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Health Effects of Exhaust Particles

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Symbols and abbreviations

COPD	Chronic Obstructive Pulmonary Disease
DPF	Diesel Particulate Filter
EU	European Union
H_2SO_4	Sulphuric acid
NO_x	Nitrogen Oxides
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
$PM_{0.1}$	Particulate Matter with diameter smaller than 0.1 µm
$PM_{2.5}$	Particulate Matter with diameter smaller than 2.5 µm
PM_{10}	Particulate Matter with diameter smaller than 10 µm
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
UFP	Ultra Fine Particle, Particulate Matter with diameter smaller than 0.1 µm
WHO	World Health Organization

EXECUTIVE SUMMARY

This report introduces general information about diesel particles and their health effects. The purpose of this report is to introduce particulate matter pollution and present some recent studies made regarding the health effects of particulate matter. The aim is not to go very deeply into the science, but instead to keep the text understandable for the average layman.

Particulate matter is a complex mixture of extremely small particles and liquid droplets. These small particles are made up of a number of components that include for example acids, such as nitrates and sulphates, as well as organic chemicals, metals and dust particles from the soil. Particulate matter comes from several sources, such as transportation emissions, industrial emissions, forest fires, cigarette smoke, volcanic ash and climate variations. Particles are divided into coarse particles with diameters less than 10 μm, fine particles with diameters smaller than 2.5 μm and ultra-fine particles with diameters less than 0.1 μm.

The particulate matter in diesel exhaust gas is a highly complex mixture of organic, inorganic, solid, volatile and partly volatile compounds. Many of these particles do not form until they reach the air. Many carcinogenic compounds have been found in diesel exhaust gas and it is considered carcinogenic to humans.

Particulate matter can cause several health effects, such as premature death in persons with heart or lung disease, cancer, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function and an increase in respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing. It is estimated that in Finland about 1300 people die prematurely due to particles and the economic loss in the EU due to the health effects of particles can be calculated in the billions.

Ultra-fine particles are considered to be the most harmful to human health. Ultra-fine particles usually make the most of their quantity and surface area, they can migrate far away from their source and they can even spread into the blood circulation and the brain. Transition metals on the surface of particles together with carcinogenic compounds found in the PM have been shown to cause cancer.

Diesel ultra-fine particles are mainly elemental carbon, organic carbon and sulphuric acid. Sulphur still exists in diesel fuel in certain regions and if the amount of sulphur in the fuel is reduced, particles are reduced as well. Metallic compounds originate mainly from the lubrication oil, but also from the fuel and engine wear.

In urban areas the amounts of particles are usually higher than in rural areas. Regulations for air quality in urban areas have been set to protect people living in the cities. Regulations are also becoming stricter in the field of internal combustion engines and particle numbers along with their mass are regulated in the EURO 6 standard.

Diesel PM can be reduced by several means. Reformulating the fuel and lubrication oil directly influences PM emissions while different aftertreatment systems can be used to remove PM from the engine exhaust gases. With a well-optimized injection system, burning is more complete and PM emissions are also reduced.

Exposure to particles can be decreased by avoiding busy roads where the level of particles is usually high, having a hobby that involves less exertion and decreasing exercise time. Outdoor activities should be reduced when PM concentration in the air is high.

1 INTRODUCTION

Air contains many kinds of small particles, especially in urban areas. These particles can be from many sources, such as sand, dust and the exhaust gases of vehicles and power plants. Depending on the source, the particles can contain many different trace elements, such as sulphur, coal and metals.

Many health effects have been linked to particles. These effects have been researched for years, and the big picture is slowing taking shape. The greatest concern at the moment is with the smallest particles, nano-scale particles smaller than 100 nm that are able to reach the lungs and even the blood circulation. Bigger particles are associated with asthma and other acute respiratory problems.

This report introduces general information about diesel particles and their health effects. After reading this report, one should know the basic health concerns regarding particles. The aim is not to go very deeply into the science, but instead to keep the text understandable for the average layman.

2 THE ORIGIN OF PARTICULATE MATTER

2.1 What is particulate matter?

Particulate matter is a complex mixture of extremely small particles and liquid droplets. These small particles are made up of a number of components that include for example acids, such as nitrates and sulphates, as well as organic chemicals, metals and dust particles from the soil. (EPA 2012.) Several elements, such as Si, Al, Ca, Fe, Ti, can be found in particulate matter as well as transition metals V, Cr, Ni Cu, Zn, Pb and inorganic ions, such as Na^+ and K^+. All these compounds together with volatile organic compounds are extremely changeable and depend on many factors, such as climate, emission sources and geographical position. (Polichetti et al. 2009.)

Particulate matter comes from many sources, such as transportation emissions, industrial emissions, forest fires, cigarette smoke, volcanic ash and climate variations. Virtually, every combustion process produces particulate matter and some combustion processes produce more than others. For example, wood burning in households and coal burning in power plants create great amounts of particulate matter.

In power plants, at least sulphur is normally cleaned from the exhaust gas using catalysts or water cleaners. In Finland, where many households burn wood for heating, households and diesel trucks produce the greatest amounts of particulate matter, households creating the most. (Hiukkastieto 2012.) Figure 1 illustrates total PM emissions of different sectors in 32 European countries. Households and services create the most of the PM_{10} and $PM_{2.5}$ emissions, followed by industrial processes and road transport. Road transport creates 14.2% of all PM_{10} emissions and slightly more $PM_{2.5}$ emissions at 15.3%.

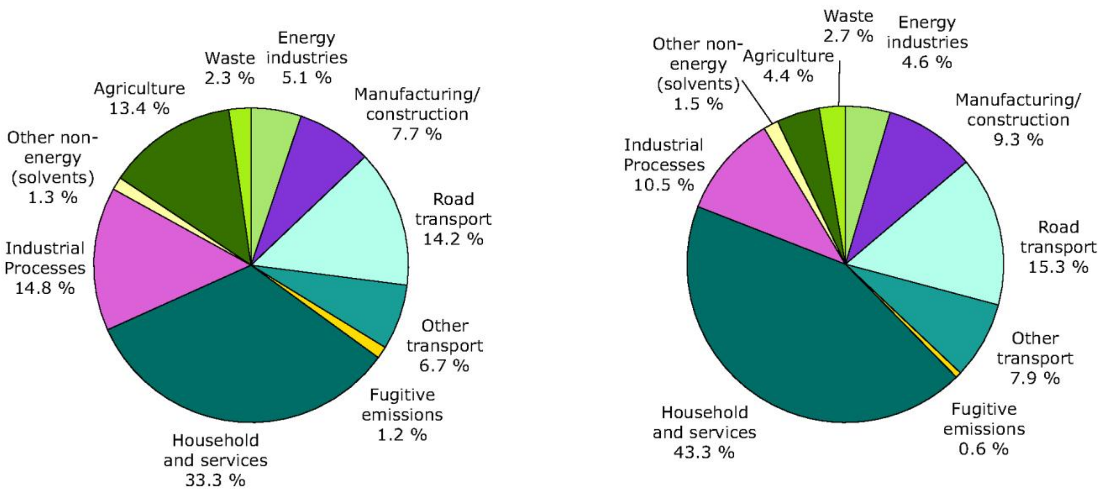

Figure 1. Contribution of different sectors (energy and non-energy) to total emissions of PM_{10} (left) and $PM_{2.5}$, 2009 in 32 European countries (EEA 2012).

2.2 Particulate matter size categories

PM is usually divided into three different size groups, coarse, fine and ultra-fine particles. PM_{10} means particulate matter having a diameter smaller than 10 µm, but greater than 2.5 µm. $PM_{2.5}$ is particulate matter smaller than 2.5 µm and having a diameter of 2.5–0.1 µm. $PM_{0.1}$, often called UFP (Ultra-Fine Particle), is particles with diameters less than 0.1 µm. PM_{10} are usually referred as coarse particles, $PM_{2.5}$ is fine particles and $PM_{0.1}$ is ultra-fine particles. (Timothy et al. 2011). As the real diameters are practically impossible to measure, sizes are usually aerodynamic diameters that indicate how the particles flow in the air.

