Measuring Vehicle Exhaust Solid and Volatile Material with Real-time Mass Monitor DMM-230

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Dekati Mass Monitor DMM-230 is a novel on-line instrument for diesel PM mass measurements, based on particle charging, inertial and electrical mobility size classification and electrical detection of charged particles. The instrument has been tested widely and with different sampling setups, and this paper focuses on the effect of volatile material on DMM data, as well as on comparison between different PM mass measurement methods.

The first DMM evaluations were made with diesel soot after removal of volatile material. The reason for this is twofold: 1) The DMM applies a new density measurement principle to its data evaluation, based on comparison between aerodynamic and electrical mobility diameters. This principle is described in e.g. (1). In DMM the ELPI/SMPS method is simplified so that the mobility size is calculated from a simple 0^{th} grade mobility analyzer data. This method, however, requires unimodal particle size distribution. This case is true for the soot mode of particles. 2) Second reason for dry particle measurements is the mostly unpredictable and uncontrolled behavior of diesel exhaust volatile material. Condensation and evaporation of volatile material results to unstable PM mass concentration and makes the comparison more difficult. It has been showed earlier that with dry particles the correlation between DMM and gravimetric measurement is very good (2).

The regulatory measurement, gravimetric determination of particulate mass, measures both solid and (semi-) volatile material. Therefore this dry particle mass is not directly comparable with regulatory measurements and there is a demand to measure the total PM mass, consisting of both solid and volatile material.

When volatile material is present, there is a possibility for bimodal PM size distribution, consisting of soot and nucleation modes. Nucleation mode particles have a very small diameter, approximately between 3 and 30 nanometers, and even though it dominates the total particle count it has a very small effect on the total particle mass. When this mode is present the DMM is unable to determine the particle mobility diameter and therefore the density measurement algorithm fails. The mobility electrode of DMM covers the size range from about 7 to 35 nanometers, so by comparing this data to impactor data it is possible to detect the nucleation mode and when it is detected a constant particle density value is used instead of the measured one. Therefore the nucleation mode does not prevent the measurement, but the presence of volatile material makes the total mass comparisons more difficult.

Another issue caused by volatile material is the evaporation from the gravimetric filter paper. This happens both during the measurement and also after the measurement, during the filter conditioning period (3). However, electrical detection instruments like DMM measure the particles as they are while entering the instrument, and evaporation of liquid particles after detection has no effect on the data.

Important parameters affecting to the volatile material condensation, nucleation and evaporation are vapor pressure and dilution ratio, dilution temperature and residence times. During a transient tests with a standard CVS tunnel these parameters are changing all the time, depending on the engine speed and load. As a result of this we are able to see different correlation with gravimetric and DMM data even if both are measuring from the CVS tunnel. Different load conditions in different transient and steady-state cycles cause different correlation.

Third important aspect is the adsorption of gas-phase volatile material on the filter paper, as shown by e.g. Chase et al. (4). This is clearly seen as a negative offset in correlation charts between DMM and gravimetric PM data.

All these issues become even more and more important when the diesel emission PM levels decrease to EURO IV and EURO V levels, and especially after diesel particulate filters the measured mass consists almost entirely of volatile material. Differences between sampling systems and measurement methods will become larger and special attention should be paid on volatile matter handling.

(1) Ristimäki, J., Virtanen, A., Marjamäki, M., Rostedt, A. & Keskinen, J. 2002. On-line measurement of size distribution and effective density of submicron particles. Journal of Aerosol Science, vol 33, pp 1541-1557.
(2) Niemelä et al., Mass Monitor and Fine Particle Sampler in vehicle PM emission measurements. 7. ETH-Conference on Combustion Generated Particles. 18th –20th August 2003
(3) Burtscher, H., 1992. "Measurement and Characterization of comustion aerosols with special consideration of photoelectric charging and charging by flame ions", J. Aerosol Sci., 23, pp. 549-595
(4) Chase, R., Duszkiewicz, G., Richert, J., Lewis, D., Maricq, M., Xu, N. (2004): PM measurement artefact: organic vapour deposition on different filter media. SAE Technical Paper Series 2004-01-0967

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Motivation

- Future and partly today’s emission limits require new measurement instruments for PM
  - Opacimeter insensitive
  - Filter measurement method tedious but duable
- Instrument must be real time
- Ideally results should be comparable with the filter measurement method

- Dekati Mass Monitor DMM-230 operates in a way which well defines PM and offers a solution for future PM measurement instrumentation
  - everything in either solid or liquid phase is measured and counted as PM

