Development of an air quality sensor system to be installed in buses

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Abstract

Low-cost sensors aim to assess air quality with high temporal and spatial resolution, being its implementation in vehicles a useful method to obtain real data of pollutant concentrations. This work aims the evaluation of the quality of particulate matter (PM) and gas sensors used in a developed prototype, compared to several reference devices. Particulate sensors OPC-N3 (Alphasense) and HPMA 115CO-004 (Honeywell), as well as carbon monoxide and nitrogen dioxide gas sensors (CO-B4 and NO2-B43F, respectively, both from Alphasense), were evaluated throughout laboratory, at air quality monitoring stations and mobile experiments. Finally, they were implemented in buses. The results dictated that particle sensors obtained excellent correlations ($R^2 \approx 1$) with the reference in the laboratory when there was no variation in temperature and relative humidity (RH). In the air quality monitoring station measurement period, the OPC-N3 showed considerable data dispersion due to RH effect, while the HPMA, despite also denoting a worse behaviour relatively to the laboratory environment, showed satisfactory correlations compared to the reference. After several corrections, the OPC-N3 improved its behaviour relative to the reference and the deviation was reduced. The mobile experiment observed an improvement in the OPC-N3 performance, however, the aim of obtaining satisfactory correlations with 1 minute concentration average was not achieved. CO-B4 obtained good correlation with the reference method (R^2=0.63) only in the mobile experiment, while NO2-B43F was not submitted to any calibration because results showed that the sensor was not appropriated for the measured range of concentrations. The final measurements along four bus routes generally showed higher PM concentrations inside the bus compared to outside. The road traffic density as well as the circumstances of each day also influenced the values recorded. The study is part of the ExpoLIS project, which aims to expand the current knowledge about air quality in cities.

***Keywords*:** Air quality; Low-cost sensors; particulate matter; carbon monoxide; mobile experiments

1. Introduction

Air pollution represents currently one of the biggest environmental risks for human health, whose effects depend on the susceptibility of each individual. Cardiovascular and respiratory diseases are the most well-known effects of exposure to air pollutants, however, uterine growth restriction during pregnancy can occur as a result of long-term exposure to pollutants, besides other health impacts (EEA, 2017; WHO, 2006; WHO, 2013).

Among the major contributors to air pollution stands the road transport sector. Buses, for example, contribute to emissions of PM, black carbon, CO, NO_2, affecting not just the people outside the bus, but also the driver and passengers themselves (Asmi et al., 2009; Heberle et al., 2019).

Nowadays, information regarding the pollutant concentrations in Lisbon is provided by the Portuguese air quality monitoring stations network (which has 5 stations in Lisbon) (QualAr, 2021). These stations require their own infrastructures and advanced sensors to transmit information continuously to the population. The development and verification of the quality of new low-cost sensors is increasing, becoming this type of sensors a viable alternative to the existing fixed monitoring stations (Snyder et al., 2013). These sensors have several advantages over fixed stations, such as lower cost, smaller size and high temporal and spatial resolution. On the other hand, the data quality from this type of sensors is often affected by meteorological factors such as RH and temperature (Crilley et al., 2020; Jayaratne et al., 2018; Nagendra et al., 2019; Samad et al., 2020). RH frequently affects the PM10 range of the sensors, as they show very high concentrations in the higher RH range, requiring corrections (Crilley et al., 2020).

This study aims to evaluate the performance of two particle matter sensors, OPC-N3 (Alphasense) and HPMA (Honeywell) (Alphasense, 2017c; Honeywell, 2019), and two gas sensors, one responsible for measuring carbon monoxide (CO-B4) and the other designed to measure nitrogen dioxide (NO2-B43F), both from Alphasense (Alphasense, 2017a, 2017b). The four sensors, implemented in a prototype developed within the ExpoLIS project, were tested in laboratory under constant temperature and RH conditions, and under variable meteorological conditions in outdoor environment, in stationary way (installed in a fixed monitoring station) and in movement. The pollutant concentrations were calculated by the sensors at each site, and then compared with reference methods. To establish comparisons, parameter such as the coefficient of determination (R^2), slope of the line (m) and relative deviation (as a percentage) were used.

After the appropriate sensor calibrations, the final purpose of the work was to implement, for the first time, the ExpoLIS prototype in buses, carrying out atmospheric pollutants' measurements in the city of Lisbon.

