Particle Number as the best approach for PEMS PM measurements

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

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- **Introduction**
- PM Measurements
- PN Measurements
- Correlation of PM with PN
- Round up
- Implications for PEMS
- Conclusions

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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 / NDUV); 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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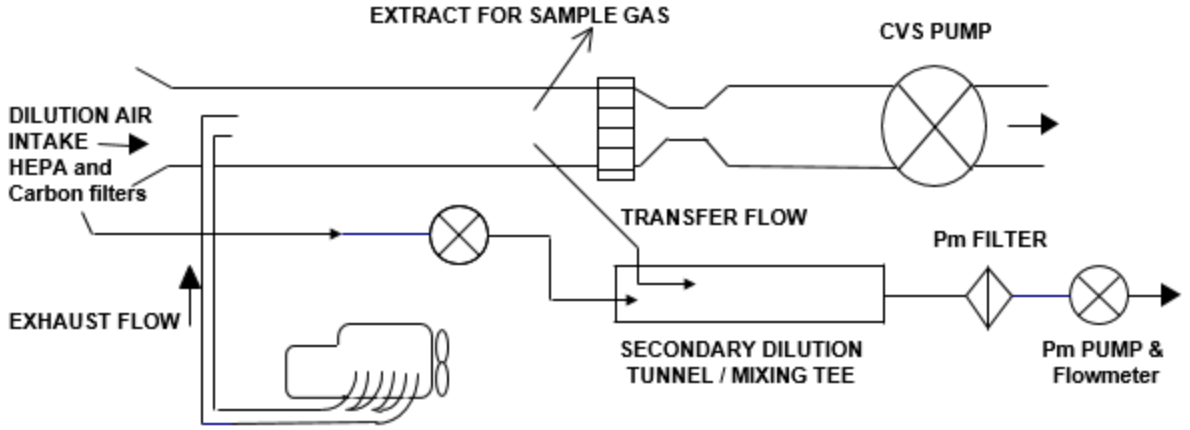
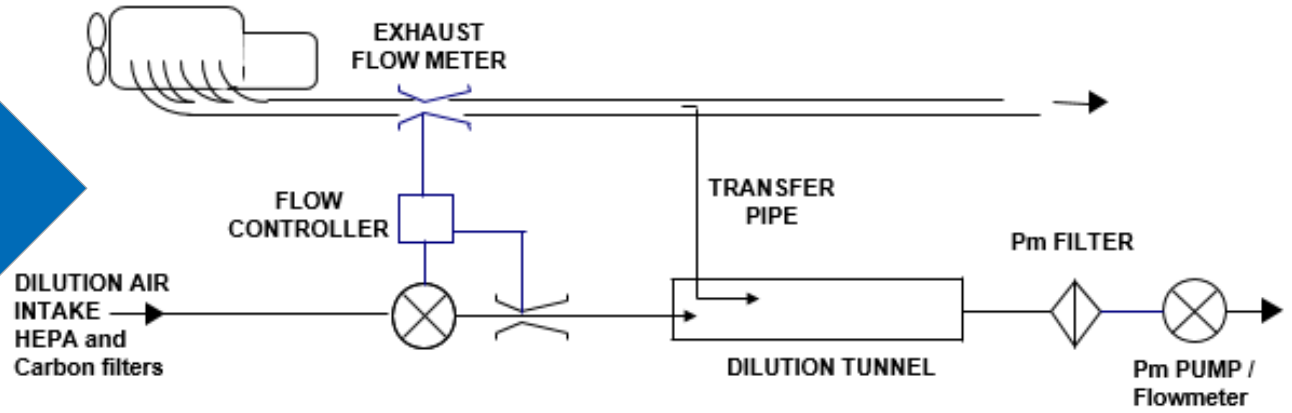
Accurate particulate filter measurement requires a dilution system that can provide a representative, proportional sample



