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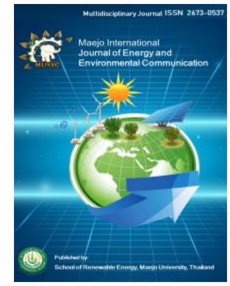

ARTICLE

PM concentrations and particle size distributions in urban areas and their health effects

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ABSTRACT

The objective of this study was to compare particulate matter (PM) emissions in terms of mass concentrations, number concentrations and particle size distributions, performed at three enclosed parking garages, adjacent open-air conditions in two streets and with indoor conditions in two labs in Belgium. PM measurements were sampled in real time using an Electrical Low-Pressure Impactor Plus (ELPI+) instrument. Particle number concentrations and mass concentrations with three size fractions of PM_1, $PM_{2.5}$ and PM_{10} were analysed. Average results are presented of the measured value obtained from the 3 garages, 2 streets and 2 labs. The results showed that the average particle mass concentrations in the garage, street and lab are 40, 16 and 23 $\mu g/Nm^3$ for PM_1, while 52, 24 and 29 $\mu g/Nm^3$ for $PM_{2.5}$ and 74, 56 and 52 $\mu g/Nm^3$ for PM_{10} respectively. The experimental results were compared with the previous studies and with the reference values recommended by the World Health Organization (WHO). In all the measurements of garage, street and lab, it has been observed that $PM_{2.5}$ and PM_{10} concentrations exceeded the 24 hr reference values recommended by WHO guidelines. Two distinct particle sizes of fine and coarse modes were observed in the mass size distributions for all the measurements. Increased mass concentrations are observed in the garage and lab in the range of 0.3 µm to 1.2 µm, when compared to the street concentrations. Particle number concentrations in the garages and streets are about 2.3 fold and 1.2 fold compared to the lab measurements. Particle number size distributions inside the garage showed increased quantities of ultrafine particles when compared to the street and lab measurements. The experimental results of the present study can be used by policymakers and concerned authorities to design and implement appropriate ventilation systems with emission control measures.

1. Introduction

Particulate matter (PM) refers to the solid and liquid particles dispersed into ambient air and these particles can vary in size, shape, and chemical composition. These particles can be classified into primary and secondary particles based on their formation pathways

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(Vallius, 2005). Primary particles are emitted directly as particles, whereas secondary particles are formed from precursor gases in the atmosphere through gas-to-particle conversion. According to size, particles can be divided into two groups (M Obaidullah, Bram, Verma, & De Ruyck, 2012). These are fine particles and coarse particles. Particles smaller than 1 μm (micro meter) in diameter are often called fine particles, while particles larger than 1 μm in diameter are usually called coarse particles (Obernberger, Brunner, & Barnthaler, 7-11 May 2007; Olli Sippula, Hokkinen, Puustinen, Yli-Pirila, & Jokiniemi, 2009a). The notations PM_1, $PM_{2.5}$ and PM_{10} fractions refer to mass concentrations of particles smaller than 1, 2.5 and 10 μm respectively. PM_1 and $PM_{2.5}$ are the most harmful for people as the particles can penetrate deep into the lungs. These particle sizes are always related to the aerodynamic diameter which represents the diameter of a spherical particle with a density of 1000 kg/m^3 having the same drag in air as the particle of interest (McDonald et al., 2000; Nussbaumer, Klippel, & Johansson, 2008; O. Sippula, 2010).

Ambient air quality is closely correlated to human activities that produce PM emissions in air. The London smog disaster of 5-10 December 1952 is a classical example which caused the prematurely death of 4000-12000 people (I.H. Moya, 2013). Fine particles are considered as a quite severe pollutant involved in a number of adverse health effects (Branis, Rezacova, & Domasova, 2005; Han & Naeher, 2006; M Obaidullah, Bram, et al., 2012). Several studies reported that increased PM 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 (Berner et al., 2004; Hackley, Feinstein, & Dixon, 2007). Another important concern of fine particle emissions from traffic sources is that they are important cooling agents in the atmosphere. Cooling occurs directly by absorbing and scattering the incoming solar radiation as well as indirectly through acting as cloud condensation nuclei that form clouds by growing into cloud droplets. Clouds then reflect the radiation away from the atmosphere (Han & Naeher, 2006).

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). There are many different varieties in the layout of parking garages such as underground garages, parking establishments, parking houses in multi-floor concepts. 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. Recently, the WHO labelled exhaust of diesel engines as carcinogenic. 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 (Baltrenas & Morkuniene, 2006; Kelly et al., 2003; Lunn, 2011; M Obaidullah, Peeters, Bram, & De Ruyck, 2012b, 2013; Yan & Crookes, 2010). These emissions are released directly from the vehicles to the air in the parking garages. There could also be additional emissions of VOC from vehicles because of the evaporation from engines and fuel tanks (Hoglund, 2004; M Obaidullah, Peeters, Bram, & De Ruyck, 2012a). 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). Indoor airborne PM has attracted the attention of many of researchers since it is also related with adverse health effects (Heydari et al., 2019). Urban people spend a large proportion of their days, include homes and workplaces (Chatoutsidou et al., 2015). It was reported that human spends approximately 80 – 90% of their time indoors and which a large share of their waking hours is allocated to the workplace (Challoner & Gill, 2014).

The objective of this paper was to compare particle emissions in terms of mass concentrations, number concentrations and particle size distributions, performed at three parking garages and adjacent open air conditions in two streets and with indoor conditions in two labs in Belgium. An Electrical Low Pressure Impactor Plus (ELPI+) was used in this study to sample particle concentrations in real time. The results obtained from the present study were compared with results from previous studies focused on particle concentrations related to roadside measurements and with the reference values recommended by the World Health Organization (WHO). Human health effects of urban PM are also discussed briefly in the study.

2. Previous Work

This section briefly reviews the findings/results related to traffic emissions published in the research articles available in the literature. Fondelli et al. (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, 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. 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. (Hess, Ray, Stinson, & Park, 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 17.3 μg/Nm^3 and 14.7 μg/Nm^3 respectively.

