ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

Fuel Effects on Particulates from Modern Gasoline Vehicles

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HEI Workshop

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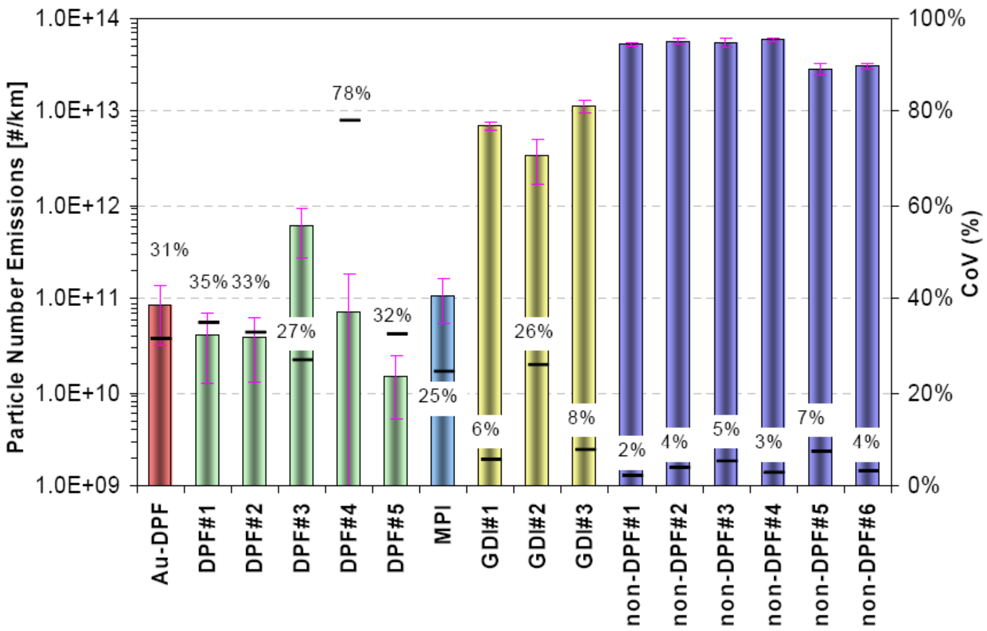
Background

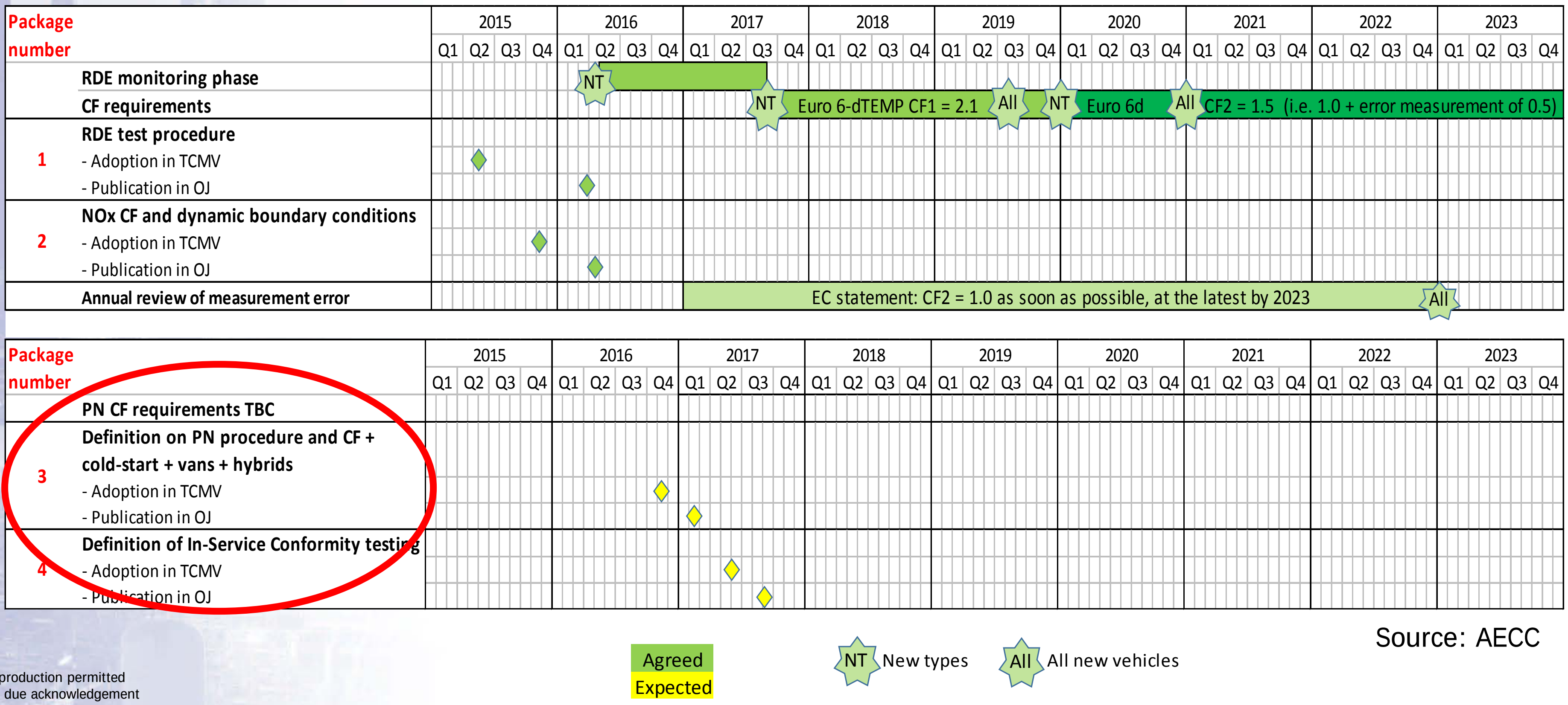
- It has been known for some time that gasoline direct injection (GDI) vehicles produce more particulate number emissions than port fuel injected equivalents and DPF equipped diesel engines
- From 2014 limits on particulate number were introduced for Euro 6 GDI vehicles which by 2017 will be equivalent to those that exist for diesel vehicles (6 x 10^{11}#/km)
- In addition, the EU Renewable Energy Directive and Fuels Quality Directives have promoted increased use of biofuels in Europe
- Specifications exist for
  - E5/E10, E85 for gasoline
  - B7, B10 and up to B20 and B30 for diesel