FULL FLOW – dilutes the whole exhaust
- **NOT suitable for on-board use**

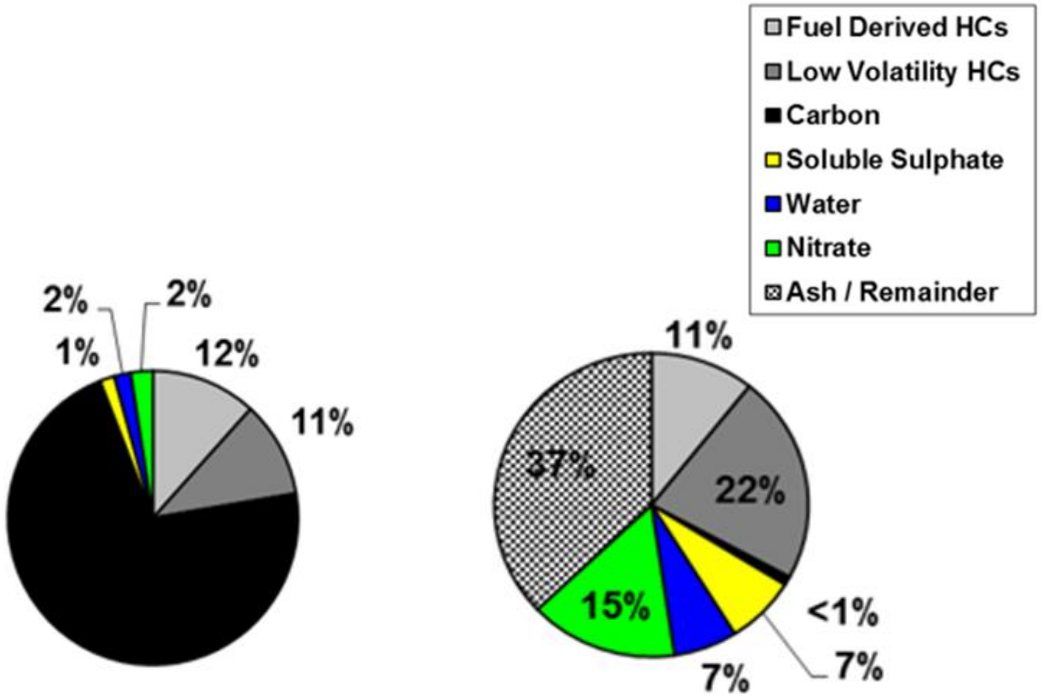
PARTIAL FLOW – dilutes a constant *fraction*
- **Can be miniaturised for on-board use**



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

In the last 30 years PM has been reduced by improving combustion, but Diesel Particulate Filter (DPF) has had the largest impact

- Engine technology improvements and 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
- PM very hard to measure accurately at post-DPF levels



