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Properties and toxicological effects of particles from the interaction between tyres, road pavement and winter traction material

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ABSTRACT

In regions where studded tyres and traction material are used during winter, e.g. the Nordic countries, northern part of USA, Canada, and Japan, mechanically generated particles from traffic is the main reason for high particle concentrations in busy street- and road environments. In many Nordic municipalities the European environmental quality standard for inhalable particles (PM₁₀) is exceeded due to these particles. In this study, particles from the wear of studded and studless friction tyres on two pavements and traction sanding were generated using a road simulator. The particles were characterized using particle sizers, PIXE and electron microscopy. Cell studies were conducted on particles sampled from the tests with studded tyres and compared with street environment, diesel exhaust and subway PM₁₀, respectively. The results show that in the road simulator, where resuspension is minimised, studded tyres produce tens of times more particles than friction tyres. Chemical analysis of the sampled particles shows that the generated wear particles consists almost entirely of minerals from the pavement stone material, but also that S is enriched for the sub-micron particles and that Zn is enriched for friction tyres for all particles sizes. The chemical data can be used for source identification and apportionment in urban aerosol studies. A mode of ultra-fine particles was also present and is hypothesised to originate in the tyres. Further, traction material properties affect PM₁₀ emission. The inflammatory potential of the particles from wear of pavements seems to depend on type of pavement and can be at least as potent as diesel exhaust particles. The results implies that there is a need and a good potential to reduce particle emission from pavement wear and winter time road and street operation by adjusting both studded tyre use as well as pavement and traction material properties.

KEYWORDS: PM10, PARTICLES, TYRES, TRACTION MATERIAL, ROAD SIMULATOR, CELL STUDY, ROAD WEAR, TRAFFIC EMISSION

1. INTRODUCTION

Numerous studies have shown that the concentration of inhalable particles (PM_{10}) in ambient air is associated with mortality and different kinds of respiratory health problems in the population (Katsouyanni et al., 2001, Peters et al., 2001, Brunekreef and Holgate, 2002, Pekkanen et al., 2002, Pope et al., 2002, Hoek et al., 2002, Kappos, et al., 2004). Particle size seems to be important since smaller fractions tend to have stronger relationships to health effects (Schlesinger et al., 2006). However, meta analysis of epidemiological studies differing between the coarser particle mode $PM_{10-2.5}$ and the finer $PM_{2.5}$, shows that there seem be health effects from both fractions (Brunekreef and Forsberg, 2005). The coarser mode seems more related to acute airway symptoms while the finer mode seems more related to cardiovascular disease. However, not only the numbers of PM are of importance for health effects, but also the qualitative properties of the particles determine the ability to induce inflammation (Øvrevik et al., 2004) This includes the size, shape, chemical composition, physical properties, material absorbed or adsorbed to the particles that may depend on several factors of which the season is one as different toxicological properties has been noted between spring and winter PM (Salonen et al., 2004). The mechanisms and properties that make particles more or less toxic are poorly understood though. To find optimal measures against high particle concentrations in public areas, it is important to study source specific particle characteristics as well as to determine what properties of the parent material are important for the release of inhalable wear particles.

Since the early eighties it has become increasingly evident that wear particles from road pavements and tyres strongly contribute to episodes with very high concentrations of inhalable particles in outdoor air (Amemyia, 1984, Fukuzaki, 1986, Hosiokangas, 2004, Swietlicki et al., 2004). These episodes normally occur during dry periods in winter and spring. During the winter season in Sweden, about 70% of light duty vehicles use studded

tyres, ranging from about 40% in the southernmost parts to over 90% in the north. Even though pavements have been improved since the 1980s and studs nowadays are mainly made of lightweight alloys instead of steel, about 100 000 tons of pavement is worn each winter season in Sweden (Jacobson, 1999). Although most of the particle mass of the wear particles is from particles that are far larger than 10 μm , a minor airborne inhalable fraction is generated and contributes to the air pollution in the road environment and might also contribute to long range transport. Also, winter sanding in urban areas contributes to dust formation, both through vehicles grinding the sand, but also through increased pavement wear by sand. In Finland a similar road simulator as in the present study, has been used to study wear particle production from tyres, pavements and winter traction material (Kupiainen et al., 2003, Räisänen et al., 2003, Kupiainen et al., 2005, Räisänen et al., 2005 and Tervahattu et al., 2006). Their most important results show that studded tyres produce more PM_{10} than non-studded tyres, that stone material properties for both pavement and traction sand are important for particle production and that traction sand act as a sand paper on the pavement regardless of which tyre type is used.

During dry periods in winter and early spring, abraded pavement and sand are ejected into the air by vehicle turbulence and cause particle concentrations to vastly exceed the environmental quality standard set for inhalable particles (Johansson et al., 2007). This standard is valid for PM_{10} and stipulates that the daily mean concentration must not exceed 50 $\mu\text{g m}^{-3}$ more than 35 days a year and the yearly mean must not exceed 40 $\mu\text{g m}^{-3}$ (EU, 1999).

The road dust problem is an issue not only in countries using studded tyres and traction sanding. Even though the problem is not as obvious, pavements as well as tyres are worn by traffic globally and produce potentially hazardous inhalable particles. In many countries, including EU-countries and the USA, non-exhaust particles are considered an important

research field due to the lack of knowledge and the complex formation and emission processes. Also, as particle contribution from vehicle exhaust is abated, the relative contribution from non-exhaust particles is increasing (Luhana et al., 2004).

The aim of this study was to characterize wear particles and to study their possible health effects. Using a road simulator in a laboratory hall it was possible to exclusively measure and characterize the generated airborne wear particles from two common Swedish pavements worn with studded tyres and to study the inflammatory potential of the particles in human macrophages and epithelial cells. Also wear particles produced using Nordic friction tyres as well as two types of traction sand were studied. This paper presents the main results from the particle characterization and the cell studies.

2. METHODS

2.1. Particle generation and characterization

2.1.1. Generation of wear particles

A road simulator (Figure 1) (Swedish National Road and Transport Research Institute, Linköping) was used to generate wear particles from studded and friction tyres running on two different pavements. Particle sampling in the simulator hall ($10 \times 8 \times 5 \text{ m}^3$) makes it possible to sample wear particles with very low contamination from surrounding sources and no influence from tail-pipe emissions. Apart from the lack of other particle sources than pavement and tyres, the simulator also has the advantage of providing the possibility to minimize the contribution from resuspension of dust not directly related to the pavement and tyres studied, which can be an important contribution and problem during field campaigns. Thorough cleaning of the entire simulator hall before each test, minimizes resuspension

from old dust originating in previous tests. The intense movement of the tyres over the pavement does not allow for deposition on the track, also contributing to minimized resuspension of newly produced dust.