H. Fromme et al. (Fromme et al., 2007) evaluated particle mass and number concentrations from school class rooms. Particle mass concentrations of $PM_{2.5}$ and PM_{10} were measured in summer and winter by a Laser Aerosol Spectrometer (LAS), while number concentrations in summer were determined using a Scanning Mobility Particle Sizer (SMPS). They found that $PM_{2.5}$ and PM_{10} concentrations in summer were 19.8 μg/Nm^3 and 91.5 μg/Nm^3 respectively, while 12.7 μg/Nm^3 and 64.9 μg/Nm^3 respectively in winter. For all parameters relating to particle mass, higher concentrations were observed in winter than in summer. The particle number concentrations were 12,145 particles/cm^3.

B. Karakas et al (Karakas et al., 2013) conducted indoor PM measurements of PM_1, $PM_{2.5}$ and PM_{10} concentrations in homes in Ankara by a Grimm EDM107 Aerosol Spectrometer. The results show that PM_1, $PM_{2.5}$ and PM_{10} concentrations in the living room were 18±8 µg/Nm^3, 31±11 µg/Nm^3 and 116±40 µg/Nm^3 respectively.

Weingartner et al. (Weingartner, Keller, Stahel, Burtscher, & Baltensperger, 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 a 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_3 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 in all cases, particle mass emissions at the exit test point gave higher concentrations being 8 times the entrance concentration for workdays, 6 times for Saturdays and 5 times for Sundays.

Fischer et al. (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 hr 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. It is observed from this study that for high traffic conditions, indoor particle mass 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, living rooms, passenger shelters have been conducted previously. However, there is scarce publication in the literature on particulate matter emissions from parking garages, streets and indoor condition in a paper. As mentioned above, these areas 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, two streets and indoor condition in two labs in Belgium.

3. Material and methods

This section briefly highlights the selected measurement areas, the experimental setup and instrument used for particulate matter measurement.

3.1 Site selection

Urban Particulate matter measurements were performed at three different enclosed parking garages and two streets and indoor condition in two lab rooms in Belgium. The garages have different layouts with varying vehicle intensity. The garages are located at the ground floor of different multi-storey buildings. The garages are equipped with natural ventilation and are opened from Monday through Friday from 7:00 am to 8:30 pm. Average parking capacity of the garages are about 120 cars.

Streets are the sub-streets of a university in Brussels and connected to the city streets. Both sides of the streets have parking places and high-rise buildings. All the sites are used for employees' and visitors' cars. It was observed during particle sampling that all sites were occupied for approximately 80 % with passengers' 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 were placed near the midpoint of each garage, where observed traffic flow was significant. For the streets, the sampling spot was located on the footpath attached to the streets. Samples were taken at a height of 0.85 m from the floor.

Indoor PM measurements were conducted in two lab rooms of a university in Brussels. The lab rooms are medium sized located in the ground floor having two doors that are used for entrance and exit. Both doors are attached to other rooms. So, particle exchanging occurs among the rooms, when the doors open. There are some scientific instruments, tools, chairs, tables, steel cabinets in the lab rooms. In addition, the roof of the lab rooms have transparent plastic glass for using of natural daylight.

The PM measurements presented in this paper were conducted on seven working days during February, March and May. A single measurement was conducted for each site for each day. The indoor temperature in the garages was about 5 ºC higher than the outside air temperature. Average results are presented of the measured value of the 3 garages, 2 streets and 2 labs.

3.2 Experimental set up and instrumenttion

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 measurement setup for particle sampling conducted for all the sites. Sample particles entering the ELPI+ device 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 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 (Marjamaki, Keskinen, Chen, & Pui, 2000). Aluminium foils greased with a diameter of 25 mm and thickness of 0.1 mm were placed on each impactor stage during particle sampling.

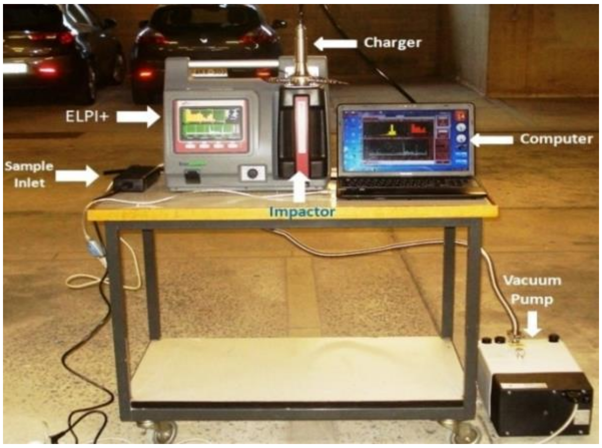

Figure 1 PM sampling setup using an ELPI+ conducted in the measurement sites

Aluminium foils with a diameter of 25 mm and thickness of 0.1 mm were placed on each impactor stages during particle sampling. All substrates are greased with Apiezon-L with a mixture of acetone were placed on each of the impactor stages to prevent particle bouncing. The ratio of grease and solvent is kept about 1:20 to 1:30. This is done by adding the grease to the solvent little by little until the liquid is nearly opaque. The impactor stages and charger parts were cleaned with water and isopropanol after every measurement. The disassembled impactor stages and the charger parts of the ELPI+ are shown in Figure 2.

Figure 2 Impactor stages and charger parts of the ELPI+ instruments

Particle number concentrations and mass concentrations of 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 to warm up and to perform the electrometer zeroing with flush on. All samples were collected for several hours during workdays for each measurement. A similar measurement protocol was followed for each particle sampling campaign. ELPI+VI software was used with the ELPI+ instrument to transfer the measured data into a data acquisition system for further processing and analysing.

