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COMPARISON OF PARTICLE EMISSIONS FROM ENCLOSED PARKING GARAGES AND STREETS

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ABSTRACT

The aim of this study was to compare particulate matter (PM) pollutants performed at three different enclosed parking garages (A, B and C) and two streets (1 and 2) in Belgium. Particle mass concentrations, number concentrations and their size distributions were measured in real time using an Electrical Low Pressure Impactor Plus (ELPI+) instrument. PM_1, $PM_{2.5}$ and PM_{10} particle ranges were characterized under this study and these concentrations were compared with the reference values recommended by the World Health Organization (WHO), United States Environmental Protection Agency (USEPA) and the European Union (EU). The results showed that the average mass concentrations in the garages ranged from 28-50 μg Nm^{-3} for PM_1, 43-60 μg Nm^{-3} for $PM_{2.5}$ and 58-90 μg Nm^{-3} for PM_{10}, while in the streets they varied from 14-18 μg Nm^{-3} for PM_1, 23-27 μg Nm^{-3} for $PM_{2.5}$ and 54-59 μg Nm^{-3} for PM_{10} respectively. The number concentrations were obtained in the range of 28×10^3 to 47×10^3 particles cm^{-3} for the garages while 17×10^3 to 22×10^3 particles cm^{-3} for the streets. In all garages, it has been observed that $PM_{2.5}$ concentrations exceeded the 24h reference values recommended by WHO and USEPA while and PM_{10} concentrations exceeded WHO and EU guidelines. Particle number size distributions showed dominant quantities of fine particles in all measurements, while two distinct particle sizes of coarse and fine modes were observed in the mass size distributions.

KEYWORDS: Particulate matter, *a*ir quality, parking garages, streets, mass concentration, number concentration, size distributions.

1. INTRODUCTION

Particulate matter (PM) refers to the solid and liquid particles dispersed into ambient air. PM specially particle size less than 2.5 μm is considered as a quite severe pollutant involved in a number of adverse health effects (Obaidullah *et al,* 2012; Han *et al.*, 2006; Branis *et al.*, 2005). 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 (Vallius, 2005; Morawska *et al.*, 2004;, Bukowiecki, 2003). Fine particles are considered more dangerous to human health because they can travel deeper into the lower respiratory tract (Hackley *et al.*, 2007; Berner *et al.*, 2004). Another important concern of fine particle emissions from traffic sources are important cooling agents in the atmosphere. There are many different varieties in the layout of parking garages such as underground garages, parking establishments, parking houses in multi-floor concepts. Parking is an integrated part of modern city planning subjected to intensive air pollution. Generally, parking is considered as a very significant factor for the planning and management of modern traffic systems (Hoglund, 2004). Smaller garages are often naturally ventilated while larger garages can have mechanical ventilation systems.

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. (Lunn, 2011). Air pollution is getting more emphasis in recent research and legislations due to its impact on human health and on the overall environmental air quality. Vehicle's exhaust is a complex mixture originated from unburned fuel, lubricant oil and combustion products. Its main pollutants are carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides **(**SO_x), volatile organic compound (VOC) and particulate matter (Lunn, 2011; Yan *et al.*, 2010; Baltrenas *et al.*, 2006; Kelly *et al.*, 2003). These emissions are released directly from the vehicles to the air in the parking garages. Furthermore, it has been shown that garages can be considered as a source of particulate matter and cause infiltration into adjoining occupied office buildings and housing apartments (Lunn, 2011).

Fondelli *et al.* (2008) used a portable particle sampler (pDR 1200) with a flow rate of 4 lpm to investigate urban particle concentration inside commuting vehicles such as four diesel powered busses and four taxis during eight working days in Florence city of Italy. The average $PM_{2.5}$ mass concentrations obtained inside the buses and taxis were 56±15 μg Nm^{-3} and 39±15 μg Nm^{-3} respectively. The urban background $PM_{2.5}$ concentrations differed between the buses and taxis of 29±12 μg Nm^{-3} and 19±12 μg Nm^{-3} measurements. Hess *et al.* (2010) evaluated particulate matter with a size fraction of $PM_{2.5}$ at passenger shelters of bus stops using two model 8520 DustTrak Aerosol monitor instruments with a flow rate of 1.7 lpm to measure particulate matter concentrations in real time. 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}.

