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Article

Characterisation of Comfort and Air Quality in an Electric Vehicle in Heating and Cooling Operations†

Luigi Russi [1,‡]* , **Paolo Guidorzi** [1] , **Beatrice Pulvirenti** [1] ,
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1   **Abstract:** This work is aimed at the experimental characterisation of air quality within a vehicle
2   cabin, by measuring at the same time the HVAC system energy consumption. Pollutant concen-
3   trations in the vehicle cabin are measured by means of a low-cost system of sensors. The effects
4   of the HVAC system configuration on the cabin air quality are discussed, such as fresh-air and
5   recirculation mode. It is shown that the PM concentrations obtained in the recirculation mode
6   are lower than those obtained in fresh-air mode, while the VOC concentrations obtained in the
7   recirculation mode are higher than those obtained in fresh-air mode. The energy consumption is
8   measured in relation to the configuration of the HVAC system and the measured concentrations.
9   The novelty of this work is the combined measurement of important comfort parameters such as
10 temperature distribution and air quality within the vehicle and the real time energy consumption
11 of the HVAC system. A wider concept of comfort is enabled, based on the use of low-cost sensors
12 in the automotive field.

13 **Keywords:** Electric vehicle, pollutant concentration, HVAC, Arduino sensors, vehicle energetics

1. Introduction

15 This paper describes a series of experimental readings of air quality and energy
16 efficiency inside the passenger compartment of a car. The measurements were carried
17 out using low cost sensor systems and connecting to the car's On-Board Diagnostic bus
18 (OBD) [1]. The temperature and the other environmental parameters inside the vehicle's
19 enclosure are affected by outside weather conditions as well as by the Heating, Ventila-
20 tion, and Air Conditioning (HVAC) working state. Reducing the power consumption
21 of the HVAC system, as well as other secondary systems of course, is of paramount
22 importance in this era of migration to electric powered transportation, and the major
23 challenge is to achieve this while maintaining high levels of comfort in the cabin. The
24 best thermal management in the cabin of the car is obtained by maximizing comfort level
25 along with minimizing electrical power demand. For example, choosing the intake air
26 recirculation mode is recommended under certain conditions to economize energy and
27 increase driving duration. EPA released fuel credits with the growth of re-circulation of
28 air in 2017. The energy benefits of the recirculation mode are undisputed, but there are
29 some points to consider: CO2 and VOC accumulation, pollutant infiltration and odour
30 problems. Cabin air quality, especially when air is re-circulating, should be measured
31 and regulated to keep concentrations of certain pollutants below specific thresholds [2].
32 It should also be mentioned that air re-circulation can produce substantial benefits in
33 relation to certain air contaminants, which are captured by HVAC filters. Research in the
34 field of vehicle air quality is leading to new methods of testing and best practices, but

Article

Air Quality and Comfort Characterisation within an Electric Vehicle Cabin in Heating and Cooling Operations[†]

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1 **Abstract:** This work is aimed at the experimental characterisation of air quality and thermal
2 profile within an electric vehicle cabin, measuring at the same time the HVAC system energy
3 consumption. Pollutant concentrations in the vehicle cabin are measured by means of a low-cost
4 system of sensors. The effects of the HVAC system configuration, such as fresh-air and recirculation
5 mode, on cabin air quality are discussed. It is shown that the PM concentrations observed in
6 recirculation mode are lower than those in fresh-air mode, while VOC concentrations are generally
7 higher in recirculation than in fresh-air mode. The energy consumption is compared in different
8 configurations of the HVAC system. The novelty of this work is the combined measurement of
9 important comfort parameters such as air temperature distribution and air quality within the
10 vehicle, together with the real time energy consumption of the HVAC system. A wider concept of
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1. Introduction

13

14 One of the major barriers to electric vehicle adoption is due to the limited amount
15 of energy stored in the batteries and needed for traction and auxiliary systems. While
16 ICE vehicles can rely on waste heat for winter requirements, an optimised thermal
17 management of heat loads and gains is crucial for BEVs, paving the way from heat
18 disposal to heat management [2].

19 Reducing the energy consumption of the HVAC system, as well as other auxil-
20 iary systems is of paramount importance in the era of migration to electric powered
21 transportation; the major challenge being to achieve this while maintaining high levels
22 of comfort inside the cabin. On one hand, the best thermal management of the car's
23 cabin is obtained by maximising comfort level along with minimising electrical power
24 demand [3–5]. On the other hand, internal air quality (IAQ) related quantities inside
25 the vehicle's enclosure are affected by outside weather conditions as well as by the
26 Heating, Ventilation, and Air Conditioning (HVAC) settings. From this perspective,
27 every improvement of the cabin thermal management must be IAQ aware [6–9].

28 As an example, choosing the intake air recirculation mode is recommended under
29 certain conditions to reduce energy use and increase driving range. Provided that energy
30 benefits of the recirculation mode are undisputed, it should also be mentioned that
31 it can produce substantial benefits in relation to certain air contaminants, which are
32 captured by HVAC filters [10], but there are some downsides to consider: CO_2 and VOC
33 accumulation, pollutant infiltration and odour problems. United States Environmental
34 Protection Agency (EPA) released fuel credits to manufacturers adopting increased air

still a standard on performance indicators does not exist. Several efforts have been made in order to define a standardized test method for automotive interior air quality [3], but this is still an open question. The Joint Research Center of the European Commission and DG Service Environment are pushing for advancement in this field by stimulating research improvements achieved through the use of low-cost sensors. Although the data measured with these types of sensors are less accurate than laboratory reference equipment, their use has grown greatly in recent years, in applications concerning indoor air quality (IAQ) [4]. This is due also to their ease of use, which makes them suitable for real-time monitoring applications. The road has therefore been opened for the use of low-cost sensors in the automotive sector, for monitoring the air quality inside the passenger compartment. In this paper, the correlation between experimentally measured air quality data and the energy spent by the HVAC system inside the vehicle cabin is investigated. Concentrations of some pollutants in the vehicle cabin [5] are measured by means of a low-cost Arduino sensor-based system [6]. The HVAC system configuration and fresh air recirculation mode of the intake air are varied while PM2.5 and VOC percentages are measured. HVAC air filter performance is evaluated by making cabin air quality measurements with and without the filter installed. The relation between consumed energy, HVAC system working state and pollutant concentrations is obtained in order to investigate a new approach to comfort maintenance inside the car cabin, and for optimizing the development of BEVs vehicles methodologies.

2. Materials and Methods

In the following subsections, the integrated experimental setup and the low-cost sensors chosen are described.

2.1. Description of the experimental setup

To characterise the thermal profile and air quality inside the vehicle cabin, two tests have been performed in real outdoor parking conditions. The vehicle was a 2018 Nissan Leaf Acenta 40 kWh, parked in the faculty parking lot with the front of the car oriented south.
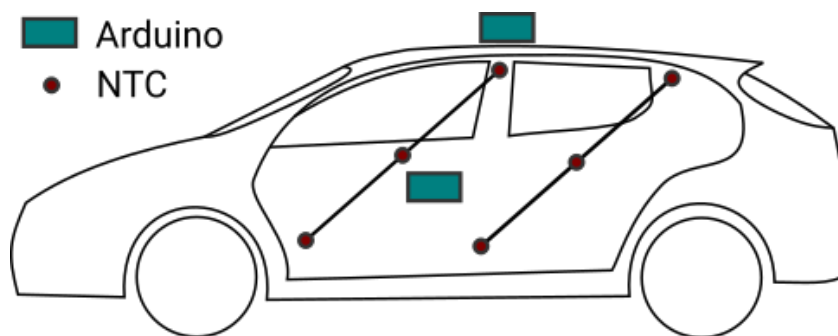

Figure 1. Lateral view of the experimental setup

The temperature distribution within the vehicle cabin is obtained with a grid of 18 DS18B20 temperature sensors following the approach used in [7] and [8] to develop a thermal model of a BEV cabin for energy consumption predictions [9]. The cabin has been ideally divided into three slices horizontally, namely top, middle and bottom level, as shown in Fig. 1 from a lateral view.

On the grid, six sensors are placed on each plane: three in the front side and three in the back side of the cabin. In addition, air quality related quantities have been measured with low-cost sensors on a single location in the cabin; near the gear shift knob together with the acquisition system.

As external conditions can strongly affect the internal micro-climate [10], a second acquisition system has been placed on the car roof. This is identical to the internal one, except for the presence of a single temperature sensor only. The presence of the second

recirculation in 2017; but cabin air quality, especially when air is recirculating, should be measured and regulated to keep concentrations of certain pollutants below specific thresholds [11,12].

Research in the field of vehicle air quality is leading to new methods of testing and best practices, but still a dedicated standard on performance indicators does not exist. Several efforts have been made to define a standardised test method for interior air quality in the automotive field [13], but this is still an open question. A possible approach to address this issue relies on fractional air recirculation, demonstrating that a compromise is achievable between the benefits of full recirculation and its side effects [14]. Other authors propose approaches based on the use of a signal from environmental prediction services [15], and/or on-board sensors [16] to trigger automatic climate control, even though there is still no clear consensus on how to implement these techniques in the HVAC system's control strategy. Such approach would require a trade-off between real time and integral I/O techniques, the former leading to large uncertainties but faster, while the latter provide slower but more stable results [17].

The Joint Research Centre of the European Commission and DG Service Environment are pushing for advancement in this field by stimulating research improvements achieved through the use of low-cost sensors. Although the data measured with these type of sensors are less accurate than laboratory reference equipment, their use has grown greatly in recent years, in applications concerning indoor air quality [18]. Their ease of use, coupled with current scientific advancements [19–21], makes them suitable for real-time monitoring applications. The road has therefore been opened for the employment of low-cost sensors in the automotive sector, such as monitoring air quality inside the passenger compartment.

This paper describes a series of experiments on air quality and energy efficiency inside the passenger compartment of an electric vehicle. The measurements were carried out using a portable low-cost sensor system and reading the car's On-Board Diagnostic bus (OBD) [1]. In this work, the correlation between experimentally measured air quality data and the energy spent by the HVAC system inside the vehicle cabin is investigated. Concentrations of some pollutants in the vehicle cabin are measured by means of a low-cost Arduino sensor-based system. The use of an open-source electronic platform like Arduino allowed fast prototyping and simplified design of the system. In addition, it helped to relax the constraint involved in the construction of hardware and software platforms for data acquisition, following a path that has been outlined by many authors in literature [22–24].

The HVAC system configuration regarding fresh-air recirculation mode of the intake air are varied while PM2.5 and VOC percentages are measured. HVAC air filter performance is evaluated by making cabin air quality measurements with and without the filter installed. The relation between consumed energy, HVAC system settings and pollutant concentrations is obtained, in order to introduce an innovative approach to comfort maintenance inside the car cabin. The novelty of this approach is a win-win perspective, aimed to the concurrent optimisation of the two aspects for BEVs thermal control. The methodology, based on low-cost sensors measurements and applied to a Nissan Leaf Acenta 40 kWh MY2018, is general and applicable to other models of electric car, to show that the use of these sensors for the control of the cabin can yield energy saving together with an optimal air quality and comfort levels.

2. Materials and Methods

In the following subsections, the integrated experimental setup and the low-cost system of sensors are described in detail.

acquisition system is needed to charachterize the environment outside the vehicle and to facilitate inside/outside comparisons with data having the same structure and same metrologic fingerprint.

The approach used in the study, conversely from the one used in ISO standards regarding interior air of road vehicles[11], does not rely on a vehicle test chamber. The latter being well documented and reliable, but not suitable for real-time operation and low-cost equipment.

To have clearer insights on HVAC capabilities, an On-Board Diagnostic (OBD) Linux platform was cleverly installed inside the car to directly retrieve and collect different variables from the electronic control units [12]. Specifically, it was the *iWave OBD-II*: a little device with an *ARM Cortex-A7* processor embedded that runs a light *Yocto Poky* Linux distribution. The *iWave OBD-II* can upload data via a 4G/LTE CAT4/CAT1 sim modem, geolocate the device with a GPS receiver and it can transmit messages with the Bluetooth Low Energy 4.2 module. Communicating via the OBD-II interface, the board reads the HVAC power consumption, the power used by the auxiliary equipment (e.g. lights, infotainment, rear defroster etc.), and the power used by the heater. A fine-time granularity monitoring of those parameters was necessary to correctly interpret how the cabin air changes throughout the experiment.

The overall measured quantities are: air temperature t_a, relative humidity RH, air pressure p_a, TVOC concentration C_{TVOC} and PM$_{2.5}$ concentration C_{PM}. The temperature is measured in 18 points as described above, while the other measurements are taken in one point. The same quantities are measured also outside the cabin. Finally, the power usage of the HVAC system is also logged. Table 1 lists the measured quantities and the correspondent accuracy.

Table 1. Measured quantities.