The smallest particles can be gas molecules with aerodynamic diameters of less than 10 nm, and some particles can be more than 100 µm which is large enough to be seen by the naked eye. The variety of different combinations is huge. Usually, in exhaust gas, the amount of smaller particles is much larger, but the particulate mass is mostly in the bigger particles. Their mass and size distributions are very different. DPF filters usually gather most of the mass, but the smallest particles may still escape with the exhaust gas.

The size range and distribution, and also typical trace elements in particles are introduced in Figure 3. Ultra-fine particles are mainly different carbon-based compounds while $PM_{2.5}$ is made of sulphur and nitrogen oxide and carbon compounds. The largest coarse particles are mainly rock material from the soil, such as silicon and aluminium.

Ultra-fine particles are normally in the air for a very short period, in urban areas however, the time of occurrence can be several hours. Ultra-fine particles compose only a couple percentages of the total mass of all particulates in the air, but their quantity is high and they are the most numerous of all particles. Moreover, the surface area of all ultra-fine particles is very high due to the large numbers of them in the air. (Pekkanen 2004.) Ultra-fine particles can migrate far away from the emit source while the biggest particles usually stay close to their origin. The origin of problematic UFPs found in the air can be tens or hundreds of kilometres away.

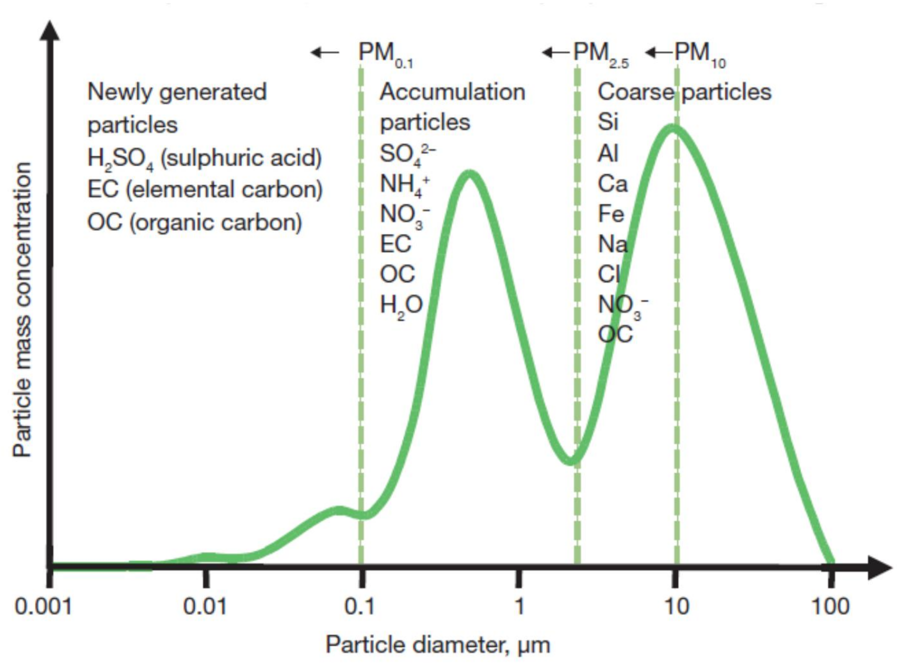

Figure 2. Particle size distribution and typical trace elements (Salonen and Pennanen 2006).

How small are these particles? To get an understandable perspective of their size, consider a single hair from a human head. A human hair is about 70 micrometers in diameter, making it almost 30 times larger than the largest $PM_{2.5}$ particle, Figure 4 (EPA 2012). It is easy to understand that particles of this size can emanate through the nose and lungs and stay inside of human body.

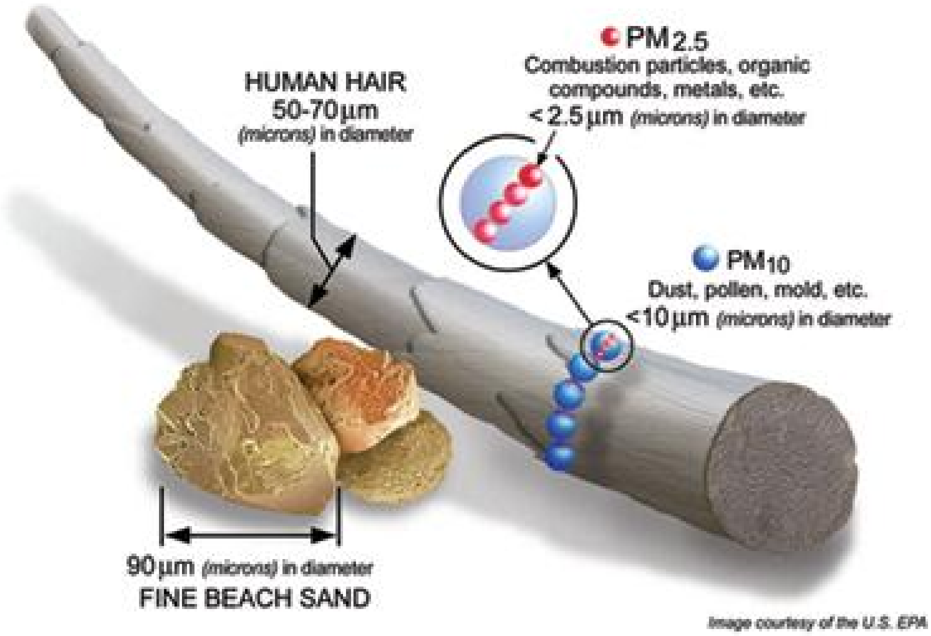

Figure 3. How big is particulate matter (EPA 1 2012)?

2.3 Urban areas collect PM

In urban areas, the amounts of particles are usually high. Urbanization itself creates particles due to more traffic, heating and cooking, and, in urban areas, more people are being affected by particles, therefore the health problems are also growing with the population. It is estimated that yearly in Finland about 1300 people die prematurely because of particles, and about 600 bronchitis cases are related to particles as well (Hiukkastieto 2012). There are no clear safe limits for any of the particle sizes, but some influence can be seen in very small concentrations in air. Especially dangerous are the smallest particles as well as polycyclic aromatic hydrocarbons (PAH) which are extremely carcinogenic and mutagenic.

PAHs have mostly been studied with animals, and it has been discovered that these animals had problems breeding and these problems also exhibited in the second generation. Birth defects and lower body weights have also been noticed, as well as effects on the skin, body fluids and the immune system. Long-term contamination has been noticed to expose subjects to a risk of lung- and stomach cancers, depending on the exposure path. PAHs are also present in cooking, especially in grilling (Agency for toxic substances and disease registry, 1996). For most people, the biggest PAH source is still tobacco.

2.4 Diesel particles

2.4.1 Origin of diesel particles

A diesel particle, more specifically diesel particulate matter (PM), is a product of the combustion of diesel in an engine. Diesel particle matter consists of unburned fuel, engine lubrication oil and small quantities of products from partial combustion and pyrolysis. (EPA 3 2002) In an ideal combustion process, all the fuel injected to the engine is burned, leaving behind only carbon dioxide and water. However, combustion in internal combustion engine is never complete. These unburned fuel and lubrication particles together with complicated chemical reactions in the combustion process create the soot that can be seen even with the naked eye as it exits the exhaust pipe. Particulate matters are a part of this exhaust gas. Especially in very old vehicles, soot can be very thick and dark and can cause immediate irritation of the lungs and coughing.

A diesel engine produces about 100 times more particulate matter than a normal petrol engine with a three-way catalytic converter per distance (Sydbom et al., 2001). If compared to a petrol engine without the converter, the rate is about ten. Regulations stipulate that new diesel vehicles and trucks must have a Diesel Particulate Filter (DPF) that cleans most of the particles from the exhaust gas. The efficiency of a typical filter is about 85–95 mass-% (Majewski, 2006). The amount of particulate matter can also be controlled with better combustion, but this increases nitrogen oxides (NO_x) in the exhaust gas. Nitrogen oxides are also very problematic, especially to the soil. This connection between PM and NO_x is called "Trade-off", and it has been troubling engine developers for years, as both emissions would have to decrease dramatically in the future. In 2013 or 2014, depending on the use of the vehicle, the regulations are going to be so strict that both emissions will need their own filter or catalysts in order to meet the limits.

