

## An Engine Exhaust Particle Sizer™ Spectrometer for Transient Emission Particle Measurements

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### Abstract

There has been increased interest in obtaining size distribution data during transient engine operation where both particle size and total number concentrations can change dramatically. Traditionally, the measurement of particle emissions from vehicles has been a compromise based on choosing between the conflicting needs of high time resolution or high particle size resolution for a particular measurement. Currently the most common technique for measuring submicrometer particle sizes is the Scanning Mobility Particle Sizer (SMPS™) system. The SMPS gives high size resolution but requires an aerosol to be stable over a long time period to make a particle size distribution measurement. A Condensation Particle Counter (CPC) is commonly used for fast time response measurements but is limited to measuring total concentration only.

This paper describes a new instrument, the Engine Exhaust Particle Sizer™ (EEPS™) Spectrometer, which has high time resolution *and* a reasonable size resolution. The EEPS was designed specifically for measuring engine exhaust and, like the SMPS system, uses a measurement based on electrical mobility.

Particles entering the instrument are charged to a predictable level, then passed through an annular space where they are repelled outward by the voltage from a central column. When the particles reach electrodes on the outer cylindrical (a column of rings), they create a current that is measured by an electrometer on one or more of the rings. The electrometer currents are measured multiple times per second to give high time resolution. A sophisticated real-time inversion algorithm converts the currents to particle size and concentration for immediate display.

### Introduction

The development of this new instrument was driven by the need to make measurements of transient size distributions. Currently the SMPS system is widely used to measure the size distribution of engine aerosols. Since the SMPS requires a minimum of 30 seconds to make a measurement, its use has been limited to stable operating conditions. CPC's have been used to measure fast engine response but are limited to measuring total concentration only.

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A number of researchers have used the components of the SMPS system (Classifier and CPC) to measure the transient concentration of one particle size at a time by fixing the particle size with the classifier and making a measurement through an entire test cycle. By repeating a test multiple times, each time with different particle size settings, it is possible to get transient results for a few particle sizes. However, this approach is very time consuming and assumes that each test will generate identical particle distributions so that multiple runs can be used to build up a high time resolution particle distribution.

A new instrument, the Engine Exhaust Particle Sizer<sup>TM</sup> (EEPS<sup>TM</sup>) provides both high temporal resolution and reasonable size resolution by using the same basic technique as the SMPS but with multiple detectors in parallel. This makes the EEPS ideal for measuring engine transients. TSI has developed this instrument based on technology licensed from Airel, Ltd. (associated with the University of Tartu, Estonia.) The EEPS joins a long line of TSI engine research instruments, based on electrical mobility, going back to the 1960's.

### Engine Exhaust Particle Sizer

The EEPS was designed specifically to measure particles emitted from IC engines and vehicles. It measures particle size from 5.6 to 560 nanometers with a sizing resolution of 16 channels per decade (a total of 32 channels). Reading the size distribution 10 times per second allows for the measurement of transient particle emissions. The mobility measurement is similar to what is done in an SMPS but

multiple electrometers are used to provide simultaneously measurements.

