Assessing some criticalities of particulate matter exposure in an urban context

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Abstract

The aim of this study was to monitor the exposure of various urban public places (a church, passenger car and bus) to a range of particle matter (PM) sizes and to evaluate the indoor air quality (IAQ). We assessed the causes of IAQ and highlighted the role of human activities in particulate matter concentrations. PM was measured using a GRIMM analyser 1.108. The preliminary measurements of average concentrations obtained for PM$_{10}$, PM$_{2.5}$ and PM$_{1.0}$ revealed that during a church service the values were 56 $\mu$g m$^{-3}$, 36.4 $\mu$g m$^{-3}$ and 32.8 $\mu$g m$^{-3}$ respectively; the values for the public transport were in the ranges of 24.4–51.7 $\mu$g m$^{-3}$, 10–18.5 $\mu$g m$^{-3}$, and 8.3–12.2 $\mu$g m$^{-3}$, respectively. The concentrations measured during the passenger car test revealed that when the A/C is switched on, the levels of PM are even half of those reached in the off mode.

Keywords: church, indoor air quality, particulate matter, urban vehicle.

1 Introduction

Particulate pollution and its impact on public health has become of great interest in terms of urban air quality management by community and regulatory authorities [1, 2]. Most research has focused on outdoor air quality (OAQ), considering various climatic scenarios, environments, pollutant sources, monitoring systems and reduction strategies [3–11].

With regard to exposure to indoor particulate matter (PM), the World Health Organization (WHO) has estimated that every year 2.7% of deaths worldwide are a result of this phenomenon, with a high incidence among children and the elderly.
Even low levels of indoor PM exposure can cause short- or long-term health effects. Wallace and Ott [13] suggested that for typical suburban nonsmoker lifestyles, indoor sources provide about 47% and outdoor sources about 36% of total daily ultrafine particle (UFP) exposure and in-vehicle exposures provide the remainder (17%).

Knowledge of the indoor air quality (IAQ) is limited, since the key is to understand the relationship between particle size and mass distribution intake and its effect on human health. Most people spend the majority (> 80%) of their time indoors (with an average of 19–20 h per day) [14, 15]. According to the EU current standard on PM (Directive 2008/50/EC), which refers only to OAQ, the 24-hour average of PM$_{10}$ concentrations (PM concentrations of aerosol particles smaller than 10 $\mu$m in diameter) should not exceed a maximum value of 50 $\mu$g m$^{-3}$ for more than 35 times in a calendar year and the annual average should not exceed 40 $\mu$g m$^{-3}$. US legislation seems less stringent, with 150 $\mu$g m$^{-3}$ for PM$_{10}$. It strictly regulates the PM$_{2.5}$ sub-fraction of PM$_{10}$ and allows only one day's exceedance a year. The yearly PM$_{2.5}$ value has been limited to 25 $\mu$g m$^{-3}$ for the annual average in EU, while the US limits it to 12 $\mu$g m$^{-3}$.

These limits are referred to the measurements observed by the Official Monitoring Stations (OMS). The high costs of the equipment limits the number of OMS in the monitored area, therefore to reduce the impact of air pollutants and improve the exposure assessment, new research are trying to characterize the urban micro-environments and identify the spatial pattern of air pollutants [16–18].

With regard to the IAQ, there are several EU and non-EU countries that have set specific values that are normally based upon ambient outdoor concentrations, potentially leading to inadequate protection of the general public who spend the majority of their time in urban environments as home, offices or other enclosed locations where the concentrations of some pollutants are often much higher than ambient levels [19]. There are still EU countries, such as Italy, that do not have a national legislation for IAQ environments [20].