2.4.2 Diesel PM composition

Particulate matter in diesel exhaust gas is a very complex mixture of organic, inorganic, solid, volatile and partly volatile compounds. The amounts of these will depend strongly on the load on the engine, the fuel and lubrication used in the engine and the aftertreatment system. The composition of the exhaust gas also depends on time. When temperature decreases, vaporized hydrocarbons condense on the surface of the PM partly in the exhaust pipe, but also when they have reached the air. Gaseous compounds compose different, new chemical compounds when they react together and with compounds found in the air. At this point, when the temperature decreases and the exhaust gas reaches the outdoor air, most UFPs are formed and gaseous hydrocarbons start to condense into small particle droplets, Figure 4 (Laurikko 2008).

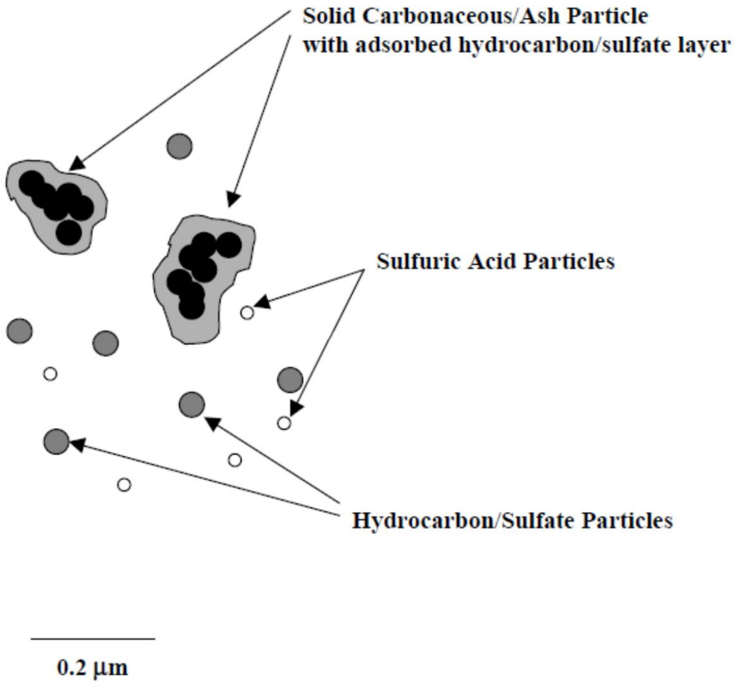

Figure 4. Schematic diagram of diesel engine exhaust particles (EPA 3 2002).

2.4.3 Carbon and sulphur in diesel PM

Ultra-fine particles consist mainly of newly generated particles, such as elemental carbon, organic carbon and sulphuric acid. In the diesel combustion process, some of the carbon has undergone pyrolysis when hydrogen has been stripped off to create what is called elemental carbon. Elemental carbon contains only carbon atoms in its pure form, but as it exists in combustion particulate matter, it is likely to contain some hydrogen atoms as well (EPA 3 2002.)

Organic carbon in the exhaust gas consists of carbon and hydrogen molecules, but they can contain small amounts of oxygen, nitrogen, sulphur or small quantities of other elements. Organic carbon in the exhaust gas is mainly the result of unburned fuel in the combustion process and small quantities of lubrication oil (EPA 3 2002).

In the combustion process, sulphur compounds are oxidized to form sulphur dioxide (SO_2) and sulphuric acid (H_2SO_4). When the temperature decreases, sulphuric acid and water condense into an aerosol that is non-volatile under ambient conditions. The mass of sulphuric acid PM is more than doubled by the mass of the water associated with the sulphuric acid. The sulphur content of the fuel has also been recognized to be a cause of increased soluble organic fraction emissions in diesel engines. Soluble organic fraction is the organic fraction of the diesel particulates and it includes the heavy hydrocarbons derived from the fuel and lubrication oil (EPA 3 2002).

Organic compounds, such as unburned fuel and lubricating oil consumed by the engine, can be trapped in crevices or cool spots within the cylinder. These trapped compounds are not sufficiently available to conditions that would lead to oxidation or pyrolysis. Depending on their volatility, these compounds contribute to gas phase organic emissions or to PM emissions. When these compounds cool down and reach the air, some of the less volatile organic compounds can absorb into the surfaces of the elemental carbon agglomerate particles. If sufficient elemental carbon sites are not available, these organic compounds may condense onto sulphuric acid nuclei to form a heterogeneously nucleated organic aerosol. Diesel particles are typically composed of elemental carbon, organic carbon and small amounts of sulphate, nitrate, trace elements, water and unidentified components, Figure 5 (EPA 3 2002).

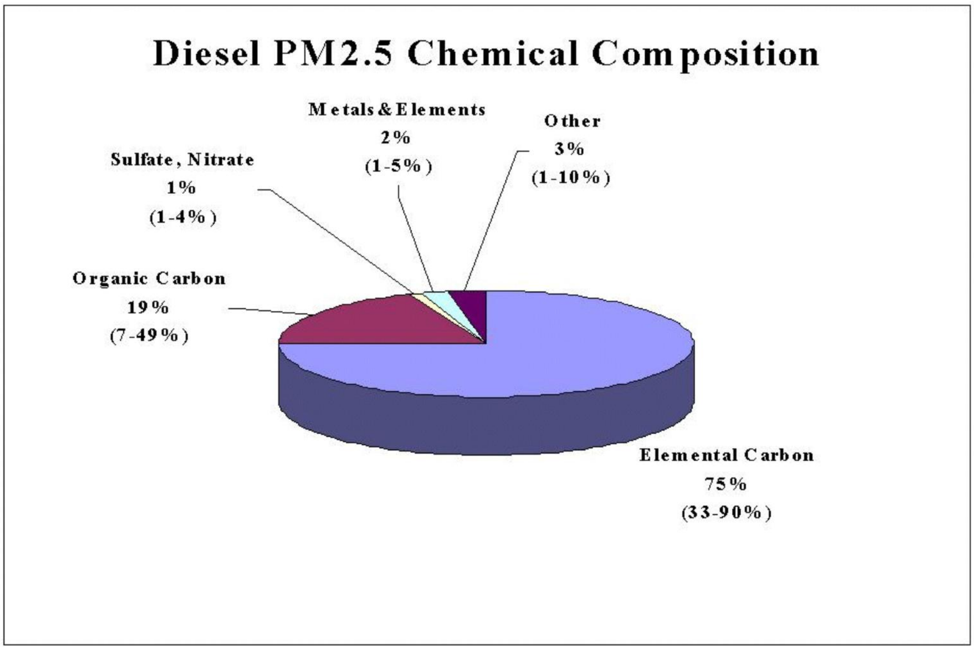

Figure 5. Typical chemical composition of diesel particulate matter (PM2.5) from post-1990 heavy duty diesel vehicle exhaust (EPA 3 2002).

2.4.4 Metals in diesel PM

Metal compounds and other elements condense on the surface of ultra-fine particles making the particles a greater risk to human health. These compounds in the fuel and engine lubrication oil are exhausted as ash. Metal ash compounds originate from lubrication oil, oil additives and mechanical wear of the engine (Sarvi et al. 2011.) Metal oxide particles have high surface reactivity and are more toxic than soot particles. (Mayer et al. 2009.)