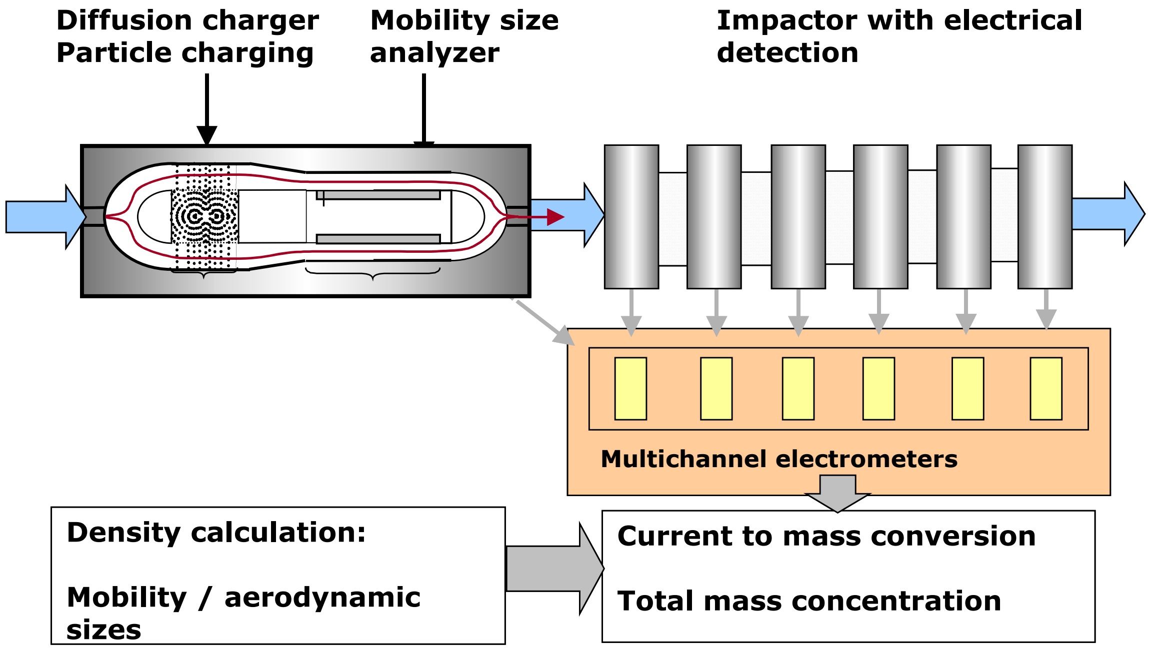
Introduction

- Despite of proposed number measurements, PM mass concentration is still the legislative requirement
- For daily (routine) measurements the most important aspects are linear mass correlation, labour cost savings, ease of use and repeatability
- (Electrical) On-line instruments have potential for higher sensitivity than traditional gravimetric measurement (Ref. PMP project)
- Second-by-second data is a valuable key information for engine development