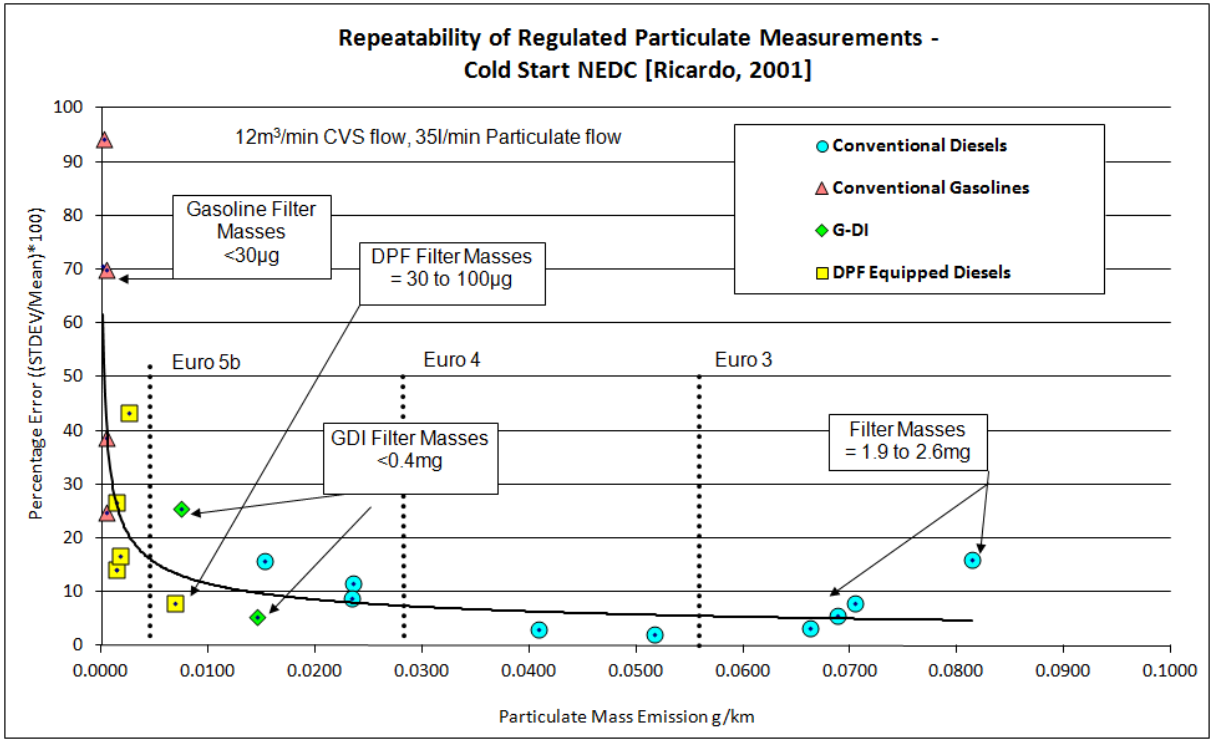
Euro V without DPF
~20 mg/kWh

Euro V with DPF
< 3 mg/kWh

Carbon almost eliminated, volatiles dominate

Introduction of DPFs reduced PM emissions to well below the gravimetric limit of detection: 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 the use of DPFs on all diesels 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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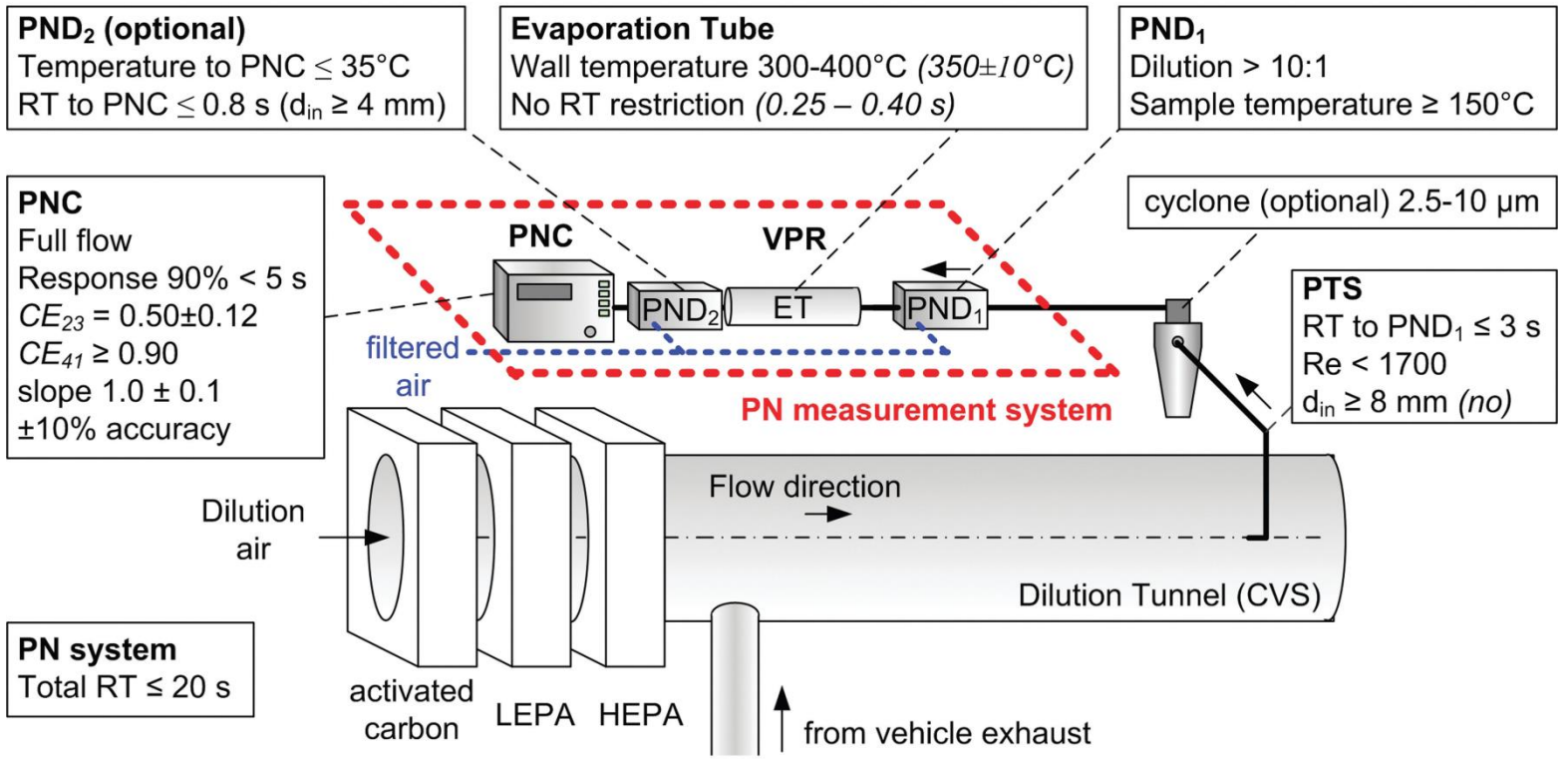
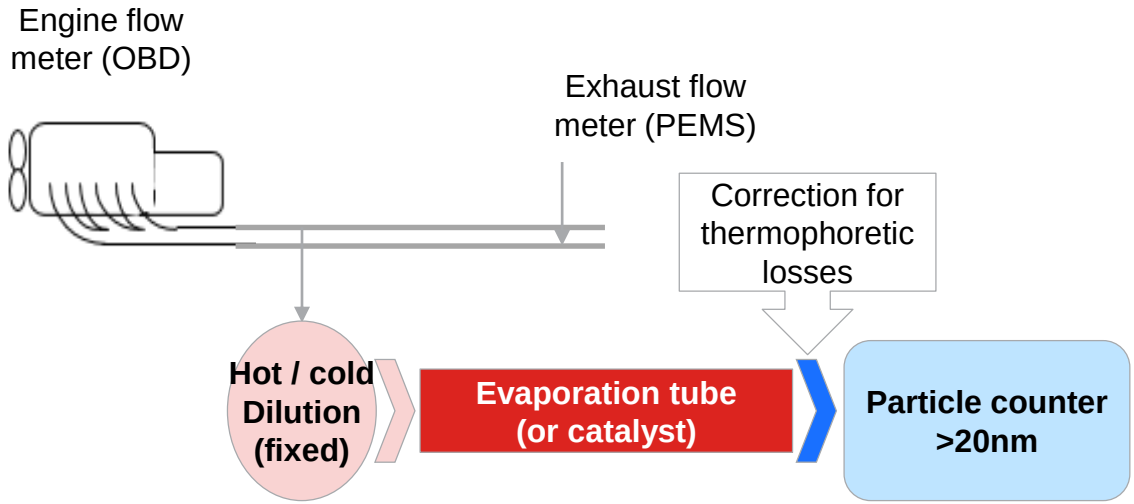
Non-volatile PN measurements now complement filter-based mass

