Investigation of Particulate Matter Pollutants in Parking Garages

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Abstract: - Air pollution is getting more emphasis in recent research and legislations due to its impact on human health and overall environmental quality. Particulate matter (PM) is one of the most important ambient air pollutants involved in a number of adverse health effects. In the case of parking garages, there are high levels of mobile PM pollutants due to air pollution coming from operation of vehicles engines. This study presents indoor PM measurements performed at three different enclosed parking garages A, B and C in two cities of Belgium with varying vehicle intensity and varying layout. Garages A and B are located in the ground floor and basement respectively of different multi-storey buildings in Brussels, while Garage C is in the ground floor of a multi-storey building in Leuven. Garage A is equipped with natural ventilation, whereas B and C have a combined mechanical and natural ventilation. Parking capacity of the garages A, B and C is 50, 130 and 185 car spaces respectively. Particle mass concentrations, number concentrations and their size distributions were measured continuously using an Electrical Low Pressure Impactor Plus (ELPI+) instrument. The impactor has 14 stages in the range of 6 nm to 10 µm. Three sizes of particles including PM 1, PM 2.5 and PM 10 were characterized under this study. The ELPI+ device was placed on a table at a height of 0.85 m from the floor. All samples were collected inside the garages for several hours during workdays for each measurement. The results indicated that the average particles mass concentrations in the garages ranged from 28 µg/Nm 3 to 50 µg/Nm 3 for PM 1, 43 µg/Nm 3 to 60 µg/Nm 3 for PM 2.5 and 58 µg/Nm 3 to 90 µg/Nm 3 for PM 10 respectively. The number concentrations were in the range of 28e+03 particles/cm 3 to 47e+03 particles/cm 3. Two distinct particle sizes of coarse and fine modes were observed in the particle mass size distributions in all examined garages, while the observed number size distributions showed dominant quantities of fine particles.

Keywords: Particulate matter, air quality, parking garages, vehicle emissions, mass concentration, number concentration, size distributions.

1 Introduction

Particulate matter (PM) refers to the solid and liquid particles dispersed into ambient air. These particles can be classified into primary and secondary particles based on their formation mechanism [1]. Primary particles are emitted directly as particles, whereas secondary particles are formed from precursor gases in the atmosphere through gas-to-particle conversion. Particles smaller than 1 µm (micro meter) in diameter are often called fine particles [1-2]. Particles larger than 1 µm in diameter are called coarse particles. The notations PM 1, PM 2.5 and PM 10 refer basically to particles with an aerodynamic diameter smaller than 1, 2.5 and 10 µm respectively [3].

Particulate matter is considered as a quite severe pollutant involved in a number of adverse health effects [4-5]. Several studies have shown that increased particulate matter concentrations in the ambient air correlate with a negative influence on the health condition of the exposed population. Fine particles are considered more dangerous to human health because they can travel deeper into the lower respiratory tract [3-7].

Modern urban areas consist of numerous elements and some of them are subjected to intensive air pollution. Parking is an integrated part of modern city planning. Generally, it is considered as a very significant factor for the planning and management of modern traffic systems [8]. There are many varieties in the layout of parking garages: underground garages, parking establishments, parking houses in multi-floor concepts. Smaller garages are often naturally ventilated while larger garages have mechanical ventilation systems.

Air pollution is getting more emphasis in recent research and legislations due to its impact on human health and overall environmental quality. Vehicle’s exhaust is a complex mixture originated from unburned fuel, lubricant oil and combustion products. Its main components are carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx),
sulphur oxides (SO$_x$), volatile organic compound (VOC) and particulate matter [9-12]. These emissions are released directly from the vehicles to the air in the garages. There could also be additional emissions from vehicles because of the evaporation from engines and fuel tanks [8].

The air quality in the garages depends on many factors such as nature of the vehicle’s engine, operating conditions, lubricating oil, emission control system, fuel consumption, garage volume, parking capacity, air exchange rate, etc. [12]. Furthermore, it has been shown that garages can become a source of particulate matter and cause infiltration into adjoining occupied office buildings and housing apartments [12-13].

Kim et al. [13] investigated carbon monoxide (CO) and particle bound polycyclic aromatic hydrocarbons (pPAH) in an urban parking garage during weekdays and weekends. CO and pPAH were measured by an L15 CO Exposure Monitor and a PAS2000 Monitor with a flow rate 2 lpm (litre per minute) respectively. Average CO-concentrations during the weekdays and weekends were 3.3 mg/Nm$^3$ and 1.5 mg/Nm$^3$ respectively, while average pPAH were 19 ng/Nm$^3$ and 2.6 ng/Nm$^3$.

