Sources and magnitude of sub-23nm non-volatile exhaust particle number emissions from the H2020 DownToTen Programme

Jon Andersson, Ricardo UK

Co-authors: Mamakos, A.; Klug, A.; Bergmann, A.; Bainschab, M.; Karjalainen, P.; Keskinen, J.; Giechaskiel, B.; Lahde, T.; Haisch, C.; Thaler, K., Piacenza, O.; Ntziachristos, L.; Samaras, Z.

2020 Cambridge Particle Meeting, June 19th, 2020 at CUED, Cambridge, UK

Sub-23nm PN vehicle technology effects using the DTT system

- **Introduction**
- The DTT measurement systems
- Approach to display comparative data
- Where results may still exceed $6x10^{11}$#/km
- PN10 (and some <10nm) emissions from various technologies
- What proportion of PN10 exists below 23nm?
- Soot as a potential moderator of <23nm PN
- Potential regulatory implications

Introduction

- "DownToTen" (DTT) project was one of three EU H2020 funded projects developing robust **p**ortable **e**xhaust **p**article **s**ampling system (PEPS) methodologies to extend the regulatory approach for particle number (PN) emissions to the sub-23 nm region. DTT completed at the end of 2019
  - New regulation for "PN_{10}" seems highly likely, in the next 2-3 years
- Initial direction of the H2020 projects, was to assess latest generations of direct injection gasoline and diesel engines under real world conditions
  - but the projects evolved to consider all technologies in the Euro 7 "technology neutrality" context
- DTT has developed a sub-23 nm PN sampling and measurement approach, and both lab-based and PEPS prototypes
- This presentation focuses on the assessment of the presence and magnitude of <23nm emissions from a large number of tests performed by various partners within DTT
  - with both lab-based and PEPS systems

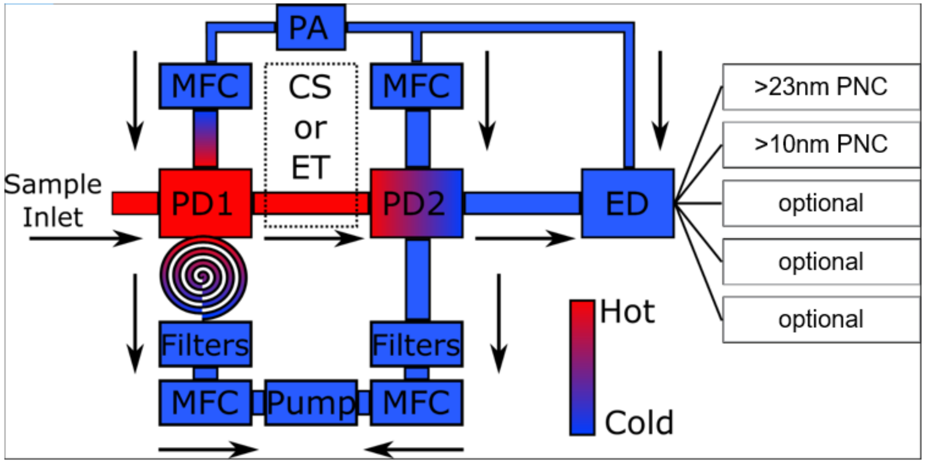
Sub-23nm PN vehicle technology effects using the DTT system

- Introduction
- **The DTT measurement systems**
- Approach to display comparative data
- Where results may still exceed $6x10^{11}$#/km
- PN10 (and some <10nm) emissions from various technologies
- What proportion of PN10 exists below 23nm?
- Soot as a potential moderator of <23nm PN
- Potential regulatory implications

DTT Measurement Systems

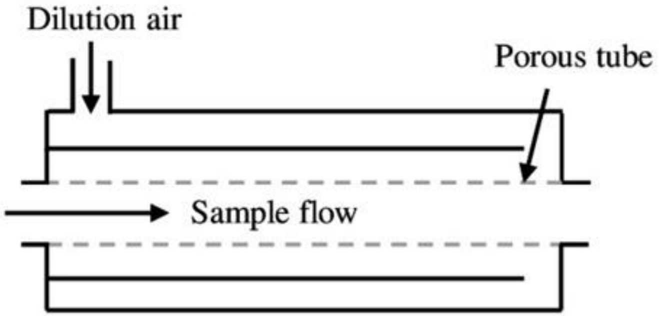
- The DTT lab measurement system consists of two porous tube diluters (PD1, PD2) and a third, optional dilution stage for sampling high particle number concentrations. This additional dilution is supplied by an ejector diluter (ED).
- Between the two PD either an evaporation tube (ET) or catalytic stripper (CS) can be placed. In this work only CS was used
- The DTT PEPS simplifies dilution and is reduced in size, weight and power consumption
- DTT system is optimised for the transmission and counting of <23nm PN, plus volatile removal

Schematic



Portable (PEPS)

