History and Future of Particle Number Legislation in Europe

The Particle Measurement Programme (PMP)

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History and Future of Particle Number Legislation in Europe

- **Setting the Scene**
- Inception and Scope of the Particle Measurement Programme (PMP)
- The Regulatory Particle
- Determination of a PN Limit Value
- Relationship between mass and number
- Benefits delivered by the particle number metric
- Future Directions
- Wrap-up

Final

Setting the Scene: What were the historic drivers for particle number legislation? The 1990's

- Drivers
  - EPEFE (aromatics & S); Auto Oil II (PM as future issue); COMEAP (and others) concerned about the long term effects of PM air pollution
  - Swiss and EU Govts, led by the UK
    - PM pollution presented the greatest health (and economic) threat
    - Submicron particles from diesels - greatest future health challenge
- Enablers
  - Fuel S just reduced in diesel and gasoline
  - DOC and TWC becoming widespread
  - Peugeot introducing DPF along with necessary engine measures
- Open questions
  - Substantial pressure on the automotive industry to develop some new technology solutions
  - Still some concerns on the relative impacts of fuels and engines (plus aftertreatment)

Setting the Scene: What were the historic drivers for particle number legislation? The 1990's

- The UK Govt of the time favoured a greener transport agenda, and its DETR co-funded research into PM emissions sources with oil and motor industries
- DETR/SMMT/Concawe Particulate Research Programme was established, which explored key knowledge gaps:
  - Particles & PM chemistry from LDV and HD engines of different technology levels
  - Impacts of aftertreatment, fuels and, to a lesser extent, lubricants
  - Instrumentation and measurement issues, and sampling influences

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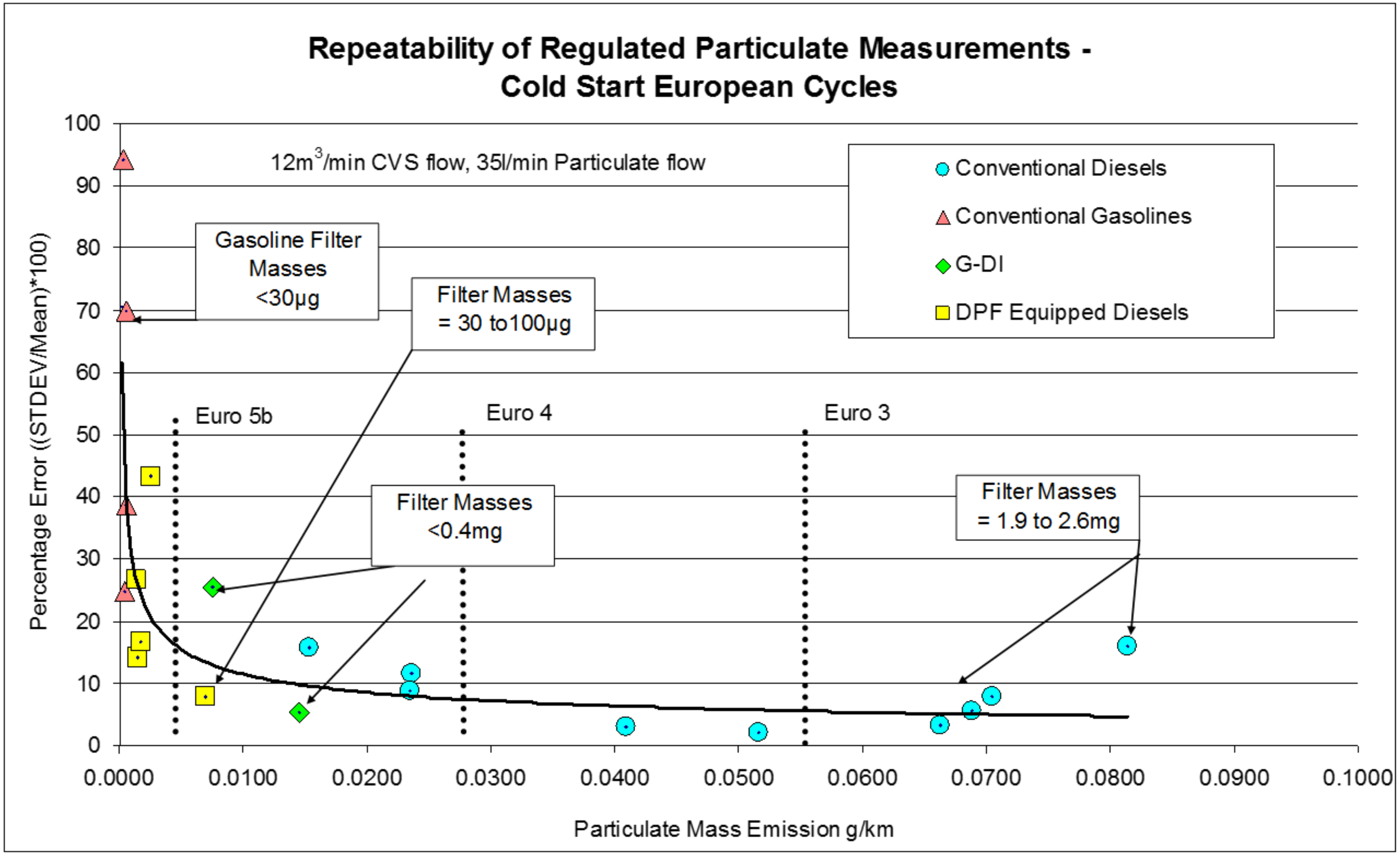
DETR/SMMT/Concawe demonstrated the poor repeatability of PM gravimetry at post-DPF levels, and the potential for a particle metric

