

Wear particles from road traffic

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Abstract

Extensive data were collected in indoor controlled runs with a circular road simulator, as well as in ambient air at both street and roof level in a number of Swedish cities in 2006 and 2007 by a variety of methods for measuring, sampling and analysing the chemical composition of primarily three different fractions of particulate matter - PM₁₀, PM_{2.5} and PM₁.

Based on elemental source profiles of various sources to the different particle fractions, receptor models were applied to derive the contributions from exhaust, brake wear, tyre wear, road surface wear, long-range transport etc., to the measured particle concentrations.

Furthermore, emission factors for the various particle fractions, as well as for a large number of contained metals, were derived for two major city streets in Stockholm and Malmö, respectively. Emission factors for each of the different source types (exhaust, brake wear, tyre wear and road surface wear) were also derived.

Corresponding emission factors for tyre wear and road surface wear were derived from the measurements in the circular road simulator. Emission factors were derived for different particle size as well as for different speeds and different types of tyres. According to the road simulator experiments, studded tyres give rise to one order of magnitude higher emissions of PM₁₀ than friction tyres, while PM₁₀ emissions caused by summer tyres is almost negligible.

The emission factor for PM₁₀ derived from the road simulator experiments corresponds well with those derived from ambient air measurements near busy streets. The main source to PM₁₀ concentrations near busy streets was found to be road surface wear ($\approx 50\%$ of the overall PM₁₀ mass), and other local traffic sources (exhaust, brake and tyre wear) contribute another 20%. On the contrary, for PM_{2.5} and PM₁ the dominant contribution is often from long-range transport.

1. Introduction

Extensive air quality monitoring shows that both national and EU air quality standards for PM₁₀ are frequently exceeded in Swedish cities, especially during the winter and early spring. There is no doubt that traffic-generated wear particles play an important role for these violations, especially since studded tyres are frequently used in Sweden during the winter season and early spring. Studded tyres have proven to drastically increase road wear and resuspension (Gustafsson *et al.*, 2009), and hence the concentrations of fine particles in curb side and urban environments.

Although the violation of the PM₁₀ standard in Swedish cities as such presents a major health problem, recent air pollution and health studies indicate that airborne particles' impact on health is more strongly linked to the finer particle fractions (e.g. PM_{2.5}, PM₁) than to PM₁₀. (Reich *et al.*, 2009). Also, an air quality directive for PM_{2.5} has recently been launched within the EU.

For road transport the need of measures to reduce PM emissions is hard to define, since the emissions of various particle size fractions only partly can be quantified by conventional methods, i.e. via emission models based on emission measurements on individual vehicles in chassis dynamometer experiments. Instead, "inverse" methods such as source receptor modelling via chemical characterization of ambient air particles are required (see e.g. Gertler *et al.*, 2000).

However, in order to study wear-related particulate matter characteristics, and to understand their formation processes associated with different types of road pavement material, tyres, friction material, etc., controlled experiments are also needed. For this purpose the circular road simulator hosted by the Swedish Road and Transport Research Institute provides an interesting approach. Previous studies in this simulator have revealed major differences in PM₁₀ generation between different combinations of road pavement, tyres and friction materials (Gustafsson *et al.*, 2009). The results indicate a great potential to minimize emissions of wear particles during the winter period by an appropriate choice of road pavement, tyres and strategies applied for reducing slipperiness. However, in general the knowledge of how the emissions of various PM size fractions are influenced by these and other wear parameters is very limited.

These issues were further addressed and analysed in the present study by a unique combined approach of applying three principally different methodologies: 1) the VTI circular road simulator, 2) various sampling methods for different size fractions of ambient air particles, including elemental and chemical speciation of particle composition, and 3) receptor models.

2. Experimental

2.1 Circular road simulator experiments

The VTI circular road simulator consists of four wheels running along a circular track with a diameter of approximately 5 m (<http://www.vti.se/4987.epibrw>). Each wheel is powered by a DC engine, by which the speed can be varied up to 70 km/h. Any type of pavement can be applied to the simulator track and any type of tyre can be mounted on the axles. The simulator is contained in a 400 m³ building, which makes it possible to sample wear particles with very low contamination from surrounding sources and no influence from tail-pipe emissions. An internal air cooling system enables the air in the simulator building to be cooled to sub-zero temperatures. A large filter fan acts as a sink to simulate outdoor sampling conditions.