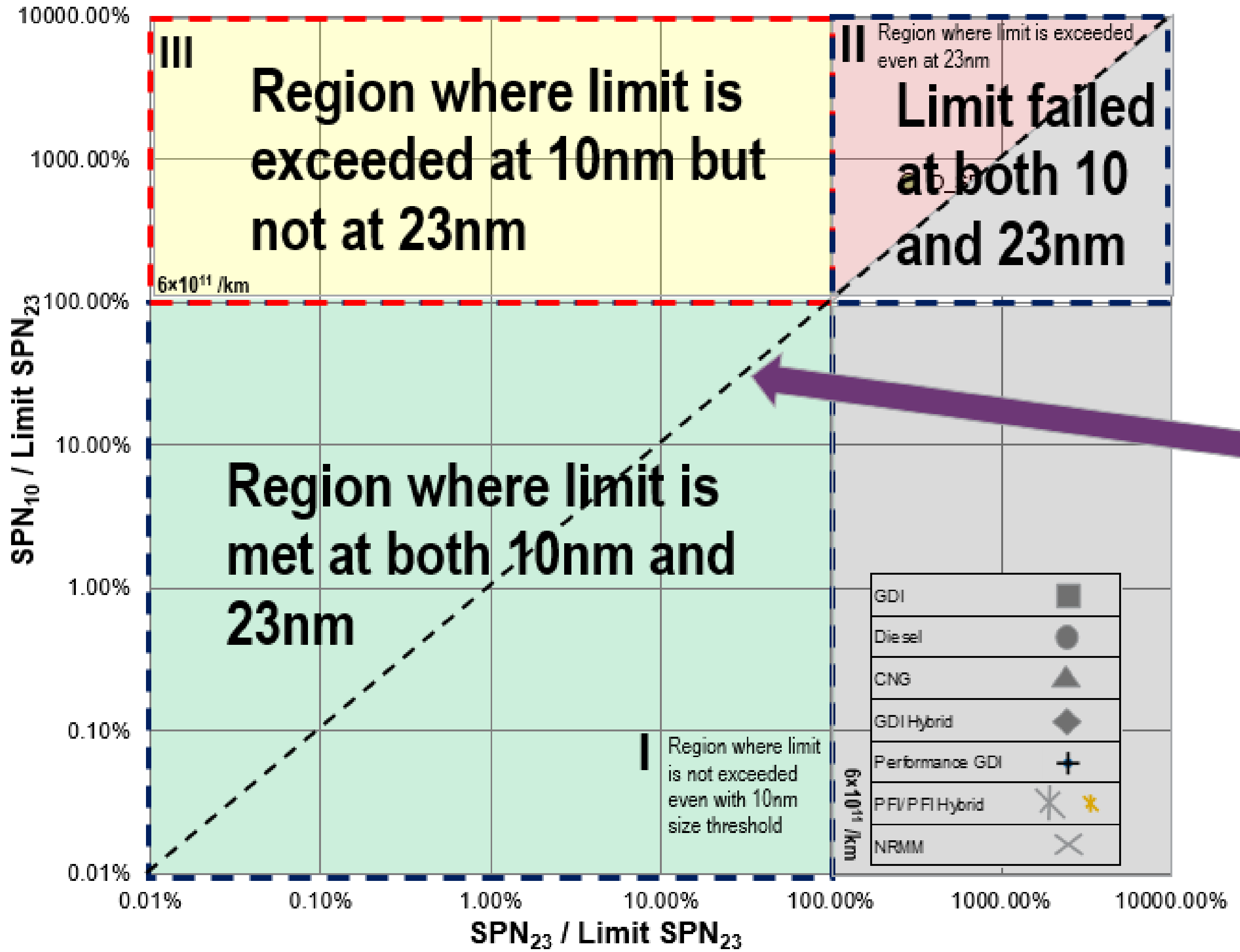
Porous tube diluter



Sub-23nm PN vehicle technology effects using the DTT system

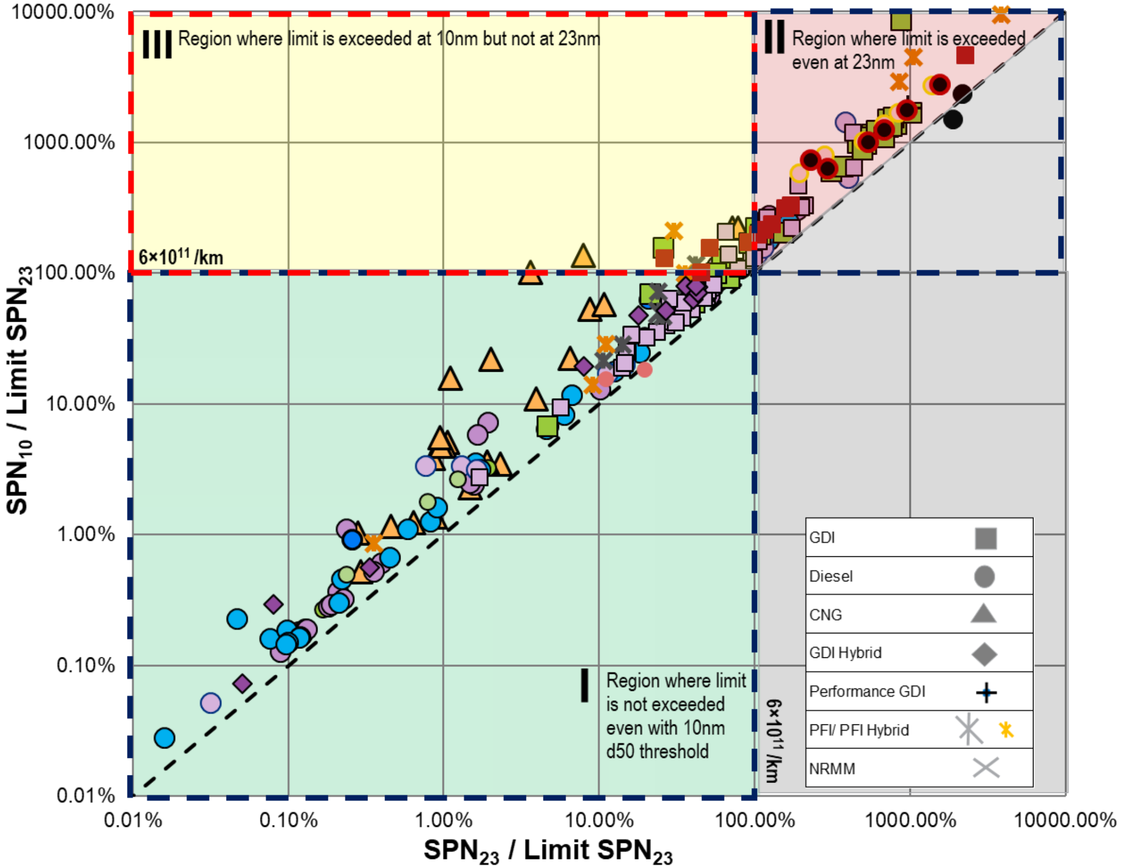
- Introduction
- The DTT measurement systems
- **Approach to display comparative data**
- Where results may still exceed $6x10^{11}$#/km
- PN10 (and some <10nm) emissions from various technologies
- What proportion of PN10 exists below 23nm?
- Soot as a potential moderator of <23nm PN
- Potential regulatory implications