Studies have found many different metals in diesel PM, e.g. zinc, iron, calcium, magnesium, phosphorus, nickel, lanthanum, aluminium and silicon. In some studies, the metallic compounds have composed up to 0.5% of the total PM with an emission rate of 1.2 mg/bhp-hr (EPA 3 2002). A study made using a medium speed diesel engine (Sarvi et al. 2001), one lubricant and two fuels, heavy and light fuel oil, discovered that magnesium, calcium and silicon originate mainly from the lubrication oil and have an influence of increasing PM emissions at the size range of 0.2–0.5 µm. Iron is formed from the fuel and lubrication oil in the combustion chamber and from metal oxide impurities resulting from engine wear whereas zinc, vanadium and nickel are found in lubricant oils. They all have effects similar to sulphur in increasing UFP emissions. Zinc is mainly found in the large fraction 0.5 µm while vanadium, nickel and iron are known to catalyze SO_2 oxidation to SO_3 which is a step towards sulphuric formation. Nickel belongs to this same group but it can be found in both fuel and lubrication oil. Aluminium is a result of engine wear that enters into the combustion chamber via the lubrication oil and has been found much less in ultra-fine particles. In general, elements from the lubrication oil are found in the larger 0.5–1.0 µm PM group while fuel composition has an influence on the finer particles, 0.2–0.5 µm. However, all particles depend strongly on what kind of lubrication oil and fuel is used.

A diesel engine emits particles smaller than 1 µm. These extremely small man-made particles massively intrude into the fine pulmonary alveoli which cannot expel particles via the mucus and cilia. These particles have an almost unrestrained penetration into the very thin membranes and into the blood circulation. Deposition of the particles is shown in Figure 6. Particles of approximately 0.01 µm are the most likely to pass through the alveoli and extremely small 0.001 µm particles can even pass into the head. Ultra-fine particles are transported throughout the body and can even cross the brain and placenta barriers. The particle concentration of undiluted exhaust from three utility engines and four cars is shown in Figure 7. Emissions of solid particles are quite uniform. This can be explained in that soot particles are formed as primary particles of almost the same size and the detected larger particles are agglomerates of these primary particles. After these particles reach the atmosphere, dilution prevents further agglomeration. (Mayer et al. 2009.) Dilution of exhaust gases causes problems in the study of particles because some of the particles are formed during dilution and it is impossible to say which particles were the products of this phenomenon.

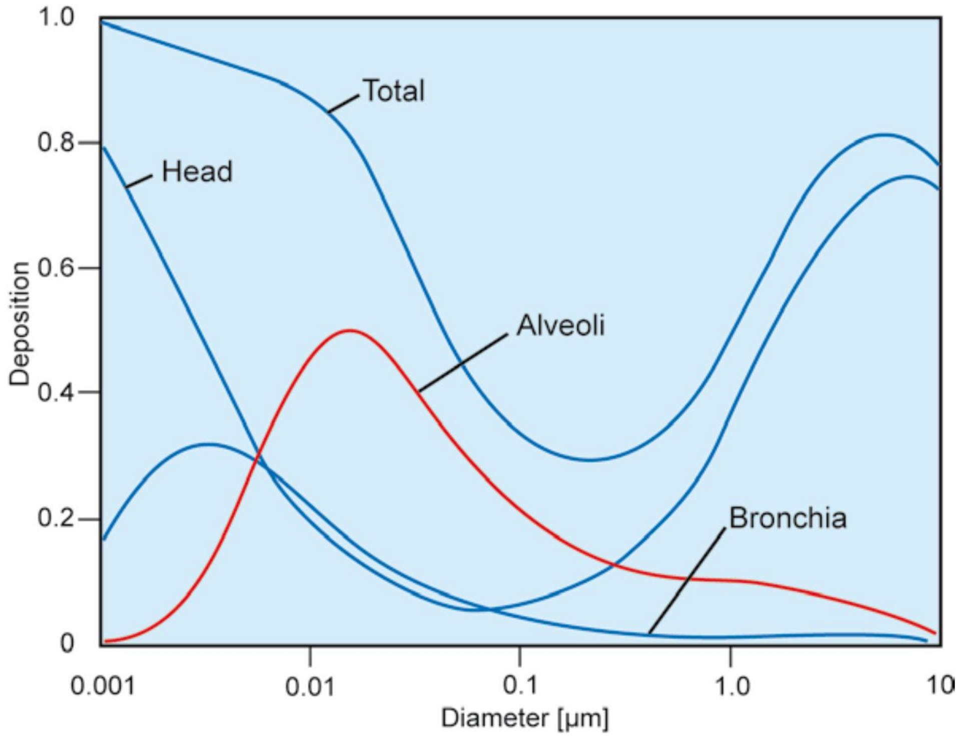

Figure 6. Fine-particles filtration as a function of diameter in the nose, bronchia and alveoli (Mayer et al. 2009).

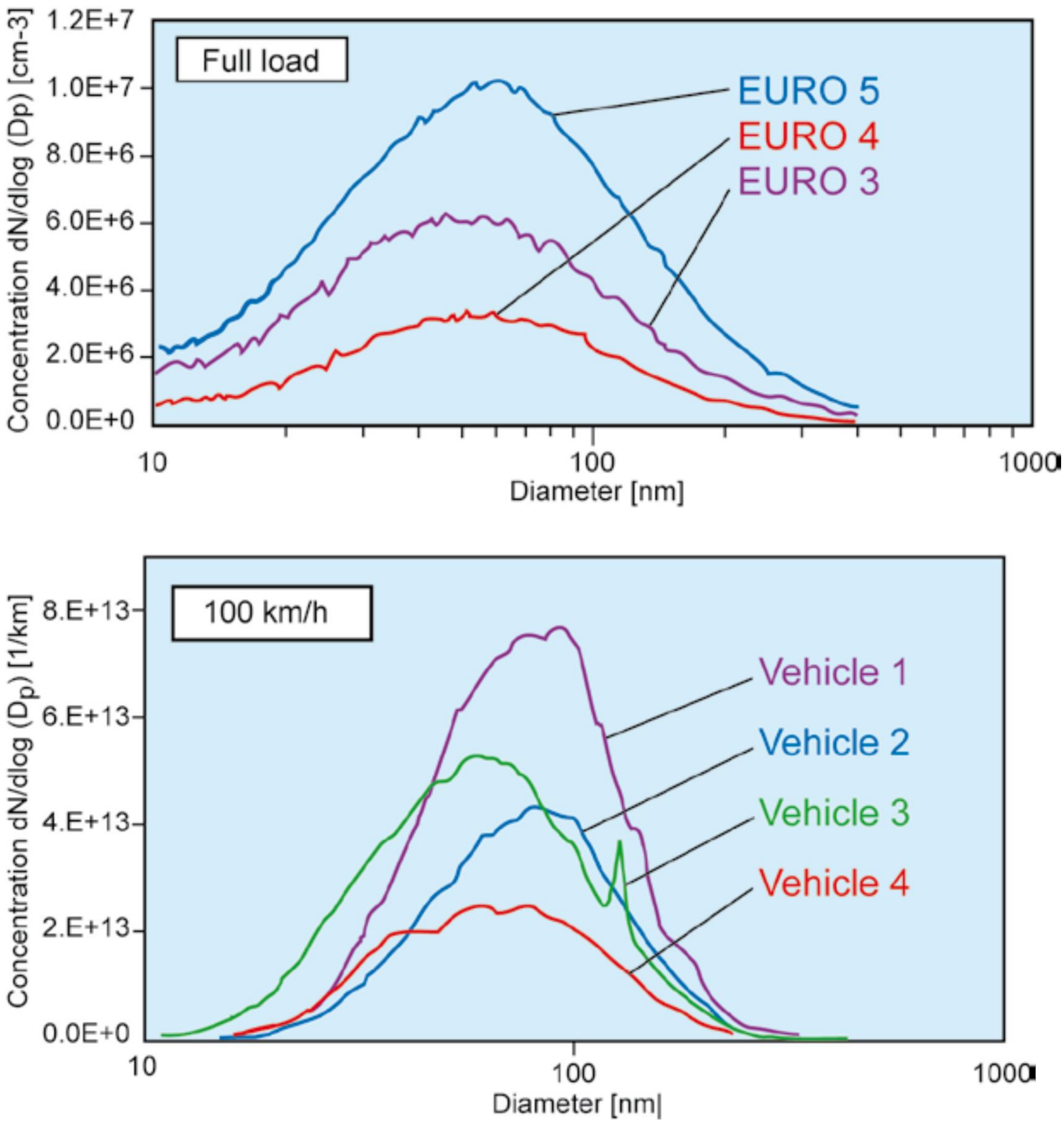

Figure 7. Particle concentration of the undiluted exhaust gas for three utility engines (above) and for four cars (below) (Mayer et al. 2009).

