PARTICLE NUMBER AS THE METRIC OF CHOICE FOR PEMS PARTICULATE MEASUREMENTS

PM and PN are both used for certification, but are they both needed for PEMS?

Jon Andersson, Ricardo UK, Shoreham Technical Centre

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- PM Measurements
- PN Measurements
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- Conclusions

Introduction

- Portable Emissions Measurement Systems (PEMS) are seeing increased use in both regulatory and environmental fields for studying vehicle emissions
- Provides real-time emissions data (1Hz) and is already being used or considered for use in several areas:
  - Real Driving Emissions and In-use Compliance for Euro 6/VI Certification
  - Insights into real emissions in the urban environment
  - Proving tests for retrofit aftertreatment systems under representative operating conditions
- Gas PEMS, based on technologies used for engine and vehicle certification, is via direct transfer of technologies from the certification laboratory
  - CO, CO_2 (NDIR); NO and NOx (dual CLD); HC (FID)
  - Other techniques are also being considered (FTIR etc)
- The measurement of particulate matter is more complex, as it is a multicomponent pollutant that is affected by many parameters
- This presentation will compare and contrast the two particulate metrics – mass and number - currently used for engine and vehicle certification and consider their application to PEMS

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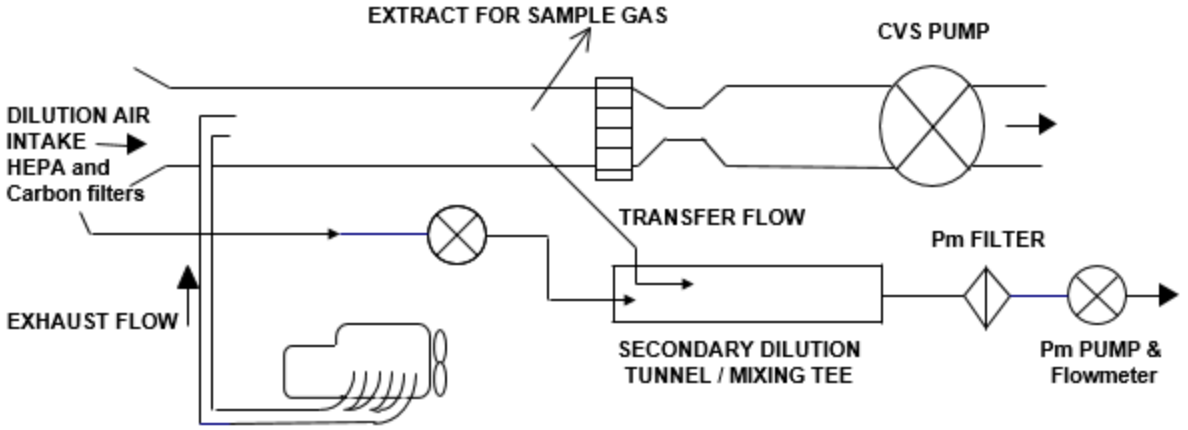
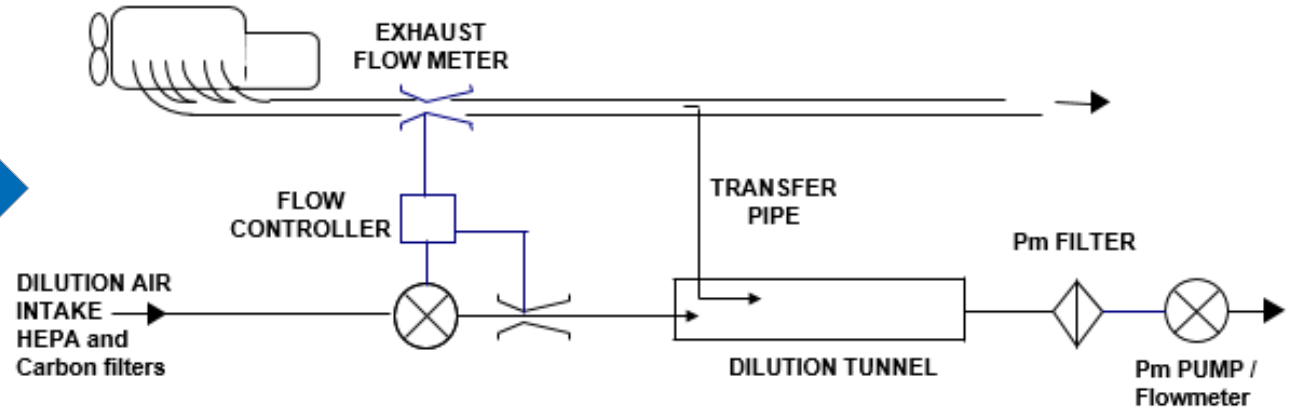
Particulate filter measurement requires a dilution system that can provide a representative, proportional sample



Full flow dilution systems:
– dilute the whole engine exhaust
- Huge stainless steel tunnels, pumps and power demand
- **NOT suitable for on-board use**