PN emissions from <23nm and >23nm testing



Line where 23nm emissions = 10nm (or <10nm) emissions

PN emissions from <23nm and >23nm testing



- **262** separate results for SPN23 and SPN10 [covering 5+ orders of magnitude]
- Data from Ricardo, LAT, TUG, AVL and JRC
- Most data from lab-based prototype system
- **Results loss-corrected using dual-CPC method (Kittelson)**
- Fewer results in SPN<10 data, but still over **200**
  - 2.5nm, 4nm and 7nm d50 PNCs
- **Data presented as normalized to $6x10^{11}$#/km (= 100%)**
  - (or relevant HD/NRMM limit)

Wide Spectrum Testing

- A wide range of global regulatory cycles have been tested on multiple vehicle and emissions control technologies in DTT

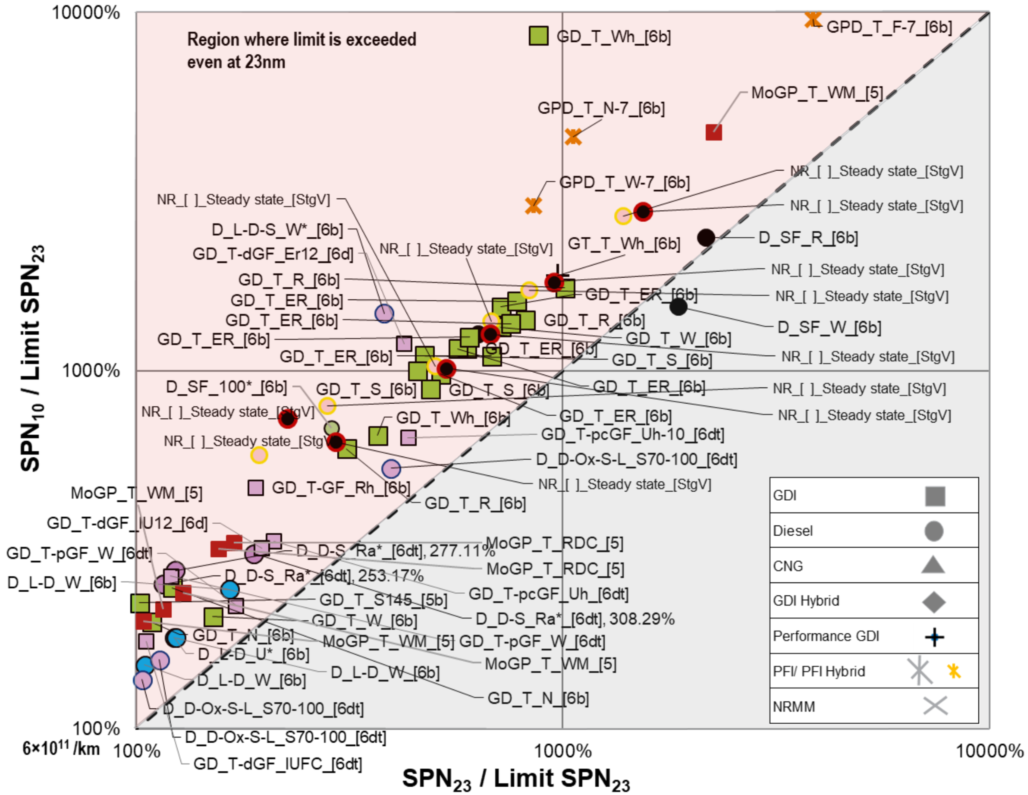
Key: Test site and technology type	Key: Aftertreatment	Key: Emissions drive cycle or test	Key: Other Factors
R = Ricardo A = AVL L = LAT J = JRC T=TUG D = Diesel DN = Diesel NRMM HD = Heavy duty diesel GP = Gasoline port injection GD = Gasoline direct injection GDH = Gasoline direct injection hybrid GPH = Gasoline port injection hybrid GDP = GDI performance vehicle MoGP= Moped GP MGP = Motorcycle GP CG = CNG (CGV = CNG van) GT= gasoline twin: direct/port injection	[ ] = No aftertreatment D = DPF Ox = DOC L = LNT S = SCR SF = SCRF T = TWC dGF = development GPF GF or pGF = production GPF GFc = coated GPF GFu = uncoated GPF GFhp = high porosity GPF GFmp = medium porosity GPF GFlp= low porosity GPF CuC = clean-up catalyst (for NH_3)	**Drive Cycles:** N = NEDC W = WLTC J = JC08 U = US06 R = RDE Ru = RDE urban WM = WMTC R47 = R47 RDC = RDC_lang Acc145 = hard acceleration to 145kph C = City (non-regulatory) SY = steady state load (Y= L,M,H) SZ = steady state speed (Z= kph) Sλx = steady state lambda x Er = ERMES IU = IUFC TfL = TfL urban interpeak Ba130 = BAB130	**Temperature variants (e.g.):** W0 = WLTC @ 0°C Jh = hot start JC08 Ra = ambient start RDE **Emission control regeneration:** W* = WLTC featuring active DPF regeneration 100* = DPF regeneration in 100kph cruise den = DeNOx des = DeSOx **Hybrid state of charge** ChSxxx = charge sustaining xxx % SoC ChDxxx = charge depleting xxx % SoC ChS = charge sustaining ChD = charge depleting

Sub-23nm PN vehicle technology effects using the DTT system

RICARDO

- Introduction
- The DTT measurement systems
- Approach to display comparative data
- **Where results may still exceed $6x10^{11}$#/km**
- PN10 (and some <10nm) emissions from various technologies
- What proportion of PN10 exists below 23nm?
- Soot as a potential moderator of <23nm PN
- Potential regulatory implications