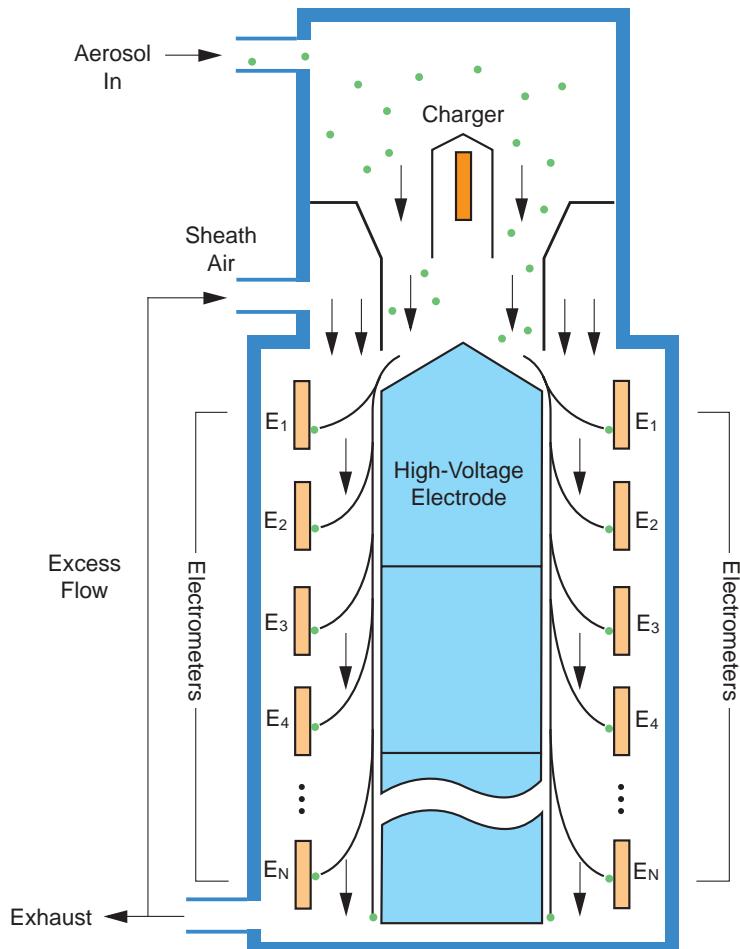


**Figure 1 Engine Exhaust Particle Sizer**

The particles enter the instrument through a cyclone with a 1  $\mu\text{m}$  cut (see figure 2). This removes large particles that are above the instrument's size range. Next, the particles pass through an electrical diffusion charger in which ions are generated that mix with the particles to provide a predictable charge based on particle size.

The particles then enter an annular space between two cylinders that is filled with clean sheath air. The particles pass next to a central rod that has a high voltage to produce an electric field that repels the particles outward to the electrometer rings. Small particles are detected at the top of the column and larger particles at the bottom.

In a traditional DMA particles enter a cylinder at the outer diameter and are attracted to a central rod by the electrical field. In the EEPS the “Inside-Out” DMA provides an outward mobility necessary for making the measurement. The particles are collected on electrometer rings transferring their current to a sensitive electrometer on each ring. The electrometers are read 10 times per second by a microprocessor which then inverts the current data to get particle sizing distribution data.