Weingartner *et al.* (1997) investigated particle emission 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. Particle number and size distribution measurements were performed simultaneously using Scanning Mobility Particle Sizer (SMPS) with a flow rate of 3 lpm at the two test stations during workdays, Saturday as well as Sunday. Particle mass concentrations (PM_3, diameter smaller than 3 μm) were measured with two tapered element oscillating microbalance (TEOM) devices having a flow rate of 3 lpm. The first station was located about 100 m after the tunnel entrance, while the second located 100 m before the tunnel exit. 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.* (2000) evaluated particulate matter ($PM_{2.5}$) concentrations of air pollutants outside and inside homes in streets with low and high traffic intensity in Amsterdam, using a Harvard impactor operated at 10 lpm for both indoor and outdoor conditions. Measurements were conducted for 24 h average during a total of 19 days in winter and spring. Indoor $PM_{2.5}$ concentrations for high traffic and low traffic intensity were 27 μg Nm^{-3} and 12 μg Nm^{-3} respectively, while outdoor $PM_{2.5}$ concentrations were 25 μg Nm^{-3} and 21 μg Nm^{-3}.

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. However, there is scarce publication in the literature on particulate matter emissions from parking garages and streets. As mentioned above, parking garages have high levels of mobile source-related PM pollutants. The aim of this study was to compare particle emissions in terms of mass concentrations with three size fractions (PM_1, $PM_{2.5}$ and PM_{10}), number concentrations and their particle size distributions, performed at three enclosed parking garages and two streets in Belgium. 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 (Morawska *et al.*, 2004; Obaidullah *et al.,* 2012). An Electrical Low Pressure Impactor Plus (ELPI+) was used in this study to sample particle concentrations in real time.

2. METHOD

This section briefly discuses the selected sites and the experimental set-up conducted for particle sampling.

2.1 Site selection

Particulate matter measurements were performed at three different enclosed parking garages (A, B, C) and two streets (1 and 2) in Belgium. The garages have different layouts with varying vehicle intensity. 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. Garages A and B are opened from Monday through Friday from 7:00 am to 8:30 pm, while garage C is opened throughout the week.

Streets 1 and 2 are sub streets of a university in Brussels and connected to the city street. Both sides of the streets have parking places. Parking capacity of the garages A, B and C is 50, 130 and 185 cars respectively. It was observed during particle sampling that all sites were occupied for approximately 80% with passengers' cars. All the sites are used for employees' and visitors' cars. For all garages, there is only one gate that is used for cars entering and leaving the garage. The sampling and measuring position in the garages was placed near the midpoint of each garage where observed traffic flow was significant. For the streets, sampling location was done on the footpath attached to the streets. Samples were taken at a height of 0.85 m from the floor.

The measurements presented in this paper were conducted on five working days during February, March and May 2012. Table 1 presents the general overview of the measurement sites and meteorological average data. Indoor temperature of the garages were measured by the ELPI+ device, while outside air temperature, humidity and wind velocity data were collected from the metrological website (www.weather.com, 2012). The indoor temperature in the garages was about 5^{o}C higher than the outside air temperature.

2.2 Experimental set-up

An Electrical Low Pressure Impactor Plus (ELPI+) was used in this study to measure particle mass concentrations, number concentrations and their particle size distribution in real time. Figure 1 shows the experimental set-up for particle sampling conducted all the sites. 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.

Table 1. Overview of the garages and meteorological condition

Particulars	**Garage A**	**Garage B**	**Garage C**	**Street 1**	**Street 2**
Type	Ground Floor	Basement	Ground Floor	Open	Open
City	Brussels	Brussels	Leuven	Brussels	Brussels
Parking spaces	50	130	185	30	30
Area (sm)	1300	3400	5000	not applicable	not applicable
Ventilation system	Natural	Natural and Mechanical	Natural and Mechanical	not applicable	not applicable
User	Employees and visitors	Employees and visitors	Employees and visitors	ordinary city traffic	ordinary city traffic
Sampling duration	3 hr 20 min	5 hr 10 min	5hr 15 min	4hr 25 min	4 hr 35 min
Indoor temp (^{o}C)	16	16	13	not applicable	not applicable
Outside temp (^{o}C)	11	12	8	16	18
Outside humidity (%)	76	76	74	55	61
Outside Wind velocity (m s^{-1})	5.5	5.1	5.8	3.6	3.8

The impactor has 14 stages in the range of 6 nm to 10 µm and each stage is electrically insulated from the others. The charged particles collected in each impactor stage produce an electrical current that is recorded by the respective electrometer channel. This current is proportional to particle numbers via mathematical algorithms (Marjamäki *et al.*, 2000). 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+. Aluminium greased foils with a diameter of 25 mm and thickness of 0.1 mm were placed on each impactor stage during particle sampling.