Zooming in to the "Exceedance Zone" whole cycles
PN23 & PN10 both exceed limits



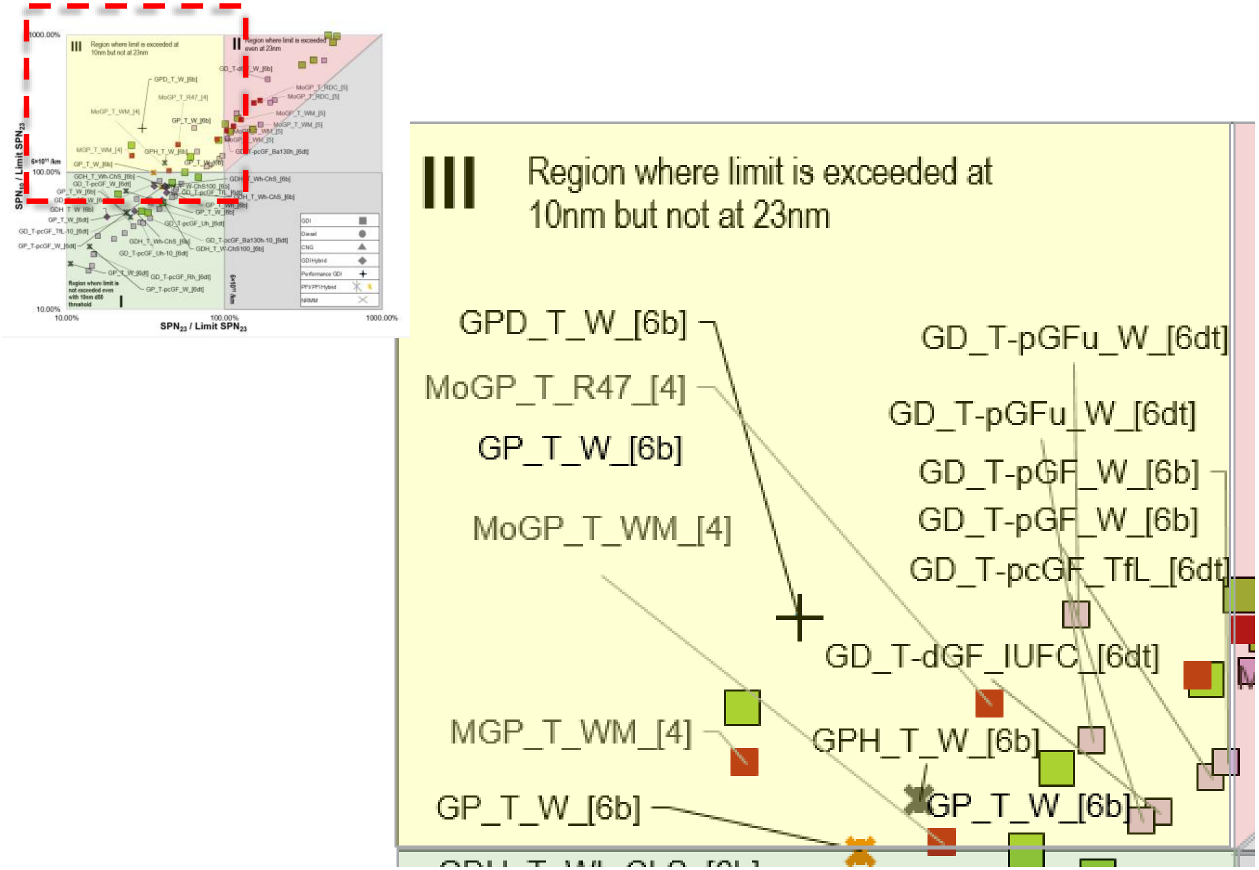
- Non-DPF diesels NRMM, LD etc(!!)
- Mopeds (oil, soot, poor combustion, no PN regulation)
- High performance PFIs (no PN regulation)
- Euro 6b GDI (6x10[12] target; high off-cycle emissions)
- Euro 5 PFI motorcycles (no PN regulation)
- Up to 6dt Diesels with DPFs (during regens or straight after)
- A few GDI vehicles of 6dT specification with development and production GPFs (non-regulatory "severe driving" tests)

Reducing PN towards compliance

Sub-23nm PN vehicle technology effects using the DTT system

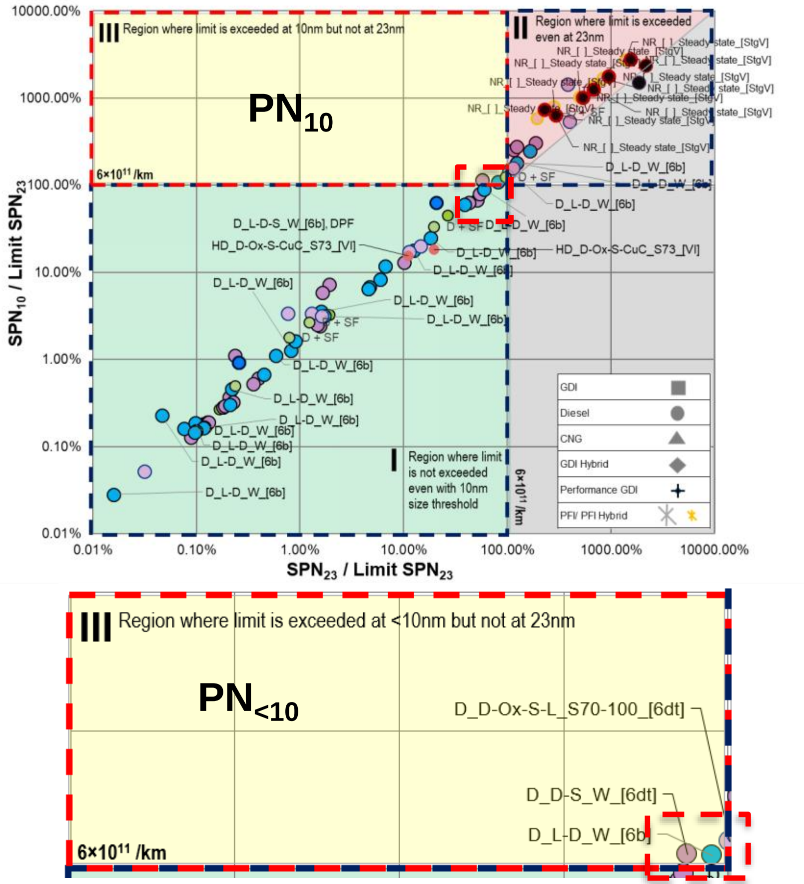
- Introduction
- The DTT measurement systems
- Approach to display comparative data
- Where results may still exceed $6x10^{11}$#/km
- **PN10 (and some <10nm) emissions from various technologies**
- What proportion of PN10 exists below 23nm?
- Soot as a potential moderator of <23nm PN
- Potential regulatory implications

