PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, **C**OST, **O**PTIMIZATION, **S**IMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Holistic approach to improve cabin air quality in electric vehicles and energy savings

Matisse Lesage[a], David Chalet[b], Jérôme Migaud[c] and Christoph Krautner[d]

[a] Nantes Université, Ecole Centrale Nantes, CNRS, LHEEA, UmR 6598, Nantes, France, matisse.lesage@ec-nantes.fr, CA
[b] Nantes Université, Ecole Centrale Nantes, CNRS, LHEEA, UmR 6598, Nantes, France, david.chalet@ec-nantes.fr
[c] MANN+HUMMEL Filtration France, Laval, France, jerome.migaud@mann-hummel.com
[d] MANN+HUMMEL GmbH, Marklkofen, Germany, christoph.krautner@mann-hummel.com

Abstract:

In electric vehicles, the Heating, Ventilation and Air-Conditioning (HVAC) function is often performed by a heat pump. Heating and cooling the cabin air drains energy directly from the vehicle's battery. In addition, these vehicles may operate in environments with high level of air pollution. In the cabin, passengers are confined to a small space where particles and harmful gases can accumulate. In addition, the ventilation system must also handle the air which does not enter the cabin through blower operation. This "infiltration" is a function of the vehicle speed and allows pollution to enter the cabin without being filtered or thermally treated.

The objective of the study is to optimize the competing goals of the HVAC system: achieving the best air quality while maintaining good thermal comfort, at minimum energy costs.

A system simulation tool is calibrated to represent the heating and cooling of an electric car. With this model, the influence of key factors is evaluated. Depending on ambient conditions and other parameters (number of occupants, vehicle speed, etc.), the blower flow rate and recirculation ratio can be adjusted to reach the objectives. The management of the proportion of fresh and recirculated air allows to regulate the humidity and carbon dioxide levels. Optimum controls are proposed as good trade-offs to reduce the power consumption, while maintaining a safe and comfortable environment for occupants. Compared to the full fresh air mode, the driving range gains are estimated in cold (−15°C) and hot (30°C) scenarios at 9 and 26 km respectively.

Keywords:

Ventilation; Filtration; Heat pump; HVAC; Driving range.

1. Introduction

Heating and cooling of the vehicle cabin is an important feature, and its design can vary a lot based on the car model. It depends on cabin size, vehicle-mounted actuators, materials, and occupants (in terms of both perception and changes in thermal environment). In full electric vehicles, the motor efficiency leads to low heat losses. Contrary to thermal vehicles, this waste heat is not enough to heat the cabin. Previous research [1] shows that the HVAC system of electric vehicles can reduce the driving range by 35% to 50%, depending on weather conditions. There are other options to reduce the HVAC system's energy usage, for example by using reversible heat pumps. A key advantage of the heat pump is its ability to provide more heat output than its electrical consumption. This is made possible by its ability to absorb energy from the environment, even in cold or hot conditions. This solution is already implemented in Tesla vehicles, Renault ZOE, or also as an option in the Volkswagen ID series.

The heat pump is integrated to the HVAC module, with other main components as the blower and the recirculation flap. Figure 1 illustrates typical airflow within a passenger car. The air inlet is often found near the base of the windshield, where the blower forces the outside air into the cabin. The outlet is generally a decompression flap located in the car body near the rear trunk. As an alternative or complement to the fresh air intake, the vehicle also has a recirculation mode. Furthermore, there is the infiltration phenomena, which occurs due to the air entering the cabin through small openings in the (not airtight) car body and this is caused by the air resistance of the vehicle. This infiltrated air is not thermally treated by the HVAC system.

https://doi.org/10.52202/069564-0216

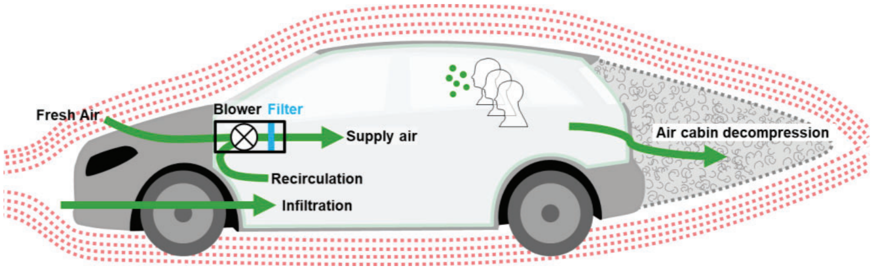


Figure 1. Overview of airflows inside a car cabin.

The global objective of the HVAC system is to provide a comfortable environment for the driver and the passengers. Thermal comfort can be characterized as a feeling of harmony with one's surroundings. Comfort in a closed environment is well documented, with many articles focused on the building sector. A passenger car cabin is significantly different because it has a small volume (generally less than 5 m^3) and can hold several passengers. In addition, driving a car requires a certain degree of attention. It is preferable to feel comfortable in order to prevent weariness, and thus a decline in driving ability. Fojtlín *et al* [2] links driver fatigue to different temperature settings. Heat stress has been found to negatively affect driver skill.

According to a standard [3], the human comfort depends on six parameters: human metabolism, clothing insulation, relative humidity, temperature, radiation, and air flow velocity. Thermal comfort, however, is a complicated idea that is challenging to guarantee and is not restricted to the aforementioned factors. This is because it's a mix of subjective, psychological and socio-cultural factors [4].

Assuming a comfortable temperature, the level of relative humidity for people should be between 30% and 70% (preferably in the range 40-60%) [5,6]. A low humidity level can irritate the eyes and throat and dry the mucous membranes and nasal passages. A high relative humidity can reduce the evaporative cooling of the body through sweating, causing a suffocating sensation. It also promotes the growth of fungi and leads to other moisture related problems. Experimental research [7] measures the comfort and fatigue of passengers in a cabin under different environmental settings and shows that an excess of water (humidity above 60%) increases the rate of fatigue related complaints, particularly on the eye dryness sensation and visual fatigue.

Moreover, air renewal, an essential component of comfort, has not yet been considered. The interior air must be changed frequently, to enable the removal of odours, contaminants, water vapour, and CO_2 (Carbon Dioxide) emitted by the materials and occupants. Monitoring the CO_2 concentration is one way to assess how well a ventilated space is perceived by humans. Carbon dioxide serves as a reliable indicator for biological effluents (i.e., odours) that are known to be unfavourable for comfort. Then, besides the comfort, the HVAC system plays an important role in keeping the driver at their full capacity. It is therefore important that temperature, humidity and CO_2 levels are regulated together in the vehicle's cabin.