2.4.5 Diesel PM reduction

Diesel particulate filters are used to remove PM from the exhaust gases after the engine. The materials and types of diesel particulate filters vary a great deal. According to their filtering principle, filters can be divided into deep-bed filters and surface filters (Eastwood 2008.) A deep-bed filter, also known as a partial filter, can reduce PM emissions 40-70% while a surface filter can reduce up to 85% of PM_{10} emissions. However, in many engine operation points, the reduction is much lower. A DPF decreases both PM mass and UFPs in the exhaust gas.

The fuel and lubrication oil properties have a direct influence on emissions. Reduction of hydrocarbons reduces PAH emissions and mutagenicity. Sulphur in the fuel contributes directly to particle emissions via the sulphate fraction and the organic fraction has been noticed to be lower with a low-sulphur fuel. On the other hand, higher levels of some PAH and higher mutagenicity have been observed with low-sulphur fuel. Low-sulphur fuel also lowers nanoparticle emissions (Eastwood 2008).

Lubrication oil consumption should be reduced. The problematic places are the valve stem, turbocharger seals, piston ring-pack, cylinder walls and the crankcase ventilation system. The metal content of the lubrication oil tends to increase the toxicity of UFPs.

By optimizing fuel injection, burning is made more complete and less unburned fuel remains. An injector nozzle with smaller holes and a higher injection pressure will allow a better fuel-air mixture and burning that is more complete. Modern fuel timing allows enormous choices for fuel injection e.g. post injection that might help to reduce PM. (Eastwood 2008.)

3 HEALTH EFFECTS

3.1 The smallest particulate matter is the most dangerous

The smaller particulate is more dangerous due to its potential for causing health effects in humans. Only smaller particles, with diameters less than 10 micrometers, are able to enter human airways and, even in very small amounts, cause health effects. Ultra-fine particles, particles less than 0.1 micrometers in diameter, are the most dangerous for human health because they can penetrate deep into the lungs, some even reaching the bloodstream. (Pekkanen 2004.) Many scientific studies have linked particle matter exposure to a number of health problems, such aggravated asthma and irregular heartbeat. (EPA 2012.) However, linking particulate matters from diesel engines to possible health effects is very difficult. First of all, it is hard to recognize where a certain particle has come from, whether from a diesel engine, the soil or households. Secondly, people breathe a thousand times more particles when smoking cigarettes than when standing on the street during rush hour. Moreover, the time one has been exposed to particulate matters is difficult to determine and long-term symptoms over the course of a human life are hard to define. One thing is certain: particles from diesel engines do cause health problems together with all the other particles from other sources. Particles with diameter of 20-40 nm are problematic for humans, Figure 6. These particles can easily become stuck to the alveoli.

3.2 What makes particulate matter dangerous?

Particulate matter in the lungs can cause oxidizing stress and inflammation which decreases the condition of a patient with bronchial disease and increases coagulation of the blood and the possibility of coronary thrombosis. Particulates can also effect autonomous radiation of the heart. Animal tests have found that PM increases inflammation of the lungs and worsens atherosclerosis. The characteristics of the particulate matter play an important role in its effects on health. However, scientist have so far been unable to determine the key facts regarding the causes of PM health effects. Transition elements in PM have been linked to inflammation reactions and these elements explain the responses caused by PM. UFPs are more active than other PM with the same mass. PM from diesel engines increases the responses of the system to allergens and probably causes cancer. However, it is still unclear what makes particulate matter dangerous: PM chemical composition, quantity, area or combination of these. (Pekkanen 2004.)

Particle size is important, but so are the particle's morphology and solubility. Particles dissolving rapidly in aqueous ambiance are diluted in the body while insoluble particles retain their toxicity and thus the intensity of their chronic impact. When more toxic substances are deposited on the surface of PM, the morphology becomes more relevant. The deposited substances are mainly PAH which is highly carcinogenic (Mayer et al. 2009.)

3.3 How do particles enter our body?

As was already mentioned, the effects of particulate matter depend on where they are deposited in the human airway. Larger particles usually deposit onto the cilium at the bronchus or somewhere in the nose and mouth region, Figure 8. This can cause tickling and irritation with coughing, but, at least for short periods, is usually not dangerous. Smaller and especially ultra-fine particles can travel all the way to the lungs and the alveoli without depositing in the bronchus. The membrane at the bottom of the alveoli is exceptionally thin so that oxygen can effectively enter into the bloodstream. UFPs and fat-soluble compounds on the surface of bigger PM are so small that they may be able to pass through this thin membrane. (Laurikko 2008.) From the alveoli they can travel anywhere within the bloodstream and their effects in the body are hard to recognize. The body can also get rid of larger particles through exhalation, usually within a matter of hours. The smaller particles in the lungs may remain inside the body for months or years. Typically, they are carried to lymph nodes or are eaten by macrophages. It may even be that some particles in the bloodstream will never exit the body (Hiukkastieto 2012).

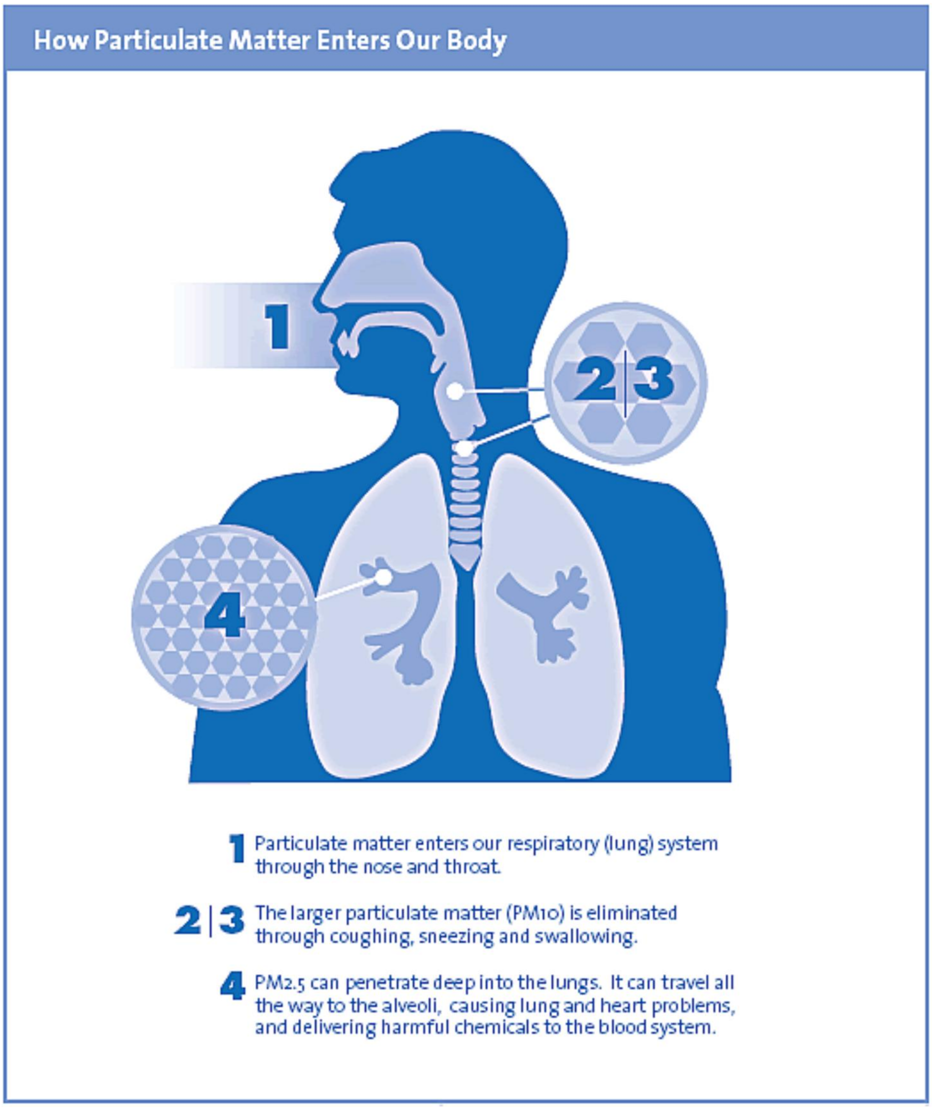

Figure 8. An illustration of the particles entering the body (British Columbia Air Quality 2012).