All gasoline technologies, PN_{10}



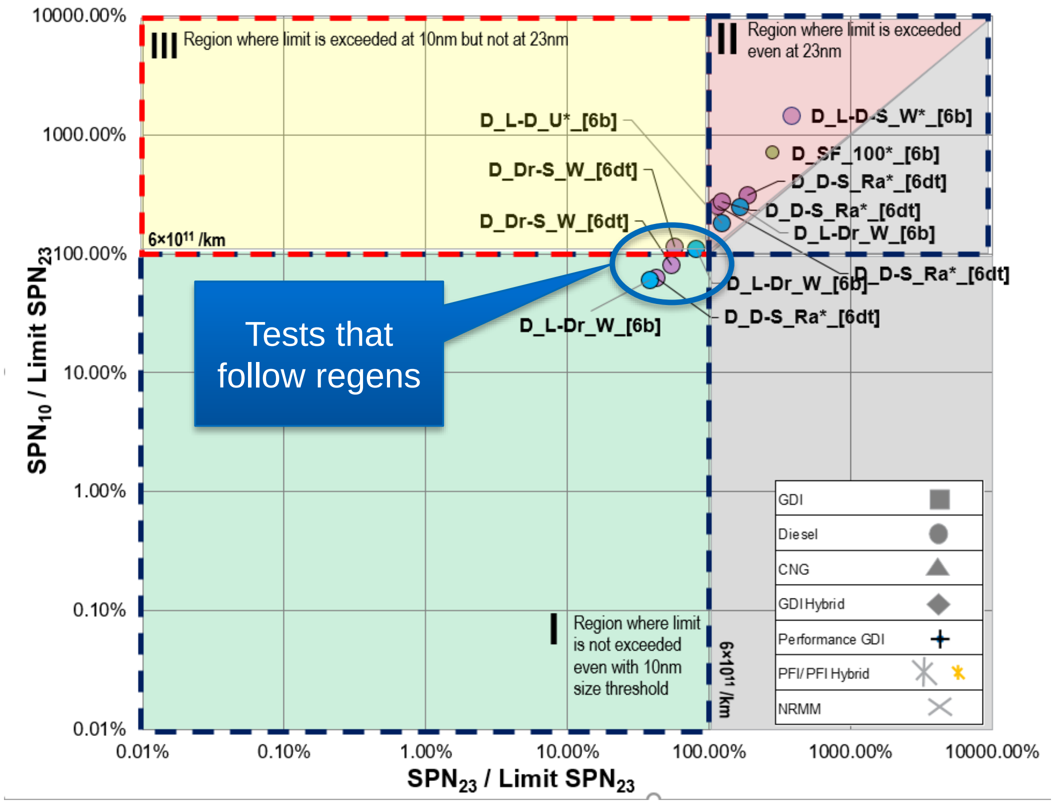
- PN_{23} limit passed, but PN_{10} failed
  - Mopeds and motorcycles (no PN regulation); some PFI
  - Some 6b GDI on standard cycles, even with GPF
  - Some 6dt GDI on non-standard cycles (TfL, IUFC etc)
- Most GPF-equipped vehicles have ‘young’ GPFs – ash accumulation minimal
- **Optimisation of GPF for higher efficiency, “future RDE”, operation is required, even at 6dt**
- GDI hybrids ***borderline*** without GPF, or fail at PN_{23} as well as PN_{10}

All diesel technologies, PN_{10} and $PN_{<10}$



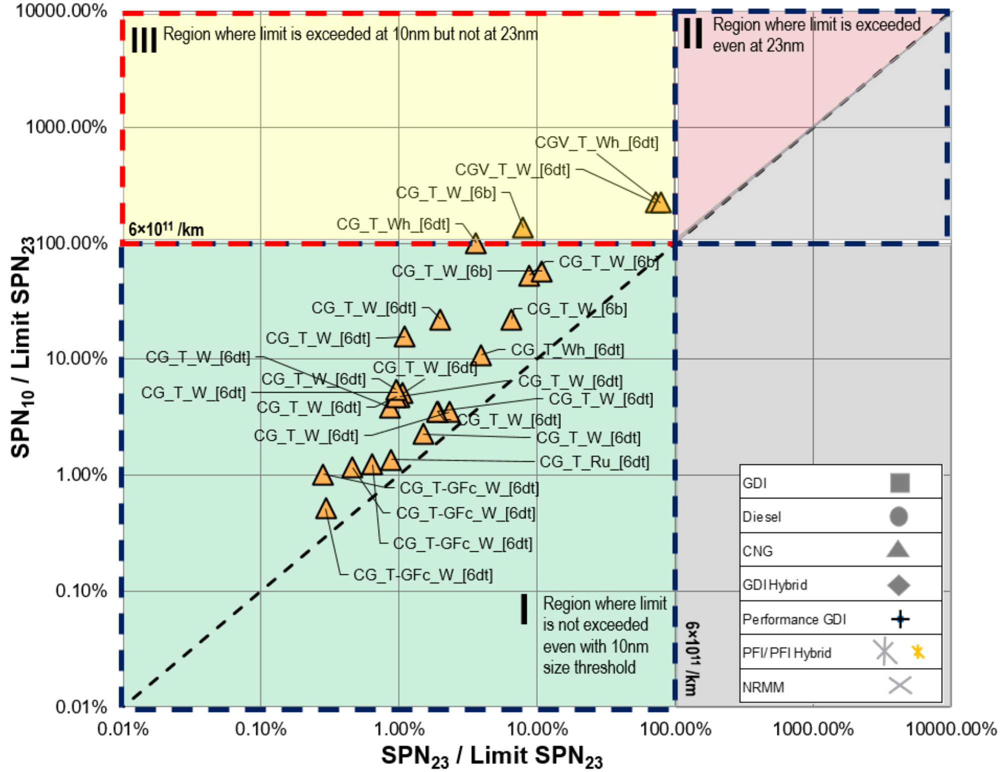
- With DPF-equipped diesels in particular, <23nm fraction is very small
  - PN10 v PN23 data sits on line y=x
- Few results where PN passes at 23nm, but fails at either 10nm or <10nm
  - non-regenerating cycles where the PN23 levels are very close to the limit, and PN<23 levels are slightly higher
- These tests occur immediately after regeneration, when the DPF is its lowest filtration state
- **DPF efficiency evolution (soot, maybe ashing) should be taken into account in Ki factor determination**