Sourcë: UNECE Particle Measurement Programme (PMP) Light-duty Inter-Laboratory Correlation Exercise (ILCE_LD) Final Report

RDE will introduce new challenges for NOx and PN

- Real Driving Emission (RDE) legislation in Europe has started to take effect from 2016 onwards
- WLTP will also be introduced in the near future to replace NEDC
- RDE testing will be carried out on typical market fuel



Source: AECC

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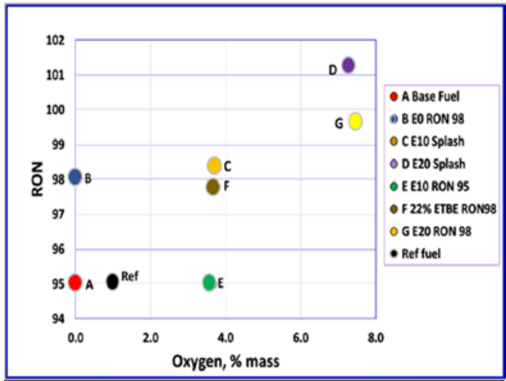
Recent Concawe Studies on Particulates

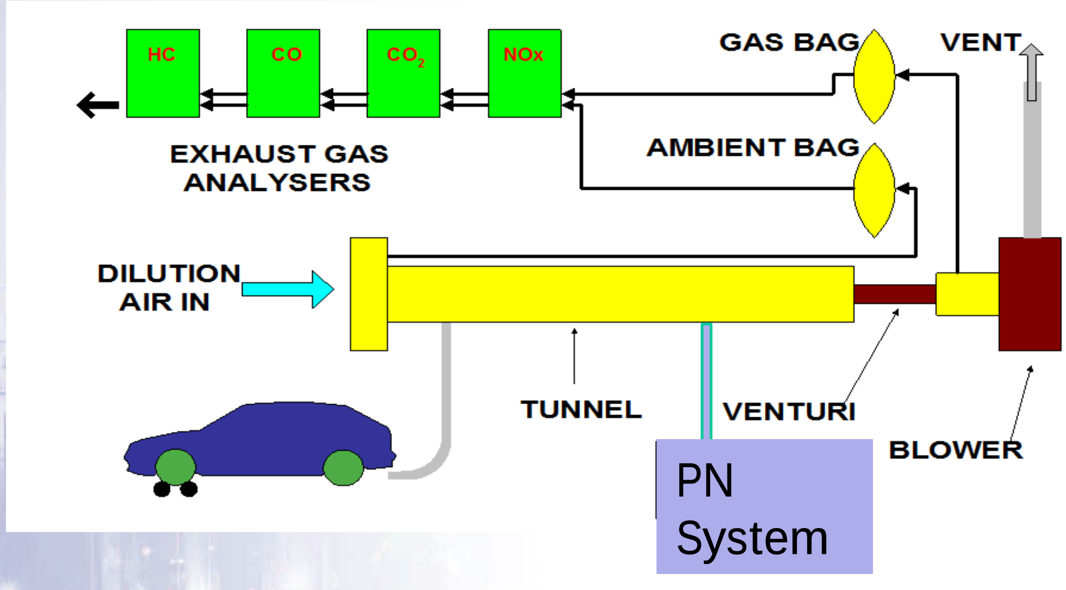
- Concawe has conducted several studies involving particulates:
  - Two gasoline passenger cars were tested over the NEDC test cycle for regulated emissions, PM, PN and fuel consumption (*Concawe report 10/16, June 2016*)
    - Fuel Matrix covering range of RON, different oxygenate types and O content
    - Matched and splash blended fuels
  - Two studies have also been conducted in conjunction with AECC (catalyst manufacturer's association)

