GDI Particles – Legislation, Current Levels And Control

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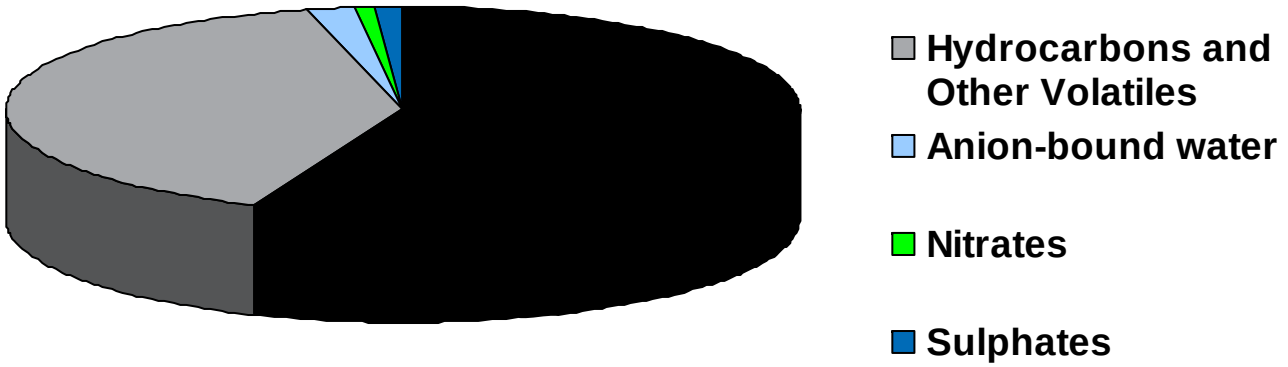
Chemistry of Particulate Matter from Lean-burn Spark Ignition Direct Injection Engines

- PM from lean DISI vehicles shows the presence of elemental carbon, lubricant derived hydrocarbons and traces of anions with associated water
  - Fuel HCs are also present adsorbed to the carbon at very low levels
  - Increases as level of carbon increases
- The methodology used in Europe for Euro 5+ Diesel legislation is expected to be used for GDI PM in the future with the mass limit at 4.5mg/km
- The presence of carbon leads to elevated numbers of solid particles relative to PFI gasoline vehicles and the prospect of particle number legislation alongside that for Diesels