PN emissions from diesel tests including, and immediately following, a DPF regeneration



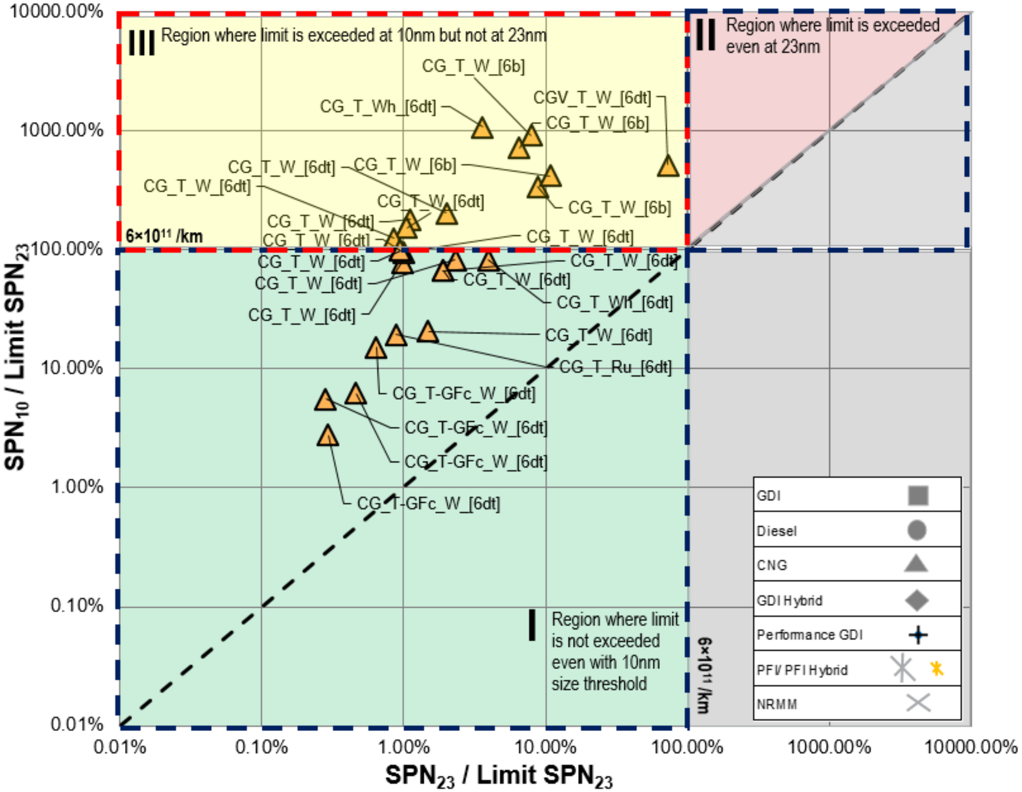
- Diesel tests that include, or immediately follow, active regenerations have elevated PN levels, and these may exceed $6x10^{11}$#/km
- There is no extra impact on <23nm PN than observed in the >23nm regime

CNG, PN_{10}



- Only 2 vehicles tested: more required
- PN_{23} limit passed, but PN_{10} failed
  - A few WLTC tests, both van and passenger car close to the limit for both PN23 and PN10, and some close to the PN10 limit but 10x below with PN23
- Many tests compliant with PN10 without GPF, including Euro 6b.
  - **If oil is the main source of <23nm PN then good oil control could make PN10 compliance possible <u>without particle filter</u>**
- Fitting "GaPF" not essential to ensure compliance with 6×10^{11}#/km at PN10?

CNG, $PN_{<10}$



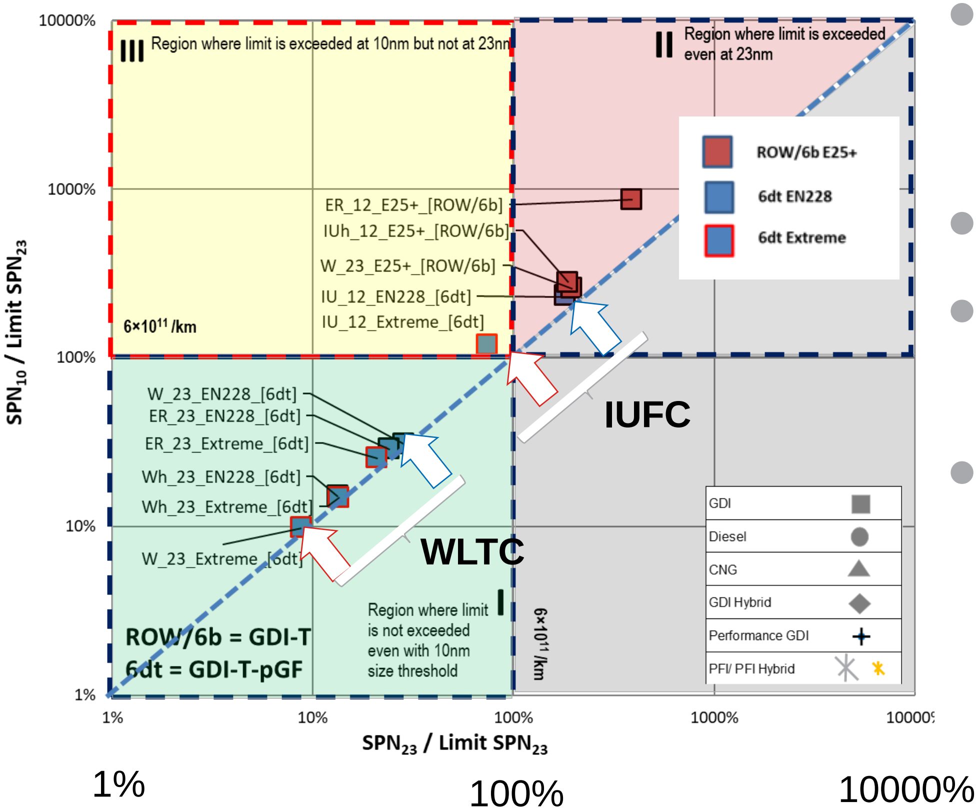
- **Key future research area**
- PN_{23} limit passed, but $PN_{<10}$ failed
  - Many more results that are compliant with limit at PN23 fail with <10nm boundary
- Less likely that 'engine measures' would enable PN to pass at <10nm
- **Retrofitting "GaPF" essential to ensure compliance with $6x10^{11}$#/km at PN<10?**
  - Regulatory conundrum if PN method can't go below 10nm (calibration challenges etc)?
  - Ashing considerations, as with gasoline