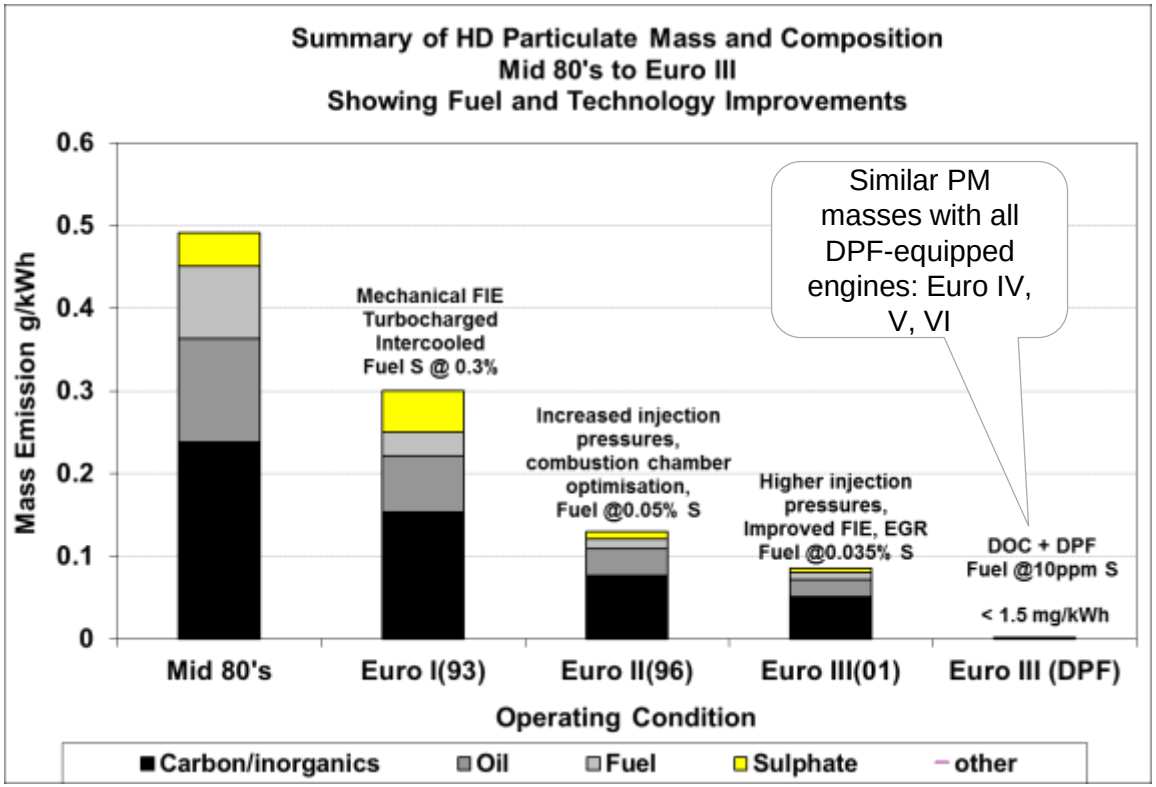
Partial flow dilution system
- samples and dilutes a fixed proportion of the exhaust flow
- Complex and expensive
- **Can be miniaturised for on-board use**

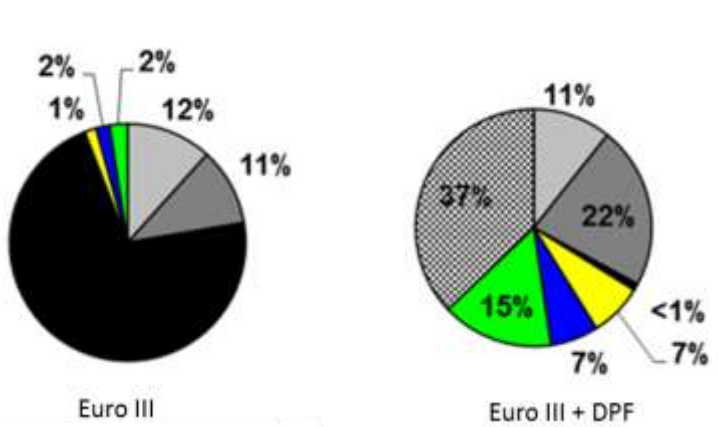


- Complex and expensive equipment is required to achieve proportional sampling from transient engine operation, and the result is a single value from a cumulative sample, determined gravimetrically

Regulatory activity has progressively targeted reduced particulate mass emissions from diesel engines