DMM operation principle and example data

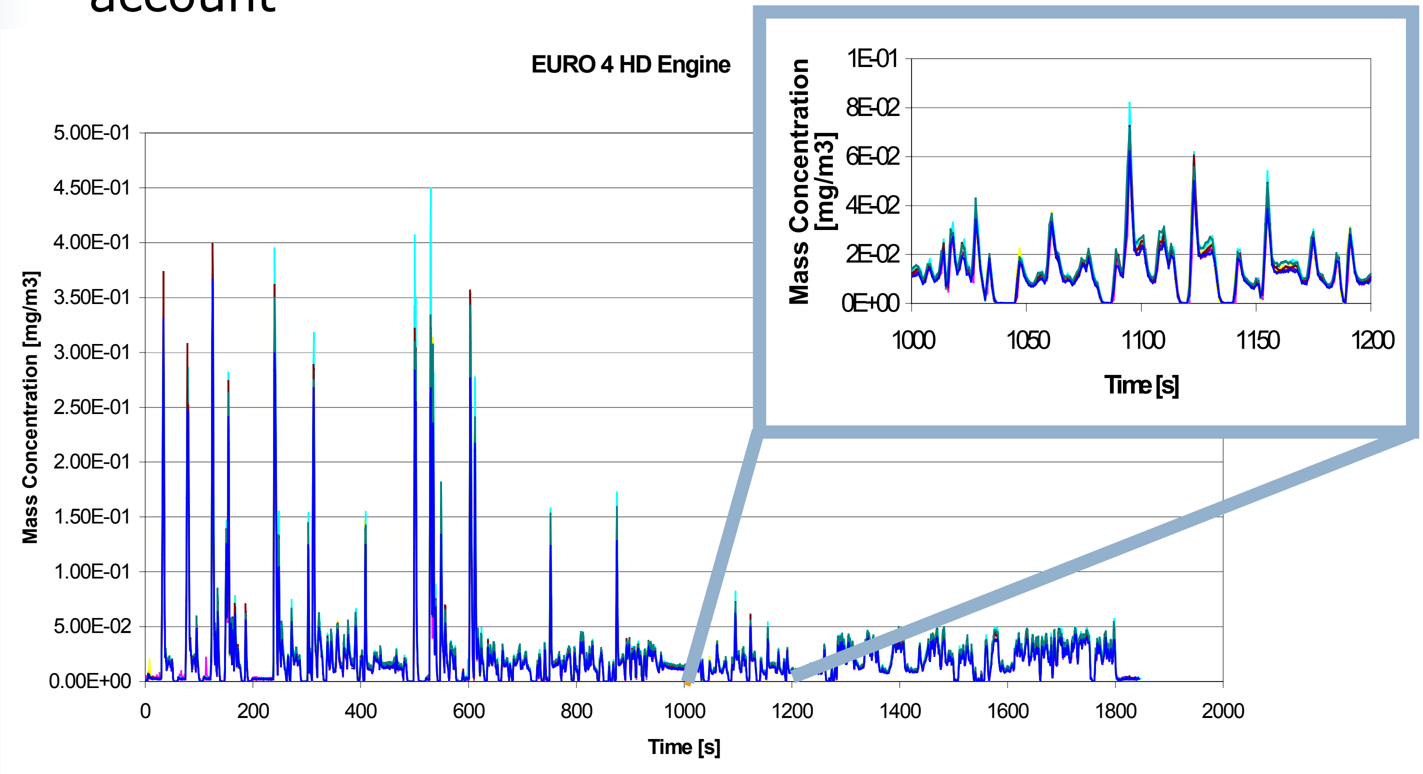
DMM-230
Dekati Mass Monitor

- Based on the ELPI™ technology:
  - Particle charging in a diffusion charger
  - Particle size classification in a low-pressure impactor
  - Electrical detection of particles
  - Density measurement by comparing aerodynamic and mobility diameters (impactor vs. charger mobility analyzer)



DMM Example data

ETC cycle, HD engine. 8 repeations, concentration about 20% below EURO 4 regulations. DR=1:80, not taken into account



Measured during the Swiss PMP program

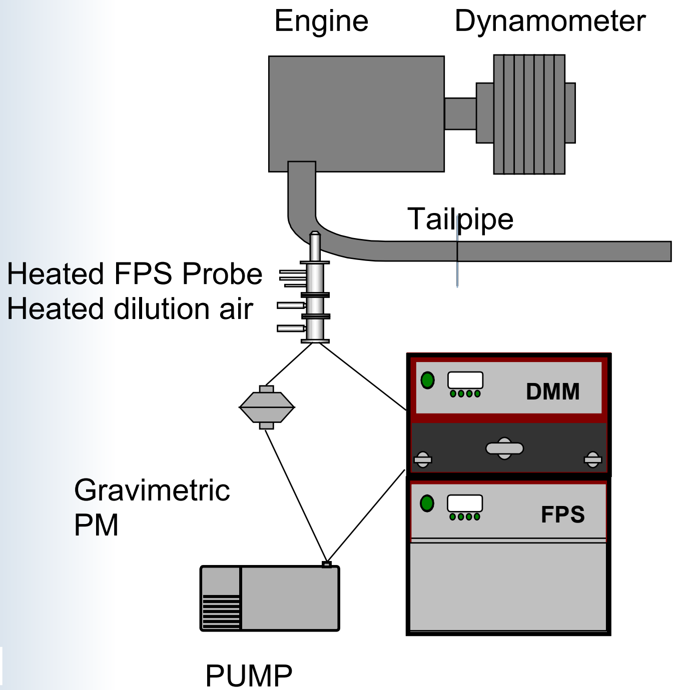
StDev 7.9%, Gravimetric PM StDev 7.7%

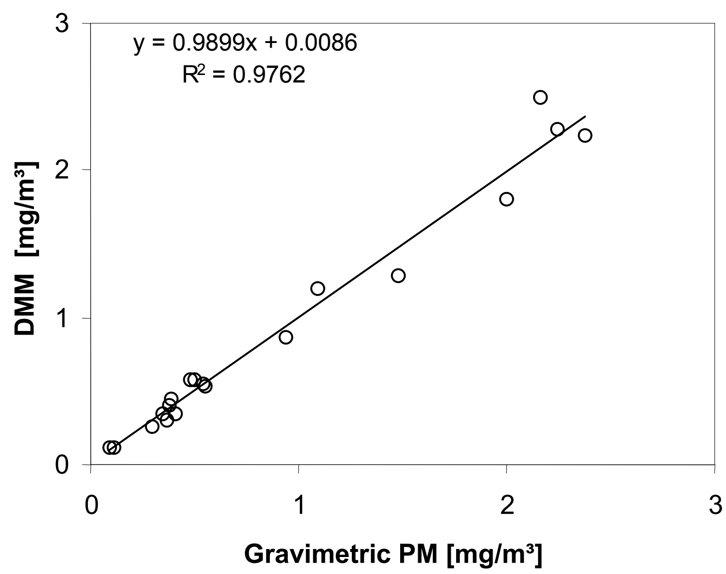
DMM 230
Common questions

- What is the correlation between gravimetric measurement and DMM data?
- How does volatile material affect on DMM result and comparison between gravimetric result?
  - Nucleation mode
  - Condensation / evaporation
  - Filter artefacts
- How different sampling systems affect to volatile material behaviour?
  - CVS tunnel, hot / cold dilution

