a car cabin thermal model has been numerically developed altogether with different passive HVAC solutions using lumped and one-dimensional system-level simulation techniques.

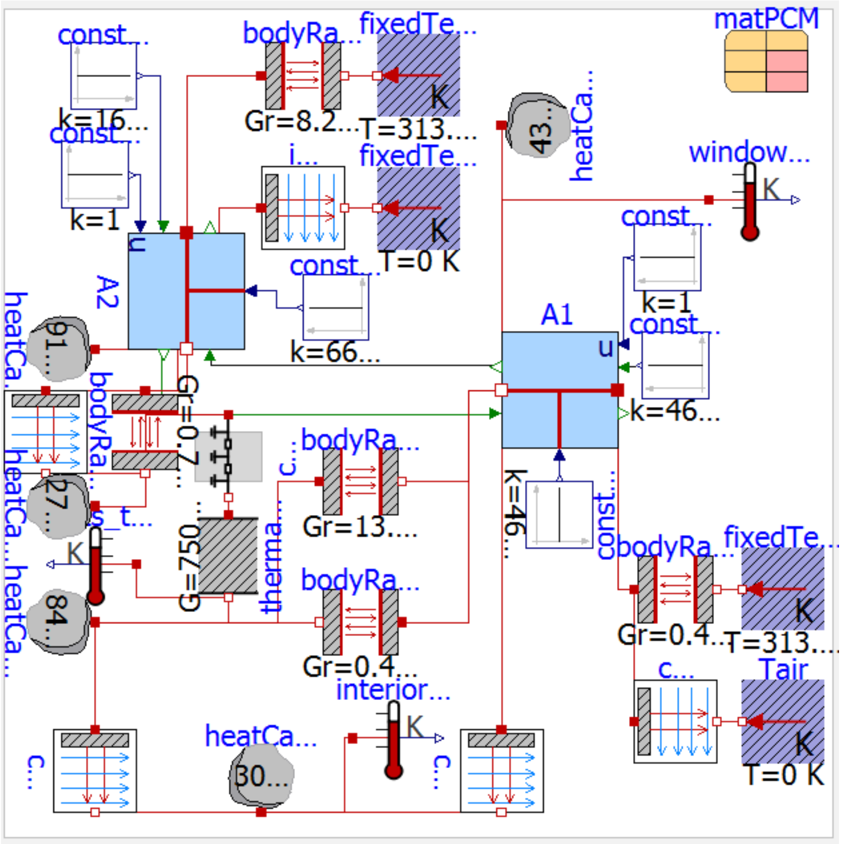


Figure 29. Open Modelica final study.

The model cannot show how window and steel absorptivity is modified, but how radiation and PCM are used in order to reduce the car cabin temperature.

Temperature analysis is shown in figure 30, where interior air cabin temperature reaches 63ºC versus the initial 75ºC. After 2h exposure, there is a temperature difference of 12ºC.