DOWN TO 10

GDI vehicles E27, EN228, Extreme; PN10

RICARDO

E27 = 27% Ethanol **EN228** = Pump E10 **Extreme** = high density, low volatility, high and heavy aromatics



- Two near identical (hardware) test vehicles from the same family (GPF Euro 6dt & ROW/6b)
- WLTC (c/h); IUFC (urban), ERMES (highway)
- PN highest from E27 non-GPF ROW/6b
  - (high EtOH is not alternative to GPF)
- High sooting "extreme fuel" has <u>lower</u> post-GPF PN than EN228 on like-for-like basis
  - Higher soot production assists in GPF filtration efficiency?
  - Counter to current belief that these fuels lead to higher tailpipe PN, even with GPF

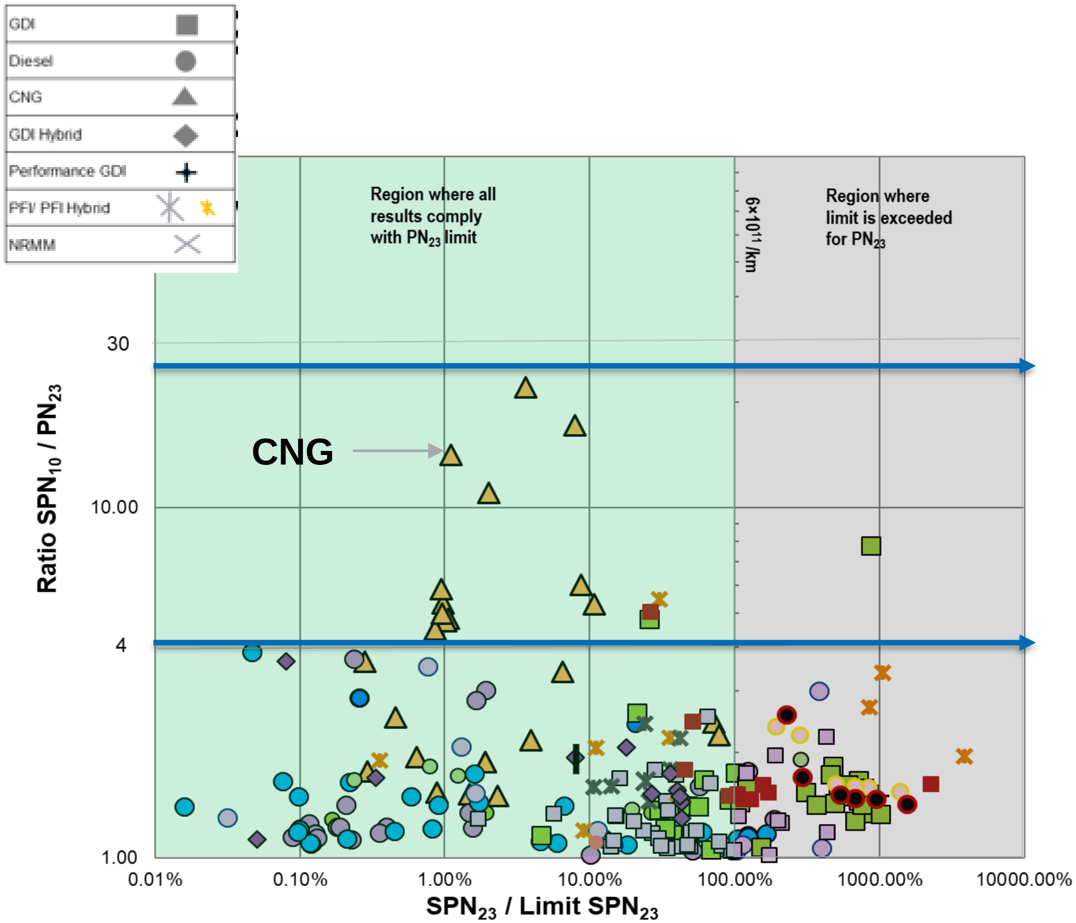
Sub-23nm PN vehicle technology effects using the DTT system

- Introduction
- The DTT measurement systems
- Approach to display comparative data
- Where results may still exceed $6x10^{11}$#/km
- PN10 (and some <10nm) emissions from various technologies
- **What proportion of PN10 exists below 23nm?**
- Soot as a potential moderator of <23nm PN
- Potential regulatory implications

DOWN TO 10

What proportion of the PN10 is between 10nm and 23nm?

