Particle sizing and number measurement with EEPS, ELPI, SMPS and CPC techniques

Maija Lappi, Päivi Aakko, Hannu Vesala (VTT Processes)
Hans-Georg Horn (TSI GmbH)

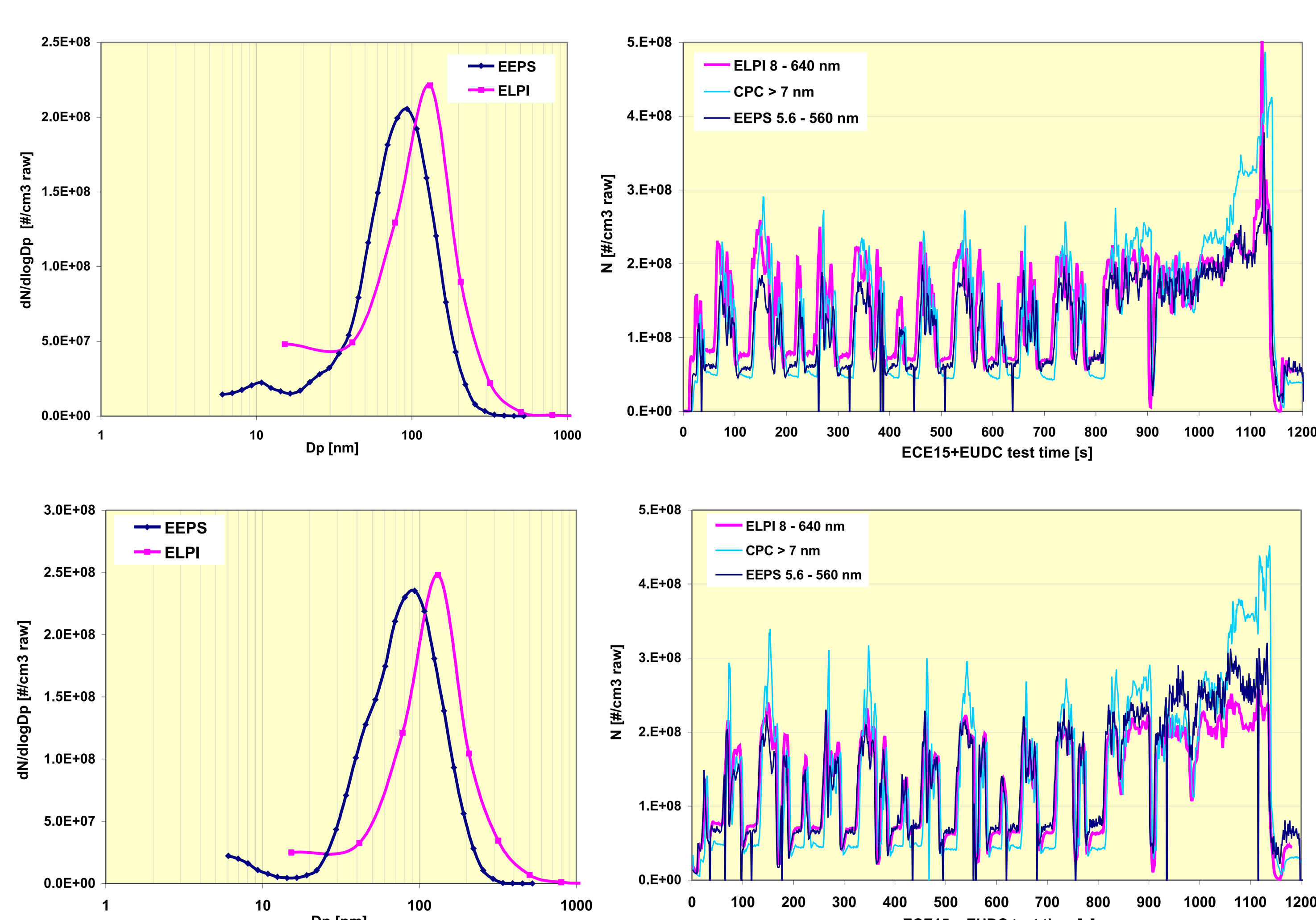
Particle size distributions and number emissions from the exhaust of a passenger car at constant speed and from the ECE15+EUDC transient test cycle were studied using several up-to-date sub-micrometer particle sizing techniques in parallel. Electrical mobility sizes and numbers were measured with a new dynamic particle sizer EEPS, nano-DMA and CPC, and aerodynamic particle sizes with ELPI. The test set-up for all instruments, i.e. dilution systems, dilution ratios and transfer line lengths was identical. Hence, possible differences in particle number emissions originated from the different operation principles of the particle sizing systems themselves (aerodynamic vs. electrical mobility separation, particle density and shape, effects on volatile matter). EEPS is advantageous in giving both high size and high time resolution which is significant in dynamic emission conditions. ELPI, CPC and SMPS are forced to compromises either in size or in time separation capabilities. In the best cases total particle numbers were within 10 % throughout the dynamic test, in the worst within 50 % for the three techniques. Comparability between instruments for particle numbers was better for the soot mode than for nanoparticles. For ultrafine particles ELPI frequently gave the highest numbers.