Variable (Unit)	Description	Sensor	Accuracy (offset + gain)
$t_a(°C)$	Air temp.	DS18B20	$\pm(0.5\,°C + 1\,\%mv^{a})$
$RH(\%)$	Air rel. hum.	BME280	$\pm(3\,\%RH + 1\,\%RH)$
$p_a(hPa)$	Air pres.	BME280	$\pm(1.5\,hPa + 0.12\,hPa)$
$TVOC(ppb)$	TVOC conc.	SGP30	$\pm(15\,\%mv)$
$PM_{2.5}(\mu g/m^3)$	PM2.5 conc.	SPS30	$\pm(10\,\mu g/m^3 + 10\,\%mv)$
$P_i(kW)$	Subsystem i power usage	OBD/Linux	$\pm(250\,W)$

^{a} mv = measured value.

Sensor performance is a device dependent issue that can be measured with various qualifiers [13] and ideally addressed individually. In this study, the same approach for all the measured quantities has been used. A sampling time of $T_s = 10$ seconds has been adopted. The raw data from the acquisition system have been filtered with a moving mean over a 1 minute period, this leads to a 6 point moving mean. Subsequently, the filtered data have been converted to time-stamped data in tabular form, and eventually re-sampled and synchronized among the three acquisition systems. The data analysis process has been performed using open source tools, python 3.8 and several scientific computing libraries (pandas, matplotlib, numpy and scipy above all) following the exploratory data analysis (EDA) approach provided in [14].

2.2. Description of the Arduino-based system of sensors

Two independent measurement systems based on Arduino Mega 2560 were built for the measurement of environmental parameters. The systems have an on-board Real Time Clock (RTC), a data logger on flash memory, a fan and a TFT display. The RTC clocks of the two systems are constantly adjusted thanks to time data received from the

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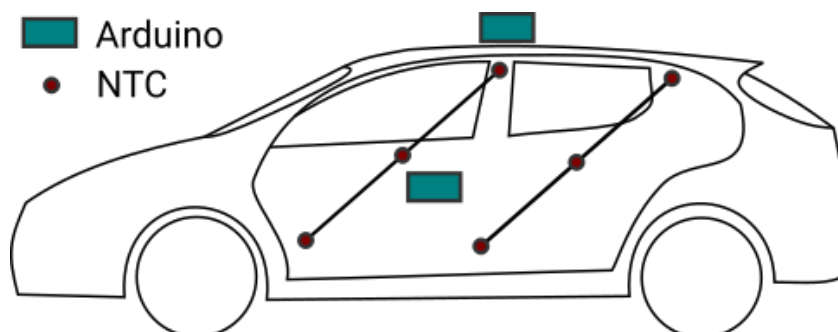

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GPS module. This operation is implemented to facilitate the synchronization of signals from the three acquisition systems.

The internal system is capable of measuring temperatures at 18 locations in the cabin (Maxim Integrated DS18B20 probes). Moreover, the internal system can measure Particulate air Matter (PM) concentration (Sensirion SPS30 sensor), air TVOC concentration (Sensirion SGP30 sensor), air CO_2 concentration (Winsen MH-Z19B non-dispersive infrared sensor), concentration formaldehyde (Winsen ZE08 sensor), air temperature, relative humidity and pressure (Bosch BME280 sensor), air flow velocity (hot wire analog sensor) and GPS position, at a single location. The external system, albeit sharing the same characteristics and using the same sensors, it lacks of the 18-spots temperature measurement, the GPS receiver and the air flow velocity sensor. Both systems are equipped with a fan that conveys air inside the device enclosure, where CO_2 and formaldehyde sensors are mounted, while the SPS30 sensor is equipped with its built-in fan. Both systems independently sampled data at 10-second intervals. All digital sensors used in the measurement device include a microcontroller that implements optimization and self-calibration algorithms.

High-precision, easy-to-use DS18B20 sensors were used to measure temperatures inside the cabin in 18 different positions; they have a typical accuracy of ±0.5°C from -10°C to +85°C and digitally transmit temperature data on a 1-Wire® bus. The use of 1-Wire protocol [15], together with the unique 64-bit serial code allows many sensors on the same bus, thus reducing the cable length and allowing to uniquely associate a sensor output with its position in the network trough a serial-position coupling. Specifically, the DS18B20 actual temperature is provided by a 12-bit analog to digital converter built-in in the digital sensor, with a fine temperature resolution up to 0.0625 °C. Its operating range is between -55°C to +125°C.

The BME280 is a high linearity and high accuracy combined temperature, humidity and pressure digital sensor. Its pressure sensing mechanism is resistive, with an operation range of 300 hPa to 1100 hPa, temperature sensing principle is of the type diode-voltage with a measurement range of $-45\,°C$ to $85\,°C$, measurement principle behind humidity is capacitive and its range is 0 % to 100 % [16]. It features an extremely fast response time $\tau_{63\%}$ of 1 s, thus enabling a consistent oversampling if compared with the current application time granularity of min.

The sensing principle of SPS30 PM sensor is based on laser-scattering, and allows mass concentration and number concentration sensing for particle sizes ranging from 1 μm to 10 μm. As discussed in [17] and [18], the SPS30 is an optical particle counter (OPC) optimised for PM2.5 and smaller particle analysis. Sensirion PM sensors are indeed calibrated using regularly maintained and aligned high-end reference instruments (e.g., the TSI Optical Particle Sizer Model 3330 or the TSI DustTrak™ DRX 8533) only for 2.5 μm particles size. Moreover, as stated in the sensor specification statement from the producer, PM4 and PM10 outputs are not directly measured but estimated from smaller particle counts using typical aerosol profiles. A miniaturized fan and a High Efficiency Particulate Air (HEPA) filter are included to reduce the optical part contamination; it also runs its fan at full speed for 10 seconds every 7 days as an automatic cleaning procedure. Mass concentration measurement range: $0\,\mu g/m^3$ to $1000\,\mu g/m^3$.

SGP30 TVOC sensor is a digital "multi-pixel" gas sensor. It uses multiple sensors, housed on a single metal-oxide gas sensor chip, placed on a thermally controlled hotplate. Digital data output from the sensor includes raw measurements of ethanol and H_2, and calculated values of TVOC and equivalent CO_2 via internal algorithm, such as automatic baseline compensation of the measurement [19]. The TVOC data range from this sensor is between 0 to 60000 ppb. This sensor's equivalent CO_2 were disregarded due to its low sensitivity to external pollutants and due to the absence of passengers in parking conditions.

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p_a(hPa)	Air pres.	Bosch	BME280	$\pm(1.5\,hPa + 0.12\,hPa)$
$TVOC$(ppb)	TVOC conc.	Sensirion	SGP30	$\pm(15\,\%mv)$
$PM_{2.5}$(µg/m³)	PM2.5 conc.	Sensirion	SPS30	$\pm(10\,µg/m^3 + 10\,\%mv)$
P_i(kW)	Subsystem i power usage	iWave	OBD/Linux	$\pm(250\,W)$

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all the measured quantities has been used. A sampling time of $T_s = 10$ seconds has been adopted. The raw data from the acquisition system has been filtered with a moving mean over a 1-minute period, this leads to a 6-point moving mean. Subsequently, the filtered data has been converted into time-stamped data in tabular form, and eventually re-sampled and synchronised among the three acquisition systems. The data analysis process has been performed using open-source tools, python 3.8 and several scientific computing libraries (pandas, matplotlib, numpy and scipy above all) following the exploratory data analysis (EDA) approach provided in [32].

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The measurement system has been characterised both in winter and in summer conditions. In the following sections, two typical conditions for winter and summer have been chosen, to characterise the HVAC system performance in heating and cooling operations, respectively. Winter tests have been performed on January 29, 2021, while summer test have been carried out from July 14 to July 15, 2021.

3. Results and discussion

In this section, the combined measures of air quality and comfort parameters, together with the energy consumption by the electric car are shown and discussed in different seasons, in order to show the differences in relation to the operational mode for the air conditioning. Moreover, an estimation of the filtration performances of the HVAC system is given, by comparing the results corresponding to new and used filters.

3.1. Measurements during heating operation

Two different test conditions have been investigated, for the winter, starting from a state of equilibrium with the external environment, obtained maintaining all systems off and all doors opened for 15 minutes. Once the equilibrium was reached, the proper test was performed while maintaining the heater on for 1 hour, the set-point temperature at its maximum of $30\,°C$, the fan speed at its maximum (position 7), all the windows and all the doors closed. During the first test, the recirculation system was off (meaning that the air ventilation system was in fresh-air configuration), during the second test the recirculation system was instead on.

3.1.1. Fresh-air configuration

The temperature measured inside and outside the cabin keeping the fresh-air mode is shown in Fig. 2(a). The air temperature inside the cabin is obtained by the average of the air temperature measurements on the sensors placed on the grid shown in Fig. 1, *i.e.*, $t_{int} = t_{avg}$. The TVOC concentration measured inside and outside the cabin in fresh-air mode are shown in Fig. 2(b). It is shown that the TVOC concentration increases
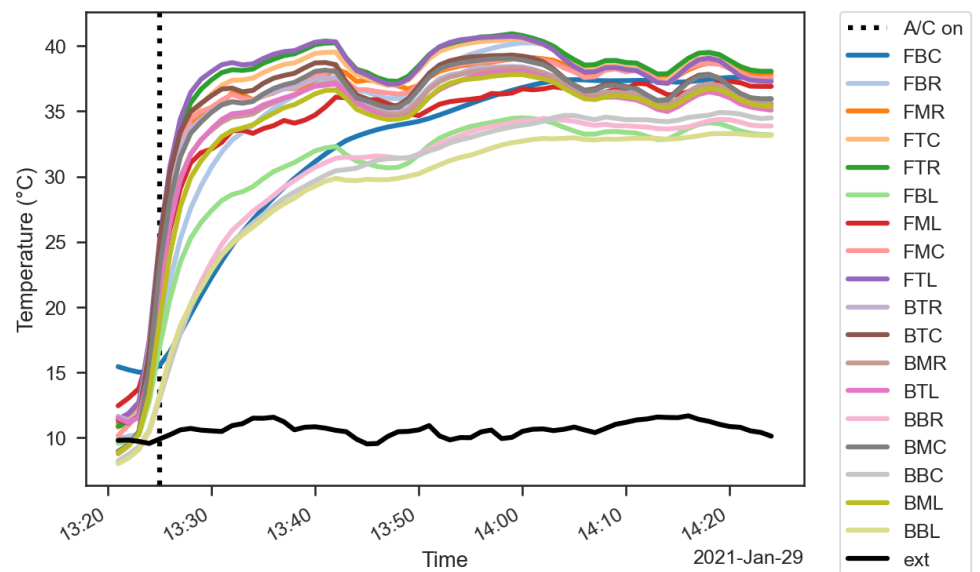
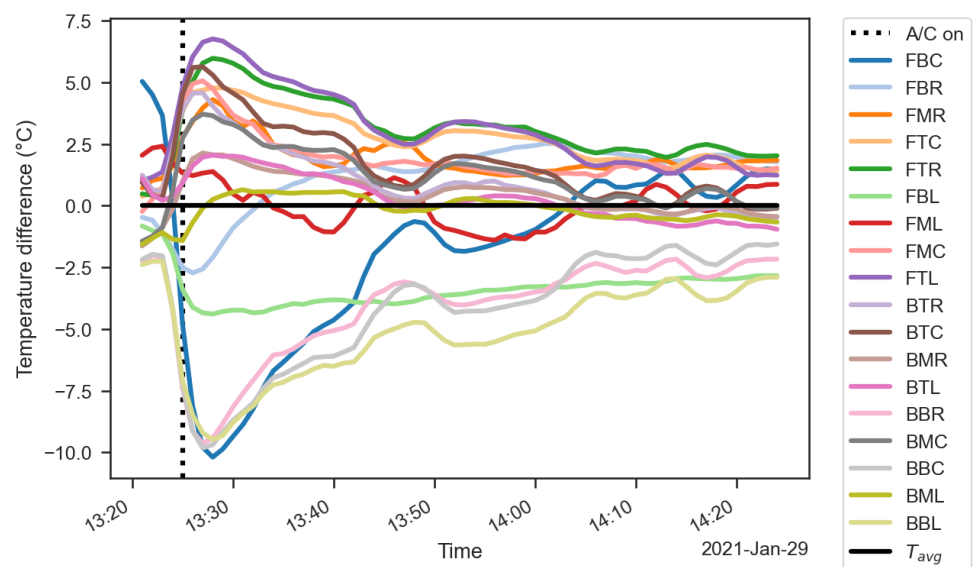**Figure 2.** Heating temperature profiles, fresh-air mode.

