Activity Deliverable

Real-time pollution City mAp thRough cOLlaborative sensIng aNd Analysis

PoC of pollution-sensing devices

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List of abbreviations

ADC	Analog-Digital Converter
AFE	Analog Front-End
AQ	Air Quality
AQI	Air Quality Index
AQHI	Air Quality Health Index
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
IoT	Internet of Things
OPC	Optical Particle Counter
PM	Particulate Matter
PCB	Printed Circuit Board
PoC	Proof of concept
P&ID	Piping and Instrumentation Diagram

Contents

1. Executive Summary

This deliverable provides specifications on how to equip vehicles with a feasibility device to measure real time and valuable samples of air to be managed as part of an air quality monitoring solution with the ultimate goal to minimize the number of people exposed to threshold values of harmful air pollution in European cities.

This deliverable contributes to the Output "Next generation of urban air pollution sensor device" presenting findings from the assessment carried out to determine the technical and operative requirements to build a novel concept on a measurement unit to equip vehicles in the best feasibility manner.

This deliverable has been developed in collaboration with the CTTC- the Heat and Mass Transfer Technological Center of the Technical University of Catalonia -UPC (Task A2002 Leader, contributes to the operational assessment, including CFD simulations), Automotive Technology Center of Galicia – CTAG (contributes to the hardware, software and mechatronics design, as well as the housing or structural shape of the unit) and Istanbul IT and Smart City Technologies Inc. - ISBAK (acting as a role of mobility operator, brings its own measurement prototypes to enhance the validation in real conditions based on previous expertise and work performed).

After a deep review of the State-of-the-Art, benchmarking and testing of commercial sensors, design requirements for the air pollution measurement unit were proposed. Individual findings were shared to determine the unit operating range, followed by its structural, design properties, hardware, and software requirements. During the execution of these activities, several meetings have been taken place to exchange findings and determine the requirements.

The main beneficiaries of the work developed are the AQ measurement industry, which obtain a product to equip vehicles in the most viable manner to upgrade the monitoring of pollutants in cities. Partners involved, Automotive Technology Center of Galicia – CTAG and Technical University of Catalonia - UPC benefits from the resulting work to improve their research and development duties related to the environmental sensing market.

The main result achieved has been a better understanding on how to get valuable air samples ensuring indicators from traffic-based PM pollution, a sticking point, which remain in the sector despite the deployment of low-cost sensors and IoT technologies have experienced great growth in recent years.

One major challenge that the study has concluded is the commercial approach of how equip vehicles with air monitoring sensors. Up today, solutions provided as portable or mobile AQ stations are away from a plug-and-play device or aftermarket product for automotive industry. The design of the structural shape contributes to vehicles equipped with the CAROLINA measurement unit could be part of a dynamic and collaborative urban air pollution monitoring network and system.

This deliverable figure out the requirements of the PoC of the novel measurement unit, which contribute to the commercialization strategy. The resulting device allows to equip vehicles in the most viable manner to upgrade the current AQ monitoring solutions in European cities. Moreover, based on the experience of partners and findings from the benchmarking analysis on measurement units we conducted, we get two approaches for viable commercial product. An accessory for luxury car brands offering passengers real time data on environmental conditions around vehicle. The second alternative is an aftermarket product, plug-and-play to generate valuable data for fleet operators and policy makers for decision making process on pollution strategies.

2. Introduction

Nowadays, many cities around the world have to deal with high levels of air pollution coming from different sources, such as industry or road transport [1, 2]. This has a significant negative impact on people health. Heart disease, lung cancer or chronic and acute respiratory diseases are examples of sickness that are enhanced by a low air quality (AQ) in the cities [1, 3]. Even recent studies indicate that high levels of air pollution increase the mortality rate from COVID-19 [4]. Therefore, specific action measures need to be taken in order for to maintain a healthy level of ambient AQ. These actions can be summarized as an Urban Air Quality Management Plan, whose basic components are [5]:

- Air quality objectives
- Monitoring
- Emission inventory
- Prediction and forecasting tools
- Control strategies and vi) public participation.

This activity KAVA studies several of these components, including Monitoring. Monitoring is necessary in order, on the one hand, to inform the population in real time of the AQ and to be able to take quick measures according to the level of pollution, and on the other hand, to have updated data in order to model and make reliable predictions of the AQ [1].

The Air Quality Index (AQI) is a numerical scale that has been used in order to describe the AQ situation in relation to a reference value at a given time and place [6]. The AQI calculation is based on the concentration of several relevant pollutants. In addition, the Air Quality Health Index (AQHI) is a tool that has been developed in order to reflect the health risks associated with simultaneous exposure to several different air pollutants [6]. It has been identified that the most significant pollutants to be taken into account regarding both indexes are [6, 7]: CO, SO_2, NO_2, O_3, $PM_{2.5}$ and PM_{10}. Therefore, in the development of this Activity, we will typically focus on the monitoring of these pollutants.

The following Sub-Section reviews the State-of-the-Art regarding different measurement options, as well as different possible types of gas and Particulate Matter (PM) concentration sensors.

2.1. State-of-the-Art review

Air quality measurement stations include all the sensors needed to measure the pollutants of interest. The stations can be classified according to their location in fixed or mobile [1, 8].

On the one hand, fixed stations have a high temporal resolution, but they have a very low spatial resolution as they are statically positioned [8]. In addition, this type of stations can incorporate larger and more accurate sensors, but at the cost of greatly increasing the economic cost.

On the other hand, mobile stations usually do not allow a high temporal resolution in measurements, but they do have a high spatial resolution since these stations can be in motion around a large area [1, 9, 10, 11, 12, 13]. Mobile stations typically should incorporate small and low-cost sensors, allowing to deploy an economical sensor network with a high number of nodes. Nevertheless, these low-cost sensors will have a lower accuracy and some of them may need periodic calibration to maintain an acceptable accuracy level [14, 15, 16].

To finish describing the types of stations, it should be added the wearable stations, which have appeared in the recent years. They are still under development [1] and present numerous design challenges, such as small package size or very low power consumption to achieve high autonomy [17].

Focusing on the low-cost sensors, until a few years ago there was no available technology to manufacture this type of sensors, so all the stations were fixed. In [18] a mobile station was developed including technology for fixed stations, but a van was needed to install all the sensors. However, the recent emergence of low-cost sensors made it possible to design increasingly reliable and accurate mobile stations. In this regard, the aim of this KAVA is to develop a mobile measurement unit (station) to be placed on a vehicle to take measurements on the move. The idea under this concept could be to deploy a fleet of vehicles, for example city buses or cabs, including these units to monitor the levels of air pollution in a city or region. As we will see below, the development of such unit will be a challenge from the aerodynamic, mechatronic, and electronic point of view.

Regarding low-cost gas sensors, they can be classified according to their operation principle [14, 19, 20, 21], standing out for their accuracy, robustness and low cost, the electrochemical and metal oxide-based sensors, being the former the most selective with respect to the target gas. The electrochemical sensors, and in particularly, the amperometric ones, generate a current that is linearly proportional to the gas concentration. The target gas reacts with the sensor electrolyte to generate such current. Therefore, from our point of view, this type of sensors seems to be the most suitable choice to reach the goal of this Activity, as these sensors have high selectivity, low power consumption, small size and they are low cost. It should be noted that electrochemical sensors need a periodic calibration to keep the accuracy level [14, 15, 16].

Concerning low-cost PM sensors, they are usually based on Optical Particle Counter (OPC) technology [14, 22, 23, 24]. A laser light source is used for particle illumination in automated OPC. The OPC detects the particle by direct light scattering from the particle, being generally 100 nm in particle diameter the lower detection limit of the OPC. Therefore, this kind of sensors are very suitable for this Activity.

With the intention of finalizing the review of the State-of-the-Art, a benchmarking is performed to identify commercial units and in this sense, to have a starting point in the development of the proposed air pollution measurement unit, which is intended to be placed on a vehicle and to take measurement with the vehicle in-motion. We have identified companies that manufacture gas sensors [25, 26] or PM sensors [27, 28] with features such as those discussed above intended for the automotive sector and designed to monitor the AQ inside the vehicles. Nevertheless, these companies have not developed a full AQ measurement unit. In [29] the Internet of Things (IoT) company has developed units named "Plug & Sense!" with different environmental and AQ measurement sensors to be easily integrated into an IoT network using the "Waspmote" hardware provided by them as well. This unit has been tested in [12] by placing it on top of a bus and collecting measurements by the city of Uppsala (Sweden), whose results are not so good as expected since the unit was not designed to take measurements on a moving vehicle.

In addition to this benchmarking, we study the unit developed by iSBAK, partner of this Activity. The unit developed by iSBAK is designed to be installed inside a taxi cap and it includes sensors to measure the concentration of different gases as well as a PM sensor. It also includes a pump to manage air sampling. The detailed study of this unit is presented in the Section 2.2.

Finally, once reviewed the State-of-the-Art, the Section 2.3 introduces an experimental study of some gas and PM commercial sensors with the intention of better understanding their characteristics and performance, as well as their limitations.

2.2. iSBAK unit analysis

The partner of this Activity, iSBAK, has designed, before the execution of this KAVA, a measurement unit which incorporates both gas and PM sensors, as well as air sampling management. Therefore, for the sake of completeness of the State-of-the-Art review, both UPC and CTAG study this unit in depth.

Figure 1 ISBAK's Air Quality Monitoring Unit

ISBAK's air quality monitoring unit consists of two main connected circuit boards. The circuit at the above is titled TCore, the other circuit at the below is titled as TSense. TCore, is a circuit, which contains the main processor and the communication modules (GSM, GPS and Bluetooth) as shown in Figure 2, while Tsense is a circuit which includes all the gas sensors (CO, NO2, SO2 and O3) as shown in Figure 3. These circuits are mounted on top of each other by header socket connectors and screws as shown in Figure 1. These connectors are used to supply power to the Tsense board and enable the communication between the two boards, TCore and TSense, via UART protocol. All the connections coming from external sockets are connected to the TCore board. In addition to that, the motor, valve, and other sensors are connected to the TSense board as shown in Figure 1. Both boards have their own micro-processor to enable them to work separately. In other words, Tsense board which involves all the gas sensors could be utilized separately in other projects using the implemented header socket.

