

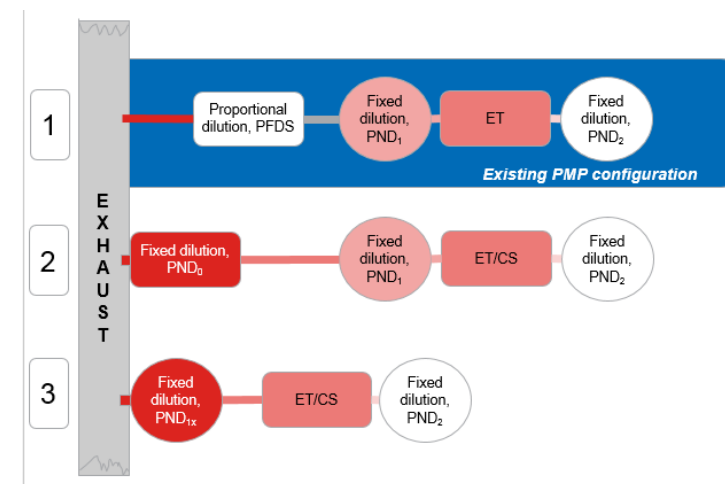
PN Counting from Raw Exhaust via Fixed Dilution

A review of potential concerns

Jon Andersson

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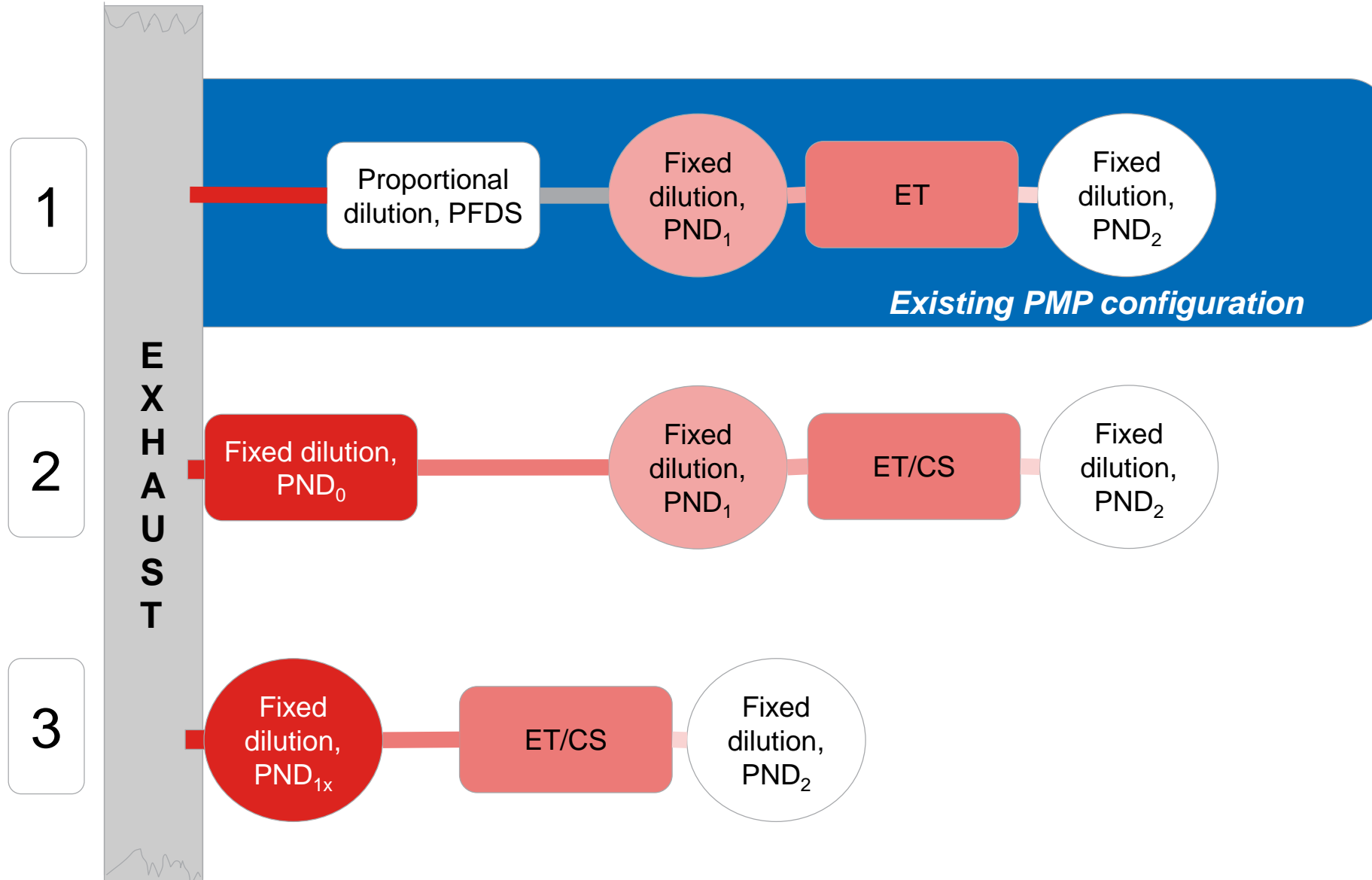
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PN from raw exhaust using fixed dilution

