Rainer Vogt, Ulf Kirchner and Matti Maricq,

Ford Forschungszentrum Aachen GmbH, Süsterfeldstr. 200, D-52072 Aachen, Germany
Ford Motor Company, Dearborn, USA

Particle number emissions are measured with two instruments according to the upcoming European emission regulations for light-duty diesel passenger vehicles and compared to data from other methods, including the current regulatory total particulate matter (PM) mass, photo-acoustic soot sensor (PASS) and engine exhaust particle sizer (EEPS). At the very low emission levels of diesel particulate filter (DPF) equipped vehicles, the solid particle number data correlate well with soot mass and with particle number measured by EEPS, if only those particles belonging to the accumulation mode are considered in the latter case.
PN differences of >100% between tests of the same vehicle are observed. Comparison of the two PN instruments and the photoacoustic soot sensor show that these are systematic differences which originate primarily with the vehicle and not from instrument uncertainties. After accounting for this, a repeatability of <8% and a reproducibility of <27% are estimated for the particle number method.
A large body of new vehicle data is presented from tests carried out immediately after production. The data show that nearly all vehicles would be below the anticipated Euro-5/Euro-6 particle number limit. The observed variability is significant and needs further investigation.

14th ETH Conference, Zürich, August 1-4th, 2010

Investigation of EURO-5/6 Level Particle Number Emissions of European Diesel Light Duty Vehicles

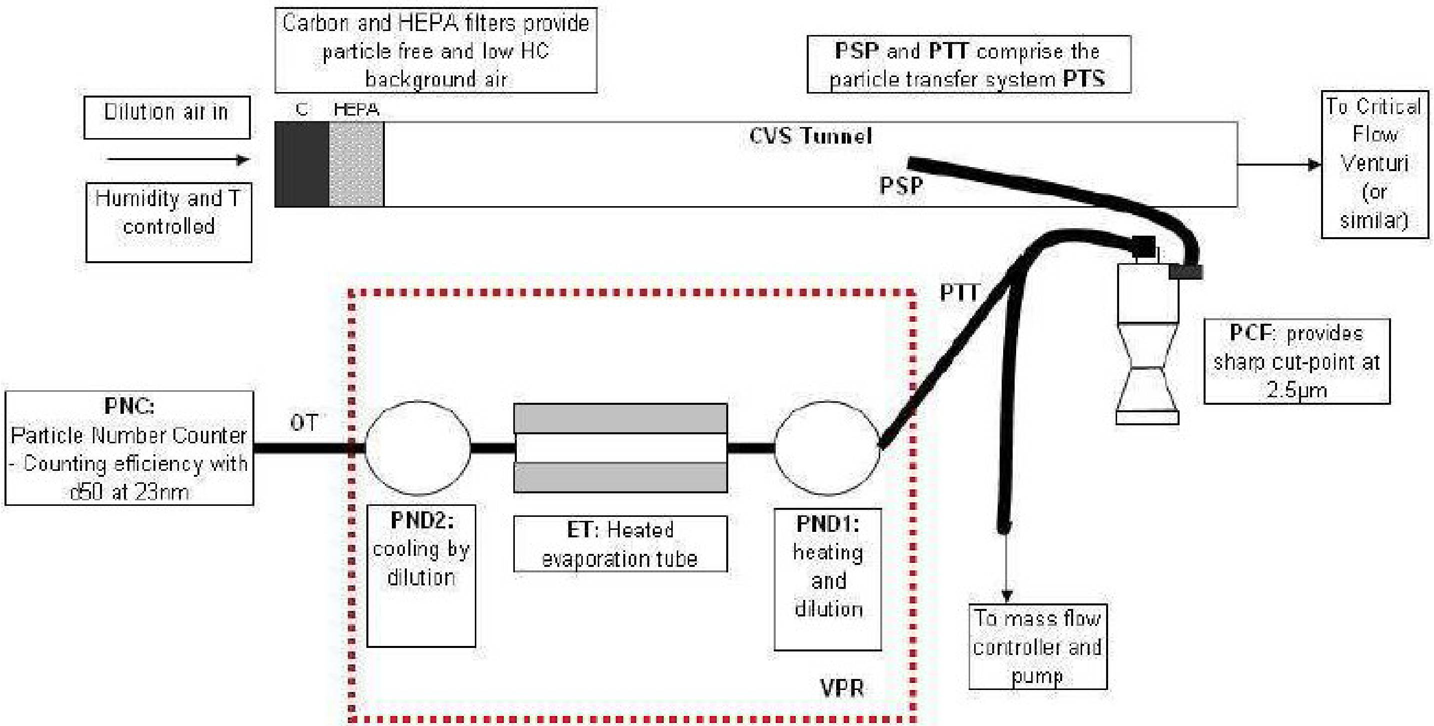
Rainer Vogt, Ulf Kirchner and Matti Maricq

Ford Motor Company

Aachen/Dearborn

Introduction

Solid particle number (PN) counting required in upcoming European emission regulation for light-duty diesel: evaporation of volatiles and dilution of sample from CVS tunnel.