EXPERIMENTAL

- **Test vehicle** A turbo-charged, 1.9 l DI direct-injection diesel car with EGR (model year 1996). Oxidation catalyst was removed to enhance bimodal particle size distribution.
- **Fuel** Finnish winter grade citydiesel with max. 50 ppm sulphur. In some tests fuel with1 % lubricant addition was used to bring up nucleation; sulphur content of this fuel was max. 75 ppm.
- **Driving conditions** Constant speeds of 40 and 80 km/h and over the transient European test cycle (ECE15+EUDC) according to Directive 70/220/EEC and its amendments.
- **Dilution** Primary dilution was accomplished with AVL SPC472 Smart Sampler mini dilution tunnel having minimised transfer line lengths (max. 50 cm); dilution air was at ambient temperature and dried with HED 0015 adsorption dryer to RH 0 %. For secondary dilution ejector was used. Primary dilution ratio ranged Dr 14 - 40 (in some cases Dr 80 - 280), and total Dr was 80 - 300.
- **Particle measurements**
  EEPS (Engine Exhaust Particle Sizer) Model 3090; size range D_b 5.6 - 560 nm, 32 channels, time resolution 0.1 s
  ELPI with a filter stage; size range D_a 8 - 10000 nm; 12 impaction stages, time resolution 1 s
  Nano-DMA TSI 3085 classifier with CPC 3025A particle counter; size range D_b 4 - 160 nm, 100 size channels, time resolution 2 min
  CPC TSI 3022A condensation particle counter; total particle number from D_b 7 - 1000 nm, time resolution 1 s

RESULTS

Particle emission formation in ECE15+EUDC transient cycle was monitored with the dynamic instruments EEPS, ELPI and CPC. For a unimodal accumulation size distribution total number of particles compared very well regardless the different measurable size ranges of the instruments, **Figure**. The particle number of soot size distribution is dominated by 30 - 300 nm particles, which are measurable by all techniques. The measuring principles of the instruments are also different. In the best cases the differences were within about 10 % throughout the dynamic test, and even in the worst case within 50 %. No tendency of any dynamic technique systematically showing superior or inferior particle numbers was seen with primary Dr 13 - 16. Particle size distributions of ELPI and EEPS also compared very well. The difference in peak D_p is well known, and is due the different measurement principles of ELPI and EEPS. ELPI current is converted to aerodynamic particle sizes and EEPS is monitoring particles having certain electrical mobility. In both techniques particles are assumed spherical.