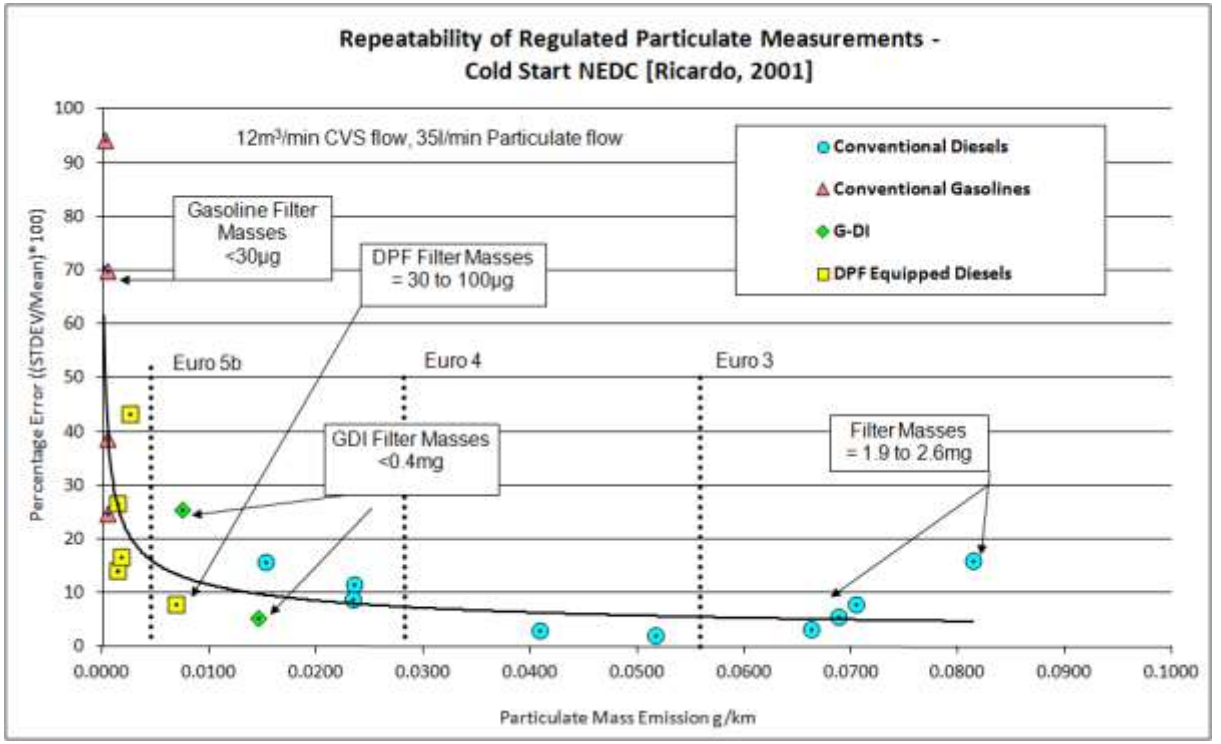
- In the past 20 years engine technology improvements, refinements to the fuel specifications (especially elimination of sulphur and reduction in aromatics) has reduced PM emissions from heavy-duty engines
  - though PM chemistry remained dominated by carbon
- However, with the introduction of DPFs, fuel and engine impacts on PM are dwarfed in comparison with the reductions achieved
  - PM chemistry post-DPF also changes radically – to become volatile dominated





Introduction of DPFs reduced PM emissions so far they couldn't be accurately measured gravimetrically: something better was needed

- The Particle Measurement Programme was started in around 2002 with the objective to "complement or replace the (filter-based) mass measurement metric"
  - The primary driver was the inaccuracy and poor repeatability of the filter-based method at low emissions levels (post-DPF)
  - The mass method wasn't accurate and repeatable enough to reliably discriminate a DPF result from a good non-DPF result



"Towards The Regulated Particulate Measurement Threshold", Jon Andersson, Ricardo, June 2001, UN-ECE GRPE, Geneva

- The regulators wished to force PM control aftertreatment and realise economic health benefits linked to reduced EC emissions – but couldn't mandate the technology without a suitable measurement method