The pavement used for the tests was stone mastic asphalt (SMA) with a maximum stone size of 16 mm, equal to the pavement of the street in Stockholm where the ambient air PM measurements were carried out in this study (see chapter 2.2). The stone matrix material was quartzite from western Sweden.

Three types of tyres were investigated: summer tyres (Nokian NRHi Ecosport), Nordic unstudded winter tyres (Nokian Hakkapeliitta RSi) and studded tyres (Nokian Hakkapeliitta 4).

The road simulator test cycle applied was 1.5 hours at 30 and 50 km/h, and 2 hours at 70 km/h.

During the test cycles the particles emitted to the air in the simulator hall were measured and/or sampled by the following instrumentation:

- Tapered Element Oscillating Microbalance (TEOM) and DustTrak for continuously measuring PM₁₀ mass.
- Aerodynamic Particle Sizer (APS) for continuously measuring the particle number distribution within the coarse fraction (particles with an aerodynamic diameter 0.5-20 µm).
- Scanning Mobility Particle Sizer (SMPS) for continuously measuring the particle number distribution within the fine fraction (particles below 1 µm). The SMPS consisted of a Differential Mobility Analyzer (DMA) and a Condensation Particle Counter (CPC).
- Small Deposit Impactor - SDI - a multi-jet low-pressure cascade impactor for sampling particles in twelve size fractions (aerodynamic diameter between 0.045 and 8.39 µm).
- Stacked Filter Units - SFU - for sampling the fine (PM_{2.5}) and coarse (PM₁₀-PM_{2.5}) fraction of particles on 47 mm diameter Nuclepore® filters.

2.2 Measurements and sampling of particles in ambient air

Measurements and sampling of particles in ambient air were made during all four seasons from early 2005 to mid 2007 in several cities, from the south to the north of Sweden. The most extensive measurements were made in a busy street canyon in Stockholm (Johansson *et al.*, 2007). Parallel measurements were made on a nearby roof, representing the urban background. Extensive similar measurements were also made in Malmö, the third largest city in the south of Sweden. Finally, PM₁₀ samples from four small-to-medium-size cities within the Swedish Urban Air Quality Network (Forsberg *et al.*, 2005, Svanberg *et al.*, 1998) were utilised for the receptor modelling exercises (see below). For the ambient air measurements the following instrumentation was used:

- PM₁₀, PM_{2.5} and PM₁ were all sampled on a daily basis (24 hours) on 47 mm and 25 mm Teflon filters, respectively, using the sampling heads developed by IVL in collaboration with the Department of Design Sciences at Lund University. The sampling head for PM₁₀ (Ferm *et al.*, 2001) has been tested with good results against reference methods for PM₁₀ in a major intercalibration exercise in Norway (Marsteen and Schaug, 2007).
- TEOM for continuous measurements of PM₁₀ and PM_{2.5} (see chapter 2.1).
- Stationary Aerosol Sampler (SAM) designed by Nuclear Physics at Lund University (Hansson and Nyman, 1985), using a PM₁₀-inlet and an impactor with aerodynamic cut-off diameter at 2.5 µm for PM_{2.5} and the coarse fraction PM₁₀ - PM_{2.5}.

SAM filter samples (as well as SFU and SDI samples from the road simulator experiments) were analyzed for their elemental content by means of PIXE - Particle Induced X-ray Emission - at the Division of Nuclear Physics at Lund University (Shariff *et al.*, 2002).

After extraction the IVL filter samples were analysed by ICP-MS for 29 elements.

2.3 Receptor modelling

The resulting datasets from both the road simulator experiments and the ambient air measurements, containing mass concentrations of various particle size fractions and their

elemental content, were subject to various modelling exercises, such as Principal Component Analysis (PCA), Positive Matrix Factorization (PMF) and Constrained Physical Receptor Modelling (COPREM). Only the results from the COPREM exercises are presented here, for the results of the other modelling, see Sjödin *et al.*, (2009).