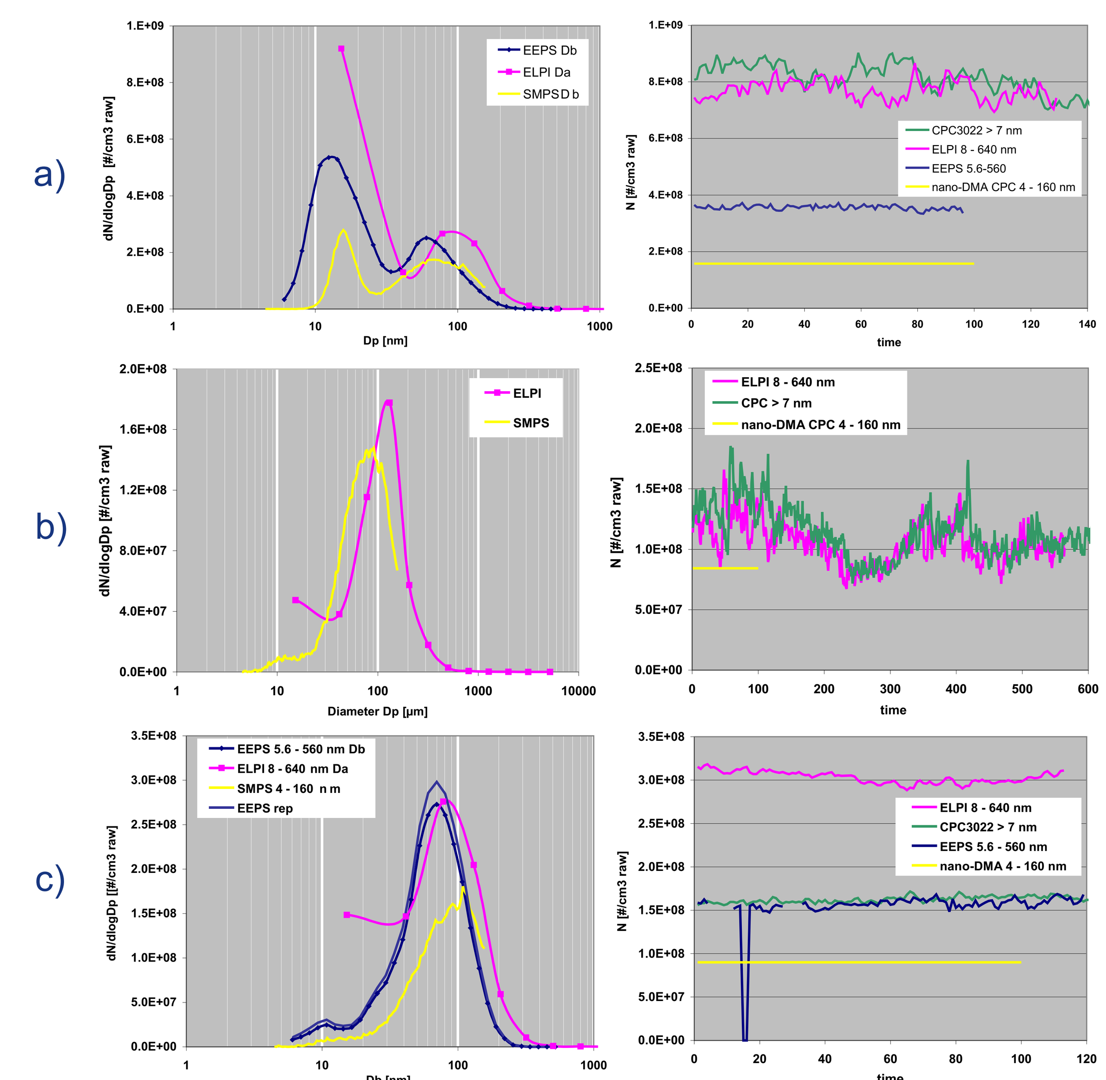


Comparison of ELPI and EEPS measurements in dynamic emission formation conditions. Top: fuel with 1 % lubricant addition (Dr 14x8), bottom: citydiesel fuel (Dr 16x8).