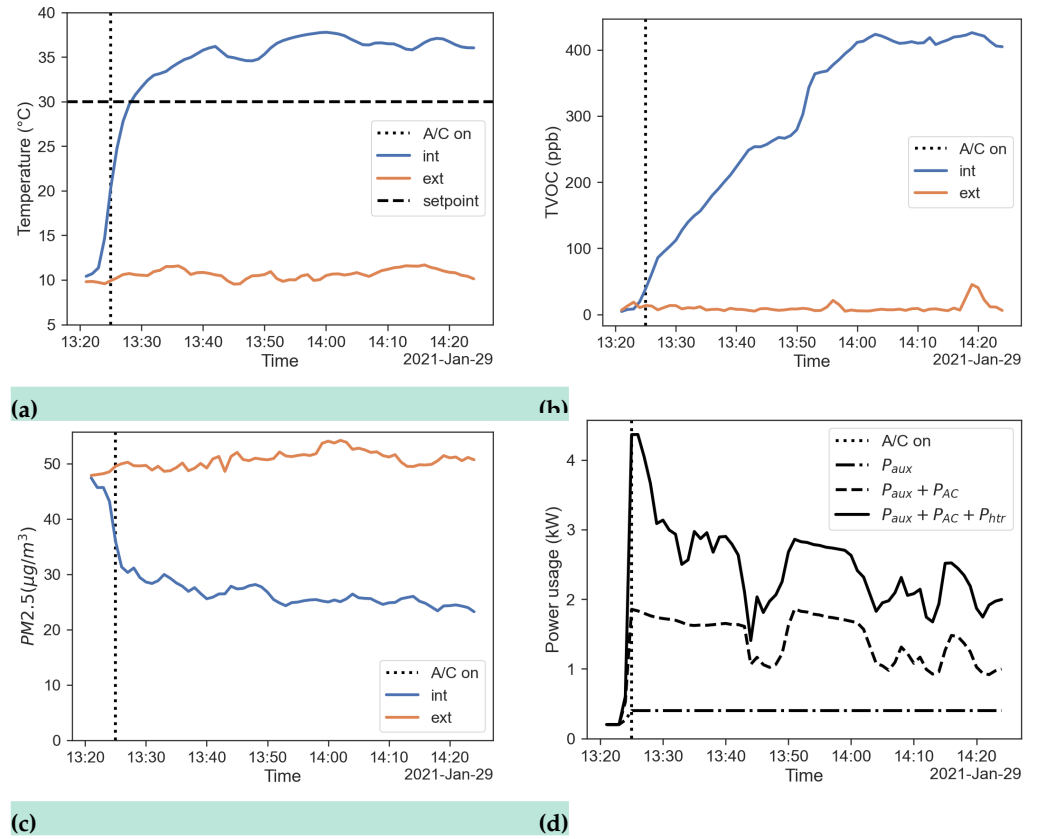**Figure 3.** Heating temperature difference profiles, fresh-air mode.

Figure 2. Results regarding the fresh-air mode. (a) Temperature inside (blue) and outside (red) the cabin; (b) TVOC concentration inside (blue) and outside (red) the cabin; (c) PM2.5 concentration inside (blue) and outside (red) the cabin; (d) power usage of the HVAC system.

while the HVAC system is working, even with a fresh-air mode. This effect is related to the presence of sources of VOC inside the vehicle cabin and build up phenomena during HVAC operation, as expected from the literature [29]. Figure 2(c) displays the PM2.5 concentration measured inside and outside the cabin in fresh-air mode. Figure shows that the PM concentrations decrease while the HVAC system is working, due to the filtering activity of the HVAC filter. This result ties with what is found in the literature [10]. For the case analysed, a filtration efficiency of about $\eta = 0.5$ for PM2.5 is ascertained. The power usage of the HVAC system, with the contributions of power used by auxiliary equipment, A/C system and PTC heater recorded by the OBD system is shown in the stacked line plot in Fig. 2(d).

3.1.2. Recirculation configuration

Similar considerations can be made for the case with recirculation activated. From the results shown in Figure 3 it is clear that the time to steady state is close to 20 min; again the over-temperature issue remains significant. TVOC concentration reached a value similar to the case without recirculation, but in a longer time with respect to the fresh-air mode. A possible explanation for this behaviour could rely on the fact the source of VOCs inside the cabin is compensated by an improved adsorption performance, as observed by [10]. The PM concentrations decrease to lower values with respect to the fresh-air mode, as shown in Fig. 3(c). This result shows that the filtration performance is improved by the recirculation mode. Figure 3(d) shows the power usage of the HVAC system. The figure shows contributions of auxiliary equipment, A/C system and PTC heater to the overall power usage.

3. Results

The measurement system has been characterised both in winter and in summer conditions. In the following sections, two typical conditions for winter and summer have been chosen, to characterise the HVAC system performance in heating and cooling operations respectively. Winter tests have been performed on January 29, 2021, while summer test have been carried out from July 14 to July 15, 2021.

3.1. Heating operation

Amid winter period, two different test conditions have been investigated, starting from a state of equilibrium with the external environment, obtained maintaining all systems off and all doors opened for 15 minutes. Once the equilibrium was reached, the proper test was performed while maintaining the heater on for 1 hour, the set-point temperature at its maximum of 30 °C, the fan speed at its maximum, all the windows and all the doors closed. During the first test, the recirculation system was off (that means that the air ventilation system was in fresh-air configuration), while during the second test the recirculation system was on.

3.1.1. Fresh-air configuration

All the experiments confirm that the heating system is capable of reaching a quasi-steady state condition in about 20 min, even though the temperature reached by the air inside the cabin is well over the set-point temperature. Figure 2 shows the readings from all the 18 temperature sensors in the cabin for the case with fresh-air mode with a 3 letters naming scheme:

1. The first letter tells us if we are in the front (F) or in the back (B) of the cabin.
2. The second letter refers to the location in vertical direction, namely bottom (B), middle (M) and top (T) plane.
3. The third letter refers to the location in the horizontal direction, namely left (L) or driver, center (C) or right (R) side.

Colder spots can be found at feet level of the back seats, moreover this is in disagreement with the studies of Nilsson on equivalent temperature of body segments [20]. In other words, analysing the results of the work that led to the development of the only available standard for comfort evaluation in vehicles (ISO-14505), we can infer that occupants will be likely to accept colder temperatures in upper body parts during winter, while here we are in the opposite situation. Data from position FBC have a different behaviour because it refers to the sensor installed inside the acquisition system box, thus suffering from thermal inertia issues.

Defining a temperature difference $\Delta t = t_i - t_{avg}$; where t_i is the temperature in one generic position of the grid, and t_{avg} the mean value of the 18 temperature readings for each timestamp; is possible to obtain Figure 3. It is worth noting that air temperature inside the cabin can reach discrepancies of more than 15 °C in the first minutes of operation, while the Δt values at the end of test is lower and the temperature distribution much more uniform.

Figure 4(a) shows the temperature measured inside and outside the cabin keeping the fresh-air mode. In the following air temperature inside the cabin is considered equal to the average of all the sensors on the grid $t_{int} = t_{avg}$.

Figure 4(b) reports TVOC concentration measured inside and outside the cabin in fresh-air mode. The system is able to detect a TVOC concentration increase while the HVAC system operates, even with an external air mixing. This behaviour confirms the presence of a source of VOC inside the Leaf's cabin and a build up phenomenon during HVAC operation, as expected from literature [11].

Figure 4(c) displays the PM2.5 concentration measured inside and outside the cabin in fresh-air mode. This result ties with what is found in literature [21], the cabin filter is well capable of lowering the PM concentration inside the car with a steady state filtration efficiency of about $\eta = 0.5$.
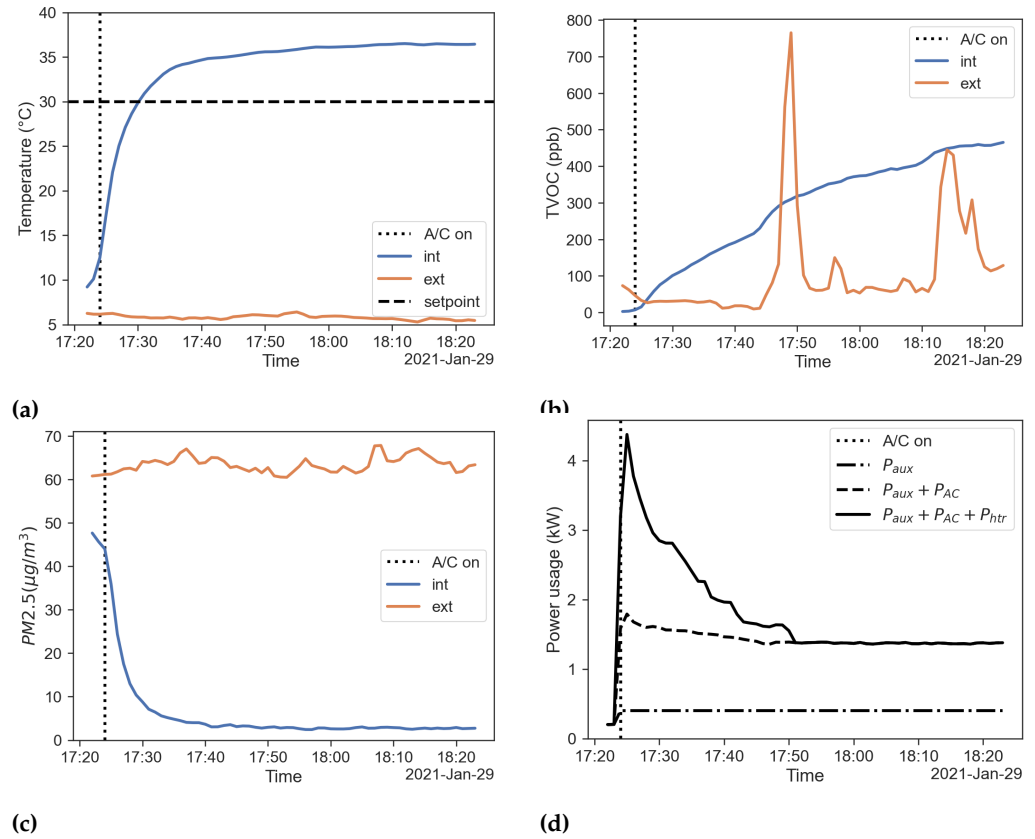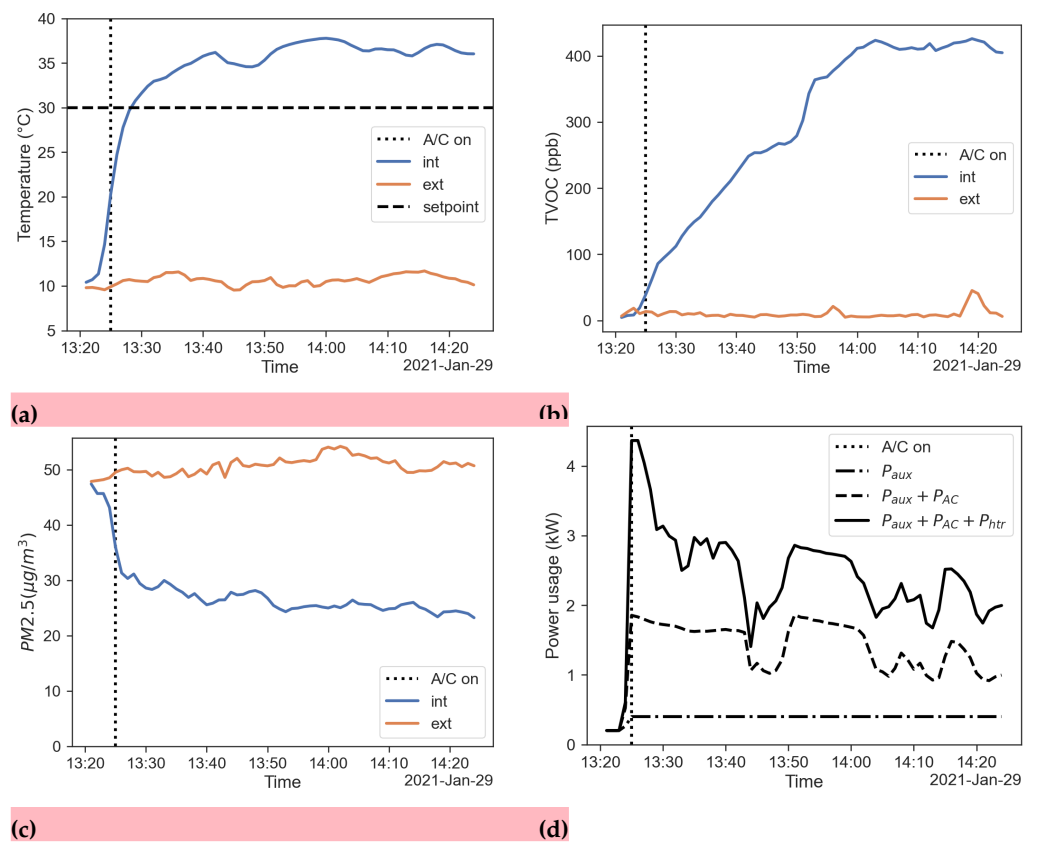
Figure 3. Results regarding the recirculation mode. (a) Temperature inside (blue) and outside (red) the cabin; (b) TVOC concentration inside (blue) and outside (red) the cabin; (c), PM2.5 concentration inside (blue) and outside (red) the cabin; (d) power usage of the HVAC system.