Epidemiological data from air pollution studies correlate PM to negative effects on human respiration, cardiovascular problems and an increase in hospitalization, cardiovascular mortality and morbidity [21, 22]. Although some studies have shown that coarse particles (diameter > 2.5 $\mu$m) cause some of these health effects, there is strong evidence that fine particles (FPs, diameter < 2.5 $\mu$m) and also ultrafine particles (UFPs, diameter <0.1 $\mu$m) are more harmful [23]. In the scientific literature, few specific studies refer to the IAQ from different environments such as public places (e.g. offices, libraries, churches, schools, hospitals, tunnels, buses, restaurants) or daily activities (cooking, pizzerias) [24, 25]. Some researchers have assessed the effect of candles and incense during religious rituals, and found an average level of PM of up to 69.6–91.6 $\mu$g m$^{-3}$, 38.9–55.5$\mu$g m$^{-3}$ and 39.3–54.5 $\mu$g m$^{-3}$ respectively, for PM$_{10}$, PM$_{2.5}$ and PM$_{1.0}$ [26, 27].

Exposure has rarely been estimated in terms of the time spent by people in various environments and the concentration of the pollutants for the period of interest [25, 28–30]. Recent long-term studies have shown associations between
PM and mortality at levels well below the current average annual WHO air quality guidelines for PM$_{2.5}$, which is 10 µg m$^{-3}$. The last WHO review highlighted that sub-daily exposures to elevated levels of PM can lead to adverse physiological changes in the respiratory and cardiovascular systems. This suggests that an average time of less than 24-hours – for example, 1 hour, similar to ozone – should be considered for air quality guidelines. In addition, the correlation between the 1-hour maximum and 24-hour average particle concentration is typically high. No studies have evaluated whether, for example, a high 1-hour exposure would lead to a different response than a similar dose given over 24 hours [31]. The latter value complies with the Threshold Limit Values (TLVs) set by the Occupational Safety and Health Administration and the American Conference of Governmental Industrial Hygienists in indoor spaces who recommend that airborne concentrations of PM$_{10}$ be limited to 10 µg m$^{-3}$ (inhalable fraction) and respirable particles (European Standard Committee defined as particles less than 4 microns in size) be kept below 3 µg m$^{-3}$ [32].

The aim of this study was to monitor exposure to a range of particle PM$_{10}$, PM$_{2.5}$ and PM$_{1.0}$ sizes and evaluate IAQ in several public and frequently used urban places i.e. a church, passenger car and bus.

## 2 Materials and methods

Particle concentration by size is a key determinant of how human exposure to particulates may elicit adverse health effects [22, 33]. The instrument used for the PM measurements was an optical particle counter (OPC), the GRIMM analyser 1.108 which was specifically designed for IAQ monitoring, filter efficiency tests, inhalation studies and the measurement of oil droplets. As highlighted by Schiavon et al. [25] this method is not the official one: environmental agencies typically use gravimetric methods in compliance with current legislation. However this analyser has been used for PM monitoring in urban environments due to its flexibility as a mobile instrument that acquires air quality data at a high spatial and temporal resolution [34]. The GRIMM analyser is thus suitable to obtain scientific results from different indoor sources of PM generation.

The measuring principle of the GRIMM apparatus is the light scattering of single particles with a semiconductor laser as a light source. Inside the measuring cell, the scattering light is led directly and via a mirror with a wide opening angle onto the detector (GRIMM 2013). In other words, every single particle is identified by light scattering and this pulse light means that the number can be assessed as well as the particle size through the intensity. Correct sizing is ensured by the use of monodisperse polystyrene latex (PSL), and suitable mass correlation can be established by the use of polydisperse dust. The density correlation can be established by mass correlation.

Grimm OPCs can either be run in particle count mode or mass concentration mode (the total particle mass concentration for particles with diameters in the respective size range is read). For an accurate interpretation, the indoor data (i.e. church, bus and passenger car) were linked with the available external environment measurements. Outdoor data were provided by fixed local air quality
monitoring stations, which are located in Verona (Italy) and owned by ARPAV, a regional agency for environmental protection [35]. Two representative stations of urban traffic and background were identified, in urban and rural zones. The daily average concentration values registered by the stations during the measurement campaign are presented in Table 1.