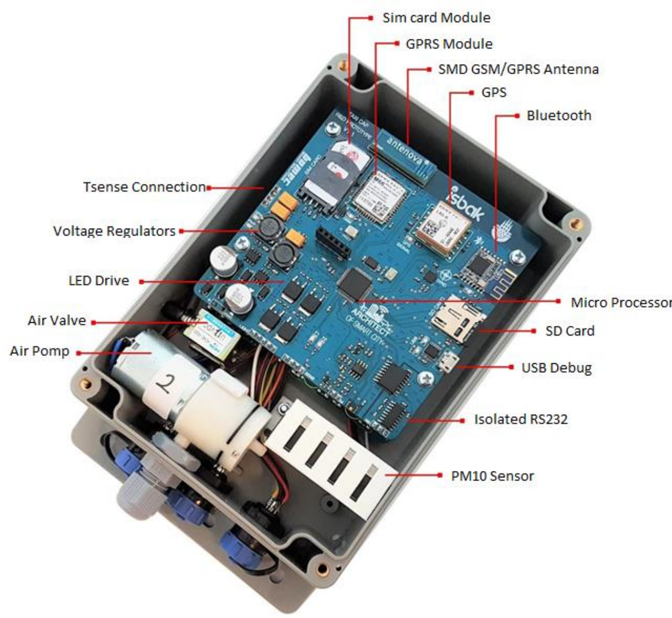


Figure 2 TCore Board Components

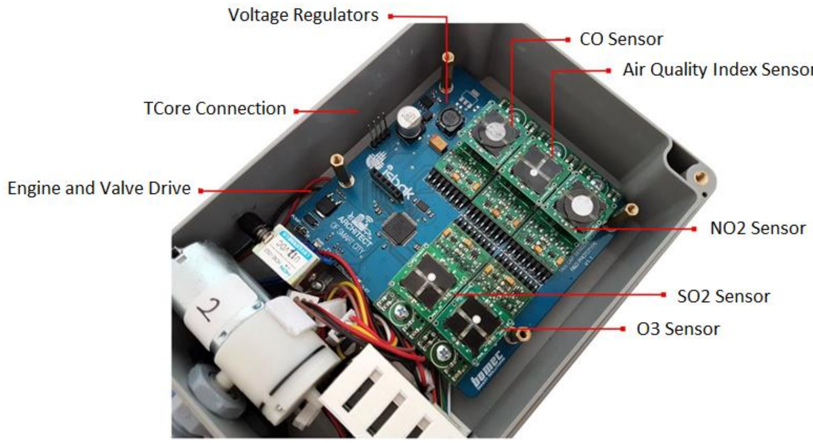


Figure 3 TSense Board Components

In Figure 4, a detailed schematic of the main components of the ISBAK's air quality monitoring unit is shown.

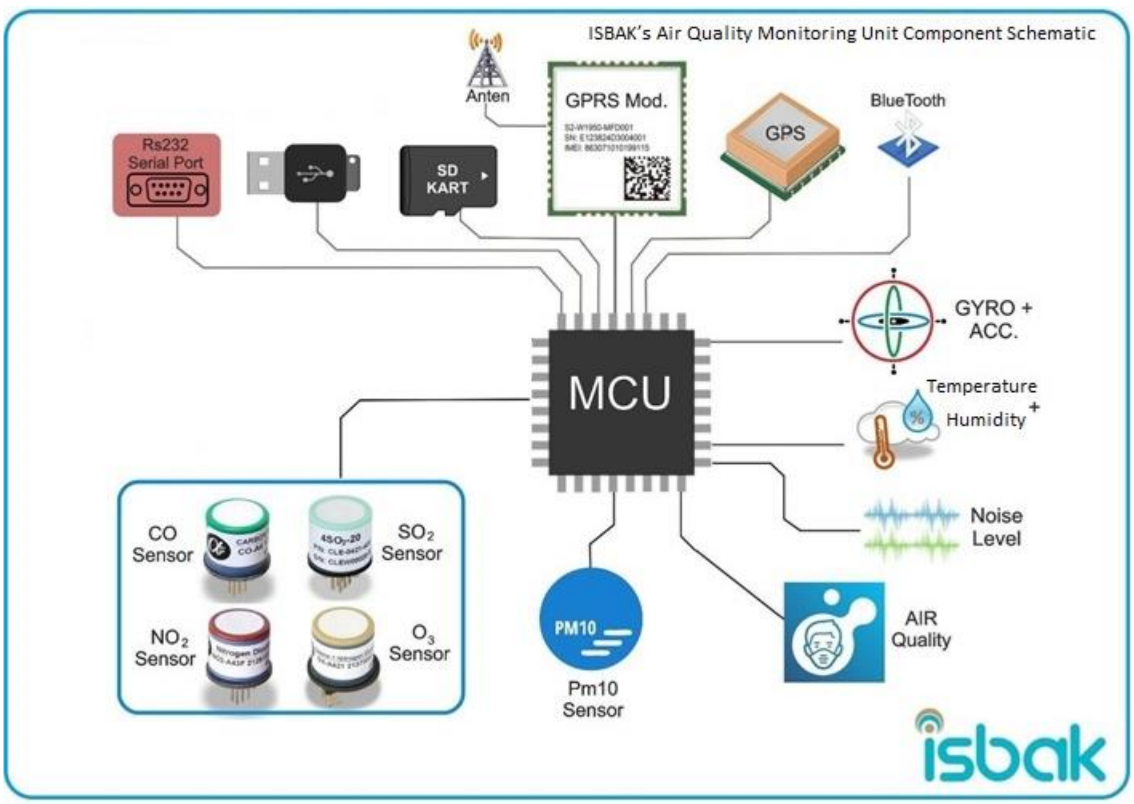


Figure 4 ISBAK's Air Quality Monitoring Component Schematic

The system can measure the amount of the NO2, CO, SO2 and O3 in ppb. The working temperature of all sensors is between -30 and 55 Celsius degrees. New generation Screen Printed Electro Chemical sensor technology is very suitable for IoT projects in terms of price and energy consumption. The properties of each measured parameter are described in Annex I.

Two iSBAK measurement units were sent to both UPC and CTAG. The unit sent to CTAG can be seen in the Figure 5. This unit has the peculiarity that, on the one hand, the PM sensor takes the sample continuously directly from the outside of the unit enclosure, and on the other hand, the valve that controls the air outlet from the unit enclosure was removed. The unit has been started up and the pump puts an air sample into the unit enclosure every about 6 minutes, and apparently both the GPS and GPRS modules seem to be working properly. Nevertheless, the writing of the measured data to the SD card did not work at any time. This did not allow to calibrate and analyse the data measured by the unit, but to study its design and behaviour.

Figure 5. iSBAK's unit sent to CTAG.

The main concern of the design of iSBAK's unit sent to CTAG is the air sample management. The pump just puts an air sample into the unit enclosure every 6 minutes, but this air is not managed in any way. Firstly, there is a risk of mixing two consecutive samples, as the air sample is stored inside the unit and it is not pulled out to the outside at any time. Secondly, when taking samples every 6 minutes, the information concerning this time slot is lost if the vehicle is in motion. Finally, and most importantly, the sample is not channelled over the sensors. The electrochemical sensors need a minimum air flow rate to work properly, i.e., to maintain stable the chemical reaction which happens into the sensor can perform a proper measurement.

Figure 6 iSBAK's unit sent to UPC.

In Figure 6, the unit sent to UPC is depicted. Same issues and concerns regarding the air management aspect, and the problem in writing to SD card were also experienced in this unit. Moreover, it was observed that the pump was not functioning in the start-up, thus not being able to send air sample to the unit enclosure. It is considered that the issues observed are due to the damage the devices suffered during their transport, as they were tested in iSBAK's installations before sending, apparently functioning correctly. The units were sent back to ISBAK for analysing and fixing the problems, with the idea of delivering again alternative properly functioning units to UPC and CTAG to take the advantage of the last months of the KAVA to test it along with the CAROLINA prototypes.

2.3. Experimental test with commercial sensors

Due to the recent improvements in manufacturing technologies related to low-cost sensors for gas and PM concentration measurement, many solutions appear in the market [14, 17, 20, 30, 22, 23]. In this section we test some sensors with the intention of better understanding their operation and limitations in order to choose the most suitable for this Activity.

Regarding low-cost gas sensors, we identify two possible options [14, 17, 20, 30]. On the one hand, SPEC sensors [31] are based on solid-state technology reaching a very small size and as commented above, these are sensors used in the iSBAK's unit. On the other hand, Alphasense sensors [32] are traditional electrochemical sensors highly optimized to give a stable and accurate response.

With regard to the PM sensors, two possible candidates are selected [14, 22, 23, 30]. The SDS011 sensor developed by Nova Fitness [33] is widely used achieving good results. The PMS series from Plantower [34] has a small size and provides accurate results under different environmental conditions.

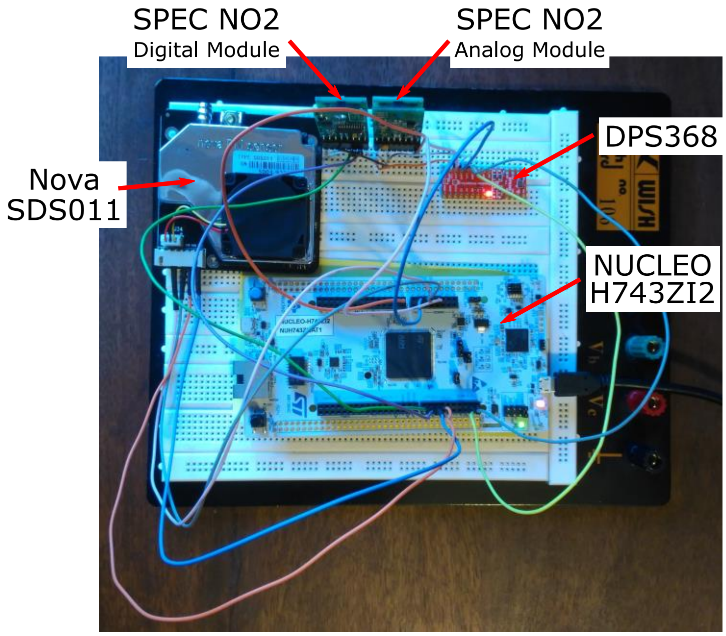


Figure 7. Experimental setup for commercial sensors test in CTAG laboratory.

Some tests are performed in CTAG laboratory to verify the selected sensors. We choose to test NO_2 sensors since the concentration of this gas has a significant variation due to the emissions of internal combustion vehicles, as it can be seen in the data collected by a local fixed station [35]. Figure 7 shows the experimental setup including some of the sensors under test. The full list of components tested by CTAG is as follows:

- 1ud. NO_2 SPEC analog module
- 1ud. NO_2 SPEC digital module
- 1ud. NO_2 Alphasense sensor
- 1ud. SDS011 Nova Fitness sensor
- 2ud. PMS7003 Plantower sensor
- 1ud. DPS368 Infineon pressure sensor
- 1ud. NUCLEO-H743ZI2 STMicroelectronics board

The NO_2 SPEC analog module includes the sensor itself and also the Analog Front-End (AFE), i.e., the analog signal conditioning circuitry needed to interface the sensor. The output of this module is a voltage, so an Analog-Digital Converter (ADC) is needed for a microcontroller to read the voltage measurements and then the microcontroller transforms these measurements into gas concentration using an algorithm designed by CTAG. In addition, these data need to be compensated in temperature, so another specific algorithm for this purpose is designed.

The NO_2 SPEC digital module, in addition to the elements included in the analog module, it also includes a microcontroller and a temperature and humidity sensor, named SiLabs SI7021. The data transmitted by the serial port of this module are already temperature compensated.

In a similar way to the SPEC analog module, the NO_2 Alphasense sensor includes the sensor and the AFE. Also, an ADC is needed to read the voltages from the sensor and an algorithm must be designed to calculate the temperature-compensated gas concentrations.

Both the SDS011 and PMS7003 sensors have serial communication and they give the $PM_{2.5}$ and PM_{10} concentration results in um/m^3 units.

The DPS368 is a miniaturized digital barometric air pressure sensor with ultra-high precision, IPx8 certified and I2C communications. It is used to verify if the gas sensors measurements are dependent on the atmospheric pressure.