2. Method

2.1 Study design

The measurements were divided into two phases: a first phase of prototype tests, composed by three different types of tests, among them laboratory tests, at air quality monitoring stations and mobile test. The second phase consisted of several bus measurements, performed with the already replicated prototype of the ExpoLIS system (composed by two boxes of sensors).

The laboratory experiments were performed in two different places, firstly in a room at Campus Tecnológico e Nuclear (CTN). CTN is one of the poles of Instituto Superior Técnico, located in Bobadela, Loures (Portugal). In a second phase the measurements took place in a private villa garage, located in Elvas, district of Portalegre (Portugal). During the first phase (at CTN), the sensors were tested under controlled conditions, i.e. with constant temperature and RH, and exposed to the pollution source of a incense stick (remaining in place and emitting smoke for a maximum of 3 or 4 hours). The pollution simulation process allowed to observe the sensors' response to an active source of fine and ultrafine particulate matter and gaseous pollutants (Tran et al., 2021). This first phase took place from 19 (7:00 p.m.) until 21 July (10:00 a.m.), which means a little more than 1 day and a half. In the second phase of laboratory tests, two separate tests were carried out, one from 9 (8:00 p.m.) to 10 August 2021 (10:15 a.m.), with an applied flow rate of 9L/min, and another test from 12 (8:00 p.m.) to 13 August 2021 (10:00 a.m.), with a flow rate of 5L/min. At this stage, the pollution source came from a car with diesel engine that has remained inside the garage during the measurements. In the first test, the car was turned on from 08:04:07 p.m. until 08:05:31 p.m., while in the second test a delay was given since the sensors start working, turning the car on at 08:58:46 p.m. and switching it off at 09:00:29 p.m.

In outdoor environment, the tests were conducted at two fixed monitoring stations located in Lisbon, specifically at Olivais (urban background station), and at Entrecampos (urban traffic station). The Olivais station is situated within a secondary school and adjacent to a primary school and a kindergarten, therefore, during school periods there is a high flow of cars near the station. Two tests were performed at the Olivais monitoring station, between 25 May 2021 and 8 June 2021, and between 28 June 2021 and 7 July 2021. To verify higher concentration and test the sensors at a different site, a test was conducted in Entrecampos, between 27 July 2021 and 5 August 2021.The Entrecampos station is located close to the Entrecampos Square, where three large Lisbon avenues intersect, resulting in heavy road traffic. The mobile test also took place in the Lisbon metropolitan area. One car with the appropriate equipment inside left at 8:50 a.m. from CTN, ending at the same place at 11:50 a.m. The route involved passes through very busy areas of Lisbon, including Avenida da Liberdade, Campo Grande, and others.

For outdoor measurements, the PM10 range of the OPC-N3 sensor required corrections due to the influence of RH on their data. During periods of high RH, the PM10 concentrations of this sensor prove to be higher than expected. Thus, based on the k-Köhler theory that relates particle hygroscopicity (the ability of particles to absorb water) and volume, an equation was developed and used in this study to obtain dry particle mass concentrations (Crilley et al., 2018):

$$\frac{m}{m_0} = 1 + \frac{\frac{\rho_w}{\rho_p}k}{-1+\frac{1}{a_w}} \quad (1)$$

Where a_w corresponds to water activity (a_w = relative humidity/100), ρ_w and ρ_p are the water density (1g/cm^3) and particle density (assuming 1.65g/cm^3), respectively. The constant k represents the slope of exponential straight of the humidogram relating the ratio m/m_0 (ratio between PM10 concentration of OPC-N3 and PM10 concentration given by the monitoring station) and a_w. Additional calibration techniques were applied to the particulate sensor data, including simple (SLR) and multiple linear regression (MLR). For gases, the electrical impulses from the sensors were required to be converted into mass concentrations, hence the calibration prioritized SLR models (2), and MLR models, with influence of temperature and RH (5), with influence of temperature only (3), and with influence of RH only (4).

$$V_{diff} = a \times Ref + b \quad (2)$$

$$V_{diff} = a \times Ref + b \times Temp + c \quad (3)$$

$$V_{diff} = a \times Ref + b \times RH + c \quad (4)$$

$$V_{diff} = a \times Ref + b \times Temp + c \times RH + d \quad (5)$$

Where V_{diff} is the differential electrode (millivolts) given by the gas sensor, Ref is the gas concentration (parts per million) measured by the reference equipment, Temp and RH are the temperature and relative humidity measured by low-cost sensor.