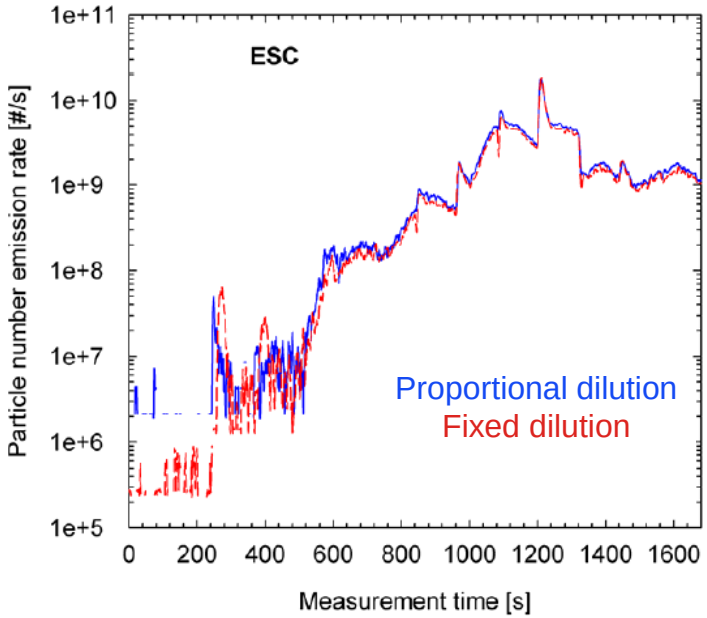
- >10 years of investigations led to the identification, development and proving of the new metric – non-volatile (solid) particle numbers