3.1.3. Comparison between fresh-air and recirculation mode in winter

The open-field tests conducted in this work have been chosen because representative of the real operating conditions of the vehicle. On the other hand, the experiments have been performed with no control on the environment outside the cabin, with repeatability issues. In order to compare the experiments, the following dimensionless temperature is defined:

$$t^* = \frac{t_{int} - t_{ext}}{t_{set} - t_{ext}} \qquad (1)$$

where t^* is the dimensionless temperature, t_{int} is the air temperature measured inside the cabin, t_{ext} is the air temperature measured outside the cabin and t_{set} is the set-point temperature. It is worth to underline that when $t_{int} = t_{ext}$, dimensionless temperature t^* is equal to 0, while when 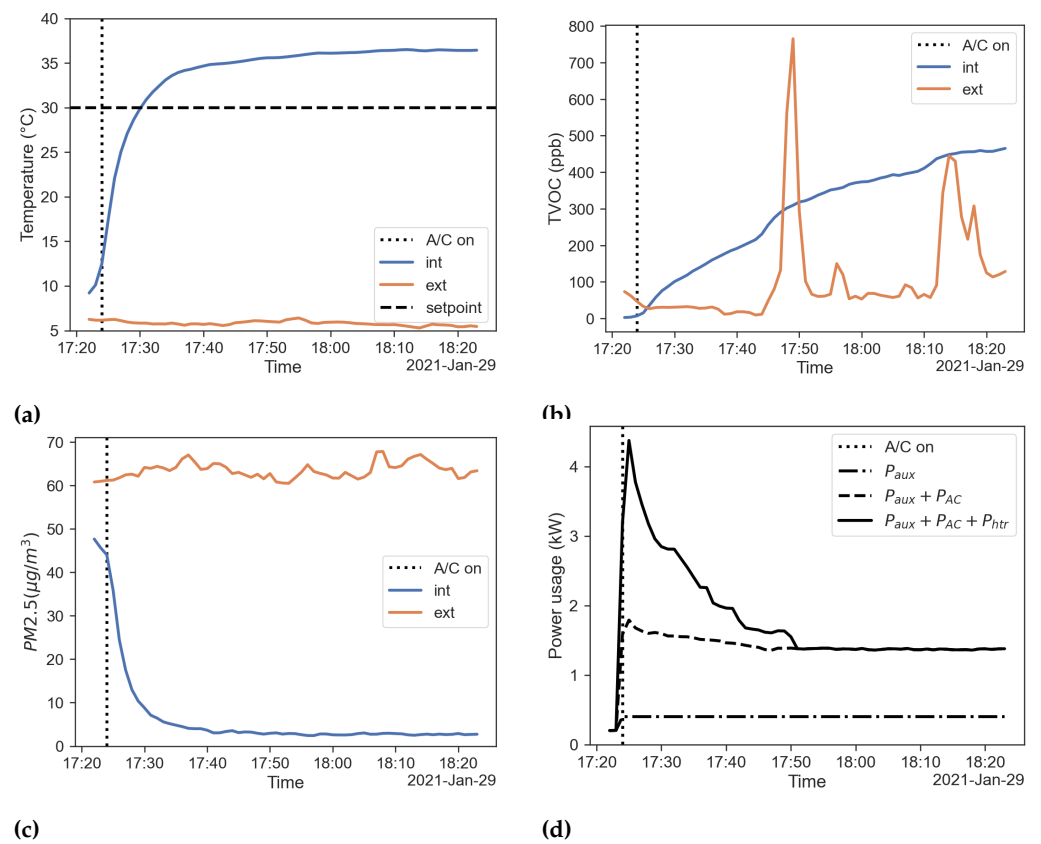$t_{int} = t_{set}$, then t^* is equal to 1. These two key points represent two relevant physical states, equilibrium with the external environment and fulfilment of the set-point request, respectively. Figure 4(a) shows a comparison between the dimensionless temperatures obtained for the two experiments. It is noticeable that the dimensionless temperature obtained without recirculation is always higher than the one obtained in the case of recirculation mode, thus suggesting that the over-temperature issue is more significant in this case. In addition, the set-point is reached faster during the fresh-air mode than during the recirculation mode.

The filtration efficiency of the vehicle can be defined using a black box approach, where the vehicle cabin is considered as a system with an unknown filtration capacity, while inlet (external) and outlet (internal) concentrations are known. The filtration efficiency is then defined by

$$\eta = 1 - \frac{C_{int}}{C_{ext}} \qquad (2)$$

(a)

(b)

(c)

(d)

Figure 4. Results regarding the fresh-air mode. (a) Temperature inside (blue) and outside (red) the cabin; (b) TVOC concentration inside (blue) and outside (red) the cabin; (c) PM2.5 concentration inside (blue) and outside (red) the cabin; (d) power usage of the HVAC system.

218   A first example of what kind of data can be acquired with the OBD system is given
219 in figure 4(d), where stacked plots of the power usage of the HVAC system are shown.

3.1.2. Recirculation configuration

221   Figure 5 shows the readings from all the 18 temperature sensors in the cabin for the
222 case with recirculation mode. Air temperature inside the cabin shows slightly higher
223 discrepancies with respect to the previous case, colder spots can be found again at feet
224 level of the back seats. Signal from the FBC sensor shows similar responsiveness issues
225 as for the case without recirculation. Higher temperature gradients in the startup phase
226 are evident from Figure 6, while a smoother profile is reached at the end of test.

Figure 5. Heating temperature profiles, recirculation mode.

Figure 6. Heating temperature difference profiles, recirculation mode.

227   Similar considerations can be made for the case with recirculation activated. From
228 the results shown in Figure 7 it is clear that the time to steady state is close to 20 min;
229 again the over-temperature issue remains significant. TVOC concentration reached a
230 similar value as the case without recirculation, but slower. A possible explanation for

Figure 7. Results regarding the recirculation mode. (a) Temperature inside (blue) and outside (red) the cabin; (b) TVOC concentration inside (blue) and outside (red) the cabin; (c), PM2.5 concentration inside (blue) and outside (red) the cabin; (d) power usage of the HVAC system.

231 this behaviour could rely on the fact that even without fresh air mixing, the source
232 of VOCs inside the cabin is compensated by an improved adsorption performance in
233 recirculation mode. This happens mostly if the breakthrough time is not yet reached [21].
234 As for the PM values, it is pretty clear from Fig. 7(c) how the filtration performance is
235 improved by the recirculation mode.

236 3.1.3. Comparison between fresh-air and recirculation mode in winter

The open field tests conducted in this work share similarities with the real operating
conditions of the vehicle. On the other hand, the experiments have been performed with
no control on the environment outside the cabin, with repeatability issues. In order to
compare the experiments, the following dimensionless temperature is defined:

$$t^* = \frac{t_{int} - t_{ext}}{t_{set} - t_{ext}} \qquad (1)$$

237 where t^* is the dimensionless temperature, t_{int} is the air temperature measured inside
238 the cabin, t_{ext} is the air temperature measured outside the cabin and t_{set} is the set-point
239 temperature. It is worth to underline that when $t_{int} = t_{ext}$, dimensionless temperature
240 t^* is equal to 0, while when $t_{int} = t_{set}$, then t^* is equal to 1. These two key points
241 represent two relevant physical states, equilibrium with the external environment and
242 fulfilment of the set-point request respectively. Figure 8 shows a comparison between the
dimensionless temperatures obtained for the two experiments. It is noticeable that the

Figure 8. Dimensionless temperature profiles, comparison between fresh-air mode (solid line) and recirculation (dashed line) mode.

243
244 dimensionless temperature obtained without recirculation is always higher than the one
245 obtained in the case of recirculation mode, thus suggesting that the over-temperature
246 issue is more significant in this case. In addition, the set-point is reached faster during
247 the fresh-air mode than during the recirculation mode.

The filtration efficiency of the vehicle can be defined using a black box approach,
where the vehicle cabin is considered as a system with an unknown filtration capacity,
while inlet (external) and outlet (internal) concentrations are known:

$$\eta = 1 - \frac{C_{int}}{C_{ext}} \qquad (2)$$

248 Figure 9 shows a comparison between the two cases. The PM filtration efficiency
249 with recirculation mode is almost double than the one with the fresh-air mode. It is
250 also noticeable that the filtration efficiency does never reach the ideal value of $\eta = 1$,
251 suggesting that infiltration rate not equal to zero occur even if the vehicle is parked.

252 An alternative method to get insights about IAQ of a vehicle cabin relies on a time
253 integrated inside/outside approach [3]. The associated index, named Cabin Air Quality
254 Index (CAQI) is defined as follows:

$$CAQI = \frac{\int_{t_i}^{t_f} C_{int}(t)\, dt}{\int_{t_i}^{t_f} C_{ext}(t)\, dt} \tag{3}$$

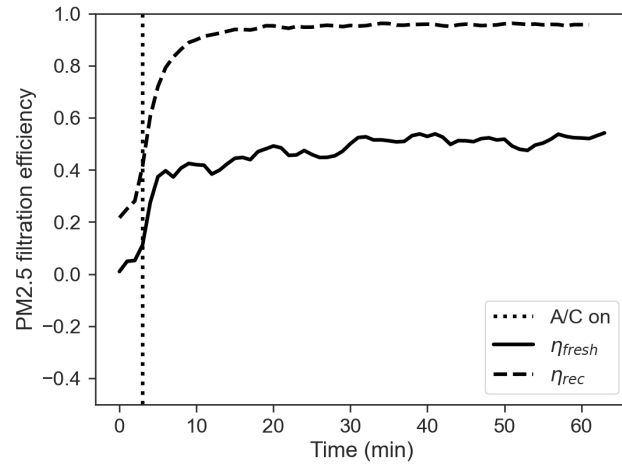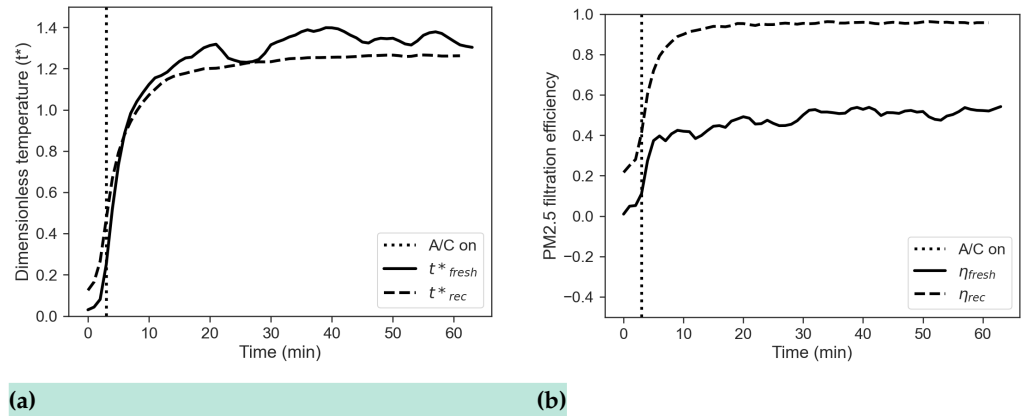255 Results based on this index for PM2.5 and TVOC are given in Figures 10 and 11.

Figure 9. Filtration efficiency, comparison between fresh-air (solid line) and recirculation (dashed line) mode.

Figure 10. CAQI for PM2.5.

Figure 12 shows the comparison between the cumulative energy consumption in the two cases of recirculation on and off, calculated as the approximate cumulative integral of $P_{tot} = P_{aux} + P_{AC} + P_{Htr}$ via the trapezoidal method in order to integrate numeric data rather than a functional expression:
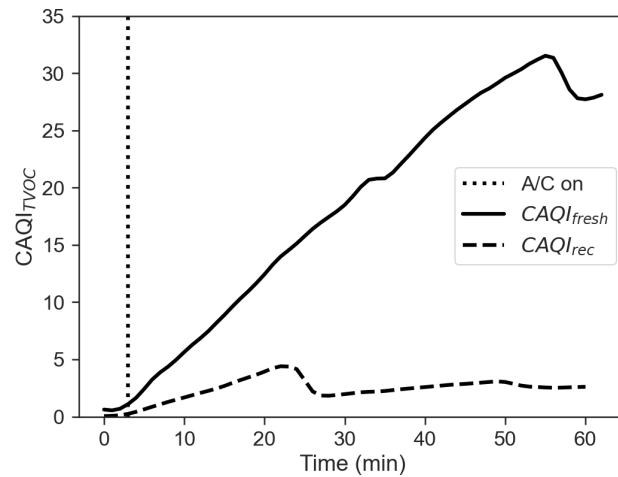
$$E = \int_{t_i}^{t_f} P_{tot}(t)\, dt \approx \frac{t_f - t_i}{2N} \sum_{n=1}^{N} \left(P_{tot}(t_n) + P_{tot}(t_{n+1}) \right) \tag{4}$$

256 where t_i is the start time, t_f the final time and N+1 the number of samples available
257 (equally spaced). The total energy consumption obtained in the recirculation mode on
258 is about 3/4 of the value obtained for the fresh-air mode. This result can explain what
259 is shown in figures 4(d) and 7(d). These figures show that the power usage from the

(a)   **(b)**

Figure 4. (a) Dimensionless temperature profiles, comparison between fresh-air (solid line) and recirculation (dashed line) mode. (b) Filtration efficiency, comparison between fresh-air (solid line) and recirculation mode (dashed line).

where C_{int} and C_{ext} are the internal and external concentrations, respectively. Figure 4(b) shows a comparison between the PM filtration efficiency obtained in the two regimes. The figure shows that PM filtration efficiency with recirculation mode is almost double than the one obtained with the fresh-air mode. It is also noticeable that the filtration efficiency does never reach the ideal value of $\eta = 1$, suggesting that infiltration rate not equal to zero occur even if the vehicle is parked.