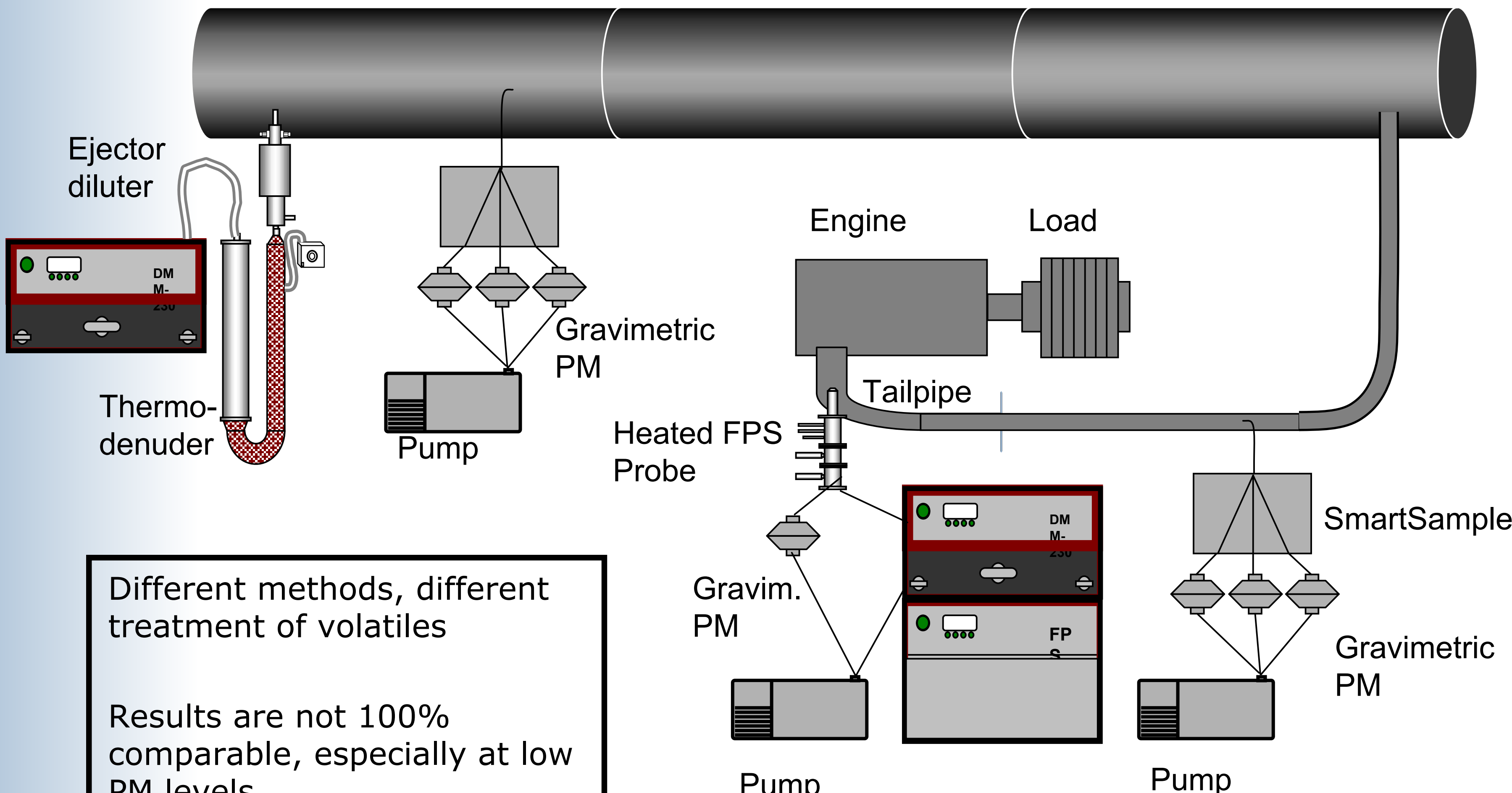
DMM-230
Dekati Mass Monitor

- Tailpipe measurement
  - hot dilution or thermodenuder
  - Density measurement requires unimodal size distribution
  - Dry (soot) particle mass is well defined
    - No evaporation, no condensation, no filter artefacts