- The principles of raw exhaust sampling were introduced by Les Hill of Horiba at the 35th PMP meeting, 4th March 2015
- The approach avoids the dual use of partial flow dilution systems (PFDS) for PM and PN simultaneously, as some issues have been observed when sampling from PFDS
 - Dual PM and PN can affect the proportionality of the exhaust split stream into the PFDS
 - Set-up and optimisation of dual sampling can require substantial additional time
 - Spatial challenges may exist within the test cell with the PN system connected to the PFDS
 - Flow compensation to account for the flow out of the PFDS to the PN system is complex and hard to achieve accurately (whichever way you do it)
 - Background PN levels likely to be reduced relative to PFDS

Possible Sampling Schematics



- Three possible approaches
 1. Existing PMP, with PFDS
 2. Additional dilution, with close-coupled "PND₀"
 3. Additional dilution but through wider-range PND_{1x}
- Close-coupled and additional dilution introduce specific changes
 - Residence time at temperature
 - Increased 'thermal stepping'
 - Dilution at very high sample temperatures, or line losses
 - Avoidance of condensation and nucleation
- Configurations could need careful specification

Potential Influences

- There are a number of factors that could present challenges to direct sampling PN measurement
- These are briefly explored in the following slides

Exhaust temperatures (Peak)

Exhaust pressures

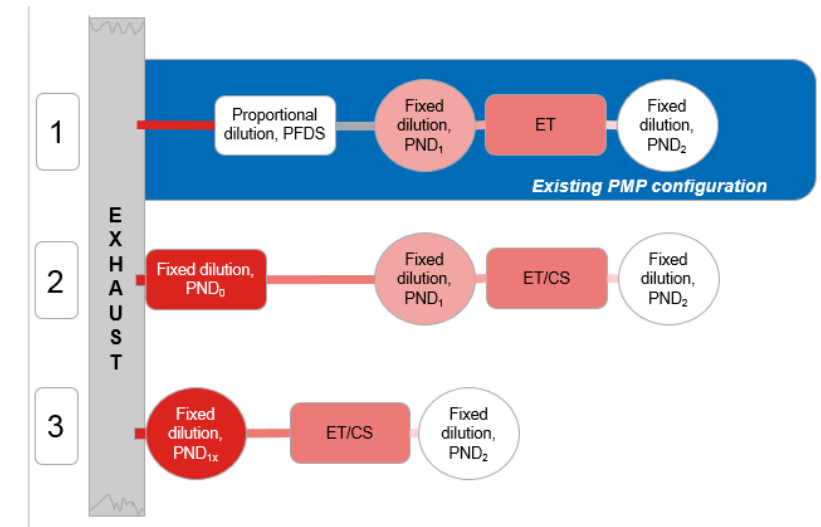
Particle concentrations

Exhaust chemistry

Time alignment of PN &
Exhaust flow

Exhaust temperatures higher than LD applications

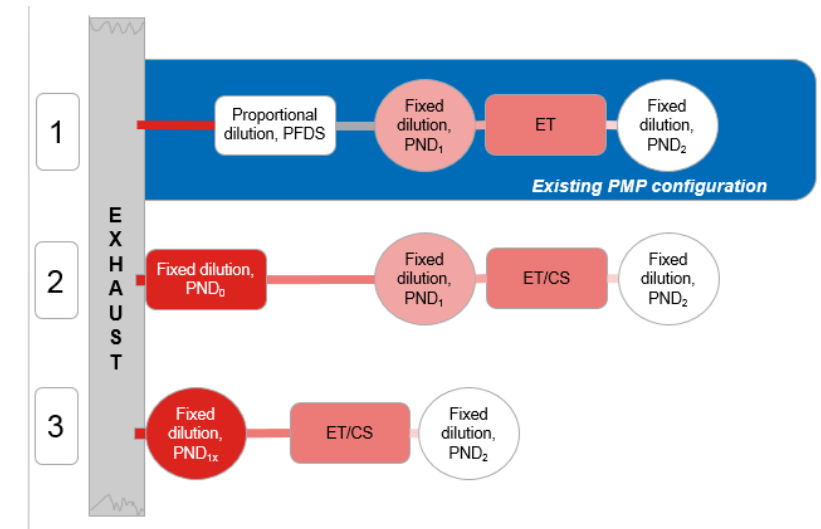