In steady-state driving conditions of 80 and 40 km/h all four measurement techniques were used. The long scanning time of the nano-DMA limits its use to static conditions only. **Figures a)** and **b)** below show the effect of increasing primary dilution ratio. Nucleation was distinct at 80 km/h with the lowest primary dilution ratio from Dr 32, and diminished with dilution ratios through Dr 80 to Dr 280. The nucleation mode peak was seen with all sizing techniques. Relative number of particles decreased in series 6 - 2.5 - 1 with increasing primary dilution ratio, measured with CPC. Tendency was the same with ELPI and nano-DMA. Nucleation in the exhaust was artificially strengthened by the lube addition, though. Without lubricant nano particle mode vanished and EEPS and ELPI gave comparable total particle numbers (Dr 14 x 8).

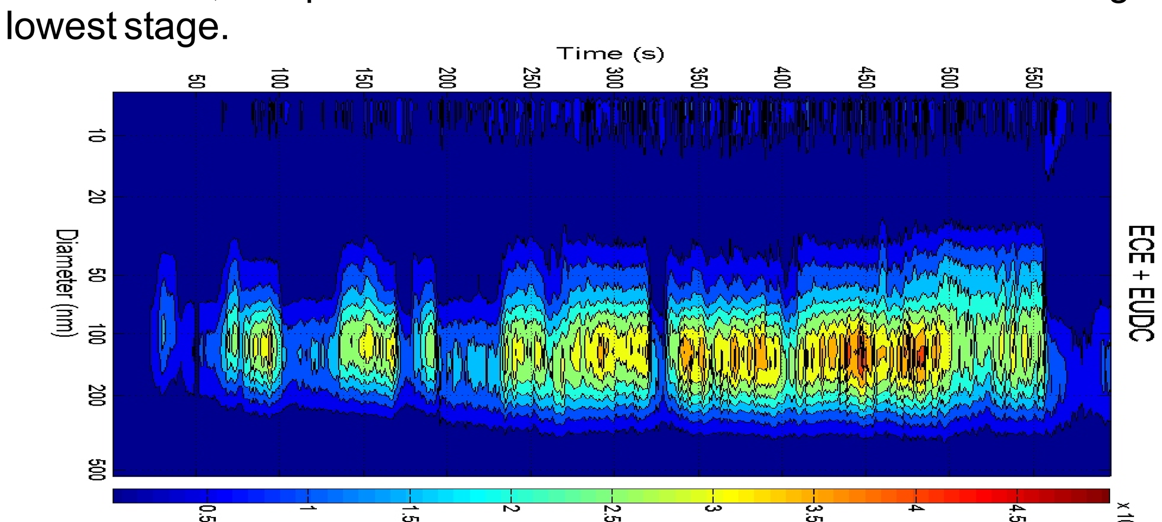
With lube, only particle numbers of ELPI and CPC correlated fairly well. EEPS gave 30 - 50 % lower numbers, and nano-DMA 50 - 80 % lower. The reduced nano-DMA numbers can only for a minor part be explained by the lower particle # cut-size of 160 nm. Between CPC and nano-DMA there was also another peculiarity related to changing dilution ratio. The share of nano-DMA and CPC measured particles changed dramatically with increasing primary dilution ratio. For Dr 32, Dr 80 and Dr 280 the ratios were 0.22 , 0.33 and 0.5, respectively. Reduction for nano-DMA was 50 %. Taking all tests into account it looks like that higher particle numbers seen by CPC are related to low primary dilution ratios, Dr 12 - 32.

At 40 km/h **Figure c)** comparability of the EEPS and ELPI was excellent for accumulation mode particles. ELPI was the only technique seeing a clear nano particle mode. At this speed the peak diameters of ELPI and SMPS were interchanged so that SMPS mobility peak size was at larger particles, about 100 nm than that of the ELPI, about 80 nm, compared to those of 80 - 100 nm and 120 nm of speed 80 km/h. This suggests that soot mode particles at 40 km/h and 80 km/h are not like fractals but have different densities. For all tests (40 km/h, 80 km/h and transient) EEPS mobility peak size was at lower diameters than that of the aerodynamic size of ELPI. Total particle flow of ELPI was overshooting due to the filter stage.