The literature review reveals different solutions to either reduce the energy consumption, enhance the comfort, or improve the air quality in a vehicle cabin: air renewal [8], efficient filters [9], air purifier [10], catalytic conversion [11]. All the filtration and air treatment solutions mainly address the air quality issue, not the energy management nor the thermal comfort since CO_2 and humidity are not filtered. Some solutions are attractive for their field of application, but their use in a car cabin is often limited by a drawback on another aspect. For example, the use of recirculation mode to reduce the energy consumption should be used with caution because of the risk of high carbon dioxide levels. There are several good concepts, but with a single objective (limited scope). The literature review does not reveal any complete solution for air quality, energy savings and thermal comfort.

2. System modelling with holistic approach

To evaluate the HVAC system of an electric vehicle, a simulation tool is developed. It is a multi-physics model based on numerous individual elements: blower, filter, cabin, etc. All individual elements are connected to represent the complete system: the holistic approach focuses on a macro scale level. The model contains all necessary elements of the heating, ventilation and air-conditioning (HVAC) of a vehicle cabin, exposed to various external interactions. This model will be used to evaluate different strategies for the HVAC system.

2.1. 1D simulation tool

For the present work, a 1D simulation level is considered. It appears to be the most suitable tool to achieve a good trade-off between computational time and accuracy of results at a system level. Neither the time required to build such a model nor the chosen system approach is compatible with a 3D simulation tool. In addition, a bloc modelling with transfer function requires many calibration data without offering sufficient robustness in the results. With a 1D model, the geometry of components is simplified and only one spatial dimension is considered (commonly in the flow direction). It allows completing transient or stationary scenarios with a fast computational time.

https://doi.org/10.52202/069564-0216

GT-Suite, a software developed by Gamma Technologies is selected for this task. It is a well-known software for system modelling at a 0D/1D level in the automotive domain. At each time step, the solver integrates the conservation equations (mass, energy and momentum) in space and time.

The complete HVAC system is depicted in the model as shown in Figure 2. It can be divided in two main parts: the heat pump (left side of the figure) and the cabin air circuit (right).

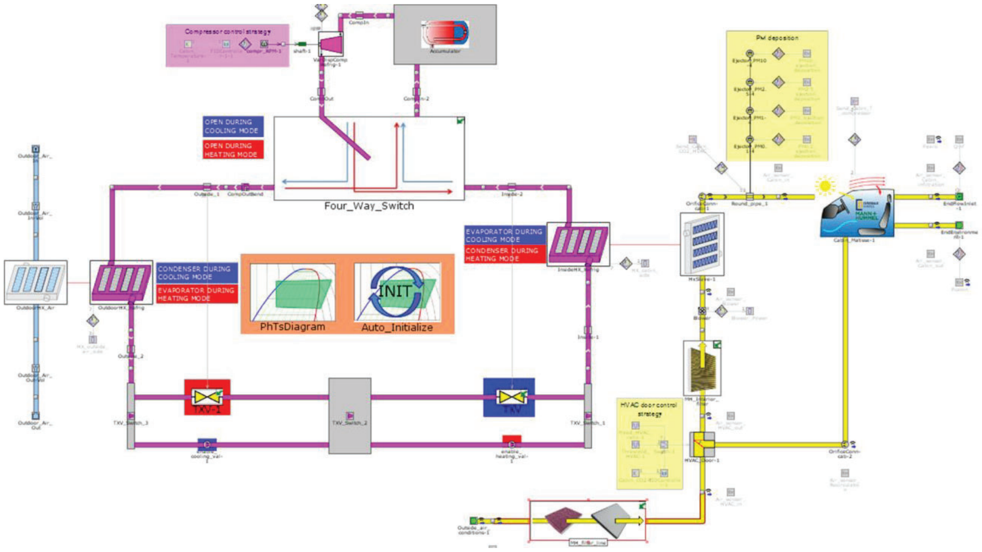


Figure 2. Overview of the complete simulation model in GT-Suite.

2.1.1. Heat pump model

This model is based on a Renault ZOE architecture, which remains a common structural design for electric vehicles. The elements of the heat pump circuit are a compressor, an accumulator, two heat exchangers, a four-way switch, two expansion valves and some piping elements. The refrigerant working fluid is R134a.

The cabin temperature is regulated by adjusting the compressor speed. This compressor is modelled from a GT-Suite template with a map-based approach relying on measured performance data. The refrigerant fluid is guided by the four-way switch from the compressor to the condenser.

In heating mode, the condenser is on the cabin side and the evaporator is on the outside air side. It is the opposite in cooling mode. The two heat exchangers are interacting with either the outside air circuit or the cabin air circuit. The outside air circuit is connected to ambient air conditions (pressure, temperature, humidity), with flow rate depending on vehicle speed (additional wind speed is assumed to be 0). For both heat exchangers, predictive correlations are used to compute Reynolds and Nusselt numbers during a simulation. The fluid phase changes are resolved in the exchangers with computation of the resulting variations in heat transfer coefficients.

The refrigerant fluid exits the condenser to enter the thermal expansion valve. It manages the flow rate of refrigerant released in the evaporator, thus controlling the superheat. Finally, the heat pump circuit is completed by a 1L accumulator upstream the compressor.

2.1.2. Air circuit model with mono-zone cabin

Like the heat pump circuit, the cabin air circuit is built with several components. The inlet of air from the outside is upstream the recirculation flap. This flap manages the amount of air coming either from the outside environment or back from the cabin. The next element after the recirculation flap is the blower and it drives the circulation of the airflow. Before entering the cabin module, the air is either heated or cooled in the heat exchanger connected to the heat pump circuit. From the cabin, the outlet is either the recirculation path or the outside environment.

Finally, an inlet is connected to the cabin element to represent the inlet of air directly from the outside into the cabin vehicle. This is called infiltration. This air, neither filtered nor set at proper temperature, can have great influence on the thermal balance (and air quality) in the cabin. The modelling and calibration of the infiltration flow rate is detailed in a previous study [12].

The cabin is a mono-zone volume based on the generic GT-Suite module to compute the thermal balance inside a medium size vehicle cabin. The mono-zone model implies that there is complete homogeneity inside the cabin. This approach against multiple volumes or CFD is motivated by fast computational time and less number of inputs required.

https://doi.org/10.52202/069564-0216

2.1.3. Humidity calculations and windshield condensation

Modifications are made in the model to consider further humidity calculations. It is a comfort parameter for occupants and a safety factor considering the condensation on front windshield and side windows. The objective is to have an accurate prediction of the humidity level and condensation risk in the cabin.

With that purpose, the standard GT-Suite windshield model is improved to include a variable heat transfer coefficient. A moving vehicle implies an air movement on the external surface of the front windshield, thus suggesting heat transfer by convection mode. The convective heat transfer coefficient can be calculated using the Nusselt number equation, as in Eq. (1), where L_c is the characteristic length of the windshield.

$$Nu = \frac{h.L_c}{\lambda}, \tag{1}$$

To simplify the model, no wind is considered. Hence, air velocity on windshield is equal to the vehicle speed. This improved convection heat transfer model allows a more accurate prediction of the windshield surface temperature, which plays an important part in the condensation risk assessment.

