MEASUREMENT OF BRAKE WEAR EMISSIONS BY THE ENGINE EXHAUST PARTICLE SIZER (EEPS) SPECTROMETER AND OPTICAL PARTICLE SIZER (OPS)

APPLICATION NOTE EEPS-007 (A4)

Contents

Importance of Non-Exhaust Engine Emissions

It is well recognized that non-exhaust emissions represent almost 50% of the total road transport contribution to PM_{10} and $PM_{2.5}$ emissions (Alemani et al. 2015). One major contributor to the non-exhaust fraction is particles generated from disc brakes (Bukowiecki et al. 2009ab, Hjortenkrans et al. 2007, Thorpe et al. 2008). As exhaust emission controls become stricter, relative contributions of non-exhaust sources, including brake wear, to traffic-related emissions will become more significant, and will raise questions as to the necessity of regulations pertaining to non-exhaust emissions (Grigoratos et al. 2015).

Regulations for brake pad performance are influenced by many bodies across the world, including the Particle Measurement Programme by the United Nations Economic Commission for Europe (UNECE-PMP). In order to continuously improve their products and ensure regulatory compliance, brake pad manufacturers conduct brake performance tests. These standardized tests can be carried out on vehicles and on dynamometers (separate from a vehicle). An overview of brake testing procedures for passenger cars and light duty trucks with hydraulic braking systems can be found in the review of Agudelo and Ferro (2005).

The standardized test procedure used to assess the effectiveness and behavior of a friction material while considering pressure, temperature and speed is defined in SAE J2522. The SAE J2522 procedure was developed in Europe by a partnership of vehicle, brake and friction material manufacturers. It contains the definition of the AK Master protocol, which has not yet obtained the status of a certification protocol. The AK Master protocol consists of 15 test sections with various speed, pressure and temperature restrictions. This consideration for speed, pressure, and temperature is of critical importance because braking is a very dynamic process, in which braking duration, energy, and brake pad temperature may change, sometimes very rapidly. There is also diversity in the materials from which brake pads and discs are formed. Due to this complexity, particle emissions may also be dynamic in terms of particle emission rate and size distribution. Considering all of these variables, a brake pad emissions measurement system must be fast and rugged, cover a wide range of particle sizes, and deliver highly repeatable and accurate data.

Measurement Method

In order to accurately characterize brake wear emissions, the selected instrumentation must be able to measure particle size over a large size range (< 10 nm – 10 µm) (Alemani et al. 2015). Changes in particle size and number may occur rapidly during a braking event due to changes in brake pad temperature, as well as changes in the friction between the brake pad and disc. In order to capture these rapid changes, the size measurements should also be performed at high frequency and with a high degree of size resolution.

In order to satisfy these requirements, TSI has combined two instruments into one measurement system: the Engine Exhaust Particle Sizer™ Spectrometer (EEPS™, Model 3090, TSI Inc.) can measure particles from 5.6 nm to 560 nm, and the Optical Particle Sizer (OPS, Model 3330, TSI Inc.) is able to measure particles from 300 nm to 10 µm. The overlap in the size ranges of these two instruments permits the size distribution data they gather to be merged into one continuous distribution, as if measured by a single instrument. Both the EEPS spectrometer and OPS gather data at a rate of 10 Hz. The EEPS spectrometer sizes particles according to their electrical mobility, while an OPS sizes particles according to their optical properties. While these measurements do differ, this difference is corrected when data from the two instruments are merged using TSI's Multiple Instrument Manager Software, MIM 2.1.

The sampling system located between the tested brake pad and the instrument inlets has to be designed carefully to provide a representative sample of the brake wear emissions. The wide particle size range makes it challenging to design a sample probe, transport line, and connections that will result in accurate data. A high flow rate is important to capture a representative sample and reduce diffusion losses in the sub 100 nm size range. While particles < 1 µm can be transferred through bends in the tubing, larger particles can be lost in bends and at corners due to impaction. For this reason a straight, non-horizontal sampling line guiding the particles to the OPS is recommended. All parts of the inlet line are conductive to ensure no electrostatic effects can lead to particle line losses. The sample flow for the OPS is isokinetic, taken from the main sampling line which continues towards the EEPS spectrometer. An additional cyclone (precyclone) was added to improve the measurement of particles in the EEPS spectrometer. The extra flow through this cyclone (about 6 L/min^{-1}) was provided by an external pump. The combined instrument system allows the addition of capillary diluters if needed (10:1 or 100:1 for the EEPS spectrometer or OPS, respectively). The schematic of our wide range fast sizer combining EEPS spectrometer and OPS is presented in Figure 1.