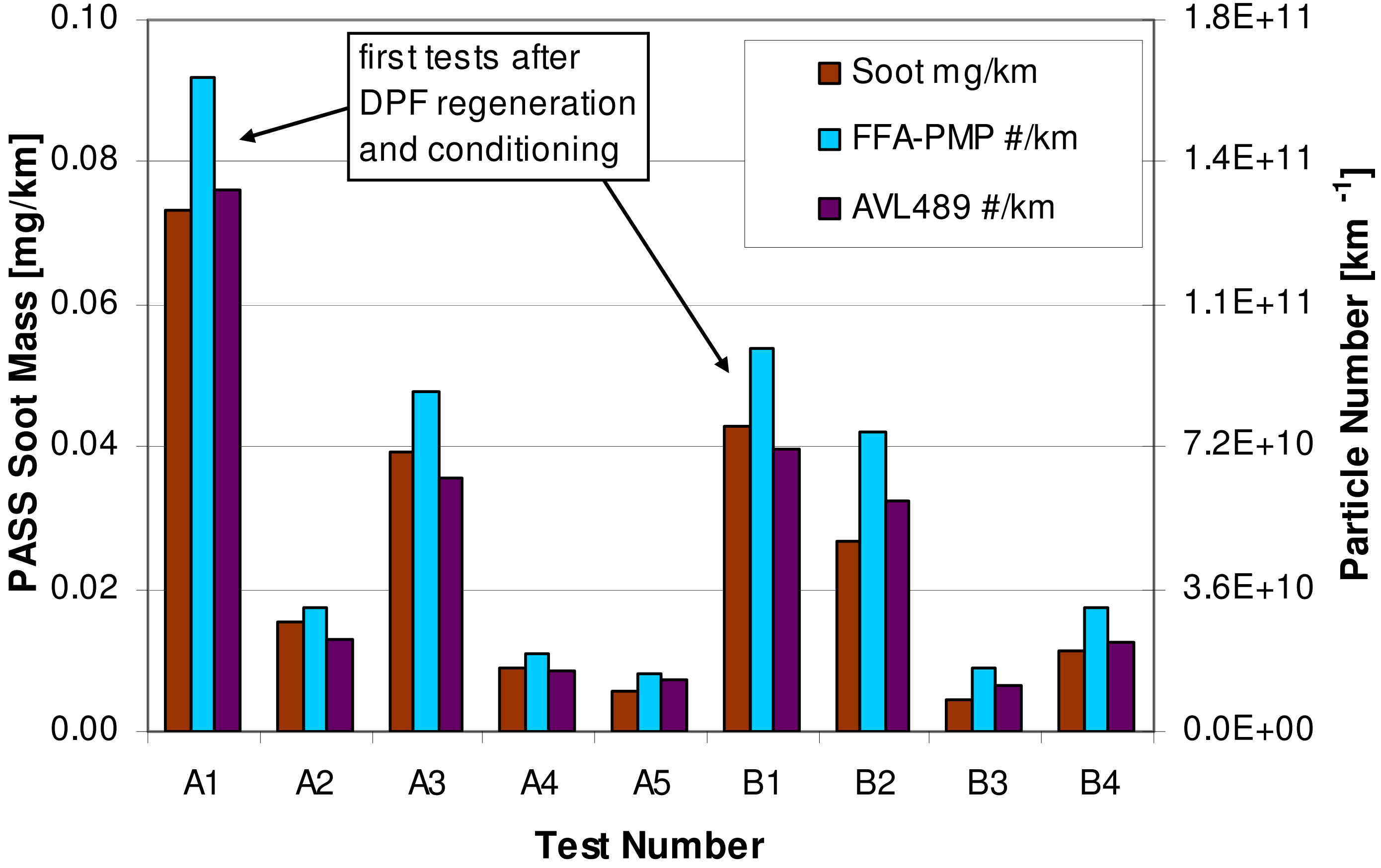
PSP: Particle Sample Probe
PTT: Particle Transfer Tube
PCF: Particle Classifier
PND: Particle Number Diluter

Experimental Setup

- Diesel passenger car 1.6 L w DPF
- New European drive cycles (NEDC) after DPF regeneration / conditioning.
- In addition to regulated components (CO, HC, NOx, total PM mass): Two fully calibrated PN instruments in parallel plus micro soot sensor (MSS). All sampling from full flow CVS.
- Use of calibrated PN instruments: average Particle Concentration Reduction Factors (PCRF) for 30, 50 and 100 nm. Counter desensitized for small particles, 50% detection efficiency for 23 nm particles according to upcoming European legislation.