An alternative method to get insights about IAQ of a vehicle cabin relies on a time integrated inside/outside approach proposed in [13]. The associated index, named Cabin Air Quality Index (CAQI) is defined as follows:

$$CAQI = \frac{\int_{t_i}^{t_f} C_{int}(t)\, dt}{\int_{t_i}^{t_f} C_{ext}(t)\, dt} \tag{3}$$

where C_{int} is the internal concentration , C_{ext} is the external concentration, t_i is the start time and t_f is the stop time. Results based on this index for PM2.5 and TVOC are given in Figure 5. The figure shows that the CAQI indexes for PM2.5 and VOC obtained for

(a)   **(b)**

Figure 5. (a) CAQI for PM2.5 and (b) CAQI for TVOC.

the fresh-air mode are much greater than the one obtained for the recirculation mode. Figure 6 shows the comparison between the cumulative energy consumption in the two cases of recirculation on and off, calculated as the approximate cumulative integral of

Figure 11. CAQI for TVOC.

HVAC system is similar for the two modes in the first minutes of operation. However, when the effects of recirculation become prevalent, the values of the HVAC power usage related to the two modes differ. Infact, while P_{tot} peaks at more than 4 kW in the first minutes of operation in both modes, it varies significantly towards the end of the test.
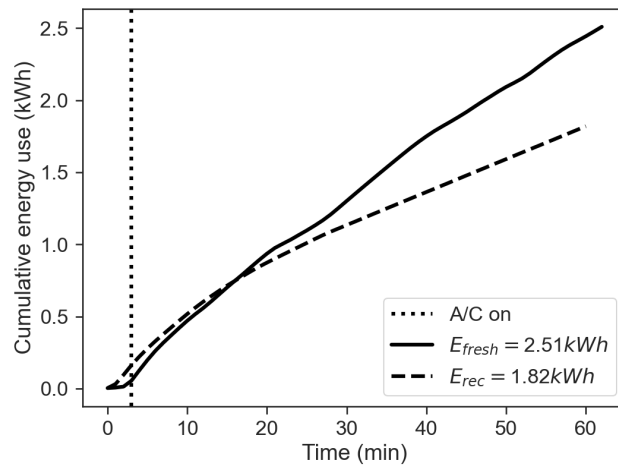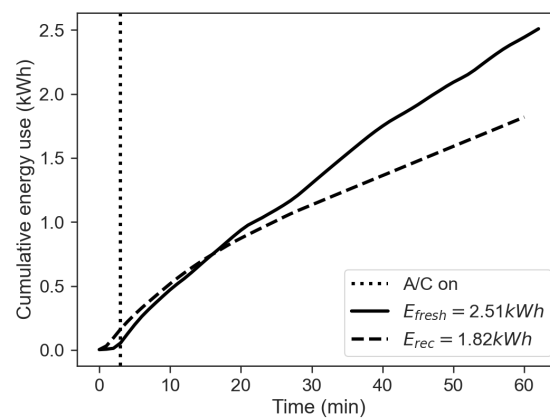

Figure 12. Cumulative energy use, comparison between fresh-air (solid line) and recirculation (dashed line) mode.

3.2. *Cooling operation*

Two different test conditions have been investigated starting from a state of equilibrium with the external environment, obtained maintaining all systems off and all doors opened for 15 minutes. Once the equilibrium was reached, the proper test was performed while maintaining the A/C on for 1 hour, the set-point temperature at its minimum of 16 °C, the fan speed at its maximum, all the windows and all the doors closed. During the first test, the recirculation system was off (that means that the air ventilation system was in fresh-air configuration), while during the second test the recirculation system was on.

3.2.1. Recirculation mode off

All the experiments confirm that the cooling system is not capable of reaching a quasi-steady state condition in about 60 min, textiti.e. the temperature reached by the air inside the cabin is far from the set-point temperature value. Figure 13 shows the

$P_{tot} = P_{aux} + P_{AC} + P_{Htr}$ via the trapezoidal method, in order to integrate numeric data rather than a functional expression:

$$E = \int_{t_i}^{t_f} P_{tot}(t)\, dt \approx \frac{t_f - t_i}{2N} \sum_{n=1}^{N} (P_{tot}(t_n) + P_{tot}(t_{n+1})) \tag{4}$$

where t_i is the start time, t_f the final time and N+1 the number of samples available (equally spaced). The total energy consumption obtained in the recirculation mode is about 3/4 of the value obtained for in fresh-air mode. This result can explain what is shown in figures 2(d) and 3(d). These figures show that the power usage from the HVAC system is similar for the two modes in the first minutes of operation. However, when the effects of recirculation become prevalent, the values of the HVAC power usage related to the two modes differ considerably. In fact, while P_{tot} peaks at more than 4 kW in the first minutes of operation in both modes, it varies significantly towards the end of the test.

Figure 6. Cumulative energy use, comparison between fresh-air (solid line) and recirculation (dashed line) mode.

3.2. Measurements during cooling operation

Two different test conditions have been investigated starting from a state of equilibrium with the external environment, obtained maintaining all systems off and all doors opened for 15 minutes. Once the equilibrium was reached, the proper test was performed while maintaining the A/C on for 1 hour, the set-point temperature at its minimum of 16 °C, the fan speed at its maximum (position 7), all windows and all doors closed. During the first test, the recirculation system was off (that means that the air ventilation system was in fresh-air configuration), while during the second test the recirculation system was on.

3.2.1. Fresh-air configuration

All the experiments confirm that the cooling system is not capable of reaching a quasi-steady state condition in about 60 min, *i.e.* the temperature reached by the air inside the cabin is far from the set-point temperature value.

Figure 7(a) shows the temperature measured inside and outside the cabin keeping the fresh-air mode. Like for the winter operation, the air temperature inside the cabin is calculated as the mean value of the 18 temperature readings for each timestamp.

Figure 7(b) shows TVOC measured inside and outside the cabin in fresh-air mode. The figure reports that the TVOC concentration is higher than that of the external air at the beginning, but decreases while the HVAC system operates. The lowest concentration is reached, despite the fluctuation on the outside. This behaviour can be explained with a drop of temperature inside the cabin combined with fresh-air mixing, thus reducing the emission from the internal sources.
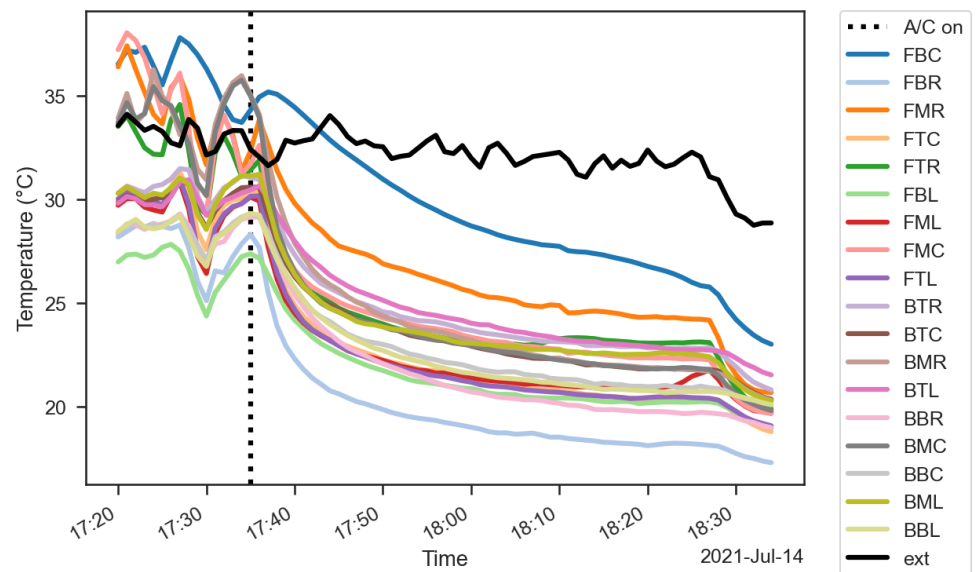
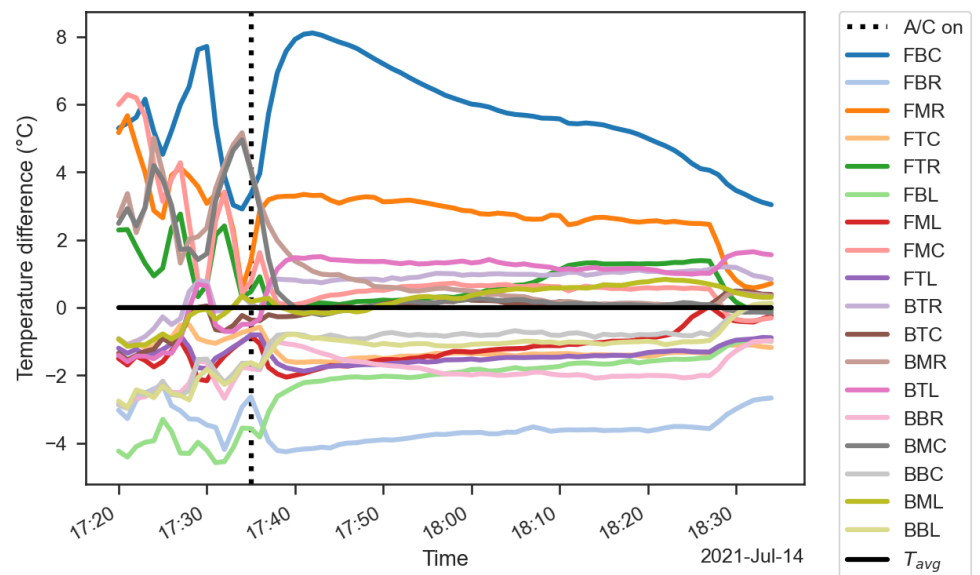**Figure 13.** Cooling temperature profiles, fresh-air mode.