4. Result and Discussion

Urban Particulate matter measurements were performed at three different enclosed parking garages and two streets and indoor condition in two lab rooms in Belgium. The real time measurements of the urban particulate matter at the sites in the range from 6 nm to 10 µm from the 14 stages of the impactor were combined in three size groups as PM_1, $PM_{2.5}$ and PM_{10} using an EPLI+VI software. Average results are presented of the measured value of the 3 garages, s streets and 2 labs. Particle emissions are generally expressed in terms of mass concentrations, number concentrations and size distributions. Particle sampling time varied from 3 hr 30 min to 5 hr 35 min for all the measurements. All current air quality standards for particulate matter refer to the weight of particles measured in µg/m^3. At present, there are no reference guidelines/standards for ambient PM_1 concentrations and the particle number emissions. The fraction of $PM_{2.5}$ has much more health effects than the PM_{10}, because the smaller particles are considered the most harmful as they have a lower mass and higher number concentrations. A given mass of smaller particles impacts on a larger surface area of lung tissue compared to an equal mass of larger particles. Therefore, the standard should also be considered to refer to particle number concentrations. It is hoped that the findings are directly applicable for improving the indoor air quality standards, urban ventilation system designs and making this study highly impactful and practical.

3.*1 Particle mass concentrations*

Figure 3 shows comparison of particle mass concentrations of PM_1, $PM_{2.5}$ and PM_{10} measured in the garages, streets and indoor conditions. $PM_{2.5}$ and PM_{10} concentrations obtained from all the measurements are compared with the international limit value recommended by the WHO. It has to be noted that the limit values are made for a 24 hr mean, while the PM measurement concentrations were conducted over a several hours average. The measurements were not performed for 24 hr because the garages and the labs are usually closed during the night. It was also not allowed to keep the ELPI+ instrument in the sites, as the instrument is very expensive. The measuring time is very important in view of fair comparisons with the reference standards. Figure 3 shows that the average particle mass concentrations in the garages, streets and labs are 40, 16 and 23 µg/Nm^3 for PM_1, while 52, 24 and 29 µg/Nm^3 for $PM_{2.5}$ and 74, 56 and 52 µg/Nm^3 for PM_{10} concentrations respectively. Figure 3 shows that in all the measurements of garages, streets and labs, it has been observed that $PM_{2.5}$ and PM_{10} concentrations exceeded the 24 hr reference values recommended by WHO guidelines.

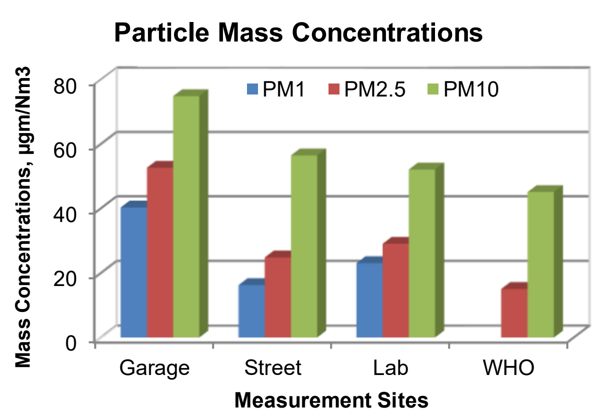

Figure 3 Comparison of PM concentrations with WHO guidelines

From the Figure 3, it is clearly seen that PM_1 and $PM_{2.5}$ concentrations in the garage measurement is much higher than the lab measurements in indoor condition followed by the street measurement.

Our particle mass concentration results for PM_1 can be compared with another study. For example, Lee et al. (Lee et al., 2006) investigated PM_1 mass concentration in heavily traffic area in Hong Kong using a Partisol Plus instrument operated at 16.7 lpm. Average concentrations of PM_1 fraction in their study were 35.9±12.4 µg/Nm^3.

The $PM_{2.5}$ concentrations level obtained in this study can be compared with other studies conducted at road sides. For example, $PM_{2.5}$ mass concentrations were measured near a street side with high traffic flow in Amsterdam using a Harvard impactor (Fischer et al., 2000). Average outdoor $PM_{2.5}$ concentrations in their investigation were 25 µg/Nm^3. In another study, PM_3 (particle diameter less than 3 µm) concentrations were measured in a road tunnel of 3.25 km long at Zurich, Switzerland using a tapered element oscillating microbalance (TEOM). The average PM_3 concentrations from the entrance and exit test stations were 25 µg/Nm^3 and 201.6 µg/Nm^3 for workdays (Weingartner et al., 1997). In another study, average $PM_{2.5}$ mass concentrations in heavily traffic area in Hong Kong using a Partisol Plus (Model 2025) instrument operated at 16.7 lpm were 52.3±18.3 µg/Nm^3 (Lee et al., 2006). Samal et al. (Samal, Gupta, Pathania, Mohan, & Suresh, 2013) measured PM in an enclosed parking garage finding concentrations much higher than ambient values, with an average of 100 µg/Nm3 up to a maximum 234 µg/m3 for $PM_{2.5}$, which is much higher than our measurements.

Our PM_{10} mass concentrations results of the streets were higher to the results of other studies that took place on road side measurements (Fischer et al., 2000; Kalabokas, Adamopoulos, & Viras, 2010). Vukovic et al. (Vuković et al., 2014) reported measurements in four parking garages in Serbia. The authors found that the experimental results of PM_{10} concentrations in all measurements were exceeding 300 µg/Nm3, which is much higher than our measurements both in garages and streets. The observations from the experimental results show that $PM_{2.5}$ and PM_{10} concentrations in garages, streets, and labs exceed the WHO guidelines. The experimental results emphasize the urgent need for targeted mitigation strategies.

4.2 Particle mass size distributions

Figure 4 illustrates particle mass size distributions obtained from the three garages and the two streets in linear and logarithmic scale respectively. It refers to particle mass concentration distributed over particle size. The abscissa 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 *d*log*(Dp),* where *Dp* is the aerodynamic diameter. 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.