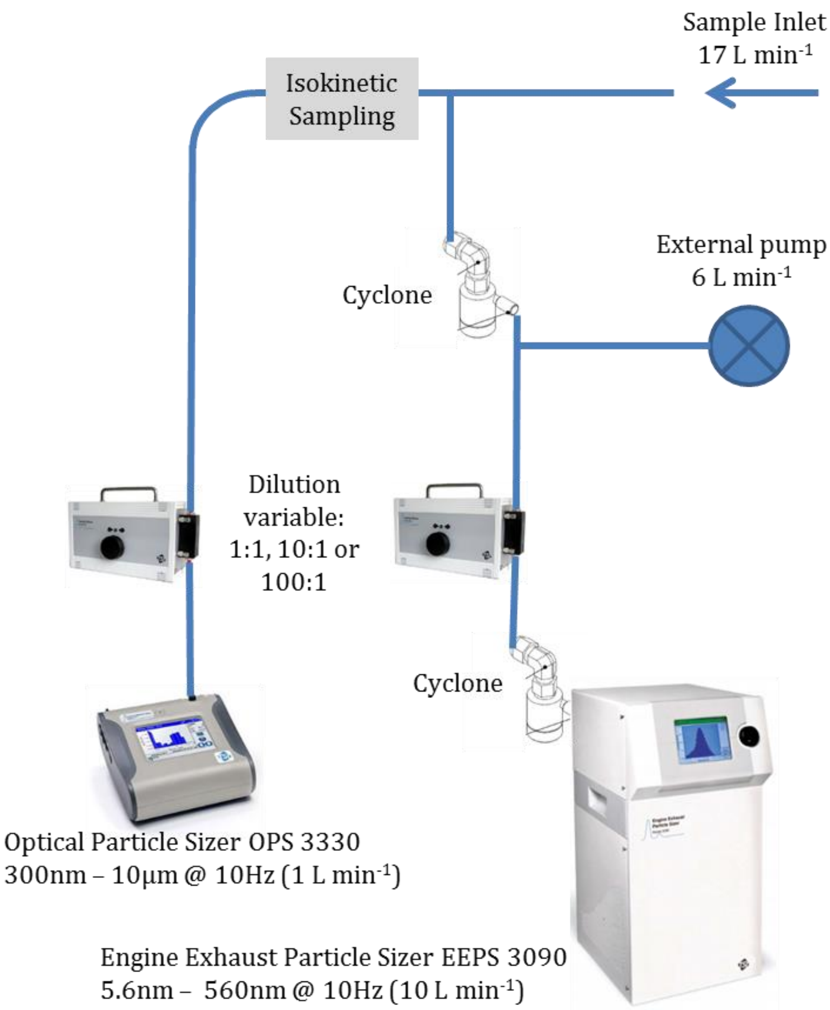

Figure 1: Schematic of the Wide Range Fast Sizer System with EEPS Spectrometer and OPS

Brake Wear Emissions Results

Number Concentration

Analogous to the engine exhaust emissions legislation, the total number concentration will be likely the most important parameter in future regulations pertaining to non-exhaust emissions. The number concentration of aerosols generated during braking events was evaluated by comparing the total number concentrations measured by the EEPS spectrometer and a Condensation Particle Counter (CPC). The Nano Water-based CPC (N-WCPC, Model 3788, TSI Inc.), which is the fastest commercially available CPC (rise time of <100 ms and time constant of 43 ms), was used at a data acquisition rate of 10 Hz. The combination of our wide range fast sizer system with the N-WCPC is presented in Figure 2.

Figure 2: Photo of the wide range fast sizer system with EEPS spectrometer and OPS as it was used for the brake wear emissions measurements. In addition to the optional three diluters pictured, a Nano water-based Condensation Particle Counter (N-WCPC) is included as a reference for total particle concentration.