Finally, the NUCLEO-H743ZI2 development board includes a STM32H743ZI microcontroller and can be programmed using the Arduino IDE. It is used to control all the sensors, implement the algorithms and transfer all the data to a personal computer for analysis.

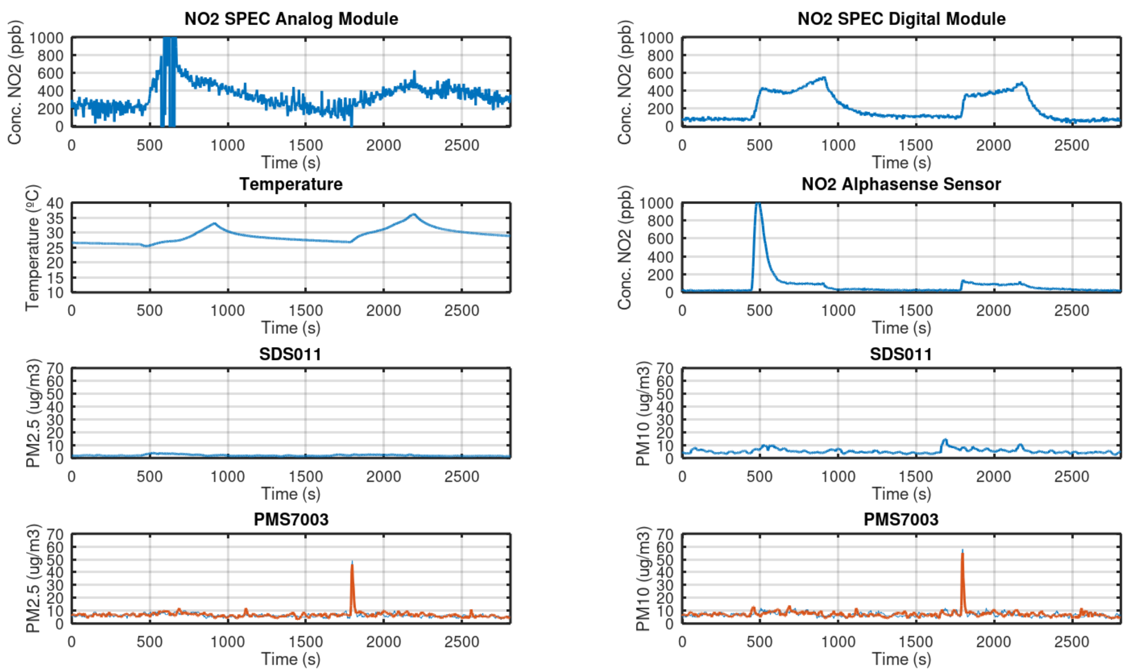


Figure 8. Experimental results of the commercial sensors test in CTAG laboratory.

The tests were performed by subjecting the selected sensors to steep gradients of different air concentrations provided by the exhaust of an internal combustion vehicle. Figure 8 depicts the experimental results. Regarding the gas sensors results, it can first be observed that the noise in the SPEC analog module is very high, followed by the digital module, with the Alphasense sensor having a much less noisy response. A digital filter was implemented to try to correct the noise of the SPEC analog module, but it was not enough. It can be also noted that both SPEC sensors have higher temperature dependence than the Alphasense sensor. From the slope of the gas sensor graphs, it can also be observed that the response speed of the Alphasense sensor is higher, reaching a slope of about 40 ppB/s. Finally, the dependence of the gas sensors with the atmospheric pressure is checked by subjecting the sensors to an altitude change of approximately 20 meters. The result is that the response of the sensors remains constant even if the atmospheric pressure changes.

Reviewing the data from the PM sensors, we can see that the response of the two PMS7003 sensors is very similar. This indicates that the variability between sensors is small. If we compare the data from both SDS011 and PMS7003 sensors, it can be seen that the PMS7003 response is slightly more stable with a less noisy output signal. Finally, when analysing the data, it can be detected that PMS7003 has a higher sensitivity.

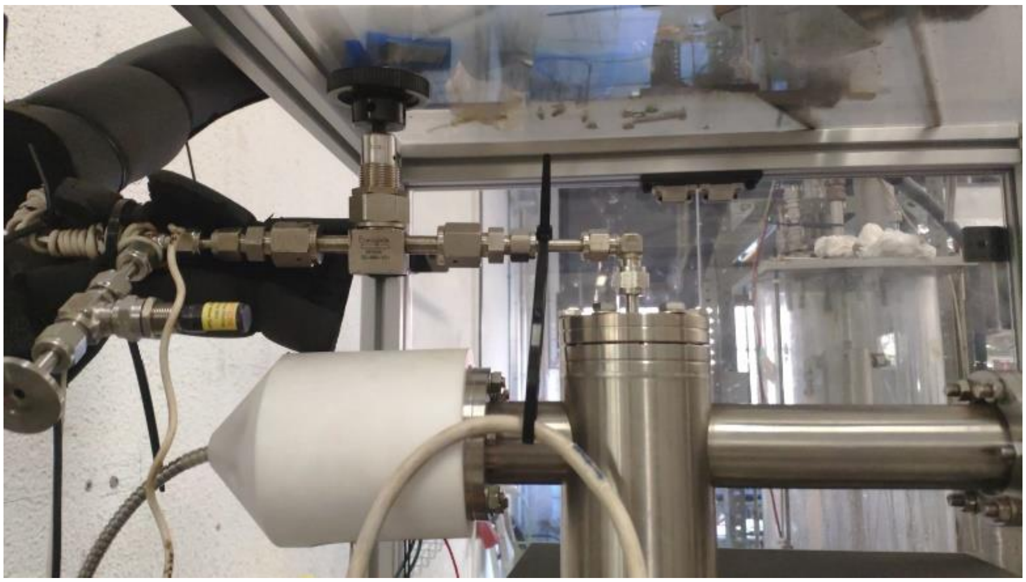


Figure 9 Double inlet inside the gas analyser already installed

An important aspect in the KAVA is the calibration of the sensors and the study of their deterioration with time. To that end, a calibration system with a mass spectrometer is available in the laboratories of the Heat and Mass Transfer Technological Center (CTTC) of the Technical University of Catalonia CTTC.

The mass spectrometer has been used at the CTTC to make measurements under sub atmospheric conditions (in an absorption refrigeration facility). To maintain the present measurement capability and incorporate a new type of measurements, according to KAVA requirements, the infrastructure is being adapted to measure in atmospheric conditions using a double inlet (see Figure 9). In Figure 10, details about the inlet are provided. Note that this is the drawing proposed by the gas analyser manufacturer, which does not correspond exactly with the lay-out of our experimental infrastructure. It only captures the details about the inlet. In each inlet, a different pressure leak (using calibrated QIC -Quartz Inert Capillary-) to assure the conditions inside the gas analyser.

In the coming weeks, the first measurements of air quality will be performed, to assure the precision of the gas analyser. The results will be compared with high precision optical sensors.

During the field tests that will be performed briefly, we will be able to monitor the mismatch of the sensors in their operation in time, to anticipate the frequency with which these require a recalibration.

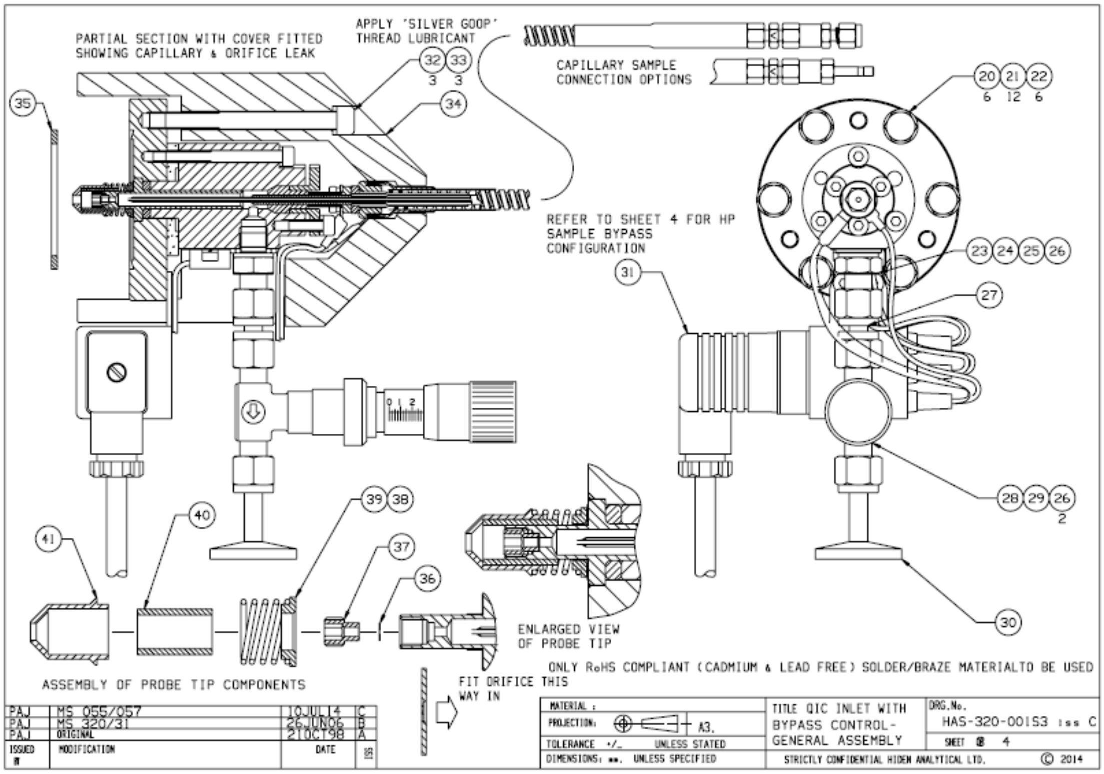


Figure 10 Details about the double inlet at the gas analyser

In the framework of task 2002, UPC has developed a basic sensor unit to be used for the testing and tuning of the future PaaS being designed simultaneously in task 2004. However, this has been done with total coordination in the present task to share and complete the experiences with regard to the design and construction of the PoC of the sensor.

In this basic sensor unit, the following sensors in Table 1 were selected:

Sensor	Link
O3	https://www.digikey.com/product-detail/en/spec-sensors-llc/968-046/1684-1049-ND/7689230
CO	https://www.digikey.com/product-detail/en/spec-sensors-llc/968-001/1684-1002-ND/6136365
SO2	https://www.digikey.com/product-detail/en/spec-sensors-llc/968-006/1684-1023-ND/6136386

NO2	https://www.digikey.es/product-detail/es/spec-sensors-llc/968-043/1684-1047-ND/7689228
VOCs	https://www.digikey.es/es/product-highlight/s/sparkfun/ccs811-indoor-air-quality-sensor-breakout-board?utm_adgroup=General&utm_source=google&utm_medium=cpc&utm_campaign=Dynamic%20Search_ES_Product&utm_term=&productid=&gclid=EAIaIQobChMI87-vyIuu6gIVCdGyCh29ygB5EAAYASAAEgLYDPD_BwE

Table 1 Selected sensors for the UPC basic sensor unit

As a result of the experience gained from comparing different types of sensors for PoC sensor unit, we opted for sensors of the same technology, but from a different brand. The selected sensors of the PoC are detailed in the next section.