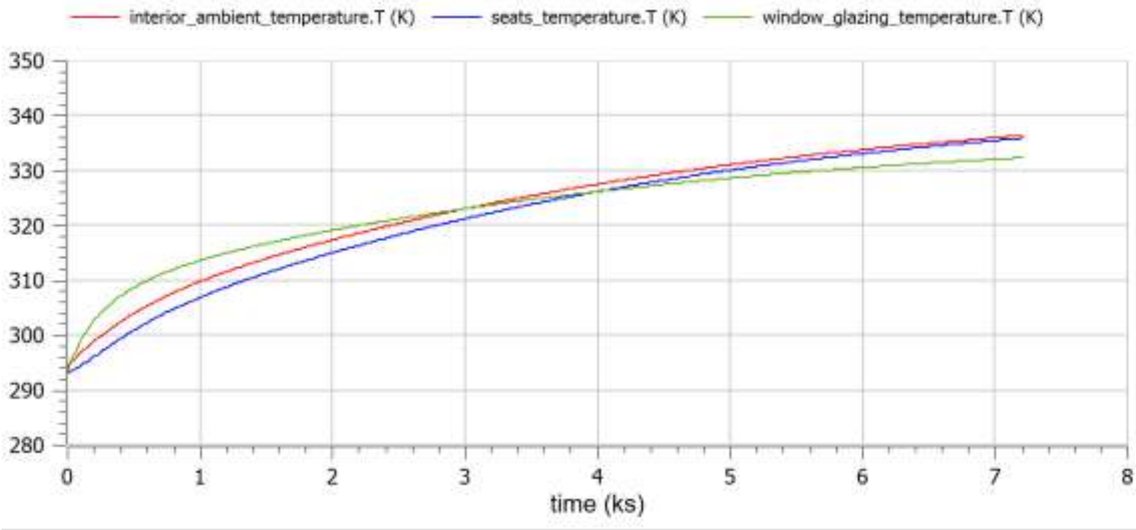


Figure 30. Final implementation temperature analysis

9.1. Results comparison

The thesis has comprised several fields: learning theoretical knowledge of passive HVAC solutions, retaking Thermodynamics content that was taught a year ago in order to perform how interior car cabin temperature is affected, for a subsequent language learning (Open Modelica). The fact of learning by myself a new language that I had never used before has implied a lot of time, dedication and effort that is not fully shown in the thesis, as only one out of 40 attempted models was finally fully representative of what occurs in the mathematical model. This fact implied a time dedication that was not fully expected, as active HVAC solutions were thought to be included at the beginning of the thesis. Table consideration at point 6 showed, however, how active solutions implied a major thermal modelization complexity, a lower interior temperature reduction, and therefore a more complex implementation viability, as well as a higher impact into the environment and major economical increase compared to HVAC passive solutions.

Having studied all passive HVAC solutions before, a comparison is now done to observe how each temperature evolves among time.

Figure 31 shows window glazing temperature evolutions with the base case study, the 5 passive HVAC solutions studied separately plus the final implementation car cabin. It can be observed that a final window temperature difference of 22ºC after 2h is obtained comparing base case solution versus the final implementation.

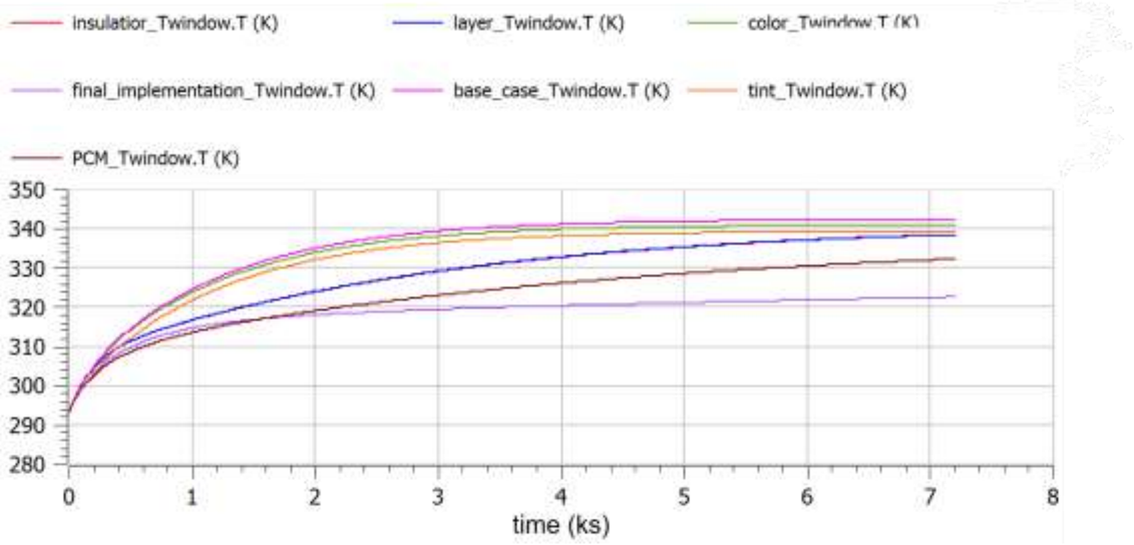


Figure 31. Window glazing temperature comparison.

Figure 32 shows seats temperature evolutions with the base case study, the 5 passive HVAC solutions studied separately plus the final implementation car cabin. It can be observed that a final seat temperature difference of 29ºC after 2h is obtained comparing base case solution versus the final implementation.