- The variability in the gravimetric PM was as large as the mass measured, so if DPFs were to be mandated, a new PM method, or alternative approach was required



Andersson and Wedekind, DETR/SMMT/CONCAWE Particulate Research Program 1998-2001. Summary Report. Ricardo Consulting Engineers

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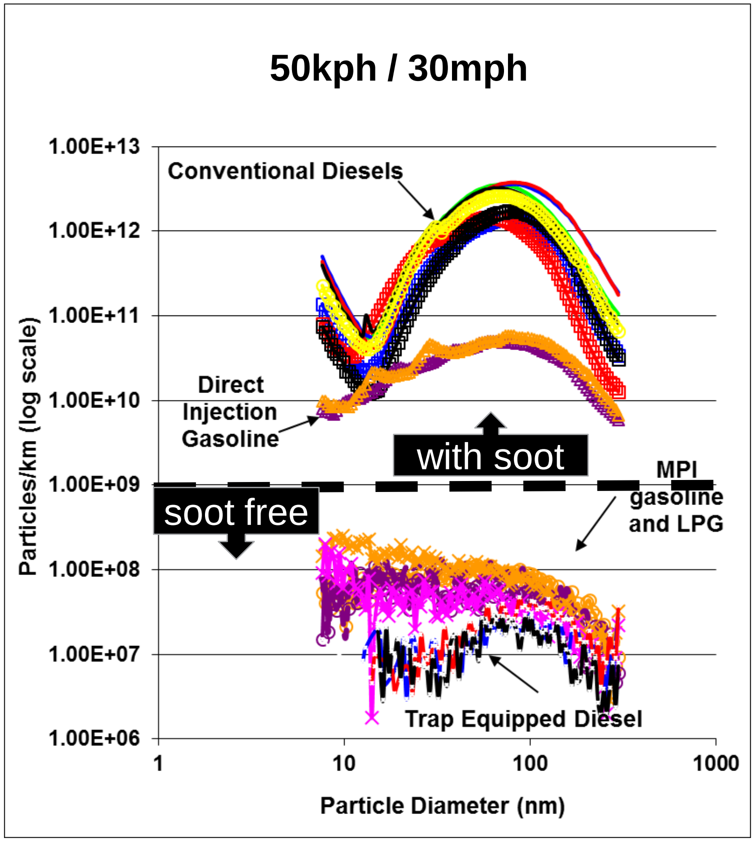
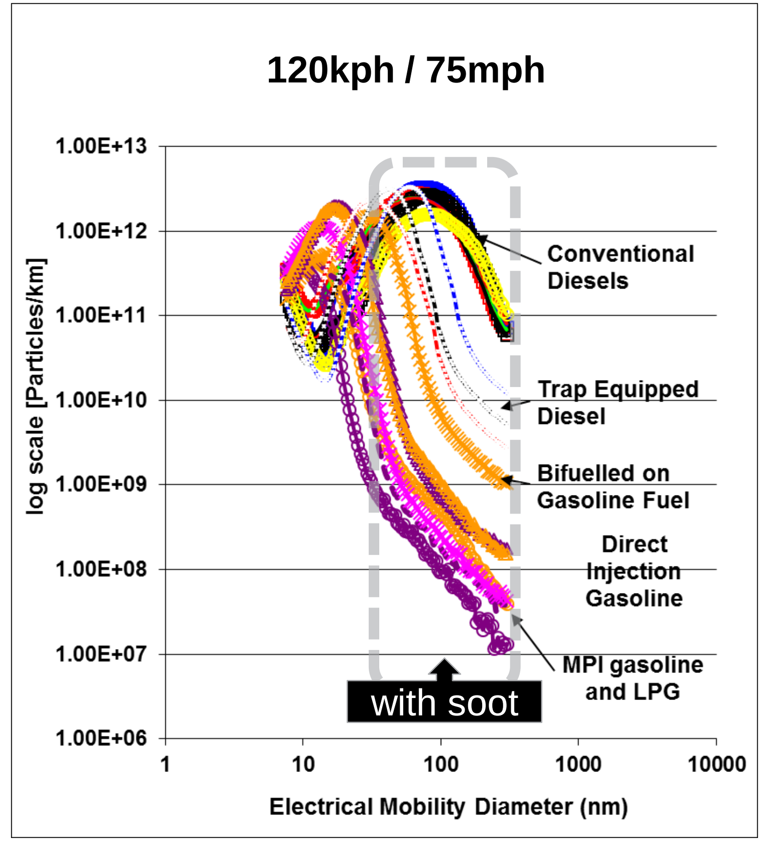
DETR/SMMT/Concawe demonstrated the poor repeatability of PM gravimetry at post-DPF levels, and the potential for a particle metric

- Particle size distribution data showed good resolution between trap-equipped and conventional oxidation catalyst-equipped diesels, *but only at low speeds…*



Five orders of magnitude separation between diesel and diesel with DPF

All technologies showed similar PN levels at high speed, but different size distributions



- To ensure resolution of DPF and non-DPF technologies, it seemed necessary to either discriminate by particle size range, or discriminate based on carbon content, or both

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Inception and scope of the PMP Programme

- The UK Govt reviewed the conclusions of the DETR/SMMT/Concawe programme:
  - PN promising, but not (yet) suitable for regulatory use
  - Soot health effects proven but size and number impacts uncertain
- Previous Euro PM limit values had failed to mandate the use of DPFs
- 'Precautionary principle' invoked – elimination of carbon particles via the use of DPFs was imperative on health grounds
  - but this couldn't be achieved without an appropriate measurement method
- UN-ECE Particle Measurement Programme (PMP) was conceived, chaired by the UK
- Political will and drive came from the EC, but PMP operated under the auspices of UN-ECE to include Switzerland's expertise, and other parties

- PMP's AIM was to identify a new method that
  - **"Complements or replaces existing mass measurement method"**
    - Measurement capability for modern **diesel engines**
      - Pre and post PM aftertreatment

    [Alternative interpretation – with and without carbon present]

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The PMP Comprised Three Phases

Phase I (2001 – 2002)
examining different candidate measurement systems and measurement metrics
[Substantial Swiss Input]