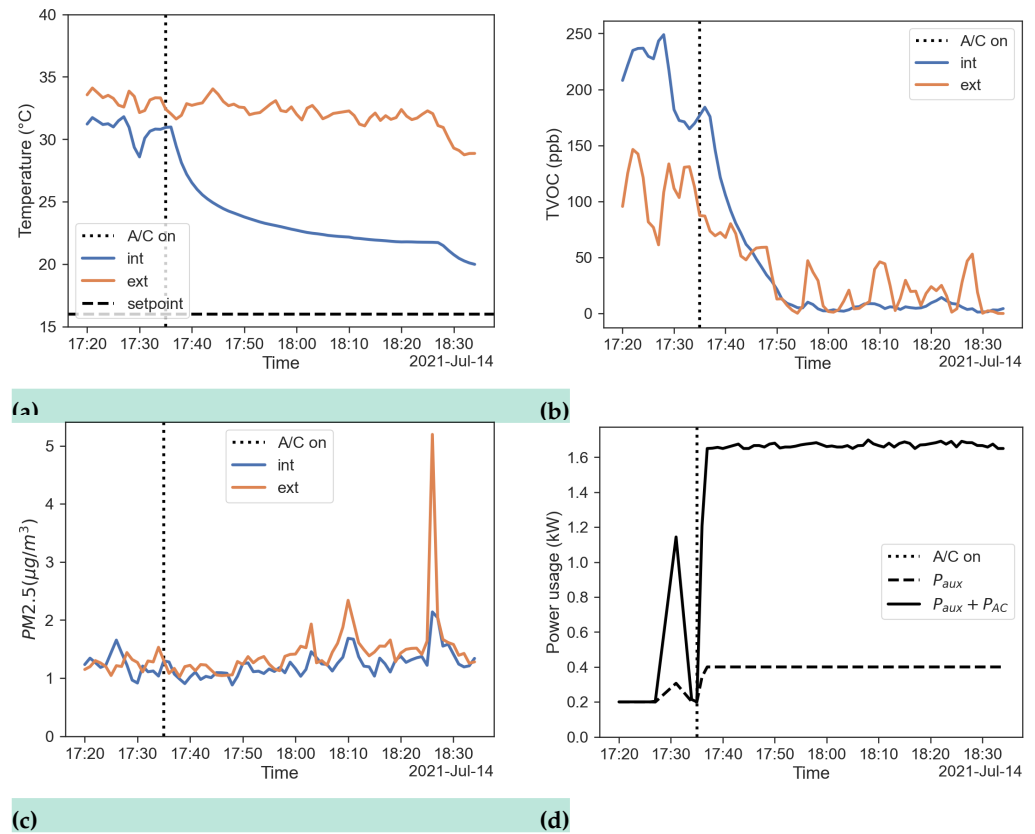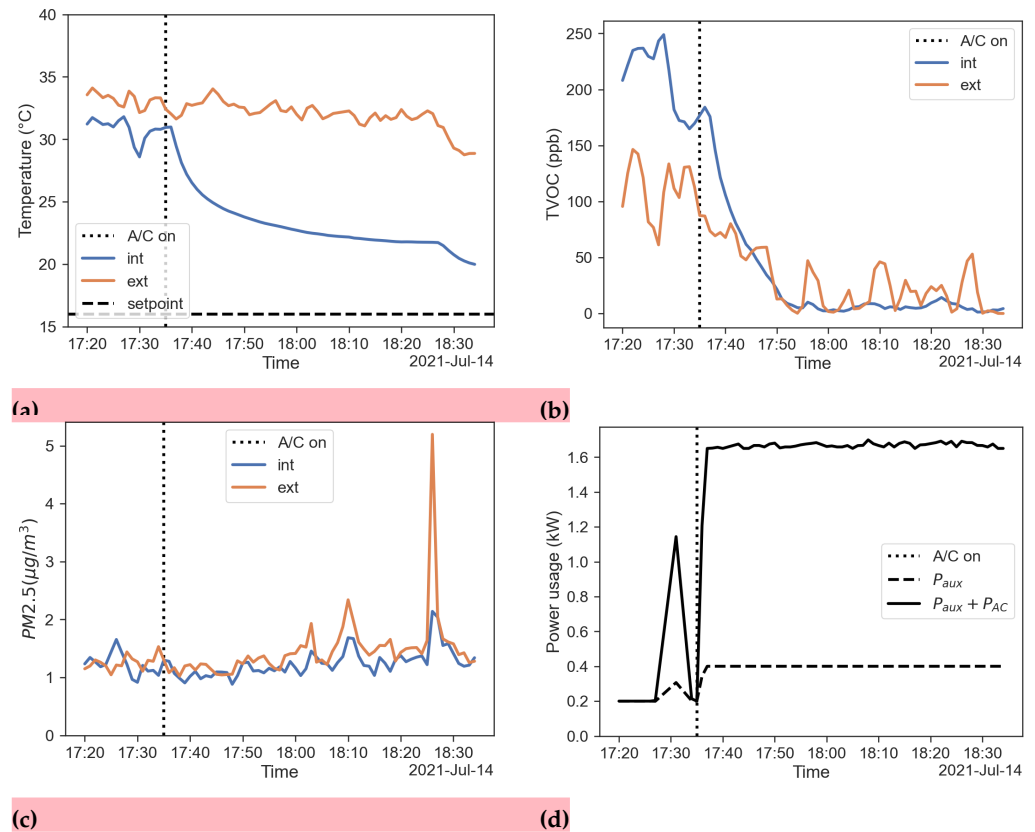**Figure 14.** Cooling temperature difference profiles, fresh-air mode.

Figure 7. Results regarding the fresh-air mode. (a) Temperature inside (blue) and outside (red) the cabin; (b) TVOC concentration inside (blue) and outside (red) the cabin; (c) PM2.5 concentration inside (blue) and outside (red) the cabin; (d) power usage of the HVAC system.

Figure 7(c) reports plots of the PM2.5 concentration measured inside and outside the cabin in fresh-air configuration. This result appears to be in contrast with the results shown by [10], *i.e.* the cabin filter is not able to lower the PM concentration inside the car with a steady state filtration efficiency $\eta = 0$ to 0.2. Here we need to consider that the value of PM2.5 concentrations measured were extremely low and under the sensor precision for that particle size range ($\pm 10 \, \mu\text{g}/\text{m}^3$).

Figure 7(d) shows the power usage of the HVAC system. The figure shows the contributions of power used by auxiliary equipment and A/C system; with PTC heater power being indeed equal to zero in cooling operation.

3.2.2. Recirculation configuration

As for the previous case with recirculation activated, time to steady state is close to 20 min of operation, while the over-temperature issue is still significant. TVOC concentration shows a different trend. Despite external concentration peaks at the end of the test, the internal one remains quite low. As for PM values, they follow a completely different trend, it is pretty clear from Fig. 8(c) how the filtration performance is improved by the recirculation mode, even with absolute values well within the precision range as is the previous test. Figure 8(d) shows the power usage of the HVAC system, with the contributions of power used by auxiliary equipment and A/C system recorded by the OBD system.

3.2.3. Comparison between fresh-air and recirculation modes in summer

Experiments in cooling as well as heating mode have been performed in real parking conditions with no control on the environment outside the cabin, repeatability issues are worsen by the increased contribution of solar load in summer. In order to compare the

readings from all the 18 temperature sensors in the cabin for the case with fresh-air mode with the same naming scheme introduced in the previous section.

Temperature discrepancies in the cabin can approach 12 °C; warmer spots can be found at top and middle locations, while bottom zone is generally colder (Fig. 14). To a certain extent, this is in agreement with a stratification of cabin air during operation, despite the vents working at full power. Looking at "Light summer" Comfort Zones defined by [20], we can infer that occupants will be likely to accept warmer temperatures in lower body parts during summer, while this result goes in the opposite direction. Self heating and thermal inertia issue of the sensor positioned at FBC position are still evident.

Figure 15. Results regarding the fresh-air mode. (a) Temperature inside (blue) and outside (red) the cabin; (b) TVOC concentration inside (blue) and outside (red) the cabin; (c) PM2.5 concentration inside (blue) and outside (red) the cabin; (d) power usage of the HVAC system.

Figure 15(a) shows the temperature measured inside and outside the cabin keeping the fresh-air mode. Like for the winter operation, the air temperature inside the cabin is calculated as the mean value of the 18 temperature readings for each timestamp.

Figure 15(b) shows TVOC measured inside and outside the cabin during the fresh-air mode. The figure reports that the TVOC concentration is higher than that of the external air at the beginning, but decreases while the HVAC system operates. The lowest concentration is reached, despite the fluctuation on the outside. This behaviour can be explained with a drop of temperature inside the cabin combined with fresh-air mixing.

Figure 15(c) plots the PM2.5 concentration measured inside and outside the cabin in fresh-air configuration. This result appears to be in contrast with the results shown by [21], *i.e.* the cabin filter is not able to lower the PM concentration inside the car with a steady state filtration efficiency $\eta = 0$ to 0.2. Here we need to consider that the value of PM2.5 concentrations measured were very low and under the sensor precision for that particle size range ($\pm 10 \, \mu g/m^3$).
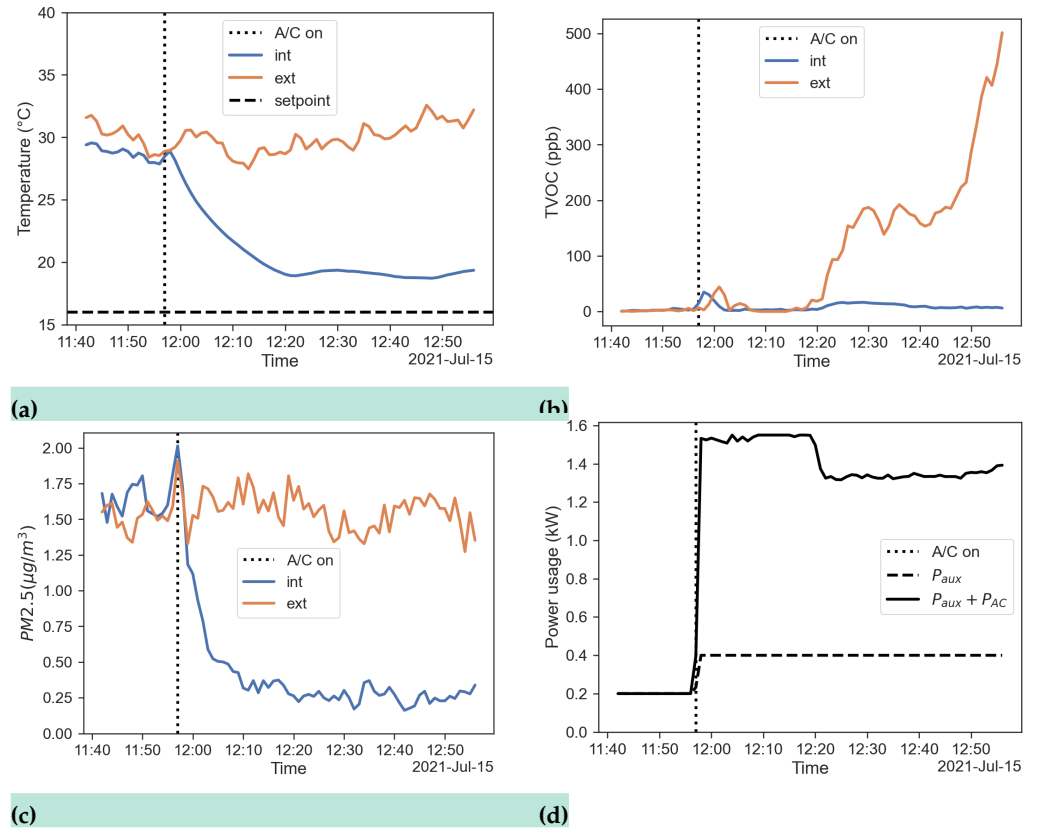
Figure 8. Results regarding the recirculation mode. (a) Temperature inside (blue) and outside (red) the cabin; (b) TVOC concentration inside (blue) and outside (red) the cabin; (c), PM2.5 concentration inside (blue) and outside (red) the cabin; (d) power usage of the HVAC system.

experiments, a temperature adimensionalisation is performed according to equation 1. Figure 9(a) shows a comparison between the dimensionless temperatures obtained for the two experiments. It is noticeable that the value of dimensionless temperature obtained with recirculation is always higher than the one obtained in the fresh-air case, thus suggesting that the cabin approaches better the set-pot in the first case. The filtration efficiency of the vehicle can be defined again using a black box approach, where the vehicle cabin is considered as a system with an unknown filtration capacity, while inlet (external) and outlet (internal) concentrations are known, according to equation 2. Figure 9(b) shows a comparison between the two cases. The PM filtration efficiency with recirculation mode is well over the one with the fresh-air mode. It is also noticeable that as for the winter case the filtration efficiency does never reach the ideal value of $\eta = 1$, but it is even lower indeed. This trend can be explained with η being function of particle size[10], but also of particle concentration itself. As shown for the winter case, another way to investigate cabin performance on airborne pollutants is provided by equation 3. Figure 10 reports the CAQI trend for PM2.5 and TVOC in fresh-air and recirculation, the latter being less prone to build up of pollutants during operation. Figure 11 shows the comparison between the cumulative energy consumption in the two cases of recirculation on and off, calculated as the approximate cumulative integral of $P_{tot} = P_{aux} + P_{AC}$ via the trapezoidal method as done in the winter case with equation 4. The total energy consumption obtained in the recirculation mode on is about 4/5 of the value obtained for the fresh-air mode. This result can explain what is shown in figures 7(d) and 8(d). These figures show that the power usage from the HVAC system is similar for the two modes in the first minutes of operation. However, when the effects of recirculation become prevalent, the HVAC power usage related to this mode decreases after about 20 min, even though the difference is less prominent than in winter operation.
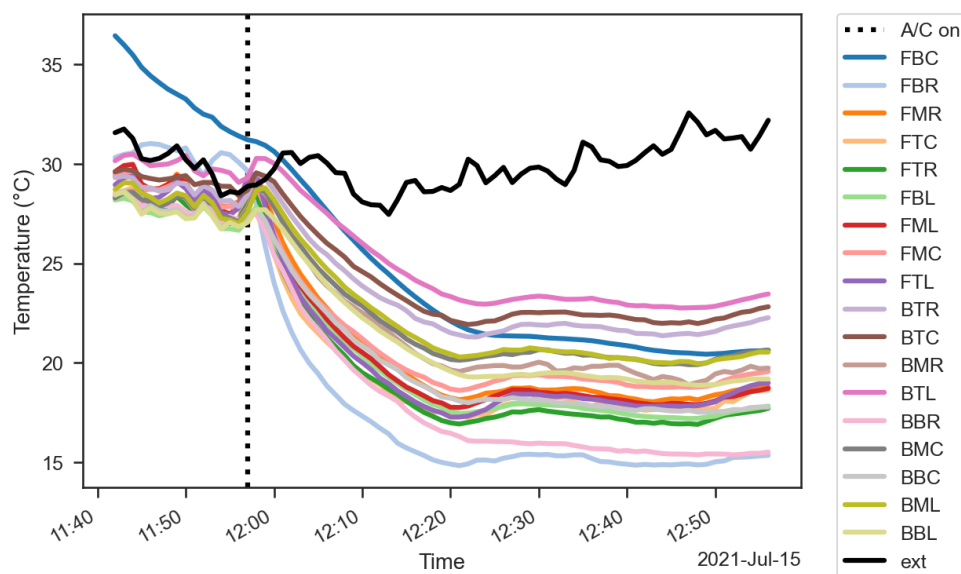
301 ### 3.2.2. Recirculation mode