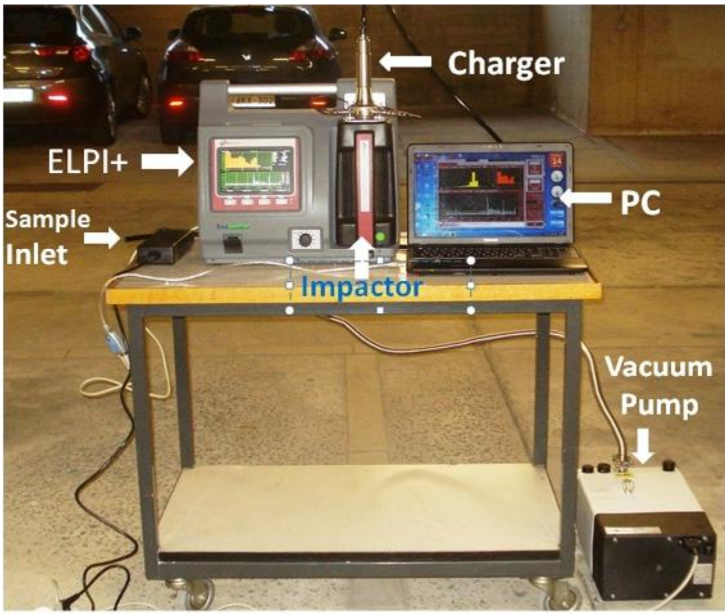

Figure 1. PM measurement set-up using ELPI+ conducted in the sites

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. Before starting each measurement, the ELPI+ device was started at least 45 min in advance and allowed to warm up the device and perform the electrometer zeroing with flush on. All samples were collected for several hours during workdays for each measurement. Similar measurement protocol was followed for each particle sampling. ELPI+VI software was used with the ELPI+ instrument to transfer the measured data into a data acquisition system for further processing and analyzing.

3. RESULTS AND DISCUSSIONS

The measurements of the particulate matter at the three garages in the range from 6 nm to 10 µm were combined in three size groups as PM_1, $PM_{2.5}$ and PM_{10} using EPLI+VI software. The average results obtained from the PM measurements at the different sites are summarized in Table 2. Particle emissions are generally expressed in terms of mass concentrations, number concentrations and size distributions. Particle sampling time varied from 3 hr 20 min to 5 hr 15 min for all the measurements.

Table 2. Average particle mass and number concentration obtained from different sites

Sites	PM_1 (µg Nm^{-3})	$PM_{2.5}$ (µg Nm^{-3})	PM_{10} (µg Nm^{-3})	Particle number (particles cm^{-3})
Garage A	28.27±1.0	42.63±3.24	58.27±12.55	$28x10^3±6x10^3$
Garage B	42.11±3.31	55.23±7.34	90.18±27.01	$47x10^3±14\ x10^3$
Garage C	49.81±4.77	59.79±9.02	75.95±40.78	$39x10^3±12x10^3$
Street 1	14.36±2.27	22.82±6.62	53.97±30.28	$17x10^3±5x10^3$
Street 2	18.10±1.05	26.72±4.79	58.79±23.83	$22x10^3±4x10^3$

PM_1 concentrations accounted 49%, 46%, 65%, 27% and 31% of the PM_{10} for garages A, B, C and streets 1 and 2 respectively, while $PM_{2.5}$ accounted 73%, 61%, 79%, 42% and 45% of the PM_{10} concentrations. From this analysis, it can be mentioned that the fractions of PM_1/PM_{10} and $PM_{2.5}/PM_{10}$ are much higher in all the garages compared to the streets. The major source of these emissions is traffic, in both garages and streets. There could be several reasons such as garage volume, parking capacity, operating of the vehicle's engine, air exchange rate, etc for the variation of PM concentrations among the garages.

3.1 Particle mass concentrations

Table 3 shows the current reference guidelines/standards for ambient particulate matter concentrations for $PM_{2.5}$ and PM_{10} (EPA, 2012; WHO, 2012; Priemus *et al.*, 2009). At present, there are no reference guidelines/standards for ambient PM_1 concentration.