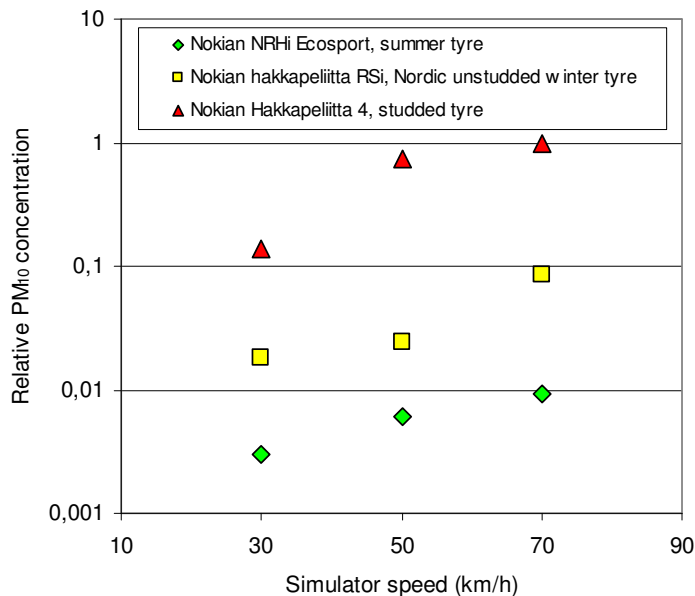
The COPREM model is a hybrid receptor model that unifies qualities from factor analytic models and chemical mass balance models (Wåhlin, 2003).

3. Results and discussions

3.1 Circular road simulator experiments

As can be seen from Figure 1, the PM_{10} emissions generated from the road simulator depends heavily on both the type of tyre and speed. Studded tyres give rise to one order of magnitude higher emissions than unstudded winter tyres, and two orders of magnitude higher than summer tyres. For all types of tyres there is also a clear and strong dependence of speed. Roughly, PM_{10} emissions are 5-10 times higher at 70 km/h compared to 30 km/h. The speed dependence seems stronger for studded tyres than for unstudded tyres, particularly between 30 and 50 km/h.

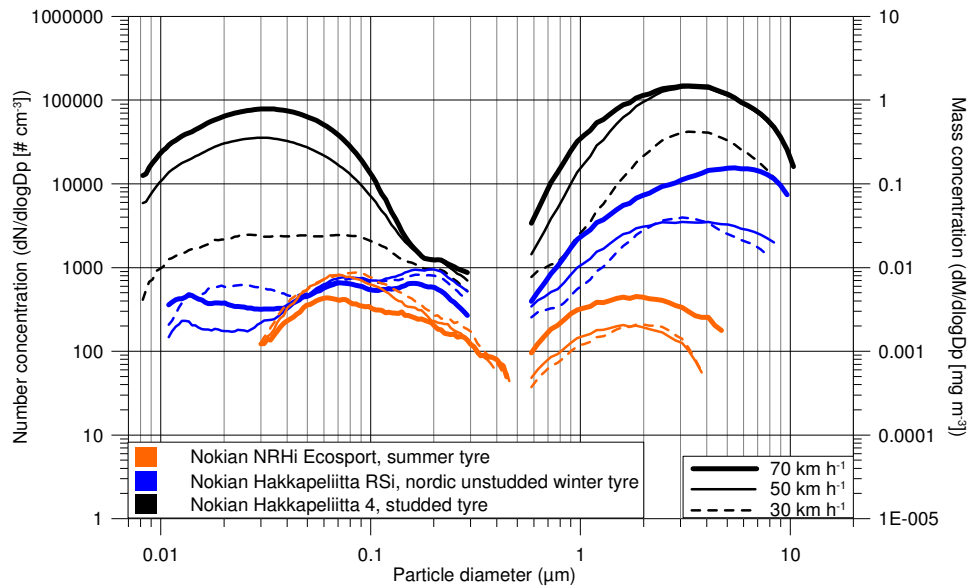
Figure 1 Relative PM_{10} air concentration in the simulator hall as a function of tyre type and speed. The data are mean values for time periods of about 10 minutes each after the PM_{10} -concentration has reached equilibrium for each speed.