Final measurements were performed on CARRIS buses along four different routes in Lisbon (Table 1). The measurements took place at two different times of the day, during the morning rush hour (starting approximately at 8:00 a.m.) and the night time (starting at approximately 8:00 p.m., ensuring that the route was not run at rush hour). After the measurements of PM2.5 and PM10 by the OPC-N3 sensors installed in each box, the data were corrected with a reference equipment, enabling the construction of pollutant concentration maps. The maps were made in *ArcMap*, one of the applications present in *ArcGIS*.

Table 1 - Description of the bus routes

Days	Routes	Bus Stop number	Travel time
25 oct (2ª)	Restauradores-Oriente	759	63 min
2 Nov (3ª)	Restauradores-Moscavide	744	46 min
3 Nov (4ª)	Odivelas-Cais do Sodré	736	55 min

5 Nov (6[a])	Portas de Benfica-Cais do Sodré	758	52 min

2.2 Measurements and sampling equipment

Inside the ExpoLIS system prototype, two particle sensors were responsible for measuring PM2.5 and PM10. The OPC-N3 sensor, from Alphasense (Alphasense, 2017c), is a larger and more expensive sensor compared to the other particle sensor used, an HPMA 115CO-004, from Honeywell (Honeywell, 2019). The OPC is an optical particle counter, widely used in this type of studies, and employs the principle of light scattering to count particles (as the HPMA sensor), using a laser that illuminates the particles when they reach the detection chamber. The reflected light from the particles passing through the laser is converted into an electrical signal and the concentration of the particles is afterwards calculated. The HPMA sensor estimates PM10 concentrations based on PM2.5 concentrations. After each test performed, the data were properly analysed, the failures in certain seconds were corrected, the data concerning time periods in which the sensors may have been off were eliminated, and the average concentrations for the several time periods were calculated. The gas sensors are electrochemical in nature, operate under fuel cell technology and are composed by four electrodes. One sensor is designed to measure nitrogen dioxide (Alphasense NO2-B43F) (Alphasense, 2017b), while another sensor measures carbon monoxide (Alphasense CO-B4) (Alphasense, 2017a). Those sensors generate electric current, which is translated into the difference between a working electrode and auxiliary electrode, and which in turn is directly proportional to the concentration of the target gas in a stable environment (Wei et al., 2018). The prototype was connected, through a tube, to an air suction pump (Leland Legacy, SKC Inc., USA), always with a flow rate of 9L min^{-1}, with the exception of a test carried out in the garage in which a flow rate of 5L min^{-1} was tested.

A particle sampler Leckel MVS6 was used in the first test period at the fixed station of Olivais. PM samples were conducted during 10 days and gravimetric analysis was conducted in which the filters were weighed on a microbalance (Sartorius R160P, Greifensee, Switzerland) and PM concentrations were determined.

A light-scattering laser photometer (DustTrak, Model 8533, TSI) was used as the reference for the particulate matter sensors. The data from this equipment were transferred to a computer using the TrakPro software Version 4.7.2.1 and corrected with the relation between the PM concentrations obtained by the gravimetry method and DustTrak in a preliminary test.

The analysers installed in the air quality monitoring stations, were a reference during the measurement period in the two stations (Olivais and Entrecampos). These instruments are previously calibrated and complies all legal requirements. The hourly average concentrations data and an air quality index for the different zones is available on the QualAR website (APA, 2021).

The IAQ-Calc Indoor air quality meter (Model 7545, TSI) was used to obtain CO concentrations, functioning as a reference for Alphasense CO-B4. The data recorded in the equipment were extracted to computer through the LogDat2 software.