Table 1: PM daily value in urban traffic and rural areas from air quality monitoring stations (ARPAV).

<table>
<thead>
<tr>
<th>Date</th>
<th>Urban traffic</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM$_{10}$</td>
<td>PM$_{10}$</td>
</tr>
<tr>
<td>June 16$^{th}$ 2013</td>
<td>26 µg m$^{-3}$</td>
<td>36 µg m$^{-3}$</td>
</tr>
<tr>
<td>June 17$^{th}$ 2013</td>
<td>29 µg m$^{-3}$</td>
<td>37 µg m$^{-3}$</td>
</tr>
<tr>
<td>June 20$^{th}$ 2013</td>
<td>30 µg m$^{-3}$</td>
<td>37 µg m$^{-3}$</td>
</tr>
</tbody>
</table>

The aim of the church environment investigation was to assess the presence and re-suspension of particulate matter, during a Sunday morning mass. Rapid cleaning and the low presence of church-goers during the week, facilitate PM deposition, and this particulate can be re-suspended during the transfer and standing-up and sitting-down of the congregation during the ceremony. If the church is small, and candles or incense are used, PM can reach high values with a consequent negative impact on health.

The measurements were conducted in the San Rocco church, a Catholic church in Pescantina (VR, Italy). The building was built in the Middle Ages and is surrounded by two single-lane streets. The church has one main area, which is 35 m long and 8 m wide, with a capacity for approximately 150 people. On Sunday, June 16 2013, measurements of the PM concentration were taken every 6 seconds inside and outdoors during the service. The tests started at 09.47 a.m. in front of the church and after two minutes, the instrument was positioned inside, at 0.90 m in height, in the centre of the building. During the mass, the entry of the priests, the homily, the Eucharist and the Holy Communion were timed as well as the standing-up and sitting down of the congregation.

Some analyses were performed to obtain information of the PM fluctuations in a bus in Verona (a large town in Italy). These variations could be due to the transit on a busy street and/or to the re-suspension of the PM during the getting in and off phases and due to the movement of the passengers. The measurements were taken for two bus routes (numbers 11 and 21), served by new buses powered by natural gas (Breda-Menarini model M240CNG, 12 m long, 88 seats, and air conditioning). The instrument was placed, as near as possible to the centre of the bus and at a height of 1.35 m.

Four tests were carried out, the first analysing the PM on bus route No. 11 between Chievo and San Michele (C–SM); the second test was performed for the same bus route but between San Michele and Porta Nuova station (SM–PN). The air conditioner was switched on, windows were closed and there was a varying number of passengers, of up to a maximum of 40 people (first test) and up to full...
capacity in the second test. The third and fourth tests were carried out during the round trip along bus route No. 21, between Porta Nuova station to Borgo Roma (PN–BR, BR–PN). In these tests, there was no air conditioning and the windows were open. A maximum of 55 passengers were present in the third test and 70 in the fourth test. The measurements started at 1.35 p.m. on Monday, 17 June and finished at 4.40 p.m. on the same day, i.e. not during the rush hour.

A typical daily activity involves driving a car. In this study, the air quality inside two passenger cars was assessed, along roads with moderate traffic. During the test, all windows were closed and the A/C was switched on with the air recirculation mode. The instrument was placed on the passenger seat and PM\textsubscript{10}, PM\textsubscript{2.5} and PM\textsubscript{1.0} were monitored every 6 seconds. At the beginning of the test, in order to acquire the background information, the data were collected with the engine off. At the end of each test, the A/C was switched off and all windows were opened after a few minutes.

3 Results

Figure 1 represents the PM\textsubscript{10}, PM\textsubscript{2.5} and PM\textsubscript{1.0} concentrations expressed in μg m\textsuperscript{-3}. The red vertical lines indicate the phase where people moved, the green lines indicate the sitting-down phases, and the violet lines the standing-up phases.