Table 3. Reference guidelines/standards values for ambient PM

Particle size fraction	WHO	USEPA	EU
$PM_{2.5}$			
annual mean (μg m^{-3})	10	15	not set
24 hour mean (μg m^{-3})	25	35	not set
PM_{10}			
annual mean (μg m^{-3})	20	50	20
24 hour mean (μg m^{-3})	50	150	50

Figure 2 presents how particle mass concentrations correlate with traffic flow during sampling in Garage C. It can be seen from Figure 2 that during morning hours as soon as traffic flow intensifies the particle mass concentrations levels start to increase as well. Sharp increases began about 8:30 am and concentrations levels were continuously high between 8:30 am to 9:00 am. It was observed that as soon as vehicles entered or left from the garages, concentrations of particle mass instantly got higher due to the operation of the vehicle's engines. Steady concentrations were observed after the cars parked.

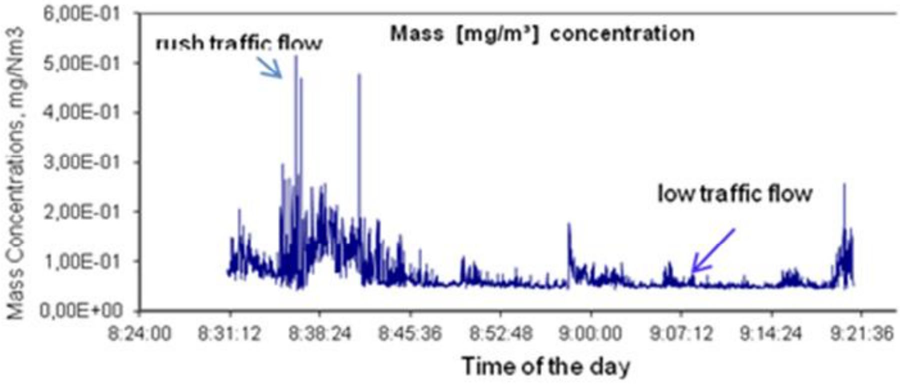

Figure 2. Particle mass concentrations as a function of traffic flow obtained from garage C

Figures 3 to 5 show comparions of particle mass concentrations of PM_1, $PM_{2.5}$ and PM_{10} measured in the three garages and two streets. $PM_{2.5}$ and PM_{10} concentrations obtained from all the measurements are compared with the international reference/guidelines recommended by the WHO, USEPA and EU. It has to be noted that the guidelines/reference are made for a 24 hr mean, while the measurement concentrations were over a several hours average.

Figure 3 shows PM_1 concentrations varied from 28.27 μg Nm^{-3} to 49.81 μg Nm^{-3} for all the garages, while 14.36 μg Nm^{-3} to 18.10 μg Nm^{-3} were obtained from the streets. From Figure 3 it is clearly seen that PM_1 concentrations in all the garages is much higher than the streets. Garage C had higher PM_1 concentrations by 44% and 17% compared to garages A and B respectively. A plausible explanation might be inadequate air exchange rate in garage C with respect to its number of vehicle parking places.

Figure 4 shows a comparison of $PM_{2.5}$ concentrations obtained from different measurements with the 24h reference guidelines recommended by WHO and USEPA. $PM_{2.5}$ concentrations obtained in all three garages vary from 42.63 μg Nm^{-3} to 59.79 μg Nm^{-3}, while in the streets vary from 22.82 μg Nm^{-3} to 26.72 μg Nm^{-3}. Garage A had lower $PM_{2.5}$ concentrations than garages B and C as shown in Figure 4. $PM_{2.5}$ 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.

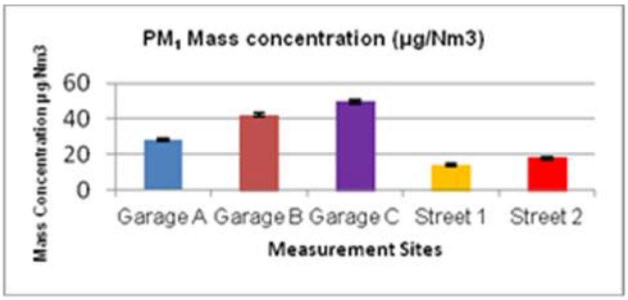

Figure 3. PM_1 concentrations obtained from different measurements

PM_{10} concentrations observed in all three garages vary from 58.27 µg Nm^{-3} to 90.18 µg Nm^{-3} while in the streets from 53.97 µg Nm^{-3} to 58.79 µg Nm^{-3}. Garage B gave higher PM_{10} concentrations by 35% and 16% compared to garages A and C respectively as shown in Figure 5. All these garages and the streets had higher PM_{10} concentrations than the limit/reference values recommended by the WHO and EU but lower than the USEPA.