3. Results and discussion

3.1 Assessment of sensors performance in indoor environments

3.1.1 Laboratory Test (CTN)

The first laboratory test, under constant temperature (28.3ºC) and RH (47.4%) conditions, and with a stimulus being provided by an incense stick, led to an excellent correlation (with R^2 close to 1) with the reference (DustTrak), both for PM2.5 and PM10. However, the particle sensors underestimated the concentrations. A SLR was applied to correct for this effect:

$$PM_{sensor} = a \times PM_{Reference} + b \quad (6)$$

Where PM_{sensor} and $PM_{Reference}$ are the PM concentration given by the sensors and reference, respectively. “a” is the slope of calibration line and “b” is the constant of equation. This correction put the equation slopes close to 1, cancelling the effect of underestimating concentrations. The first laboratory test dictated average PM2.5 concentration of 26.19 µg/m^3 and 26.20 µg/m^3 from the OPC-N3 and HPMA, respectively. However, the incense stick was not emitting pollutants throughout the whole period. Therefore, considering the period when the incense was lit and the next two hours, the average concentration of PM2.5 measured by the OPC-N3 and HPMA was 230.72 µg/m^3 and 231.24 µg/m^3, respectively. These values were similar to those reported in the study of Tran et al. (2021), in which in one case there was constant burning of incense sticks in houses. Regarding PM10, the average concentration given by the OPC-N3 and HPMA was 54.52 and 52.68 µg/m^3, respectively. The values obtained by the sensors when using incense sticks revealed that they should not be used in indoor environments, as they affect not only indoor air quality but also human health. With the first laboratory test, the particle sensors responded effectively to the stimulus given by the incense, so a new laboratory test was performed, with a new stimulus given by a car.

3.1.2 Laboratory Test (Garage)

The reference equipment showed a decrease in measured concentrations compared to the CTN test. The decrease in concentrations may have affected the effectiveness of the sensors, which verified a worse correlation with the reference. The OPC-N3 reported an R^2 of 0.67 and 0.66 for PM2.5 and PM10, respectively, while HPMA reported an R^2 of 0.54 and 0.63 for PM2.5 and PM10, respectively. The reason for the weaker correlation with the reference may be also due to the variation in meteorological conditions, since the temperature varied between 26.5ºC and 31.8ºC, and RH varied between 28.2% and 41%. The flow rate applied was the same (9L/min), so this cannot have been the reason. Given the varying meteorological conditions, the applied correction already included these two factors:

$$PM_{sensor} = a \times PM_{Reference} + b \times Temp + c \times RH + d \quad (7)$$

Where Temp is the temperature, RH is the relative humidity and the variables a, b and c are the slopes of $PM_{Reference}$, Temp and RH, respectively. “d” is the constant of equation. The multiple linear correction significantly improved the correlation between the sensors and reference, with the OPC-N3 sensor obtaining the best R^2, of 0.83 and 0.7 for PM2.5 and PM10, respectively. The average concentrations of PM2.5 and PM10 (in µg/m^3) measured by the particle sensors were 5.96 and 13.98, respectively. The average PM2.5 concentration measured by the two sensors (5.96 µg/m^3) is a similar value to the one obtained in a study carried out in three car parks, in which hourly average PM2.5 concentrations between 4 and 7 µg/m^3 were recorded (Liu & Zimmerman, 2021).

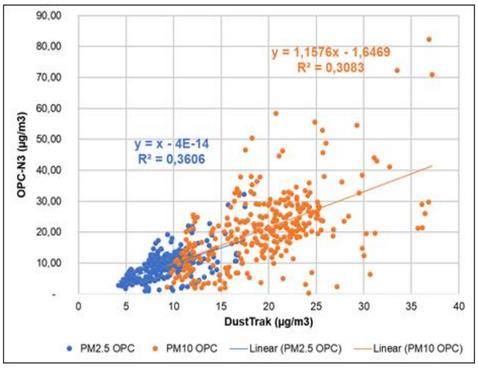
At the garage, a new experiment, with a lower applied flow rate (5L/min), and with the car engine running just 1 hour after the sensors were turned on, showed a decrease in the correlation of the particle sensors with respect to the reference, with R^2 below 0.5. This test only served to confirm that the flow rate of 9L/min, provided by the pump, is the optimal flow rate for the sensors. Even after corrections with MLR, the performance was not as good as in the other tests.

In both laboratory tests there was no reference equipment for CO, however, the sensor showed sensibility to the stimulus given, both by the incense and by the car gases, presenting very high electrode differential values in those moments of extreme pollution.