Mass, number, size, EC, active surface, chemistry …

Phase II (2002-2003)
evaluated a range of promising measurement techniques and sample conditioning systems and recommended the most suitable

Revised PM "Solid" PN

Phase III (2004-2010)
validated the recommended measurement techniques via inter laboratory test programmes:
Reliability, repeatability and reproducibility, methodology
Golden Engineer to help steer…

- Validation for light duty testing completed in 2006 and reported in 2007
- Validation for heavy-duty testing completed in 2009 and reported in 2010
- PMP working group recently revived and continues into 2015

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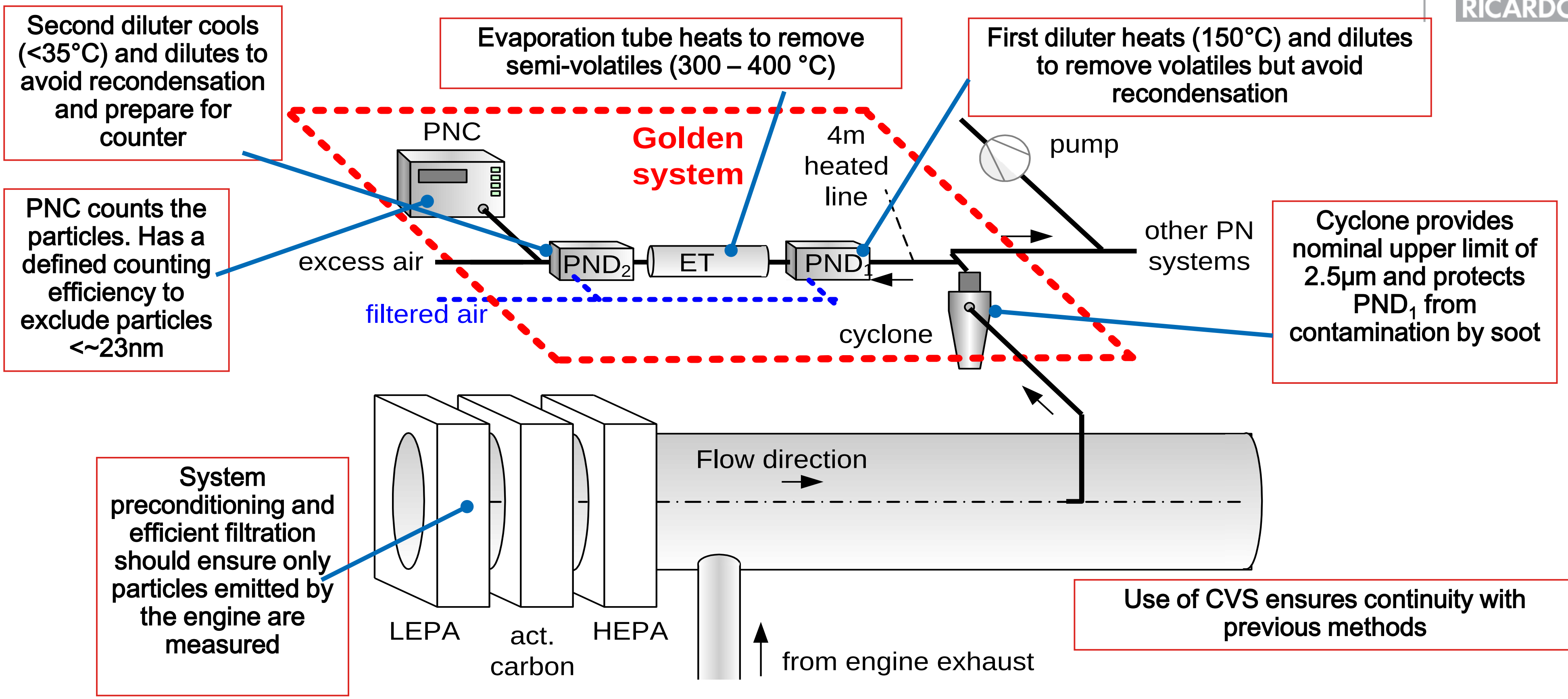
The Measurement System Defines The “Solid” Particle Measured