- PN gives a cumulative result (particles/km or kWh) but also a real-time profile 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, HD (Euro VI) and 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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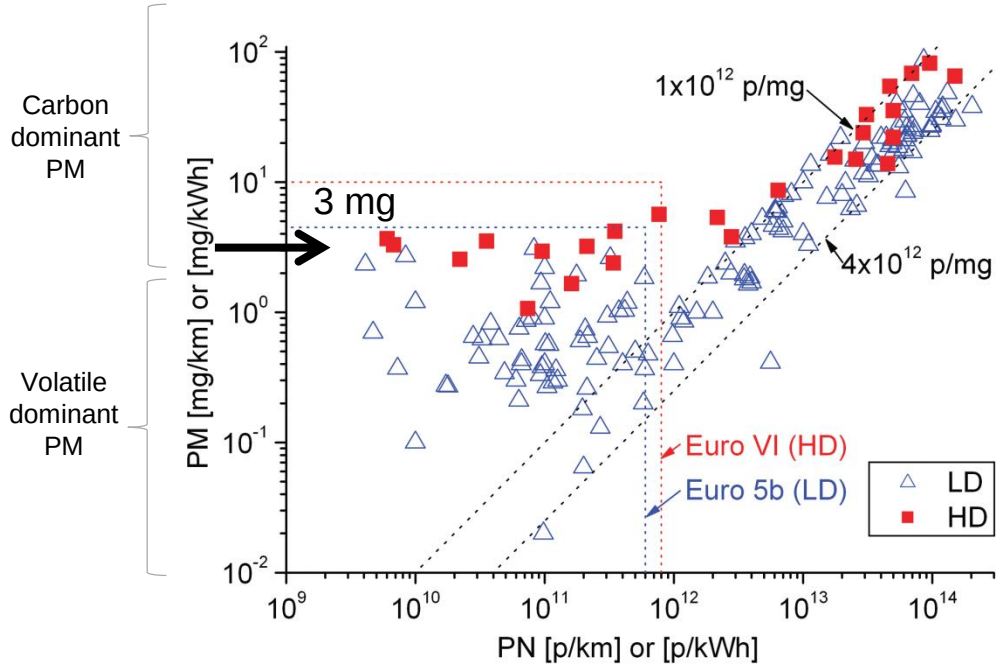
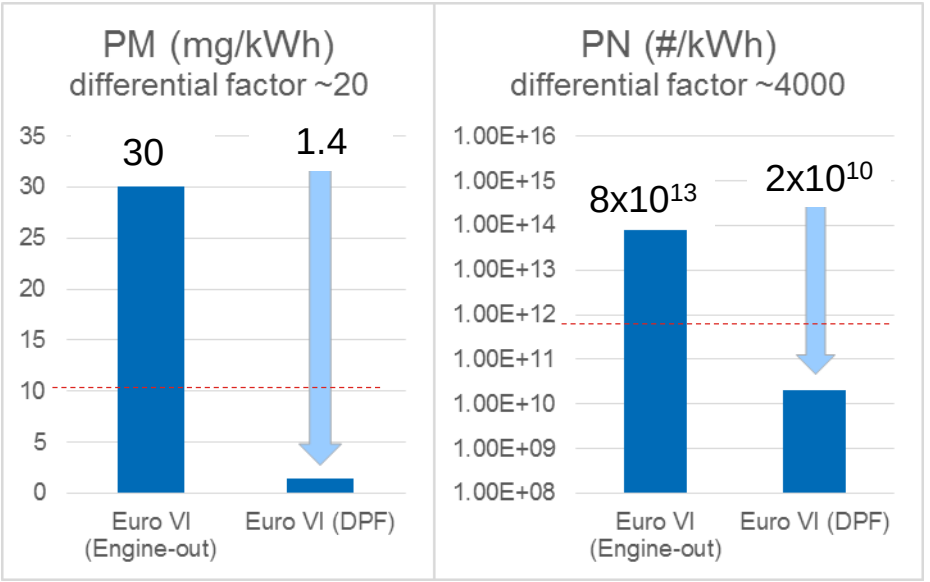
How does PN relate to PM?