RICARDO



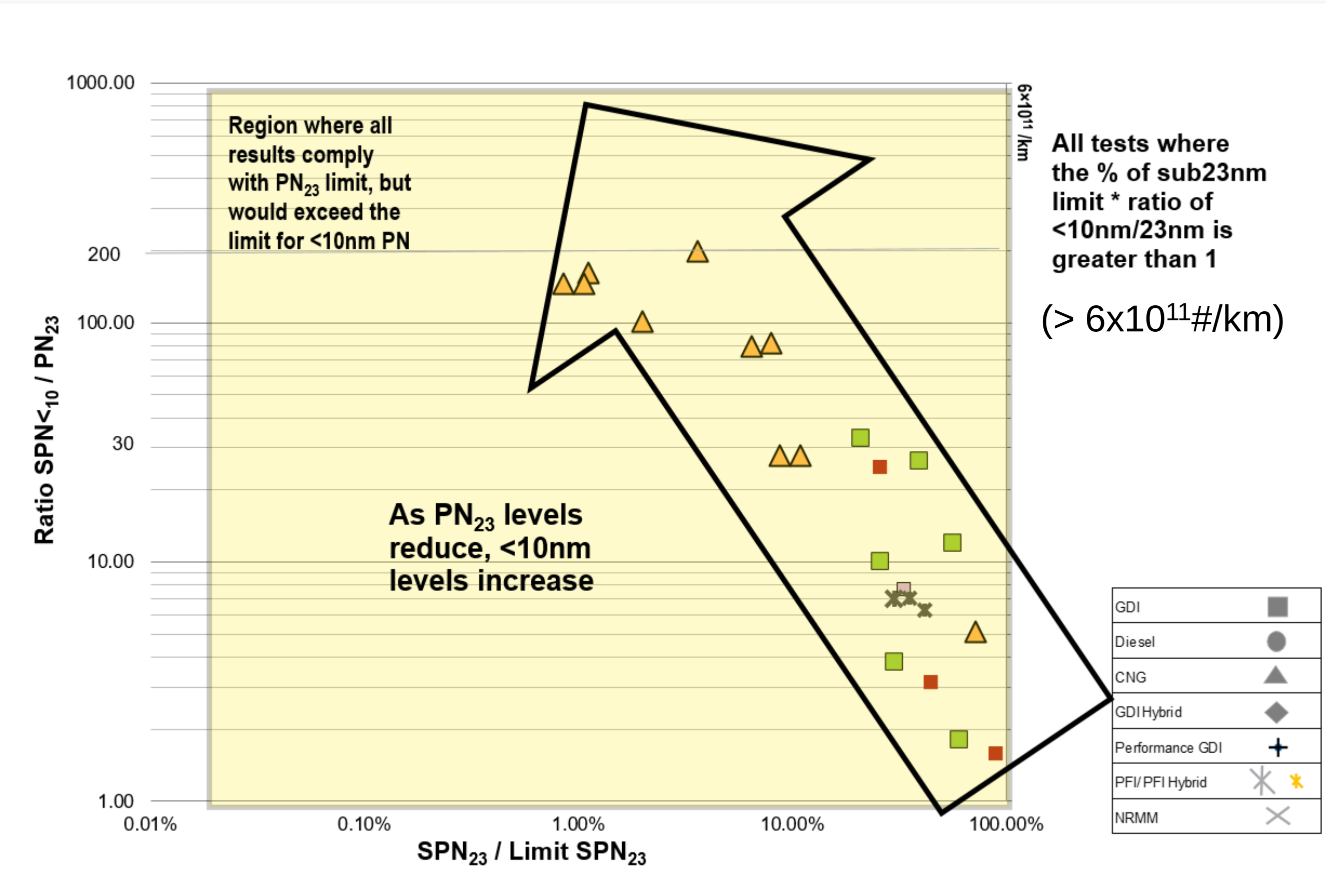
- With the exception of CNG, **PN10 levels are generally less than 4x PN23 levels (<80% of total between 10nm and 23nm)**
- CNG PN10 levels may be **close to 30x PN23 levels (<97%)**
- DPF-Diesels show very low levels of <23nm PN except for short periods during active regenerations

HORIZON 2020

Sub-23nm PN vehicle technology effects using the DTT system

- Introduction
- The DTT measurement systems
- Approach to display comparative data
- Where results may still exceed $6x10^{11}$#/km
- PN10 (and some <10nm) emissions from various technologies
- What proportion of PN10 exists below 23nm?
- **Soot as a potential moderator of <23nm PN**
- Potential regulatory implications

Soot suppresses the nanoparticle mode…



- With the exception of CNG, and across all technologies tested, PN<10 levels are generally less than 30 x PN23 levels (<97% sub-23nm)
- CNG PN2.5 levels may be close to 200 x PN23 levels (~99.5% sub 23nm)
- The lower the soot (>23nm PN & applications without GPF) the higher the <23nm emissions
  - Data only from tests where <23nm emissions would exceed $6x10^{11}$#/km

Sub-23nm PN vehicle technology effects using the DTT system

- Introduction
- The DTT measurement systems
- Approach to display comparative data
- Where results may still exceed $6x10^{11}$#/km
- PN10 (and some <10nm) emissions from various technologies
- What proportion of PN10 exists below 23nm?
- Soot as a potential moderator of <23nm PN
- **Potential regulatory implications**

PN Regulation: Potential Implications of DTT data

PN10 regulation necessary?

- HIGHLY PROBABLE, for gasoline; POSSIBLY, for diesel
  - 6dt GDI may exceed the limit, even at 23nm. **GPF development required for off-cycle**
  - EO GDI PN10 generally < 5x10^{12}#/km. 88% efficiency GPF is required to match the limit value, and 94% efficiency is required to give a 50% safety margin. **PN10 will mandate more efficient filters**
  - Diesel (with DPF) PN very low & <23nm fractions small, except in regenerations. **PN10 regulation may require "partial" regeneration strategies for lower PN**

PN<10 regulation necessary?

- Potentially YES, for CNG (and other gas?)
  - CNG vehicles emit up to 6x10^{12} particles/km >2.5nm but **even non-optimised particle filters can be very effective**
  - How to mandate the use of these filters?
  - **PN<10 compliance for CNG would require 10^{10} limit for the PN10 range!!**

Any questions?

- For more information visit www. downtoten.com