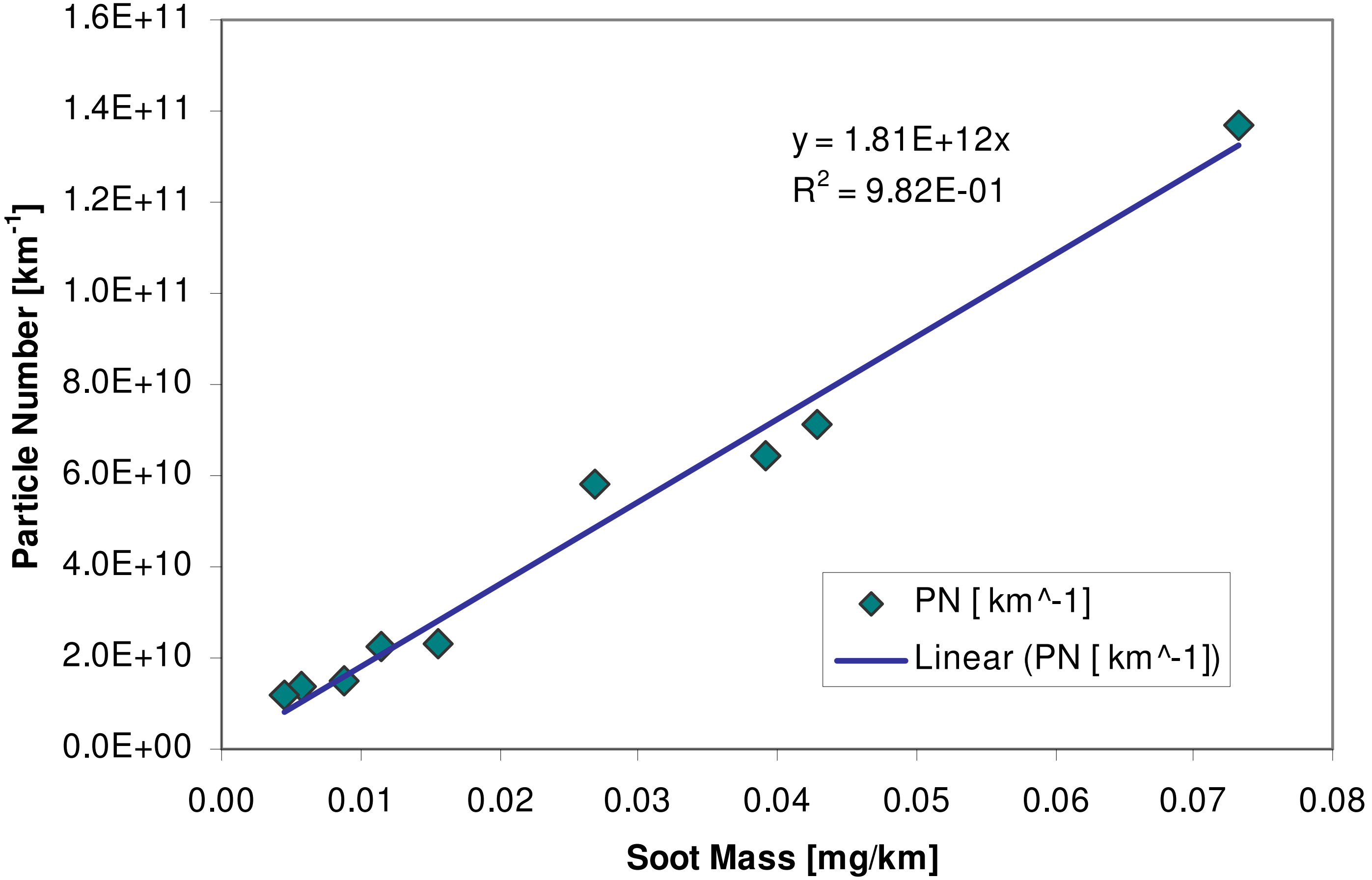
PN compared to Soot Mass

All three parallel methods (2x PN and soot mass) show consistent trend.