- HD diesel engines see temperature maxima similar to light-duty diesel, but with more time spent at higher load / higher temps
 - High load operation exhaust temperatures to $\sim 550^{\circ}\text{C}$
 - Peak temperatures during active DPF regeneration to 600°C
 - Potential for LNT regeneration / desulphation (negligible applications) temps of 650°C
- R49 Regulation also includes gas engines: CNG and dual fuel (often diesel pilot)
 - CNG engines derived from diesels – similar temperature regimes to diesel engines (diesel manifolds)
 - Possibly 680°C peak (SI and DI)?
 - Specific CNG designs (heat resistant manifold / turbine)
 - Stoichiometric engines could approach 900°C ?
- **Sample transport from exhaust to first diluter and from diluter to ET/CS may have substantial gradient, leading to thermophoretic losses**
- **High exhaust temperatures with gas engines may challenge diluter materials**



- **Larger thermal gradient with [2] than [3] could mean greater losses**
- **Complexity of variable diluter in [3] may be more challenging for high temperature materials than [2]**
- **Fast, early dilution with [2] & [3] will minimise nucleation and condensation**

Exhaust Pressures

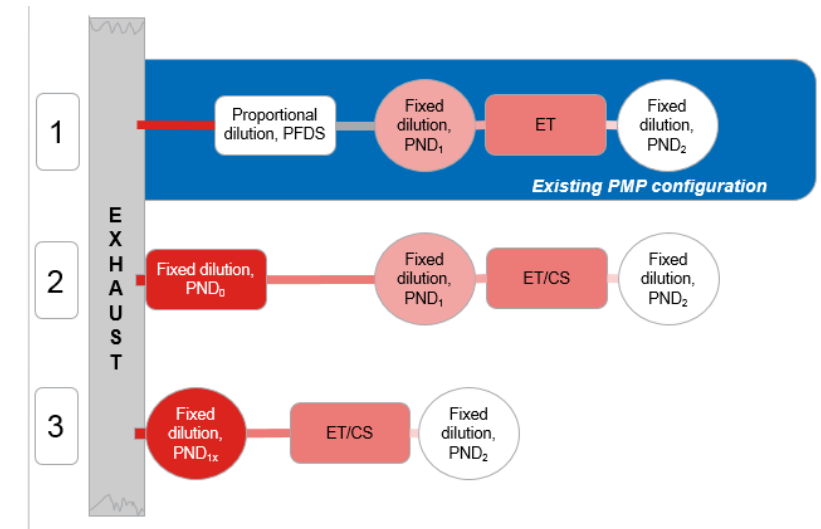
- Sampling takes place downstream of emissions control system components
 - Atmospheric pressure
 - Pressure pulses (up to 100mb?) will impact ability of primary diluter to sustain fixed ratio
 - Dilution characteristics may impact validity of PCRF calibration
- **Permissible pressure changes to be defined in the regulation**
- **Alternative dilution configuration may add complexity to PCRF calibration**