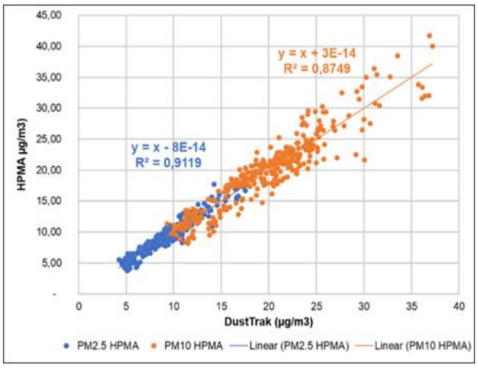
3.2 Assessment of outdoor sensor performance

3.2.1 Air quality monitoring station test

During the tests performed at the fixed stations it was possible to establish correlations with the station equipment, in addition to the reference already used in the laboratory (DustTrak). At Olivais station, the OPC-N3 sensor obtained weak correlations with DustTrak (R^2 of 0.19 and 0.07 for PM2.5 and PM10, respectively) and high dispersion of values. With the station equipment, the correlations obtained were also weak, with R^2 of 0.04 and 0.12 for PM2.5 and PM10, respectively. The HPMA sensor demonstrated good performance for PM2.5 and PM10 when compared with the DustTrak equipment, with R^2 of 0.74 and 0.82, respectively. Compared to the station equipment, the HPMA sensor showed satisfactory R^2 for PM10 (0.64), while in the PM2.5 range the R^2 was below 0.5 (0.45). The large dispersion of values of the OPC sensor coincides with some field studies already performed with this sensor. Bauerová et al. (2020) observed the poor performance of an OPC-N2 sensor when compared with references, with R^2 of 0.15 for PM2.5. In the PM10 range, concentrations were high in periods with high RH, which impaired the correlation with the reference. This pattern demonstrated by the PM10 range of the OPC sensor also stood out in the test performed at Olivais station, as expected. During periods with RH peaks, the OPC-N3 also recorded PM10 peaks. This trend required correction, however, the DustTrak does not obtain the mass concentration of dry particles, so the correction based on the k-Köhler theory was only applied to the relationship between the sensors and the station equipment. As the temperature and RH varied throughout the test, between 13.4ºC and 38.3ºC and between 21.9% and 89.2%, respectively, equation 7 was used to apply the correction that includes these two variables to the PM2.5 and PM10 data from both sensors relative to DustTrak (Figure 1).



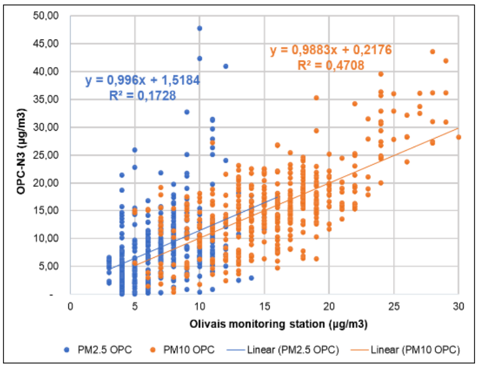
(i)



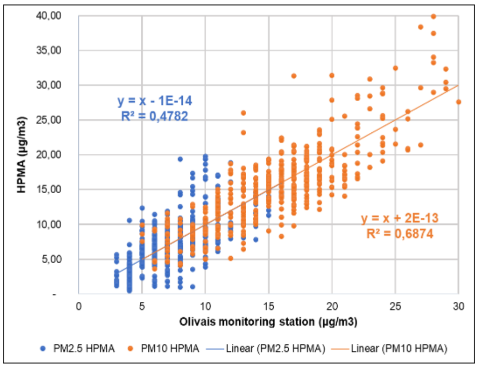
(ii)

Figure 1 - Olivais station test - Correlation between PM2.5 and PM10 concentrations (hourly averages) of the DustTrak (reference) and the OPC-N3 (i) and HPMA (ii) sensors, operating at a flow rate of 9L/min (corrected data)

As previously mentioned, the PM10 data from the OPC were subjected to the correction based on the k-Köhler (Equation 1), using the concentrations (of dry particles) from the station equipment. After the RH correction, for PM10 data a correction with the MLR was further applied only with temperature influence. For PM2.5 data from the OPC sensor, PM2.5 and PM10 data from the HPMA sensor, Equation 7 was applied, since they did not show an exponential trend in the relationship with RH and a correction with equation 1 was not effective. Thus, the results of the correlation between corrected sensor data with the station are shown in Figure 2.