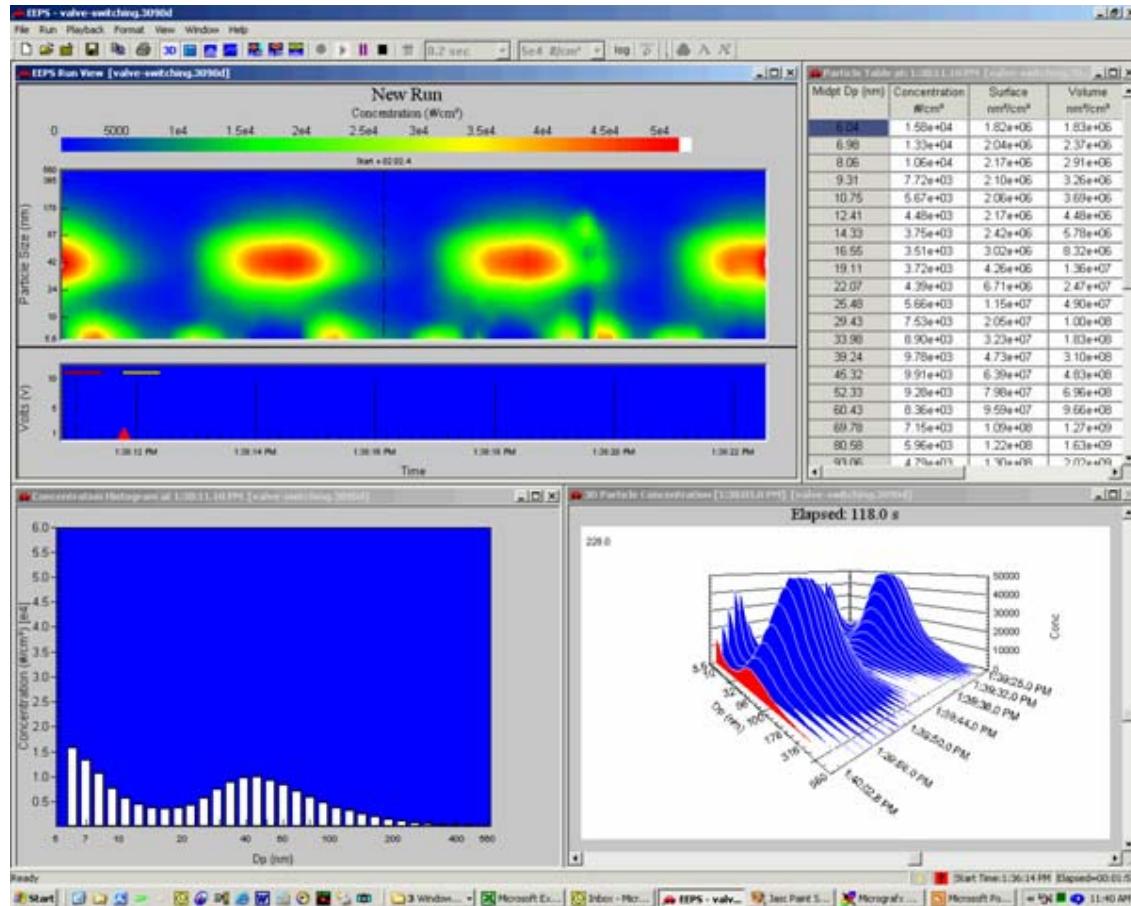
**Figure 2 Schematic of EEPS**

### Data Inversion

The current data from the 22 electrometers does not directly relate to specific particle size channels. Particles that enter the EEPS at the same time are detected at different times, on different electrometers, depending upon size and charge. In addition, particles of the same size are not equally charged, they are charged according to a charge distribution, and are therefore detected on multiple electrometers. The data inversion algorithm accounts for these factors and generates a curve of concentration versus particle size. This curve is then divided into equally spaced channels on a log scale to give the size distribution information. Size distributions are determined 10 times per second and sent to the instrument display and to an attached computer where the data can be further displayed and logged.

## Data display and software

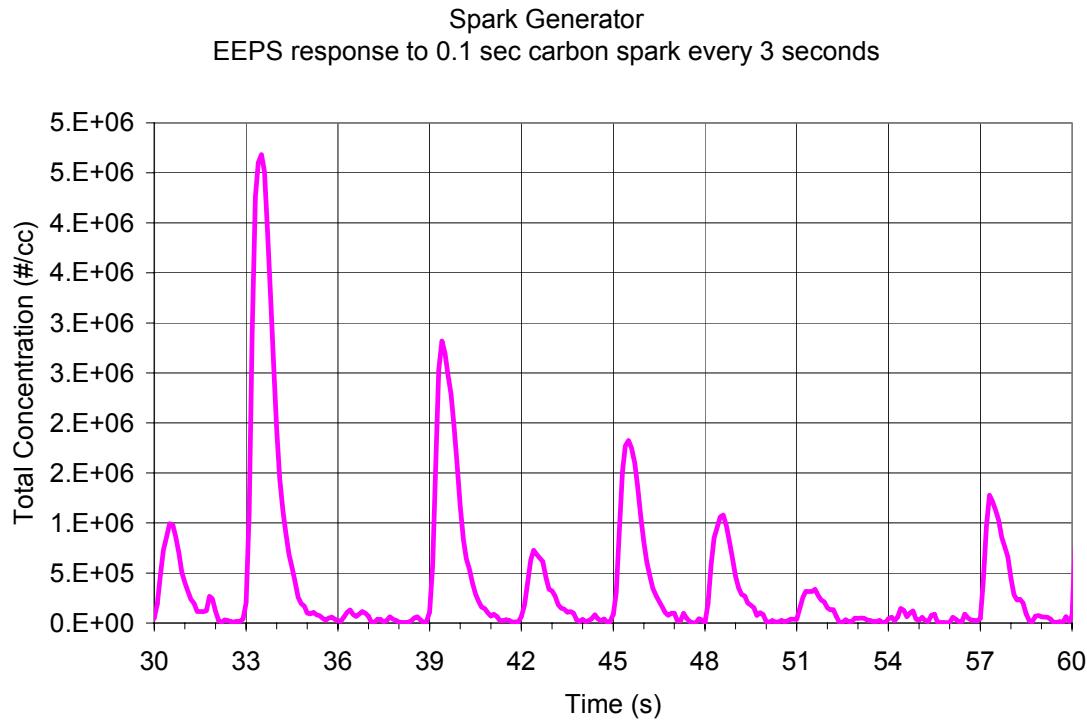
Size distribution data is displayed once per second, with a one second average, on the front panel color VGA display of the EEPS. This display is intended to be an aid in making sure the instrument is properly connected to the particle source. The software also displays one second averaged data, while the data is being collected. The three main graphic screens and the data table are all updated with the same one second average when the data is being collected. During data playback the data can be displayed for every 100 milliseconds (0.1 second) or in averages from 0.2 to 60 seconds.