Figure 1. The VTI road simulator.

The simulator consists of four wheels running a circular track with a diameter of 5.3 m. A DC motor is driving each wheel and the speed can be varied up to 70 km h^{-1} . At 50 km h^{-1} a radial movement of the wheels is started to force the tyres to wear evenly on the pavement. The simulator track can be equipped with any type of pavement and any type of tyre can be mounted on the axles. No ventilation of the simulator hall was used, but pressure gradients might have caused minor self-ventilation.

It should be kept in mind though, that the laboratory conditions at the simulator are not directly comparable to reality in terms of absolute concentrations. The tight turn, 100% studded tyres, dry conditions, constant speed without accelerations and decelerations and

small air volume all adds to the non-realistic conditions. The tight turn of the wheels cause pavements to wear approximately 3-4 times faster than on roads, even though simulator and road wear has a very good linear correlation (Jacobson, 1994). Whether or not the characteristics of the particles are affected of the tight turn is not known.

Before each test the simulator hall, including the track and the machine is cleaned using a high-pressure water cleaner. The hall is allowed to dry thoroughly before tests are performed.

For this investigation two different common road surface materials was used; dense asphalt concrete (ABT) with granite (Skärlunda, Sweden) as the major stone material and stone mastic asphalt (ABS) with quartzite (Kärr, Sweden) as the major stone material. The granite pavement type (ABT) is used on roads with low traffic intensity and has medium durability, while the quartzite pavement (ABS) is used on roads with high traffic intensity and is considered to have high durability. Two types of winter tyres where used. Light duty vehicle studded tyres with light weight studs (Gislaved Nordfrost III) were used with the two different surface materials and light duty vehicle Nordic friction tyres (Nokian Hakkapellitta Q) were used on the ABS pavement.

The traction materials tested were washed crushed stone (Skärlunda granite, 2-4 mm, Sweden) and unwashed natural sand (Kolbyttemon, 0-8 mm, Sweden). The materials are two commonly used traction materials and size fractions in Sweden. The traction materials were weighed and spread evenly on the road simulator track. The amounts used were 250 and 500 g m⁻², respectively, the lower representing normal traction sand dose.

In total, seven combinations of tyres, pavements and winter traction materials were used (Table 1). The tests were performed at 30, 50 and 70 km h⁻¹. When using traction materials

the speed was reduced to 15 and 30 km h⁻¹, since the material rapidly was swept off the track due to the wheels' movement. After a pavement change the road simulator was run 50 000 rounds or 200 000 wheel passes at 50 km h⁻¹ to resemble a normally worn pavement.

Table 1. Combinations of pavements, tyres and traction materials used.

Combination code*	Pavement type	Stone material	Tyre	Traction material	Speed(s) (km h⁻¹)
ABT/G/S	ABT (dense asphalt concrete)	Granite (G)	Studded (S)	No	70
ABS/Q/S	ABS (stone mastic asphalt)	Quartzite (Q)	“	No	30, 50, 70
ABS/Q/F	“	“	Friction (F)	No	“
ABS/Q/S/CS	“	“	Studded	Crushed stone (CS) 2-4 mm (washed)	15, 30
ABS/Q/F/CS	“	“	Friction	Crushed stone (CS) 2-4 mm (washed)	“
ABS/Q/S/NS	“	“	Studded	Natural sand (NS) 0-8 mm (unwashed)	“
ABS/Q/F/NS	“	“	Friction	Natural sand (NS) 0-8 mm (unwashed)	“

* Combination code describes pavement type/stone material/tyre type/traction material (when present).

2.1.2. Particle sampling for analysis

Sampling of particles for Scanning Electron Microscopy (SEM) analysis as well as for the cell studies was conducted using a high volume sampler (Sierra-Andersen/GMW Model 12000) equipped with glass fiber filters (Munktell MG 160). The flow through the PM₁₀ inlet was according to CEN standard EN 12341; 1998 (1133 l min⁻¹). The sampler was placed in the same position, 2 meters from the edge of the pavement, during all experiments. The filter samples were collected during several hours of running the road simulator at 70 km h⁻¹. Before and after sampling, the filters were handled only with tweezers. After sampling, they were folded twice and put in an aluminium foil envelope and stored at -70

°C until analysis. Fine and coarse fraction samples for subsequent PIXE analysis were collected on 47 mm diameter Nuclepore polycarbonate membrane filters mounted in Stacked Filter Units (SFU; Norwegian Institute for Air Research, NILU, Kjeller, Norway). By using two consecutive filters with different pore sizes (8 µm for the first coarse fraction filter and 0.4 µm for the second fine fraction filter), the SFU configuration can separate aerosol particles according to size (Cahill et al., 1979). The PM₁₀ inlet in front of the SFU was of the Gent type (Hopke et al., 1997). An SDI multi-jet low-pressure cascade impactor (Maenhaut et al., 1996) was used to collect highly size-resolved aerosol particle samples in 12 size fractions (aerodynamic cut-off diameter between 0.045 and 8.39 µm). Nuclepore polycarbonate membrane filters were used as collection substrates and they were greased with vacuum grease solved in toluene. For each cascade impactor sampling two blanks (also greased) were taken, analysed and proper correction was performed. The wear particles were collected using a PM₁₀-inlet (Rupprecht & Patashnick Co., Inc., USA) with a subsequent own design aerosol splinter with 10 lpm to the SDI and 1 lpm to an Aerodynamic Particle Sizer (APS, model 3321, TSI Inc., USA). The sampling efficiency in the splinter and the transport losses for the SDI and the APS measurements were calculated. The entire difference was less than 10% for all aerodynamic particle sizes less than 10 µm.

Scanning Electron Microscopy (SEM) was made using a LEO Gemini 1550 with Energy Dispersive Spectroscopy (EDS) (Link ISIS). A SEM stub was covered with silver glue and gently pressed towards the particle covered high volume sampler filter surface. The stub was gold coated to prevent charging. Since particles were abundant, single particle EDS analysis was not useful. Instead, area analysis at a magnification of 2000 times was used. Several analyses in different areas of the stub surface were made on each sample to ensure that the presented EDS spectrum was representative.