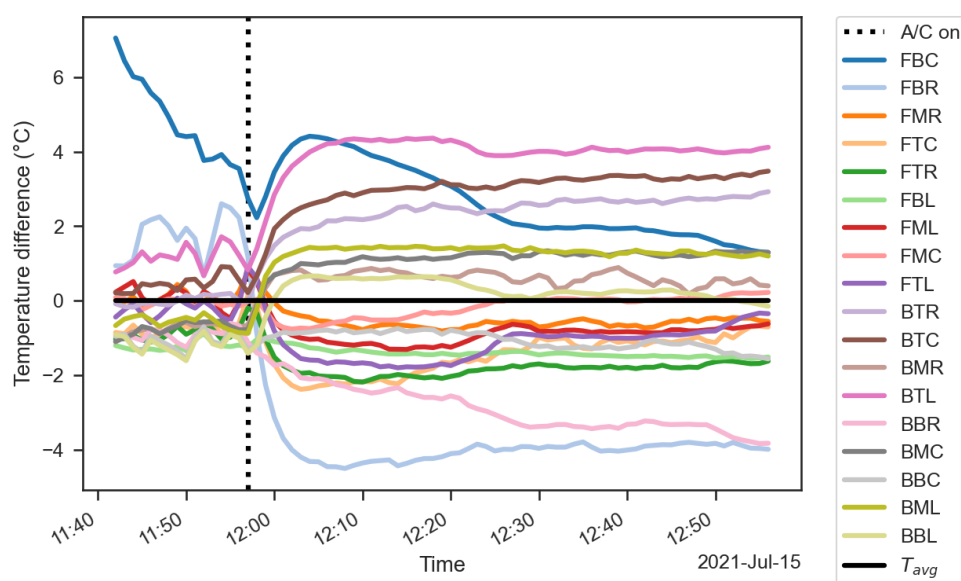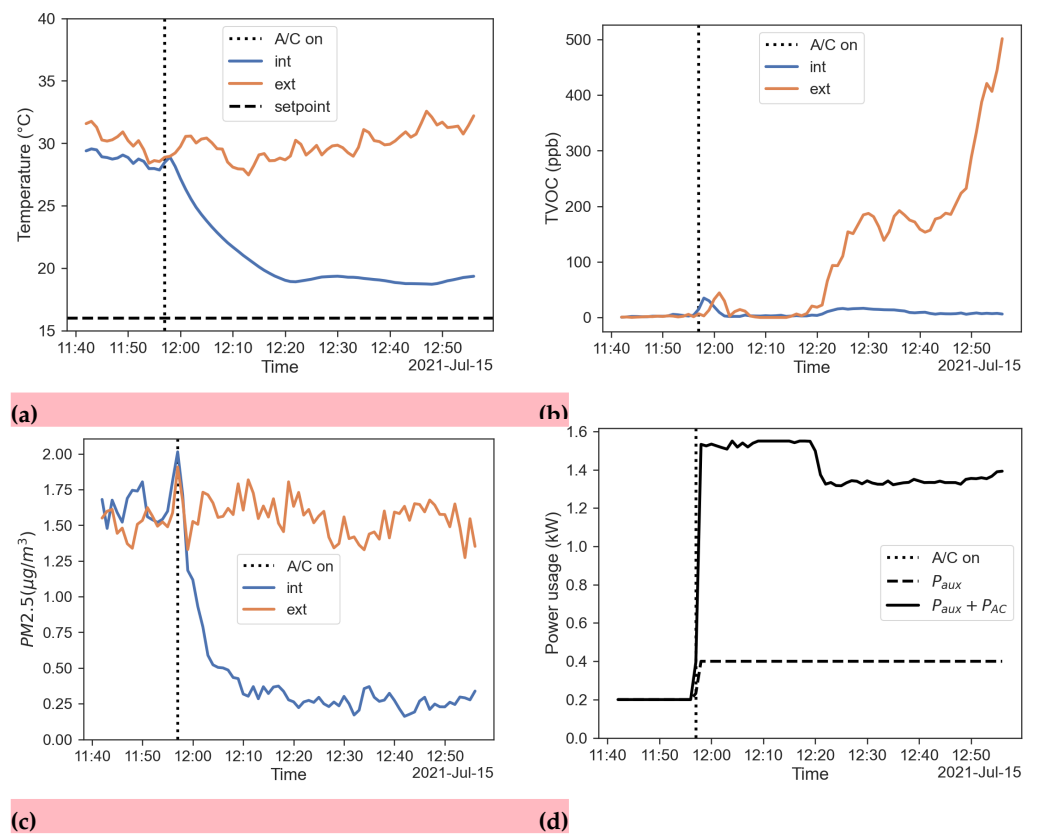**Figure 16.** Cooling temperature profiles, recirculation mode.

Figure 17. Cooling temperature difference profiles, recirculation mode.

302 Figure 16 shows the readings from all the 18 temperature sensors in the cabin for the
303 case with recirculation mode. Air temperature stratification with respect to the vertical
304 axis is again considerable, colder spots can be found at feet level of the back seats. The
305 main difference with the fresh-air case is that bottom right location are well capable of
306 reaching the set-point temperature.

307 As for the previous case with recirculation activated, time to steady state is close
308 to 20 min of operation, while the over-temperature issue is still significant. TVOC
309 concentration show a totally different trend. Despite external concentration peaks
310 at the end of the test, the internal one remains quite low. As for PM values, they
311 follow a completely different trend, it is pretty clear from Fig. 18(c) how the filtration
312 performance is improved by the recirculation mode, even with absolute values well
313 within the precision range as is the previous test.

(a)

(b)

(c)

(d)

Figure 18. Results regarding the recirculation mode. (a) Temperature inside (blue) and outside (red) the cabin; (b) TVOC concentration inside (blue) and outside (red) the cabin; (c), PM2.5 concentration inside (blue) and outside (red) the cabin; (d) power usage of the HVAC system.

314 3.2.3. Comparison between fresh-air and recirculation modes in summer

315 Experiments in cooling as well as heating mode have been performed in real parking
316 conditions with no control on the environment outside the cabin, repeatability issues
317 are worsen by the increased contribution of solar load in summer. In order to compare
318 the experiments, a temperature adimensionalisation is performed according to equation
319 1. Figure 19 shows a comparison between the dimensionless temperatures obtained
for the two experiments. It is noticeable that the value of dimensionless temperature

Figure 19. Dimensionless temperature profiles, comparison between fresh-air (solid line) and recirculation (dashed line) mode.

320
321 obtained with recirculation is always higher than the one obtained in the fresh-air case,
322 thus suggesting that the cabin approaches better the set-pot in the first case.
323 The filtration efficiency of the vehicle can be defined again using a black box
324 approach, where the vehicle cabin is considered as a system with an unknown filtration
325 capacity, while inlet (external) and outlet (internal) concentrations are known, according
326 to equation 2. Figure 20 shows a comparison between the two cases. The PM filtration
327 efficiency with recirculation mode is well over the one with the fresh-air mode. It is also
328 noticeable that as for the winter case the filtration efficiency does never reach the ideal
329 value of $\eta = 1$, but it is even lower indeed. This trend can be explained with η being
330 function of particle size[21], but also of particle concentration itself.
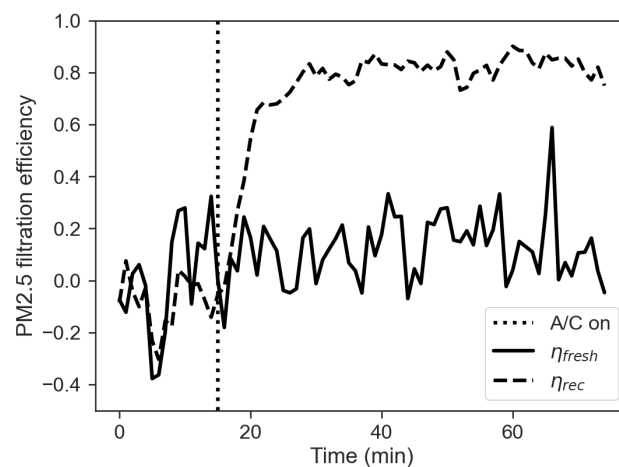

Figure 20. Filtration efficiency, comparison between fresh-air mode (solid line) and recirculation (dashed line) mode.

331 As shown for the winter case, another way to investigate cabin performance on
332 airborne pollutants is provided by equation 3. Figures 21 and 22 report the CAQI trend

for PM2.5 and TVOC in fresh-air and recirculation, the latter being less prone to build
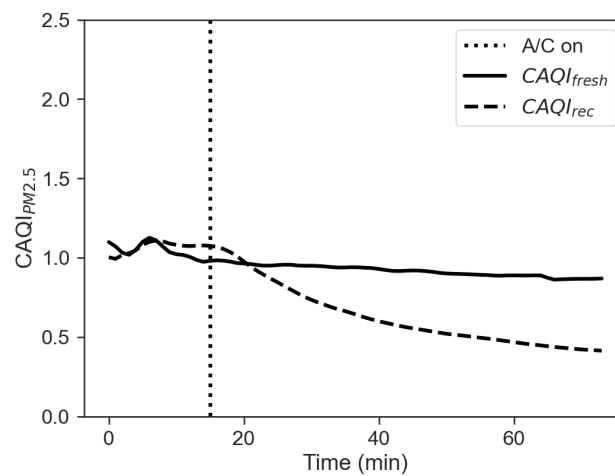up of pollutants during operation.
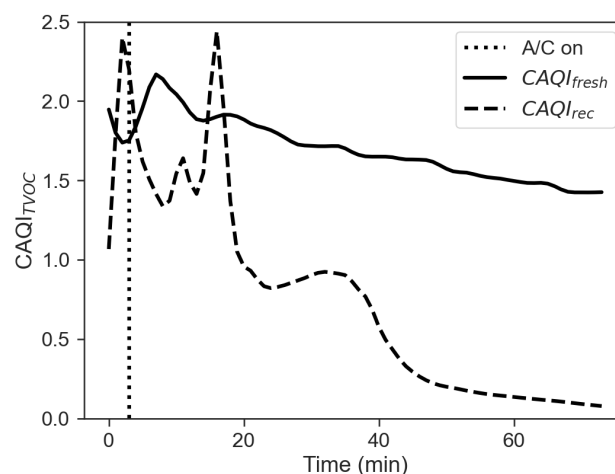

Figure 21. CAQI for PM2.5.

Figure 22. CAQI for TVOC.

Figure 23 shows the comparison between the cumulative energy consumption in
the two cases of recirculation on and off, calculated as the approximate cumulative
integral of $P_{tot} = P_{aux} + P_{AC}$ via the trapezoidal method as done in the winter case with
equation 4. The total energy consumption obtained in the recirculation mode on is about
4/5 of the value obtained for the fresh-air mode. This result can explain what is shown in
figures 15(d) and 18(d). This figures show that the power usage from the HVAC system
is similar for the two modes in the first minutes of operation. However, when the effects
of recirculation become prevalent, the HVAC power usage related to this mode becomes
lower after about 20 min, even though the difference is less prominent then in the winter
operation.