Chemical Analysis of PM Euro 4 VW FSI



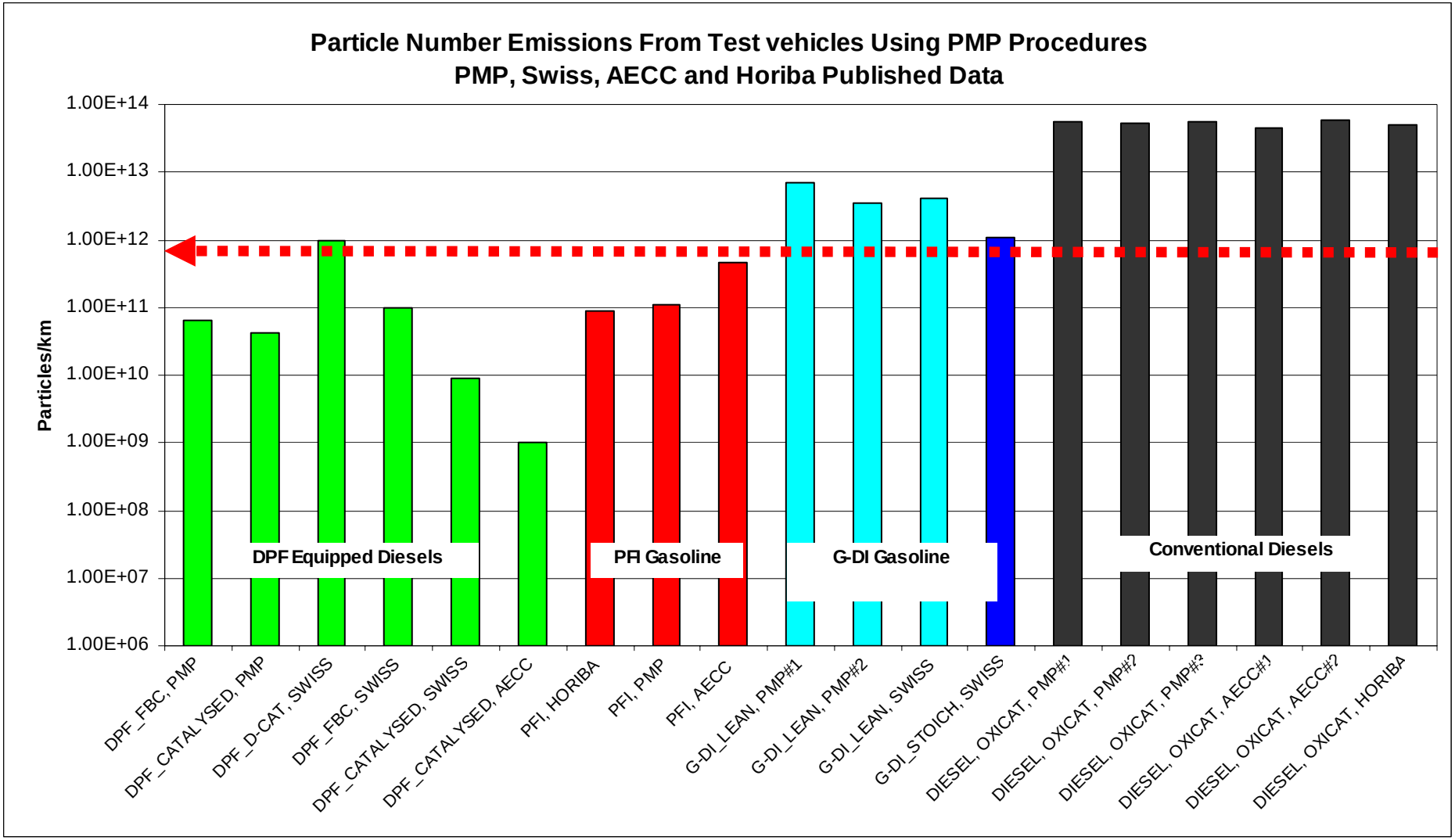
Ricardo data

Legislation

- PM will be required to be measured from GDI vehicles for Euro 5+ (2011), with the limit of 4.5mg/km equivalent to that for light-duty Diesels
- An intention to require particle numbers for Euro 6 is also given, but no limit value is proposed
  - Interestingly the documentation does not currently discriminate between positive ignition types, so this implies particle number measurements could be required from PFI and GDI types
  - There is little data available on the emissions of DI gasoline vehicles (in the public domain) but is it likely that OEMs are studying this internally
- Early discussions suggested that it might be required that OEMs monitor the emissions of DI vehicles during the Euro 5 period and report them outside of the certification procedure
  - Omitted from the regulatory documentation
- **So where are we now?**

Euro 5 Emissions Limits		New	All New Vehicles
		Approvals	Sold
Euro 5 Inception	PN	None	None
	PM	5.0mg/km; Current method	5.0mg/km; Current method
From 1st September 2011	PN	6×10^{11}/km	None
	PM	4.5mg/km; PMP method	5.0mg/km; Current method
From 1st January 2013	PN	6×10^{11}/km	6×10^{11}/km
	PM	4.5mg/km; PMP method	4.5mg/km; PMP method

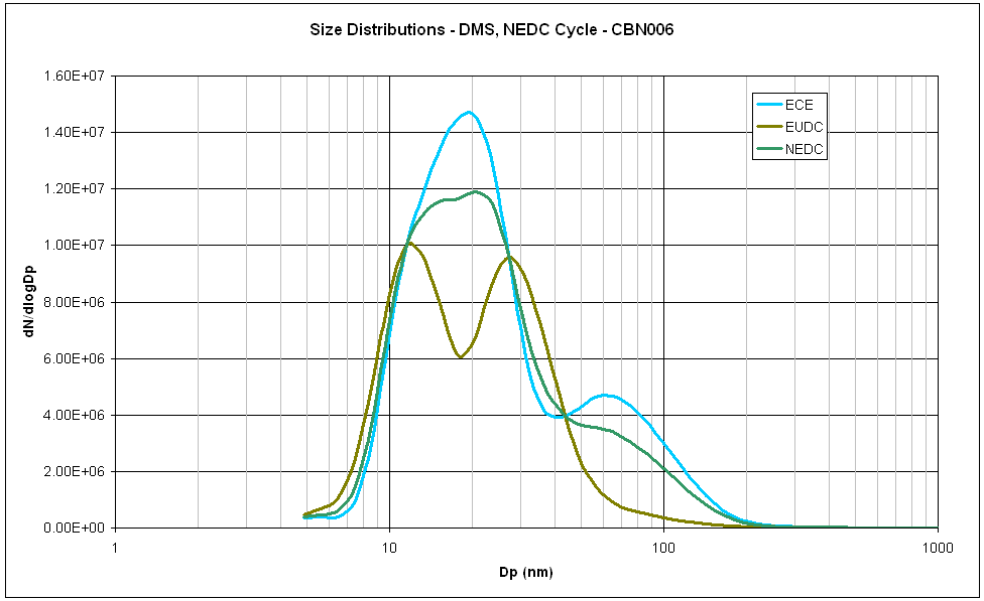
PFIs unlikely to exceed PMP limit value, but no results yet from a DI that meets 6x10^{11}/km



”Rolling road” baseline investigation of particles from two spray-guided GDI vehicles: BMW120i and Mercedes CLS

- Mercedes CLS 350CGI (V6, twin exhaust line)
- BMW 120i (4 cylinder single exhaust line)
  - Particle number (>~20nm) data were logged in real-time during NEDC cycles using DMS500 and the PMP equipment
- Typical PMP particle number emissions were in the range **2 - 4 x 10^{12}/km**, which is **2 to 7 times higher** than the particle number limit for Diesel vehicles at Euro 5.
  - Higher emissions have been observed for other latest generation lean DI vehicles
  - Similar results from homogenous DI vehicles
- Particulate mass emissions were typically **2 to 2.5mg/km** from both vehicles using the PMP method
  - >50% below the Euro 5 limit of 4.5 mg/km.