Assuming that all the water in the air above saturation condenses from gas into liquid, the condensation mass (mass of water per mass of dry air) can be computed with the mixing ratio as in Eq. (2).

$$\text{if } X_w > X_{ws} \text{ then } Cm\left(g_{water}/kg_{dry\ air}\right) = X_w - X_{ws}, \text{ with: } X_w\left(g_{water}/kg_{dry\ air}\right) = \frac{M(H_2O)}{M(air)}\frac{x_w}{1-x_w}$$

$$\text{and } X_{ws}\left(g_{water}/kg_{dry\ air}\right) = \frac{M(H_2O)}{M(air)}\frac{P_{ws}}{P_{tot}-P_{ws}} \tag{2}$$

Besides the calculation of the condensation mass, a complementary factor is created in order to have a second option to evaluate the creation of condensate. More precisely, it is made to estimate the risk of fog formation on the glass surfaces inside the vehicle's cabin. This factor, so called $Fog\ risk$, is based on the calculation of relative humidity on the glass surfaces, as in Eq. (3).

$$Fog\ risk = \frac{P_w}{P_{ws}}, \tag{3}$$

The partial pressure of water vapour (P_w) is obtained with Dalton's law ($P_w = P_{tot}.x_w$) where the mole fraction of water is taken from the mono-zone cabin air. The partial pressure of water vapour at saturation (P_{ws}) is calculated from the saturation tables, in which the temperature is taken at the wall of the involved surface (e.g., windshield temperature at cabin side). According to the definition of the factor:

- There should be condensation if $Fog\ risk$ is above 100%
- There should not be condensation if $Fog\ risk$ is below 100%

The fog risk factor gives additional information to the computation of condensation mass. On one hand if the condensation mass is zero, the fog risk factor gives an assessment to know the margin before condensation: the situation is more perilous with a 99% fog risk rather than a 1% risk. On the other hand, if the condensation mass is strictly positive, the fog risk factor gives knowledge about the closeness to regain a clean windshield: condensation with a 101% fog risk is easier to remove than condensation with a 150% fog risk.

The main limitation in the calculation of the condensation mass and the fog risk factor is the mono-zone approach. Indeed, the whole air volume inside the cabin is seen as one entity. There is no possibility to separate or orient the air flow driven by the blower. For instance, Figure 3 displays a photo of the windshield during an experiment made in the scope of this project. There is condensation on a major part of the windshield, besides a small area highlighted in the picture (zone A). This is explained by the air blown in this direction from the vent grid located at the bottom of the windshield. Locally, the humidity conditions do not trigger condensation while compared to the rest of the windshield. Such a phenomenon cannot be evaluated with the simulation model as is. So, the condensation mass and the fog risk factor only give a global evaluation.

Figure 3. Evidence of condensation on the windshield during an experiment.

https://doi.org/10.52202/069564-0216

2.1.4. Thermal model

There is a thermal interaction between the air flowing through the cabin, the internal elements and the outside environment factors (sun, wind). The modelling of the cabin involves many processes, showcased in Figure 4.

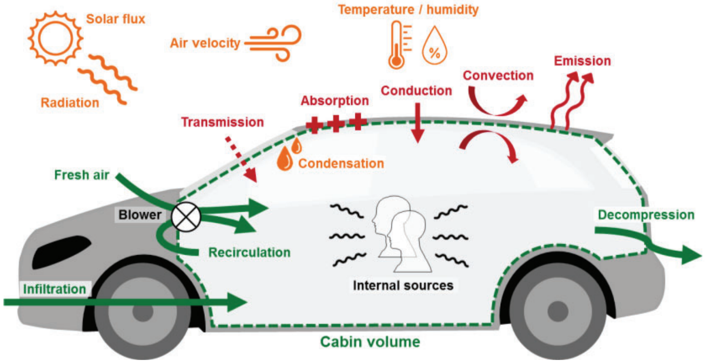


Figure 4. Model of the thermal behaviour of a car cabin.

The mono-zone modelling implies that the air temperature is homogeneous inside the whole cabin. The cabin characteristics are imported in the simulation code. A standard three-layer material is selected for doors, floor and roof: polyamide, polyurethane and stainless steel. Material properties like mass and geometry (thickness and surface area) are adjusted to match the characteristics of a Renault ZOE.

A solar view factor describes the portion of solar flux reaching each part of the cabin. The sun is considered to be at full height (90°C) for all simulations. Hence, the solar flux mostly affects the roof and the windshield while the side and rear parts of the car experience a lower impact. An absorptivity coefficient (0.4) and an emissivity coefficient (0.96) are introduced to represent the solar effect on the outside of roof and doors. Another set of coefficients is used for the glass windows (0.15 for absorptivity and 0.9 for emissivity), with the addition of a transmission coefficient (0.7).

The modelling of the cabin floor thermal interaction is obtained with convection at both sides: internal and external. Heat rate through the three-layer floor material is calculated with conduction. Similar modelling is also possible for the roof and side doors of the cabin, with the addition of the solar flux on the external side. This modelling is also the same for all glass surfaces (windows and windshield) but with a single layer instead of a three-layer material. The thermal effect on the internal lumped material of the cabin is governed by the solar flux coming through the glass surfaces. Finally, two heat sources are included in the cabin:

- 100W that represents the heat coming from the electrical motor and the dashboard auxiliaries
- 75W per person, which is the heat input from occupants [13,14]

2.1.5. Passenger model

In the model, the number of occupants is multiplied by the amount of heat, CO_2 and humidity emitted by an average adult. A CO_2 injector placed in the cabin volume simulates the exhalation flow rate from the occupants: CO_2 mass flow rate of 18.75 L/h. This value is an average for one human adult in normal seated activity level (e.g. office work, paper reading, driving…) [15]. The variability of CO_2 exhalation flow rate can be widely discussed as it is influenced by numerous factors, like age, metabolic rate, stress level, activity level, etc.

Breathing and sweating of the occupants is also a source of humidity. This is highly dependent on the ambient conditions (temperature and humidity) and human factors (clothing, activity level, metabolism, age, weight, etc.). Average values and models are found in the literature [16–18]. The main factors of influence that are relevant are the temperature and humidity. In the model, different cases are implemented depending on outside conditions: 30 g/h in cold condition (below 10°C), 50 to 65 g/h in standard condition (around 20°C and 50% of relative humidity) and 100 g/h in hot and humid condition (above 30°C and 65% of humidity). These values are fixed for the duration of a simulation, i.e., there is no dependence with cabin temperature. Lastly, the model considers that this H_2O source is emitted in pure vapour condition (and not liquid). It has a direct impact on the cabin humidity level, with consequences on the performance of the heat exchanger (e.g., condensation) connected to the heat pump circuit.