3.4 Common health effects

The most common health effects are respiratory problems, along with heart- and cardiovascular diseases. Irritation of the airways, coughing and difficulty breathing are common symptoms and can be detected on a dusty street where lots of vehicles are going past. Irritation of the eyes, nose and mouth can also be detected. Coronary heart disease and problems in brain blood circulation are also associated at some level (Hiukkastieto 2012). Persons with heart or lung diseases, children and older adults are the most likely to be affected by particulate matters and even healthy adults may experience temporary symptoms from exposure to elevated levels of particulate matter in the air (EPA 2012). The most serious and unfortunate effect is premature death. Studies have shown that PM content in the air is connected to increased illness and premature death. Especially for persons with asthma and respiratory diseases, increased PM content in the air deteriorates the working order of the lungs and increases hospital admissions. Mortality is higher on days when PM content in the air is abundant. (THL 2012.)

Effects depend on the size, shape and chemical activity of the particles, as well as on personal tolerance. As was already mentioned, the smallest particles are the greatest concern at the moment. They can reach into the alveoli and into the blood. This is due to their aerodynamic differences, as the smaller particles follow the inhale flow and the bigger particles get stuck before the lungs. Asthmatic persons and persons with chronic obstructive pulmonary disease (COPD), as well as patients with cardiovascular diseases and small children are the most susceptible to fine particles (Salonen and Pennanen 2006).

Some studies have been made of direct exposure to particles or diesel exhaust gases. Most of the data is from routine register data or monitored from a specific group, such as COPD patients. In this manner, it can be calculated that urban air is more polluted than that of the countryside and that certain professions, such as asphalt or metal workers, can be more exposed to the risks of particles. One study (Peretz et al, 2008) used volunteers to research whether direct exposure to diesel exhaust for a short time had an effect on heart rate. Young adult volunteers were exposed to filtered air or two different levels of diluted air. The levels were 100 or 200 µg/m3 of fine particulate matter. Their heart rate variability and levels were measured once before exposure and four times afterwards. The conclusion was that no clear and consistent effect on heart rate variability was found. Some small changes could be observed but these were too small and random for any conclusions to be made. This was a very short-term test, but it still indicates that the exposure needs more time or PM content to have an effect.

Moreover, particles can cause health problems all over the body, not only in the lungs. For example, ultra-fine particles are so small that they can migrate even to the brain. Once in the brain, the toxic substances in PM may have an influence on Parkinson's disease (Laurikko 2008).

Short-term exposure, hours or days, can aggravate lung disease and cause asthma attacks and acute bronchitis. It may increase susceptibility to respiratory infections as well. Short-term exposures have been linked to heart attacks and arrhythmias. Short-term exposure usually does not cause health problems in healthy children and adults, although temporary minor symptoms may be experienced. Long-term exposure requires many years, for instance, living many years in an area where PM levels are high. Long-term exposure has been associated with reduced lung function and the development of chronic bronchitis and premature death. (EPA 2, 2003.)

3.5 PM and the cardiovascular system

The association between particulate matter and heart disease was found in the mid-nineties when attention was given to the increased number of hospital admissions on days when PM concentration of the air was high. Nowadays, it has been widely admitted that PM content of the air has an influence on human health. When evaluating the effects of air pollution on health, possible previous diseases must to be taken into account and special attention must be given to patients with cardiovascular diseases. (Peters 2005.)

Studies have confirmed that an increase of 10 $\mu g/m^3$ in PM_{10} results in an increased risk of hospitalization for myocardial infarction (MI). In a high-risk population, even temporary exposure to high concentrations of $PM_{2.5}$ increases the risk of MI after just a few hours. The development of atherosclerosis has also been linked to exposure to air pollutants in both animals and humans. Furthermore, a link between exposure to PM and heart rate variability (HRV) has been found in additional studies.

3.6 Diesel PM

3.6.1 Cardiovascular system

In a study (Mills et al. 2007), 20 men with stable coronary artery disease pedalled an exercise bike for one hour in a laboratory where the air was either clean or contaminated with exhaust gas. The amount of PM in the exhaust gas was similar to that of a heavily used traffic lane, 300 $\mu g/m^3$. All the men had had a heart attack at least a half year earlier and they had all been cared for normally. The men had been symptomless for at least 24 hours before the study. Heart and lung function, irritation of the airways and changes in blood clotting were measured. The engine used in this study was a 4.5 litre industrial diesel engine at idling speed. According to the results, the exercise caused an asymptomatic lack of oxygen in the heart muscle, especially when PM was in the air. Moreover, the blood test revealed a decrease in the blood clot dissolution process which may contribute to thrombosis.

Another study (Polichetti, et al 2009) confirms health effects for heart rate variability (HRV). Nine healthy non-smokers were working as highway patrol officers and their HRVs were measured. The study discovered a significant change in HRV, an increase in the number of ectopic beats and an increase in inflammation and coagulation markers. Interestingly, these effects have been observed just a few hours after exposure to mainly traffic-related particles.

3.6.2 Brain activity

Brain activity was investigated in a study (Cruts et al., 2008) where ten healthy men were exposed to diesel exhaust gas with PM concentration of 300 $\mu g/m^3$ for one hour. The men's brain activity was measured using electrical quantitative electroencephalography (QEEG) at 8 different sites on the scalp. The volunteers did not know if the air was clean or not and the specific smell of diesel exhaust was ambient in the fresh air as well which prevents psychological symptoms. Scientist noticed changes in the brain's front lobe after half an hour. This is thought to be caused by nanoparticles of the exhaust gas and it is suspected that these ultra-fine particles can migrate directly from the air into the brain.

In an animal test made in the United States with rats, it was shown that fat-soluble particles can emanate from the nasal cavity epithelium to the brain. Long-term exposure may also have an influence on the ability to learn in children and on Parkinson's disease, because ultra-fine particles are toxic to the neurons in brain. (Laurikko 2008.)

3.6.3 Cancer

In addition to diesel exhaust gas being able to cause cardiovascular diseases, a connection between diesel exhaust and cancer has been found, and diesel exhaust gases are generally classified as carcinogenic to humans. Several carcinogenic compounds have been found in exhaust gas, such as benzene, formaldehyde, 1,3-butadine and ethylene dibromide. Furthermore, many probably-carcinogenic hydrocarbon compounds have been found on the surface of PM. Nevertheless, scientifically it is still unknown what part or parts of the PM cause health problems and why; only these connections to human health have been found. (Laurikko 2008.)

A common way to study the effects of PM on cancer is to divide people into different occupational groups and investigate how different groups react to diesel PM. This method can, however, be unreliable and other factors that may influence the results are impossible to determine. Based on this kind of studies, it can be said that diesel PM increases the risk of different cancers in general. Parent et al., (2006) investigated in Canada how lifetime PM exposure influences the development of cancer. Males with pulmonary cancer and males with other cancers were chosen for this study and their lifetime exposures were very accurately charted as well as all other factors that could disturb the study. They discovered that exposure to diesel particulate increases the risk for cancer even more than smoking cigarettes. Surprisingly, PM from a gasoline engine did not seem to increase risk to cancer at all. It is impossible to reliably determine that diesel PM causes cancer, studies have however, confirmed that diesel PM together with all PM from other sources can increase the risk of cancer.