Figure 3 presents the total particle number concentrations as measured by the EEPS spectrometer and the N-WCPC. The results show the excellent agreement between the N-WCPC and the EEPS spectrometer using the soot matrix. For more information on the EEPS matrices we refer to the App. Note EEPS-005 and the corresponding publications by Wang el al. a, b (2015).

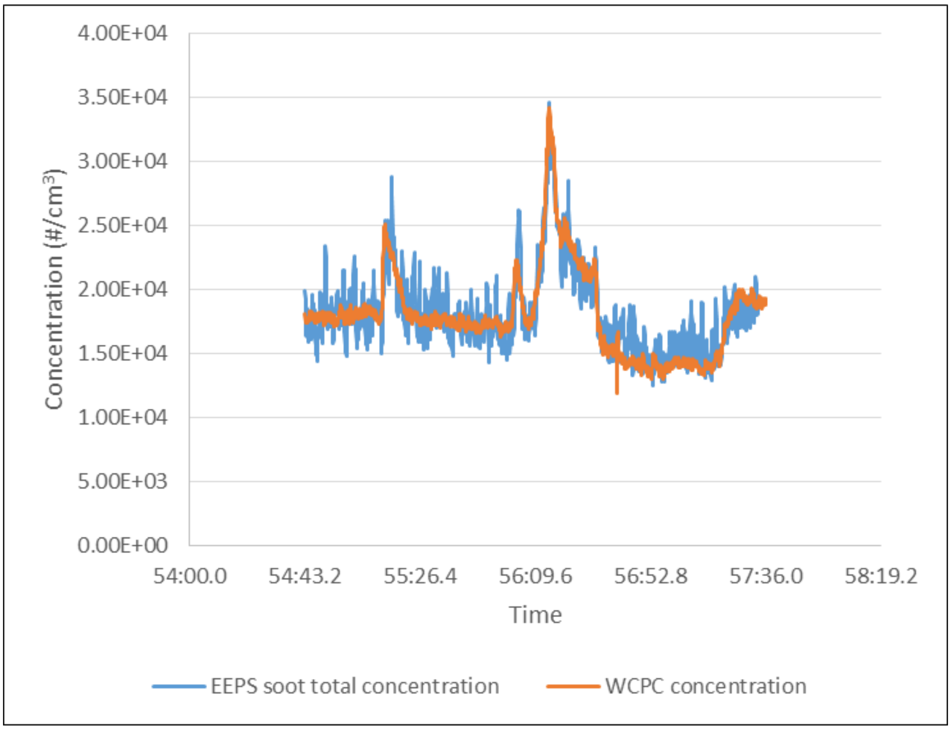

Figure 3: Total particle number concentration of brake wear emissions as measured by EEPS spectrometer (using soot matrix) in blue and by the N-WCPC in orange.

Size Distributions

Data from both the EEPS spectrometer and the OPS can be read and imported into the Multiple Instrument Manager Software MIM 2.1. It is designed to merge the data from the OPS and the EEPS spectrometer. As examples for measurement results, three merged size distributions of brake wear emissions are presented in Figure 4. Panels (a) and (b) of Figure 4 show number-weighted size distributions from low-energy and somewhat higher-energy braking events, respectively.