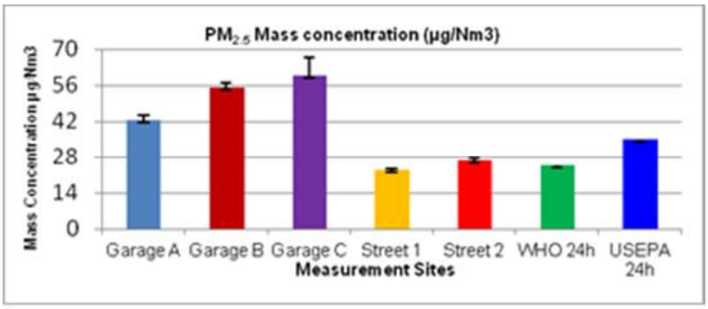

Figure 4. $PM_{2.5}$ concentrations obtained from different measurements

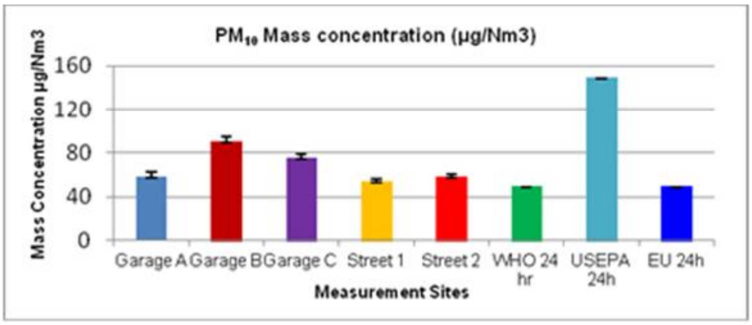

Figure 5. PM_{10} concentrations obtained from different measurements

3.2 Particle mass size distributions

Figure 6 illustrates particle mass size distributions obtained from the three garages and two streets. Since the formation mechanism of the particulate matter is quite complex and usually includes several concurrent paths, the particle size distributions may reveal more than one peak.

Two distinct modes appear in Figure 6. One shows a peak in fine particles with aerodynamic diameter between 0.3 µm to 0.8 µm. The other shows a peak in coarse particles around 5 µm size. Similar mass distributions have already been observed in other studies (Sippula *et al.*, 2009; Berner *et al.*, 2004; Boman *et al.*, 2004; Kelly *et al.*, 2003). Bimodal mass size distributions were observed of the atmospheric particles measured by a low pressure impactor (LPI), with one mode was at about 400 nm and other one at about 4 µm (Berner *et al.*, 2004). The differences between garage and street results are mainly in the fine particle range. In the garage, particles ranging from 0.15 µm range to 1.1 µm are strongly increased. Between 0.3 µm and 1.1 µm the amount of particles in the garages is around 8 to 10 times higher when compared to the streets. Fine mode fractions particles in the mass size distribution graphs might consist of organic matter as the most of the cars run by diesel engine, and the coarse fraction particles may consist of combination of organic and inorganic matter.

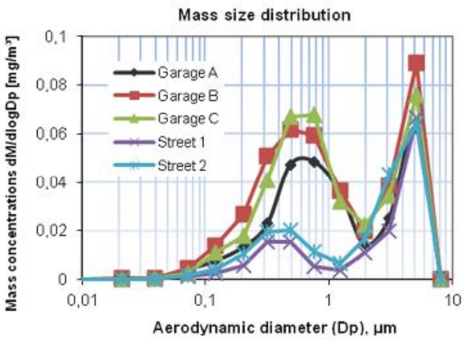

Figure 6. Mass size distributions measured by ELPI+, obtained from different measurements

3.3 Particle number concentrations

Figure 7 shows time series of particle number concentrations obtained from garage C. It can be seen from Figure 7 that number concentrations for garage C highly correlate with traffic flow during the sampling period. Highest particle concentrations were observed in the morning rush traffic flow from 8:30 am to 9:00 am and steady concentrations were observed after the cars parked. When vehicles entered or left the garages, particle number concentrations instantly got higher due to the operation of the vehicle's engine.