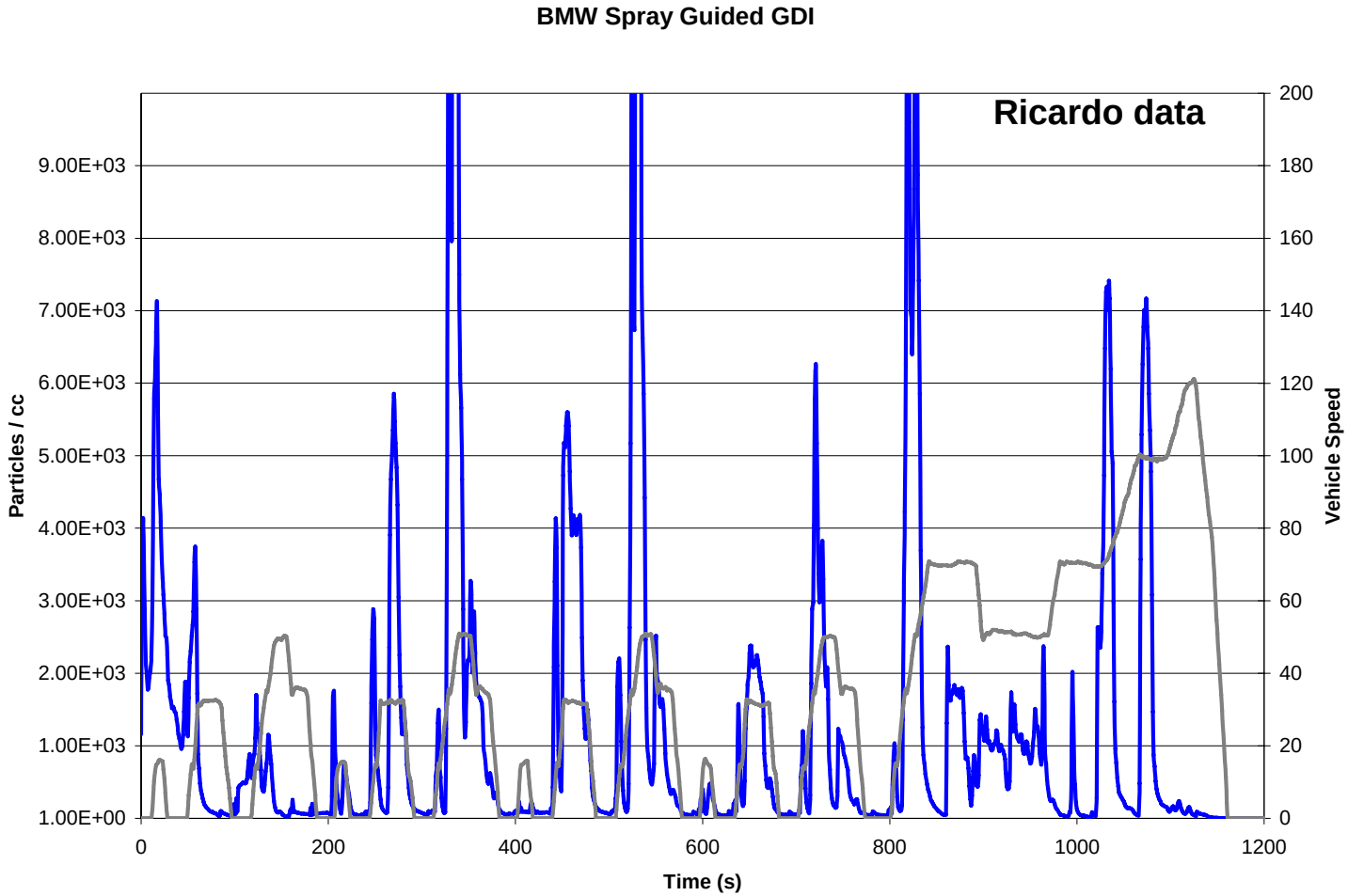
Size Distributions From an NEDC Cycle – BMW120i



Ricardo data

Modern spray guided GDI applications have >2 x10^{12} particles / km

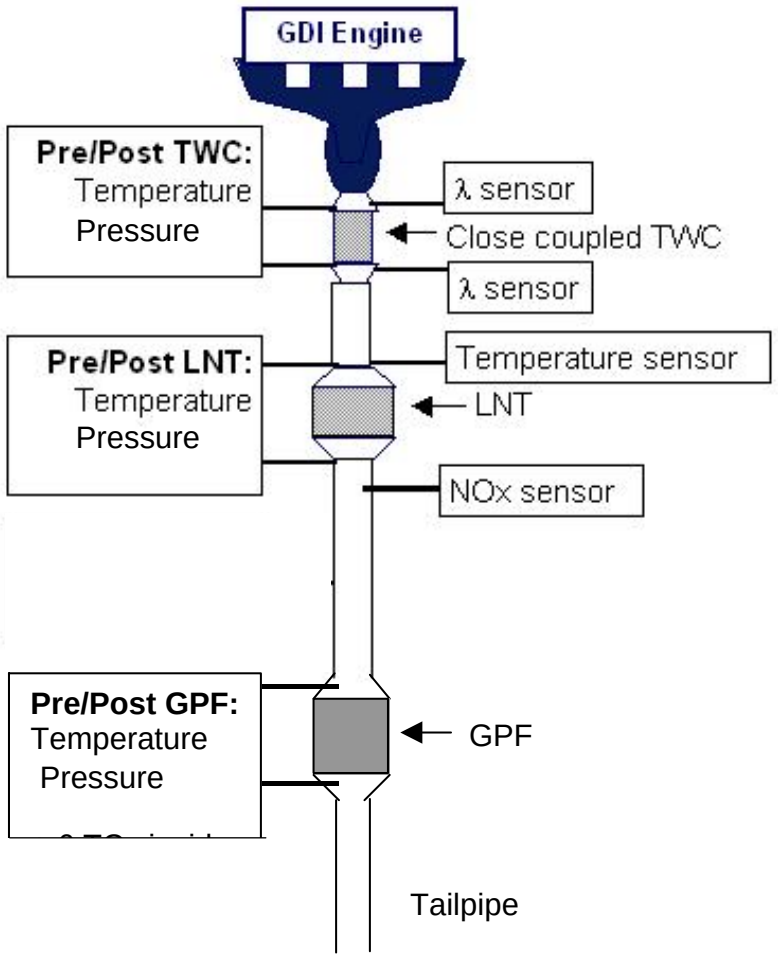
- Limit for diesel is 6 x 10^{11} particles / km
  - >70% efficiency required for particle number
- PM mass <3mg/km (limit = 4.5mg/km), so PM control is sufficient