Fondelli et al. [14] evaluated urban particle concentration inside commuting vehicles such as buses and taxis in Florence city of Italy. A portable particle sampler (pDR 1200) with a flow rate of 4 lpm was used inside four diesel powered busses and four taxis during eight working days. The average PM$_{2.5}$ concentrations were 32 µg/Nm$^3$ and 20 µg/Nm$^3$ in buses and taxis respectively. They found that PM$_{2.5}$ mass concentrations inside the vehicles correlated well with the urban ambient air of PM$_{2.5}$ concentrations measured at the monitoring stations.

Hess et al. [15] investigated particulate matter with a size fraction of 2.5 µm at passenger shelters of bus stops. Two model 8520 DustTrak Aerosol monitor instruments with a flow rate of 1.7 lpm were used to measure simultaneously particulate matter concentrations. They found that average PM$_{2.5}$ concentrations at the inside and outside of a bus shelter were 17.24 µg/Nm$^3$ and 14.72 µg/Nm$^3$. Inside PM concentrations were higher than the exposure of an outside bus shelter due to the presence of cigarette smoke.

Weingartner et al. [16] performed aerosol emissions measurement in a road tunnel of 3.25 km long, which is divided into separate tubes with only one direction of the traffic flow in each tube. Measurements were performed simultaneously at two test stations during workdays, Saturday as well as Sunday. The first station was located about 100 m after the tunnel entrance, while the second located 100 m before the tunnel exit. Particle mass concentrations (PM$_1$) were measured with two tapered element oscillating microbalance (TEOM) devices having a flow rate of 3 lpm. The average PM concentrations from the entrance and exit test stations were 25 µg/Nm$^3$ and 201.6 µg/Nm$^3$ for workdays, 12.8 µg/Nm$^3$ and 70.9 µg/Nm$^3$ for Saturday, 10.9 µg/Nm$^3$ and 52.7 µg/Nm$^3$ for Sunday. It is observed that all cases particle mass emissions at the exit test point give higher concentrations with 8 times than the entrance concentration for workdays, 6 times for Saturdays and 5 times for Sundays.

Fischer et al. [17] evaluated particulate matter (PM$_{2.5}$) concentrations of air pollutants outside and inside homes in streets with low and high traffic intensity in Amsterdam. Test measurements were performed for 24 h average with Harvard impactors operated at 10 lpm for both indoor and outdoor conditions during a total of 19 days in winter and spring. Outdoor PM$_{2.5}$ concentrations for high traffic and low traffic intensity were 25 µg/Nm$^3$ and 21 µg/Nm$^3$ respectively, while indoor PM$_{2.5}$ concentrations were 27 µg/Nm$^3$ and 12 µg/Nm$^3$. It is observed from this study that for high traffic conditions, indoor PM concentrations are about 10% higher than outdoor.

The above literature overview illustrates that a number of studies on particulate matter concentrations related to traffic emissions in tunnels, inside commuting vehicles, passenger shelters have been conducted previously. But, no publications were found in literature regarding particulate matter concentration in parking garages. As mentioned above, parking garages have high levels of mobile source-related PM pollutants. So, while the occupation level by people in parking garages might be low, there is a strong justification to examine PM concentrations in parking garages. The aim of this study was to characterize indoor particulate matter concentration dynamically, in terms of mass concentrations with three size fractions (PM$_1$, PM$_{2.5}$ and PM$_{10}$), number concentrations and their particle size distributions. An Electrical Low Pressure Impactor Plus (ELPI+) was used to continuously sample and measure particle matter at three enclosed parking garages in Belgium under this study.

2 Method
This section briefly presents the selected sites, the experimental set-up and the existing guidelines for ambient particulate matter.
2.1 Site selection
PM measurements were performed at three different enclosed parking garages A, B and C in two cities of Belgium with varying vehicle intensity and different layout. Garages A and B are located at the ground floor and basement respectively of different multi-storey buildings in Brussels, while Garage C is at the ground floor of a multi-storey building in Leuven. Garage A is equipped with natural ventilation, whereas B and C have a combined mechanical and natural ventilation. Mechanical ventilation systems are generally installed in larger enclosed garages to supply adequate fresh air and to remove the air contaminants within a reasonable amount of time in order to maintain an acceptable level of air quality.