In Figure 2 the measured particle size distributions in the simulator hall are shown for the same three tyre types and speeds as in Figure 1. The coarse fraction, i.e. particles with an aerodynamic diameter above $2.5 \mu m$, makes up most of the PM_{10} mass (shown to the right in the diagram). For all three tyre types and all particle sizes, concentrations increase with speed. The peak concentration is shifted towards smaller particles for summer tyres compared to winter tyres

The particle number distributions are shown to the left in Figure 2. The only apparent particle mode is generated by the studded tyres, peaking at about 30 nm and clearly increasing with increasing speed. The particle modes observed during the runs with unstudded winter tyres and summer tyres are independent of speed, indicating that their source(s) are not the interaction between tyre and pavement. It is more likely that their origin is background aerosols.

Figure 2 Particle size distributions for the three tyre types investigated in the road simulator. Left: Number distributions of particle. Right: Mass distributions of particles.

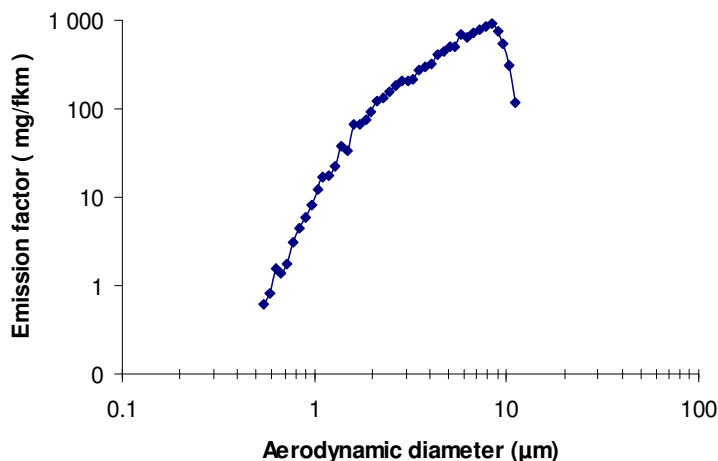


The simulator experiments showed a clear influence of pavement, tyre temperature and air humidity on the amount of particles generated. It was found that granite-containing asphalt generated much more particles than quartzite. Furthermore, quartzite with smaller aggregate size (<11 mm) generated less PM₁₀ than the larger aggregate size (<16 mm). These results indicate that by making proper choices regarding pavement material and maximum aggregate size, wear can be minimized. These results are in accordance with Räsänen et al. (2003).

The particle generation decreased with increasing temperature for both studded and unstudded winter tyres, whereas the opposite relationship was observed for summer tyres. The particle generation decreased with increasing specific humidity for all three types of tyres.

The APS data was used to derive emission factors from the road simulator experiments for various particle size fractions. Figure 3 shows the size-resolved emission factor values. The decrease in the emission factor value at around 8 µm is caused by the increased sampling efficiency of the PM₁₀ inlet. Summing all emission factor values obtained for each particle size yields a PM₁₀ emission factor value of about 350 mg/vehicle km.

Figure 3 Estimated PM emission factors (g/vehicle km) as a function of particle aerodynamic diameter for studded tyres at speed 50 km/h in the road simulator experiments.



3.2 PM emission factors derived from ambient air measurements

Road traffic PM emission factors in mg/vehicle km were estimated from the ambient air measurements using NO_x as a tracer for traffic emissions as described in Johansson *et al.* (2009):

$$Ef^{PM} = Ef^{NO_x} \cdot \frac{C_{Street}^{PM} - C_{UB}^{PM}}{C_{Street}^{NO_x} - C_{UB}^{NO_x}}$$

where Ef^{PM} and Ef^{NO_x} are the emission factor for PM and NO_x, respectively. C_{Street} and C_{UB} are the measured concentrations at street level and urban background, respectively. Calculated PM₁₀ (and PM_{2.5}) emission factors from the ambient air measurements in Stockholm (and Malmö) are presented in Figure 4 and Table 1, respectively.