3. Unit development

This Section describes the development of an air pollution measurement unit as proof-of-concept to be positioned on a moving vehicle. The goal of this first design version of the measurement unit, which is explained in detail in this Section, is to study and validate the proposed technology overcoming the current challenges, so we consider it not essential to include both wireless communication and power supply by battery to meet this goal. However, as mentioned in the previous section, CTTC-UPC is developing a basic sensor unit to study practical aspects regarding the design of a PaaS which is the scope of the simultaneous task 2004. This study involves the alternatives on communication technologies. In Section 3.1, different options or approaches to reach an optimum unit design are explained. In Section 3.2, the measurement unit chosen as the best option for this Activity is described in detail, including Computational Fluid Dynamics (CFD) simulations in Section 3.3 that help in the design of the unit and verification of its operation.

3.1. Analysis of different proposed approaches

One of the biggest constrains for the operation of the air pollution measurement unit is given by the electrochemical gas sensors. According to manufacturers' specifications, this type of sensors requires a constant air flow of approximately 500 ml/min for about 45 seconds to have an accurate response. Therefore, we design a unit including an air sample storage tank. So, the idea behind this unit is that a sample is stored into a tank at 2 atm using an air pump. Then, the sample is released over the sensors for 45 seconds, time enough to make an accurate measurement.

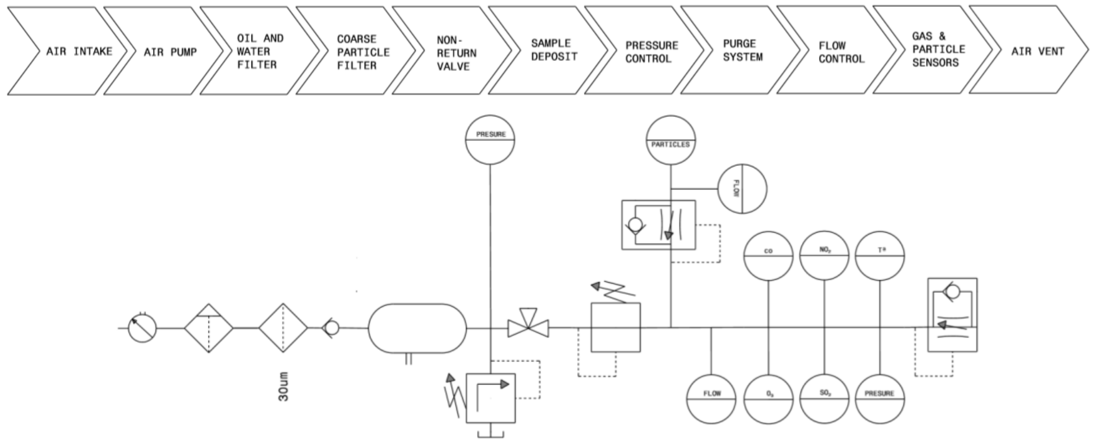


Figure 11.Components scheme and P&ID of the unit working at 2 atm.

On top of Figure 11 is shown a scheme enumerating the components which comprise the unit that works at 2 atm. The air sample enters into the unit through an air intake designed to avoid small unwanted objects, as for example, small stones. Then, the pump impulses the air through a couple of filters and then the clean air is stored in a tank. The filters avoid oil and water, as well as PM of diameter higher than 30 µm. Finally, the air sample is released over the sensor through a valve that controls the air flow in order to meet the requirements from the electrochemical sensors. On bottom of Figure 11, the Piping and Instrumentation Diagram (P&ID) for this unit is shown.

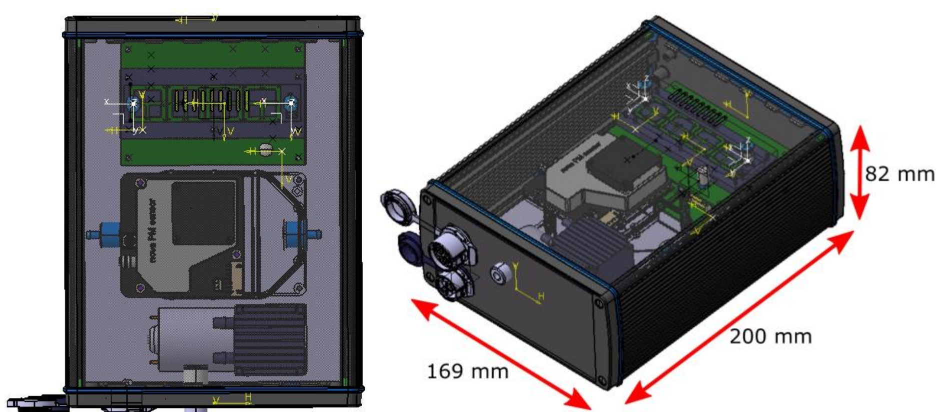


Figure 12. Mechatronics CAD design of the unit working at 2 atm.

Figure 12 shows the Computer-Aided Design (CAD) of the unit working at 2 atm. It is achieved a small unit enclosure. In Figure 13, a detailed view of the components which comprises this unit is depicted. It includes the filters, the air pump, an own designed tank, the gas sensors into an own designed air channel, a PM sensor and finally, the pneumatic and electronics control elements. The electrochemical gas sensors chosen for this unit are the SPEC sensors and the PM sensor chosen is the SDS011 sensor.

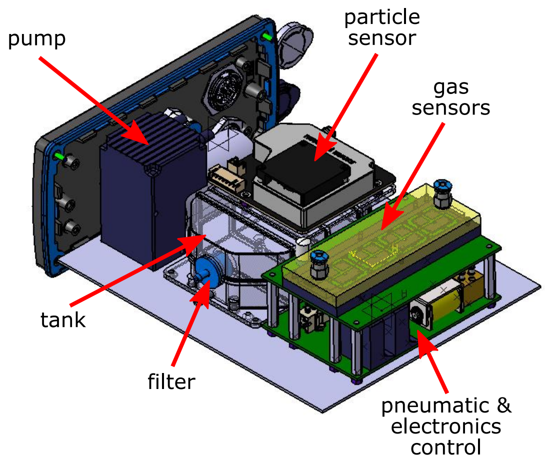


Figure 13. Detail of the components which comprise the unit working at 2 atm.

The unit working at 2 atm is designed to take accurate measurements every 45 seconds. Nevertheless, this unit has some disadvantages:

- The unit size, without including the housing, is quite wide and high, which will negatively influence the aerodynamics when placed on the roof of a vehicle.
- The unit design is very complex since it has an air tank working at 2 atm, where a lot of both mechanic and pneumatic components are needed for its proper operation.
- All the air quality information for the 45 seconds that the measurement lasts is lost if the vehicle is in motion.

Therefore, in order to overcome the disadvantages mentioned above and taking as a starting point the measurements presented in Section 2.3, we propose a unit that takes measurements in real time and works at atmospheric pressure. From the results in Section 2.3, it seems that the electrochemical gas sensors selected, especially those from Alphasense, are fast enough taking measurement to work in real time under the test conditions. In the next Sub-Section, the design of a proof-of-concept unit taking into account these considerations are explained in detail.

3.2. Unit design

The air pollution measurement unit design involves multidisciplinary knowledge in hardware, software and mechatronics, as well as in CFD simulations as shown in Section 3.3.

From the best of our knowledge and after reviewing the State-of-the-Art, benchmarking and testing some commercial sensors, below we propose the main requirements to be considered in the air pollution measurement unit development:

- Gas concentrations to be measured: CO, SO_2, NO_2, O_3
- PM concentrations to be measured: $PM_{2.5}$, PM_{10}

- Environmental sensors:
    - ✓ Temperature
    - ✓ Humidity
    - ✓ Pressure
- Operation range of the system (basically constrained by the sensors):
    - ✓ -10ºC to 40ºC (continuous)
    - ✓ 15% to 85% RH (continuous)
    - ✓ 80kPa to 120 kPa (continuous)
    - ✓ -30ºC to 70ºC (one-time)
    - ✓ 5% to 95% RH (one-time)

- Air flow rate and air speed for electrochemical gas sensors:
    - ✓ 0.1-0.2 m/s approx.
    - ✓ 500 mls/min
- Air flow rate for PM sensor:
    - ✓ 250 ml/min

- Dust and oil filter. Ex.: Porous PTFE membrane
    - ✓ Filtering PM > 10 um
- Condensed water filter. Ex.: Porous PTFE membrane
- No-reactive materials for air conducts. Ex.: Teflon™ (PTFE), polypropylene, stainless

- Low cost
- Small form factor
- System installation: vehicle roof to avoid direct measurements from an exhaust pipe
- Waterproof and portable system
- Easy sensor replacement

- Stable power supply
- AFE for each electrochemical gas sensor
- Gas concentration calculation: Temperature, Relative Humidity and Pressure dependence
- Digital filtering: avoid abrupt variations due to noise and out-of-scale points
- Sample acquisition control: timestamp and geolocation (data extracted from vehicle)
- Communication with PC

Within the framework of this Activity we propose the design of a proof-of-concept unit to validate the proposed idea and technologies. The proof-of-concept unit may not include all the above-mentioned requirements, but we will try to make it as close as possible to a pre-commercial version.

The design of the different elements that make up the air pollution measurement unit is shown in detail below. As commented, it requires dealing with different knowledge fields. The unit includes a main channel where the air taken from the outside circulates continuously and where the environmental and electrochemical gas sensors are placed. A secondary channel is also included to channel the air to the PM sensor. Finally, a microcontroller manages the measurement process and communications.

HW & SW design

This section describes the hardware and software development for the measurement unit. Regarding the hardware design, the selected components are the following:

- Electrochemical gas sensors from Alphasense. These sensors are selected because of their fast response and low noise, as seen is Section 2.3.
- PMS7003 PM sensor from Plantower. This sensor is selected due to its small size and low noise output signal.
- Si7021-A20 temperature and humidity sensor from Silicon Labs. This chip is selected because it has high accuracy, low power consumption and I2C communications, as well as a cover to protect the sensor.
- DSP368 pressure and temperature sensor from Infineon. This chip is selected because of its high precision, IPx8 certification and I2C communications.
- NUCLEO-H743ZI2 development board from STMicroelectronics. This board is characterized by its versatility, high processing power, small size and easy programming, as it can be programmed using the Arduino IDE. The NUCLEO board also includes a 16 bits ADC.

It should be noted than all sensors and the remaining components meet the requirements introduced above. The integration strategy of all these elements consists of a specific Printed Circuit Board (PCB) in which lied all the sensors. This PCB is connected to the NUCLEO board directly, without wires, creating a stack of components.

Figure 14. Electrochemical gas sensor on the left and PMS7003 Plantower PM sensor on the right.

Figure 14 shows an example of the electrochemical gas sensors selected to be included in the measurement unit, in particular, the CO sensor. These sensors from Alphasense have four terminals to be connected directly to a PCB. This enables the possibility of easy replacement. Figure 14 also shows the selected PM sensor which measures both $PM_{2.5}$ and PM_{10}. It has a size of 48×37×12 mm, an internal fan to move the air through and serial communications.