Testing of BMW118i engine with GPF on Ricardo test bed

- Since the BMW118i GDI operates in lean mode, a Lean NOx Trap (LNT) is necessary to control NOx emissions.
- Both Ricardo sensors and original vehicle sensors was used on the testbed
- Two different filters were tested post LNT
  - One open filter (metallic)
  - One wall flow filter (SiC)
- A Horiba emissions analyser and a Cambustion DMS500 were used in and switched between engine out and tailpipe position, i.e. pre TWC position.
- Pre and Post filter pressures were measured during the testing.

Ricardo sensors **Vehicle sensors**

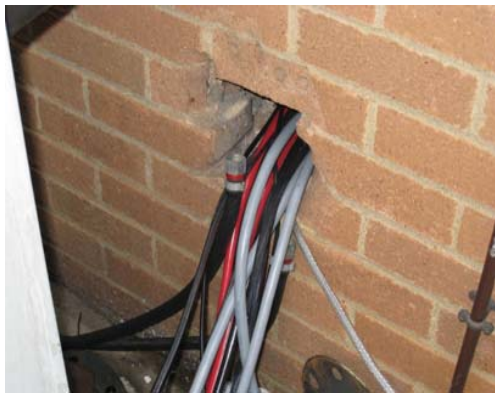


Engine installation on test bed

- A BMW 118i 4-cylinder spray guided GDI engine was installed on a transient testbed.
- The vehicle sensors maintained contact with the installation via umbilical cords