2.1.6. Ventilation strategies: opti-CO_2 and opti-H_2O

In the cabin air circuit, the ratio of fresh air against recirculated air is controlled by the recirculation flap. Control of the recirculation ratio is required to reduce the energy consumption, particularly in rough environments with extreme temperatures. It can be set at a predefined variable or constant value for a simulation scenario. For safety and health concerns, a full recirculation mode is not possible. Two additional modes are created in the model: “opti-CO_2” and “opti-H_2O”. In both cases, the opening of the recirculation flap is controlled by a PID regulator. The idea is to find a trade-off between moderate energy consumption and safe air inside the cabin.

In the opti-CO_2 mode, the recirculation flap is regulated between its two extreme positions to achieve a target CO_2 concentration in the vehicle. As no regulation exists for vehicle in-cabin CO_2 level, a standard limit value between 1100 and 2000 ppm can be selected to keep passengers in a comfortable and safe space. According to an experimental study [19] this level is not associated to health risks, but is the baseline to first signs of cognitive dysfunctions (e.g. lack of concentration). The ASHRAE guideline [20] states that the comfort limit for air renewal in a closed space is strongly correlated to a CO_2 level below 1100 ppm. This limit can be discussed for a vehicle application, where the level and duration of exposure can be quite variable.

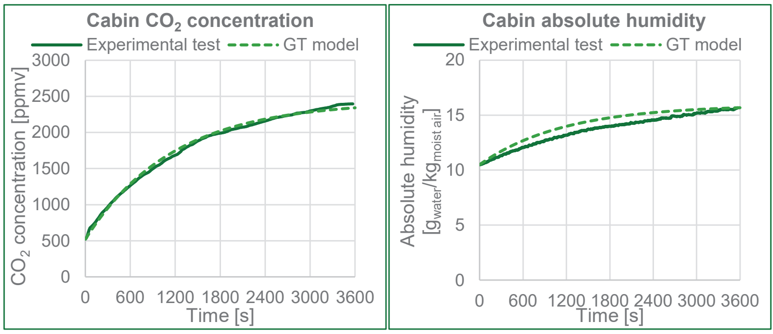
Similar to the opti-CO_2 mode, a control of the recirculation flap is implemented to limit the condensation issue. This opti-H_2O mode is based on the variable that monitors the risk of fogging on the front windshield. The target of the PID regulator is a fog risk of 95% (5% margin before condensation).

2.2. Calibration and validation with experimental data

If available, the input model data is filled to match the characteristics of a Renault ZOE (eco2 phase 1). It is a full electric car (88 ch), with five doors and a cabin volume of 2.5 m^3. In the scope of this project, different test campaigns (more than 20) are used to calibrate and validate the simulation model. Otherwise, the generic data provided by GT-Suite for similar sized-vehicle and components is used. This is as per the recommendation in the software manual and only considered if the input data is limited. Such data is mostly based on predictive correlations and literature models. Then, the calibration stage allows to adjust the parameters.

A small sample of the validation tests are described in this article, and a separate paper focuses on the infiltration topic [12]. The idea is to compare the experimental results with the simulation results. The test conditions are then reproduced in the simulation tool. Given the large number of experimental evidence, only a few examples are shown in this paper.

Figure 5 depicts the evolution of the CO_2 and humidity concentrations in the cabin over time. The test is done with a parked vehicle (0 km/h) for a duration of one hour. The blower flow rate and recirculation ratio are fixed respectively at 180 kg/h and 94%. This ventilation condition leads to a rise of the CO_2 and humidity concentrations in the cabin. Once again, the simulation tool gives similar results to the tests.



Vehicle speed	0 km/h
Cycle duration	3600s
Blower flow rate	position 4 out of 8 = 154 m^3/h (180 kg/h)
Recirculation ratio	94%
Amb. temperature	15°C
Ambient humidity	82%
Ambient CO2	445 ppmv
Occupants	1 (only the driver)
Water emission	50 g/h per person

Figure 5. Sample of the validation of the simulation tool with experimental results regarding cabin CO_2 concentration and absolute humidity.

These results are a part of larger experimental test campaigns, covering a diverse range of environmental conditions. It shows that the simulation tool can predict accurately the cabin state regarding temperature, CO_2 concentration and humidity level.

3. Results and discussion

3.1. Potential increase in driving range with the opti-CO_2 strategy

The traditional ventilation setting in a passenger car is the fresh air mode (0% recirculation). This configuration leads to a good amount of air renewal, but it is not optimised for the energy consumption of the HVAC system. In an electric vehicle, the heat pump energy required to heat or cool the cabin is drained directly from the battery, thus decreasing the driving range. Controlling the recirculation ratio is necessary to decrease the impact of the HVAC system, particularly in rough environments with extreme temperatures. For health and safety related concerns (CO_2 intoxication), a full recirculation mode is not possible. The idea of the opti-CO_2 mode is to find a trade-off between a moderate energy consumption and safe air inside the cabin.

Table 1 depicts the maximum recirculation ratio allowed to keep the cabin CO_2 concentration below the target. These values depend on the number of occupants (and their CO_2 emission), the blower flow rate, and the infiltration flow rate. If the CO_2 target is increased from 1100 to 2000 ppm, the recirculation ratio can be set to a higher value.

https://doi.org/10.52202/069564-0216

Table 1. Regulation of CO_2 concentration with a blower flow rate of 200 m3/h and assuming no infiltration.

	Stabilized volumetric recirculation ratio in opti-CO_2 mode	
Number of occupants	Target = 1100 ppm	Target = 2000 ppm
1	79%	90%
2	61%	83%
3	42%	75%
4	21%	65%
5	2%	57%

The power consumption for heating and cooling is calculated using the simulation tool. Three ambient scenarios are compared: summer, winter, and spring. The outside temperatures are 30°C, −15°C and 19°C, respectively with a solar flux of 750, 250 and 500 W/m^2. The heat pump targets a cabin temperature of 19°C in the case of winter and spring, and 25°C in the summer. The other simulation settings, along with the results regarding power consumption and driving range gain estimations are given in Figure 6. The range is roughly estimated using Eq. (4):

$$Range_{loss} = Range_{max} - \frac{Range_{max}}{1 + \frac{Specrange * Power}{Speed}} \tag{4}$$

The maximum driving range is 300 km, with a specified range of 6.6 km/kWh and an average speed of 47 km/h as described in WLTC (Worldwide harmonized Light-duty vehicles Test Cycles). The "range gain" chart (Figure 6) is calculated by subtracting the $Range_{loss}$ of the given configuration to the common 0% recirculation case.