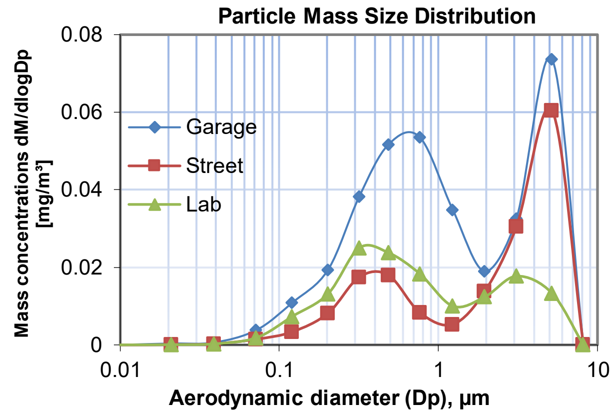

Figure 4 Comparison of mass size distribution obtained from different measurements

Two distinct modes appear in the Figure 4 of mass size distribution. 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 between 0.4 µm to 0.5 µm size. Similar mass distributions have already been observed in other studies (Berner et al., 2004; Boman, Nordin, Bostrom, & Ohman, 2003; Kelly et al., 2003; Olli Sippula, Hokkinen, Puustinen, Yli-Pirila, & Jokiniemi, 2009b). Bimodal mass size distributions were observed of the atmospheric particles measured by a low pressure impactor (LPI), with one mode was at the particle size about 0.4 µm and other was about 4 µm (Berner et al., 2004). It can also be seen from Figure 4 that the mass concentration up to particle size 50 nm is very small amount (below 1 µg/Nm^3). Therefore, these particles do not appear in Figure 6 in the number side distribution graph in Section 4.4. The differences among the results on particle mass concentrations 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 2.5 times higher when compared to the streets and 1.7 times higher of the room conditions.

From all the measurements, it shows that in all the cases of the mass size distributions graphs, particles between 10 nm and 100 nm represent a very small amount of mass, therefore these particles are not seen in the mass size distribution graphs. Because of low mass fractions, these particles are difficult to observe. When considering number size distributions, particles between these sizes (10 nm and 100 nm) show maximum concentration of particle number. These small size particles are considered very harmful for human health as they penetrate lower the alveolar region of the lung

Fine mode fractions particles of the garages 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. The coarse mode particles are typically formed mechanically by the abrasion of road materials, tyres and brake linings, soil dust raised by wind and traffic turbulence, etc.

The sources of PM emissions from streets might be vehicle exhaust, wear of vehicle components such as tyres, and road-induced dust. Pavement abrasion can eject inorganic particles that may contain cadmium (Cd), aluminium (Al), silicon (Si), calcium (Ca) potassium

(K), and sodium (Na), while metals such as lead (Pb), copper (Cu), zinc (Zn) and antimony (Sb) may be found in brake and tyre wear particles (Hjortenkrans, Bergbäck, & Häggerud, 2006; Jekel, 2019; Lindbom et al., 2006). Tyre wear particles can also be formed as evaporative emissions due to heating of the tyre followed by condensation and coagulation. This process forms particles in the nanometer (nm) scale size and contributes much less to the total mass emissions. These particles become airborne aerosols and can travel for long distances due to their smaller sizes. The concentrations of particulates can vary hourly or daily due to changes in wind velocity and direction or atmospheric instability (M Obaidullah, 2014; M Obaidullah, S Bram, & J De Ruyck, 2018b; M Obaidullah, Bram, et al., 2012). Indoor PM concentrations in the labs derive from outdoor particulate matter concentrations and human activities, cleaning activities, operations of the lab instruments, particle exchange during doors opening and closing. However, more studies are required to evaluate the parameters producing these high values of particulate matter concentrations in indoor condition.

4.3 Particle number concentrations

Figure 5 shows the comparison of particle number concentrations obtained from the measurements. The results show that the Garages have much higher particle number emissions that the streets followed by indoor labs.

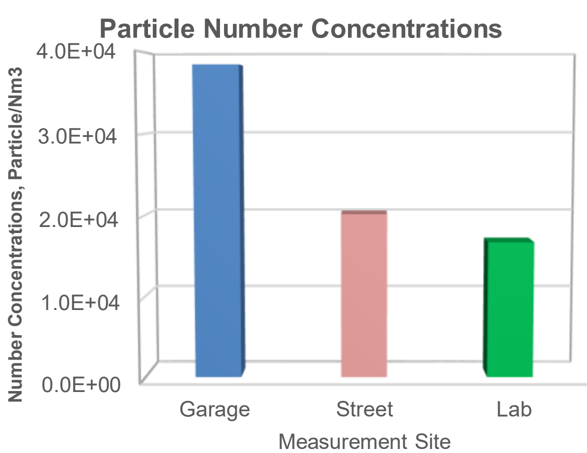

Figure 5 Comparison of particle number concentrations obtained from the measurements

Particle number concentrations at the measurements of garage, street and labs 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 51×10^3 particles/cm^3, measured using an SMPS in a traffic tunnel have been reported by Weingartner et al. (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.

The existing World Health Organization (WHO)/European Union (EU)/ US Environmental Protection Agency (EPA) norms limit the particle emissions in terms of total mass concentrations from the combustion appliances (Villeneuve, Palacios, Savoie, & Godbout, 2012). However, nowadays much attention is focused across the globe as well as in the EU member states to extend this approach to the particle number concentrations and size distributions, because of their impact on the global environment, the air quality and the adverse human health (M Obaidullah, Svend Bram, & Jacques De Ruyck, 2018a; M Obaidullah et al., 2018b; M Obaidullah, Bram, et al., 2012; Md Obaidullah & De Ruyck, 2021).

4.4 Particle number size distributions

The size distribution of particle number concentrations is one of the significant parameters for evaluating its environmental health and climate effects. Figure 6 shows typical particle number size distribution 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 distribution graphs was observed in all the measurements. Similar size distributions were observed in another study (Weingartner et al., 1997). D. Imhof et al. (Imhof et al., 2006) evaluated submicron particle number size distributions in road tunnels with traffic regimes by Scanning Mobility Particle Sizer (SMPS). The authors found particle size distributions nucleation mode with a geometric mean diameter of approximately 25–35 nm. These particles are formed by condensation of the exhaust gas directly after emission, a homogeneous nucleation process. They mainly consist of volatile material which contains organic species from unburned fuel. The concentrations of these submicron particles depend on several factors such as ambient temperature and relative humidity (Baltensperger et al., 2002; Bukowiecki, Dommen, Prévôt, Weingartner, & Baltensperger, 2003; Tobias et al., 2001).