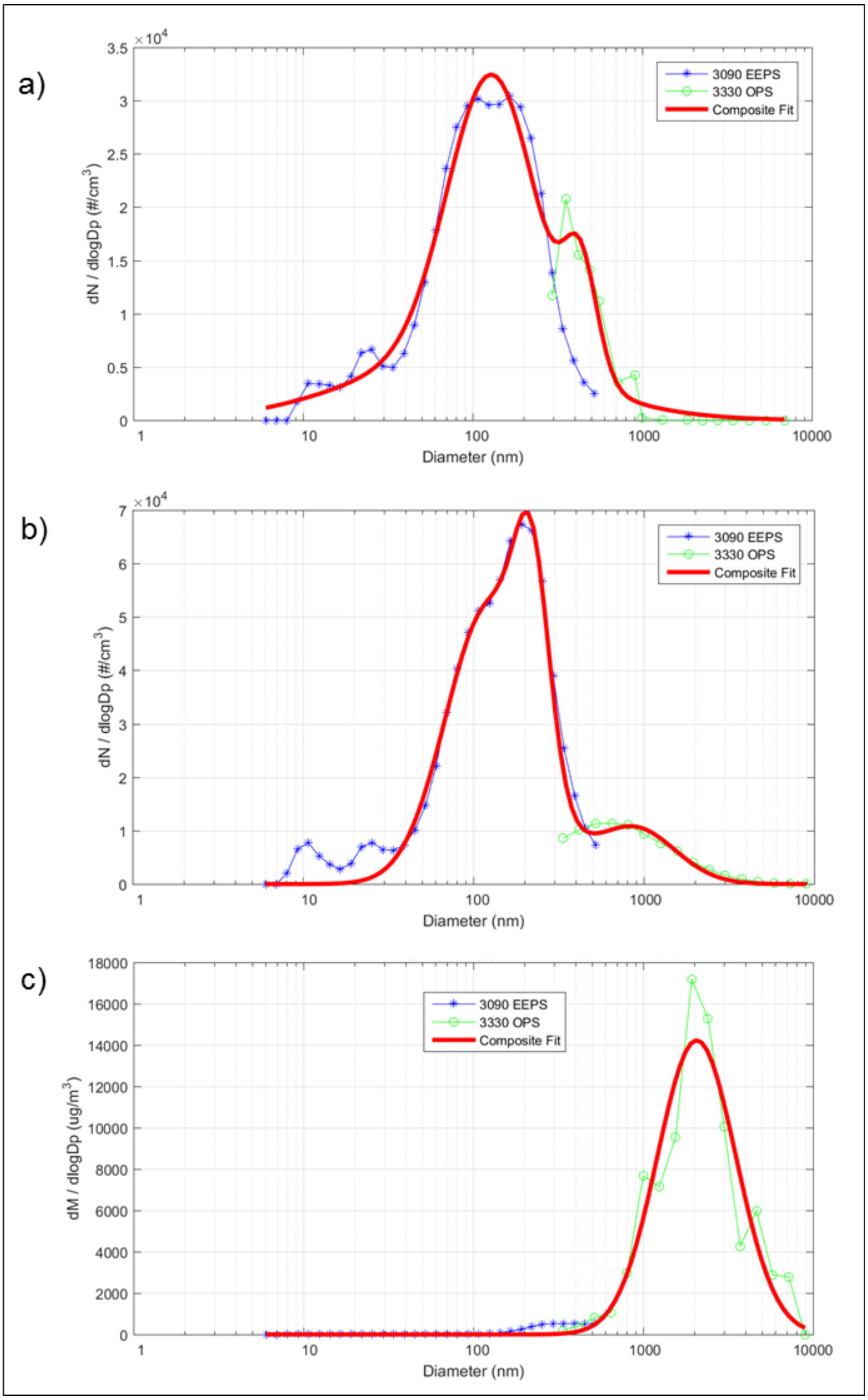

Figure 4, a-c: Particle number concentrations from brake events with low (a) and high (b) energy; calculated particle mass concentration (using a density of 1 g m^{-3}) from the brake event shown in Panel c (same scan as b).

The dominant particle size in both events is around 100 to 200 nm. Especially during the low-energy event the particle concentration in the size range above 1 µm is significant. Panel (c) shows the mass-weighted size distribution, assuming a density of 1 g m^{-3} for the calculation, corresponding to the number size distribution shown in panel (a). The peak above 1 µm indicates that supermicron particles can represent a very critical component of brake wear emissions in terms of mass contribution. The high energy event, on the other hand, produces the bimodal distribution shown in panel (b), with a second peak around 500 nm. The variability in particle size distributions shown in Figure 4 demonstrates the need for an instrumentation system capable of measuring particles over a wide size range. While the data shown here are not intended to represent all potential braking conditions, they do demonstrate the suitability of the EEPS spectrometer and OPS to conduct measurements of brake wear emissions.