The SFU and SDI samples were analyzed for their elemental content by means of PIXE (Particle Induced X-ray Emission) at the ion beam analytical facility of the Division of Nuclear Physics at Lund University (Shariff et al., 2002). The elemental source profiles of the various combinations of tyre and pavement for the SFU samples, enrichment factors were calculated versus a commonly used soil reference composition describing the proportions of the elements occurring in igneous rocks of the continents (Kaye and Laby, 1959). Titanium (Ti) was used as tracer element for soil. These enrichment factors were calculated in the traditional way as:

$$EF(Ti) = \frac{[X_{PIXE}] / [Ti_{PIXE}]}{[X_{REF}] / [Ti_{REF}]} \quad (1)$$

Here, square brackets denote elemental concentrations of elements X and Ti in the PIXE sample and the soil reference respectively. The calculated enrichment factors can be used to assist source receptor modelling in urban environments.

2.1.3. Particle size distributions

The particle size distribution measurements at the road simulator were performed with an Aerodynamic Particle Sizer (APS, model 3321, TSI Inc., USA) and a Scanning Mobility Particle Sizer (SMPS, TSI Inc., USA). The APS was equipped with an omni directional PM₁₀ inlet (Ruprecht & Patachnik) and the sampling time was set to 60 s. The APS was placed about 2 m from the edge of the pavement and the height of the inlet was about 2 m from the floor (1 m above the pavement). The SMPS system consisted of a Differential Mobility Analyzer (DMA, model 3071, TSI Inc., USA) and a Condensation Particle Counter (CPC, model 3010, TSI Inc., USA). The aerosol and the sheath air flow rates were set to 0.3

1 min⁻¹ and 3 l min⁻¹ respectively, giving a detectable size range of 15–700 nm with up and down scan timings of 90 s and 30 s respectively. The SMPS system was placed outside the closed room housing the road simulator and the aerosol was sampled through a 2.0 m ¼” copper tube. During the testing sessions, the background aerosol was measured before starting the road simulator. For calculated mass concentrations a density of 2.6 and 1.0 was used for the APS and SMPS measurements respectively.

To exclude effects of contamination from the electrical motors powering the road simulator, measurements of size distributions close to a ventilation opening were made. This ventilation air proved to be even cleaner than the background air in the simulator hall. Further, reference measurements have been conducted on summer tyres and the measured particle concentrations are then always lower than the background, hence the particle emission from the road simulator itself is very low.

The particle mass concentrations were also measured using an optical instrument DustTrak (TSI Inc, USA) with a time resolution of 1 s. The DustTrak was placed close to the APS instrument at the same approximate height above the floor.

2.1.4. Mineral content

Samples of Skärlunda granite and Kärre quartzite were finely grinded and analyzed using an X-ray diffractometer (XRD) with CuK_α X-ray tube. The mineral content was determined with Rietveld-analysis and was calculated for the crystalline phases and normalized to 100% (Table 2).

Table 2. Mineral content in and Nordic ball mill value for Skärlunda granite (used in the ABT pavement) and Kärre quartzite (used in the ABS pavement).

Mineral	Formula	Skärlunda granite (% of weight)	Kärre quartzite (% of weight)
Amorphous part		Yes	Yes
Silica dioxide	SiO ₂	30.3 ± 0.9	73.9 ± 2.1
Microcline	KAlSi ₃ O ₈	35.2 ± 1.2	17.0 ± 1.8
Albite	NaAlSi ₃ O ₈	34.5 ± 1.2	9.1 ± 1.2
Nordic ball mill value		appr. 7	appr. 6

2.1.5. Generation and sampling of reference particles

As references for the cell study particles from street level and subway particles were used. The street particles represent real world springtime PM₁₀ influenced by pavement but also mixed with exhaust particles, long range transported particles and other local sources. Subway particles are wear particles, as the particles produced in this study, but with a totally different composition dominated by iron. The often very high particle concentrations in subway stations are subject to health related research interests. PM₁₀ - samples were collected by The City of Stockholm Environment and Health Administration, during early spring at a highly traffic intensive street (Hornsgatan) and in a subway station (Mariatorget) in Stockholm, Sweden, respectively, using a high volume sampler (Sierra-Andersen/GMW Model 12000) equipped with glass fibre filters (Munktell MG 160). The flow through the PM₁₀ inlet was according to CEN standard EN 12341; 1998 (1133 l min⁻¹). The sampler was placed in the same position during remainder of the sampling period.

Diesel particles were generated (AVL MTC AB, Stockholm, Sweden) according to a standardized test protocol (70/220/EEC) and during the particle sampling the engine was run according to the European driving cycle (NEDC). This includes cold start, city and highway driving. All particle sampling was done on diluted exhaust in order to apply to the maximal temperature 52°C allowed by the regulation. A side flow was lead through a Teflon filter on which the particles were collected.

2.2. Cell exposure experiments

2.2.1. Recovery and preparation of particles prior to cell exposure experiments

Due to high levels of material the wear particles, generated from the tyre–pavement interaction, were shaken loose from the filters, while the particles from the street and from the subway station needed to be recovered from the filters by incubation in a 14 ml tube (Falcon, NJ, USA) with autoclaved MilliQ water in a ultra sonic bath (Metason 120, Struers, Copenhagen, Denmark) for 20 minutes. The filters were removed and the tubes were then stored in –70 °C before being freeze dried (Heto, Allerød, Denmark) in order to remove the liquid. The DEP filters were either treated as described above (water fraction) or incubated with methanol, which were evaporated under nitrogen gas (methanol fraction). A piece of the filter that were visually particle free were cut out, MilliQ water treated in the same way as described above and the material recovered was used in control experiments as blanks.

2.2.2. Cell exposure

Human monocytes were isolated from heparinized human whole blood and allowed to differentiate in to macrophages as previously described (Lindbom et al., 2006). Briefly, on

top of 20 ml Polymorphrep (Axis Shield, Oslo, Norway) 5 ml Lymphoprep was added to form a gradient, to which 25 ml of whole blood was added. The samples were centrifuged at room temperature in a swing-out rotor at 480g for 40 minutes without brakes. This resulted in separation of the leukocytes in two bands, with the upper band just below the plasma consisting of mononuclear leukocytes. The monocytes were transferred to a new 50 ml tube (Costar, Cambridge, MA), which was filled with cold Krebs-Ringer glucose (KRG) without Ca^{2+} and centrifuged 480g for 10 minutes at 4°C. The supernatant was discarded and the pellet suspended in 5 ml KRG without Ca^{2+} and centrifuged 250g for 7 minutes at 4°C in order to remove the platelets. This was repeated at least three times or until the supernatant was clear. The pellet was then suspended in 2 ml Macrophage-SFM medium (Invitrogen, Carlsbad, CA) supplemented with antibiotics (100 U/ml penicillin and 100 µg/ml streptomycin, Invitrogen). The cells were counted in a Bürker chamber and 1 million cells/well were sown out in 24-well plates and allowed to adhere for one hour in a cell incubator (Galaxy, Biotech, Northants, England) at 37°C, 5% CO_2 (these parameters applies to all the cell types used). Thereafter, the cells were washed with 37°C KRG with Ca^{2+} until no loose cells remained. After ten days of incubation, the monocytes had morphologically derived into macrophages. The cells were counted with a grid ocular (Zeiss) at 20x magnification. Using this magnification the grid represents a square area of 0.0025 cm^2 (one well of 1.9 cm^2 includes 760 such squares), which makes it possible to calculate the number of macrophages remaining after the incubation (Lindbom et al, 2006).