Parking capacity of the garages A, B and C is 50, 130 and 185 car spaces respectively. All the garages are used for employee’s and visitor’s cars. Indoor temperature in the garages was about 5°C higher than the outside air temperature. The sampling and measuring position in the garages was placed near the midpoint of each garage where observed traffic flow was significant. For all garages, there is only one gate that is used for cars entering and leaving the garage. The measurements presented in this paper were conducted during February and March 2012.

2.2 Experimental set-up
An Electrical Low Pressure Impactor Plus (ELPI+) was used in this study to continuously measure indoor particle mass concentrations, number concentrations and their particle size distribution in real time. Fig. 1 shows the working principle of the ELPI+ and the measurement set-up for particle sampling in the garages. Sample particles entering the ELPI+ are first charged in the charger. After being charged, the particles are introduced in the cascade impactor in order to be separated on the basis of their inertia and their aerodynamic diameter.

The impactor has 14 stages in the range of 6 nm to 10 µm and all stages are electrically insulated. The charged particles collected in each impactor stage produce an electrical current which is recorded by the respective electrometer channel. This current is proportional to particle numbers via mathematical algorithms [18]. In addition, the ELPI+ contains a flush pump and a high voltage (HV) power supply. The flush pump is used to zero the electrometers by pumping High Efficiency Particulate Air (HEPA) filtered air through the instrument. A vacuum pump with a flow rate of 10 lpm is connected to a power supply in order to suck the sampling air through the ELPI+.

Three sizes of particles including PM$_{1}$, PM$_{2.5}$ and PM$_{10}$ were characterized under this study. The ELPI+ device was placed on a table at a height of 0.85 m from the floor. All samples were collected inside the garages for several hours during workdays, starting from 8:00 am in the morning for each measurement. ELPI+ VI software was used with the ELPI+ instrument to transfer the measured data into a data acquisition system for further processing.

Fig. 1: Working principle of the ELPI+ and PM measurement set-up conducted in the garages

2.3 Existing guidelines for ambient PM
The most commonly used existing reference guidelines/standards for ambient particulate matter concentrations are those of the World Health Organization (WHO), United States Environmental Protection Agency (USEPA) and the European Union (EU). They are based on results from research on adverse health effects of particulate matter performed in the last decades. All current air quality standards for PM refer to the weight of particles measured in units of µg/m$^3$. Table 1 shows the current reference guidelines/standards for ambient particulate matter concentrations [19-21].

<table>
<thead>
<tr>
<th>PM</th>
<th>WHO</th>
<th>USEPA</th>
<th>EU</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$ annual mean (µg/m$^3$)</td>
<td>10</td>
<td>15</td>
<td>not set</td>
</tr>
<tr>
<td>PM$_{2.5}$ 24 hour mean (µg/m$^3$)</td>
<td>25</td>
<td>35</td>
<td>not set</td>
</tr>
<tr>
<td>PM$_{10}$ annual mean (µg/m$^3$)</td>
<td>20</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>PM$_{10}$ 24 hour mean (µg/m$^3$)</td>
<td>50</td>
<td>150</td>
<td>50</td>
</tr>
</tbody>
</table>
3 Results and Discussions

The particle emission characteristics are generally expressed in terms of mass concentrations, number concentrations and size distributions. Mass concentration is defined as the mass of particles per unit volume of air, while mass size distribution is mass concentration distributed over particle size. Number concentration of particles is number of particles per unit volume of air, and number size distribution is number concentration distributed over particle size.

The averaged results obtained from the indoor PM measurements at the three garages are summarized in Table 2. It was observed during particle sampling that all garages were occupied approximately 90% with passenger’s cars.

Table 2: Average particle mass and number concentrations obtained from different garages

<table>
<thead>
<tr>
<th></th>
<th>Garage A</th>
<th>Garage B</th>
<th>Garage C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling time</td>
<td>3hr20m</td>
<td>5hr10m</td>
<td>5hr15m</td>
</tr>
<tr>
<td>PM$_{1}$ (µg/Nm$^3$)</td>
<td>28±1</td>
<td>42±3</td>
<td>50±5</td>
</tr>
<tr>
<td>PM$_{2.5}$ (µg/Nm$^3$)</td>
<td>43±3</td>
<td>55±7</td>
<td>60±9</td>
</tr>
<tr>
<td>PM$_{10}$ (µg/Nm$^3$)</td>
<td>58±13</td>
<td>90±27</td>
<td>76±41</td>
</tr>
<tr>
<td>Particle number</td>
<td>28e3±6e3</td>
<td>47e3±14e3</td>
<td>39e3±12e3</td>
</tr>
</tbody>
</table>

3.1 Particle mass concentrations

Figs. 2 to 4 show comparisons of particle mass concentrations of PM$_{1}$, PM$_{2.5}$ and PM$_{10}$ measured in the three garages under examinations and compared with the reference values recommended by the WHO, USEPA and EU.