Methods for PM mass measurement



Different methods, different treatment of volatiles

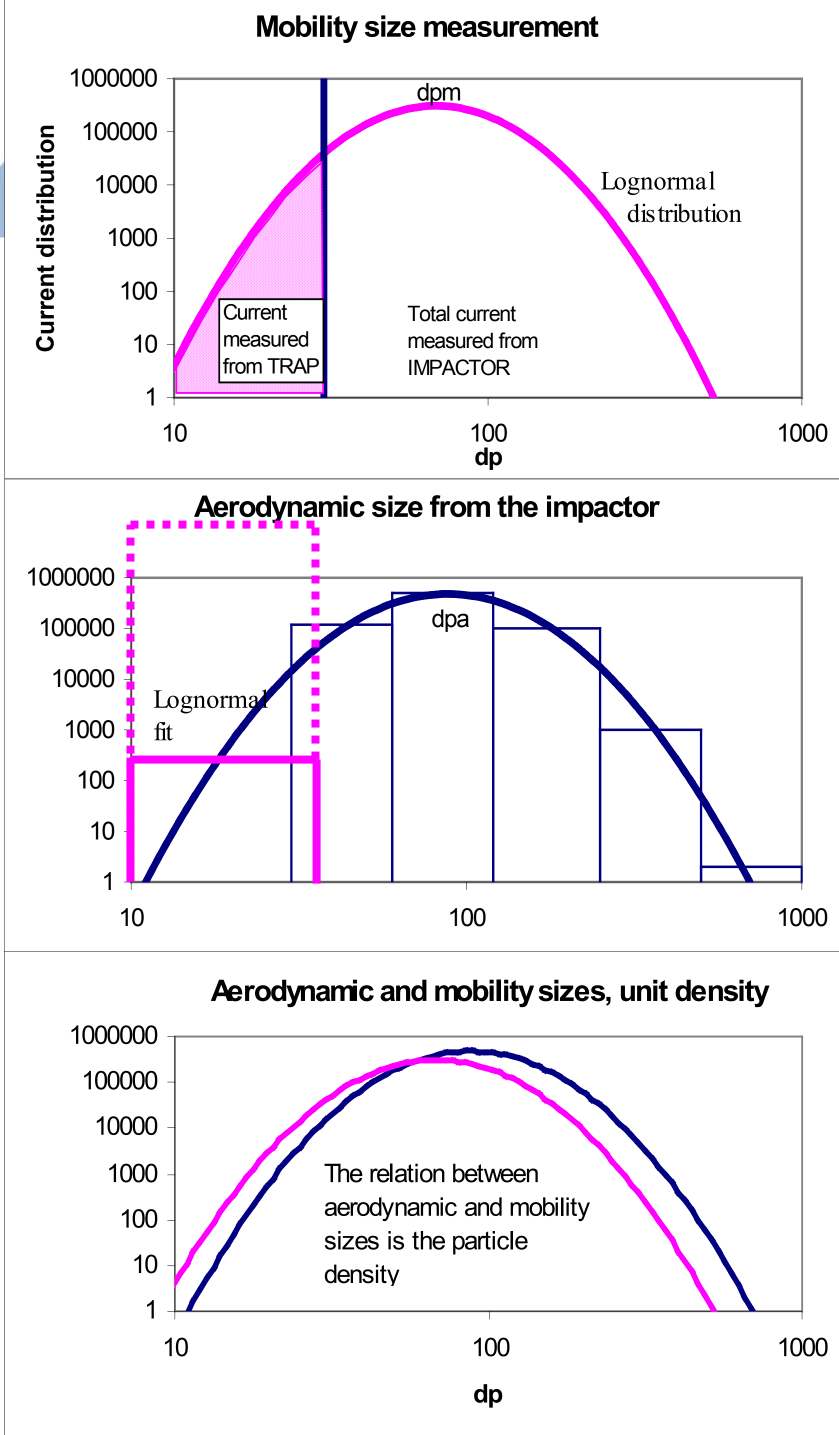
Results are not 100% comparable, especially at low PM levels