**Figure 3 EEPS Data Formats**

The software display in figure 3 shows the data display formats. The upper left graph is the main controlling graph. It is a 2 dimensional contour graph with the size on the vertical axis, time on the horizontal axis and color indicating concentration. Directly below the contour graph is a graph that can display analog inputs such as drive cycle parameters (i.e. engine speed, load, and/or torque). The lower left hand graph is a 2 dimensional graph of size versus concentration. The lower right hand graph, a 3 dimensional sizing graph, shows size distribution graphs over time. The table in the upper right hand corner shows concentration versus particle size in units of count, surface area, volume, mass and density (density can be set the same for all sizes or set individually for each particle size).

The data displayed in figure 3 is from an oil aerosol source that was switched on and off with two second intervals. The valve switching results in aerosol that ramps



**Figure 4 Measurements on EEPS to Spark Generated Aerosol**

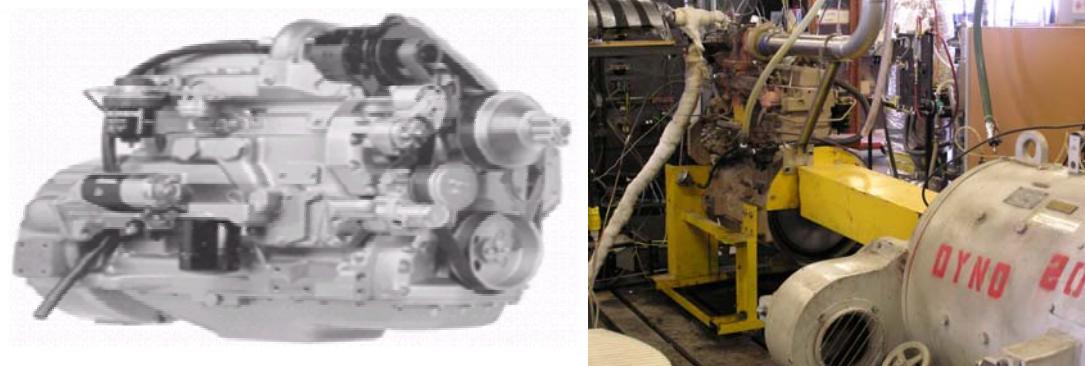
quickly up and down.

Figure 4 shows concentration pulses detected by the EEPS in response to a spark aerosol generator. A carbon arc spark is created for 100 milliseconds every three seconds. The output of the spark generator is highly variable so the peaks vary dramatically in concentration. The spark generator is mounted directly to the input connection of the EEPS. Because the concentration varies from spark to spark it is hard to use the rise time as an indicator of the true response time. The fall time is a better indicator and is in the range of 0.5 second. However, some of this time is due to dispersion in the sampling lines rather than the inherent instrument response.