As can be seen by both Figure 4 and Table 1, road wetness and time of the year has a large impact on the PM₁₀ emission factor. For the street canyon in Stockholm the mean emission factor for PM₁₀ for dry periods was estimated to 280 mg/vehicle km and 80 mg/vehicle km for wet periods. From November to April the emission factor was 4-6 times higher for dry periods compared to wet periods. From May to October the difference was less than a factor 3.

Wet and dry periods were not defined in the same way in the two cities; therefore the results in Figure 4 and Table 1 are not easily comparable. However, it is clear that also in Malmö the PM₁₀ emission factor is markedly higher in the early spring (March) compared to the summer (June). The share of studded tyres is generally higher in Stockholm (peak share: ≈70 %) than in Malmö (peak share: ≈30 %), due to the differences in climatic conditions.

Figure 4 *PM₁₀ emission factors in mg/vehicle km (monthly averages based on measurements during 2006-2008) for the street canyon in Stockholm, derived from ambient air measurements during wet periods (blue line) and dry periods (black line).*

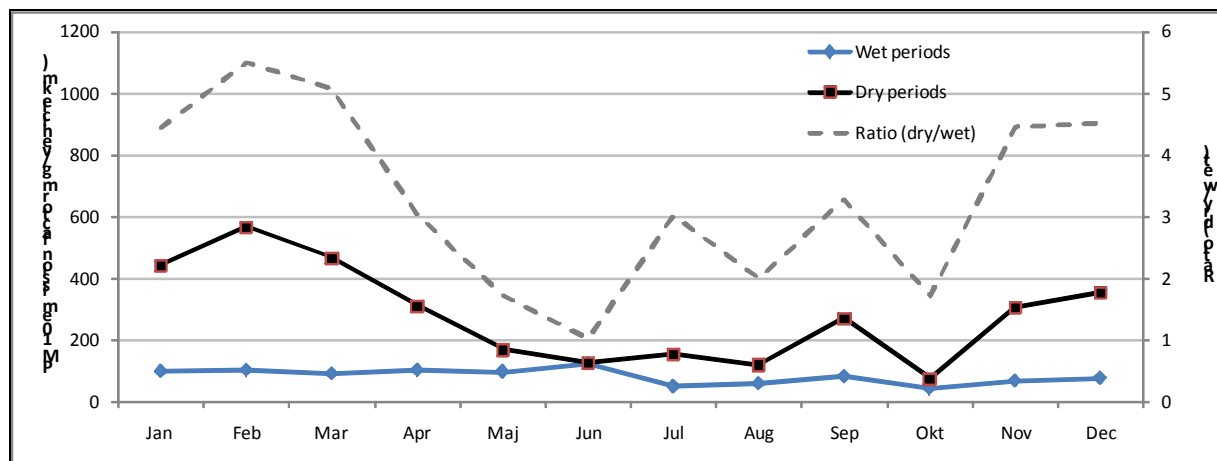


Table 1 *Average PM₁₀ emission factors (monthly averages 2005 in mg/veh. km) for the street canyon in Malmö, derived from ambient air measurements for wet and dry periods.*