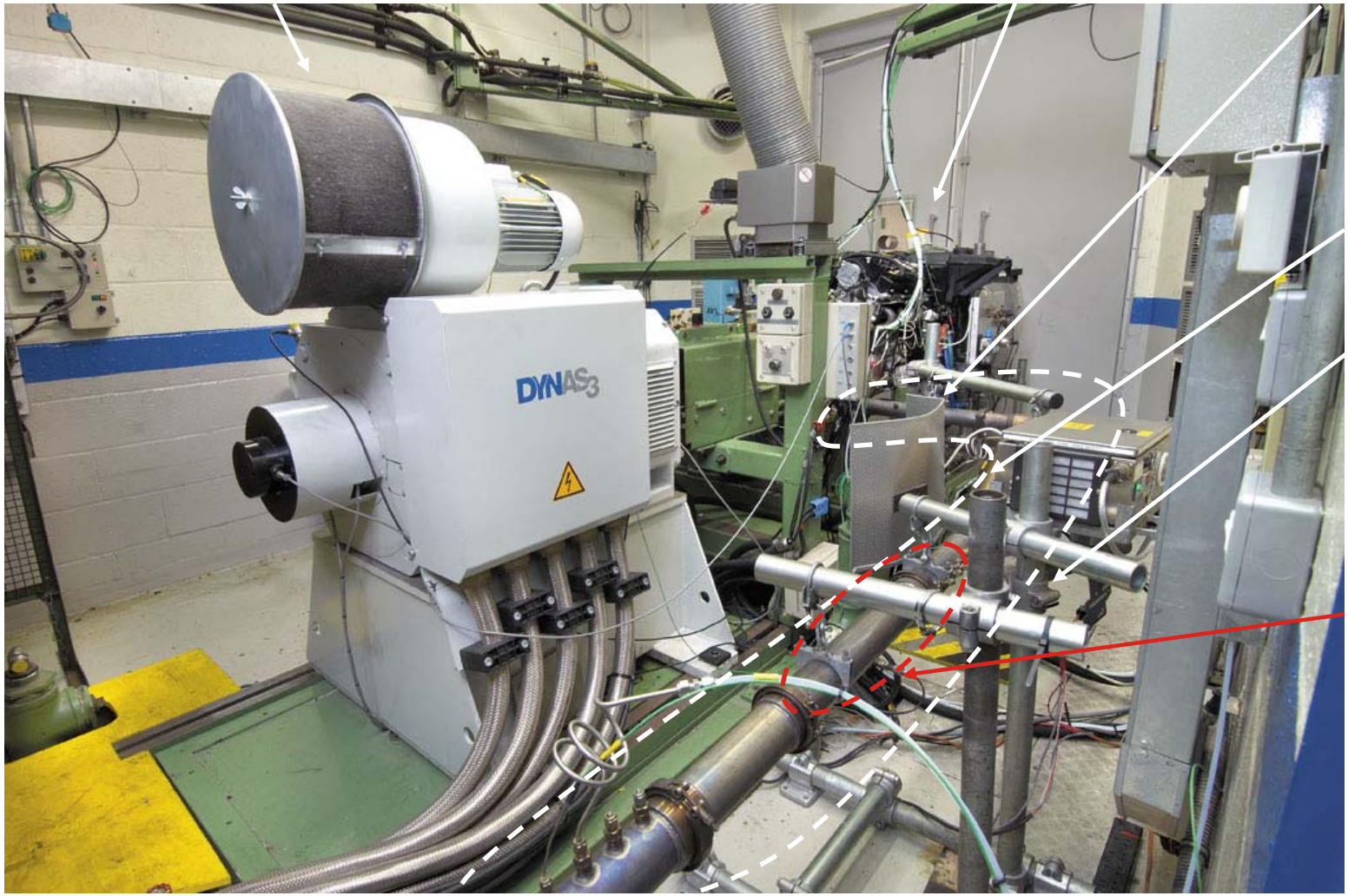
Vehicle outside testbed

Main ECU umbilical



ECU control cables entering the testcell through the wall

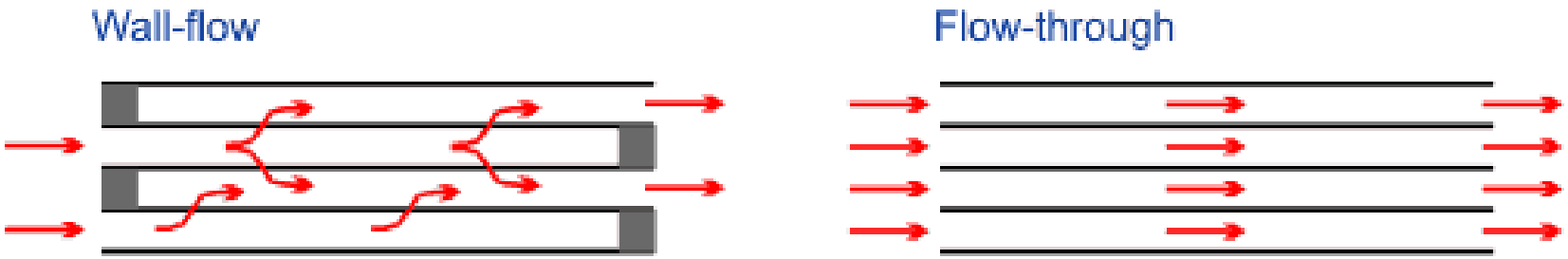
Overview of engine test cell installation



Particle size distribution and number concentration measurements

- A Cambustion DMS500 was employed to measure particle size distributions in the range 5nm to 1000nm
- Measurements were made upstream and downstream of the GPF and comparisons made between the data acquired
  - Size distributions
  - Size related efficiency
  - Real time integrated number (5nm to 1000nm)
  - Size distribution data were converted to mass and the PM emissions estimated

GPF configurations:

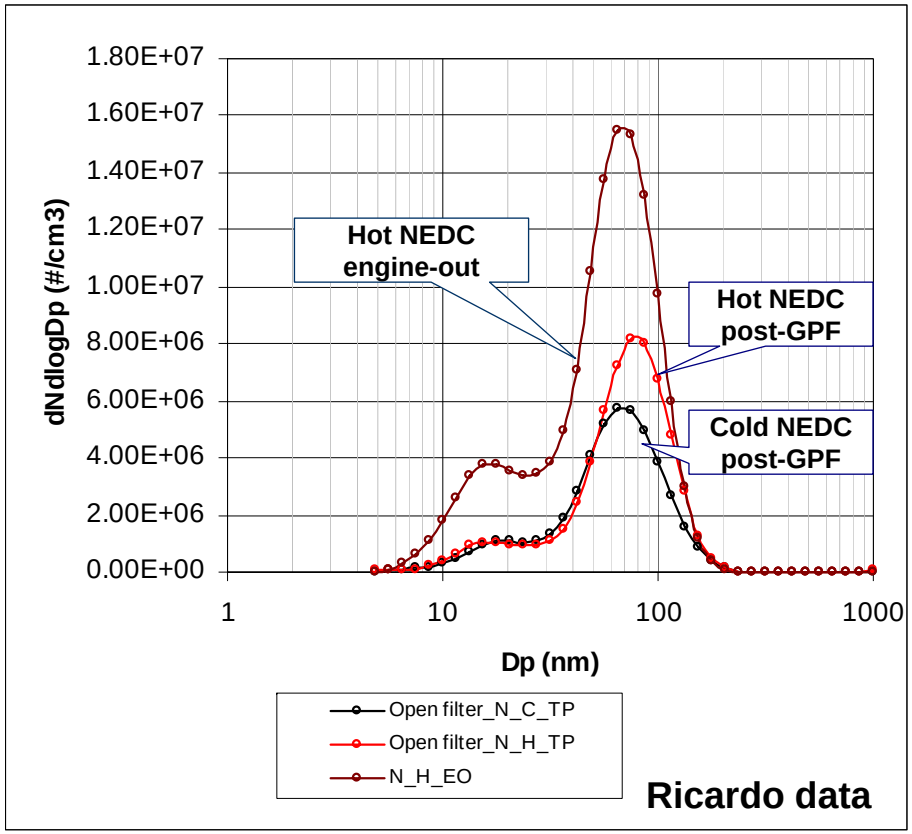


- A flow diversion-type filter has also been tested

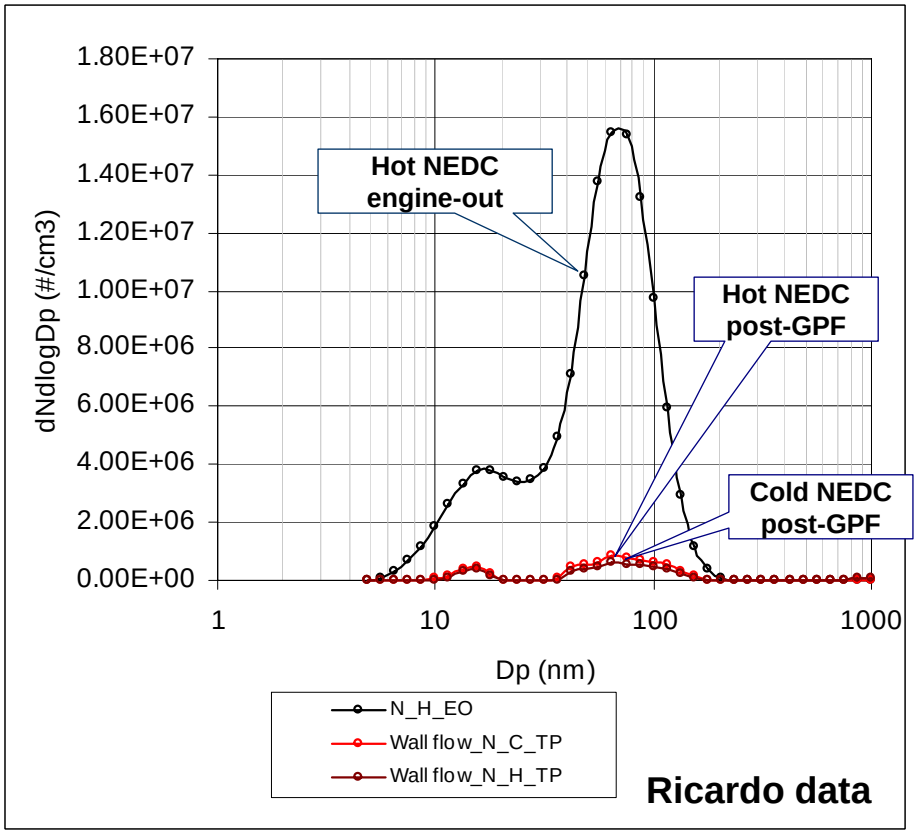
Source: Dieselnet

Open filter and wall-flow filter designs have similar effects on particle control as those seen on Diesel applications

Novel Open filter:



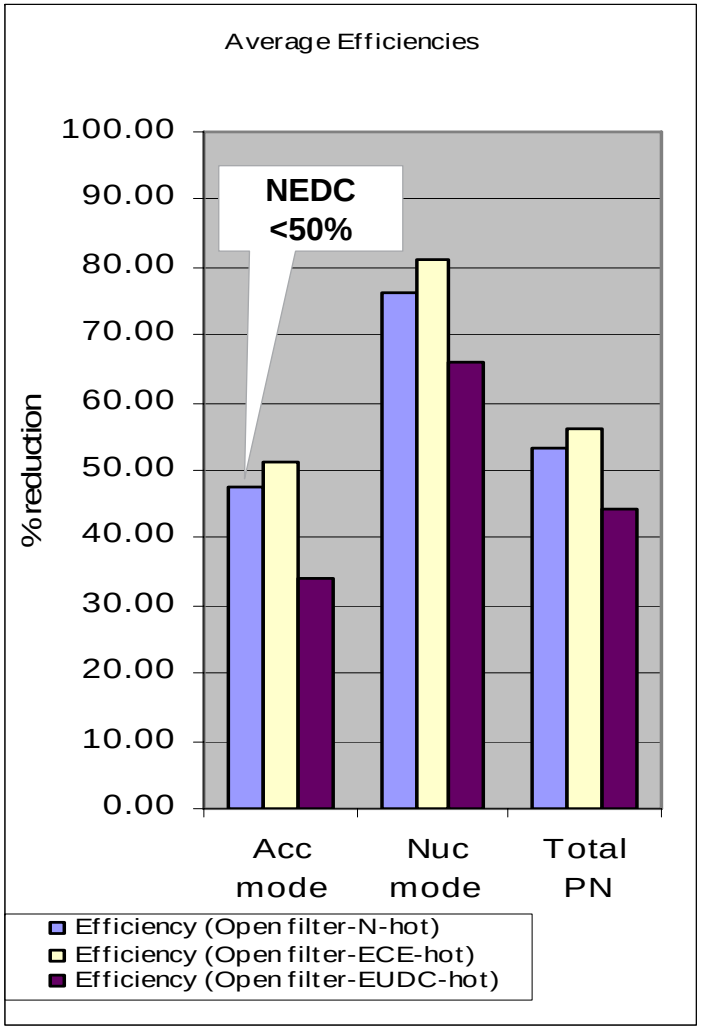
Novel Wall-flow filter:



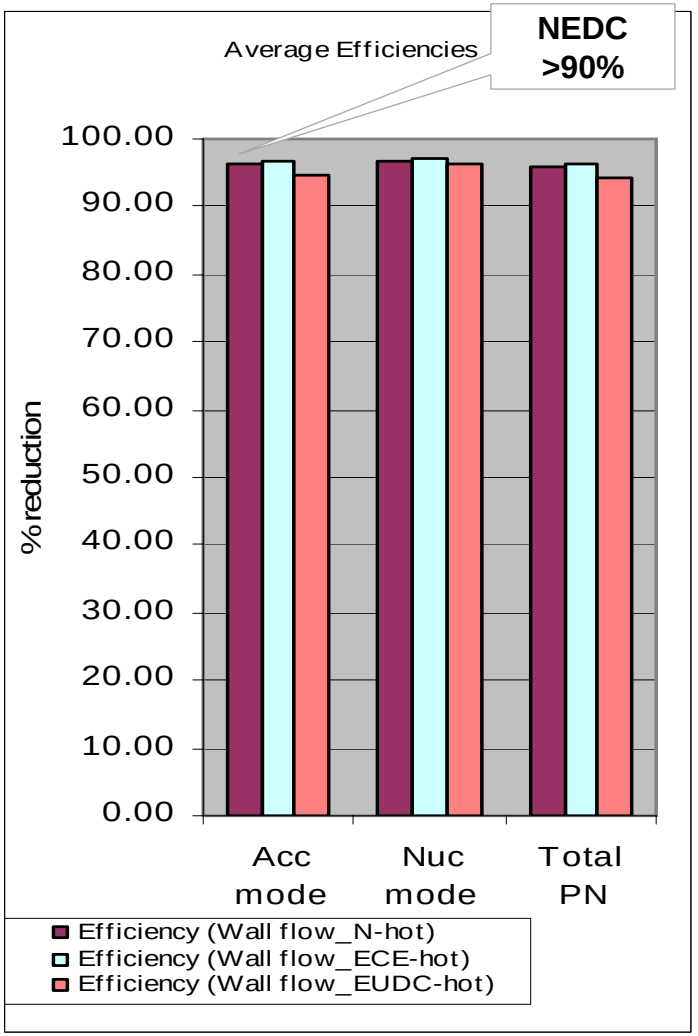
Source: Internal research

Filtration Efficiencies from hot NEDC cycles

Open filter: not quite good enough - yet

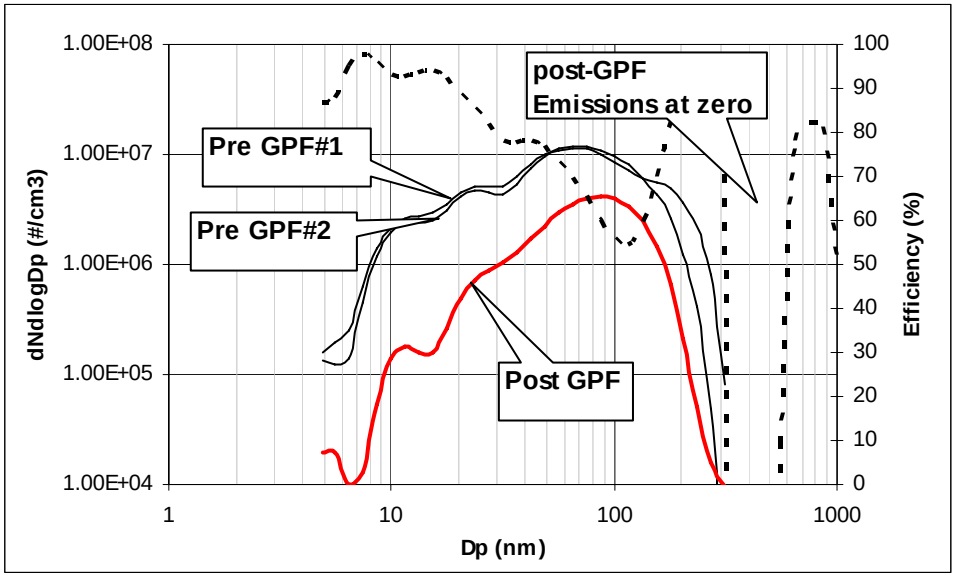


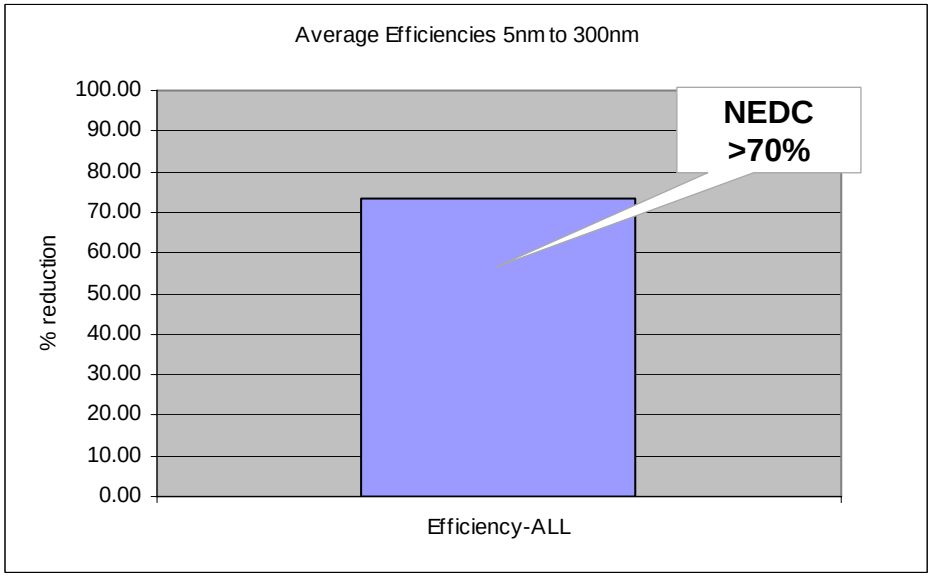
Wall flow filter: >90%



Source: Internal research

Filter substrates can be 'optimised' to meet the required filtration efficiency and limit backpressure