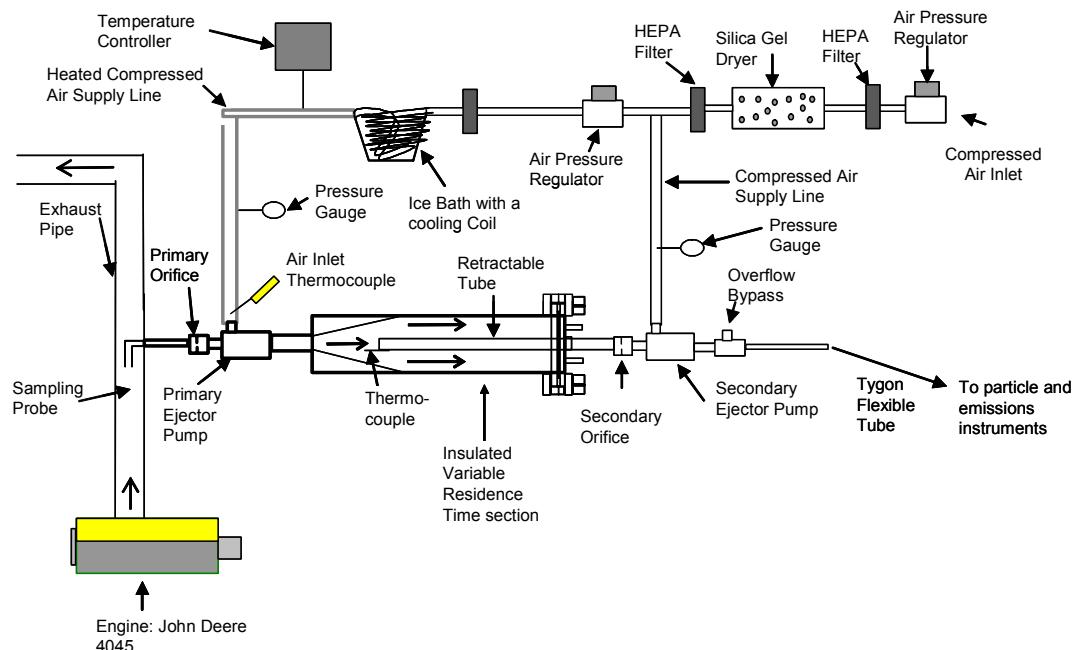
### Engine Test Results

The engine test results in this paper were from tests taken on an engineering prototype version of the EEPS. The engine was a 4045 T John Deere diesel engine which is installed in the Center for Diesel Research in the Mechanical Engineering Department at the University of Minnesota. It is an in-line, 4-cycle engine with a displacement of 4.5 liters. The rated power is 125 hp at 2400 rpm (intermittent).

Figure 5 shows a picture of the engine and the engine connected to a dynamometer. Figure 6 shows the particle sampling system used in the engine testing. The first stage of the sampling system used a heated ejector diluter and heated dilution air. The diluter is followed by an ageing chamber that allows the size distribution to stabilize. Following the ageing chamber is a second cool ejector diluter. Both diluters use clean dry air for dilution.



**Figure 5 Measured Charge per Particle verses Electrical Mobility Diameter for Charger**



**Figure 6 Sampling system for Engine Measurements**

The first set of engine data (figure 7) compares the total concentration from the EEPS (with one second average) with the concentration output of a 3022A CPC. The engine conditions are 10% load. As the concentration varies with time, the output of the EEPS tracks well with the CPC data. The spikes in the data correspond to emission changes that occurred in this engine when operated under these conditions. These “hiccups” can be heard in the engine and are clearly visible in the data. Because the one second data updates on the CPC and the one second average on the EEPS data do not necessarily overlap completely, and the response of the CPC is considerably slower than the EEPS, the relative height of the spikes are not necessarily the same on the two traces.