(i)



(ii)

Figure 2 - Olivais station test - Correlation between PM2.5 and PM10 concentrations (hourly averages) of the Olivais monitoring station (reference) and the OPC-N3 (i) and HPMA (ii) sensors, operating at a flow rate of 9L/min (corrected data)

Regarding the performance of the gas sensors, the CO-B4 sensor data were corrected using the 4 equations for the gases calibration, and the best calibration was obtained from the Equation 5.

At Entrecampos station, the OPC-N3 showed once again a weak correlation with the station, with R^2 of 0.17 and 0.25 for PM2.5 and PM10, respectively. Regarding the HPMA sensor, it obtained an R^2 of 0.13 and 0.52 for PM2.5 and PM10, respectively. For this reason, a correction identical to the one applied at Olivais station was used, a double correction for PM10 data from the OPC and correction from equation 7 for PM2.5 OPC, PM2.5 and PM10 HPMA.

At Entrecampos station, the range of CO concentrations measured by the station equipment showed to be considerably short, preventing the proper calibration of the CO-B4 electric impulses.

3.2.2 Mobile Test

On the mobile test, the particle sensors obtained worse results, with wider dispersion in data, than in the station tests, probably attributed not only to meteorological but also to other factors that influence negatively the quality of the particle sensors data. Concerning the performance of the gas sensors, the CO-B4 sensor was calibrated with the data provided by the IAQ-Calc (reference). The best calibration was obtained from Equation 5 (Figure 3).

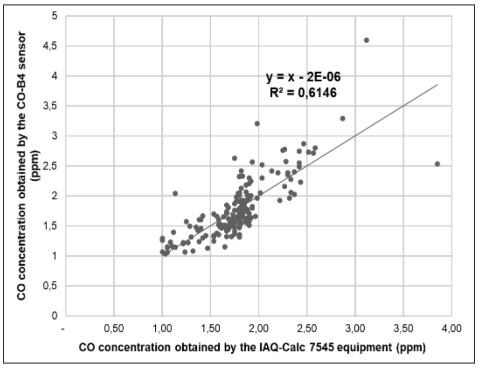


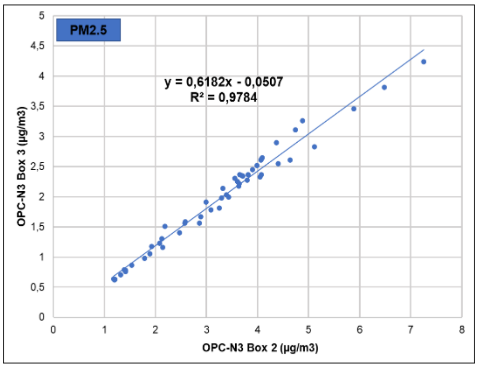
Figure 3 - Mobile test - Correlation between CO concentrations (1 minute averages) of IAQ-Calc 7545 (reference) and CO-B4 sensor (corrected data)

CO-B4 showed better results when calibrated with other personal calibration equipment compared to a calibration based on a fixed monitoring station. The reason for the better calibration from the personal equipment is the concentration range given by the personal equipment as it is significantly higher than the range given by the station.

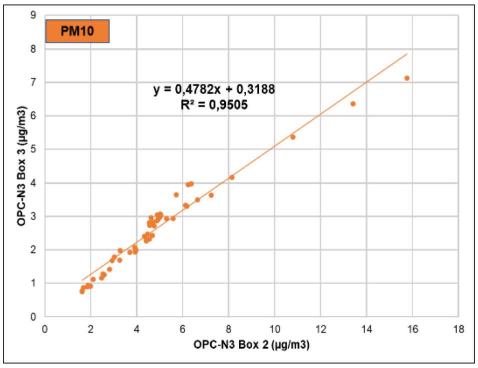
3.3 Implementation of the prototype on buses

3.3.1 Calibration of the OPC-N3 sensors

Between 19 and 22 October 2021, at CTN, the two boxes and a DustTrak operated simultaneously. Based on the correlation obtained between each sensor and the reference, it became possible to calibrate the data obtained in buses, using the Equation 6. Figure 4 displays the correlation between the PM concentrations given by the two OPC-N3 sensors present in the boxes.



(i)



(ii)

Figure 4 - Correlation between PM2.5 (i) and PM10 (ii) concentrations (hourly averages) of OPC-N3 sensor in box 2 with OPC-N3 sensor in box 3

The two OPC-N3 sensors showed excellent correlation between PM2.5 and PM10 data, ensuring that data from box 2 and box 3 were well balanced and of good quality.