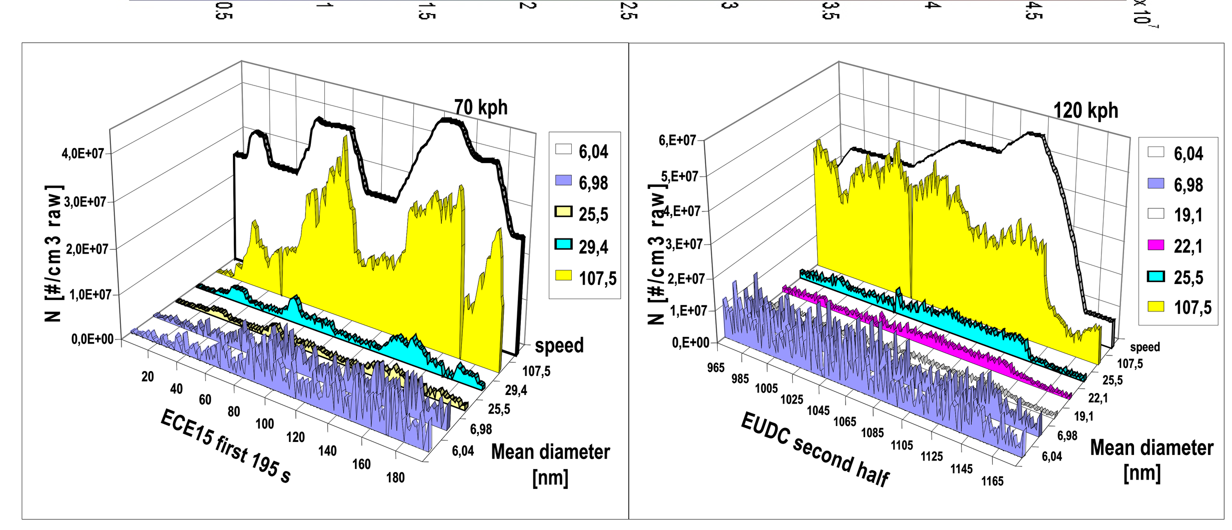


Comparison of ELPI, EEPS and SMPS measurements at static driving speed of Audi
a) 80 kph/two-stage dilution, Dr 32 x 8
b) 80 kph/one-stage dilution, Dr 280
c) 40 kph/Dr 34 x 8.

In the 3D pictures below, **Figure**, two things are noteworthy. During the low speeds of ECE15 the accumulation mode was peaking in range 97 - 107 nm, whereas at higher speeds of EUDC at larger particles, between 107 - 124 nm. Secondly, for D_b < 20 nm particles formation seemed to be independent of test speed or load profile. Numbers are fluctuating and look more or less random in generation. D_b > 20 nm particle formation follows the speed diagram and is predictable. One possible explanation is the different origin of the nano and accumulation mode particles. The smallest particles are for the most part lube based, and lube consumption of the engine is not directly proportional to engine load or speed. Accumulation mode particles are mainly fuel-based soot. As the size resolution of EEPS is better than that of ELPI, this phenomenon is not visible with the ELPI having a broad size range 8 - 30 nm on the lowest stage.