Regression Analysis of PN vs. Soot

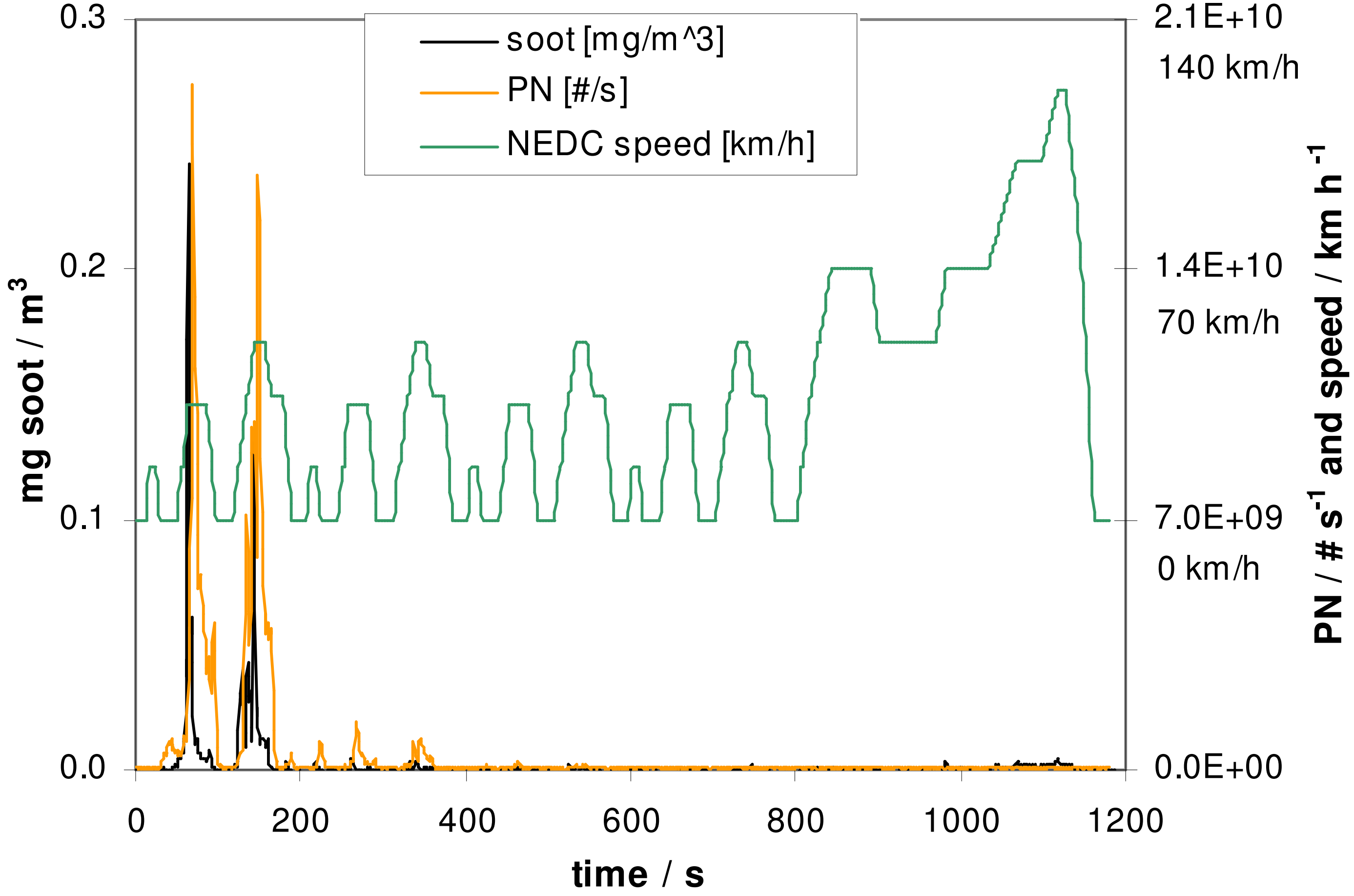
Very good (R^2>0.98) correlation of PN with soot;
1 mg soot corresponds to ~2 x 10^{12} particles.