Volatile material and DMM data: Nucleation mode

DMM-230

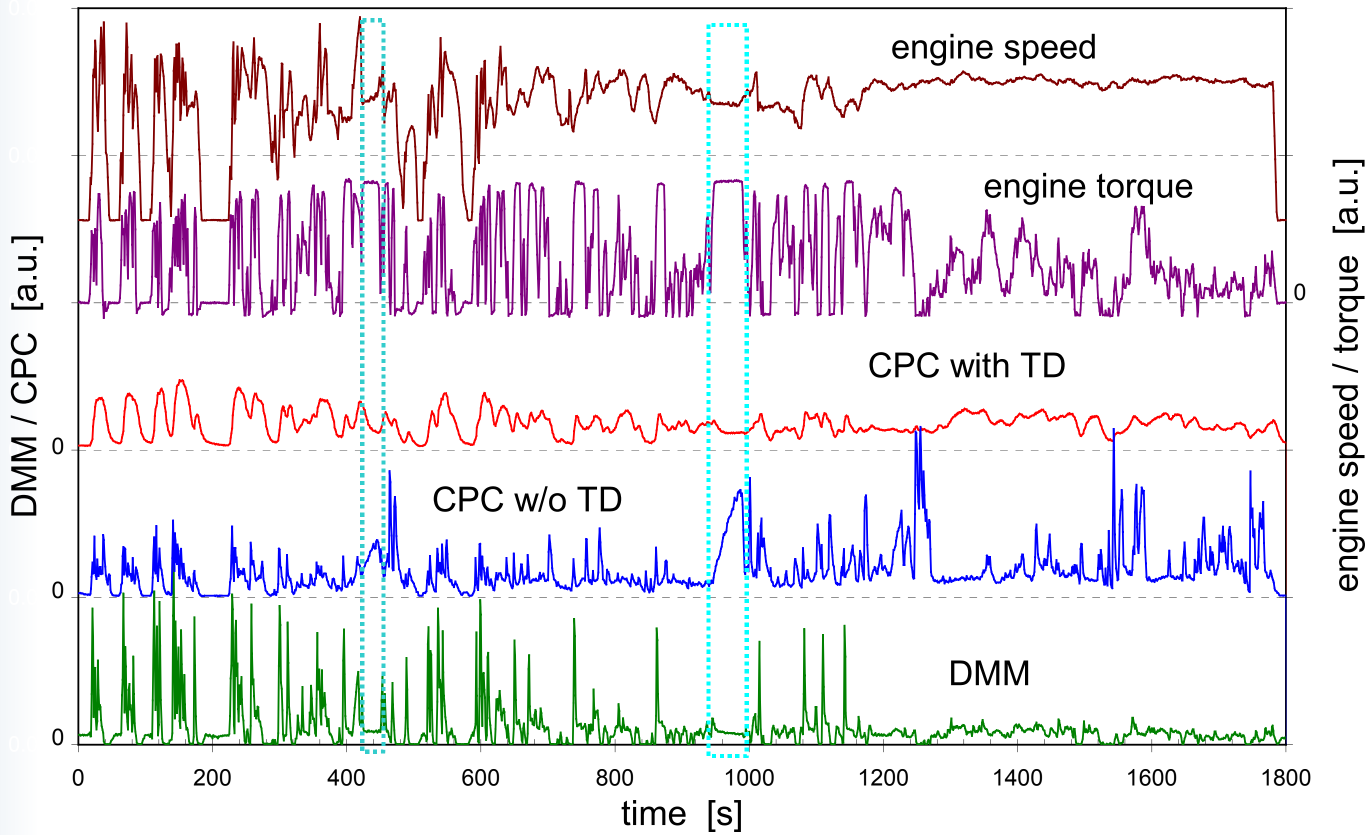
Density measurement

- Covers the particle size range from about 6 nm to 2.5 microns
  - Mobility channel from about 6 nm to 35 nm
- Continuous examination of distribution modality
  - bimodal distribution results to pre-defined density value (ρ=1)
- Nucleation mode detected and unit density assumed



Transient measurement

Heavy duty diesel engine, European transient cycle ETC. CVS tunnel + ejector diluter



Conclusion 1

Nucleation mode, if present, is detected by DMM

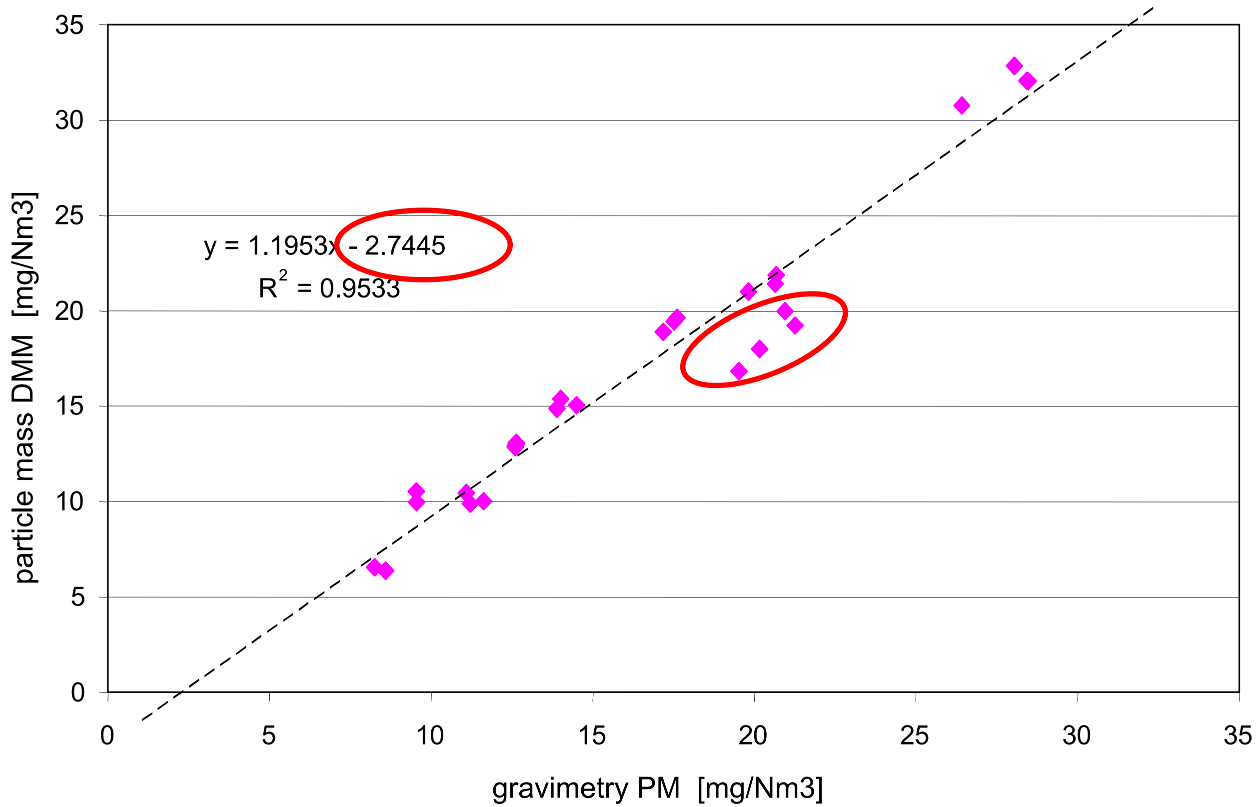
When existent average particle density close to one. This is assumed and does not cause error on the mass measurement