3.6.4 Ultra Fine Particles

Alföldy et al. (2009) investigated lung deposition of diesel particles. Filter mass and particle number distribution were measured from nine light-duty Euro 1, 3 and 4 vehicles without diesel particulate filters or catalysts, at different speeds and with different fuels. The results were used for a stochastic lung deposition model where deposition fractions and deposition profiles of the inhaled particles were determined. They discovered that particulate mass and number concentration themselves are not sufficient to determine possible health effects. Accurate determination of the volatile mass distribution and the non-volatile accumulation mode surface area distribution is suggested to be a more important factor when health effects are considered. Particles with high surface area cause more inflammatory response in the lungs.

An animal study made in Great Britain (Brown et al., 2001) used ultra-fine polystyrene particles to demonstrate the role of particle surface area to proinflammatory response and to oxidative stress in the lungs. Animal models were used and an *in vitro* study was measured. The results were paralleled with Alföldy et al., 2009. In the animal model, significantly greater neutrophil influx into the rat lung was observed with 64 nm particles compared to 202 nm and 535 nm particles. They suggested that surface area drives inflammation in the short term and UFPs cause greater inflammatory response in lungs because of the higher surface area. In the *in vitro* study, the changes in intracellular calcium concentration were measured and they discovered that only ultra-fine polystyrene particles induced a significant increase in cytosolic calcium ion concentration. These findings also suggest that ultra-fine particles composed of low-toxicity material, such as polystyrene, have proinflammatory activity as a consequence of their large surface area. This supports a role for such particles in the adverse health effects of PM.

3.7 The human body has a mechanism for rejecting particles

The human body has several mechanisms for disposing of accumulated dust and other particles. Humans have always breathed air that contains sand, volcanic ash and burning gases of forest fires, for example. Most of the particles anywhere in the respiratory system are disposed of by coughing, or are detached onto the mucus and disposed of along with it. Water-soluble contents can probably reach the bloodstream through small capillaries in the respiratory tract, but they continue to the kidneys and are disposed of with the urine before causing any harm. The lipid-soluble compounds can reach the phospholipid membrane inside the cells and therefore are disposed of more slowly. The solid particles are the hardest to get rid of. Depending on the size and chemical compounds of the particles, the white cells in the lungs might not be able to fight against them. Once again, the ultrafine particles are practically impossible to fight against, and they can pass into the bloodstream through the epithelial or endothelial cells or gaps between them. Their path within the bloodstream is very unpredictable, and they can attach to blood vessels, or to the heart, liver and bone marrow. The particles can have many effects, such as oxidation and inflammation, DNA dysfunctions and cell deaths. The greatest concern is the increased risk of cancer that may occur from DNA changes. Oxidative stress also inflames the bronchial walls and alveoli, and may have serious effects, such as chronic asthma, COPD and coronary heart disease (Salonen and Pennanen 2007). People with these diseases were already mentioned to be more vulnerable to particles, but, due to exposure, these diseases can occur in healthy persons as well. Other harm, such as elevated blood coagulation and decreased gas exchange in the lungs, can also be detected. A person’s health and resistance to different illnesses can vary greatly, so precise predictions are practically impossible to make. There will always be many more variables present, such as diet and other lifestyle choices. The results are always only statistical and they show probabilities. However, on a large scale the particles seem to increase mortality as is seen from gathered epidemiological studies, shown in Table 1. $PM_{2.5}$ seems to have much more influence than PM_{10}, as could be assumed in the light of earlier findings. The table was taken from the report of Salonen and Pennanen (2006), but the findings are from Pope and Dockery, 2006.

Table 1. Increase in mortality, observed in epidemiological studies among susceptible population groups (Pope and Dockery, 2006).

Particle parameter	Time scale	Increase in mortality
PM_{10} (10 µg/m³)	Daily changes in concentrations	0.2 – 0.8%
PM_{10} (10 µg/m³)	Difference in annual average concentrations	1 – 4%
$PM_{2.5}$ (10 µg/m³)	Daily changes in concentrations	0.6 – 1.2%
$PM_{2.5}$ (10 µg/m³)	Difference in annual average concentrations	6 – 17%

3.8 Risk groups

Physical activity and hard exertion make a person breathe faster and more deeply and, at this point, more particles enter into the lungs. This is why even healthy persons can be affected by PM symptoms. However, the greatest risk is for persons with heart or lung disease, such as coronary artery disease, congestive heart failure and asthma or COPD because particles aggravate these diseases. People with diabetes are at risk as well because diabetes often hides underlying cardiovascular disease. (EPA 2 2003.)

Older adults can have undiagnosed heart or lung disease or diabetes and together with children they are at increased risk. Older adults have been noted to visit hospitals more and some can even die when PM content of the air is high. The lungs of children are still under development and they spend a lot of time outdoors. Moreover, they are more likely to have asthma or acute respiratory disease and PM can aggravate these symptoms. Other factors, such as high blood pressure or elevated cholesterol levels, can increase the risk of heart attacks when PM content is high regardless of the human's age. (EPA 2 2003.)

3.9 How can you avoid PM?

Symptoms and health effects are related to activity and the time spent in air having high concentrations of PM. The longer a person is active outdoors and the more strenuous the activity outdoors, the more possible it is to suffer symptoms. For instance, a hard and long jog outdoors increases the risk of being affected by particles. Something can, however, be done to avoid these harmful effects. If an activity includes prolonged or heavy exertion, the time of the exercise should be decreased or, if possible, substitution of another hobby involving less exertion would be better for health, a walk instead of a jog, for example. The level of particles in the air should be monitored and outdoor activities should be switched to days when particle levels are lower. Particle levels are normally higher near busy roads and these areas should be avoided. (EPA 2 2003.) Another way to influence air quality and PM content of the air is to drive less miles in passenger cars. For instance, in urban areas where air quality is often bad, choosing public transportation instead of a car is a good way to influence PM content. The train, tram and metro are run by electricity in many cities and are more ecological than coaches operated with diesel engines. Last but not least, walking and biking to work and to the local market does not emit any PM.

4 REGULATIONS FOR AIR QUALITY

Due to the findings regarding particles as well as the other harmful toxins in the air, some legislative regulations have been made to protect people. The air quality in Finland is regulated by the EU. Some of the regulations are more like guidelines and targets, but some are strict rules.

The Finnish national guidelines have been developing since the year 1984 when the first guidelines were established. WHO and the Finnish ministry have improved the guidelines over time and, in 1996, the government of Finland incorporated the regulations for outdoor and indoor air in national legislation. The values are shown in Table 2. The table is from the report of Salonen and Pennanen, 2006.

In 2008, the new air quality directive was launched in the EU (2008/50/EY). The directive set the air limit for $PM_{2.5}$ to 25 µg/m^3, first as a target until the year 2010 and then as a strict rule from the year 2015. The next target is to lower the limit to 20 µg/m3 from the year 2020. The directive also tries to lower overall exposure to particles about 10–20% over the years 2010–2020 (Hiukkastieto 2012). It is estimated that a mere reduction in PM_{10} concentrations by only 5 µg/m^3 would prevent between 3300 and 7700 deaths per year in European countries (Polichetti et al. 2009).

Table 2. Finnish national guideline for outdoor air (Salonen and Pennanen 2006).