### CPC vs. EEPS Data

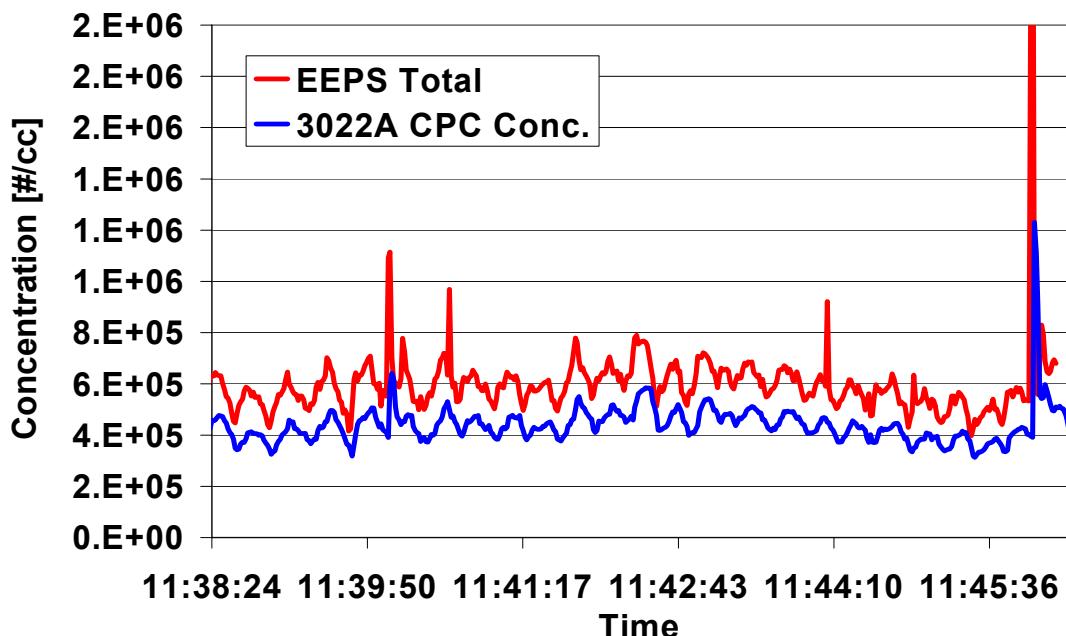


Figure 7 Concentration comparison EEPS to 3022A CPC

Figure 8 shows the size distribution changes that occur when the engine load is rapidly changed from 10% load to 75% load and back. The particles distributions show both nucleation and accumulation modes.