    1) Comparison of NEDC, WLTP and on-road RDE cycles on commercial Gasoline DI vehicle fitted with GPF (*3rd International conference on RDE emissions, Berlin, 2015*)

    2) Second study focused more on RDE including on-road and simulated chassis dyno testing on Gasoline DI vehicle with and without GPF (*paper for SAE 2017 World Congress*)
  - Studied diesel properties on PM and other emissions
    - On Euro, 4,5 & 6 vehicles over NEDC and WLTP (*SAE PF&L, Paper SAE 2016 – 01-2246)*



GDI Particulates Study Experimental Set Up



- Conduct fuel tank drain
- Fill with 15 litres of test fuel
- Set type pressure
- Conduct 2 NEDC cycles on the chassis dynamometer
- Conduct fuel tank drain
- Fill with 15 litres of test fuel
- Full exhaust leak check
- Tyre pressure check
- Preconditioning cycle – ECE + 2 x EUDC
- Overnight soak
- Run NEDC test (ECE + EUDC)

Carry out 2x

- Objective: Investigate the effect of fuel properties on particulates and other emissions from modern gasoline DI vehicles
- Particulate number and distribution measured using the PMP protocol with cyclonic separator, two thermo diluters in series followed by CPC
- Two vehicles were tested using the NEDC protocol
  - Euro 4 - 2.4litre NA 6-cylinder DI with TWC
  - Euro 5 - 1.8litre TC 4-cylinder DI with TWC