3.3. Effect of filter conditions on filtration performance

In this section we report some results regarding the filtration performances of the
Leaf cabin filter (Figure 24). In detail we performed two tests in summer operating
conditions manipulating the filter. First, we performed the experiment without the filter.
Then, a second experiment was performed after installing a new brand filter. Figure
24(a) shows that the presence of the filter has an effect of filtration efficiency, lowering
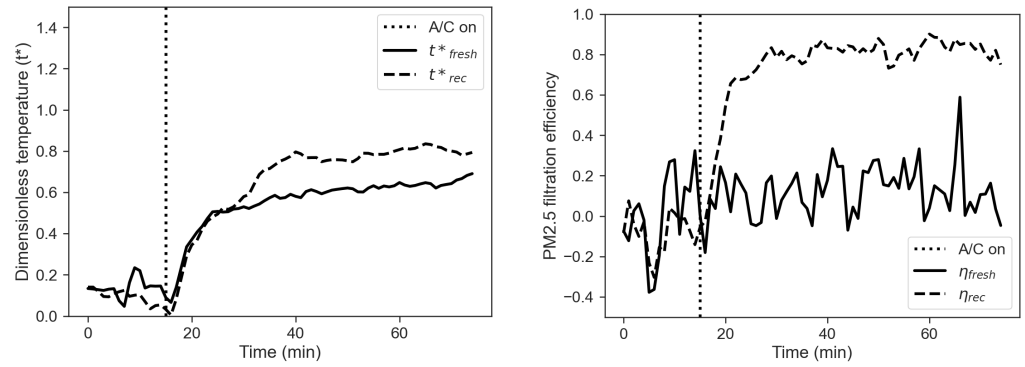its value from 80 % to 60 %. The figure shows that even without a filter the recirculation

Figure 9. (a) Dimensionless temperature profiles, comparison between fresh-air (solid line) and recirculation (dashed line) mode. (b) Filtration efficiency, comparison between fresh-air (solid line) and recirculation mode (dashed line).
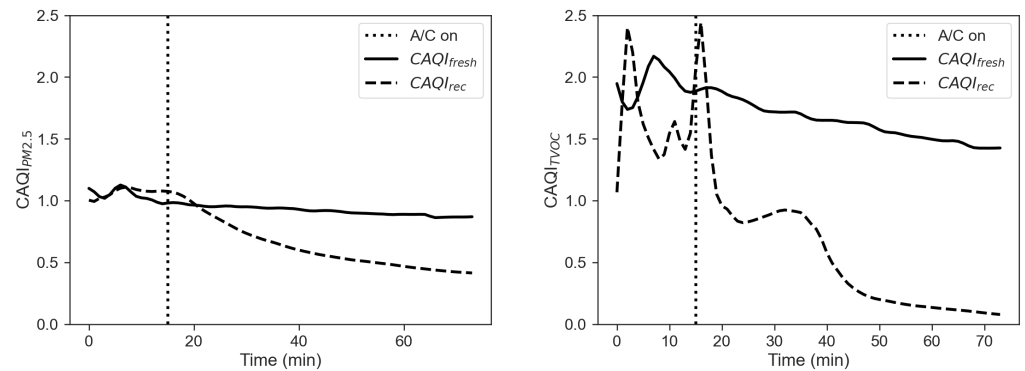

Figure 10. (a) CAQI for PM2.5 and (b) CAQI for TVOC.

3.3. Effect of filter conditions on filtration performance

In this section we report some results regarding the filtration performances of the Leaf cabin filter (Figure 12). In detail we performed two tests in summer operating conditions manipulating the filter. First, we performed the experiment without the filter. Then, a second experiment was performed after installing a brand-new filter. Figure 12(a) shows that the presence of the filter has an effect of filtration efficiency, lowering its value from 80 % to 60 %. The figure shows that even without a filter the recirculation mode provides a sort of filtration. This result suggests that part of the filtration is made by the filter and part is given by other devices in the HVAC system, *i.e.* a fraction of the pollutants is captured by the evaporator fins, or by the ducts between the cabin and the evaporator. Curves for fresh-air mode show filtration efficiency around zero for both the cases (no filter and with a filter), with more fluctuations for the case without a filter. Then, the presence of the filter does not improve the air quality within the cabin both by using a filter and by not using it.
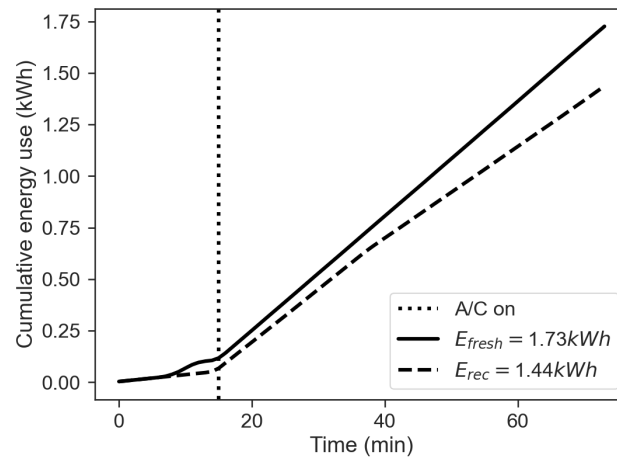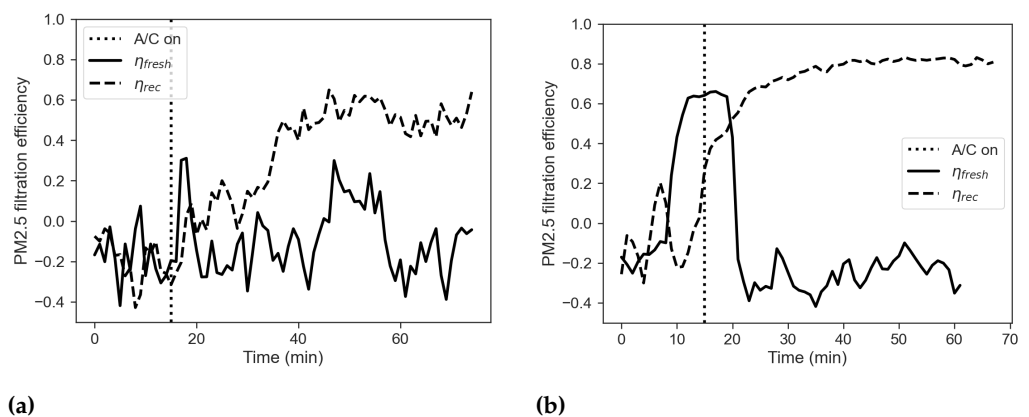
Figure 23. Cumulative energy use, comparison between fresh-air mode (solid line) and recirculation (dashed line) mode.

mode provides a sort of filtration. This result suggests that part of the filtration is made
by the filter and part is given by other devices in the HVAC system, *i.e.* a fraction of the
pollutants is captured by the evaporator fins, or by the ducts between the cabin and the
evaporator. Curves for fresh-air mode show filtration efficiency around zero for both
the cases (no filter and with a filter), with more fluctuations for the case without a filter.
Then, the presence of the filter does not improve the air quality within the cabin both by
using a filter and by not using it.

(a)

(b)

Figure 24. Filtration efficiency, comparison between fresh-air mode (solid line) and recirculation
(dashed line) mode, with 24(a) no cabin filter installed and 24(b) with brand new cabin filter
installed.

4. Discussion

In this paper, a characterisation of the air quality within the cabin of a battery electric
vehicle (BEV) has been shown. The temperature, PM and VOC concentrations have
been measured by means of a low-cost Arduino-based system of sensors. Comparisons
between the air quality obtained in the cabin during different configuration modes of
the air-ventilation system have been carried out.

The main differences outlined are related to the fresh-air and recirculation configu-
rations. The temperature distributions have been monitored and analysed along with the
energy consumption of the HVAC system. The results show that, while PMs are filtered,
VOCs concentrations tend to increase during operation in recirculation mode. At the
same time, the HVAC energy consumption in recirculation mode after 1 h of operation is
about 72 % and 82 % of the energy consumption observed in fresh-air mode for heating
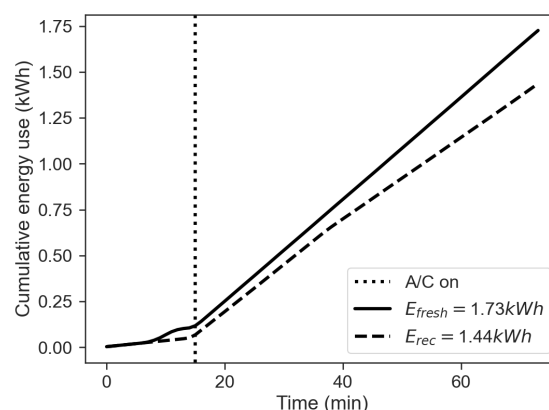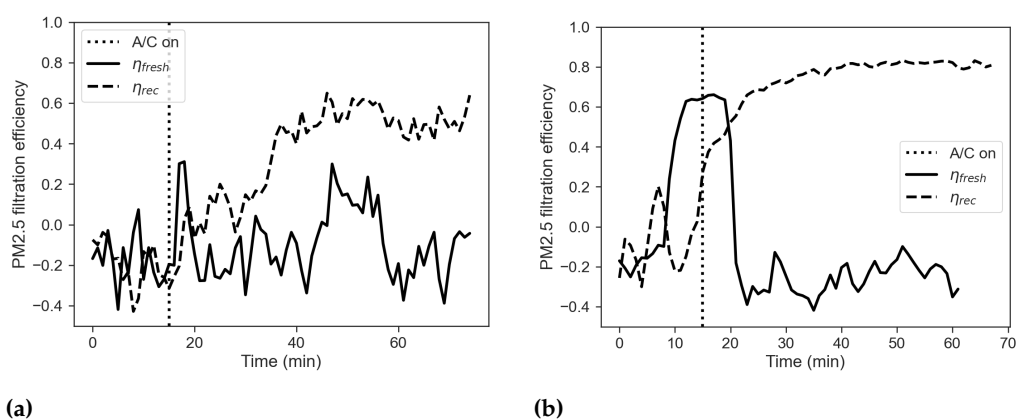
Figure 11. Cumulative energy use, comparison between fresh-air mode (solid line) and recirculation (dashed line) mode.

(a)   **(b)**

Figure 12. Filtration efficiency, comparison between fresh-air mode (solid line) and recirculation (dashed line) mode, with 12(a) no cabin filter installed and 12(b) with brand new cabin filter installed.

4. Conclusions

In this paper, a characterisation of the air quality within the cabin of a battery electric vehicle (BEV), together with real time measurements of HVAC system energy consumption has been presented. The temperature, PM, and VOC concentrations have been measured by means of a low-cost Arduino-based system of sensors. Comparisons between the air quality obtained in the cabin during different configuration modes of the air-ventilation system have been carried out.

The results show that, while PMs are filtered, VOCs concentrations increase during operation in recirculation mode. At the same time, the HVAC energy consumption in recirculation mode is about 70 % of the energy consumption measured in fresh-air mode during heating operation. In cooling operation, the HVAC energy consumption in recirculation mode is about 80 % of the energy consumption measured in fresh-air mode.

Recirculation mode is found to be the best choice for BEVs, both for reducing some pollutants concentrations and for saving energy. The use of a new filter can improve the filtration efficiency in recirculation mode.

The methodology presented in this paper, applied to a Nissan Leaf Acenta 40 kWh, can be easily extended to other vehicles. This approach is very important for BEVs as the parameters analysed are crucial for these vehicles. In fact, the air quality is strongly related to air-circulation modes, such as the fresh-air or recirculation modes. The recirculation mode should be chosen for energy saving in order to extend the BEV drive range, but a fresh-air mode is needed in some cases, to ensure low concentrations

and cooling operation respectively. Moreover, cabin over temperature issues are observed in both fresh-air and recirculation mode. This result, despite being consistent in terms temperature different, has an opposite impact on system performance depending on the season considered; in the winter case a temperature higher than the set-point might be interpreted as a waste of energy and could be avoided, in the summer case a higher than set-point temperature might suggest that the HVAC system is undersized for cooling operation.

Temperature gradients inside the cabin pose also questions about the correct location of the measurement point. On one hand, discrepancies are significant and can approach 15 C; on the other hand, their uniform behaviour after the startup phase could suggest that a reduction of the measuring points could be attempted without compromising spatio-temporal resolution.

Thermal aspects are crucial for determining the energy consumed by the inbuilt climate control system outside, and outside air temperature is not the only parameter of interest; also solar irradiance and wind speed have an impact on cabin temperature. Future studies must address also these quantities to possibly obtain a proper model of the vehicle cabin.

Recirculation mode remains the best choice for BEVs both for reducing some pollutants concentrations and for saving energy. The use of a new filter can improve the filtration efficiency in recirculation mode, while does not make difference in fresh-air mode. These results need to be compared with the CO_2 concentrations obtained in recirculation mode, in order to find the minimum energy consumption together with the best air quality within the cabin in a win-win approach. An optimal data-driven duty-cycle of recirculation activation and deactivation could be defined to optimize both comfort needs and energy consumption.

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Abbreviations

The following abbreviations are used in this manuscript:

of pollutants within the cabin. Control systems should consider these results in order to manage the HVAC system operation in a win-win approach for BEVs.

Abbreviations

The following abbreviations are used in this manuscript:

BEV	Battery Electric Vehicle
HVAC	Heating, Ventilation and Air Conditioning
A/C	Air Conditioning
PTC	Positive Temperature Coefficient
IAQ	Internal Air Quality
OBD	On-Board Diagnostic
MY	Model Year
I/O	Inside/Outside
NTC	Negative Temperature Coefficient
PM	Particulate Matter
VOC	Volatile Organic Compounds

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BEV	Battery Electric Vehicle
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Internal Air Quality
OBD	On-Board Diagnostic
NTC	Negative Temperature Coefficient
PM	Particulate Matter
VOC	Volatile Organic Compounds
FTL	Front Top Left
FTC	Front Top Center
FTR	Front Top Right
FML	Front Middle Left
FMC	Front Middle Center
FMR	Front Middle Right
FBL	Front Bottom Left
FBC	Front Bottom Center
FBR	Front Bottom Right
BTL	Back Top Left
BTC	Back Top Center
BTR	Back Top Right
BML	Back Middle Left
BMC	Back Middle Center
BMR	Back Middle Right
BBL	Back Bottom Left
BBC	Back Bottom Center
BBR	Back Bottom Right

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