Emission Time Traces (1)

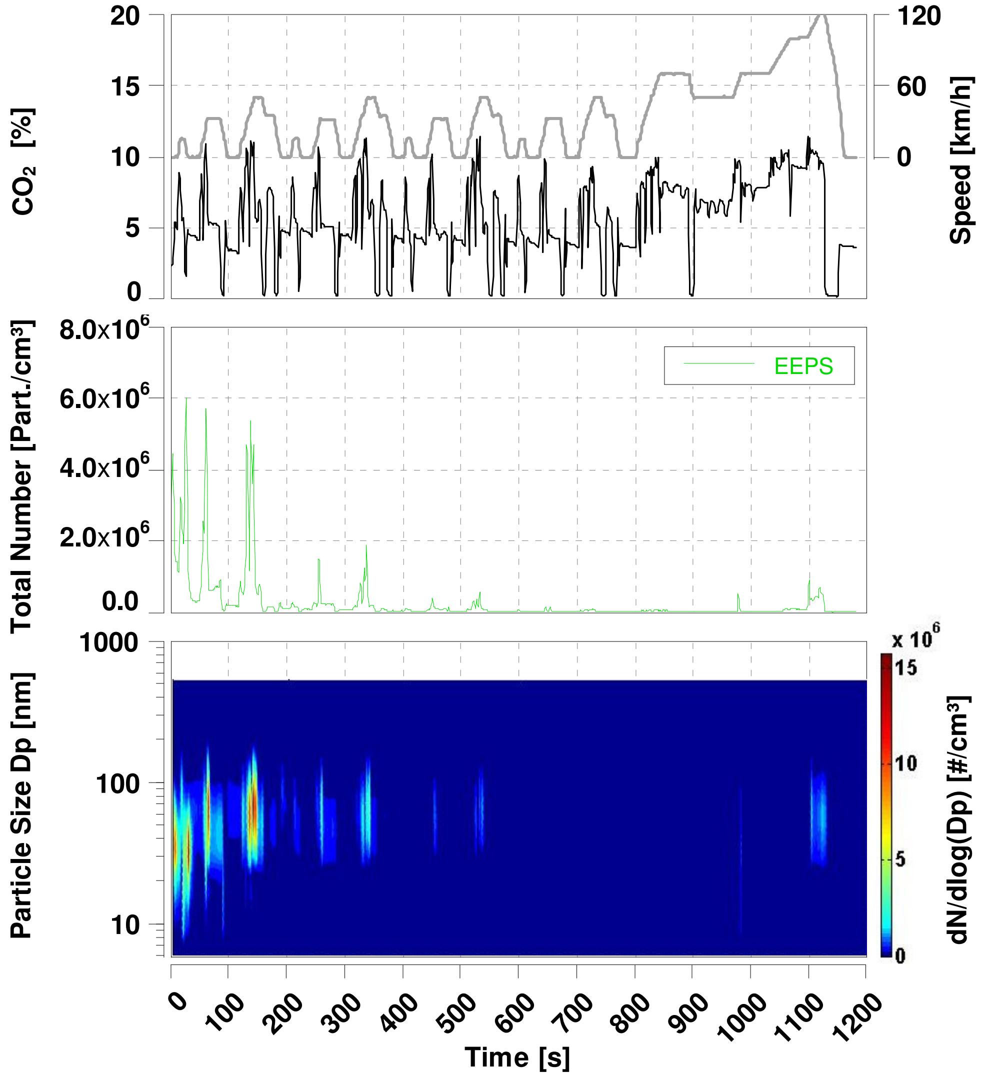
Strong decrease of soot and PN emissions after ~200 s, more than engine out decrease => increasing filter efficiency.

High efficiency level, initial ~99.7% increase to >99.9%



Emission Time Traces (2)