It can be noted that particle emissions from the garages and streets 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 a 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. The identification of fine and coarse modes in particle size distributions adds depth to the understanding of urban air quality.

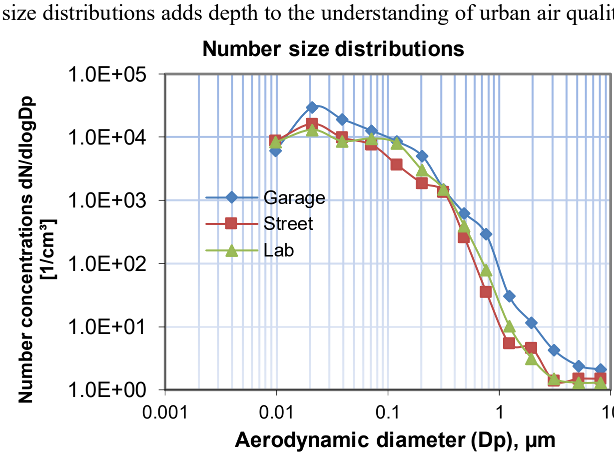

Figure 6 Comparison of number size distribution obtained from different measurements

Number size distributions from all measurements showed dominant quantities of ultra-fine particles. This is an important parameter because it affects the air quality much than particle mass concentrations. Particles numbers between 1 µm and 10 µm represent a very few number of particles, therefore these particles are not seen in the number size distribution curves. However, when considering mass size distributions, particles between these sizes (1 µm and 10 µm) show maximum concentration of particle mass.

4.3 Human health effects

Particulate matter (PM) is a pollutant that affects the health of millions of people throughout the globe. Coarse particles deposit mainly in the upper part of the respiratory tract due to inertial impaction, interception, gravitational sedimentation and dispersion. Fine particles (≤ 1 µm), generated via a combustion process have a high probability of deposition in deeper parts of the respiratory tract due to their high diffusion. Exposure to such fine particles can affect severe health effect both lungs and heart. A person inhales about 6 to over 12 m^3/day of ambient air, depending on age and physical activity. This air contains a wide variety of particle sizes from geological and anthropogenic pollutants. It has been reported most of the PM_{10} mass is deposited in the nose and throat, while about 60 % of inhaled $PM_{0.1}$ is deposited in the lung (Lighty, Veranth, & Sarofim, 2000). It has also been suggested that ultra fine particles (≤ 100 nm) might be the most harmful fraction of fine particles due to their high penetration efficiency into alveolar region of the lungs and further into blood circulation (Lighty et al., 2000). The health effects of the ultrafine particles are larger than that of the coarse particles. A given mass of ultrafine particles impacts a larger surface area of lung tissue than an equal mass of larger particles. It is mentioned that particle number size distributions showed dominant quantities of fine particles in all measurements, as shown in Figure 6 in the previous section.

People with heart or lung diseases, children and older adults are the most likely to be affected by particle pollution exposure. However, even a healthy person may experience temporary symptoms from exposure to elevated levels of particle pollution (I. H Moya, 2013).

Pollution in the air may place an undue burden on the respiratory system and contribute to increased morbidity and mortality, especially among susceptible individuals in the general population [4]. Human health impacts are caused by a wide range of gases and particles. Particulate matter has been correlated to serious health damage in Europe and North America over the last 150 years. Most studied episodes were the smog experienced during the 1950s, which led to the development of the Clean Air Act in the UK.

Short-term exposures to urban PM emissions have been associated primarily with premature mortality, increased hospital admissions for heart or lung causes, acute and chronic bronchitis, asthma attacks, emergency room visits, respiratory symptoms, and restricted activity days. Several epidemiological studies reported that significant relationship between exposure duration and cardiovascular or respiratory diseases (Diez Roux et al., 2008; Miller et al., 2007; Turner et al., 2011). Pope III et al. (Pope III & Dockery, 2006) conducted a study to determine correlation between short-term PM exposure and clinical admissions for cardiac cases in eight European cities. The outcome from the study suggests that short-term effect of PM exposure is mainly attributable to diesel particulate matter. Le Tertre et al (Le Tertre et al., 2002) conducted a study on short term PM effects on cardiovascular diseases in eight European cities. The authors found that a significant effect of PM_{10} on admissions for cardiac causes (all ages), and cardiac causes and heart disease for people over 65 years. Analitis et al. (Analitis et al., 2006) conducted a study on short-term effects of ambient particles on cardiovascular and respiratory mortality. The authors found strong correlation between short-term exposure and cardiac cases; an increase in PM_{10} by 10 µg/Nm3 translated into an increase of 0.76% in cardiovascular deaths and 0.58% in respiratory deaths. In addition, of all of the common air pollutants, $PM_{2.5}$ is associated with the greatest proportion of adverse health effects related to air pollution.

Long-term (months to years) exposure to $PM_{2.5}$ has been linked to premature death, particularly in people who have chronic heart or lung diseases, and reduced lung function growth in children. The effects of long-term exposure to PM_{10} are less clear, although several studies suggest a link between long-term PM_{10} exposure and respiratory mortality. The International Agency for Research on Cancer (IARC) published a review in 2015 that concluded that particulate matter in outdoor air pollution causes lung cancer (Claxton, 2015). Boldo et al. (Boldo et al., 2006) studied the impact of long-term exposure to particulate matter PM2.5 on human health in relation to mortality and life expectancy in European cities. The study showed that an estimated about 17000 premature deaths including about 12000 cardiopulmonary deaths and about 5500 lung-cancer deaths were attributable to long-term annual exposure. These deaths were found to be avertible with 15 µg/Nm^3 reduction in exposure level, while also improving life expectancy by one month to two or more years. Miller KA et al. (Miller et al., 2007) studied 65000 postmenopausal women with no previous cardiovascular diseases in 36 U.S. metropolitan areas for 6 years. The risk of suffering cardiovascular event and cardiovascular mortality was found to have increased by 24% and 76% respectively for a 10 µg/Nm^3 increase in $PM_{2.5}$ at 95% confidence interval. Recent studies reported that smaller PM particles may be more toxic to human health (Lu et al., 2023; M Obaidullah, S Bram, & J De Ruyck, 2019; M Obaidullah, Svend Bram, & Jacques De Ruyck, 2019; M Obaidullah et al., 2013).