- **Pressure transients in exhaust that impact dilution ratio will have larger effect in [1] than [2] & [3]**
- **PCRF calibration of fewer components in [3], but monodisperse PN concentrations lower after first diluter**
- **PCRF calibration of PND₀ (+ transfer tube) possible in isolation for [2]**

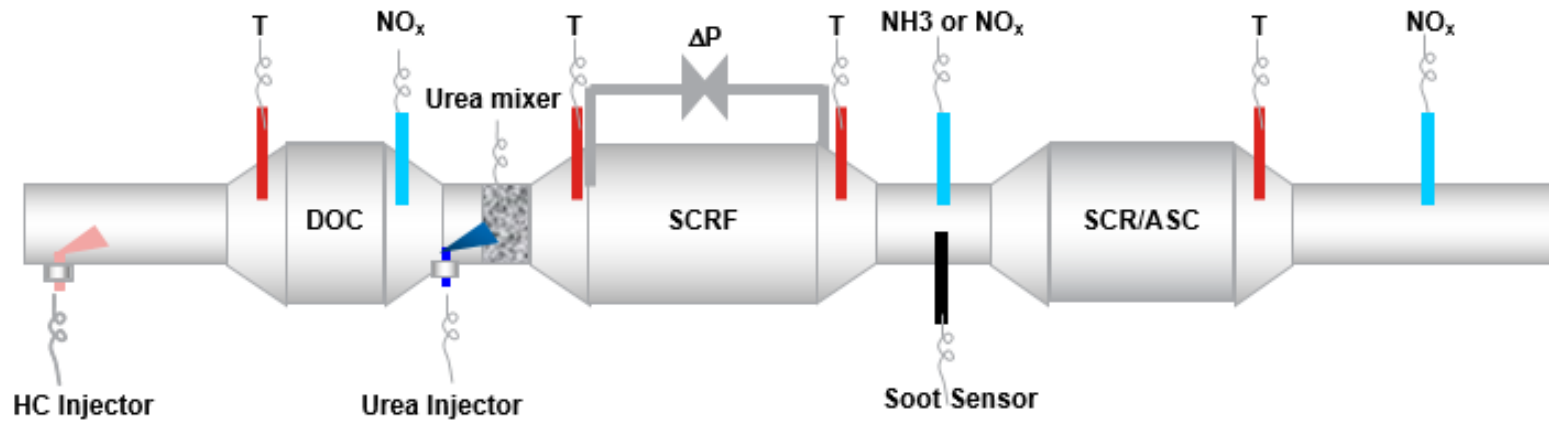
Particle Concentrations

- For certification testing, measurement system will be applied to non-volatile particles from
 - DPF equipped diesels
 - Potentially, GPF and non-DPF gas engines
- Typical PN concentrations will peak in the range $10^6 - 10^8$ particles/cm³
- Concentrations may be as low as $10^2 - 10^3$ particles/cm³
- Losses in catalytic stripper would lead to even lower particle concentrations
- **Potentially 3 stages of dilution could lead to over-dilution of the sample and additional opportunities for particle loss / larger PCRFs / lower accuracy / increased challenge for calibration**
- **2-stages of dilution could be sufficient (raw sample into PND1?)**