- Measurement employs a condensation nucleus counter, but uses sample pre-conditioning to eliminate the most volatile particles which may contribute significantly to variability
- Solid particles defined by the measurement equipment
  - ~23nm to 2.5µm and surviving evaporation in the range 300°C to 400°C (350°C)
  - Analogous to heated FID hydrocarbon method
- System sufficiently sensitive to determine differences in fill-state of DPF; repeatability as low as 2% with non-DPF

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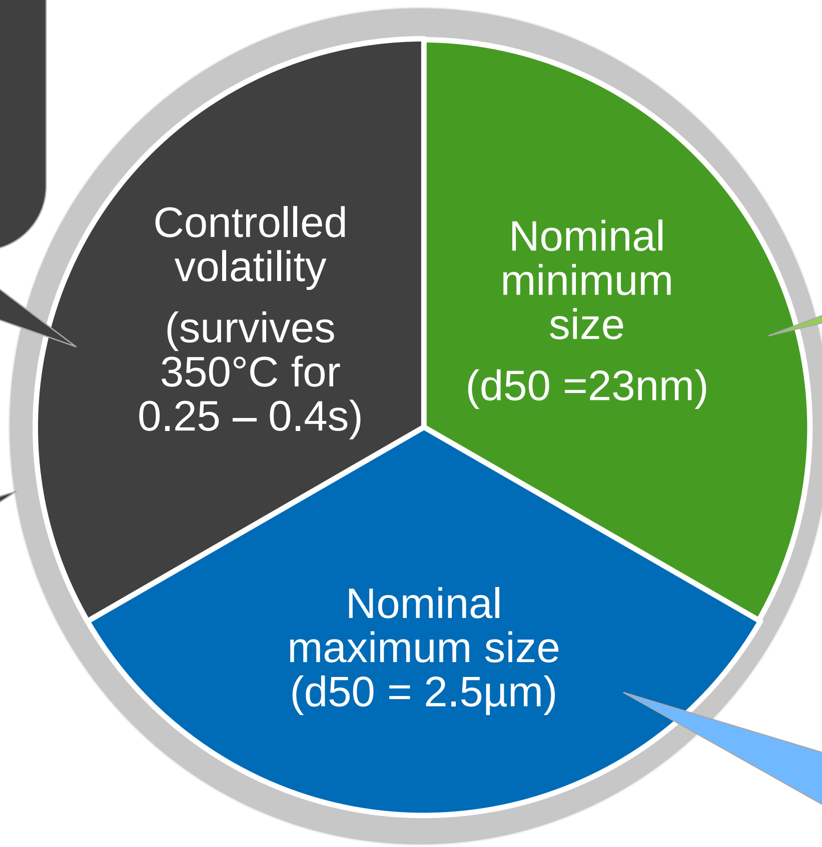
What does a European regulatory non-volatile particle look like?

Non-volatile particles are measured: volatile particles eliminated by dilution and evaporation

Vast majority of Carbonaceous particles are ALWAYS counted



Minimum size of primary carbon sphere ~20nm

Readily available CNC with d50 at 23nm

Not of critical importance, but parallels AQ measurements; also protects first diluter from particle contamination

- Calibration was, and remains, a challenge!
  - Particle Concentration Reduction Factor (PCRF) corrects for losses and dilution inaccuracies in the measurements