The particles were resuspended in the cell growth medium for respective cell type and sonicated. The cells were then incubated with a final concentration of 10, 50, 100, 250 and 500 µg ml^{-1} for 18 h in a total volume of 1 ml per well. In the experiments where polymyxin B or the iron chelator deferoxamine mesylate (DFX) was used, 10 µg ml^{-1} polymyxin B or 100 µM DFX was mixed with the PM suspension before addition to the cells. The

concentrations used for LPS exposure were $1 \mu\text{g ml}^{-1}$. After the exposure, the medium were transferred to Eppendorf tubes and stored at -70°C until analysis.

2.2.3. Analysis of cytokines

The cytokines IL-6, IL-8 and TNF- α were measured with QuantiGlo kit (R&D-systems, Minneapolis, MN) using a Lumistar (BMG Labtechnology, Offenburg, Germany) luminometer, according to the manufacturers instruction. According to the manufacturer, the detection limit for IL-6 was $<0.2 \text{ pg ml}^{-1}$ with linearity of $0.3\text{--}3000 \text{ pg ml}^{-1}$, for IL-8 the detection limit was $<0.8 \text{ pg ml}^{-1}$ with linearity of $1.6\text{--}5000 \text{ pg ml}^{-1}$ and for TNF- α the detection limit was 0.45 pg ml^{-1} with linearity of $2.2\text{--}7000 \text{ pg ml}^{-1}$.

2.2.4 Analysis of cell viability

The viability of the cells was analyzed using the Trypan blue method. The cells were incubated for 15 minutes in the cell incubator with a 1:1 dilution of 0.1% trypan blue and phosphate buffered saline (PBS I), where after the cells were washed three times with PBS I in order to remove excess trypan blue before evaluation of the viability.

2.2.5. Analysis of endotoxin content

The different PM types were analyzed for LPS content using Endotoxate (Sigma) according to instructions from the manufacturer. The lowest detectable LPS amount with this test is 0.006 ng ml^{-1} .

2.2.6. Statistics

All values are given as mean $\pm$ standard error of the mean (SEM). Repeated measurements ANOVA was used when comparing different exposure levels of one particle type and three ways ANOVA with Tukeys post hoc test was used when comparing different types of particles. P-values < 0.05 were considered as significant. Repeated measurements ANOVA allows it to be accounted for that the experiments were done at different times and that multiple measurements were done each time. Three ways ANOVA was chosen to make it possible to take into account that the monocyte derived macrophages were isolated from blood donated from several different donors at different time points.

3. RESULTS

3.1. Effects of pavement, tyre and speed on particle concentration

The particle concentration in the laboratory hall stabilizes after about 20 minutes due to the equilibrium between generation and deposition of particles (Figure 2). The particle concentration produced by wearing the granite asphalt (ABT) with studded tyres was stabilized at a level about 3-4 times higher than for quartzite (ABS). When friction tyres were used on the ABS pavement, the particle concentration was between 60 and 100 times lower for 30, 50 and 70 km h⁻¹ than for studded tyres as calculated from APS data with background concentration subtracted. The particle concentration when friction tyres are used is increased by about 2 to 6 times (higher for greater speed) compared to the background concentration in the simulator hall.

Figure 2. The PM_{10} concentration of wear particles in the road simulator hall versus time as measured by the DustTrak aerosol instrument. The figure shows the concentration increase during acceleration to 70 km h^{-1} for three combinations of pavements and tyres. The concentration reaches a constant level after approximately 20 minutes.

The effect of speed was only studied on the ABS pavement. Speed increases particle concentration for both studded and friction tyres, but the magnitude of the increase is much higher for studded tyres (Table 3).

When using traction material, the particle concentration rapidly increases to an initial peak after which the concentration decreases. Increasing the speed after some time caused a new peak followed by a more rapid decrease (Figure 3). In combinations with traction material, unwashed natural sand overrun with studded tyres gave the highest particle concentrations in

the study, followed by the same material used with friction tyres, indicating a high initial content of finer particle fractions easily suspended by both tyre types. The combinations with washed crushed stone generated lower concentrations, but also here the studded tyres resulted in higher particle concentrations.

Table 3. Mean number and mass concentrations with standard deviation for ABT/G/S, ABS/Q/S and ABS/Q/F (see Table 1). The wear particles were sampled using a PM₁₀-inlet and measured using a SMPS and an APS.

ABT/G/S

	SMPS 0.016 – 0.72 μm		APS 0.52-10.0 μm	
	Concentration			
	Number [# cm ⁻³]	Mass* [μg m ⁻³]	Number [# /cm ³]	Mass* [mg/m ³]
Background	1 680 ±505	5.4 ±0.6	7.1 ±2.6	0.01 ±0.01
70 km h ⁻¹	26 500 ±460	39.1 ±1.2	697 ±11	1.24 ±0.02

ABS/Q/S

	SMPS 0.016 – 0.72 μm		APS 0.52-10.0 μm	
	Concentration			
	Number [# cm ⁻³]	Mass* [μg m ⁻³]	Number [# /cm ³]	Mass* [mg/m ³]
Background	1 600 ± 100	6.2 ± 1	5.0 ± 2.5	0.003 ± 0.002
30 km h ⁻¹	1 400 ± 60	3.7 ± 0.3	41 ± 1	0.18 ± 0.01
50 km h ⁻¹	8 200 ± 200	5.7 ± 0.4	183 ± 5	0.57 ± 0.01
70 km h ⁻¹	18 100 ± 200	8.7 ± 0.9	361 ± 7	0.76 ± 0.02

ABS/Q/F

	SMPS 0.016 – 0.72 μm		APS 0.52-10.0 μm	
	Concentration			
	Number [# cm ⁻³]	Mass* [μg m ⁻³]	Number [# cm ⁻³]	Mass* [μg/m ³]
Background	1 250 ± 30	2.0 ± 0.5	9.6 ± 1.0	2.7 ± 0.5
30 km h ⁻¹	1 660 ± 60	1.5 ± 0.13	7.9 ± 0.2	5.6 ± 0.7
50 km h ⁻¹	7 230 ± 100	2.1 ± 0.3	9.5 ± 0.2	8.5 ± 0.8
70 km h ⁻¹	25 200 ± 300	4.1 ± 0.7	27 ± 1.0	16.0 ± 3.7

* For calculated mass concentrations a density of 1.0 and 2.8 was used for the SMPS and APS measurements, respectively.