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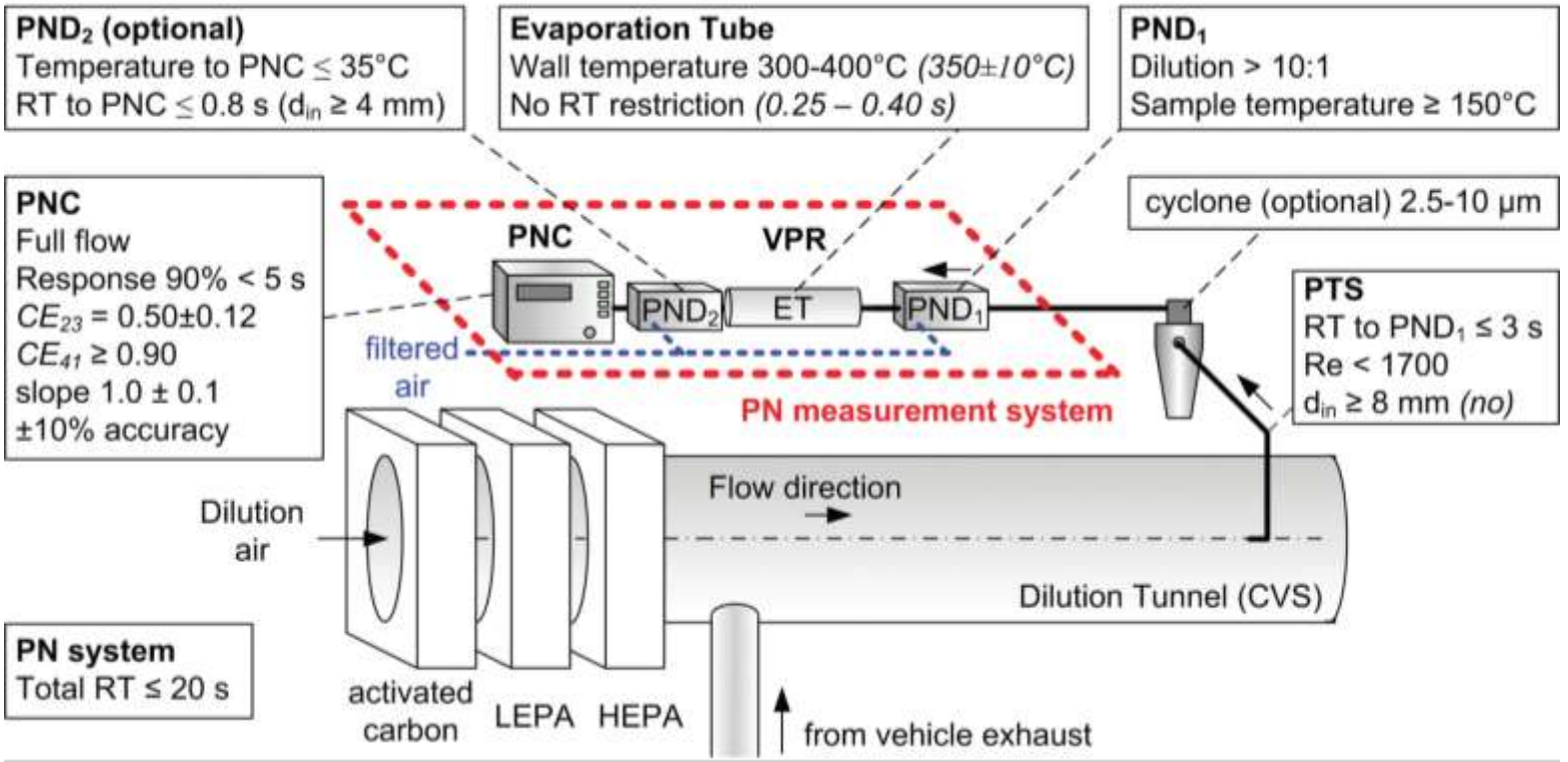
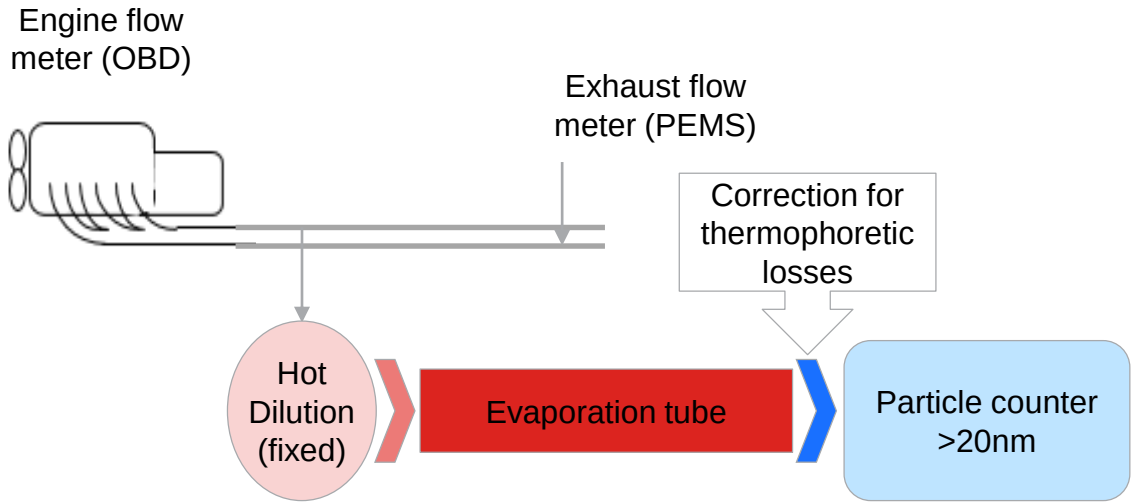
Non-volatile PN measurements now complement filter-based mass