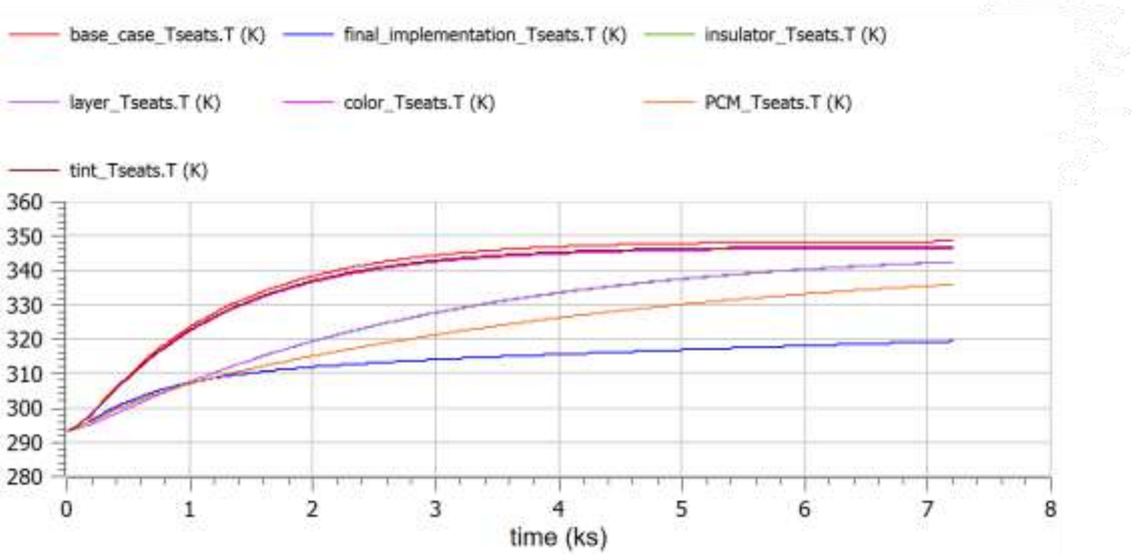


Figure 32. Seats temperature comparison.

Figure 33 shows interior temperature evolutions with the base case study, the 5 passive HVAC solutions studied separately plus the final implementation car cabin. It can be observed that a final interior temperature difference of 27ºC after 2h is obtained comparing base case solution versus the final implementation.

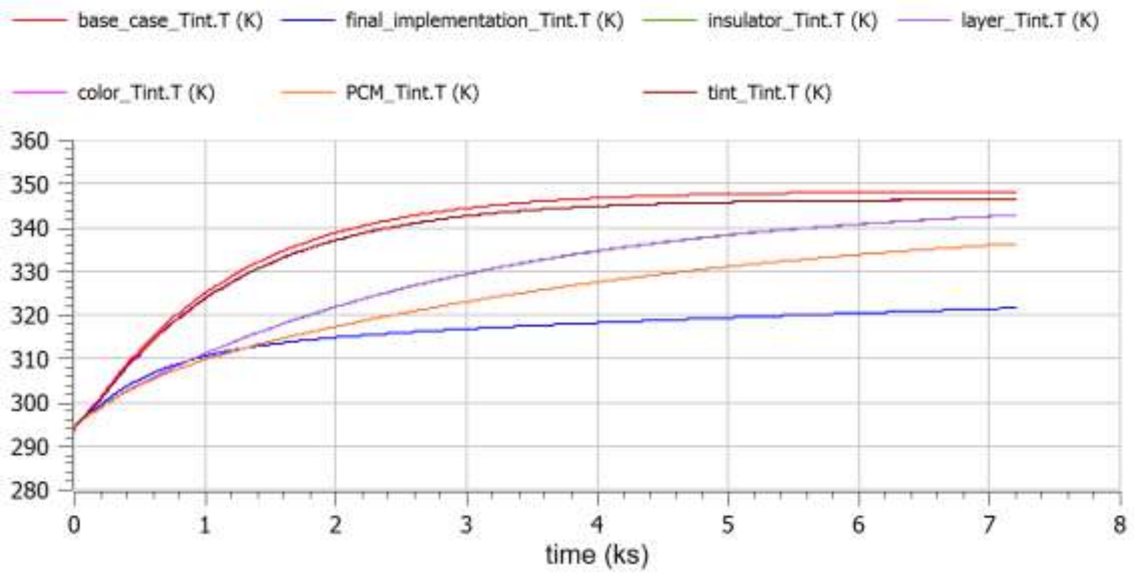


Figure 33. Interior temperature comparison.