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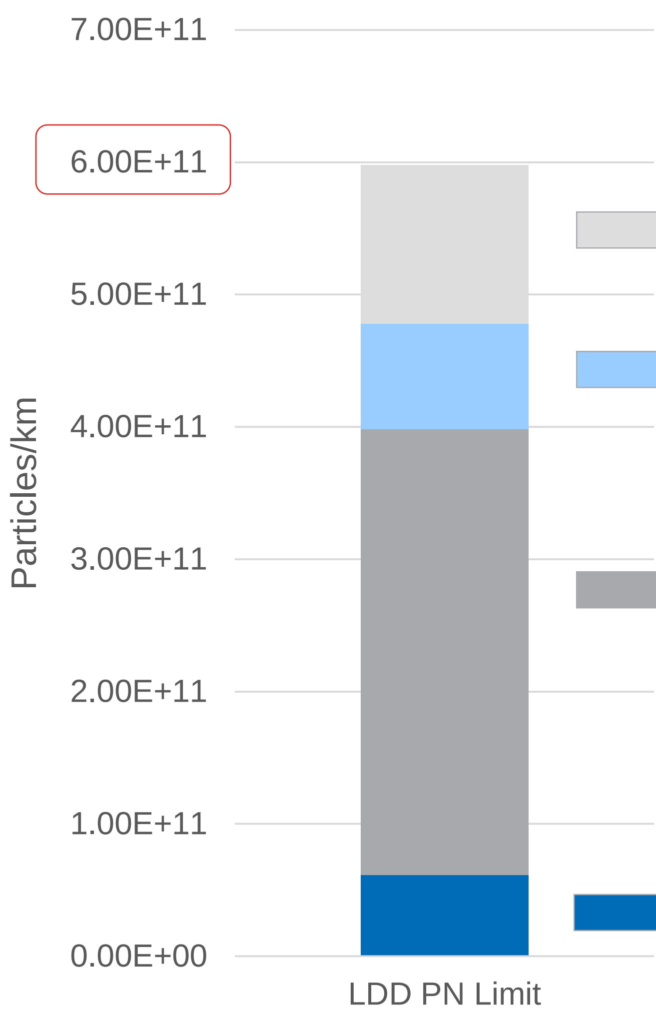
Determination of Particle Number Limit Value (Light-duty Diesel) of 6 x 10^{11} particles/km included many factors



Results' Correction: Losses and dilution errors of ~20% (PCRF)

Engineering Margin: +20% of the total mean and variability terms

Variability: 6 x standard deviation of the mean emissions result

Mean NEDC emission from 6 DPF—equipped diesels in validation exercise

- Limit value constructed from several factors
- Aim to be easily complied with by DPF diesel, but above:
  - Non-DPF emissions
  - Partial / open filter efficiencies (~60%)
- Typical non-DPF PN emissions value was 5x10^{13} /km
- Filtration efficiency required > 98%