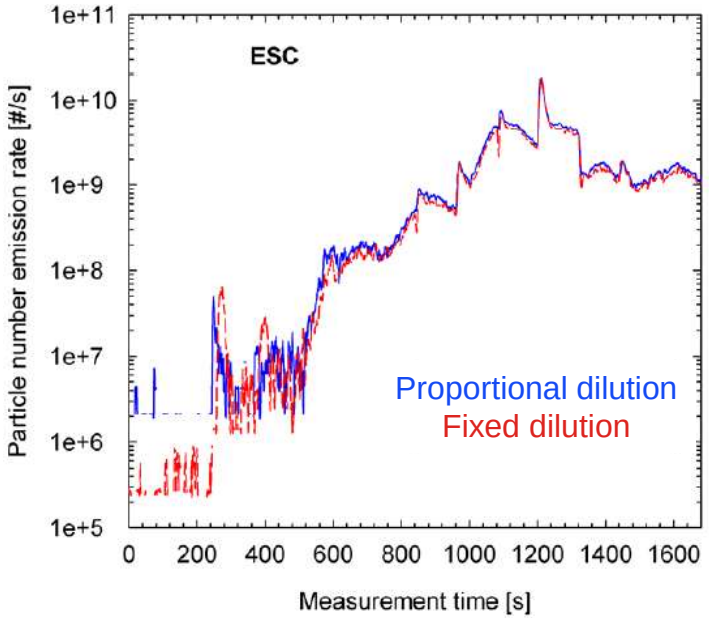
- >10 years of investigations led to the identification, development and proving of the new metric – non-volatile (solid) particle numbers



- PN gives a cumulative result (particles/km or kWh) but also a real-time view of particles released from the exhaust pipe
- Now PN is applied to certification of light-duty diesel from Euro 5b, gasoline DI during Euro 6, HDD (Euro VI) and possibly will be applied to NRMM at Stage V

Non-volatile particle number can be measured directly from raw exhaust using a simplified measurement approach





- A simplified non-volatile PN system can easily be applied to raw exhaust measurements (this was first done for light-duty vehicles and HD engines many years ago)
  - Proportional dilution not required, so simple dilution approaches can be used
  - Diluters permit measurement at both non-DPF and post-DPF emissions levels
- Particle concentration measured at fixed dilution in raw exhaust is converted to emission rates by using either on-board exhaust mass flow from the engine (OBD) or from the tailpipe flow meter (PEMS)
- It is also possible to use some instrumentation designed for regulatory use for PEMS PN

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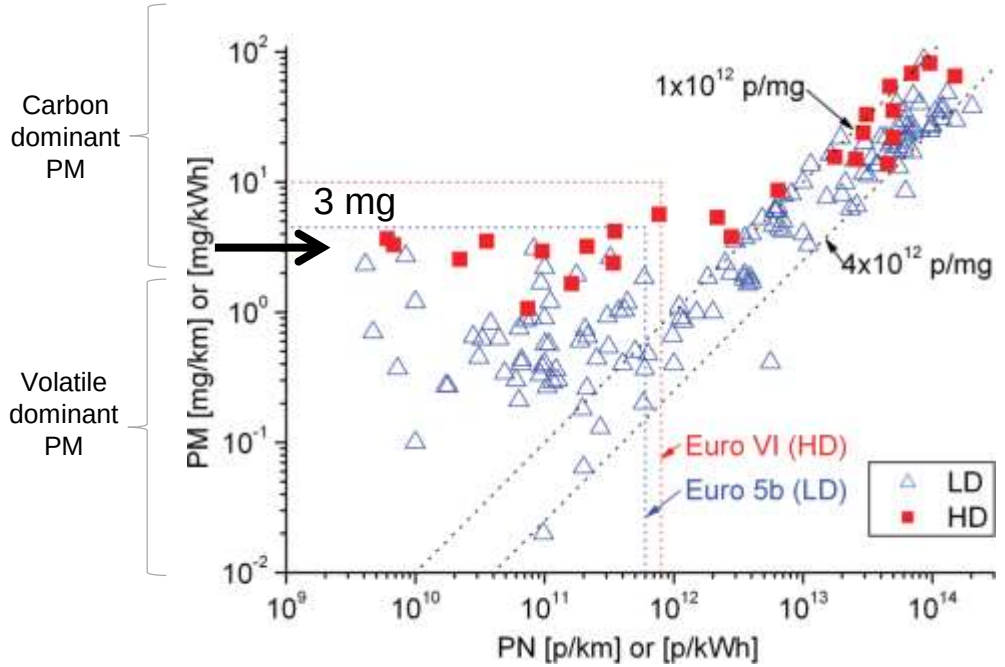
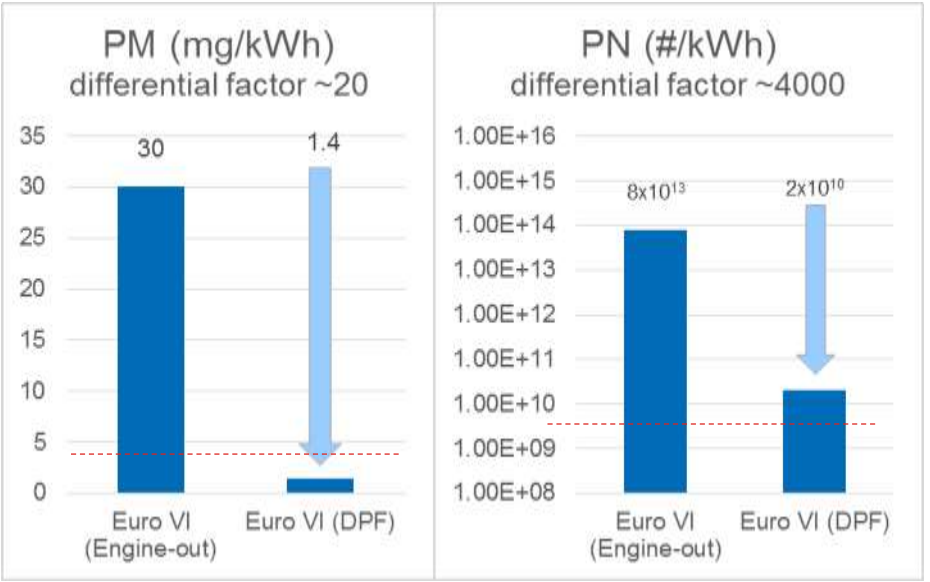
How does PN relate to PM?