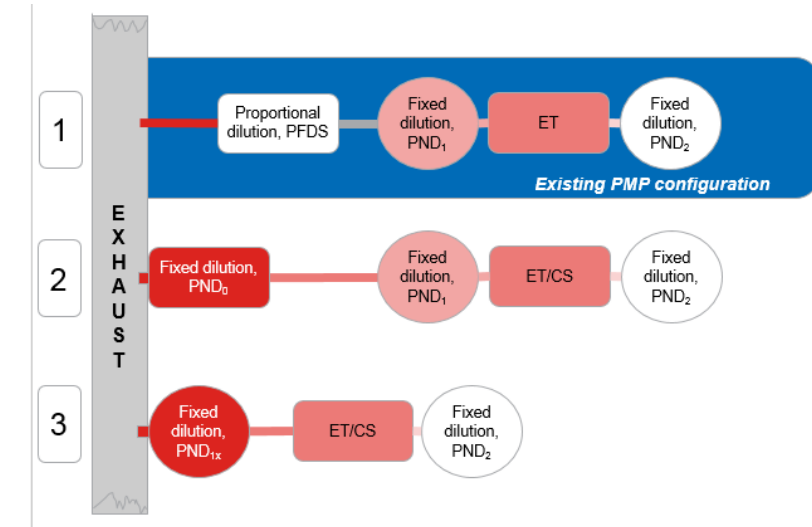


- **Over-dilution of sample issues potentially greatest with [2]**
- **Some residence time at dilution may be required to stabilise sample**

Exhaust Chemistry (SCR)



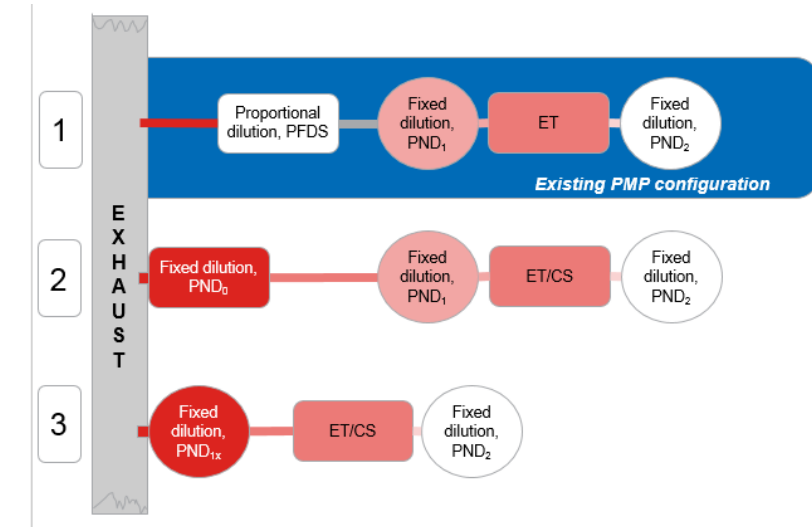
- Unreacted urea may be present in the exhaust system and in combination with water, ammonia and other urea breakdown products, such as isocyanic acid, deposits can form
 - These may evolve and become thermally stable, or decompose
- **Deposits might form in the exhaust and decay, or shed, eventually being counted as particle artefacts**
- **Materials may accumulate in the first diluter and evolve, contaminating the diluter and impacting effective dilution ratios, or shed particles**
 - **Inaccurate quantification may result**



- **Temps >300°C at primary diluter should resist formation of polymeric materials**
- **[3] likely to be advantageous in resisting deposit formation, but if deposits do form and shed particles, the largest artefact will be observed due to high DR correction**
- **Aftertreatment with DPF post-SCR unlikely to experience any issues**

Exhaust Chemistry (CNG)