![Figure 1: Concentration curves of PM\textsubscript{10}, PM\textsubscript{2.5} and PM\textsubscript{1.0} over time during the church service; red vertical lines indicate the phase where people moved, the green lines refer to the sitting-down phases and the violet line refer to the standing-up phases.](image-url)

The maximum concentration peaks of PM\textsubscript{10} occurred when people were moving inside the church and there is a good correlation for the other peaks regarding the stand-up and sit-down phases. The time profile of particle
concentrations during the service confirmed that particle levels were associated with the various rituals. PM$_{2.5}$ and PM$_{1.0}$ were less influenced by the movements, in fact there was a low variation from 10.15 to 10.30 (people sitting), compared with the continuous variation of PM$_{10}$.

Table 2 gives the PM average and the maximum values inside the church during the Catholic Mass. The church particle concentrations for all the PM sizes studied exceeded the EU annual air quality guidelines both for church services, such as Mass, and for ambient background air in the church. These results cannot be considered as representative of all churches and other places of religious services, because they report the specific effects of particular actions (burning candles and incense).

<table>
<thead>
<tr>
<th>Average (µg m$^{-3}$)</th>
<th>Maximum (µg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{10}$</td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>56.0</td>
<td>36.4</td>
</tr>
</tbody>
</table>

Our measurements highlighted that A/C and closed windows can reduce the PM$_{10}$ concentration and maintain the PM$_{2.5}$ and PM$_{1.0}$ values constant. Given that the buses were new, the A/C was probably working optimally. Figures 2 represent the concentration curves during the journeys from C to SM from BR to PN. In both, the peaks are connected with the bus stop and the passengers getting on and off.

![Figure 2: PM Concentration curves over time during the C–SM and BR–PN tests.](image)

Table 3 shows that bus line 11, which has A/C and closed windows, has lower concentrations than line 12, where the PM values are almost double. In the BR–PN test, the concentrations of PM$_{2.5}$ and PM$_{1.0}$ have significant variations due to the external background concentration.
Table 3: PM average and maximum values in bus line n. 11 and n. 21.

<table>
<thead>
<tr>
<th>Bus line</th>
<th>PM10</th>
<th>PM2.5</th>
<th>PM1.0</th>
<th>PM10</th>
<th>PM2.5</th>
<th>PM1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>C–SM</td>
<td>28.3</td>
<td>13.9</td>
<td>11.5</td>
<td>85.1</td>
<td>20.9</td>
<td>16.3</td>
</tr>
<tr>
<td>SM–PN</td>
<td>24.4</td>
<td>10.0</td>
<td>8.3</td>
<td>116.4</td>
<td>16.2</td>
<td>12.8</td>
</tr>
<tr>
<td>PN–BR</td>
<td>51.7</td>
<td>18.5</td>
<td>12.2</td>
<td>231.1</td>
<td>44.0</td>
<td>18.5</td>
</tr>
<tr>
<td>BR–PN</td>
<td>37.3</td>
<td>16.1</td>
<td>11.5</td>
<td>67.4</td>
<td>21.5</td>
<td>14.3</td>
</tr>
</tbody>
</table>

The high PM concentration and variations during the test, can be correlated with the spatial variation in fine particulate matter (PM$_{10}$) within urban areas which is associated with traffic and steep gradients in levels of finer particles occur within tens of metres from the roadside [1, 9, 10, 29, 36].

There was a reduction in particulates when the A/C was switched on (green vertical line in Figure 3) and a considerable increase when the A/C was switched off (violet vertical line). The trend is the same for both car 1 and car 2. The figure highlights that during the initial phase of getting into the car and the movements once inside the car, increase the PM concentrations, whilst the open windows reduce the particulate concentrations.

![Figure 3: PM concentration curve in time during Car 1 test; the red vertical line indicates getting into the car, the green line refers to the A/C switched on, the violet line refers to the A/C switched off, and the orange line indicates that the windows were open.](image)

Table 4 reports the PM measurements in the two cars; the first had been vacuum cleaned several days before the measurements were taken; whereas the second car had not been vacuumed. The car cleaning rate significantly influenced the PM concentration, where the PM rates were double for car 2 compared to car 1. When the A/C is on, the PM levels were half those reached in the off mode.
Table 4: PM concentration during car tests.