- There is a good correlation between PM and PN for both LDV and HDV – until a DPF is fitted, and the dominance of the volatile fraction confounds the relationship
  - 1mg of PM emitted equates to ~2x10^{12} particles (PN detection limit is < 10^{10})

PN correlates well with PM when there is no DPF in place: down to ~3 or 4 mg/kWh / ~2.5 mg/km.

PM becomes no more than a pass/fail test when efficient wall-flow DPFs are fitted

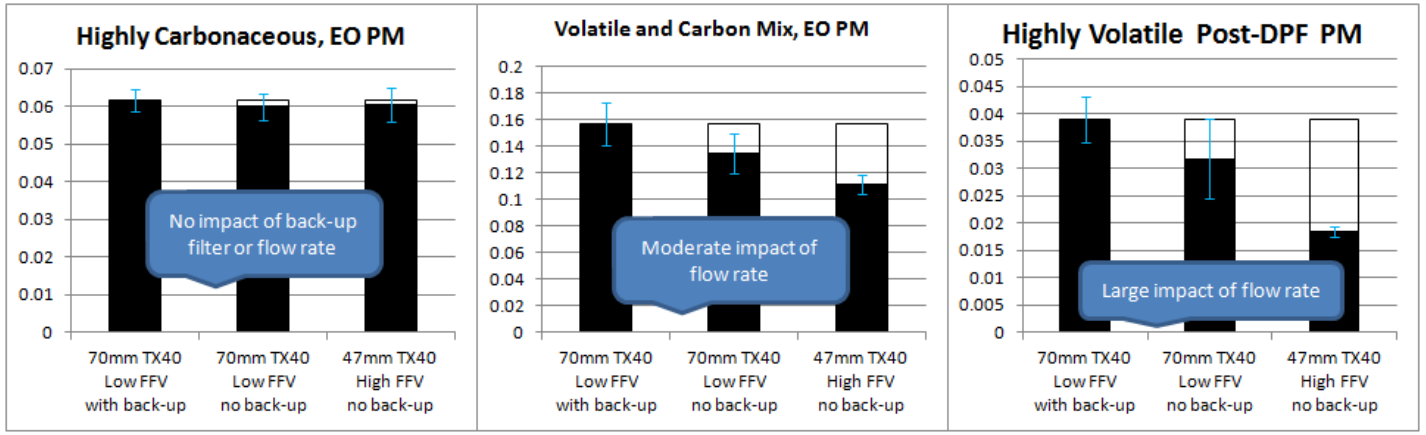


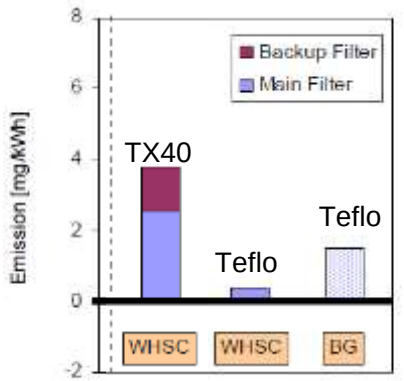


Measurement of Automotive Nonvolatile Particle Number Emissions within the European Legislative Framework: A Review; **Aerosol Science and Technology ; Volume 46, Issue 7, 2012;** Giechaskiel, Mamakos, Andersson, Dilara, Martini, Schindler & Bergmann

PM: problems with volatiles when measuring post-DPF PM (see SAE 2004-01-1990)

- Volatile-dominant particulate means highly unrepeatable and inaccurate quantification
  - Volatile levels are influenced by dilution system type and sampling parameters
    - the volatile mass collected is dependent on the flow rate (face velocity), filter temperature and chemistry of the volatiles
  - Filtration medium has an influence
    - glass fibre (and quartz) filters have a higher affinity for volatiles than Teflon-coated GF filters or Teflon membranes (which give different results to each other…)
  - Dilution system backgrounds can contribute significantly
    - System background contributions can be higher than the sample collected!