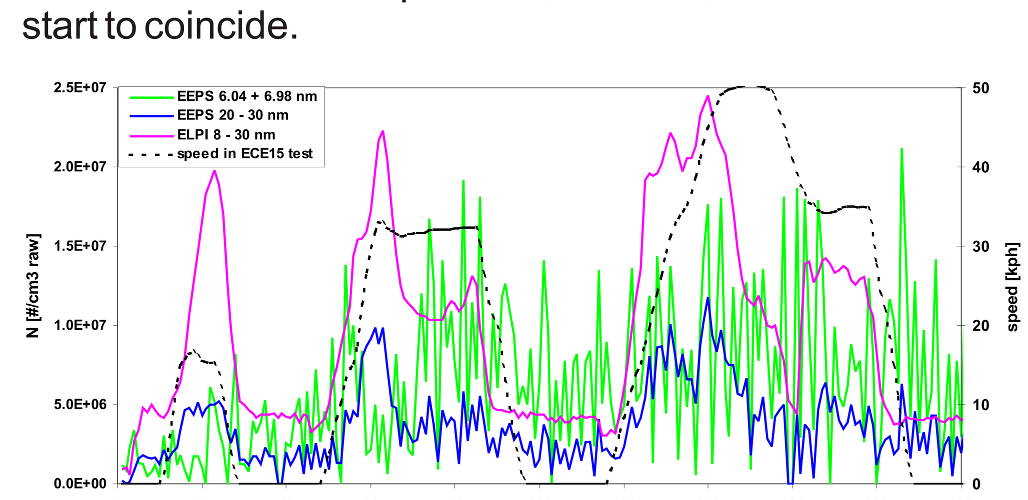


EEPS size spectrum during the first 195 s of ECE15 and at the 50 - 70 -100 - 120 km/h speeds of EUDC.



EEPS images of accumulation mode and nanoparticles during the ECE15+EUDC test.

Illustration of the different responses of EEPS and ELPI for <30 nm nanoparticles is shown in the **Figure** below. If the smallest particles, <20 nm, of the EEPS trace are omitted, profiles of the emission flows start to coincide.



Response of EEPS and ELPI online particle sizing istruments in monitoring nanoparticles in ECE15 test cycle.

CONCLUSIONS

- For the unimodal accumulation mode particles from transient European driving cycle total particle numbers of EEPS, ELPI and CPC compared well.