It can be mentioned from the above literature discussion indicating that exposure to elevated concentrations of PM is responsible for frequent morbidity and hospital admissions, cardiovascular diseases, respiratory disorders and mortality. This is evident from the continuation of the above discussion airborne PM is one of the most significant harmful pollutants to human health with both short term and long term exposure linked to increased mortality.

5. Conclusions

Monitoring of ambient particle mass and number concentrations is very important to assess the risk to human health. Particulate matter concentrations at three sites of garages, streets and labs 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} Following conclusions can be drawn from this study.

- 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. Particle number size distributions inside the garages showed increased quantities of ultrafine particles when compared to the street measurements.
- The results of the present study can be used by policymakers and concerned authorities to design and implement appropriate ventilation systems with emission control measures. Factors to consider are: proper garage volume, number of parking places, fuel composition, gearing, and speed.
- It can be mentioned from the health effect discussion that airborne PM is one of the most relevant pollutants to human health with both short term and long-term exposure linked to increased mortality.
- Since the fine particles are believed to be more harmful, more attention should be focused to fine particle regulations. Since their mass is not so relevant, the regulations should focus on the particle amounts in number rather than mass.

Nomenclature

EU	European Union
ELPI	Electrical Low Pressure Impactor
ELPI+	Electrical Low Pressure Impactor Plus
Dp	particle diameter
hr	hour
LAS	Laser Aerosol Spectrometer
lpm	liter per minute
PM	particulate matter
SMPS	Scanning Mobility Particle Sizer
VOC	volatile organic compounds
US	United States
µm	micrometer
nm	nanometer
mg	milligram
TEOM	Tapered Element Oscillating Microbalance
°C	Degree Celsius

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References

Analitis, A., Katsouyanni, K., Dimakopoulou, K., Samoli, E., Nikoloulopoulos, A. K., Petasakis, Y., . . . Cambra, K. (2006). Short-term effects of ambient particles on cardiovascular and respiratory mortality. *Epidemiology, 17*(2), 230-233.

Baltensperger, U., Streit, N., Weingartner, E., Nyeki, S., Prévôt, A., Van Dingenen, R., . . . Ten Brink, H. (2002). Urban and rural aerosol characterization of summer smog events during the PIPAPO field campaign in Milan, Italy. *Journal of Geophysical Research: Atmospheres, 107*(D22), LOP 6-1-LOP 6-14.

Baltrenas, P., & Morkuniene, J. (2006). Investigation of particulate matter concentration in the air of Zverynas district in Vilnius. *Journal of environmental engineering and landscape management, 14*(1), 23-30.

Berner, A., Galambos, Z., Ctyroky, P., Fruhauf, P., Hitzenberger, R., Gomiscek, B., . . . Puxbaum, H. (2004). On the correlation of atmospheric aerosol components of mass size distributions in the larger region of a central European city. *Atmospheric Environment, 38*(24), 3959-3970. doi:http://dx.doi.org/10.1016/j.atmosenv.2004.02.056

Boldo, E., Medina, S., Le Tertre, A., Hurley, F., Mücke, H.-G., Ballester, F., & Aguilera, I. (2006). Apheis: Health impact assessment of long-term exposure to PM 2.5 in 23 European cities. *European journal of epidemiology, 21*(6), 449-458.

Boman, C., Nordin, A., Bostrom, D., & Ohman, M. (2003). Characterization of Inorganic Particulate Matter from Residential Combustion of Pelletized Biomass Fuels. *Energy & Fuels, 18*(2), 338-348. doi:10.1021/ef034028i

Branis, M., Rezacova, P., & Domasova, M. (2005). The effect of outdoor air and indoor human activity on mass concentrations of PM10, PM2.5, and PM1 in a classroom. *Environmental Research, 99*(2), 143-149. doi:http://dx.doi.org/10.1016/j.envres.2004.12.001

Bukowiecki, N., Dommen, J., Prévôt, A., Weingartner, E., & Baltensperger, U. (2003). Fine and ultrafine particles in the Zürich (Switzerland) area measured with a mobile laboratory: an assessment of the seasonal and regional variation throughout a year. *Atmospheric Chemistry and Physics, 3*(5), 1477-1494.

Challoner, A., & Gill, L. (2014). Indoor/outdoor air pollution relationships in ten commercial buildings: PM2.5 and NO2. *Building and Environment, 80*, 159-173. doi:https://doi.org/10.1016/j.buildenv.2014.05.032

Chatoutsidou, S. E., Ondráček, J., Tesar, O., Tørseth, K., Ždímal, V., & Lazaridis, M. (2015). Indoor/outdoor particulate matter number and mass concentration in modern offices. *Building and Environment, 92*, 462-474.

Claxton, L. D. (2015). The history, genotoxicity, and carcinogenicity of carbon-based fuels and their emissions. Part 3: Diesel and gasoline. *Mutation research/reviews in mutation research, 763*, 30-85.

Diez Roux, A. V., Auchincloss, A. H., Franklin, T. G., Raghunathan, T., Barr, R. G., Kaufman, J., . . . Keeler, J. (2008). Long-term exposure to ambient particulate matter and prevalence of subclinical atherosclerosis in the Multi-Ethnic Study of Atherosclerosis. *American journal of epidemiology, 167*(6), 667-675.

Fischer, P., Hoek, G., van Reeuwijk, H., Briggs, D., Lebret, E., Van Wijnen, J., . . . Elliott, P. (2000). Traffic-related differences in outdoor and indoor concentrations of particles and volatile organic compounds in Amsterdam. *Atmospheric Environment, 34*(22), 3713-3722.