M. Bergmann et al., ETH Conference 2008;
Atmospheric Environment 43, 1908-1916 (2009)



- Euro-4 DPF vehicle
- tailpipe sampling with FPS and EEPS

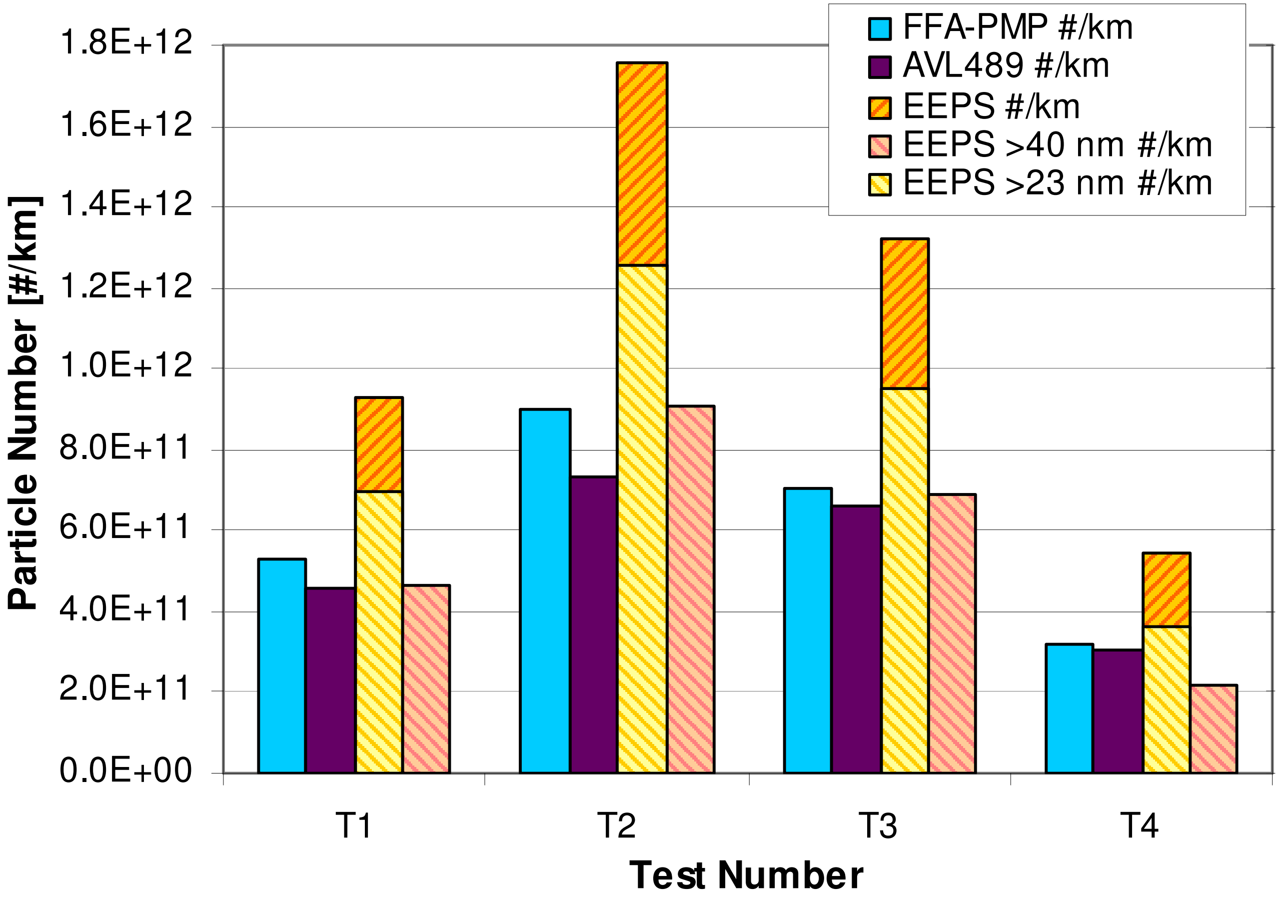
=> some PN measurable during cold start