Therefore, it can be stated that final implementation shows that not only interior, seat and window temperatures have been reduced into 321 K 319K and 322 K respectively after 2h thermal analysis, but also show a smoother temperature variation, specially at the start or beginning of the thermal study (between 0 and 2000 s)

Solutions found do not suppose a major environmental impact in car manufacturing or assembling from both suppliers and car companies, as it is possible to use a window tint, reduce exterior color absorptivity, adding or modifying thermal insulators, introducing low emissivity materials and also an organic PCM, despite being an expensive passive HVAC solution.

Temperature diminish is directly translated into energy saving, not only under these specific situations, but also under a wide variety of weather and exterior conditions. This will be translated into a wider autonomy range and electricity saving.

9.2. Results validation

Results shown previously have resulted with an interior car cabin temperature global temperature of 75ºC when it is exposed to a sun radiation of $I_T = 1105\,W/m^2$ and an exterior ambient temperature $T_{ext} = 45\text{ º }C$. In order to validate the project, boundary conditions will be modified to compare results with the article: "Parked electric car's cabin heat management using photovoltaic powered ventilation system", M. Kolhe, S. K. Adhikari, and T. Muneer [27], where figure 34 shows a maximum temperature of 62ºC when being exposed under an average radiation $I_T = 900\ W/m^2$ and a $T_{ext} = 40\ º\ C$, shows a maximum interior car cabin temperature of 64ºC

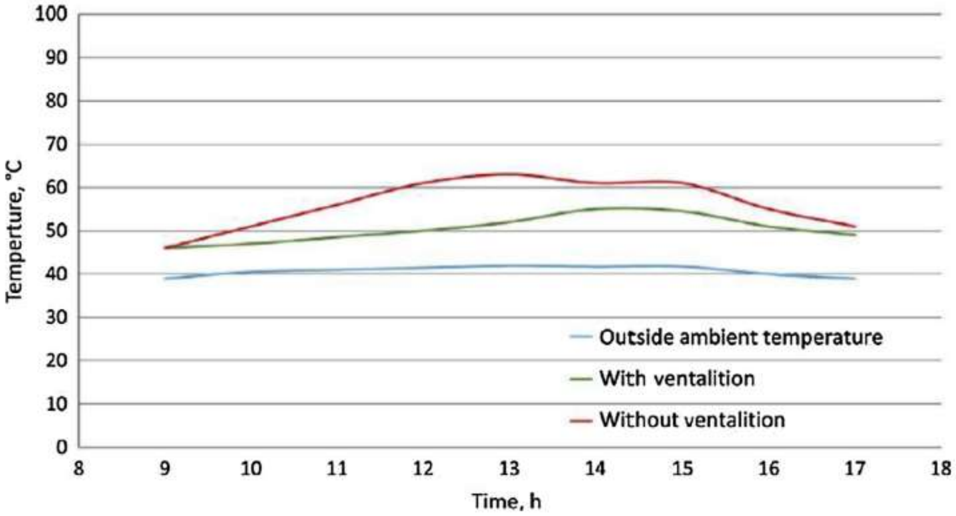


Figure 34. (Parked electric car's cabin heat management using photovoltaic powered ventilation system, M. Kolhe, S. K. Adhikari, and T. Muneer)

Results show that modifying boundary conditions into our car cabin model in modelica, with the ones considered in the study shown above ($I_T = 900\ W/m^2$ and a $T_{ext} = 40\ º\ C$), the temperature evolution after 2h reaches 63ºC, represented in figure 35.