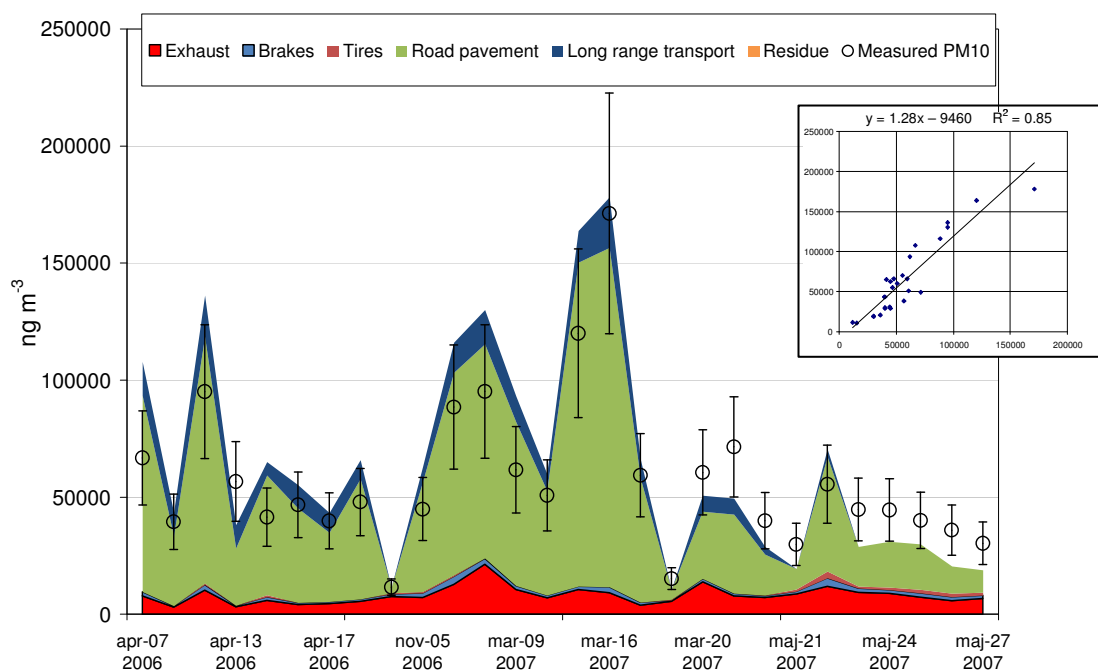
	March	April	May	June
$Ef^{PM_{10}}$ wet + dry periods	330	220	190	90
$Ef^{PM_{10}}$ wet periods only	100	110	110	30
$Ef^{PM_{2.5}}$ wet + dry periods	50	50	30	30
$Ef^{PM_{2.5}}$ wet periods only	40	60	40	10

3.3 Receptor modelling based on ambient air data

The COPREM model was applied to the PM data and contained elemental data from the ICP-MS analysis from the ambient air measurements carried out in Stockholm and in the four small-to-medium-size cities. The road simulator experiments yielded important results as regards the elemental source profiles for both studded tyre wear and road wear, which were applied in the receptor modelling. Other source profiles were taken from the literature.

The results for PM₁₀ for the busy street canyon in Stockholm are presented in Figure 5. Of the estimated overall average PM₁₀ emission factor of 310 mg/vehicle km, road wear accounted for 227 mg (≥70%), exhaust for 39 mg, break wear for 7 mg and tyre wear for 2 mg per vehicle km. Similar source contribution patterns were achieved in the receptor modelling for the four small-to-medium-size cities. The estimated overall average PM_{2.5} emission factor of 76 mg/vehicle km, road wear accounted for 56 mg (≥70%), exhaust for 17 mg and break wear for 2 mg per vehicle km. PM₁ emission factors could not be estimated from the ambient data due to lack of data. However, source contributions to PM₁ were estimated to 38% for exhaust, 35% for road wear, 27% for long-range transport and 0.5% for brake wear.

Figure 5 Contributions to total PM₁₀ (ng m⁻³) in a busy street canyon in Stockholm by different sources according to the COPREM model runs. In the scatter plot calculated PM₁₀ concentrations are compared with measured PM₁₀ concentrations.



4. Conclusions

This study has shown that studded tyres give rise to one order of magnitude higher emissions of PM₁₀ than unstudded (friction) winter tyres, and two orders of magnitude higher PM₁₀ emissions than summer tyres, implying that PM₁₀ emissions caused by summer tyres are almost negligible. Furthermore, it was found that studded tyres emit ultrafine particles, whereas other types of tyres do not. The emission factor for PM₁₀ derived from the road simulator experiments corresponds well with those derived from ambient air measurements near busy streets. The main source to PM₁₀ concentrations near busy streets was found to be road surface wear (≈50% of the overall

PM₁₀ mass), and other local traffic sources (exhaust, brake and tyre wear) contribute another 20%. On the contrary, for PM_{2.5} and PM₁ the dominant contribution is often from long-range transport, although road wear through the use of studded tyres appears to be an important source also for the smaller particle size fractions.

5. References

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