Fondelli, M. C., Chellini, E., Yli-Tuomi, T., Cenni, I., Gasparrini, A., Nava, S., . . . Jantunen, M. (2008). Fine particle concentrations in buses and taxis in Florence, Italy. *Atmospheric Environment, 42*(35), 8185-8193. doi:http://dx.doi.org/10.1016/j.atmosenv.2008.07.054

Fromme, H., Twardella, D., Dietrich, S., Heitmann, D., Schierl, R., Liebl, B., & Ruden, H. (2007). Particulate matter in the indoor air of classrooms-exploratory results from Munich and surrounding area. *Atmospheric Environment, 41*(4), 854-866. doi:http://dx.doi.org/10.1016/j.atmosenv.2006.08.053

Hackley, B., Feinstein, A., & Dixon, J. (2007). Air pollution: impact on maternal and perinatal health. *Journal of Midwifery & Women's Health, 52*(5), 435-443.

Han, X., & Naeher, L. P. (2006). A review of traffic-related air pollution exposure assessment studies in the developing world. *Environment international, 32*(1), 106-120.

Hess, D. B., Ray, P. D., Stinson, A. E., & Park, J. (2010). Determinants of exposure to fine particulate matter (PM2.5) for waiting passengers at bus stops. *Atmospheric Environment, 44*(39), 5174-5182.

Heydari, G., Taghizdeh, F., Fazlzadeh, M., Jafari, A. J., Asadgol, Z., Mehrizi, E. A., . . . Arfaeinia, H. (2019). Levels and health risk assessments of particulate matters (PM2. 5 and PM10) in indoor/outdoor air of waterpipe cafés in Tehran, Iran. *Environmental Science and Pollution Research, 26*(7), 7205-7215.

Hjortenkrans, D., Bergbäck, B., & Häggerud, A. (2006). New metal emission patterns in road traffic environments. *Environmental Monitoring and Assessment, 117*(1), 85-98.

Hoglund, P. G. (2004). Parking, energy consumption and air pollution. *Science of The Total Environment, 334-335*(0), 39-45. doi:http://dx.doi.org/10.1016/j.scitotenv.2004.04.028

Imhof, D., Weingartner, E., Prévôt, A., Ordonez, C., Kurtenbach, R., Wiesen, P., . . . Ekström, M. (2006). Aerosol and NOx emission factors and submicron particle number size distributions in two road tunnels with different traffic regimes. *Atmospheric Chemistry and Physics, 6*(8), 2215-2230.

Jekel, M. (2019). *Scientific Report on Tyre and Road Wear Particles, TRWP, in the aquatic environment*. Retrieved from

Kalabokas, P., Adamopoulos, A., & Viras, L. (2010). Atmospheric PM10 particle concentration measurements at central and peripheral urban sites in Athens and Thessaloniki, Greece. *Global NEST Journal, 12*, 71-83.

Karakas, B., Lakestani, S., Guler, C., Guciz Dogan, B., Acar Vaizoglu, S., Taner, A., . . . Gullu, G. (2013). *Indoor and outdoor concentration of particulate matter at domestic homes.* Paper presented at the Proc. of World Academy of Science, Engineering and Technology.

Kelly, K. E., Wagner, D. A., Lighty, J. S., Sarofim, A. F., Rogers, C. F., Sagebiel, J., . . . Palmer, G. (2003). Characterization of exhaust particles from military vehicles fueled with diesel, gasoline, and JP-8. *Journal of the Air & Waste Management Association, 53*(3), 273-282.

Le Tertre, A., Medina, S., Samoli, E., Forsberg, B., Michelozzi, P., Boumghar, A., . . . Ayres, J. (2002). Short-term effects of particulate air pollution on cardiovascular diseases in eight European cities. *Journal of Epidemiology & Community Health, 56*(10), 773-779.

Lee, S., Cheng, Y., Ho, K., Cao, J., Louie, P.-K., Chow, J., & Watson, J. (2006). PM1. 0 and PM2. 5 characteristics in the roadside environment of Hong Kong. *Aerosol Science and Technology, 40*(3), 157-165.

Lighty, J. S., Veranth, J. M., & Sarofim, A. F. (Writers). (2000). Combustion Aerosols: Factors Governing Their Size and Composition and Implications to Human Health [doi: 10.1080/10473289.2000.10464197], *Journal of the Air & Waste Management Association*: Taylor & Francis.

Lindbom, J., Gustafsson, M., Blomqvist, G., Dahl, A., Gudmundsson, A., Swietlicki, E., & Ljungman, A. G. (2006). Exposure to wear particles generated from studded tires and pavement induces inflammatory cytokine release from human macrophages. *Chemical research in toxicology, 19*(4), 521-530.

Lu, J., Wu, K., Ma, X., Wei, J., Yuan, Z., Huang, Z., . . . Wu, X. (2023). Short-term effects of ambient particulate matter (PM1, PM2.5 and PM10) on influenza-like illness in Guangzhou, China. *International Journal of Hygiene and Environmental Health, 247*, 114074. doi:https://doi.org/10.1016/j.ijheh.2022.114074

Lunn, R. M. (2011). *Diesel exhaust particulates*. Retrieved from http://ntp.niehs.nih.gov/ntp/roc/twelfth/profiles/DieselExhaustParticulates.pdf

Marjamaki, M., Keskinen, J., Chen, D.-R., & Pui, D. Y. H. (2000). Performance evaluation of the electrical low pressure impactor (ELPI). *Journal of Aerosol Science, 31*(2), 249-261. doi:http://dx.doi.org/10.1016/S0021-8502(99)00052-X

McDonald, J. D., Zielinska, B., Fujita, E. M., Sagebiel, J. C., Chow, J. C., & Watson, J. G. (2000). Fine Particle and Gaseous Emission Rates from Residential Wood Combustion. *Environmental Science & Technology, 34*(11), 2080-2091. doi:10.1021/es9909632

Miller, K. A., Siscovick, D. S., Sheppard, L., Shepherd, K., Sullivan, J. H., Anderson, G. L., & Kaufman, J. D. (2007). Long-term exposure to air pollution and incidence of cardiovascular events in women. *New England Journal of Medicine, 356*(5), 447-458.

Moya, I. H. (2013). *Energy scenario analysis at local scale integrating technology, air pollution and human health risk assessments.* (Ph. D. Ph. D.), Vrije Universiteit Brussel, Belgium.