3.3.2. Average PM concentrations on each route and differences between times of the day

The average concentrations of PM2.5 and PM10 measured by the OPC-N3 sensor present in box 2 (inside the bus) are shown in Figure 5.

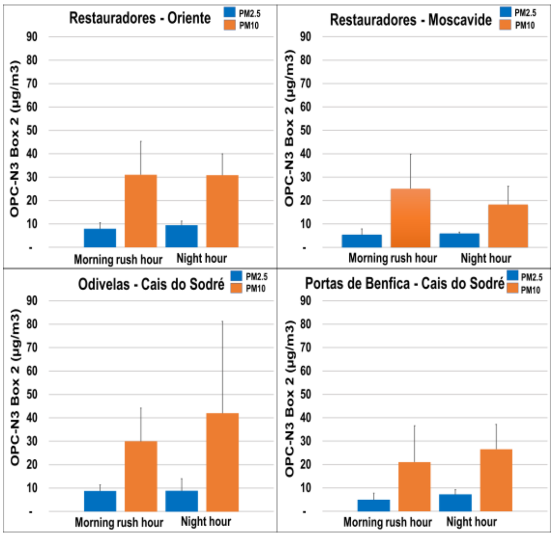


Figure 5 - Average PM2.5 and PM10 mass concentrations, and standard deviation, measured inside the bus by the OPC-N3 sensor, for the four routes performed (corrected data)

During the morning rush hour, the highest PM2.5 and PM10 concentrations were recorded on the Odivelas-Cais do Sodré and Restauradores-Oriente routes, respectively, with mean concentrations and standard deviation of 9 ± 3 µg/m^3 e 31 ± 14 µg/m^3, respectively. For measurements performed during the night, the highest average concentrations on PM2.5 and PM10 were found on the Restauradores-Oriente and Odivelas-Cais do Sodré, respectively, with mean concentrations and standard deviations of 9 ± 2 µg/m^3 e 42 ± 39 µg/m^3, respectively. Measurements at night hours (hours with usually less intense road traffic) revealed concentrations many times higher than those recorded at peak hours, and one of the main reasons was due to intense road traffic in Lisbon at the beginning of the measurement nights. The strike of the Lisbon Metro coincided with two days of measurements, which led to a higher number of occupants on buses until later hours, as well as a higher number of vehicles on the road.

3.3.3. Indoor/Outdoor relationship

Table 2 shows the values of the ratio between the concentrations verified inside and outside the bus by the two OPC-N3 sensors, for the four routes performed. In the Restauradores-Oriente route, performed at night time, the sensor in box 3 presented error information, which made any calibration impossible.

Table 2 - Ratio of indoor to outdoor PM2.5 and PM10 concentrations

Route	**PM range**	**Relationship Indoor/Outdoor**		
		Morning rush hour	**Night hour**	**Average of both periods**
Restauradores – Oriente	PM2.5	1.36		1.36
	PM10	1.54		1.54
Restauradores – Moscavide	PM2.5	2.18	1.75	1.96
	PM10	1.87	1.80	1.84
Odivelas – Cais do Sodré	PM2.5	1.94	0.92	1.43
	PM10	1.97	1.17	1.57
Portas de Benfica – Cais do Sodré	PM2.5	3.56	3.09	3.32
	PM10	5.03	4.29	4.66

Overall, concentrations of PM inside the bus were higher than concentrations outside, except in the Odivelas-Cais do Sodré route, in which PM2.5 concentrations were higher outside than inside. This route occurred on a night of intense road traffic, especially in the first part of the route, causing not only the resuspension of a large amount of dust, but also the emission of fine particles from the exhaust pipes of the vehicles (from the bus itself and from other vehicles). Despite the exception registered in this route, PM2.5 concentrations were, in general, higher inside the bus than outside, as it happened in a similar study developed by Molle et al. (2013).

3.3.3. Spatial distribution of PM concentrations

In Figure 6 is represented an example of the spatial distribution map of PM2.5 concentrations along the Odivelas-Cais do Sodré route at night-time. The route was divided into 6 zones and for each zone the mean concentrations were calculated.