Eventually for the three scenarios, the best trade-off between energy consumption and safe air environment is achieved with the opti-CO_2 mode. Compared to the traditional "full fresh air" mode, the power gains of the heat pump in winter, spring and summer scenarios are respectively 14%, 19% and 38% (1100 ppm target). These gains are important because they can directly influence the driving range. In the 0% recirculation case, the range loss is estimated at 88, 26 and 85 km in the winter, spring and summer scenarios, respectively.

Vehicle speed	WLTC	Infiltration	Yes
Cycle duration	1800s	Number of occupants	2
Outside CO_2	400 ppm	Blower flow rate	200 m^3/h

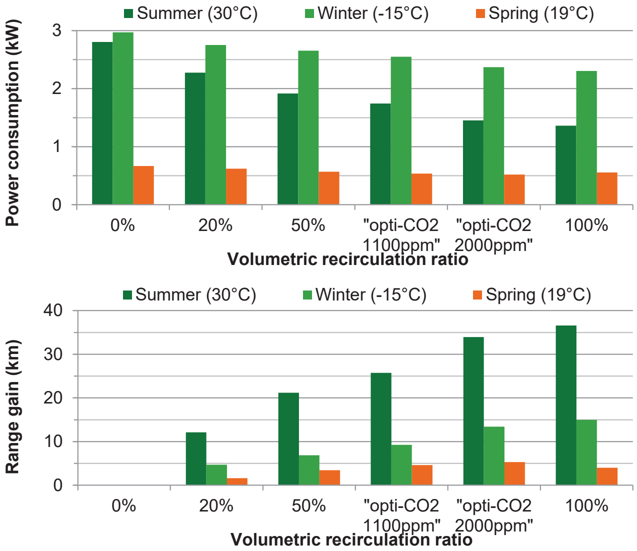


Figure 6. Power consumption (of compressor heat pump) needed for thermal comfort and impact on the driving range of an electrical vehicle.

With the opti-CO_2 mode at 1100 ppm, the driving range is increased by 9, 5 and 26 km compared to the full fresh air case. Increasing the opti-CO_2 target from 1100 to 2000 ppm gives an additional range gain in the three scenarios: 8, 4 and 1 kms. These benefits must be weighed against the potential health risks caused by slightly higher CO_2 exposure. The health aspect is not well documented, so it is difficult to give a precise health assessment in the range between 1100 to 2000 ppm. Besides, a different strategy could be applied to the HVAC system. In the simulation tool, the CO_2 target is continuously fixed over time. A new control strategy could set the target at a higher value in steady state mode, but provide periods of fully fresh air. Nevertheless, the results presented in this section give an idea of the influence of the CO_2 target on increasing the driving range. The objective of the next subsection is to assess another risk inside the cabin: humidity accumulation.

3.2. Humidity level and evidence of fogging risk

The humidity level is evaluated with the simulation tool in simple scenarios. The objective is to establish the conditions under which condensation can occur on the glass surfaces inside the cabin. Different ambient temperatures are tested, from −10°C to +10°C, with a relative humidity of 85%. A moderate solar flux of 250 W/m^2 is also considered. The vehicle speed is set to 60 km/h for a duration of 10 minutes. A fixed speed is preferred rather than a realistic driving cycle to limit the variations due to infiltration. There are two occupants in the cabin. Each person emits water vapour at a 50 g/h rate. The blower flow rate is set to 200 m^3/h, which corresponds to a medium blower position in a Renault ZOE.

Different recirculation modes are compared, including the standard 0% and 100% fresh air modes. Depending on the vehicle speed, such ventilation settings can trigger infiltration. The infiltration flow rate is null in the fresh air mode, and at 20 m^3/h in recirculation mode. An additional recirculation mode is implemented in the simulation: opti-CO_2. The target of CO_2 concentration in the cabin is fixed at 2000 ppm. With two occupants, the recirculation mode is activated during 425s. This is the time required to increase the CO_2 concentration to 2000 ppm. Then, the fresh air ratio is fixed to 5%. The main simulation results of humidity and fogging with two occupants are given in Figure 7.

Vehicle speed	60 km/h	Infiltration	Yes	Ambient humidity	85%
Cycle duration	600s	Number of occupants	2	Solar flux	250 W/m^2
Blower flow rate	200 m^3/h	Water emission	50 g/h per person	Opti-CO_2 target	2000 ppm

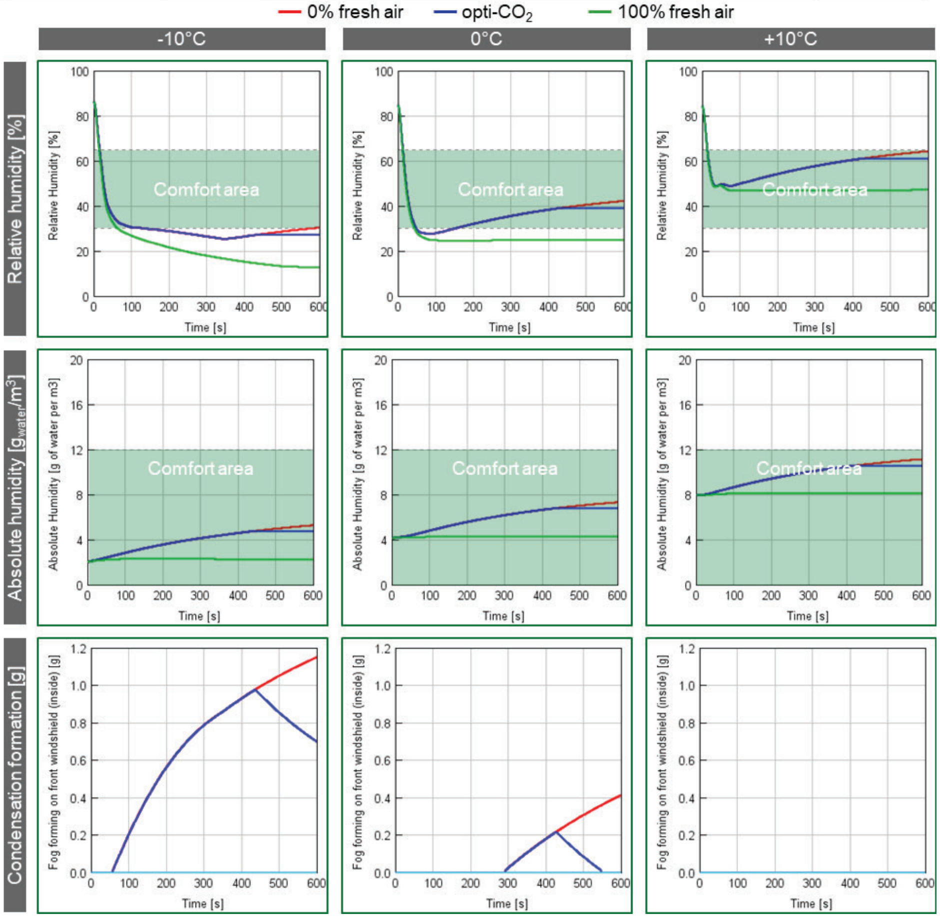


Figure 7. Cabin humidity level and fog formation in the front windshield for three ambient temperatures, and three recirculation modes.