Moya, I. H. (2013). *Energy scenario analysis at local scale integrating technology, air pollution and human health risk assessments, in Department of Mechanical Engineering.* (PhD), Vrije Universiteit Brussel: Belgium.

Nussbaumer, T., Klippel, N., & Johansson, L. (2008). *Survey on measurements and emission factors on particulate matter from biomass combustion in IEA countries.* Paper presented at the Proc. 16 th European Biomass Conference and Exhibition.

Obaidullah, M. (2014). *Particle Emissions from Small Scale Biomass Combustion Appliences.* (PhD), Vrije Universiteit Brussels (VUB), Belgium.

Obaidullah, M., Bram, S., & De Ruyck, J. (2018a). Investigation on Gaseous and Particle Mass Emissions from Automatically Fired Small Scale Heating System Under Laboratory Conditions. *International Journal of Renewable Energy Development, 7*(2), 111-121.

Obaidullah, M., Bram, S., & De Ruyck, J. (2018b). An Overview of PM Formation Mechanisms from Residential Biomass Combustion and Instruments Using in PM Measurements. *International journal of energy and environment, 12*, 41-50.

Obaidullah, M., Bram, S., & De Ruyck, J. (2019). Measurements of Particle Emissions and Size Distributions from a Modern Residential Pellet Stove under Laboratory Conditions.

International Journal of Systems Applications, Engineering & Development, 13, 1-9.

Obaidullah, M., Bram, S., & De Ruyck, J. (2019). Particle mass and gaseous emissions from small scale modern wood stoves. *International Journal of Energy Applications and Technologies, 6*(2), 57-64.

Obaidullah, M., Bram, S., Verma, V., & De Ruyck, J. (2012). A Review on Particle Emissions from Small Scale Biomass Combustion. *International Journal of Renewable Energy Research (IJRER), 2*(1), 147-159.

Obaidullah, M., & De Ruyck, J. (2021). PARTICLE NUMBER EMISSIONS AND SIZE DISTRIBUTIONS FROM RESIDENTIAL WOOD STOVES UNDER LABORATORY CONDITIONS. *Suranaree Journal of Science & Technology, 28*(5).

Obaidullah, M., Peeters, L., Bram, S., & De Ruyck, J. (2012a). *Investigation of Particulate Matter Pollutants in Parking Garages*. Paper presented at the Latest advancement in Biology, Environment and Ecology, G. Enescu University, Iasi, Romania.

Obaidullah, M., Peeters, L., Bram, S., & De Ruyck, J. (2012b). Measurements of Particle Concentrations and Size Distributions in Three Parking Garages. *International journal of energy and environment, 6*(5), 508-515.

Obaidullah, M., Peeters, L., Bram, S., & De Ruyck, J. (2013). Comparison of particle emissions from enclosed parking garages and streets. *GNEST, 15*(4), 457-465.

Obernberger, I., Brunner, T., & Barnthaler, G. (7-11 May 2007). *Fine particle emissions from Modern Austrian small scale biomass combustion plants.* Paper presented at the 15th European biomass conference and exhibition, Germany.

Pope III, C. A., & Dockery, D. W. (2006). Health effects of fine particulate air pollution: lines that connect. *Journal of the Air & Waste Management Association, 56*(6), 709-742.

Samal, C. G., Gupta, D., Pathania, R., Mohan, S., & Suresh, R. (2013). Air pollution in micro-environments: A case study of India habitat centre enclosed vehicular parking, New Delhi. *Indoor and Built Environment, 22*(4), 710-718.

Sippula, O. (2010). *Fine particle formation and emission in biomass combustion.* (Ph. D), University of Eastern Finland, Finland.

Sippula, O., Hokkinen, J., Puustinen, H., Yli-Pirila, P., & Jokiniemi, J. (2009a). Comparison of particle emissions from small heavy fuel oil and wood-fired boilers. *Atmospheric Environment, 43*(32), 4855-4864.

Sippula, O., Hokkinen, J., Puustinen, H., Yli-Pirila, P., & Jokiniemi, J. (2009b). Particle emissions from small wood-fired district heating units. *Energy & Fuels, 23*(6), 2974-2982.

Tobias, H. J., Beving, D. E., Ziemann, P. J., Sakurai, H., Zuk, M., McMurry, P. H., . . . Kittelson, D. B. (2001). Chemical analysis of diesel engine nanoparticles using a nano-DMA/thermal desorption particle beam mass spectrometer. *Environmental Science & Technology, 35*(11), 2233-2243.

Turner, M. C., Krewski, D., Pope III, C. A., Chen, Y., Gapstur, S. M., & Thun, M. J. (2011). Long-term ambient fine particulate matter air pollution and lung cancer in a large cohort of never-smokers. *American journal of respiratory and critical care medicine, 184*(12), 1374-1381.

Vallius, M. (2005). *Characteristics and sources of fine particulate matter in urban air.* (Ph. D.), University of Kuopio, Finland.

Villeneuve, J., Palacios, J. H., Savoie, P., & Godbout, S. (2012). A critical review of emission standards and regulations regarding biomass combustion in small scale units (<MW). *Bioresource Technology, 111*(0), 1-11. doi:http://dx.doi.org/10.1016/j.biortech.2012.02.061

Vuković, G., Urošević, M. A., Razumenić, I., Kuzmanoski, M., Pergal, M., Škrivanj, S., & Popović, A. (2014). Air quality in urban parking garages (PM10, major and trace elements, PAHs): Instrumental measurements vs. active moss biomonitoring. *Atmospheric Environment, 85*, 31-40.

Weingartner, E., Keller, C., Stahel, W. A., Burtscher, H., & Baltensperger, U. (1997). Aerosol emission in a road tunnel. *Atmospheric Environment, 31*(3), 451-462. doi:http://dx.doi.org/10.1016/S1352-2310(96)00193-8

Yan, X., & Crookes, R. J. (2010). Energy demand and emissions from road transportation vehicles in China. *Progress in Energy and Combustion Science, 36*(6), 651-676. doi:http://dx.doi.org/10.1016/j.pecs.2010.02.003