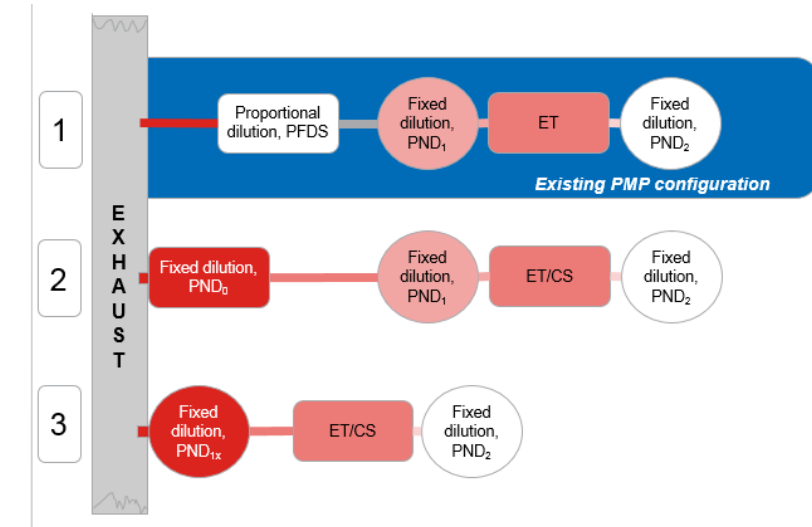
- Exhaust storage and release phenomena are well known
 - Deposition and later thermal release of low / semi-volatile materials can occur downstream of emissions control systems, including DPFs
 - Gas engines running at temperatures above those of diesel engines can evaporate higher boiling components which may recondense into ‘non-volatile’ particles
 - Stoich CNG may have TWC only – minimal scope to capture these materials if released during combustion – and very high exhaust temps
 - Very high boiling components may derive from synthetic lubricants / polymers may decompose
 - Potentially these could manifest as non-volatile particles and / or condense in the heated diluter
 - **Materials released at >800°C may condense and contaminate the first diluter**
 - **These materials may also challenge the ET if sufficiently high concentrations are present**
 - **Tetracontane boils at 524°C**
- Lean CNG engines could potentially be equipped with SCR systems
 - Issues with SCR deposits may exist, as with diesel



- **Rapid high dilution at [3] may resist deposition even at high exhaust temperatures**
- **Contamination of first diluter in [2] of greater concern?**
- **Large volume of PFDS reduces impact of any deposits**

Dilution and time alignment

- With DPF equipped diesels particle concentrations are typically reduced to a narrow band of low concentrations across a wide range of engine operation
 - Partial flow dilution systems with appreciable dilution volume also have a smoothing effect on the sample
 - Inaccuracies in time alignment of exhaust flow (e.g. from compression of exhaust) have minimal impact on overall calculation of PN – and the eventual calculated emissions level is likely to be well below the limit value
- With gas engines (non-GPF) the peak and range of PN concentrations are greater
 - Inaccuracies in time-alignment will have a greater impact and the outcome of the calculation will be much closer to the limit value
 - **Alignment of gas engine signal needs to be accurate**
- PND_0 dilution could be very rapid, so if sampling takes place close to a catalyst outlet exhaust sampled could be inhomogeneous
 - **Sample needs to be representative / well mixed**
 - **Sample may need minimum residence time for stabilisation**

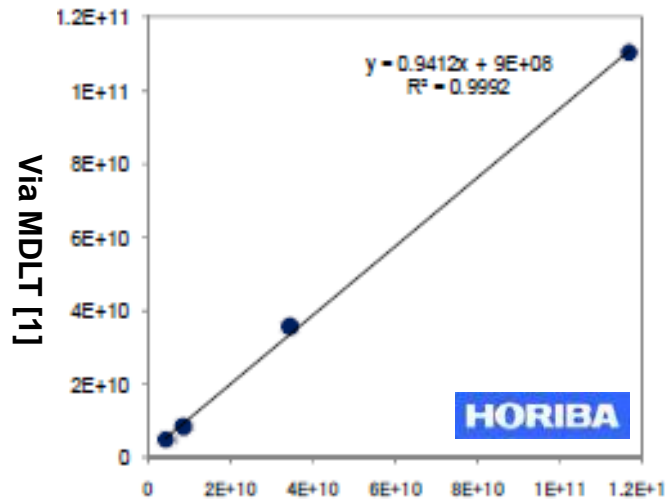


- **Mixing prior to sampling in exhaust a greater issue for [2] and [3] than for [1]**
- **Precise time-alignment less critical for DPFs than gas engines**