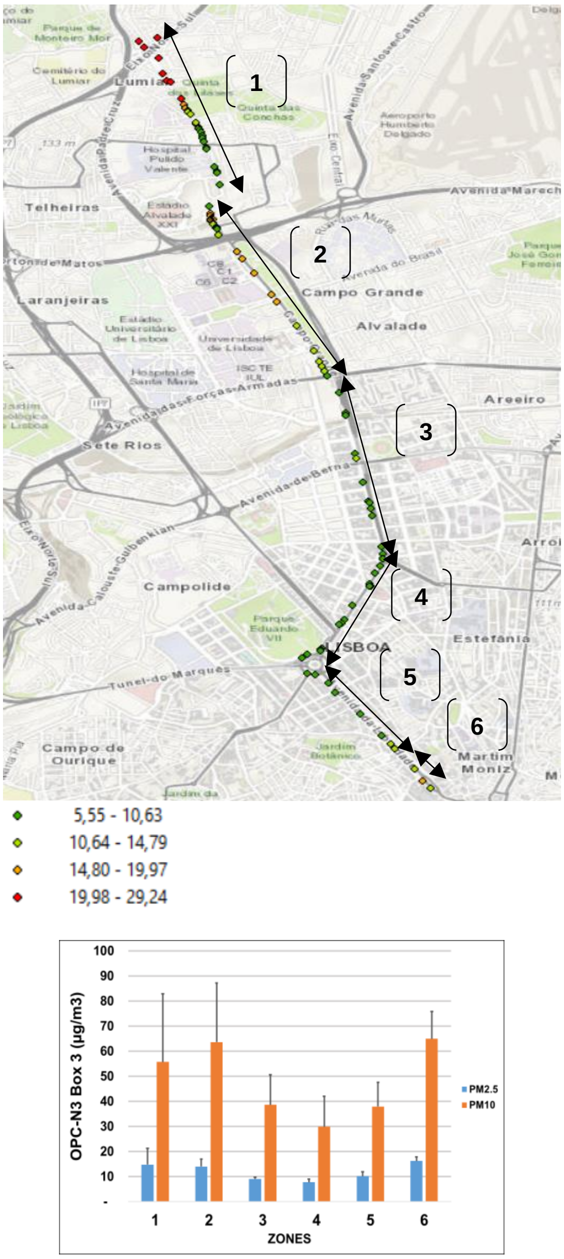


Figure 6 - Map of PM2.5 concentrations (30 second averages) along the bus route between Odivelas and Cais do Sodré, and average concentrations of PM2.5 and PM10 per zone.

The route verified mean concentrations of PM2.5 and PM10 of 9 ± 5 µg/m^3 and 36 ± 27 µg/m^3, respectively. The highest values of PM2.5 and PM10 were recorded in the zones 1, 2 and 6 of the route. The red colour visible in the first part of the route (Lumiar and Campo Grande) was related to the traffic congestion experienced during the night of 3rd November. Road traffic and the gathering of people near the Campo Grande area may have led to the resuspension of a large amount of airborne dust. On the approximation to zone 3, the traffic intensity was not so significant, there were not as many traffic stop-start situations and concentrations were lower. Zone 6 presented a large number of buses due to the many bus stops in the area and therefore the concentrations were elevated again.

4. Conclusion

The prototype of the ExpoLIS system was primarily tested in the laboratory at two different locations. In the CTN test, the particle sensors performed well in relation to a reference equipment. However, at a garage, in presence of a car engine stimulus, the sensors performed worse. Laboratory tests showed that both the OPC-N3 sensor and the HPMA sensor show better correlations when exposed to very high concentrations, but at lower concentrations a scattering of the data is observed. Furthermore, both particle sensors revealed to underestimate PM2.5 and PM10 concentrations in relation to the reference. In the measurement phase at the Olivais and Entrecampos stations, the particle sensors, especially the OPC-N3 sensor, significantly decreased their performance when exposed to varying temperatures and RH. Correction based on k-Köhler theory and MLR proved to be essential on the improvement of data quality. The gas sensors achieved the best results in the mobile test, where the correction from Equation 5 offered the best calibration. After testing the sensors, the box was replicated in order to record values inside and outside buses along four different routes. The sensors revealed their capacity to perform air quality measurements, both in the indoor environment, assessing the bus occupants' exposure, and in the outdoor environment, identifying pollution hotspots.

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