Figure 3. The PM_{10} concentration of wear particles in the road simulator hall versus time as measured by the DustTrak aerosol instrument. The figure shows the concentration increase during acceleration to 15 km h^{-1} for four combinations of traction material and tyres. The concentration reaches a peak 15 – 30 minutes after start and decreases as the traction material is moved off the track. The second peak is caused by an increase of speed to 30 km h^{-1} .

3.2. Particle size distributions

The mass size distributions of the wear particles generated by the studded tyres, sampled with the PM_{10} -inlet and calculated from the APS measurements, have very similar appearances for all tested speeds (Figure 4), although the dense asphalt with granite (ABT) results in a higher particle concentration than the pavement with quartzite (ABS). The mass size distribution shows a mode at $4\text{--}5 \text{ }\mu\text{m}$ and a peak at $7\text{--}8 \text{ }\mu\text{m}$. The peak is artificial as the distribution is truncated by the PM_{10} inlet at $10 \text{ }\mu\text{m}$. Friction tyres were only tested on the

ABS pavement and result in a similar pattern although the concentrations are extremely low compared to the studded tyre combinations.

Figure 4. Mass size distributions in the road simulator hall for ABT/G/S (top), ABS/Q/S (middle) and ABS/Q/F (bottom). The wear particles were sampled using a PM_{10} -inlet and measured using an Aerodynamic Particle Sizer.

Mass size distributions for friction and studded tyres with traction material are similar to low speed distributions without traction material, but with higher concentrations. It is stressed that these size distributions are sampled from the peak concentration during the beginning phase at the tests. After the peak concentration, larger fractions decrease successively. For each traction material, crushed stone and natural sand, respectively, the peak of slightly coarser particles (7-8 μm) seems to increase when studded tyres are used (Figure 5).

Figure 5. Mass size distributions in the road simulator hall for combinations 4-7 with traction material. The wear particles were sampled using a PM_{10} -inlet and measured using an Aerodynamic Particle Sizer.

A somewhat unexpected result is that ultra-fine particles ($< 0.1 \mu\text{m}$) seem to be formed by the tyre-pavement interaction (Figure 6). For the combination with dense asphalt with granite (ABT) and studded tyres at a speed of 70 km h^{-1} , a peak in the number distributions at about 40 nm dominates the number distribution. Changing pavement to ABS does not

affect the number size distribution. Decreased speed of the road simulator results in lower number concentration, but with same distribution (peak about 40 nm). When friction tyres are used on the ABS pavement, however, the size distribution shifts towards smaller diameters. The particle diameter is also affected by speed. At 70 km h⁻¹ the peak appears at about 20 nm, and at 50 and 30 km h⁻¹ the peak shifts below the SMPS's lower size limit (16 nm). The ultra-fine particles have been described in greater detail in Dahl et al. (2006).

Figure 6. Number size distributions of particles 16–723 nm in the road simulator hall for the ABS/Q/S and ABS/Q/F at different speeds. The particles were measured using a Scanning Mobility Particle Sizer.

3.3. Physical and chemical properties of particles

Figure 7 shows typical SEM-pictures of particles from the two pavements worn with studded tyres together with SEM-pictures of the particle samples from an urban street environment and the subway used in the cell study. The jagged appearance and fresh mineral surfaces strongly emphasize that most of these particles are mineral particles freshly worn from the pavements' stone material. The ABT granite particles have a more flaky appearance

than the ABS quartzite particles which, in turn, has a grainier appearance, which is likely to be an effect of differences in the mineral structures of the rocks (Figure 7, top pictures). In contrast, the particles from the natural sand combinations appear weathered and more rounded, indicating the occurrence of already present, weathered particles suspended by the tyres.

Figure 7. SEM photos of PM_{10} from ABT/G/S (upper left), ABS/Q/S (upper right), urban street (lower left) and subway (lower right). The magnification was 2000 times.

EDS spectra emphasize the minerogenic origin of the wear particles (Figure 8). Silica dominates the spectra together with oxygen, aluminium and potassium. The silica peak is more dominant in the combination with studded tyres and ABS pavement with quartzite, which is expected since quartzite is totally dominated by silica. The spectrum for friction

tyres on ABS is likely to be more affected by the filter material, since the low particle concentration gave sparse contribution to the filter sample. Nevertheless, silica has a high peak and calcium and magnesium are both exclusive for this combination.

Figure 8. EDS spectra for three combinations (cps = counts per second).

The SFU-filters analyzed with PIXE (only elements with $Z \geq 13$, Al detected) show that the relative elemental composition agreed well with the mineralogical content given in Table 2 for the elements in common (aluminium, silica and potassium), although aluminium was found in slightly higher relative concentrations in the PIXE samples. Such small deviations are however to be expected since Table 2 only includes the major mineral fractions, and several additional crystal elements are found in the PIXE samples, for instance Ca, Ti, Mn and Fe. There were no detectable differences between the coarse and fine fraction samples of the SFU-filters. The SDI cascade impactor samples were also analyzed by PIXE. The elemental composition is quite stable over the entire SDI particle size range (0.11 to 10 μm). Figure 9 shows the relative elemental mass contributions versus aerodynamic particle size for the five most common elements (S, K, Ca, Fe and Zn) excluding the two most dominating mineral elements, Al and Si. In all cases the speed of the tyres was 70 km h^{-1} . Examining the tyre related elements show that S is enriched in the sub-micrometer stages for all tested combinations of tyres and pavements, and particular for the friction tyres (Figure 10). Also Zn is greatly enriched when running friction tyres, and for all particle sizes. The same pattern emerges from the SFU samples, confirming that most of the mass originates from the pavement, and only a relatively small mass contribution from the tyres. Using PIXE analysis, the tyre contribution is manifested mainly for the elements S and Zn that are important components of the rubber vulcanizing process. The PIXE relative elemental composition agreed well with the mineralogical content given in Table 2 for the elements in common (aluminium, silica and potassium), although aluminium was found in slightly higher relative concentrations in the PIXE samples. Such small deviations are however to be expected since Table 2 only includes the major mineral fractions, and several additional crustal elements are found in the PIXE samples, for instance Ca, Ti, Mn and Fe.