=> very low PN during remainder

almost no nucleation mode particles

Solid vs. total PN

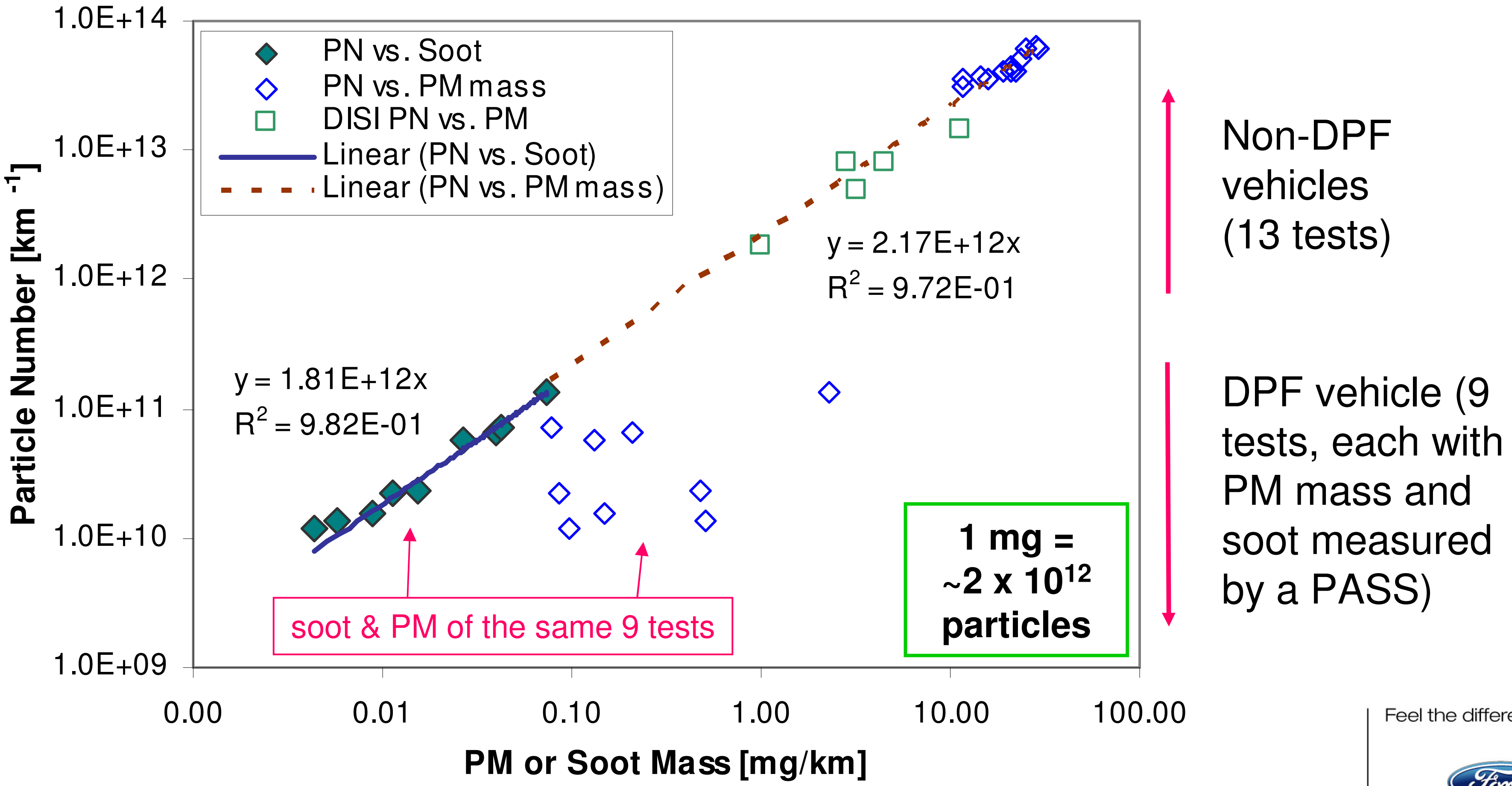
Total PN measured by TSI Engine Exhaust Particle Sizer (EEPS) is higher than solid PN >23 nm as expected.