- 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

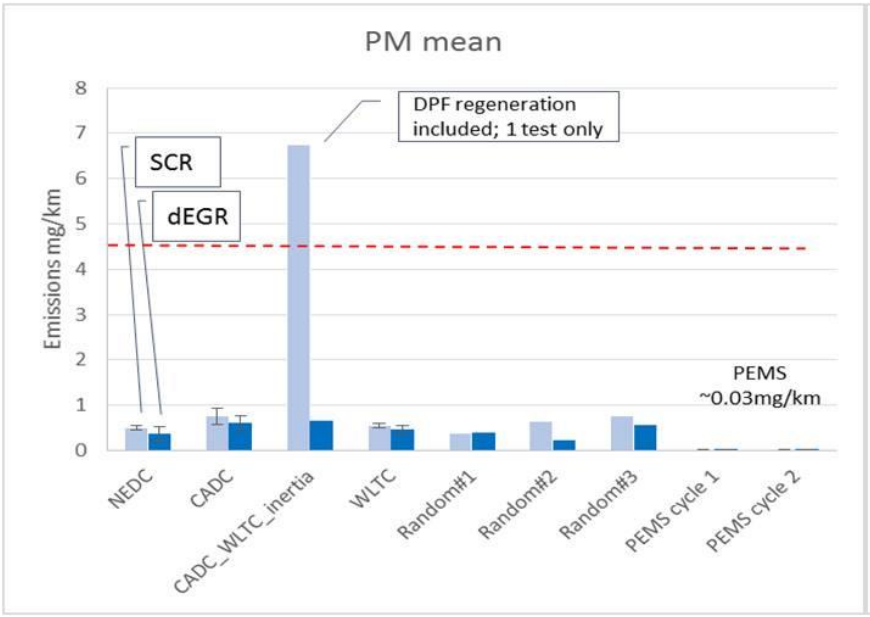


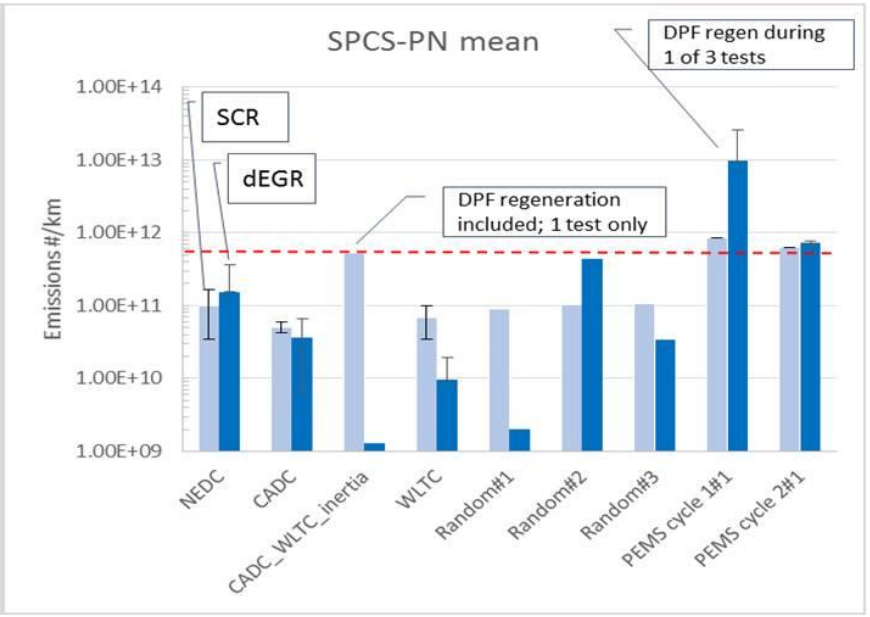


Measurement of Automotive Nonvolatile Particle Number Emissions within the European Legislative Framework: A Review; **Aerosol Science and Technology ; Volume 46, Issue 7, 2012;** Giechaskiel, Mamakos, Andersson, Dilara, Martini, Schindler & Bergmann