Figure 9. Relative elemental mass contributions as function of equivalent aerodynamic diameter for elements detected with PIXE ($Z \geq 13$, Al) for an SDI impactor sample collected for ABT/G/S at 70 km h^{-1} .

The calculated enrichment factors is showed in Table 4 and not surprisingly, the main components of the specific pavement minerals (Al, Si and K) were found to be enriched versus the average soil composition, using Ti as tracer element. Other typical crystal elements (Ca, Mn and Fe) were not enriched versus Ti, indicating the presence of additional minerals others than those listed in Table 2, but in smaller amounts. Cu and Zn were greatly enriched, especially for the friction tyres (~200 times versus soil titanium). Since S is not included in the soil reference used, enrichment factors could not be calculated for this element, but the presence of sulphur is a clear indication of high enrichment of this element versus a typical soil composition.

Ultra-fine particles differ from the coarser fraction morphologically. They have very heterogenic forms such as carbon chains, droplets and granules (Figure 11). Overall, these

Figure 10. Relative mass concentration of Zn, Fe, Ca, K and S in wear particles from ABT/G/S (above), ABS/Q/S (middle) and ABS/Q/F (below), excluding dominating mineral elements Al and Si.

particles seem to have an organic origin, indicating other sources than the coarser particles. A more detailed analysis on the ultra-fine fraction can be found in Dahl et al. (2006).

Table 4. Enrichment factors (EF) for the SFU samples for various combinations of tyre and pavement (see table 1) versus the average calculated versus a soil reference composition (Kaye and Laby, 1959). Titanium (Ti) was used as tracer element for soil, and averages were taken over both fine and coarse samples.

Element	Soil (ppm)	EF ABT/G/S 70 km h⁻¹	EF ABS/Q/S 30, 50, 70 km h⁻¹	EF ABS/Q/F 30, 50 km h⁻¹
Al	26100	7.47	6.16	7.84
Si	101800	6.09	8.43	5.28
K	15467	7.99	4.32	4.51
Ca	30950	0.81	0.32	1.14
Ti	3367	1.00	1.00	1.00
Mn	987	0.86	0.49	1.58
Fe	30950	1.91	0.77	5.67
Cu	53.3	8.59	7.04	136
Zn	403	47.3	6.47	217

3.4. Cell study

Secretion of cytokines. In a preliminary test macrophages were exposed to the material recovered from the visually particle free filter pieces. The cells were exposed to 10 µg/ml of the recovered material and the cytokine levels in the culture medium were measured after 18 h of incubation. Only extracted material from Subway filters induced a significant release of TNF-α as compared to unexposed cells. Subway filters (6.4 ± 3.7 vs. control (unexposed

Figure 11. Examples of morphology of sub-micron particles collected for ABT/G/S.

cells) 1.7 ± 1.8 pg/ 10^4 cells, $p = 0.023$, mean $\pm$ SEM of three experiments performed as duplicates). The values for the other cytokines when cells were stimulated with filter extract did not differ from the controls (data not shown). Therefore, in all subsequent experiments, unexposed cells were used as control and used as comparison to the particle exposed cells. Figure 12 shows the amount of TNF- α (panel A), IL-8 (panel B) and IL-6 (panel C) that are secreted in to the cell growth medium from monocyte-derived macrophages exposed to 10, 50, 100, 250 or 500 μ g/ml (250 and 500 μ g/ml were not used for the diesel particles due to lack of material) of respective particle type. In order to compensate for the variation in cell numbers between the experiments the secreted cytokine amount is expressed as pg/ 10^4 cells. The results (figure 12, panel A) show that all of the investigated particle types induce a liberation of TNF- α and a significant increase ($p < 0.01$) was seen already at the lowest dose of 10 μ g/ml, compared to unexposed control cells. Comparison between the different doses used for respective particle type significant ($p < 0.05$) differences were seen for Granite that induced an increase for all doses except between 100 and 250 μ g/ml. Quartzite induced an increase between all doses, except at 100 μ g/ml. Quartzite induced an increase between all doses, except at 100 μ g/ml. Street showed an increase between 10 and 50 μ g/ml and there after a decrease. Subway displayed an increase between 10 and 50 μ g/ml and then a drop at 100 μ g/ml. Diesel (water extracted) induced an increase between doses. The similar pattern seen for methanol extracted diesel particles did not reach statistical significance. Furthermore, when comparing different types of particles a higher ($p < 0.05$)

Figure 12. Secretion of TNF- α (panel A), IL-8 (panel B) respectively IL-6 (panel C) from macrophages into the cell growth medium exposed to 10, 50, 100, 250 and 500 $\mu\text{g/ml}$ of respective particle type for 18 hours. Exposure to 250 and 500 $\mu\text{g/ml}$ of diesel particles was not done due to lack of particles. Diesel water = water extracted diesel particles, Diesel methanol = methanol extracted diesel particles. Unexposed cells (cell growth medium only) were used as controls. The cytokines were analyzed as described in the Material and Methods section. All values are mean $\pm$ SEM from 3-8 separate experiments with 2-3 exposures in each experiment. As positive control (not showed in the histograms) LPS 1 $\mu\text{g/ml}$ was included in each experiment releasing 422 ± 103 , 1313 ± 156 , and 455 ± 124 pg/ml $\times$ 10,000 cells of respective cytokine.

Panel A) TNF- α secretion, * = $p < 0.01$ compared to controls (unexposed cells)

Panel B) IL-8 secretion, * = $p < 0.05$ compared to controls (unexposed cells)

Panel C) IL-6 secretion, * = $p < 0.05$ compared to controls (unexposed cells)

Differences in cytokine release between the particle types are discussed in the Results section.

TNF- α secretion was observed at the 10 $\mu\text{g/ml}$ exposure level for Street as compared to the equivalent dose of all other types of particles used and Granite induced a higher secretion as compared to Subway. At the 100 $\mu\text{g/ml}$ exposures the difference between Street and Granite and the two Diesel types respectively was no longer present. However, Granite and Street both induced a higher TNF- α secretion as compared to Quartzite and Subway.

The cellular IL-8 response to exposure of different concentrations of particles is illustrated in figure 12, panel B. All of the investigated particle types induce a liberation of IL-8 and a significant increase ($p < 0.05$) was seen already at the lowest dose of 10 $\mu\text{g/ml}$, compared to unexposed control cells. When comparing the different doses used for respective particle type significant ($p < 0.05$), differences were seen for Granite, Quartzite and Street that induced an increase between 10 and 50 $\mu\text{g/ml}$ and there after a decrease. The increases seen for Diesel particles did not reach statistical significance. A comparison of the different particle types reveals a difference at the 100 $\mu\text{g/ml}$ exposure level. Granite induces a higher ($p < 0.05$) level as compared to Subway, while Street induces a higher ($p < 0.05$) level as compared to Subway as well as to Quartzite.