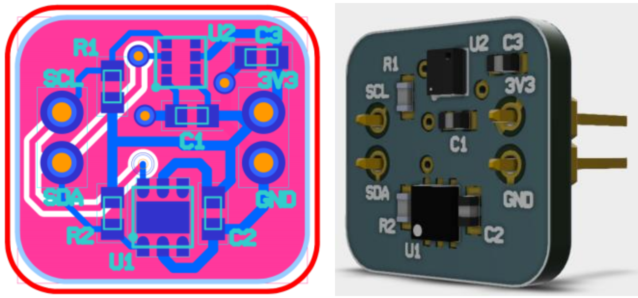


Figure 15. Layout on the left and 3D view of the environmental PCB including temperature, humidity and pressure sensors.

Both ICs including the temperature, humidity and pressure sensors are lied in a small PCB, namely environmental PCB in Figure 15, designed to be connected directly to the PCB which includes the gas sensors. The environmental PCB also includes the components needed for the I2C communications. The goal of this small PCB is to keep the design in line with the gas sensors enabling the possibility of easy sensor replacement, similar to the procedure for the gas sensors.

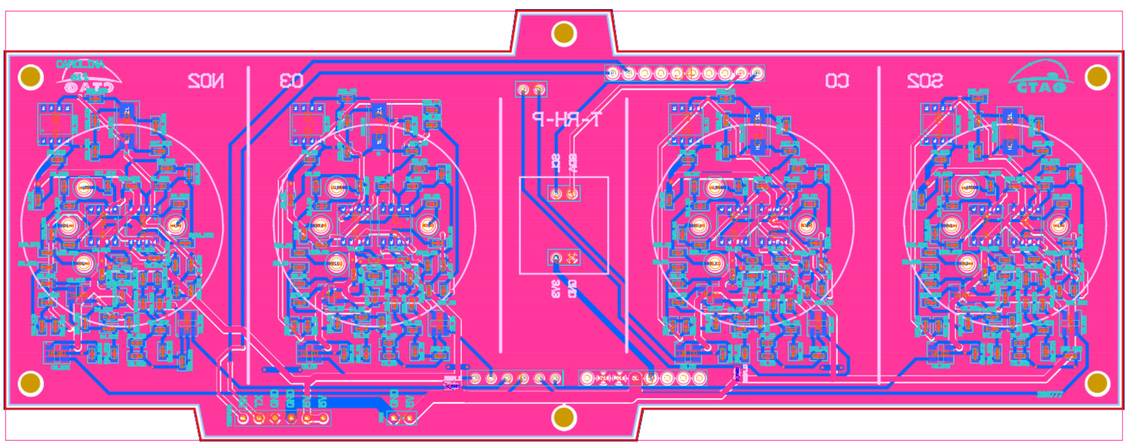


Figure 16. Layout of the PCB including the AFE for the gas sensors as well as the circuitry needed for the rest of sensors.

Figure 16 shows the layout of the PCB which include the AFE for the electrochemical gas sensors, the connectors for the environmental PCB, the connector for the PM sensor and the connector for a fan, which is part of the mechatronic integration explained is the next Sub-Section. Each gas sensor needs a specific AFE which is designed to be compatible with the ADC of the NUCLEO board.

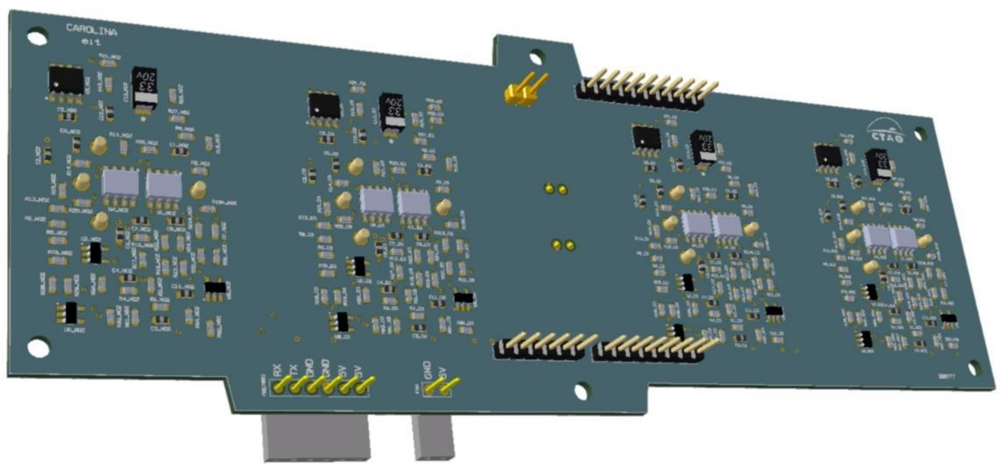


Figure 17. Bottom 3D view of the PCB including the AFE for the gas sensors as well as the circuitry needed for the rest of sensors.

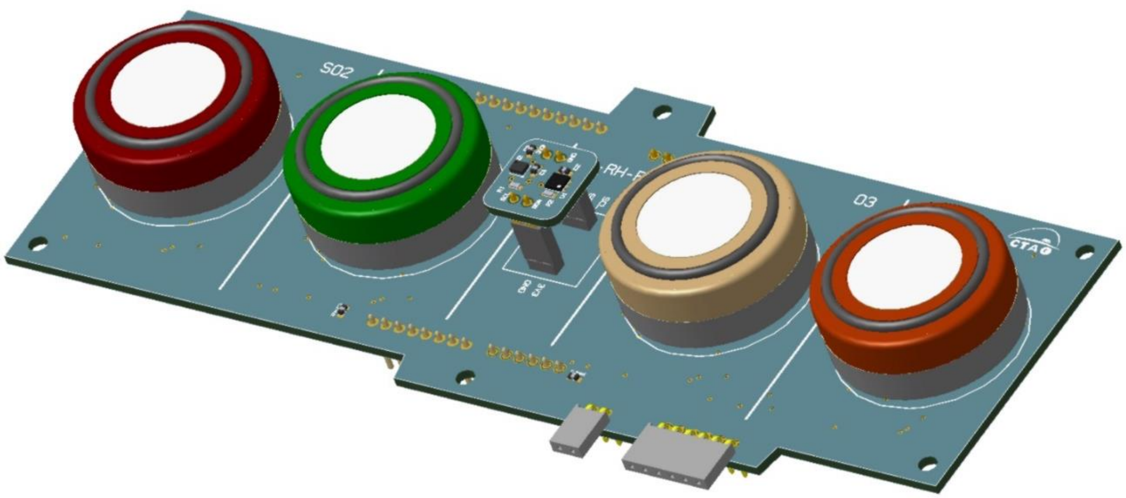


Figure 18 Top 3D view of the PCB including the AFE for the gas sensors as well as the circuitry needed for the rest of sensors.

Figure 17 and Figure 18 show the 3D view of the PCB including the four gas sensors, the environmental PCB which includes the temperature, humidity and pressure sensor, the PM sensor connector, the fan connector and the connectors for the NUCLEO board. As it can be seen in Figure 18, all sensors are in line and at the same level to be easily placed into a channel through which the air sample would flow.

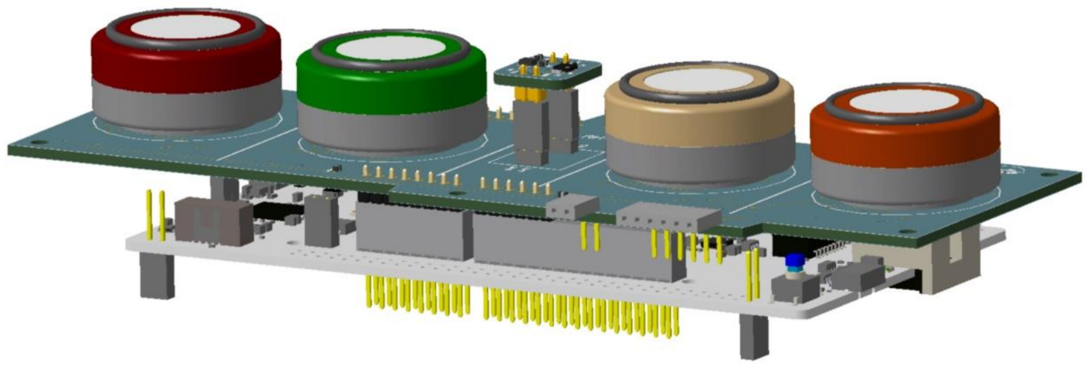


Figure 19. HW elements stacked up including sensors, PCB and NUCLEO board.

Finally, Figure 19 shows all the HW elements stacked-up, including the NUCLEO board. The result is a compact set of elements, easy to assemble and with no moving parts.

Regarding the software design, it includes sensors reading management, data pre-processing and communications control. The microcontroller of the NUCLEO board reads the data of temperature, humidity and pressure from the integrated sensors using I2C communications. The $PM_{2.5}$ and PM_{10} concentrations are read directly by the microcontroller using serial communications. The microcontroller also reads the voltage generated by the AFE of the four electrochemical gas sensors using the 16-bits ADC. Then, these voltages are transformed into gas concentrations using an algorithm that takes into account the environmental data.

Once all the data of interest has been acquired and calculated, a digital filter is applied to avoid abrupt variations and out-of-scale points, $\bar{x}(t) = \propto \cdot\, x(t) + (1 - \propto) \cdot x(t^{-})$, where $x(t)$ is the actual data, $\bar{x}(t)$ the filtered data, t the time, t^{-} the time in the previous step and $\propto$ the filter coefficient. Finally, all the filtered data are sent by the microcontroller to a PC through USB. The measurement rate can be configured depending on the final scenario, being 5 second a standard measurement rate.

The following Sub-Section describes the design of the mechatronic and housing elements of the air pollution measurement unit, including the fastening of the HW elements.

Mechatronic and Housing design

The air pollution measurement unit includes two different structural parts. A mechatronic part houses the HW elements and a USB connector, as well as a filter and a fan. Another part, a housing, covers the mechatronic part providing the unit with design and style, as well as aerodynamic behaviour and fastening elements to the vehicle roof.

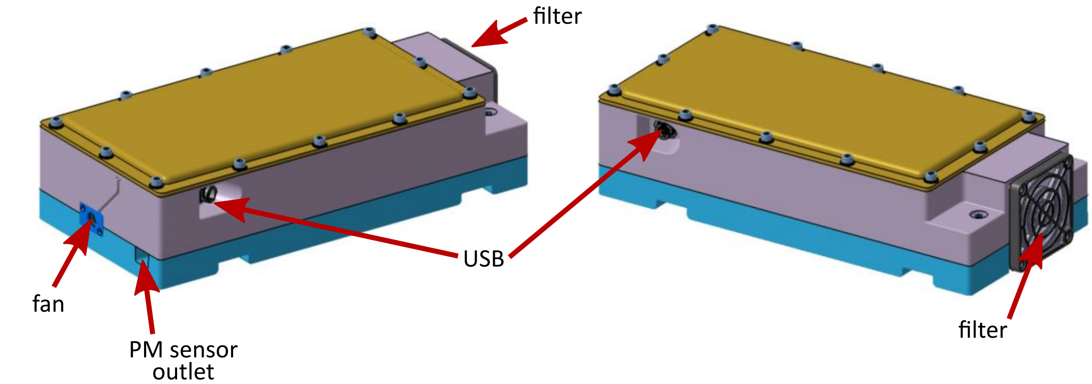


Figure 20. External view of the mechatronic part of the measurement unit.