Fig. 2 shows PM$_{1}$ concentrations observed in all three garages ranging from 28 µg/Nm$^3$ to 50 µg/Nm$^3$. Garage C had higher PM$_{1}$ concentrations by 44% and 17% compared to garages A and B respectively. A plausible explanation might be an inadequate ventilation in garage C with respect to its number of vehicle parking places.

PM$_{2.5}$ concentrations observed in all three garages vary from 43 µg/Nm$^3$ to 60 µg/Nm$^3$. Garage A had lower PM$_{2.5}$ concentrations than garages B and C as shown in Fig. 3. PM$_{2.5}$ concentrations in the three garages A, B and C exceeded the WHO 24h reference values with 71%, 121% and 140% respectively, the USEPA 24h reference value were exceeded with 22%, 58% and 71% respectively.

PM$_{10}$ concentrations observed in all three garages vary from 58 µg/Nm$^3$ to 90 µg/Nm$^3$. Garage B gave higher PM$_{10}$ concentrations by 35% and 16% compared to garages A and C respectively as shown in Fig. 4. All these garages had higher PM$_{10}$ concentrations than the limit/reference values recommended by the WHO and EU.

3.2 Particle mass size distributions

Fig. 5 illustrates particle mass size distributions obtained from three garages A, B and C. The abscise represents the particle aerodynamic diameter in logarithmic scale plotted against the ordinate which shows the ratio of total mass concentration
(dM) to the logarithm of the channel width (dlog(Dp)), where Dp is the aerodynamic diameter.

There are two distinct particle modes in the mass size distribution graphs shown in Fig. 5 obtained from all the measurements. One was having a maximum peak of the fine mode at around 500 nm of size and another was having a maximum peak of the coarse mode at around 5 µm size. The profiles of mass distribution represented in several modes have already been observed by other authors [7, 11, 22-23]. Since the formation mechanism of the particulate matter is quite complex and usually includes several concurrent paths, the particle distributions profile plotted in a logarithmic scale may reveal more than one peak.

3.3 Particle number concentrations

The number concentrations measured in the garages were in the range of 28e+03 particles/cm³ to 47e+03 particles/cm³. Garage B had higher particle number concentrations by 41% and 16% compared to garages A and C respectively. Particle number concentrations at the three garages were dominated by fine particles. As the garages are attached to the entrance of the buildings, these pollutants can migrate to the office spaces and thus degrade indoor air quality.

3.4 Particle number size distributions

Fig. 6 shows typical number size distributions of particles measured at the three garages. The size distribution consists mainly of particles with aerodynamic diameter between 20 and 25 nm. A single peak in the number size distributions graphs was observed at the three examined garages. Similar size distributions were observed in another study [16]. It can be noted that vehicle emissions are highly dynamic and are formed from a reactive mixture of hot gases and particles. As the hot exhaust gases leave the tailpipe of a vehicle, they are cooling and condensing to form large numbers of particles in the air. These particles are generally in the size range less than 30 nm and compose the nucleation mode.

4 Conclusions

Indoor PM concentrations at three enclosed parking garages in Belgium were measured continuously using an Electrical Low Pressure Impactor (ELPI+). The measurements of the particulate matter in the range from 6 nm to 10 µm were combined in three size groups as PM₁, PM₂.₅, and PM₁₀ and compared with the reference limit values recommended by WHO, USEPA and EU.

The results indicated that the average particles mass concentrations in the garages ranged from 28 µg/Nm³ to 50 µg/Nm³ for PM₁, 43 µg/Nm³ to 60 µg/Nm³ for PM₂.₅, and 58 µg/Nm³ to 90 µg/Nm³ for PM₁₀ respectively. The number concentrations were in the range of 28e+03 particles/cm³ to 47e+03 particles/cm³.

PM₂.₅ concentrations levels of the three garages A, B and C exceeded 71%, 121% and 140% respectively than the WHO 24h reference values, while 22%, 58% and 71% exceeded than the USEPA 24h reference value.

Two distinct particle sizes of coarse and fine modes were observed in the particle mass size distributions in all examined garages, while the observed number size distributions showed dominant quantities of fine particles.

5 Acknowledgement
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