Often forgotten fact: Nucleation mode has practically no effect on the total mass when soot mode is present

Volatile material and DMM data: Correlation with gravimetry

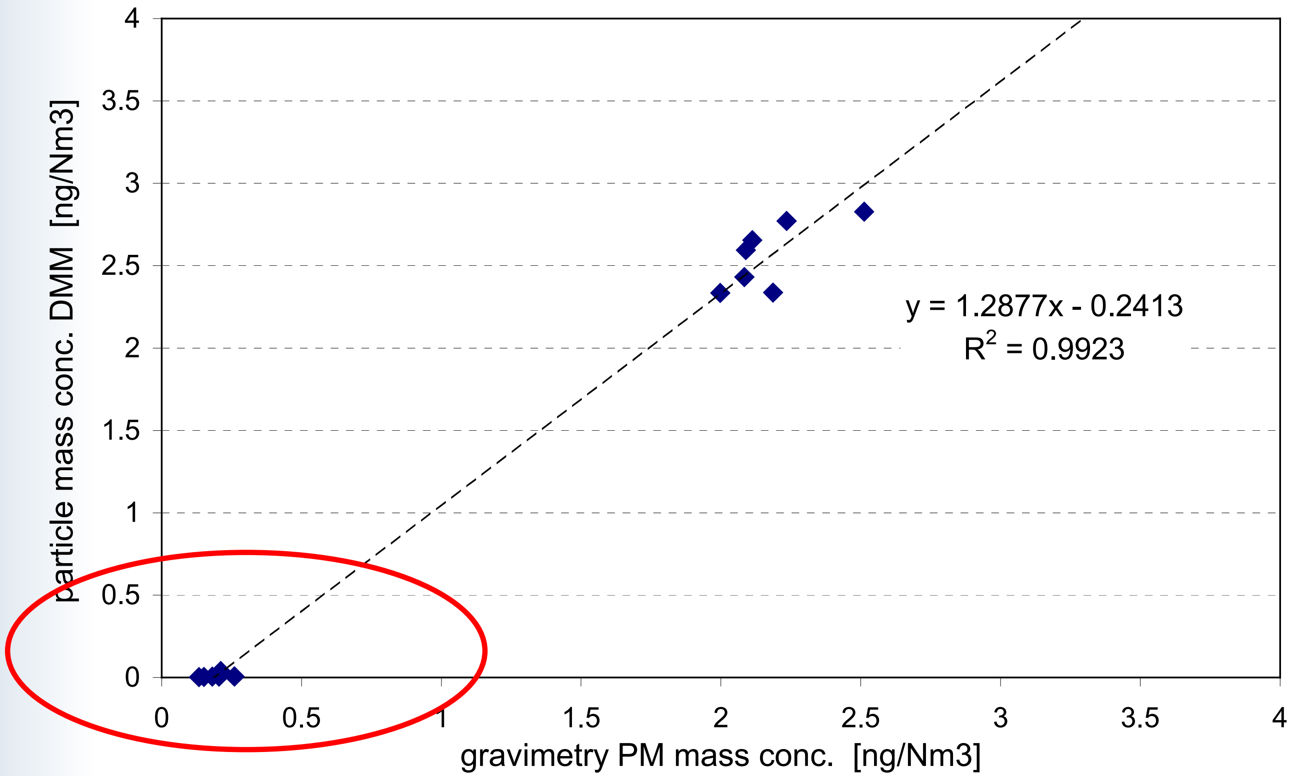
DMM vs. Gravimetric PM

- DMM measuring from the CVS tunnel +one ejector diluter, different transient cycles



DMM vs. Gravimetric PM

- DMM measuring from the tailpipe (hot dilution, 2 ejector diluters)