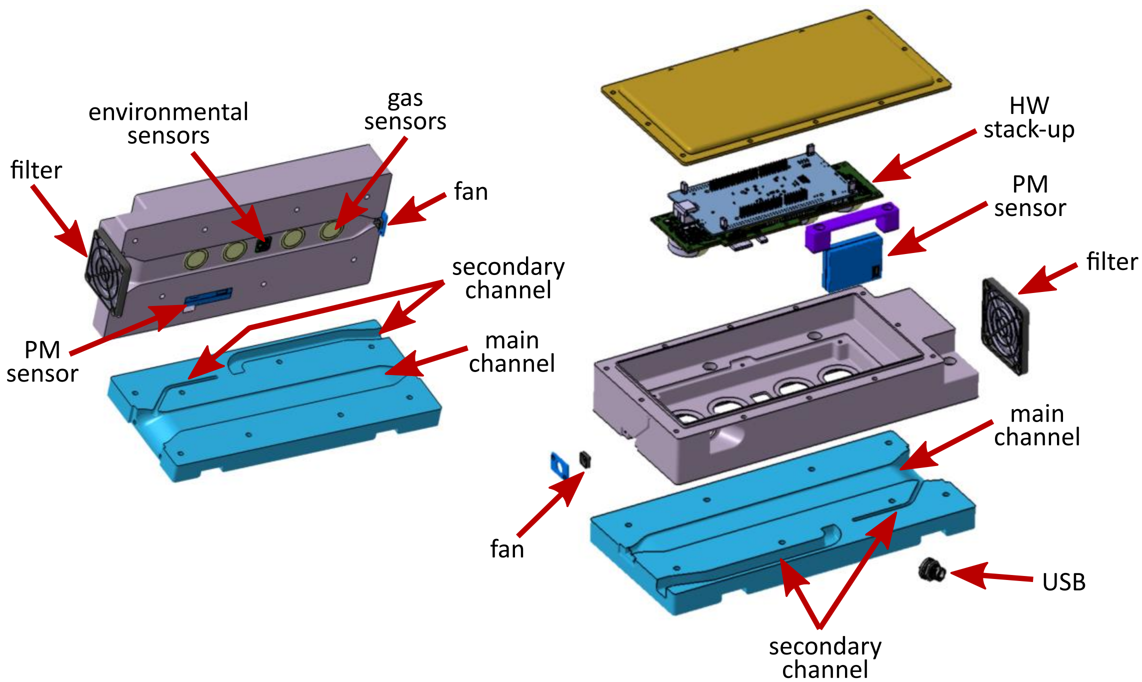


Figure 21. Interior view of the mechatronic part of the measurement unit.

Figure 20 shows the outside and **¡Error! No se encuentra el origen de la referencia.** the inside of the mechatronic part of the unit with an exterior size of 280x130x69 mm^3. A G2 filter is installed at the air inlet to prevent oils and unwanted particles. Next, a main and secondary channel are built. The former is designed to accommodate the environmental and gas sensors, and the latter to accommodate the PM sensor. A mini fan is positioned at the outlet of the main channel to force the air sample out. Finally, the hardware elements are housed maintaining the watertightness and a USB IP67 connector is installed and connected to the NUCLEO board for power and data transmission.

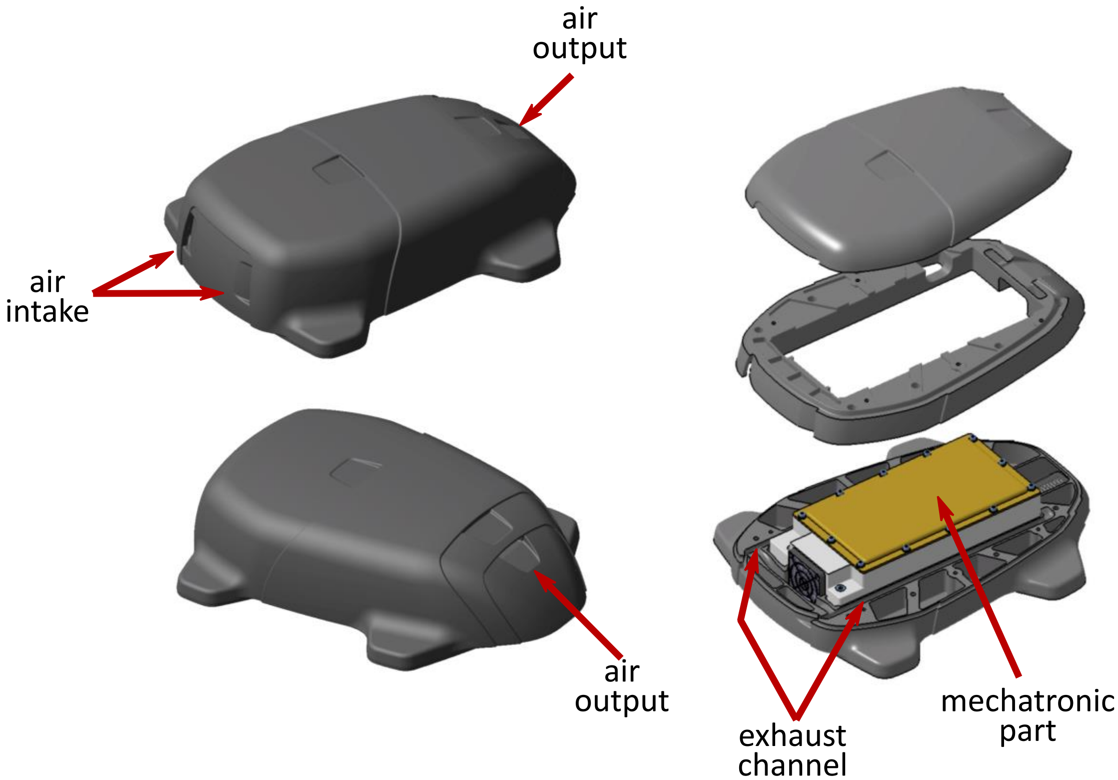


Figure 22. Housing of the air pollution measurement unit.

The housing of the air pollution measurement unit with an exterior size of 415x320x102 mm^3 and the air ducts from the outside to the mechatronic part are shown in Figure 22. The air enters through the air intake and it is branched into two channels, one with a direct outlet to the outside of the housing (exhaust channel) and another that leads the air to the filter of the mechatronic part. In this way, the air is continuously circulated through the exhaust channels due to the vehicle speed, and it is the mini fan that forces the air sample from the exhaust channels to the mechatronic part. The housing is fixed to the vehicle roof by means of magnets.

As shown, the housing gives the support to the unit, aerodynamic performance, and style. In the following Sub-Section, the air pollution measurement unit is studied from the aerodynamic point of view through CFD simulations.

3.3. CFD simulations

A numerical CFD set-up has been designed and tested by CTTC-UPC aimed at studying the fluid-dynamics behaviour of the air within the measurement unit during its various operating phases, including the case of the stationary vehicle and the cases of vehicle moving with different speeds.

Simulation concept and domain

The domain reflects the internal channels of the device depicted in Figure 22, aimed at collecting the external air and directing part of the flow to the internal channel where the measurement units are placed. The domain is depicted in Figure 23. The Fan/Extractor has the function of keeping a stable air flow in the internal channel, guaranteeing the prescribed air flow and velocity in the proximity of the measurement units. Hence, the simulation is aimed at verifying the operating condition of the measurement unit and the working point of the extractor for different external conditions.

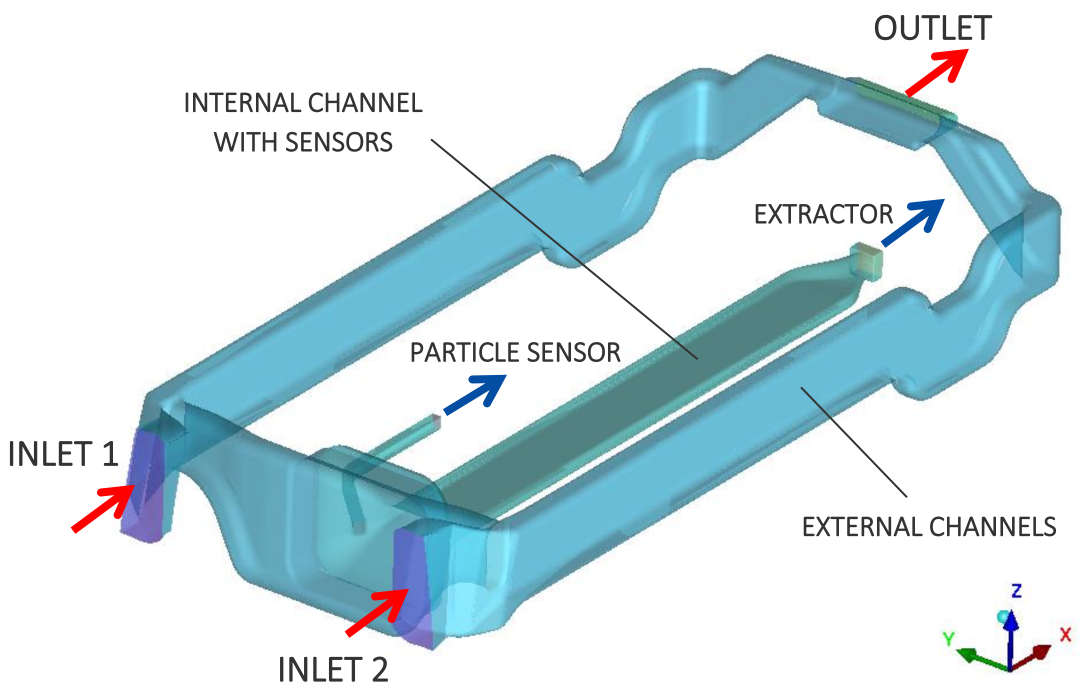


Figure 23. Description of the geometry adopted in CFD cases.

Numerical Model

The CFD model is developed on the open source platform OpenFOAM [36]. The *pimpleFoam* solver is employed, which is a transient solver for incompressible, turbulent flow of Newtonian fluids on a moving mesh. The PIMPLE algorithm merges feature of PISO and SIMPLE algorithms. PISO is an acronym for Pressure Implicit Splitting of Operators for time dependent flows while SIMPLE stands for Semi-Implicit Method for Pressure Linked Equations which is used for steady state problems.

A LES (Large Eddy Simulation) approach is employed, in particular, using the WALE (Wall-Adapting Local Eddy-viscosity) Sub-Grid Scale (SGS) model [37]. It is an algebraic eddy viscosity model (0-equation model), which relies on the definition of a sub-grid scale viscosity to model the dissipation. The *nutkWallFunction* condition for the SGS viscosity is applied close to the solid boundaries to avoid bad solutions close to the walls, by providing a wall constraint on the turbulent viscosity.