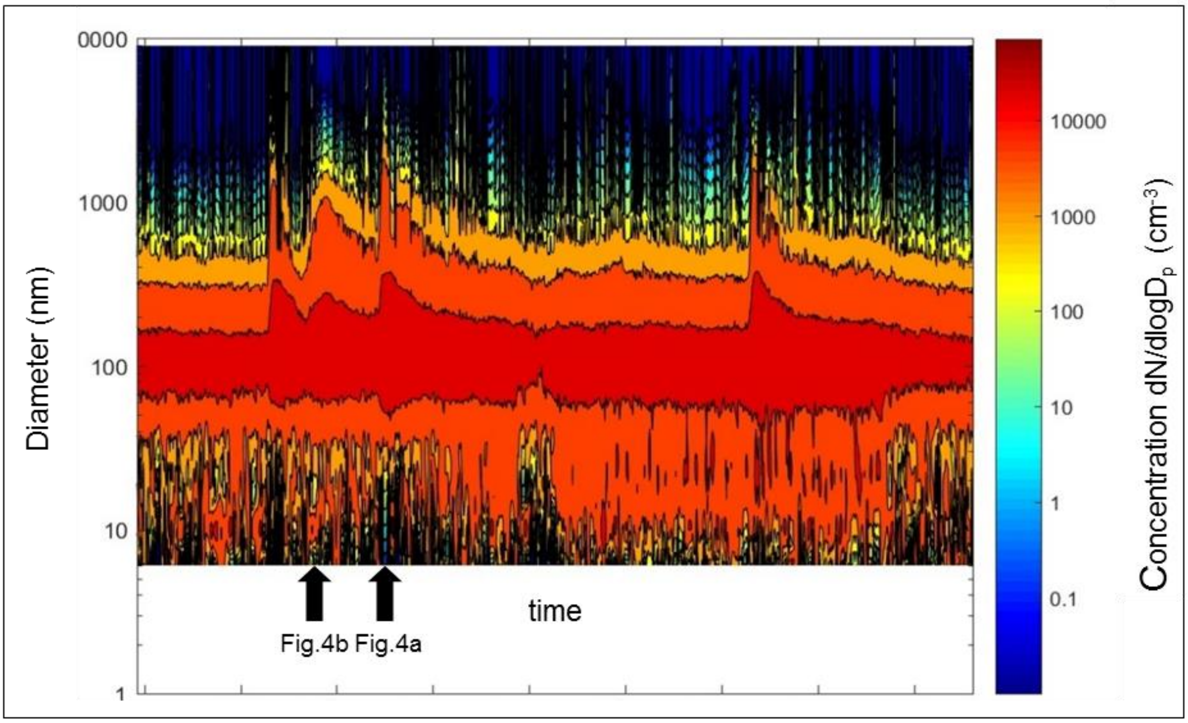

Figure 5: Time series of merged size distributions with a time resolution of 10 Hz for several braking events. The plot shows approximately 2.5 minutes of data for the size range of 6 nm – 10 µm. The number concentration is shown in the color scale at right. The arrows indicate the time of selected scan shown in Figure 4.

Size Distribution Changes

The change in the particle size distribution over time can be observed in the contour plot in Figure 5. It shows the evolution of the differential concentration (dN/dlogDp) from 5.6 nm to 10 µm; single size distributions, such as shown in Figure 4, represent a slice of the contour plot shown in Figure 5, with a time resolution of 10 Hz. The time series shown in Figure 5 suggests that the dominant particle size throughout the three brake events depicted was around 100 nm, and that at most times the distributions are unimodal. It's important to note that, depending upon braking conditions, particles larger than 1 µm may be observed (upward-pointing spikes of red and orange). It is also possible that the emissions may exhibit a bimodal size distribution (as suggested by the thin red "islands" in the lower right portion of the plot).

Conclusions

The measurement of brake wear emissions is very complex. A system covering a wide size range with a high time (10 Hz) and size resolution is required. Particles emitted during friction processes may change rapidly in terms of size and number concentration. Unimodal size distributions are common, but bimodal distributions are also possible when particles larger than 1 µm are observed. Particle instruments that can measure over a distribution range from few nm to several µm with high frequency are clearly needed to characterize emissions from the entire braking process. Data gathered using the EEPS spectrometer–OPS system are provided for ease of use in one file. Particle number size distributions characterize the brake wear emissions and number concentration data may be incorporated into future regulations or measurements standard. The combined setup with EEPS spectrometer and OPS shows a clear advantage in dynamometer brake emission measurement. The number-weighted size distribution can be converted into a mass-weighted size distribution in the size range from 5 nm to 10 µm. This provides information on the emitted PM_{10} level, which is still under discussion. Besides this the mass distribution gives a good insight on where the main of material comes from that determines brake wear.

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EEPS-007 Rev. B-(A4)

Printed in U.S.A.