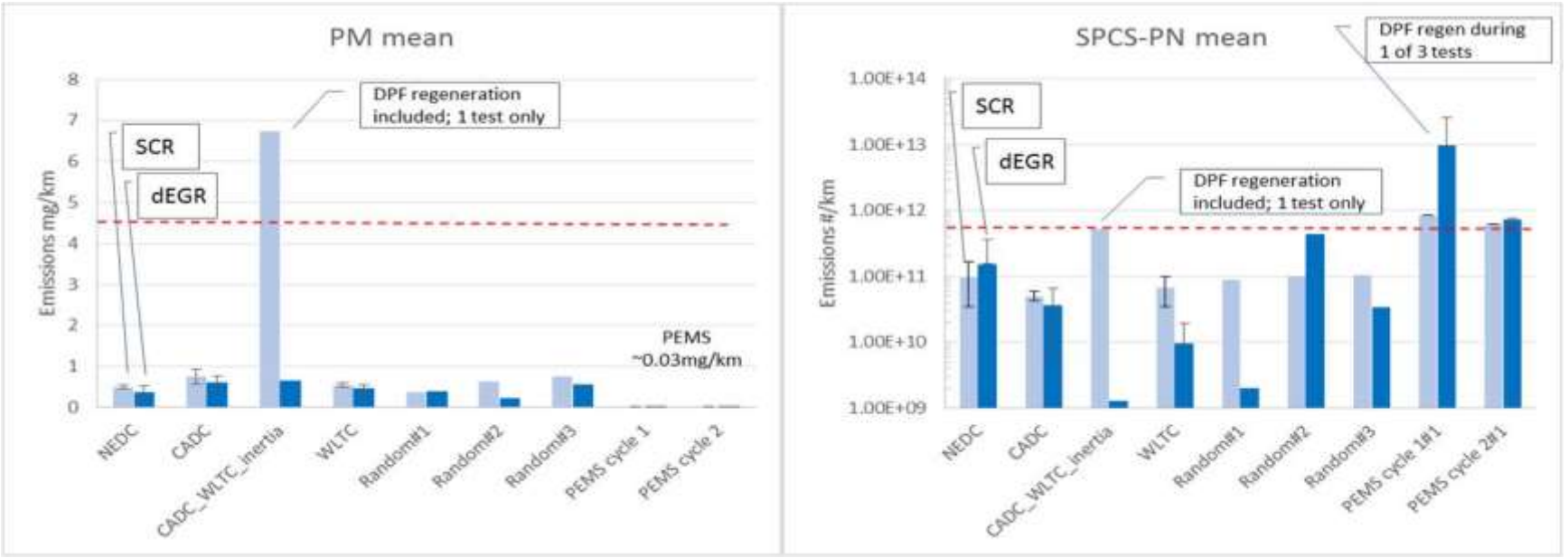




Andersson, J., Clarke, D., and Watson, J., "*UK Particulate Measurement Programme (PMP): A Near US 2007 Approach to Heavy Duty Diesel Particulate Measurements - Comparison with the Standard European Method,"* SAE Technical Paper 2004-01-1990, 2004, doi:10.4271/2004-01-1990.

Comparison of PEMS PN and PEMS PM on Euro 6 LD diesel

SCR vehicle meets 4.5mg/km PM limit when weighted for regeneration frequency.



- PEMS PM filter masses similar to those for chassis dyno tests at 30 – 50µg
- All tests' PM filters 'clean and white'; no visible carbon emissions
- Low g/km PM for PEMS tests may be due to adsorption / desorption of volatiles during the test and division by long cycle distances (c. 100km)
  - PM result is nonsense
- PN results consistent with expectations: in-laboratory and on-road
  - Slightly higher PEMS-PN due to volatile PN or wider measured PN size range

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Round up

- PM is measured as part of engine and vehicle legislation
  - It's difficult to measure PM on board, as a proportional sample is required
  - When a fully functional DPF is fitted volatiles dominate PM, repeatability is very poor, sampling has a major influence on the result
  - PM method becomes a pass/fail test below ~4mg/kWh
  - PM delivers only a single value and no real-time data
- PN is also measured as part of engine legislation
  - Measurements can be relatively easily made on board and a real-time signal is delivered, so real time particle production can be studied
  - A cumulative PN result can be simply generated
  - PN correlates well with PM, so long as solid materials (carbon) dominate the PM chemistry
  - PN is orders of magnitude more sensitive than PM and enables accurate determination of post-DPF particle emissions
    - A good DPF can be discriminated from a cracked or failed DPF
- **PN-PEMS looks promising, but what does it have to deliver?**

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Requirements of PEMS Particulate Measurements