https://doi.org/10.52202/069564-0216

The relative humidity in the cabin depends mainly on the outside temperature. In all cases, the relative humidity is dropping very quickly at the beginning of the cycle. In approximately one minute, the level drops from 85% to a value between 25% and 50%. At −10°C, the humidity ranges between 13% and 30% at the end of the simulation, which is just below the minimum requirement for comfort. At each step of increasing the temperature by 10°C, the relative humidity increases as well. At 0°C and 10°C, the comfort area is globally more achievable. The absolute humidity is kept below the comfort limit in all cases. Regardless of the temperature, humidity is increased by 17% when switching from the fresh air mode to the recirculation mode. It reaches 3.1 g_{water}/m^3 at the end of the simulation.

The amount of condensation on the windshield is also shown on Figure 7. It depends on the amount of water inside the cabin, and the wall temperature of the windshield on the cabin side. In fresh air mode, there is no condensation, regardless of the temperature. In recirculation mode, although there is less humidity at lower temperature, there is more condensation. It appears approximately one minute after the start at −10°C, and after five minutes at 0°C. During these iterations, the relative humidity decreases rapidly, but the absolute humidity increases. Once the absolute humidity reaches a sufficient level along the windshield temperature, there is condensation. At −10°C, it is up to 1.2 g at the end of the cycle, and 0.4 g at 0°C. However, at +10°C, there is no condensation.

The analysis of the amount of condensation in the opti-CO_2 configuration is very interesting. Until 425s, the condensation curve follows the 0% fresh air curve. This is because the vehicle is in recirculation mode to increase the CO_2 level. At 425s, the condensation amount is 1.0 g at −10°C, and 0.2 g at 0°C. At this time, the CO_2 concentration hits the target (2000 ppm). Then, the fresh air ratio is regulated at 5% to stabilise the CO_2 level. From 425s to 600s, the condensation amount decreases in opti-CO_2 mode. At −10°C, it is down to 0.7 g at the end of the cycle. At 0°C, there is no more condensation after 550s.

Inversely, in recirculation mode, there is still fog forming at the end of the cycle, the condensation amount is still increasing. Then, there is a large difference of condensation behaviour between the two configurations (opti-CO_2 mode vs. recirculation mode). However, the change in fresh air ratio is not much (5% vs. 0%). It means that a slight change of the recirculation flap position can lead to a large change in fogging.

A sensitivity analysis is made with the simulation tool. The responsiveness of the humidity level and the condensation amount against several parameters is summarised in Table 2.

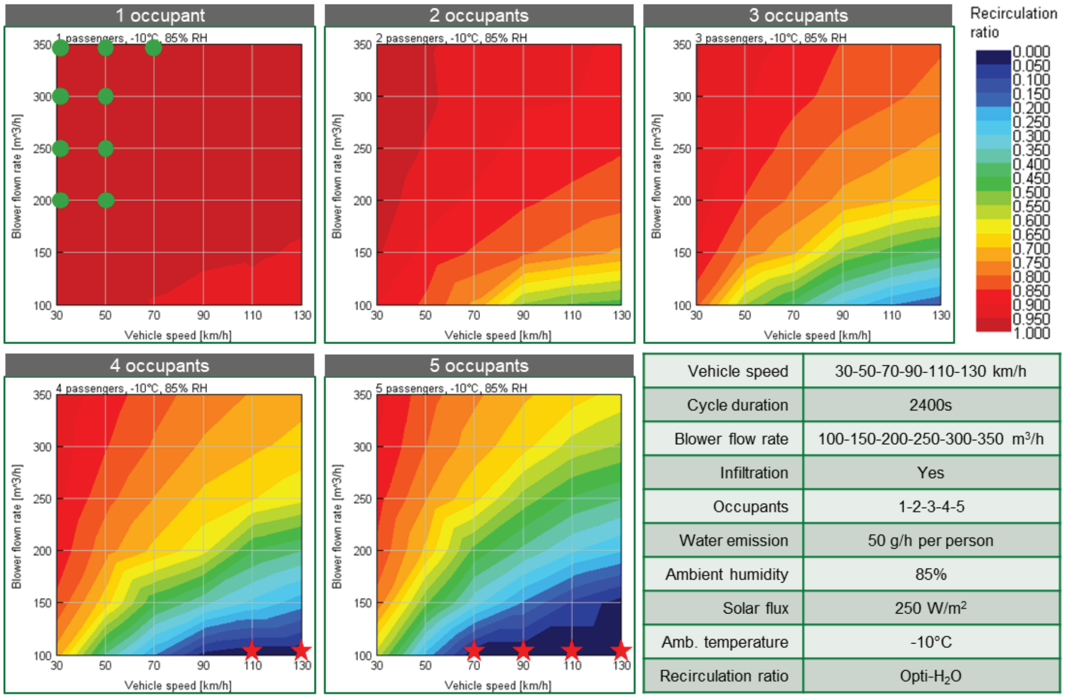
Table 2. Influence of four parameters on the cabin humidity and amount of condensation.

If …… increases (↗),	then humidity level …….	and condensation ……
temperature	increases (↗)	decreases (↘)
fresh air ratio	decreases (↘)	decreases (↘)
blower flow rate	decreases (↘)	decreases (↘)
number of occupants	increases (↗)	increases (↗)

Globally, there is a higher relative and absolute humidity in the cabin as the temperature increases. However, the level of condensation on the front windshield is higher for lowest temperatures. At +10°C, there is no condensation. Besides, for all outside temperatures, the recirculation mode leads to a higher level of humidity and a higher level of condensation. The fresh air mode prevents the appearance of condensation on the front windshield, even at −10°C. Then, the blower flow rate has a limited influence on the humidity level and condensation. A minimum flow rate is required to limit condensation, but the gains at high blower flow rates are small. Finally, as the number of occupants increases, the source of humidity in the cabin increases as well. This leads to a much higher level of humidity in the cabin, and a higher risk of fog formation on the windshield.