Best match for EEPS >40 nm: different measurement principle, no specific calibration.



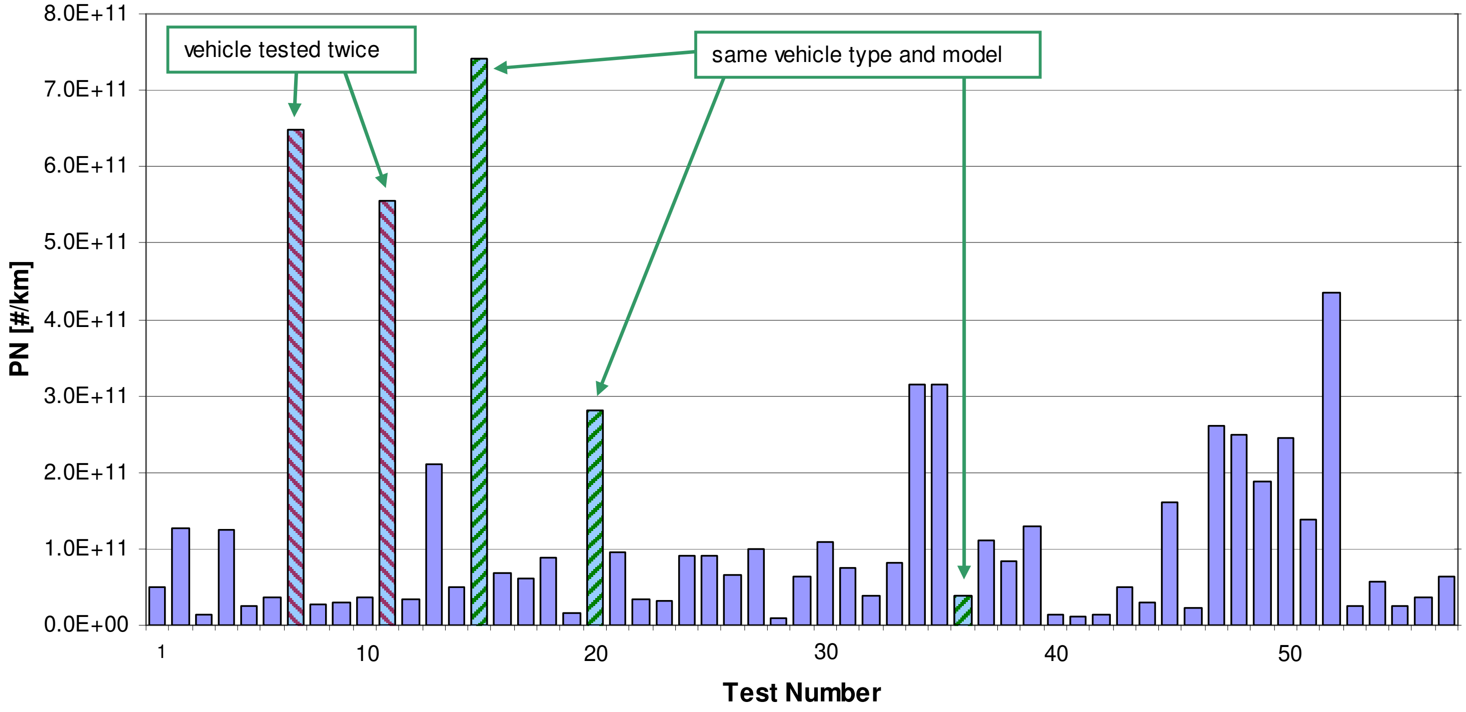
Particle mass vs. PN

- Non-DPF vehicles: very good correlation of PM mass with PN.
- DPF vehicles: correlation overwhelmed by artifacts of filter methods (~0.5 mg/km). Good correlation for soot, same slope as non-DPF => similar particles (size, density).



Testing Variability

- Testing of new, conditioned vehicles at the production plant.
- Large variability of different vehicles of same type and model. Even for the same vehicle >10% difference at 2nd test.
- Effect of vehicle or method? Error analysis required.



Error Estimation I: Repeatability

Error propagation of inputs in formula to calculate PN results:

$$N = \frac{V \times k \times \overline{C}_s \times \overline{f}_r \times 10^6}{d}$$

Main contributions to repeatability identified:

- PNC flow. Daily measurements over several months: ±2%.
- Repetition of PCRF calibration, i.e. stability of PN dilution: ± 5%.

Repeatability (one CVS / PN instrument)	
CVS volume(ΔV/V)	1%
distance (Δd/d)	0.2%
PNC counting accuracy (Δk/k)	0%
PNC flow (ΔC/Cs)	2%
PCRF uncertainty, daily (Δfr/fr)	5%
Volatile particles	0%
CVS tunnel background	0.02% - 0.2%
total repeatability	**± 8%**

Error Estimation II: Reproducibility

Main contributions to reproducibility:

- PNC flow. Daily measurements of 2 instruments: ±5%.
- PNC counting accuracy. Difference between 2 instruments, which are within legal limits: ±10%.
- PCRF uncertainty. Comparison of 2 instruments with real diesel exhaust size distribution
  - instrument "at the limit", 70%, 80% and 100% penetration
  - "low losses" instrument, 90%, 95% and 100% penetration for particle sizes 30, 50 and 100 nm, respectively: ±10%.

Reproducibility (several CVS facilities / PN instruments)	
CVS volume(ΔV/V)	1%
distance (Δd/d)	0.2%
PNC counting accuracy (Δk/k)	10%
PNC flow (ΔC/Cs)	5%
PCRF uncertainty (Δfr/fr)	10%
Volatile particles	1%
CVS tunnel background	0.02% - 0.2%
total reproducibility	**± 27%**

Summary and Conclusions I

- PN differences of >100% between tests of the same vehicle.
- Comparison of two PN instruments and correlation to a photoacoustic soot sensor at extremely low emission levels (<0.08 mg/km): differences are mostly variability of the vehicle.
- Estimations for PN method repeatability: ~8% and reproducibility ~27%. Good numbers for aerosol measurements.
- Following regeneration the DPF efficiency increases from 99.7% to 99.97% relative to the same vehicle without a DPF. Formation of a soot cake is a likely explanation, but needs further investigation.
- Solid PN emissions of newly manufactured DPF Diesel vehicles showed test to test variability with a CoV up to 110%. This needs to be taken into account when emission standards are discussed.

Summary and Conclusions II

- Good correlation observed between PN emissions and soot mass, which corresponds to 2×10^{12} particles per mg.
- Correlation of solid PN to soot mass extends from DPF equipped to non-DPF vehicles. This is consistent with soot as dominant component of modern, oxidation catalyst equipped, light duty diesel vehicles and a uniformly high filtration efficiency of DPFs versus particle size.
- The upcoming European legal limit of 6×10^{11} particles/km corresponds to 0.3 mg/km soot, which is over an order of magnitude more stringent than the PM mass limit of 4.5 mg/km.
- Comparison of solid PN emissions to the accumulation mode particles measured with an EEPS shows that nucleation particles are effectively removed by the regulation compliant solid particle count instruments.
- Please also see Kirchner et al. SAE 2010-01-0789