Boundary conditions for velocity and pressure are listed in Table 2:

	Velocity	Pressure
EXTRACTOR	pressureInletOutletVelocity	fanPressure
INLET	inletOutlet	fixedValue (=0 for stopped car)
OUTLET_SMALL	flowRateInletVelocity	zeroGradient
OUTLET_BIG	inletOutlet	fixedValue
CHANNEL	noSlip	zeroGradient

Table 2 Boundary conditions for the numerical model

Extractor/FAN

The smallest fan from the SUNON Mighty Mini Fan Series has been chosen. The characteristics are indicated in Figure 24. The presence of the fan within the numerical set-up is taken into account by means of the *fanPressure* boundary conditions. The output of the numerical analysis will help to understand the working point of the fan and whether it is in condition of working properly.


Mighty Mini Fan

10X10x3 mm 12x12x3 mm 15x15x3 mm 17x17x3 mm

Size (mm)	Model (IP55)	Model (IP58)	Rating Voltage (V)	Operating Voltage (V)	Power Current (mA)	Power Consumption (Watts)	Speed (RPM)	Air Flow (l/min)	Static Pressure (Pa)	Noise (dB(A))
10x10x3	UF3A3-500 UF3A3-700	UF3A3-500B UF3A3-700B	3	2.0-3.5	96	0.29	17000	3.43	10.44	21.0 / 30cm
12x12x3	UF3C3-500 UF3C3-700	UF3C3-500B UF3C3-700B	3	2.0-3.5	97	0.30	16500	5.95	18.91	28.3 / 20cm
15x15x3	UF3F3-500 UF3F3-700	UF3F3-500B UF3F3-700B	3	2.0-3.5	36	0.10	14500	8.75	20.36	30.0 / 30cm
17x17x3	UF3H3-500 UF3H3-700	UF3H3-500B UF3H3-700B	3	2.0-3.5	37	0.10	13000	16.27	21.21	32.0 / 30cm

Figure 24 Chosen fan characteristics

Preliminary results: the stationary car case

A preliminary simulation is carried out on meshes with decreasing sizes, in order to verify the correctness of the numerical set-up and to check the mesh convergence. A typical mesh employed for the simulations is reported in Figure 25. Mesh features are reported in the following table:

Mesh Name	Number of nodes	Simulation time on 16 CPUs [s]
Internal Geometry 2 (IG2)	78k	79
IG3	182k	467
IG4	800 k	6326
IG6	1.1 M	9125

Table 3 Mesh features employed in the preliminary cases

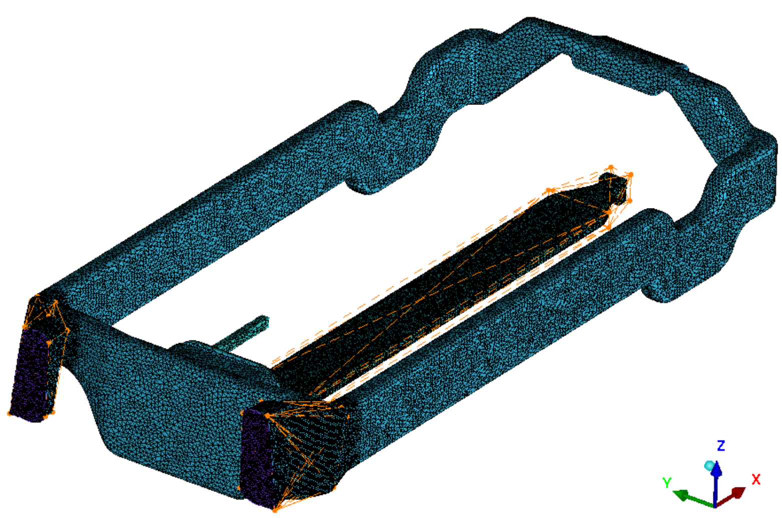


Figure 25. Mesh employed for the internal channels' representation.

The simulated case consists in the case of the measurement device placed on a stationary car (0 pressure in all the inlet ports). The data extracted regard the mass flow rate and the pressure at the fan/extractor, and the velocity in the internal channel. In Figure 26 two typical colour maps for velocity magnitude and pressure at steady state are reported- Additionally, the flow profile in the internal channels and the working point of the fan are checked.

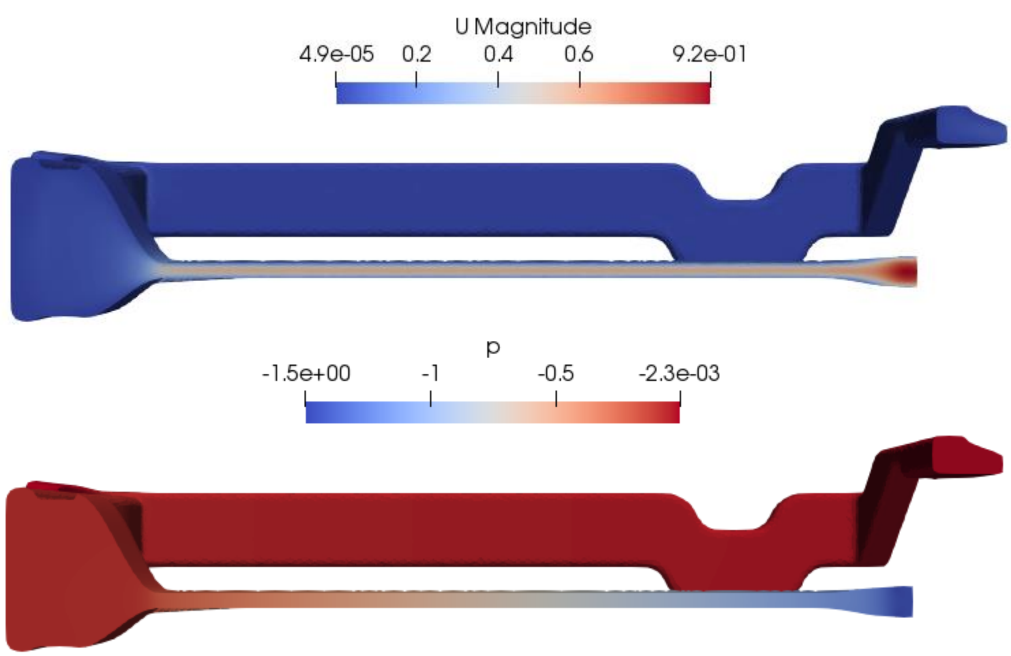


Figure 26. Typical velocity and pressure maps obtained from CFD analysis.

As it can be seen from the results reported in the following plots, the convergence of the mesh is obtained with IG4, since the use of a finer mesh does not involve a noticeable change in the results in terms of pressure and velocity. In particular Figure 27, depicting the mass flow rate at the fan outlet, shows how the results from IG6 totally overlap to IG4. The pressures at the outlet, depicted in Figure 28, are practically the same for all the meshes. The velocity at a certain probe in the internal channel, reported in Figure 29, is very close between IG4 and IG 6. Finally, Figure 30 depicts averaged velocity profiles in the internal channel at steady state, showing how only the coarsest mesh, IG2, present quite different results. However, all meshes provide reasonable results of the same order of magnitude, with very limited differences. Therefore, even the coarsest mesh can be used to perform fast qualitative analyses. Indeed, the working point of the fan obtained with the four meshes is practically the same, as reported in Figure 31.

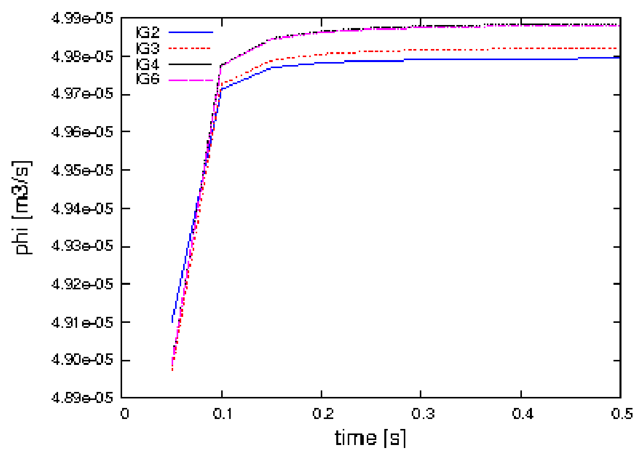


Figure 27. Volumetric flow rate at the extractor obtained in CFD analysis for the stationary car case.

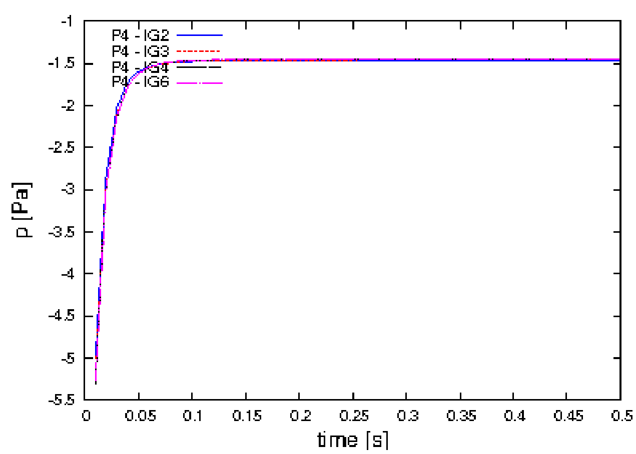


Figure 28. Pressure at the extractor obtained in CFD analysis for the stationary car case.

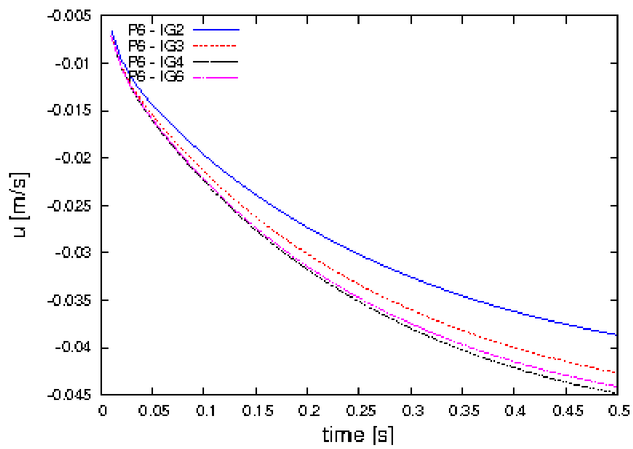


Figure 29. Velocity obtained in CFD analysis for the stationary car case.

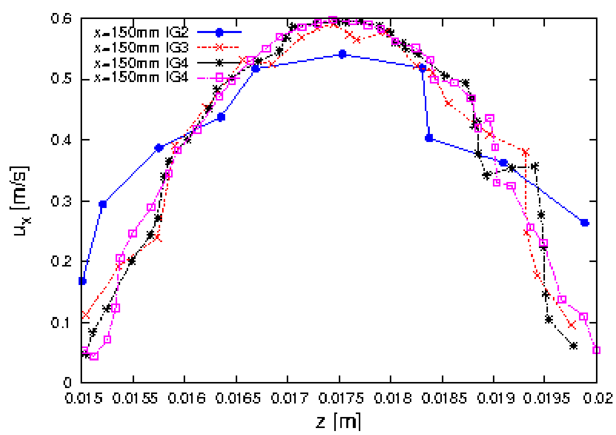


Figure 30. Velocity profile in the internal channel for the stationary car case.