3.3. Investigation of the opti-H_2O strategy

The opti-H_2O is applied to a set of simulations with the ambient temperature −10°C. The objective is to obtain the ideal recirculation ratio in each situation. Different parameters are varied to obtain a wide range of results. The blower flow rate is set between 100 and 350 m^3/h. The vehicle speed is fixed over time for each simulation, between 30 and 130 km/h. This allows the full spectrum of infiltration to be covered. Finally, the number of occupants is a major parameter for the humidity aspect. It is set between one and five. The other simulation parameters are fixed as described in Figure 8. In total, 180 simulations are performed: 6 vehicle speeds, 6 blower flow rates and 5 number of occupants. The cycle duration (2400s) is long enough to reach stabilisation in all cases. The recirculation ratio at the end of the simulation is presented in the five contour plots of Figure 8. Each map represents a single number of occupants, i.e., 36 simulations. The recirculation ratio at 2400s is given between 0 (full fresh air mode) and 1 (full recirculation mode). It should be noted that the fog risk might cross the 95% target during the transient stage of the cycle, thus condensation could appear.



Vehicle speed	30-50-70-90-110-130 km/h
Cycle duration	2400s
Blower flow rate	100-150-200-250-300-350 m^3/h
Infiltration	Yes
Occupants	1-2-3-4-5
Water emission	50 g/h per person
Ambient humidity	85%
Solar flux	250 W/m^2
Amb. temperature	-10°C
Recirculation ratio	Opti-H_2O

Figure 8. Recirculation ratio in stabilised stage of opti-H_2O mode at −10°C, depending on vehicle speed (x axis), blower flow rate (y axis) and number of occupants (map).

In some cases (red stars), the 95% target cannot be reached even with 100% fresh air. The fog risk stays above 95% as there is too much humidity in the cabin. These cases are for a low blower flow rate combined with a high number of occupants and a high vehicle speed. These cases must be avoided to prevent continuous fog formation. In other cases (green dots), the 95% target cannot be reached event with 100% recirculation. These cases are not really an issue because the fog risk stays below 95%. It is possible to reach the minimum energy consumption without any risk of condensation. In the simulation, it occurs only with one occupant, at high blower flow rate and low vehicle speed.

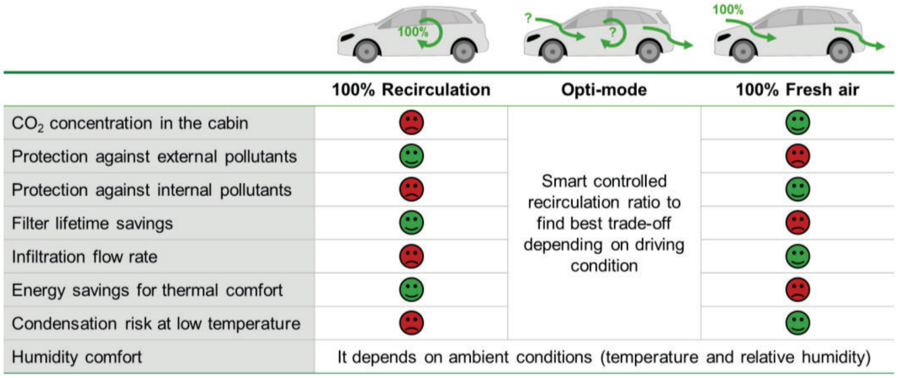
The analysis of the results can be divided in three parts. Firstly, as the number of occupants increases, the humidity level in the cabin increases as well. A higher amount of fresh air is required to avoid condensation. With five occupants, at a medium speed (50 km/h) and medium blower flow rate (200 m^3/h), the recirculation ratio should be kept below 70%. With a single occupant in the cabin, whatever the ventilation settings, the recirculation ratio can be kept above 90% with a low risk of fog formation.

Secondly, as the blower flow rate increases, the recirculation ratio can be increased. Indeed, the idea is to keep a certain amount of fresh air that enters the vehicle. For a fixed amount of fresh air, the recirculation ratio can be increased if the total flow rate increases as well.

Finally, for a fixed blower flow rate, a higher vehicle speed tends to decrease the recirculation ratio. There are two impacts of a higher vehicle speed. On one hand, the infiltration flow rate increases. This brings more fresh air into the cabin, which helps for the condensation issue and also leads to a higher recirculation ratio. On the other hand, the windshield convection coefficient increases with speed. There is more heat exchange on the outside surface of the windshield, which leads to a colder temperature in the interior surface. At the end of the simulation, the interior windshield temperature is 6.6°C at 30 km/h, and −3.7°C at 130 km/h. A lower windshield temperature triggers the formation of condensation. This would lead to a lower recirculation ratio to avoid condensation. Due to the shape of the map, the impact of the convection coefficient is larger than the impact of infiltration: higher vehicle speed leads to lower recirculation ratio.

3.4. Air quality considerations

The air quality includes management of the CO_2 and H_2O species, but also the different pollutants in and out of the vehicle environment: volatile organic compounds (VOCs), fine and ultrafine particles (PM and UFP) or pollutant gases such as ammonia (NH_3). Alongside the regulation of temperature, CO_2 and humidity, the goal of the HVAC system is to provide a clean environment for the passengers. This function is performed by a filtration system, comprising of one or several filters. Then, the energy management strategy can influence the design of the filtration system. Depending on the pollution source (within the cabin or outside the car), the best position of the filter can be in the fresh air path or in the supply air path. In a small and closed volume, an interior pollutant can rapidly degrade the health of the occupants. Similarly, an external pollutant may expose passengers to a health risk. In both cases, the ventilation strategy alone cannot provide a safe solution. As shown in Figure 9, both the recirculation and fresh air modes have some drawbacks. The use of filter appears as a more sustainable solution.



	100% Recirculation	Opti-mode	100% Fresh air
CO_2 concentration in the cabin	☹	Smart controlled recirculation ratio to find best trade-off depending on driving condition	☺
Protection against external pollutants	☺		☹
Protection against internal pollutants	☹		☺
Filter lifetime savings	☺		☹
Infiltration flow rate	☹		☺
Energy savings for thermal comfort	☺		☹
Condensation risk at low temperature	☹		☺
Humidity comfort	It depends on ambient conditions (temperature and relative humidity)		

Figure 9. Pros and cons of the different recirculation strategies.

Most vehicles have a single filter placed on the supply air path. This approach, which allows to get rid of a proper portion of the pollutants, can be improved by introducing additional and more efficient High Efficiency Particulate Air (HEPA) filters. This high-end media has >99% efficiency against fine particles. Thereby, it can decrease the level of particulate matter exposure for the passengers. With this technology, the lifetime of the filter must be evaluated to have a durable system. An aged filter has a high differential pressure that can decrease the blower performance. So, the ventilation system could include an air quality control strategy, alongside energy and humidity optimization strategies. A smart cabin air Filtration system (Smart CAF) has been evaluated in a study [21].