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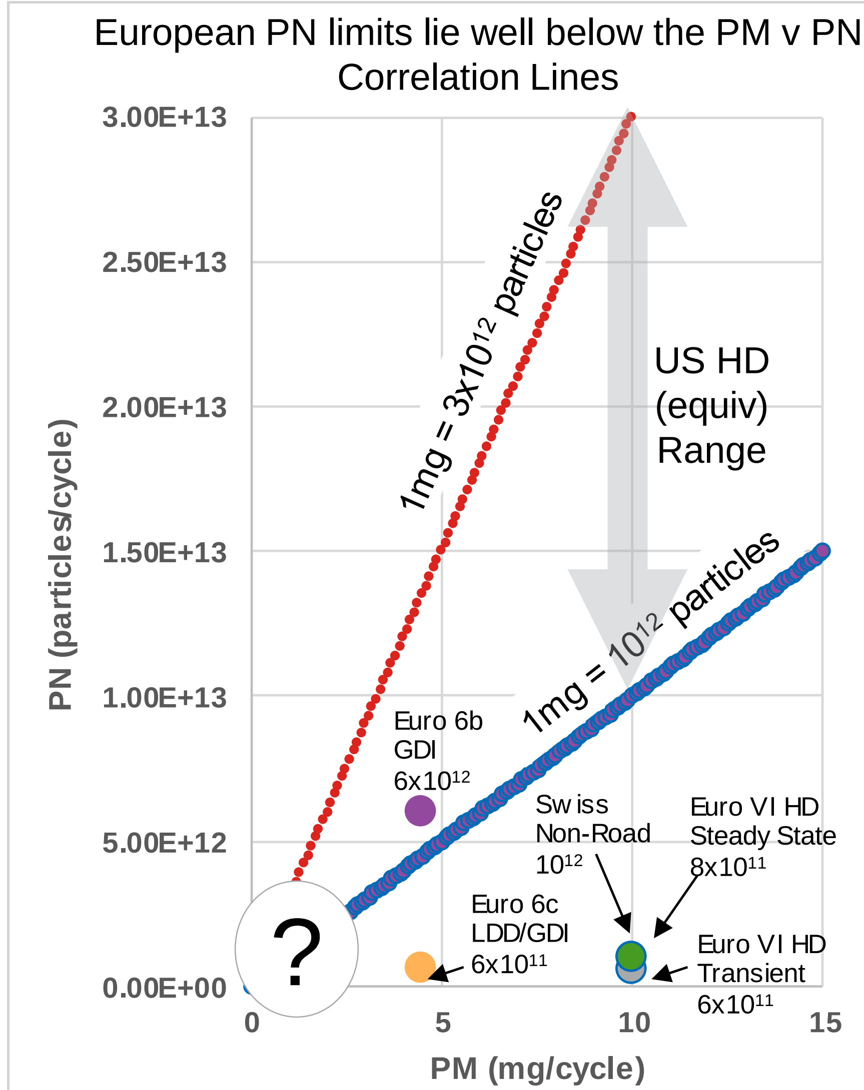
Current PN limits in EU and CH are there to Mandate DPFs, and the PM limit is of no consequence in this respect

- There is no relationship between PM and PN embedded in European regulations
- Several studies have shown that for diesels, 1mg equates to between 10^{12} and $3x10^{12}$ particles
- European PN standards are much tougher than PM standards
  - Euro 6 LDD regulations require $6x10^{11}$ particles and 4.5mg
  - 4.5mg could equate to $>10^{13}$/km
  - Applications with DPFs can deliver $<10^{10}$ particles and well below 0.5 mg
- The PN regulation effectively mandates DPFs and has also ensured they have high efficiencies
- PM remains part of the regulation
  - Volatiles are still controlled



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What the Particle Number Approach has Delivered

- Proven effectiveness of mandating DPF fitment to all LD and HD diesel on-road engines
  - PN widely applied to diesel certification across Europe
  - High efficiency DPFs mandated and ‘effective’ PM emissions reduced to ≤ 0.2 mg/kWh / 0.2 mg/km (mass metric cannot force this)
  - Primary PM_{10} / $PM_{2.5}$ reductions in European cities
  - Better filters for low back pressure and high efficiency developed
- Number of applications equipped with DPFs in Europe is at least 30 million
  - At average mileage of 10,000 km / year, PN emissions at the limit value and engine-out emissions at $5x10^{13}$/km, total PN emissions reduced by $>10^{25}$ /year
- Reductions in urban PM are delivering health benefits
  - Post-DPF PN vehicle emissions levels are often lower than in the intake air
  - Combined DPF and SCR systems now promise low PM with low NO_2 in the urban area

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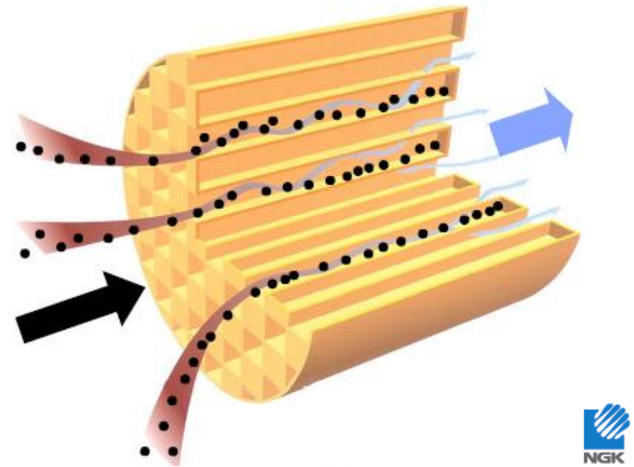
Future Regulatory Directions – Near Term