Pollutant	Time	Guideline value	
Carbon monoxide (CO)	1 hour 8 hours	20 mg/m^3, 8 mg/m^3	maximum maximum
Nitrogen dioxide (NO_2)	1 hour 24 hours	150 µg/m^3, 70 µg/m^3	monthly 99th percentile second-highest monthly value
Sulphur dioxide (SO)	24 hours annual	250 µg/m^3, 80 µg/m^3	monthly 9th percentile second-highest monthly value
Total suspended particles (TSP)	1 hour 24 hours	120 µg/m^3, 50 µg/m^3	annual 9th percentile maximum
Thoracic particles (PM_{10})	24 hours	70 µg/m^3	second-highest monthly value
Malodorous sulphur compounds (TRS)	24 hours	10 µg/m^3	second-highest monthly value, reported as sulphur

The need for strict rules is clear when all the information is put together. Table 3 shows estimations of the health impacts of $PM_{2.5}$ in EU25 countries and Finland. The numbers show that fine particles create enormous numbers of premature deaths, illnesses and days off from work and school. Depending on the calculations, the economic loss is 268 to 781 billion Euros in the EU25 area (Salonen and Pennanen, 2006). Measuring the air quality in cities and developing combustion engines, filters and fuel quality is exceptionally important and cheap compared to these numbers, not to mention the tragedy caused by deaths and diseases.

Table 3. Estimated health impacts of $PM_{2.5}$ in EU and Finland (Salonen and Pennanen 2006).

Estimated impact on health	EU25	Finland
Premature death	347,900	1,270
Years of life lost	3,618,700	13,840
Infant deaths (up to the age of 1)	677	2
Chronic bronchitis (over the age of 27)	163,800	620
Hospital admissions for respiratory and cardiac conditions (ages up to 100)	100,300	383
Number of days children required respiratory medication (ages 5 to 14)	4,218,500	11,310
Number of days adults required respiratory medication (over the age of 20)	27,741,700	104,450
Number of days children exhibited lower respiratory tract symptoms (ages 5 to 14)	192,756,400	778,870
Number of days of reduced activity among the working population (ages 15 to 64)	347,687,000	1,323,390
Economic loss	€268 billion - €781 billion/a	€1 billion - €2.9 billion/a

Exhaust emissions have been regulated for a couple of decades and the amount of particulate matter in exhaust gas has significantly decreased. PM has been regulated by mass, for instance, when the Euro 1 standard for heavy duty diesel engines, such as busses and trucks, came into effect in 1992, the PM limit was 0.612 g/kWh (≥85 kW). Today, the same limit is 0.02 g/kWh and, in 2013, when Euro 6 comes into effect, the limit decreases 50% to 0.01 g/kWh. In addition to the Euro 6, the numbers of PM will be regulated along with the PM mass. PM numbers is an even greater determining factor when measuring PM emissions, and the PM limit for Euro 6 will be 8.0×10^{11} 1/kWh (DieselNet 2012).

5 CONCLUSIONS

Particulate matter is a serious human health concern. Especially the smallest particles are the most dangerous to human health. Small particles are unpredictable and can enter deep into the lungs and even into the bloodstream. The chemical composition and surface area of particles varies a great deal. Particles with condensate organic carbon or metallic compounds on the surface are the most dangerous. These particles also consist of PAH compounds which are a serious concern to health. Many studies have demonstrated a link between particulate matter and health problems. Common health problems, such coughing and difficulty breathing, can often be detected after short-term exposure to particles while long-term symptoms increase admittances to hospital and shorten life. The active surface area of UFPs is suggested to be the most harmful for human health.

Table 4. Common health effects related to PM (Salonen and Pennanen 2006).

Particle size	Short term exposure	Long term exposure
Coarse particles, PM_{10}	Exacerbation of Asthma and COPD Respiratory infections	COPD?
Fine particles, $PM_{2.5}$	Exacerbation of Asthma and COPD Respiratory infections Exacerbation of Coronary heart disease	Shorten life COPD Exacerbation of Atherosclerosis Asthma? Allergy?
Ultra-Fine particles, $PM_{0.1}$	Exacerbation of Asthma and coronary heart disease	Not enough studies

Diesel engines are a significant source of particulate matter together with all transportation means. Diesel engines produce a great deal of ultra-fine particles and many carcinogenic compounds have been found in the exhaust gas. Studies have proved that diesel particles cause irregular heartbeat and can even reach to the brain. However, the normal air that people breathe is always a mix of different particles from different sources. For example, the origin of particles on a busy road can be from internal combustion engines, street dust and transboundary pollution.

Fuel and lubrication oil properties define to a great extent what kinds of particles are formed in a diesel engine. Sulphur in the fuel increases ultra-fine particles while metals in the lubrication oil increase metal oxides. Special attention should be paid to the development of fuels and lubrication oils. In many cases, these play a greater role in the formation of particles than engine technique.

PM studies have developed a great deal in the past years. Direct exposures to certain PM, such as diesel PM, can be investigated with accurate dose exposure. It would be very important to clarify exactly what makes PM dangerous for health. When the most problematic matter in PM is known, it could be regulated and reduced. So far we have to regulate the mass and the number of PM. Limiting PM number along with PM mass is a good direction for decreasing PM content in the air.

6 SUMMARY

This report introduces general information about diesel particles and their health effects. The purpose was to introduce particulate matter pollution and present some recent studies made regarding the health effects of particulate matter. The aim was not to go very deep into the science but instead to keep the text understandable for the average layman.

Particulate matters come from several sources, such as transportation emissions, industrial emissions, forest fires, cigarette smoke, volcanic ash and climate variations. Particles are divided into coarse particles with diameters less than 10 µm, fine particles with diameters smaller than 2.5 µm and ultra-fine particles with diameters less than 0.1 µm.

Particulate matter is a complex mixture of extremely small particles and liquid droplets. These small particles are made up of a number of components that include for example acids, such as nitrates and sulphates, as well as organic chemicals, metals and dust particles from the soil. Several elements, such as Si, Al, Ca, Fe, Ti, Pb, transition metals V, Cr, Ni Cu, Zn, and inorganic ions such as Na^+ and K^+ can be found in particulate matter. All these compounds together with volatile organic compounds are extremely changeable and depend on many factors, such as climate, emission sources and geographical position.

The particulate matter in diesel exhaust gas is a highly complex mixture of organic, inorganic, solid, volatile and partly volatile compounds. Many of these particles do not form until they reach the air. Many carcinogenic compounds have been found in diesel exhaust gas and it is considered to probably be carcinogenic to humans. A diesel engine produces about 100 times more particulate matter per distance than a conventional petrol engine equipped with a three-way catalytic converter. Sulphur in the fuel and metals in the lubrication oil have an influence on particle matter. Special attention should be paid to these compounds in the development of fuels and oils.

Particulate matter can cause several health effects, such as premature death in persons with heart or lung disease, also cancer, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function and increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing.

The largest coarse particles are mainly rock material from the soil, such as silicon and aluminium. Ultra-fine particles compose only a couple percentages of the total mass of all particulates in the air, but their quantity is high and they are the most numerous of all particles. Moreover, the surface area of all ultra-fine particles is very high due to the large numbers of them in the air. Ultra-fine particles are normally in the air for a very short period, however, in urban areas the time of occurrence can be several hours.

It is estimated that, in Finland, approximately 1300 people die prematurely due to particles and the economic loss in the EU due to health effects of particles can be calculated by billions.

Ultra-fine particles are considered as the most harmful to human health. Ultra-fine particles can migrate far away from their source and they can even reach into the blood circulation and the brain. The active surface area of UFPs is high and this is suggested to be the most harmful for human health. Transition metals on the surface of particles together with carcinogenic compounds found from the PM have been shown to cause cancer.

In urban areas, the amounts of particles are usually higher than in rural regions. Regulations for air quality in urban areas have been set to protect people living in the cities, and vehicle emission limits are coming stricter all the time.

Exposure to particles can be decreased by avoiding busy roads where the level of particles is usually higher, having a hobby that involves less exertion and decreasing exercise time. Outdoors activities should be reduced when PM concentration in the air is high.

The greatest risk is to persons with heart or lung disease, such as coronary artery disease, congestive heart failure and asthma or COPD because particles aggravate these diseases. People with diabetes are at risk as well. Older adults have been noted to visit hospitals more and some can even die when PM content of the air is high. The lungs of children are still under development and they spend a lot of time outdoors. They are more likely to have asthma or acute respiratory disease, and PM can aggravate these symptoms. Other factors, such high blood pressure or elevated cholesterol levels, can increase the risk of heart attacks when PM content is high regardless of the age of the human.

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