4. Conclusion

There is a difficult challenge with the ventilation system. In order to decrease the energy consumption to heat or cool the cabin, it is best to increase the recirculation ratio. However, it is not possible to have a prolonged full recirculation mode in the vehicle without having a high condensation risk and high concentration of CO_2. Both the opti-CO_2 and opti-H_2O modes intend to maximize the recirculation ratio up to a safe level. Consequently, it reduces the power consumption of the HVAC system. The gains in driving range compared to the common fresh air mode result to only a few kilometres. This is particularly appealing for electric vehicles in cold or hot regions. In the opti-CO_2 mode, the idea is also to provide good thermal comfort and keep the CO_2 concentration in the cabin at a safe level. In the opti-H_2O mode, the goal is to prevent the formation of condensation on the windshield. In a complete system, the opti-H_2O mode should probably be prioritised over the opti-CO_2 mode because it is a safety aspect for driving the vehicle.

These modes are only tested with the simulation tool and it has some limitations. The main one is that it is a mono-zone model. In most vehicles, it is possible to orient the blower flow rate in different directions, including toward the windshield. This can be a strategy to manage the level of humidity near the windshield.

Acknowledgments

The work in this article is done in a joint International Research Chair entitled “Filtration systems: fluid dynamics and energy consumption reduction” between MANN+HUMMEL and Ecole Centrale de Nantes. This research work is financially supported by the French Government and managed by the National Research Agency (ANR) with the Future Investments Program. The authors want to thank Antoine Bouedec for his contributions to the experiments.

Nomenclature

Cm	Condensation mass (mass of water per mass of dry air), g/kg
h	Convective heat transfer coefficient, W/m^2/K
Lc	Characteristic length of the windshield, m
$\mathrm{M}()$	Molecular weight of species (), kg/mol
Nu	Nusselt number, -
$\mathrm{p}_{\mathrm{tot}}$	Total pressure of air, Pa
p_{ws}	Partial pressure of water vapour at saturation, Pa

x_w	Mole fraction of water, -
X_w	Mixing ratio (mass of water vapour per mass of dry air), g/kg
x_{ws}	Mole fraction of water at saturation, -
X_{ws}	Mixing ratio at saturation, g/kg

Greek symbols

λ	Thermal conductivity, W/m/K

References

[1] Farrington R, Rugh J. Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range. In Washington (DC), USA: National Renewable Energy Laboratory; 2000.

[2] Fojtlín M, Fišer J, Pokorný J, Povalač A, Urbanec T, Jícha M. An innovative HVAC control system: Implementation and testing in a vehicular cabin. Journal of Thermal Biology. 2017 Dec 1;70:64–8.

[3] ASHRAE Handbook - Fundamentals. SI Edition. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers); 2013. 1134 p.

[4] Schriver-Mazzuoli L. La pollution de l'air intérieur Sources, Effets sanitaires, Ventilation [Internet]. Dunod; 2009 [cited 2021 Jun 2]. 273 p. Available from: http://international.scholarvox.com/book/45006325

[5] Arundel AV, Sterling EM, Biggin JH. Indirect Health Effects of Relative Humidity in Indoor Environments. Environmental Health Perspectives. 1986;65:351–61.

[6] Matton TJP. Simulation and Analysis of Air Recirculation Control Strategies to Control Carbon Dioxide Build-up Inside a Vehicle Cabin [PhD thesis]. [Ontario, Canada]: University of Windsor; 2015.

[7] Tsutsumi H, Hoda Y, Tanabe S ichi, Arishiro A. Effect of Car Cabin Environment on Driver's Comfort and Fatigue. In: SAE Technical Paper [Internet]. Detroit, MI, USA: SAE Technical Paper; 2007 [cited 2020 Mar 6]. Available from: https://www.sae.org/content/2007-01-0444/

[8] Grady ML, Jung H, Kim Y chul, Park JK, Lee BC. Vehicle Cabin Air Quality with Fractional Air Recirculation. In: SAE Technical Paper [Internet]. Detroit, MI, USA: SAE Technical Paper; 2013 [cited 2020 Jan 24]. Available from: https://www.sae.org/content/2013-01-1494/

[9] Jung HS, Grady ML, Victoroff T, Miller AL. Simultaneously reducing CO 2 and particulate exposures via fractional recirculation of vehicle cabin air. Atmospheric Environment. 2017 Jul;160:77–88.

[10] Burtscher H, Loretz S, Keller A, Mayer A, Kasper M, Artley RJ, et al. Nanoparticle Filtration for Vehicle Cabins. In: SAE Technical Paper [Internet]. 2008 [cited 2020 Jan 24]. Available from: https://www.sae.org/content/2008-01-0827/

[11] Matte-Deschênes G. Modélisation de l'efficacité de capture de filtres particulaires pour moteur Diesel [MSc thesis]. [Montréal, Canada]: Ecole Polytechnique de Montréal; 2014.

[12] Lesage M, Chalet D, Migaud J. Experimental analysis and quantification of air infiltration into a passenger car cabin. Transportation Research Part D: Transport and Environment. 2021 Oct 1;99:103006.

[13] Li W, Sun J. Numerical simulation and analysis of transport air conditioning system integrated with passenger compartment. Applied Thermal Engineering. 2013 Jan;50(1):37–45.

[14] Marcos D, Pino FJ, Bordons C, Guerra JJ. The development and validation of a thermal model for the cabin of a vehicle. Applied Thermal Engineering. 2014 May;66(1–2):646–56.

[15] Yoon SH, Ahn HS, Choi YH. Numerical study to evaluate the characteristics Of HVAC-related Parameters to reduce CO2 concentrations in cars. International Journal of Automotive Technology. 2016 Dec;17(6):959–66.

[16] Gładyszewska-Fiedoruk K, Teleszewski TJ. Modeling of Humidity in Passenger Cars Equipped with Mechanical Ventilation. Energies. 2020 Jun 10;13(11):2987.

[17] Zemitis J, Borodinecs A, Frolova M. Measurements of moisture production caused by various sources. Energy and Buildings. 2016 Sep;127:884–91.

[18] Dullinger C, Struckl W, Kozek M. A modular thermal simulation tool for computing energy consumption of HVAC units in rail vehicles. Applied Thermal Engineering. 2015 Mar;78:616–29.

[19] Satish U, Mendell MJ, Shekhar K, Hotchi T, Sullivan D, Streufert S, et al. Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance. Environmental Health Perspectives. 2012 Dec;120(12):1671–7.

[20] Petty S. Summary of ASHRAE's Position on Carbon Dioxide (CO2) Levels in Space. Energy & Environmental Solutions.

[21] Lesage M, Del Fabbro L, Migaud J, Chalet D, Le Nain, Eduin E, Ebnet D. Cabin air quality and energy savings in electric vehicles by using a smart filtration system. In: FILTECH [Internet]. Cologne, Germany; 2019 [cited 2020 Feb 24]. Available from: https://hal.archives-ouvertes.fr/hal-02330724

https://doi.org/10.52202/069564-0216