<table>
<thead>
<tr>
<th></th>
<th>Average (µg m$^{-3}$)</th>
<th>Maximum (µg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM$_{10}$</td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>Car 1</td>
<td>A/C switch on</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>A/C switch off</td>
<td>44.5</td>
</tr>
<tr>
<td>Car 2</td>
<td>A/C switch on</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>A/C switch off</td>
<td>56.7</td>
</tr>
</tbody>
</table>

Daily exposure can result in adverse health effects, particularly if the fine fraction (PM$_{2.5}$) of PM is high. To evaluate the importance of the PM$_{2.5}$ of total PM, the ratio of fine and coarse particulate fractions was calculated. Figure 4 shows the ratio for each general test: bus line No. 11 C–SM, passenger car–car 1 and the church, respectively.

![Fine and coarse fraction particulate concentration ratio.](image)

It is clear that the church test presents the more constant value over time with an average value of 0.66. The passenger car test has the highest value and with the A/C switched on (0:09–0:31 time) there is a major correlation between PM$_{2.5}$ and PM$_{10}$, with a maximum value of 0.93.

4 Conclusions and outlooks

We have highlighted the anomalies that PM can give rise to, even though limits for OAQ are imposed by legislation. We selected various indoor environments to characterize the concentrations of indoor particulate matter. As expected, the
indoor PM concentration was strongly influenced by the outdoor environment as well as human movements, electronics, frequency of cleaning etc. On the basis of what is described in the introduction, 40 µg m\(^{-3}\) and 10 µg m\(^{-3}\), respectively for PM\(_{10}\) and PM\(_{2.5}\), can be adopted in order to compare the results, even though the measurements were taken on sampling at short time.

The time profile of particle concentrations during the church Mass seems to confirm that particle levels were associated with religious rites, where the average amount of particles inhaled by the congregation passed the annual legislation limits. Similar conclusions were reached by Polednik [27] who found that PM concentrations were connected with the increased activity of the congregation (standing up, kneeling and leaving the church). The concentration decrease rates of fine particles after the Mass had finished were in most cases lower than the concentration of the coarse fraction. This could be explained by the movement of the congregation during Mass or by the air ventilation correlated with the opening of doors.

Daily exposure may result in adverse health effects. The journey time exposure by bus revealed the strong variation in PM with the bus stopping and the passengers getting on and off. The bus with A/C and closed windows had lower concentrations than the other bus where PM values were higher by a factor of up to 90%.

Using one’s own car – when the car is clean and the A/C is switched on – seems to be the best way to travel to avoid exposure to PM. Exposure to PM is thus both temporally and spatially less variable and shows stronger correlations between getting into the car and in-car activities.

The PM\(_{2.5}\)/PM\(_{10}\) indicator highlighted the importance of fine particles over the total particle matter, which may imply a relationship between the two PM fractions. Our study confirms that the air quality in indoor spaces is strictly dependent by human behaviours/choices like turning on/off the conditioning systems influence the PM concentration with respect to outdoor levels. To improve the air quality especially in indoor spaces it is needed to increase the awareness on which behaviour and action can impact more on public health.

Improving the characterization of air quality in the indoor and outdoor micro-environments using low-cost sensors [5] can lead to an enhancement of the exposure assessment, providing a scientific basis to develop an holistic decision support system [37, 38] that combines a deterministic approach for outdoor with a probabilistic approach for indoor concentrations to help policy makers to reduce the health impact over population.

In the future, other public places and daily activities could be investigated by creating chemical profiles and better source apportionment by either source-receptor with respect to oriented modelling. Increasing the level of collaboration between health experts and policy makers for indoor guidelines would help to reduce the risk of exposure for humans.
References