- DISI PN at Euro 6c will align with light-duty diesel ($6x10^{11}$ particles/km)
  - Possibly achievable without a gasoline particle filter, but throughout vehicle life?
  - GPF applications are already being developed for certification and safe in-use compliance
  - Suitability of the current PN method for this SI engines must be proven
- Real Driving Emissions (RDE) requirements are leading research into the development of PN-PEMS for certification purposes
- Widened application (relative to Swiss Ordinance) of PN controls to NRMM at Stage V to include:
  - Wider power-bands; some spark ignition as well as diesel; new application types
  - PN from active regenerations and open engine breather vent systems

GPF Substrate



Engine Classes Possibly Subject to PN Control at Stage V

19kW – 37kW	• Small diesel engine class; SI also included
>37kW < 56kW	• Diesel only above 37kW
>56kW – 129kW	• Dominant category in NRMM • Technologies similar to on-road HDD
>130kW – 560kW	• Substantial applications • Technologies similar to on-road HDD

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Future Regulatory Directions – Later?

- The current PN regulation was developed for diesel, so is restricted to the size range above which carbonaceous particles are to be found (> ~20nm), and works well!
  - With low carbon emitting engines and vehicles: SI liquid, SI gas, diesels with DPFs, it is possible that numbers of particles equivalent to those seen from non-DPF applications are being emitted below the measurement range of the current system
  - Recent research has shown that
    - Smaller non-volatile particles do exist
    - DPFs capture these smaller particles with high efficiency
    - Emissions from SI applications may be very high, ***especially without GPFs***
  - With some modifications, the existing measurement approach could be adapted to a lower size threshold of ~10nm, but no lower
    - Calibration challenges increase hugely with lower d50 than 10nm
    - Complete elimination of volatile particles may need catalytic approach
    - **Change to 10nm d50 could be achieved if it is proven necessary**

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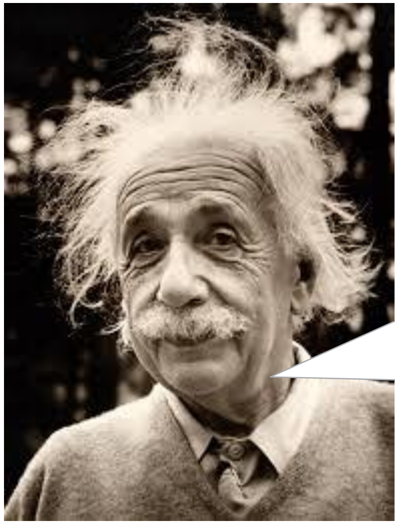
Wrap-up

- Political will, technological maturity in engine control and aftertreatment, the right fuel, strong health evidence for reducing PM and common ground between stakeholders – as well as the need for improved measurements - drove the development of a new measurement metric
- PMP took ~10 years to investigate and develop the PN metric
  - But for LDD the mechanism of legislation was in place after only 3 years
- PN delivers increased sensitivity and accuracy in quantifying diesel particle emissions
- A PN limit was developed that forced diesel emissions to be reduced by >98%: a reduction readily achievable by existing emissions control technologies
- The twin aims of developing a new metric and forcing technologies that eliminate carbon particle emissions from diesel engine exhausts were fully achieved
- Future application of the PN approach to spark-ignition engines and challenging exhaust chemistries, plus the simplification of calibration processes, are the subject of on-going research
- Finally, a question: PN emissions will soon be regulated for on- and off road, CI and SI applications, **is it time to measure success with a number-based AQ method?**

Thanks for listening



"Not everything that counts can be counted, and not everything that can be counted counts…"

"but counting particles counts!"