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

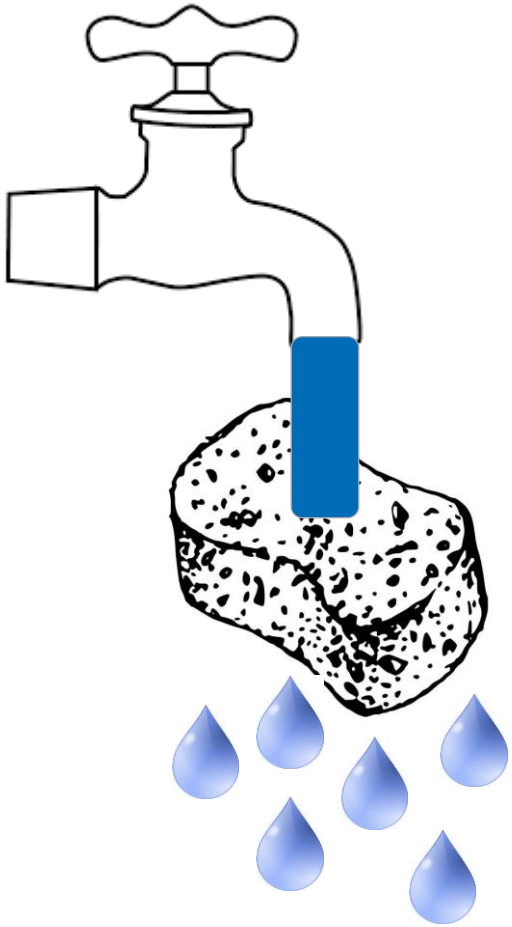
Euro 6 SCR vehicle meets 4.5mg/km PM limit when weighted for regeneration frequency.





- PN results consistent with expectations: in-laboratory and on-road broadly agree
- 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
- Extremely low g/km PM for PEMS – much lower than lab drive cycle results
  - ***PM result is nonsense, but why?***

Why PM is meaningless post-DPF…



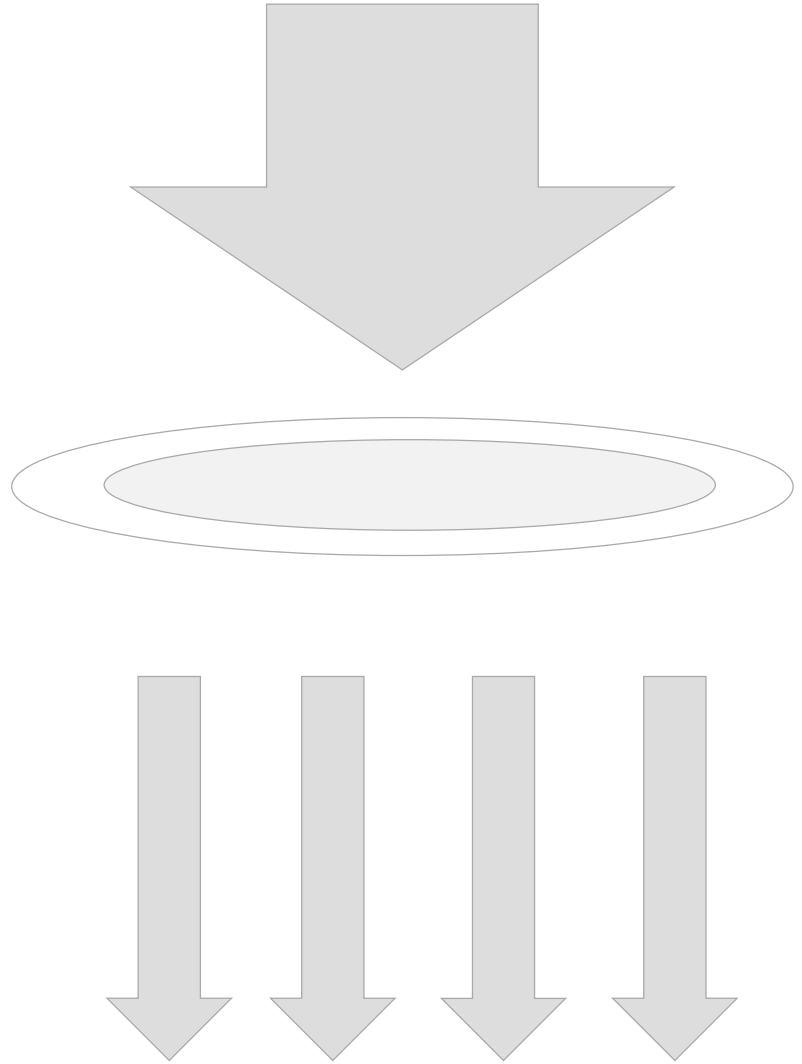
1) Volatile materials flow into the filter like water into a sponge