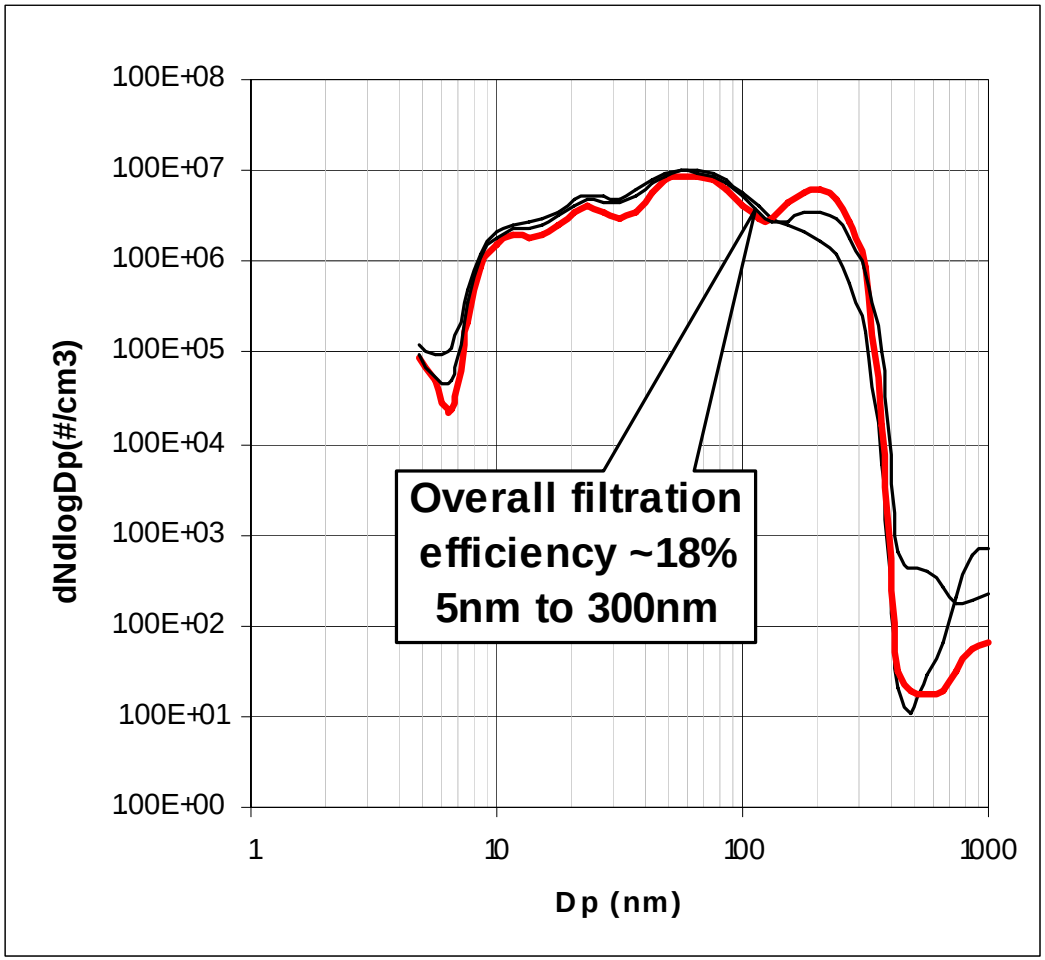


- >70% target can be hit
- Other parameters which proved important
  - Exhaust flow rate
    - Higher velocity increased inertial deposition
  - Upstream size distribution
    - Engine measures can make a difference

Ricardo data

Source: Internal research

Flow-through designs don’t work so well…



Ricardo data

Summary

- Lean-burn gasoline DI vehicles generate more carbonaceous soot, which in turn elevates particle numbers above those seen from PFI variants
  - The PM target of 4.5mg/km is comfortably met by modern spray-guided DI vehicles, but at best particle number emissions are more than 3 times the Diesel PN limit of $6x10^{11}$/km
  - PFI vehicles do not appear to require traps to meet the PN limit
- Preliminary studies have shown that both ‘open’ filter types and wallflow filters are able to remove particles from GDI exhaust, with filtration behaviour similar to that seen with Diesel soot
- GPFs of >70% efficiency will be required for even spray-guided DI to meet the PMP PN limit – if it is set at the same level as that required for Diesel vehicles
- It is possible to optimise GPF to reduce engine backpressure and hit a filtration target of >70%

GDI Points to ponder

- Spray guided direct injection will be a core technology for the next generation of engines
  - MPIs have a role to play in low cost gasoline engines
- Focus is CO_2 reduction and lean DI enables this (as do other technologies)
- Need to understand impact of stratified region on particle number generation
  - Reducing stratified region is not the answer (for reducing particles) as this will erode the fuel penalty advantage of the lean DI
  - Has the evolution of technology from air to wall to spray-guided DI reduced PN?
- Will higher injection pressures reduce solid particle number, create small volatile particles, or have no obvious effect?
- How will lean DIs designed to run on ethanol impact particle number generation and subsequent control?
- What are the aftertreatment layout options for low PN and Low CO_2:
  - Close-coupled DPF for passive regeneration?
  - Pre or post LNT position?
  - 4-way catalyst?

Source: 8pt Dark Grey (R 167, G 169, B 172)