General points

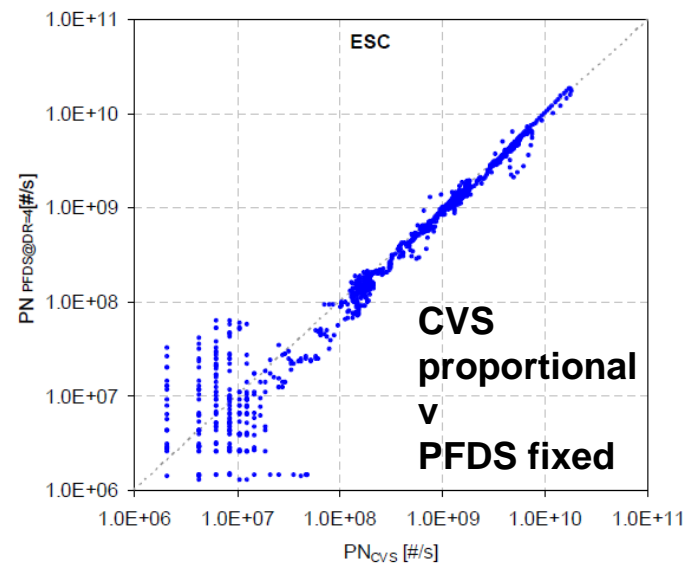
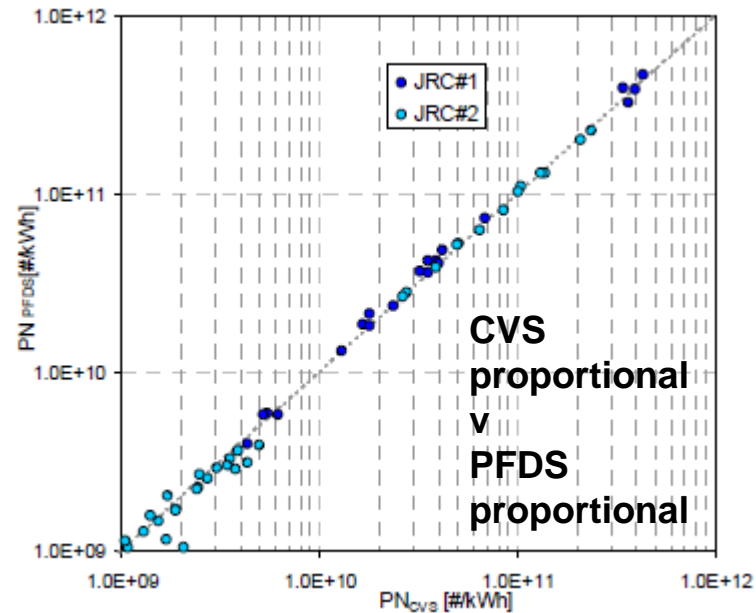
- Some of the challenges identified may already be addressed in relation to sampling of particles and gases for existing analytical equipment
 - Instrument manufacturers may have solutions
- Points for consideration seem to be
 - Additional diluter (PND₀) or wider-range PND₁?
 - Sample routing from exhaust to first diluter (especially at very high temps)
 - Temperature of initial diluter (avoidance of thermophoresis / challenge for materials)
 - Residence time / volume in first diluter (stabilisation of sample / limitation of losses)
 - Diluter resistance to contamination
 - Pressure changes in exhaust influencing dilution ratios (PCRf uncertainty)
 - High exhaust temperatures generating particles from lube and SCR
 - Importance of accurate time-alignment increased with non-DPF PN calculation

Limited data exists showing direct sampling compared with MDLT sampled PN, but data are promising



Direct Sampled [2]

- Horiba data shows ~6% higher PN from DPF diesel when using direct sampling approach
 - Lower PN losses and background?
- Linearity appears good



- PMP HD engines' data showed good correlation of two PN systems with CVS and PFDS using proportional dilution
 - Effectively two variants of [1]
- In another expt, the CVS was compared with the PFDS, but with the PFDS at fixed dilution
 - Effectively a CVS variant of [1] v a PFDS variant of [2]
- Linearity also appears good