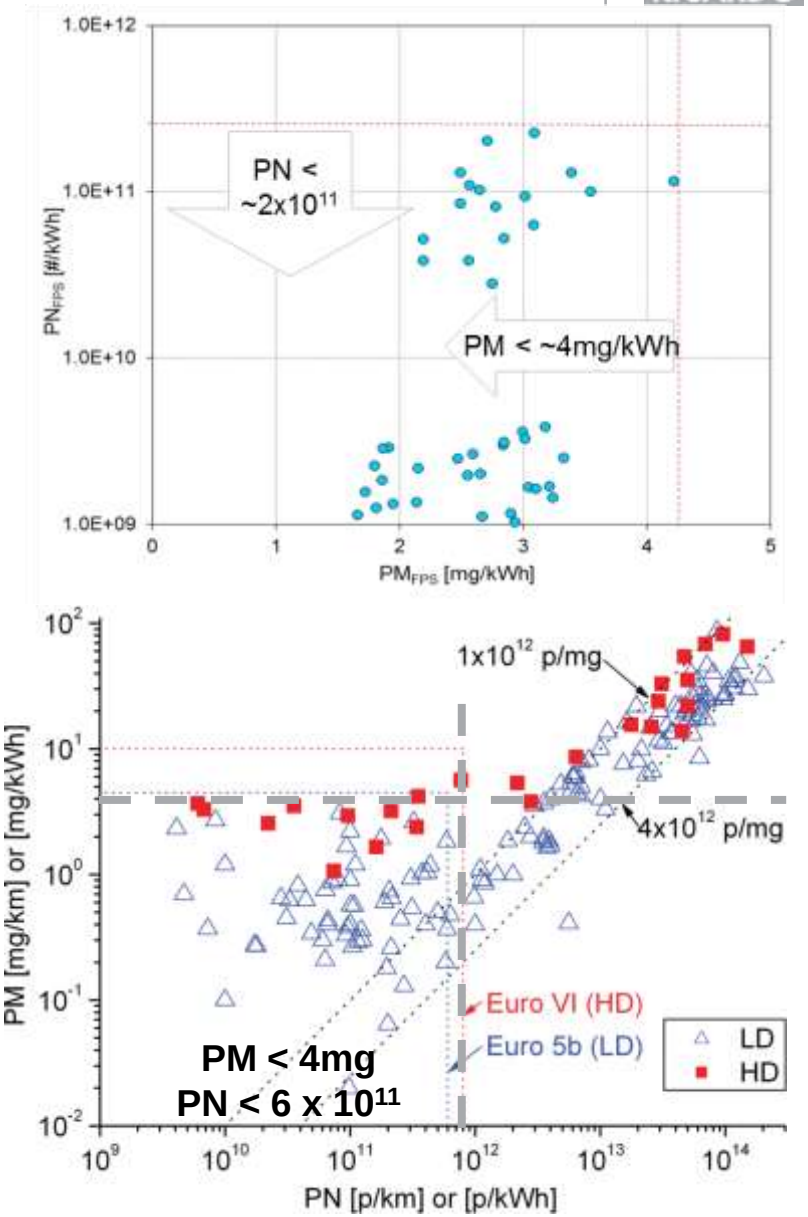
- Why do PEMS Particulate measurements?

	Euro 6/VI RDE	On-road emissions research	Retrofit DPF evaluations
Exact emissions levels of PM	Not required in Europe	Desirable	Desirable
Exact emissions levels of PN	Yes	Desirable	Desirable
Compliance with European certification standard	Yes	No	No
Real-time particulate production	No	Yes	Desirable
Compliance with DPF performance standard / validation of filtration efficiency	No	No	Yes

- While PM cannot fulfil the PN related requirements, PN-PEMS can provide relevant data regarding PM emissions and thus meet all the requirements above

Specific Case: PN-PEMS and DPF Retrofit Evaluations

- Exact PM cannot be quantified by PN, but a worst case of ~4mg can be inferred for any post-DPF PN emission near or >10^{12} particles (/km, /kWh, /m^3)
- Engine-out PN can provide a good estimate of engine-out PM, through the correlation: ~2x10^{12}particles ~ 1mg
- PN can be determined accurately and compared with the certification standard
- Real-time PN emissions can be studied, providing data on both PM and PN emissions, and events such as regenerations
- Comparison of engine-out and post-DPF PN can provide an accurate assessment of absolute DPF filtration efficiency, and validate or fail a filter against a performance criterion



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Conclusions

- In the certification laboratory, and on the road, the measurement of PM presents practical challenges and lacks sufficient sensitivity to allow accurate quantification of PM from vehicles equipped with efficient wall-flow DPFs
  - The accuracy of post-DPF PM measurements enables little more than pass/fail discrimination during controlled certification testing
- Researchers, regulators and local authorities require different knowledge from an on-board particulate device and neither PM nor PN is perfect
  - but Euro 6/VI regulations have ruled out PM-PEMS in favour of PN
- The real-time nature of PN-PEMS and its greater sensitivity allows particulate emissions to be studied in greater detail, and both engine-out and post-DPF emissions to be quantified accurately
- PN results can also be used to estimate PM levels
  - Reasonably well non-DPF and below a threshold post-DPF
- PN can be used to accurately determine the efficiency of a DPF for comparison with other filters, against historical data to evaluate deterioration, or to meet a performance standard
- It is more time-consuming and complex to measure PM and PN PEMS than to measure gases. If this additional effort is to be made, then the advantages of PN-PEMS are clear.

Any questions?

- Ricardo now has experience using PEMS on:
  - Buses in Brighton
    - Euro III, IV, V, retrofit SCR
  - Euro 6 light-duty diesel vehicles
    - Including PM and PN
  - Euro VI heavy duty trucks

http://www.ricardo.com/Documents/RQ%20pdf/RQ%202014/RQ%20Q3%202014/RQ_Q3_2014.pdf