2) Like a sponge, the filter has a limit of how much material it can hold

3) After the limit is reached, any more volatiles just displace existing ones

4) The maximum filter mass = volatile storage limit

5) Any increase in distance, time, work just ***reduces*** specific mass emissions



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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 (NO DPF!!)
  - 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

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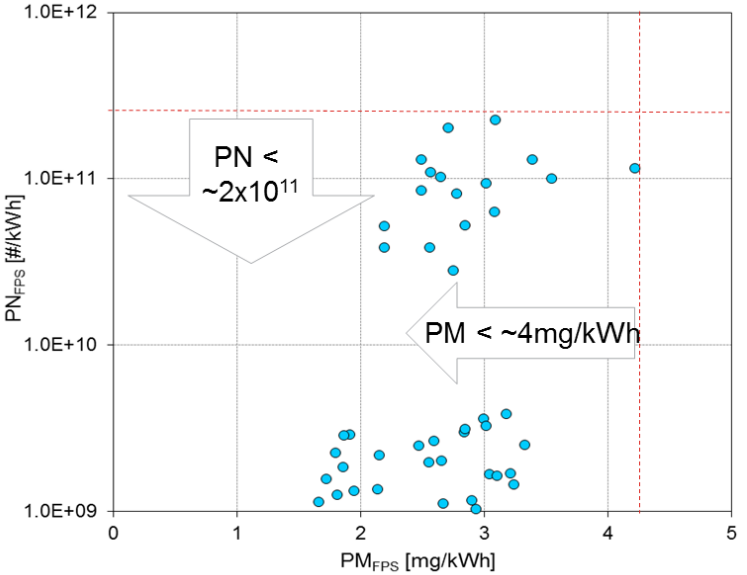
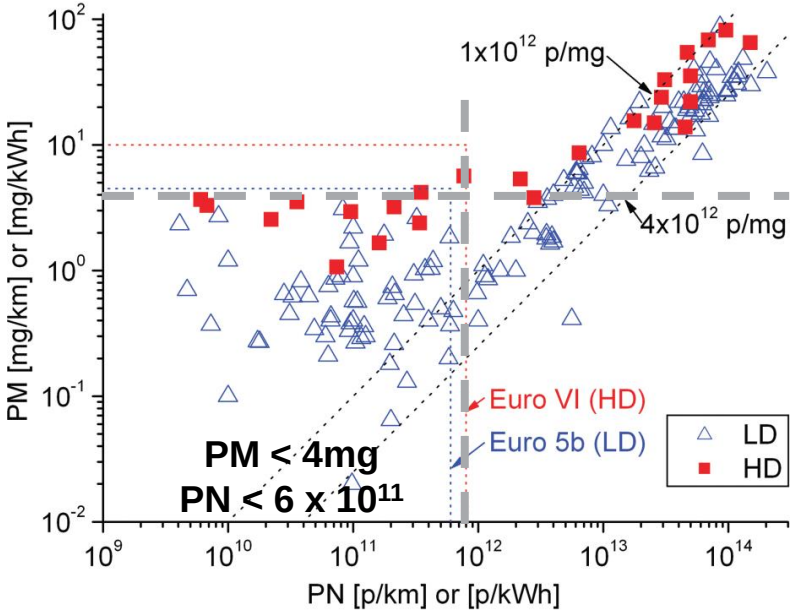
Specific Case: PN-PEMS and DPF Retrofit Evaluations

- **<u>Exact PM cannot be quantified by PN</u>**, 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 an estimate of engine-out PM, through the correlation: ~2x10^{12} particles ~ 1mg
- PN can be determined accurately and compared with the lab 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

- Measurement of PM from DPF diesels impractical
  - No 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
- PN-PEMS is
  - Much more sensitive
  - Allows particulate emissions to be studied in real-time and cumulatively
  - Non-DPF and post-DPF emissions quantified accurately
- PN results can be used to estimate PM levels
  - Reasonably well non-DPF and below a threshold value 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.

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Any questions?

- Ricardo now has experience using PEMS on:
  - Buses in Brighton
    - Euro III, IV, V; Euro III retrofit SCR
  - Many Euro 6 light-duty diesel passenger cars and vans
    - Including PM and PN
  - Several Euro 6 light-duty gasoline vehicles
    - Including PN, with and without particle filter
  - Euro VI heavy duty trucks
  - Stage IIIB and IV NRMM
- PN is now a fully integrated analyser within the suite of PEMS measurement devices

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