The ability of the particles to induce IL-6 secretion at different concentrations (Figure 12 panel C) as compared to control cells shows that the pattern is similar (with the exception for Subway that failed to induce a significant secretion at any dose used) for this cytokine as for the other two, with Granite and Street as those particle types that causes the highest liberation. When comparing the different doses used for respective particle type significant ($p < 0.05$) difference was seen for Granite and Quartzite that induced an increase between 10 and 50 $\mu\text{g/ml}$. The increases seen for Diesel particles did not reach statistical significance. Furthermore, when comparing different types of particles a higher ($p < 0.05$) IL-6 secretion

was observed at the 50 and 100 µg/ml exposures for Granite as compared to Quartzite and Subway.

Figure 12 also shows that there was no significant difference in the ability to induce secretion for any of the three cytokines between the two methods for extracting diesel particles from the filters (water respectively methanol extraction).

Results of inhibitors. The only particle type that showed some inhibition in its ability to induce cytokine secretion by polymyxin B was street particles. The liberation for IL-6, IL-8 and TNF-α was 39.2 ± 18.2 , 11.0 ± 11.0 and $42.0 \pm 12.9\%$ respectively compared to macrophages exposed to street particles without polymyxin B, but no significance was reached. When the different PM was combined with DFX, a slight inhibitory effect of IL-8 secretion was noted for Quartzite (928 ± 64 for Quartzite vs. 785 ± 27 for Quartzite + DFX, $p = 0.031$), but not for any of the other types of PM.

Endotoxin content. Only street particles showed a positive result for endotoxin content, which is in accordance with earlier investigations, where endotoxin has been associated with urban particles. According to the manufacturer, the E-TOXATE test should give positive results down to 0.05 EU ml^{-1} . In order to check for the presence of E-TOXATE inhibitors in the samples to be tested, a positive control of 0.2 EU ml^{-1} is added to each sample to check for E-TOXATE inhibitors. Our results indicate that Granite, Quartzite and subway particles contain less than 0.05 EU/ml ($\sim 0.01 \text{ pg ml}^{-1}$), while street particles contain 0.05 EU ml^{-1} or more of endotoxin. None of the particle types contains E-TOXATE inhibitors.

Cell viability. The viability for the macrophages exposed for respective particle type is shown in Table 5.

Table 5. Viability of Monocyte-Derived Macrophages As Judged by Trypan Blue Exclusion^a.

Particle type	Control	10 µg ml ⁻¹	100 µg ml ⁻¹	250 µg ml ⁻¹	500 µg ml ⁻¹
ABT/G/S	96 ± 1.0	93 ± 8.0	91 ± 1.0	78 ± 12	67 ± 15 ^b
ABS/Q/S	96 ± 1.0	92 ± 3.0	89 ± 3.1	77 ± 12	77 ± 6 ^b
Street	96 ± 1.0	77 ± 23	63 ± 7.5 ^b	43 ± 6.0 ^b	30 ± 10 ^b
Subway	96 ± 1.0	73 ± 21	38 ± 6.3 ^b	40 ± 10 ^b	33 ± 6 ^b
Diesel (w) ^c	96 ± 1.0	— ^e	— ^e	— ^e	— ^e
Diesel (m) ^d	96 ± 1.0	100	100	— ^e	— ^e

^aThe values are expressed as % viable macrophages after 18 h of exposure to 10, 100, 250, and 500 µg/ml of respective particle type. Values are based on the results from 3 to 4 different experiments except for the diesel (m) value which is based on one experiment due to lack of particles. Comparisons between different types of particles are presented in Results. ^b $p < 0.05$ vs control (unexposed cells). ^c Diesel (w)) extracted with water. ^d Diesel (m)) extracted with methanol. ^e Not tested due to lack of particles.

4. DISCUSSION

The results of this study strongly supports the point that studded tyres contribute to high particle levels in road and street environments and give a 60-100 times higher concentration than friction tyres. Kupiainen et al. (2005) showed in a study, using a road simulator similar to the one used in this study, that studded tyres compared to friction tyres only causes about 1.7 times higher particle concentration at 15 km h⁻¹ and about 5 times at 30 km h⁻¹. This to be compared to a 65 fold increase in the present study at 30 km h⁻¹. Both studies show an increased particle formation when using studded tyres in conditions with minimized resuspension, but the reasons for these very large differences are not clear. Factors such as test temperature (colder during studies in e.g. Kupiainen et al., 2003 and Kupiainen et al, 2005), room cleaning between experiments influencing amount of resuspension, volume and ventilation of the test facilities and differences in instrumental setup, are probably important parts of the explanation. Lower temperatures make pavement binder less elastic which might cause a more effective abrasion of the more firmly fixed pavement stones. Also, low

temperatures make tyre rubber harder, which may increase the stud force. Winter tyre rubber is designed to stay soft also at lower temperatures, while summer tyre rubber is harder.

Since the dense asphalt pavement with granite (ABT) generates much more particles, the pavement with quartzite (ABS) should be preferred in a dusty street environment. Today, there is not enough knowledge about which pavement properties are the most important for particle formation. However, it can not be concluded that high wear resistance of the pavement stone material automatically guarantees low particle generation. Ongoing studies at VTI will continue to study how different properties of the pavement such as stone material, stone size and pavement construction, influence the particle emissions.

The calculated particle mass distributions in this study confirm field measurements, which indicate that studded tyres strongly contribute to concentration of particles with a diameter less than 10 μm and also have the potential to strongly contribute to the fraction of particles smaller than 2.5 μm and maybe also the fraction smaller than 1 μm . There is an obvious increase in particle mass (and number) concentration with increasing speed. Stud force is directly proportional to speed which increases the pavement wear

SEM micrographs and EDS spectra of wear particles as well as the PIXE analysis of the SDI and SFU samples confirm that mineral particles totally dominate the wear from studded tyres on both the quartzite and granite pavements. Tyre and stud particles are absent in the SEM micrographs of particles. This might be due to the fact that they are too large to be sampled as PM_{10} or too small to be observed at this magnification (lowest detection particle size about a few hundred nm). However, the SDI samples show an increased proportion of S for submicron particles, which may indicate that, at least a part of the generated tyre

particles are submicron. This is most obvious for the SDI samples from the friction tyre test (ABS/Q/F).