- With 1 % lubricant addition in the fuel all sizing techniques showed clear nucleation (at 80 km/h) with the lowest dilution ratio Dr 32, and diminishing nucleation with increasing dilution ratios through Dr 80 to 280. The relative total number of particles decreased in series 6 - 2.5 - 1, respectively, with CPC.
- In nucleating conditions ELPI typically detected higher particle numbers than EEPS or SMPS.
- The better size resolution of EEPS compared to ELPI revealed independence of the flux of smallest particles, <20 nm, on vehicle speed. These particles are probably lubricant originated.

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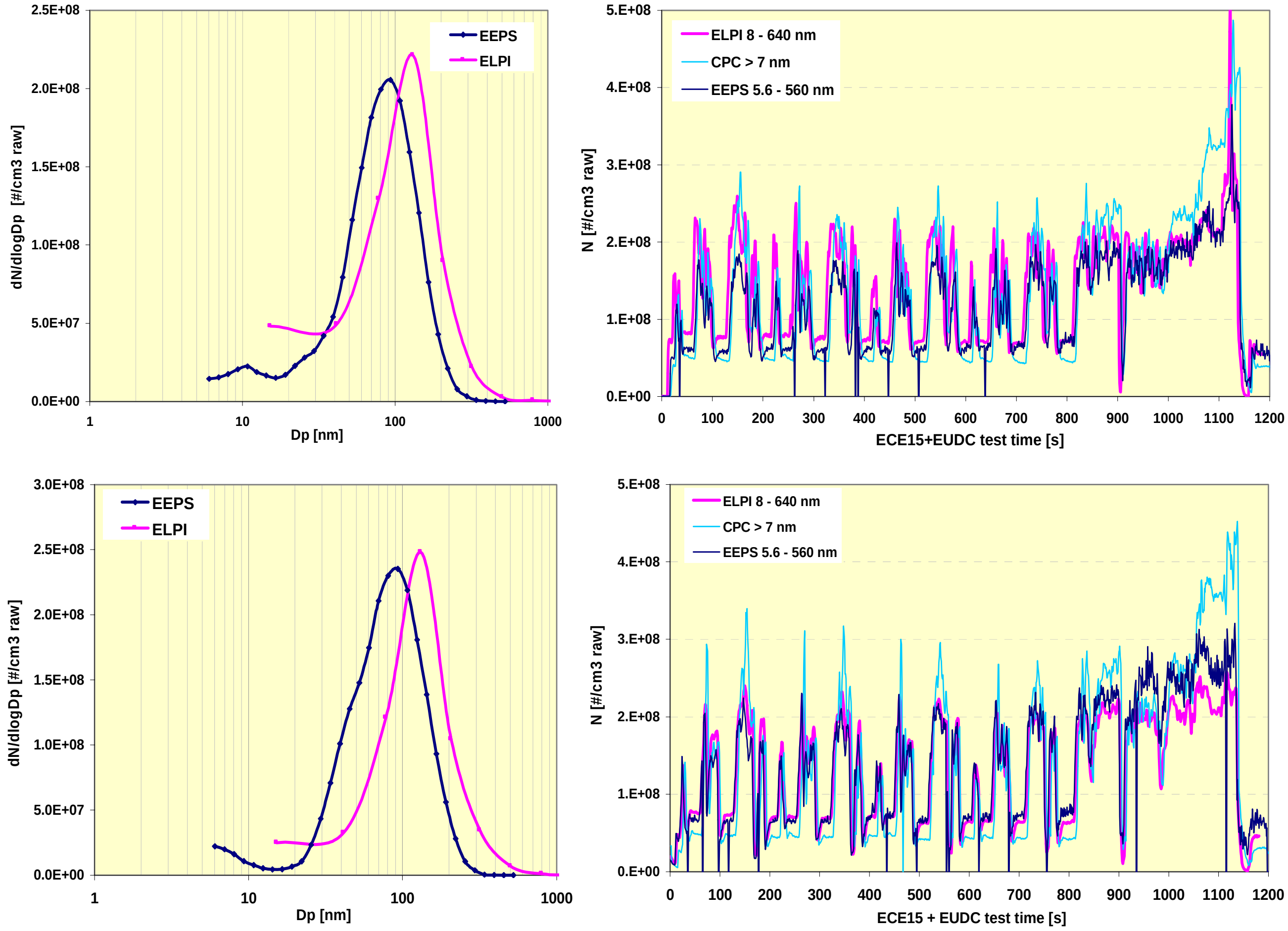