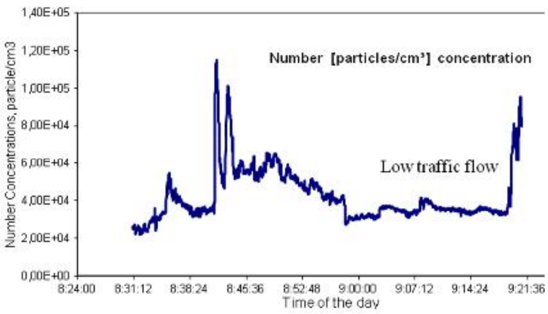

Figure 7. Particle number concentration as a function of traffic flow, obtained from garage C

The number concentrations measured in the three garages A, B and C were in the range of $28x10^3$ particles cm^{-3} to $47x10^3$ particles cm^{-3} while from $17x10^3$ particles cm^{-3} to $22x10^3$ particles cm^{-3} were observed in the streets. 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. These show to be in the same range or slightly lower than the results obtained in other studies. For example, particle number emissions of $51x10^3$ particles cm^{-3}, measured by SMPS in a traffic tunnel have been reported (Weingartner *et al.*, 1997). Therefore, the smallest particles can make the highest contribution to the total particle number concentrations. As the garages are attached to the entrance of the buildings, these particles can migrate to the office spaces and thus can degrade indoor air quality.

3.4 Particle number size distributions

Figure 8 shows typical particle number size distributions graphs obtained from all the measurements. The highest amounts of particles are found in the aerodynamic diameters between 20 and 25 nm. A single peak in the number size distributions graphs was observed in all the measurements. Similar size distributions were observed in another study (Weingartner *et al.*, 1997). It can be noted that vehicle emissions are highly dynamic and are formed from a chemically 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 ambient air. These particles are generally in the size range less than 30 nm and compose the nucleation mode. The size of particles depends on the variety of sources and processes which lead to their formation, and on the material from which the particles are formed and there is still significant scientific knowledge gap behind these processes. When comparing the garage and street results, it is observed that most of the particle numbers nearly double over the full range of sizes.

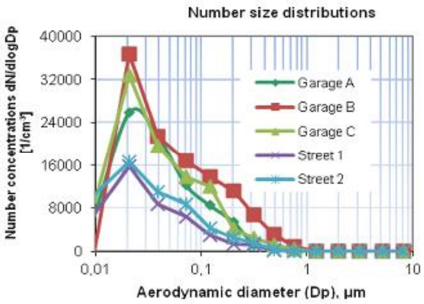

Figure 8. Number size distributions measured by ELPI+, obtained from different measurements

4. CONCLUSIONS

Particulate matter concentrations at three enclosed parking garages and two streets in Belgium were measured in real time 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 PM_1, $PM_{2.5}$ and PM_{10} and compared with the international reference limit values recommended by WHO, USEPA and EU. Following conclusions can be drawn from this study.

- The results showed that the average particles mass concentrations in the garages ranged from 28-50 µg Nm^{-3} for PM_1, 43-60 µg Nm^{-3} for $PM_{2.5}$ and 58-90 µg Nm^{-3} for PM_{10}, while in streets varied from 14-18 µg Nm^{-3} for PM_1, 23-27 µg Nm^{-3} for $PM_{2.5}$ and 54-59 µg Nm^{-3} for PM_{10} respectively.
- The number concentrations were obtained in the range of $28x10^3$ particles/cm^3 to $47x10^3$ particles cm^{-3} for the garages while $17x10^3$ particles cm^{-3} to $22x10^3$ particles cm^{-3} for the streets. Number concentrations in garages are increased rather uniformly when compared to the street measurements.
- $PM_{2.5}$ 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. All these garages and the streets had higher PM_{10} concentrations than the limit/reference values recommended by the WHO and EU but lower than the USEPA.
- Particle number size distributions showed dominant quantities of fine particles in all measurements, while two distinct particle sizes of coarse and fine modes were observed in the mass size distributions. Increased mass concentrations are observed in the garages in the range of 0.3 µm to 1.1 µm, when compared to the street measurements.

5. ACKNOWLEDGEMENT

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