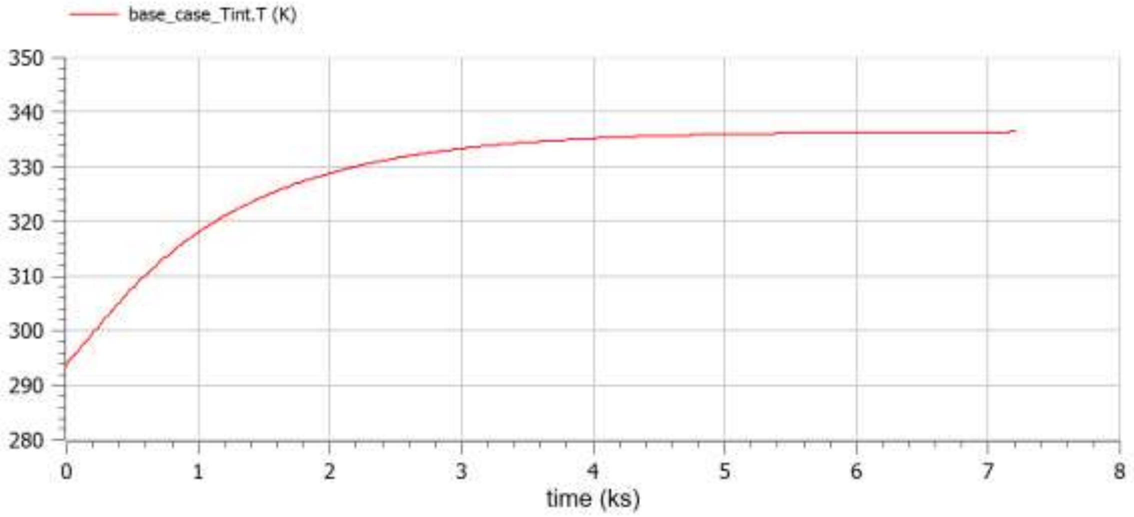


Figure 35. Car cabin interior temperature validation under $I_T = 900\ W/m^2$ and a $T_{ext} = 40\ º\ C$.

Despite car cabin simplicity in modelica, where only 3 surfaces are considered and only 5 material properties are implemented, it can be stated that there is a slight difference of only 1ºC. Therefore, it can be stated that the car cabin model is a fair representation on how a car cabin is heated.

10. Economical study

The goal of the thesis in economic terms was to minimize expenditures, it was established not to exceed a total of €100 for unforeseen events such as choosing the software for the thermal analysis. Finally, an open-source program was used so this budget has not been necessary.

All information obtained has been through eBIB so no document was purchased and, most importantly, the model has been designed and calculated through Open Modelica, a multi-domain modeling language that can be obtained for free.

Therefore, the economical objective set at the beginning of the thesis has been accomplished.

11. Environmental study

From the environmental point of view, passive HVAC solutions implemented into the car cabin suppose an interior temperature diminish of 27 ºC compared to initial car cabin model, when being exposed under solar radiation $I_T = 1105\ W/m^2$ and exterior ambient temperature T_{ext}= 45ºC.

Solutions implemented do not only reduce temperature under these boundary conditions mentioned, but also have a direct effect on day-to-day use, which translates into an energy saving method, specially of air conditioning. In addition to this, materials inside the car such as plastics and leathers do not suffer such a significant degradation because of temperature diminish.

Therefore, solutions found do not suppose a major environmental impact in car manufacturing or assembling from both suppliers and car companies, as it is possible to use a window tint, reduce exterior color absorptivity, adding thermal insulators, introducing low emissivity materials and also an organic PCM, despite being an expensive passive HVAC solution.

12. Gender equality

During the course of the project, the elaboration has been carried out between two people of male and female gender, in this course there has been no discriminatory treatment conditioned by race, gender, religion, social class, etc.

13. Conclusions and future work

Thermal analysis show how final implementation presents that not only interior, seats and window temperatures have been reduced into 321 K 319K and 322 K respectively after 2h thermal analysis, but also that there is a smoother temperature variation, specially at the start or beginning of the thermal study (between 0 and 2000 s)

Solutions found do not suppose a major environmental impact in car manufacturing or assembling from both suppliers and car companies, as it is possible to use a window tint, reduce exterior color absorptivity, adding or modifying thermal insulators, introducing low emissivity materials and also an organic PCM, despite being an expensive passive HVAC solution.

Temperature diminish is directly translated into energy saving, not only under these specific situations, but also under a wide variety of weather and exterior conditions. This will be translated into a wider autonomy range and electricity saving.

Further projects and ambitions following are not only improving car dimensions and material complexity, but also introducing active HVAC solutions to have a total global scope and improvement of interior ambient temperature and energy saving.

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