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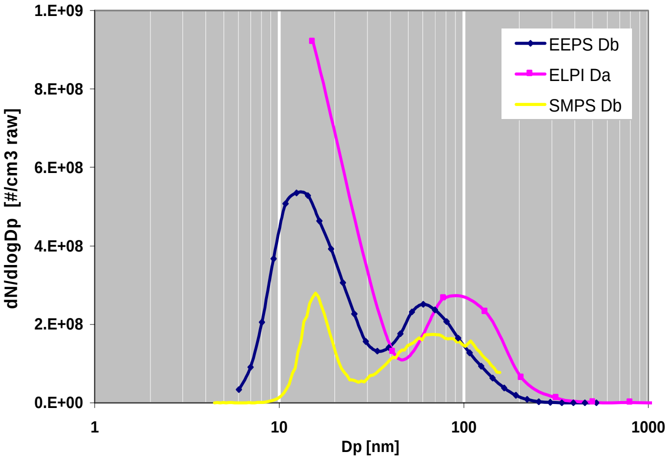

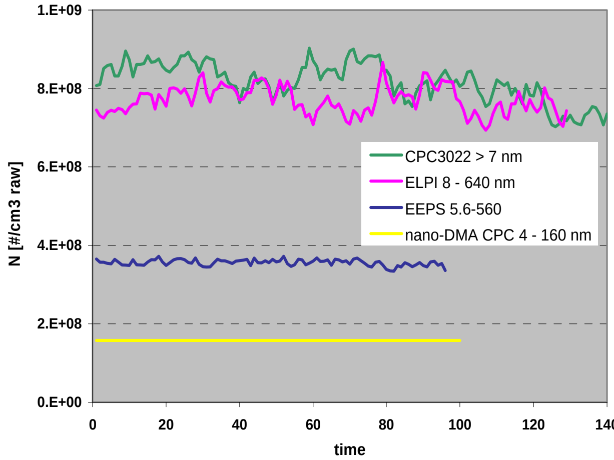

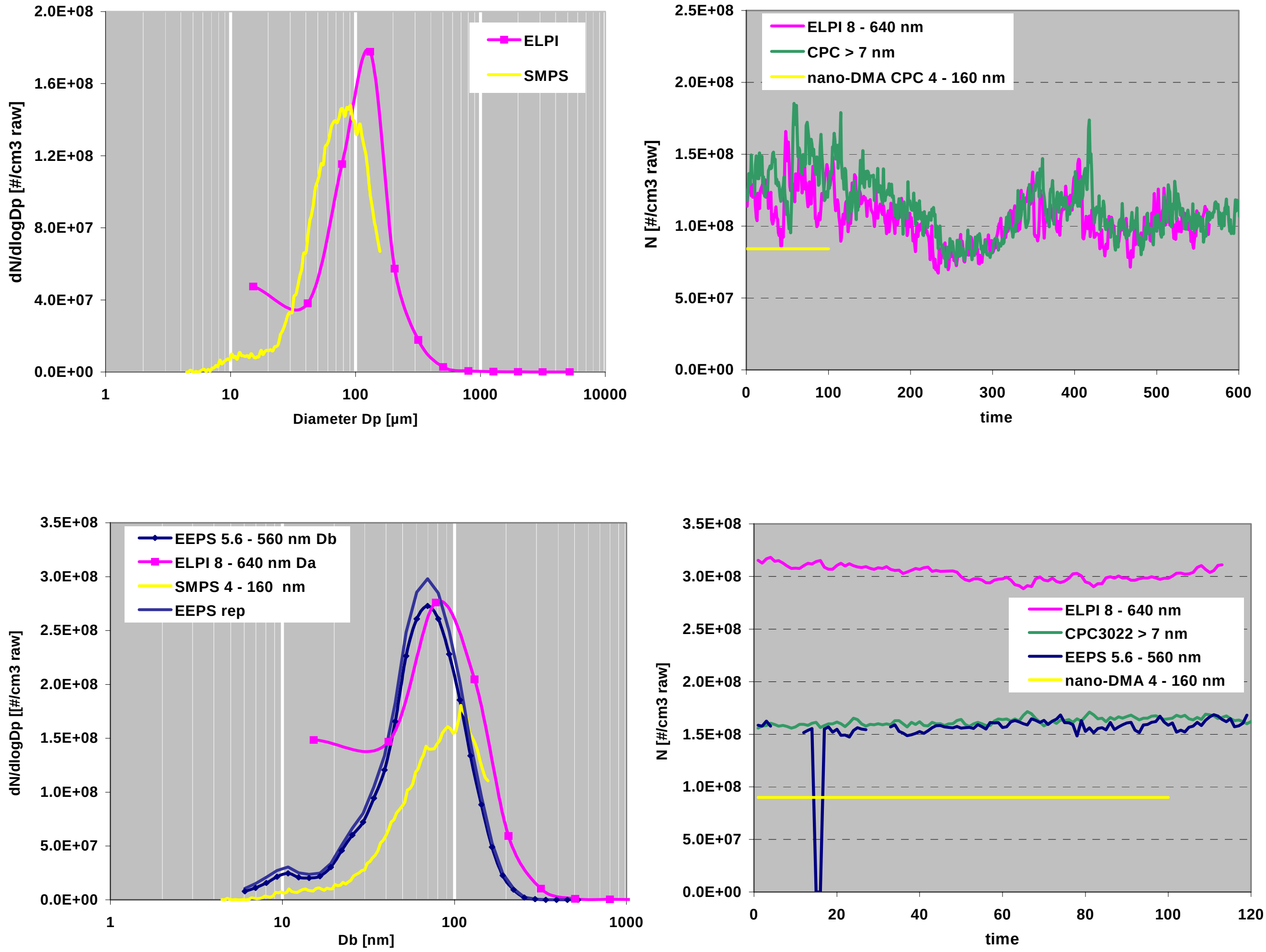

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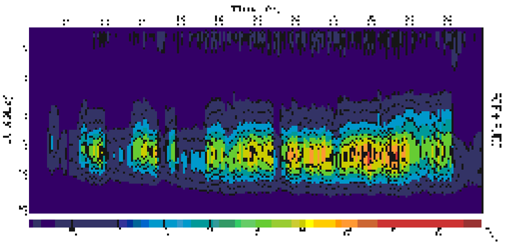

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