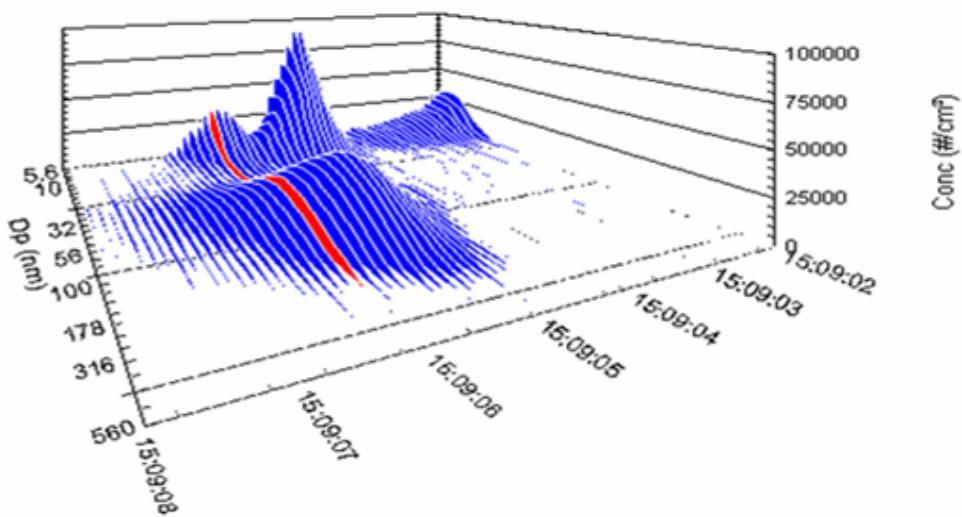
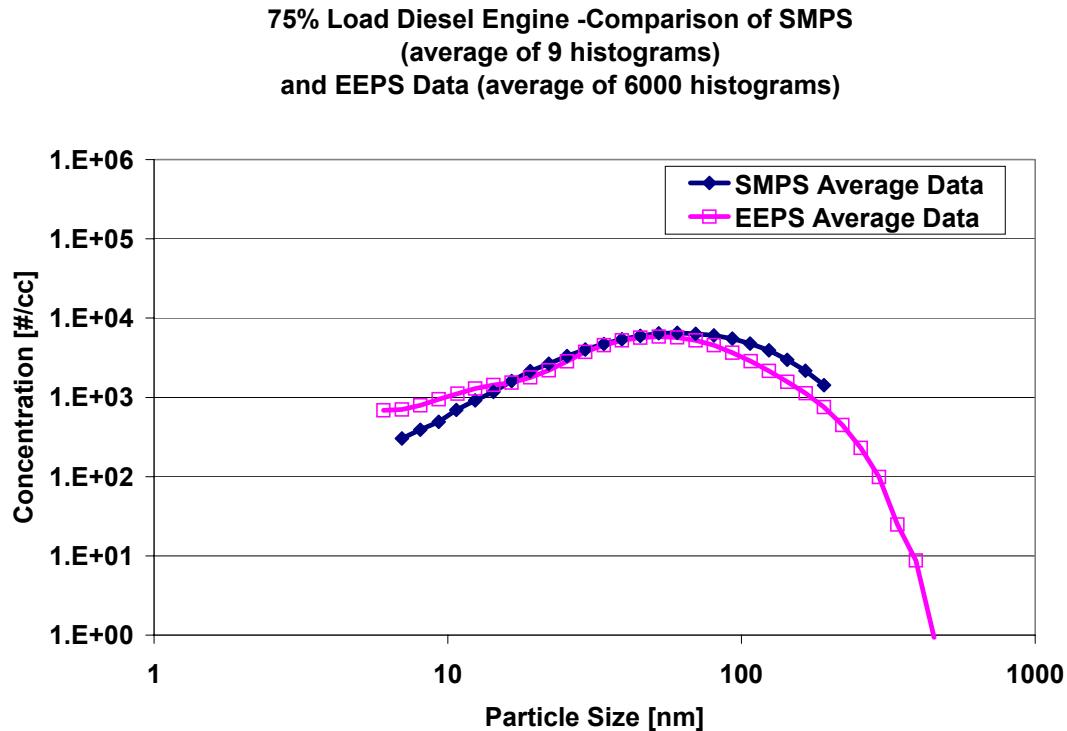


Figure 8 Change in size distribution with time during transient engine conditions

In figure 9 the size distribution data of the EEPS is compared to that of the SMPS. Because of the faster time resolution of the EEPS the data for the EEPS data shown is the average of 6000 size distributions and it corresponds to the same time interval as the 9 SMPS histograms. The particle size distribution agrees fairly well over most of the size distribution. For the smaller particle sizes we suspect the SMPS data shows lower concentration due to diffusion losses. The higher sample flow of the EEPS lowers the diffusion losses. The size range covered by the EEPS is wider



**Figure 9 Size Distribution Comparison SMPS versus EEPS**

than the size range covered by a single scan of a SMPS and covers the entire range of interest for vehicle exhaust particles.

### Summary

The Engine Exhaust Particle Sizer (EEPS) is a new instrument capable of measuring size distributions of transient nucleation and accumulation mode particles. Its fast response allows for the measurement of transient signals. It has faster response than CPC's but tracks well with CPC concentrations. The size distributions measured correlate well with SMPS results. It covers the size range of interest for engine exhaust measurements. The EEPS is an instrument that makes it possible to easily measure transient engine particle size distributions with a time resolution and size resolution that has not been possible before.