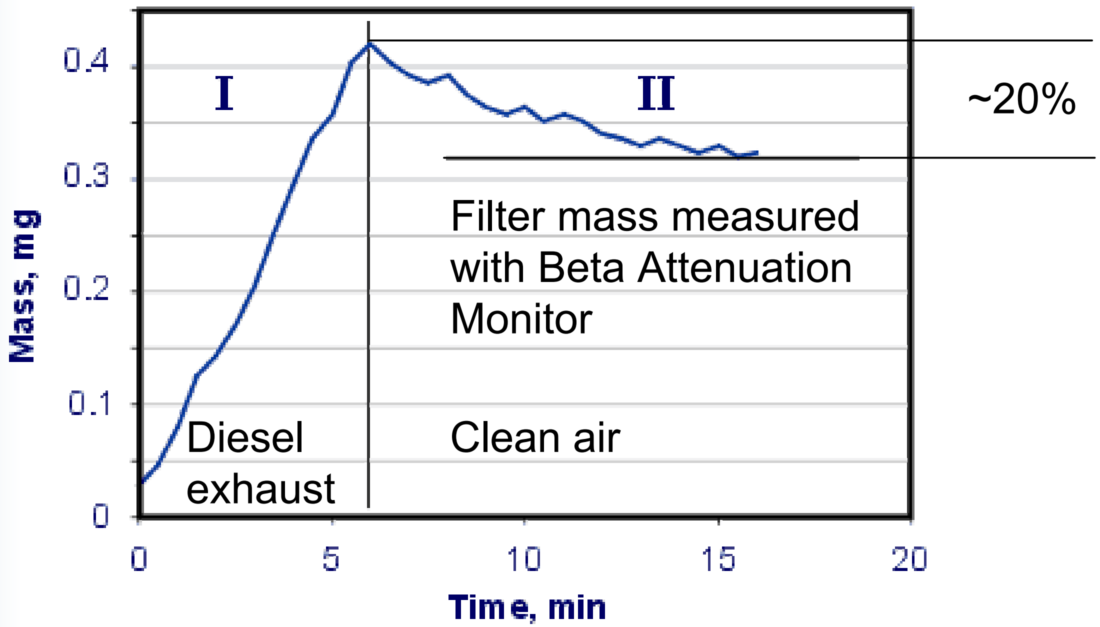


(Data measured during the Swiss PMP phase 2)

Evaporation

- Because of evaporation the filter mass decreases during conditioning

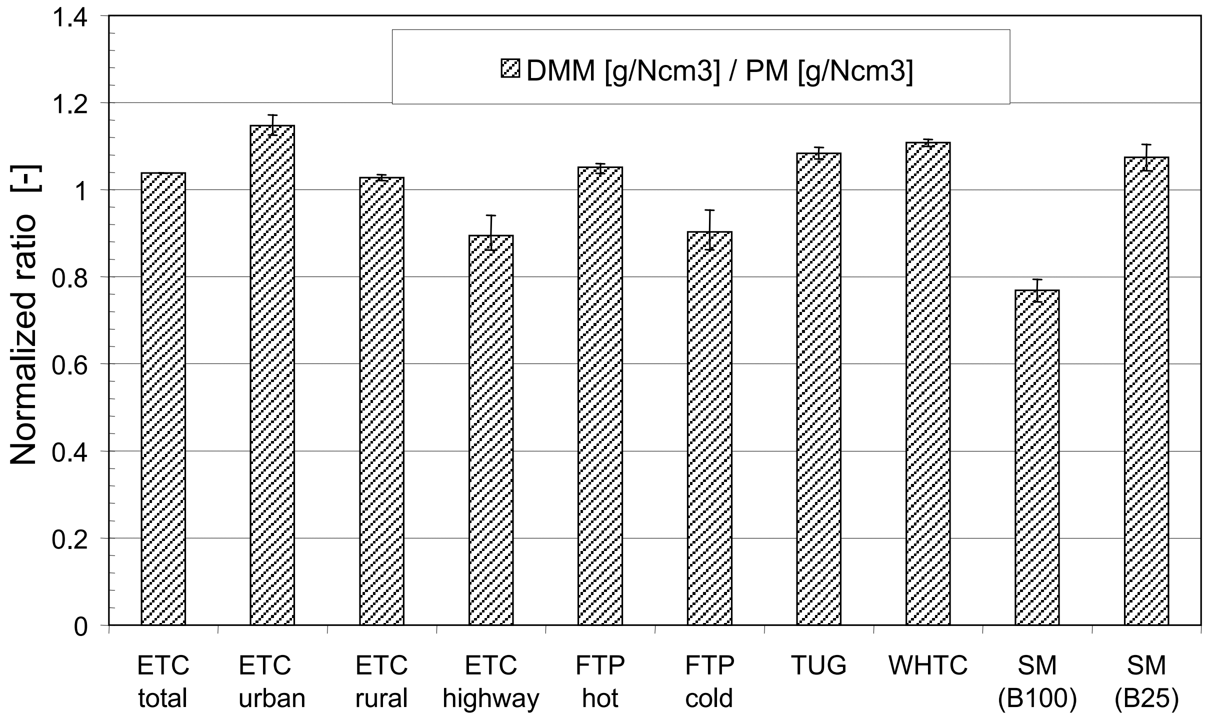
- There is also evaporation during the measurement:



http://www.dieselnet.com/tech/measure_pm_col.html; Original data from Burtscher, H., 1992., J. Aerosol Sci., 23, pg. 549-595

Effect of volatiles

- HD Engine, DMM measuring from the CVS tunnel (one ejector diluter)



CVS DR:	10.7	14.0	8.5	9.7	19.2	19.2	10.7	18.7	3.8	5.0
CVS T[°C]:	50.2	50.3	52.2	50.0	40.6	30.6	44.4	33.3	118	63

Conclusions

- DMM measures the PM mass with high accuracy and high sensitivity
- Volatile material or nucleation mode do not prevent DMM measurement, but those make comparisons more difficult
- Volatile material and its behaviour affect to all mass measurement systems
- Gravimetric PM is not the absolute truth