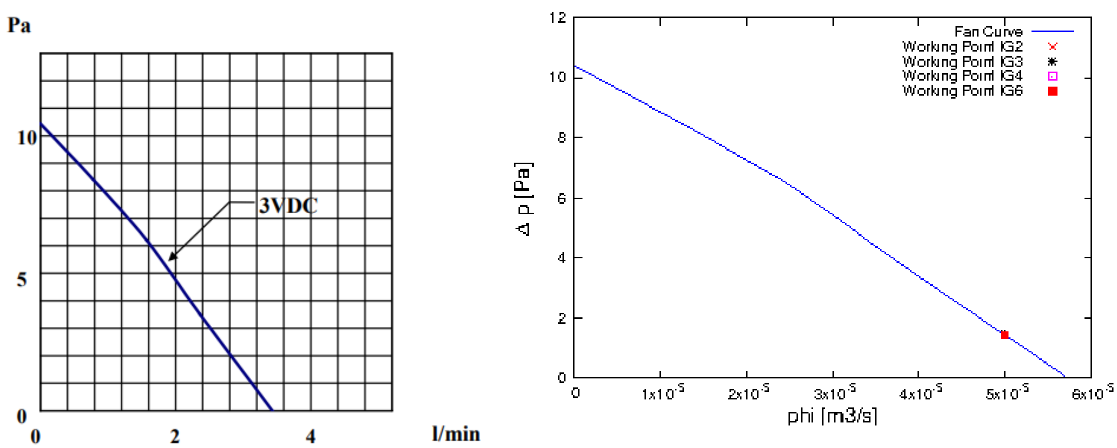


Figure 31.Fan working point for the stationary car case.

Conclusions and future work

The results reported in this section demonstrate how a numerical set-up has been successfully assembled to simulate the fluid dynamic behavior of the air inside the measurement device. In particular, the results reported here refer to the case of the stationary car. The CTTC-UPC is currently working to obtain results also for the case of the moving car by calibrating the corresponding set-up.

Hence, the numerical model will allow the testing of a certain fan for the given configuration and domain in order to assess its capability of ensuring an appropiate flow rate in the internal channel, where the sensors are placed.

Future work also consists of proposing changes to the internal geometry of the system to optimize its operation and ensure that the flow characteristics in the internal channel (in terms of flow rate and velocity) are optimal to allow the correct functioning of the environmental sensors.

Once the numerical simulation infrastructure is prepared and tuned, it will be relatively fast to iterate for different variations that can be proposed regarding the configuration and geometry of the unit.

4. Results

In the framework of the activity A20002 of the CAROLINA activity, the requirements for the development of an air pollution measurement unit are determined, as well as, a functional design to equip vehicles by placing on its roof, enabling collection of air measures in real time, and hence contributes to build the dynamic and collaborative urban air pollution monitoring network.

After a deep review of the State-of-the-Art, **benchmarking and testing of commercial sensors, design requirements for the air pollution measurement unit are proposed**. These requirements, discussed in the beginning of Section 3.2 of this Report, include which types of gases, particles and environmental parameters should be measured. The **unit operating range is also defined, as well as its structural and design properties.** Finally, the unit both **hardware and software requirements** are also **described**.

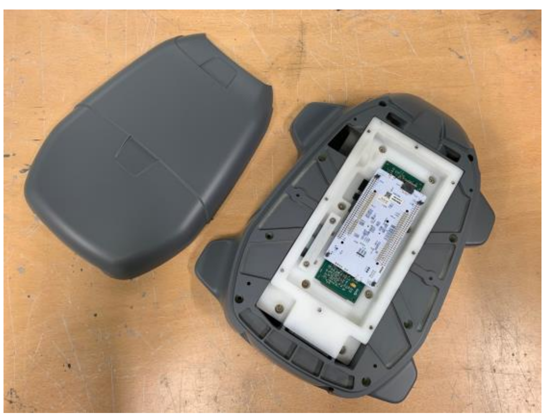
Following the proposed requirements, the hardware and software design of a proof-of-concept unit is described. The **hardware design includes electrochemical gas sensors to measure CO, SO_2, NO_2 and O_3 concentration, PM sensor to measure $PM_{2.5}$ and PM_{10} concentration and environmental sensors to measure temperature, humidity, and pressure.** A PCB is also designed to include all the sensors and circuitry needed for their proper operation. This PCB is connected to a board including a microcontroller creating a stack of hardware elements easy to assembly. Figure 14 to Figure 19 show the details of such hardware elements. Finally, the **software** design includes the **control of the measurement process, data pre-processing and communications management.**

The hardware elements are housed in a mechatronic design that also includes a USB connector, a filter, a fan and channels to drive the air samples. This mechatronic part is included in a housing that gives support to the unit, aerodynamic behaviour, fastening elements to the vehicle roof, as well as design and style. Figure 20 to Figure 22 show the mechatronic and housing elements in detail.

The operation of the unit is as follows. The air enters through the air intake due to the vehicle speed and is continuously circulated through exhaust channels. From these exhaust channels, another duct leads the air to the mechatronic part of the unit. A G2 filter is installed at the air inlet of the mechatronic part to prevent oils and unwanted particles. This filter leads to the main and secondary channels. The former is designed to accommodate the environmental and gas sensors, and the latter to accommodate the PM sensor. A mini fan is placed at the main channel outlet to force the air sample in from the exhaust channels and force the air sample out of the main channel to the outside of the unit. The hardware elements are housed maintaining the watertightness and a USB IP67 connector is installed and connected to the microcontroller for power and data transmission.

Finally, CFD simulations are performed in order to study the most adequate geometry for the air intake as well as the circulation of the air in the vicinity of the sensors, allowing for a flow rate within the ranges required for their correct operation, which is an essential aspect for the correct operation of the system. Numerical simulation infrastructure is essential for the selection of fans and filters. Once the numerical simulation infrastructure is prepared and tuned, it will be relatively fast to iterate for different variations that can be proposed regarding the configuration and geometry of the unit.

Photos of the resulting prototype

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5. Conclusions and Lessons learnt

This work showed that although the deployment of low-cost sensors and IoT technologies have experienced great growth in recent years, the sticking point remain on how to get valuable air samples ensuring indicators from traffic-based PM pollution.

One major challenge that the study has concluded is the commercial approach of how equip vehicles with air monitoring sensors. Up today, solutions provided as portable or mobile AQ stations are away from a plug-and-play device or aftermarket product for automotive industry. The design of the structural shape contributes to vehicles equipped with the CAROLINA measurement unit could be part of a dynamic and collaborative urban air pollution monitoring network and system.

The main noteworthy obstacles addressed was the design an accurate configuration of the mechatronic part which requires several interactions for its re-thinking and re-shape. In particular, one of the biggest technical constrains for the operation of the air pollution measurement unit is given by the electrochemical gas sensors. Initially, the idea was based on the inclusion of an air sample storage tank at 2 atm using an air pump. With this idea, it was not feasible to obtain an economic and ergonomic unit. **On the one hand, a challenge is to ensure that the fluid reaches the sensors with determined conditions of velocity and flow rate within the range of operation of these. On the other hand, the air in the work zone of the sensors must be renovated in a suitable manner without having rests of samples of air corresponding to previous instants. The work done so far involves reasonable achievements in the mentioned challenges. The progress in satisfactorily resolving these challenges will be the key to final success.**

Although the Covid-19 pandemic and lockdown have had a profound impact on mobility and air pollution in Europe, results from [38], a public survey launched in May 2020 in 21 cities across Europe (Barcelona, Madrid, Roma, Milan, Pris, Marseille, Lille, Lyon, Toulouse, Nice, Berlin, Hamburg, Köln, Frankfurt, Munich, London, Manchester, Birmingham, Leeds, Glasgow and Brussels), showed that **46% of citizens were planning to use private car (own or car share) on work days once the lockdown will be fully lifted.** Which leads us to the conclusion there is a real need to make further progress on how to improve the reduction vehicle-related emissions in our cities.

Future work may include further development of pilot scenarios to validate the maturity of the measurement unit and improve the analysis of the sensor data quality, study the air quality scenario on new normal after COVID in European cities, and validate the commercialization strategy as an accessory for luxury car brands offering passengers real time data on environmental conditions around vehicle or the alternative is an aftermarket product, plug-and-play to generate valuable data for fleet operators and policy makers for decision making process on pollution strategies.

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Annex I

Detail of the properties of the measurement unit provided by partner ISBAK.

CO Sensor:

>0-5 ppm measurement range

>20 ppb resolution

>%15 measurement tolerance

14 mW in measurement mode in standby mode 100 uW energy consumption

NO2 Sensor:

>0-5 ppm measurement range

>20 ppb resolution

>%15 measurement tolerance

14 mW in measurement mode in standby mode 100 uW energy consumption

SO2 Sensor:

>0-20 ppm measurement range

>50 ppb resolution

>%15 measurement tolerance

12 mW in measurement mode in standby mode 100 uW energy consumption

O3 Sensor:

>0-5 ppm measurement range

>20 ppb resolution

>%15 measurement tolerance

12 mW in measurement mode in standby mode 100 uW energy consumption

IAQ Sensor:

>0-400 ppm measurement range

>100 ppb resolution

>%15 measurement tolerance

12 mW in measurement mode in standby mode 100 uW energy consumption

PM10 Sensor:

>1 ug/m3 measurement accuracy 20 mA max. Energy consumption

Analog output

Noise Sensor:

Waterproof electret microphone has been used as a noise sensor in the system.

The audio signal received from the microphone is transmitted to the analog unit of the microprocessor and processed via opamp circuits.

Measurement Range : 45 – 120 dB

Temperature Sensor:

Temperature Sensor is located on the edges of the taxi cap and it is interacted with the outside's air.

> Measurment Between -40 +125 Degrees

>0.5 degree resolution

>Completely waterproof

Humidity Sensor:

The humidity sensor has been placed into the circuit board due to exposure by dust, humidity, and water. When the air is taken in, moisture is measured here.

>Measurement between 0-100%

>+-2 resolution

Gyro Sensor:

The vertical pulses sensed by Gyro Sensor determine pit and deformation on the roads and informs the center.

3-axis gyroscope and a 3-axis accelerometer

Gyro Measurement Range: + 250 500 1000 2000 ° / s

> Angular Accelerometer Measurement Range: ± 2 ± 4 ± 8 ± 16 g

Bluetooth:

>HM11 coded module has been used

>Low Energy Consumption with BT4.0 Technology

> Communication within 30 meters.

GPS:

The reason for choosing the Quectel L80 as a GPS Module is that it has its antenna on it. Therefore, it does not require external antenna installation. Since the antenna being on the pole, mounting, soldering, circuit design and caused by connector due to other uses losses are minimized.

GPRS Module:

With its low dimensions, M66 GPRS Module has provided a great advantage for the circuit that includes much hardware. It also contains an active GPS antenna circuit, which ensures good connection performance using a single SMD Antenna. Using the SMD antenna eliminates the need to install the antennas outside the box.

SD CARD/ USB/ RS-232:

SD Card ensures that data is recorded continuously. In this way, any data loss is not experienced even in cases of disconnection, etc. It can be removed and accessed to the data file upon request. 4GB SD Card can store data for more than 5 years. RS232 port and USB port provide communication with a computer, tablet, etc. device. The RS232 port connects to the iTaxi device and get the availability information of the taxi and transfer the collected data to this device if required.