The number size distributions provide clues to the origin of the sub-micron particles. Figure 6 shows the distributions at steady state for studded tyres and friction tyres on the ABS (quartzite) pavement. First, number size distribution when running studded tyres and friction tyres are different. Second, for the studded tyres, the overall shape of the particle size distributions remains nearly identical between 50 and 70 km h⁻¹, and only the number concentration increases with speed. In contrast to this, the geometric median diameter of the number size distributions tend to increase with speed when the friction tyres are run on the same quartzite pavement. While not entirely conclusive, this indicates that the type of tyre used has the largest influence on the ultra-fine particles that are produced, and thus also that the ultra-fine particles are likely to originate from tyre wear.

Speed determines the amount of mechanical stress in the tyre material and thus the temperature of the tyre. Increased temperature is therefore hypothesised to be responsible for the increased emissions from the tyres of loosely bound reinforcing filler material and evaporation of semi-volatile softening oils. The mixture of oils used as softening fillers in the tyres might affect the size of the submicron particles that are produced. Since the temperature in the road simulator hall was neither measured nor controlled, any possible effect of ambient temperature on the nucleation rate and the particle size distribution could not be observed.

The results of the cell study indicate that particles from studded tyre wear of pavements can induce inflammation in airways and that the type of stone material used in the pavement is important for the level of this contribution. This is well in line with recent results by Refsnes

et Al. (2006) showing that mylonite and gabbro induced a marked MIP-2 (corresponds to human IL-8) response in rat alveolar macrophages compared to basalt, feldspar, quartz, hornfels and fine grain syenite porphyry. The importance of the type of stone material is further emphasized by the results reported by Creutzenberg et al. (2006) demonstrating a different inflammatory effect in rats after intratracheal instillation of two quartz samples. One being a well-characterized positive control DQ12 quartz and the other being geologically ancient quartz isolate from bentonite. Control rats were given saline only. Bronchoalveolar lavage analysis showed that, relative to the controls, the total leukocyte counts at 3 days were elevated in both the quartz isolate and positive control groups. At 28 and 90 days, the quartz isolate values were no longer different from the control values whereas the corresponding positive control values were about 12 and 65 times greater than control values. Demonstrating that the control quartz leads to a progressive inflammatory response in contrast to the bentonite quartz isolate, which causes a much weaker non progressive inflammatory response in the rat lung. Furthermore our results also indicates that wear particles (this particle type) is at least as large potential health risk as already well studied traffic related particles as i.e. diesel particles. All studied particles induced release of IL-6, IL-8 and TNF- α , where the PM₁₀ particles from ABT pavement with granite and PM₁₀ particles from an urban street produced the strongest response.

The results from this study show that there is a potential for improving air quality along roads and streets where high concentrations of particles are related to wear particles, through improving pavement material, reducing the use of studded tyres, reducing speed and also through using washed traction material. Two pavements have been tested here, but many more should be investigated to be able to give proper recommendations about the stone material, size fractions, binders and construction that should be used. The pavements tested have constructions normal for Nordic conditions and comparatively durable stone materials

typical for Swedish conditions. In countries where studded tyres are not used, smaller stone sizes and different constructions are used as well as local stone material. The durable crystalline rocks found in the Nordic countries are sparse in the rest of Europe. Instead, sedimentary rocks, not as durable are common and used in pavements. How these differences affects particle production is unknown. Particle production from pavements are likely to be related to both construction and material properties and should be studied together with how pavement properties, such as surface texture and total wear, vary during the year. New projects at the VTI road simulator are currently investigating some of these issues.

Studded tyres are the single most important factor for particle generation from pavements. To limit studded tyre use requires good knowledge of associated effects regarding traffic safety. In Sweden, studded tyres are a natural part of winter traffic safety and a law regulates their use. Even though studded tyres do have better friction on icy roads. Increasing knowledge on possible health effects and well known negative environmental effects (wear, noise and rolling resistance) have led to a discussion about the socioeconomic pros and cons of studded tyre use in Sweden. In some other countries studded tyres have been banned or subjected to charges, mostly because of the costs associated with pavement wear, but also on the basis of their health impact. In Norway, for example, some of the larger cities impose studded tyre charges to lower their use. This has been possible due to supporting results from health and safety research as well as good information projects during approximately 10 years. In contrast to what one might fear, a recent study has confirmed that reduced use of studded tyres does not increase the accident frequency in Oslo (Rosland, 2005). It may be argued that this is a result of changed driver behaviour. Nevertheless, good knowledge about the socioeconomic effects of the reduced use of studded tyres is necessary before this measure can be recommended.

5. CONCLUSIONS

From this investigation it can be concluded that:

- Pavement wear caused by studded tyres causes substantial PM_{10} formation.
- Particle emissions from friction tyres – with respect to both number and mass – are several tens of times lower than from studded tyres for the same speed.
- Particles from road wear caused by studded tyres are almost as inflammatory as particles from an urban street, more than particles from the subway and at least as inflammatory as particles from diesel exhaust
- Since particle size distributions generated from both pavements, ABT with granite and ABS with quartzite are very similar, the difference in inflammatory potential is likely to be related to other particle properties than size.
- The particle emissions from all combinations of tyres and pavements increase strongly with increasing speed.
- A highly resistant ABS pavement with quartzite produces markedly less particles than an ABT pavement with local granite.
- Traction material consisting of washed, crushed stone (2-4 mm) considerably reduce particle concentration compared to unwashed natural sand (0-8 mm).
- Studded tyres cause higher emission of particles than friction tyres also when using traction materials.
- High number emissions of ultrafine particles (< 100 nm in diameter) are observed in the experiments. The number median diameter varies with tyre type used, indicating that tyre wear is a likely source of these ultrafine particles.

- Elemental analyses of particle size-resolved SDI and SFU aerosol samples show that most of the PM₁₀ for elements detected with PIXE originates from the pavement, with only a relatively small mass contribution from the tyres.
- The relative aerosol elemental composition (for Al, Si and K), agrees well with the mineralogical content of the main identified constituents of the ABS and ABT pavements.
- The relative elemental composition is quite stable over particle size range 0.11 to 10 μm and different combinations of tyre and pavement show only small differences. However, S – a vulcanizing agent in tyres – is enriched in the sub-micrometer stages for all tested combinations of tyres and pavements and particular for the friction tyres. Also Zn – a vulcanization activator – is greatly enriched when running friction tyres and for all particle sizes. Both S and Zn are enriched relative to the mineralogical composition of the pavements.

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