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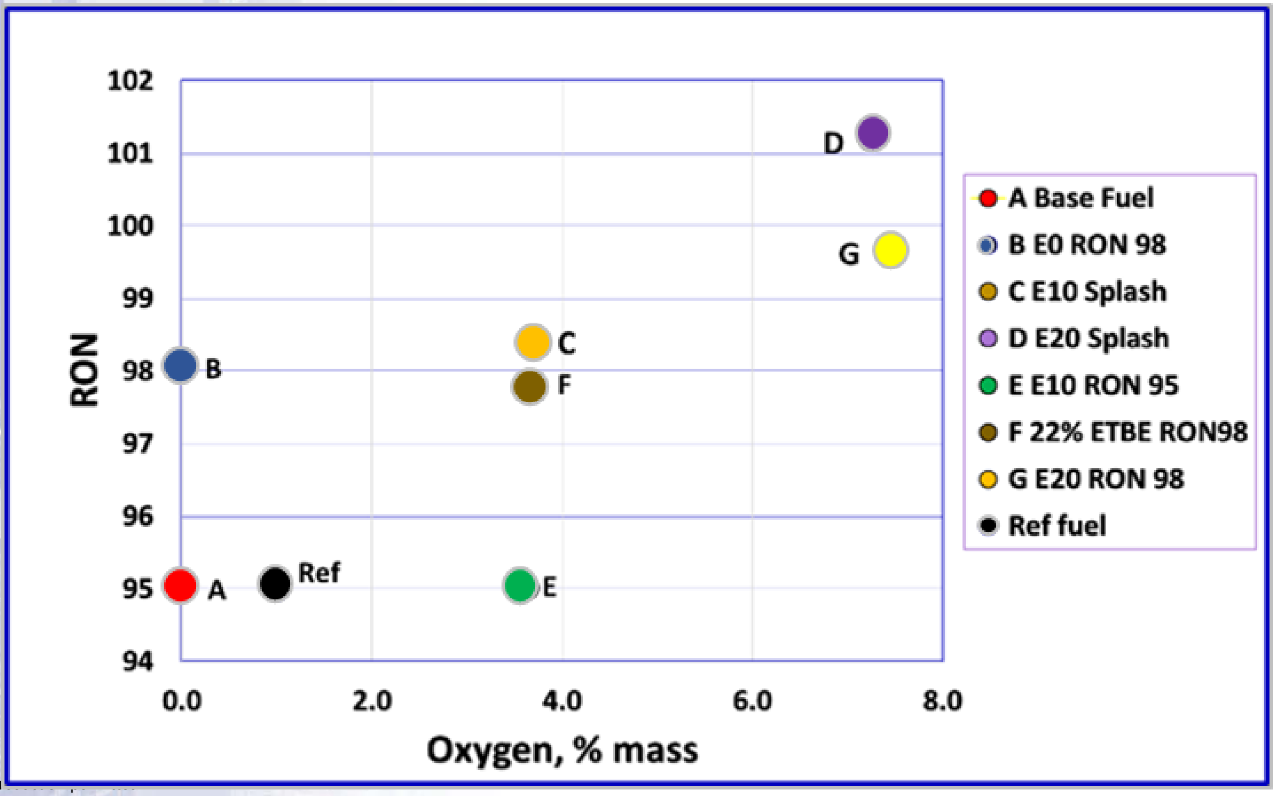
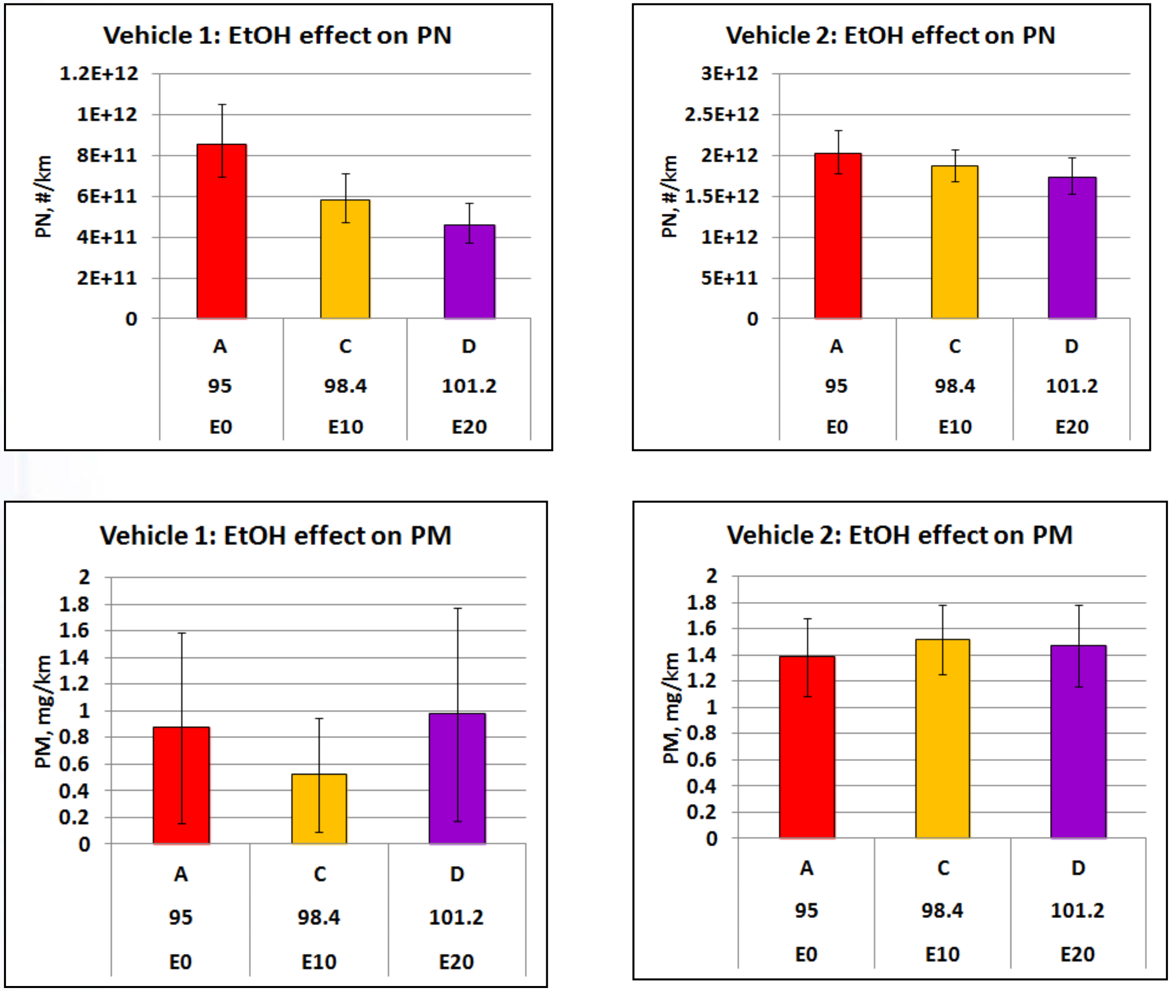
GDI Particulates Study
Fuel Matrix and Testing Sequence

- Fuel Matrix covering range of RON, oxygenate types and O content
- Matched and splash blended fuels
- Each fuel tested twice in randomized sequence



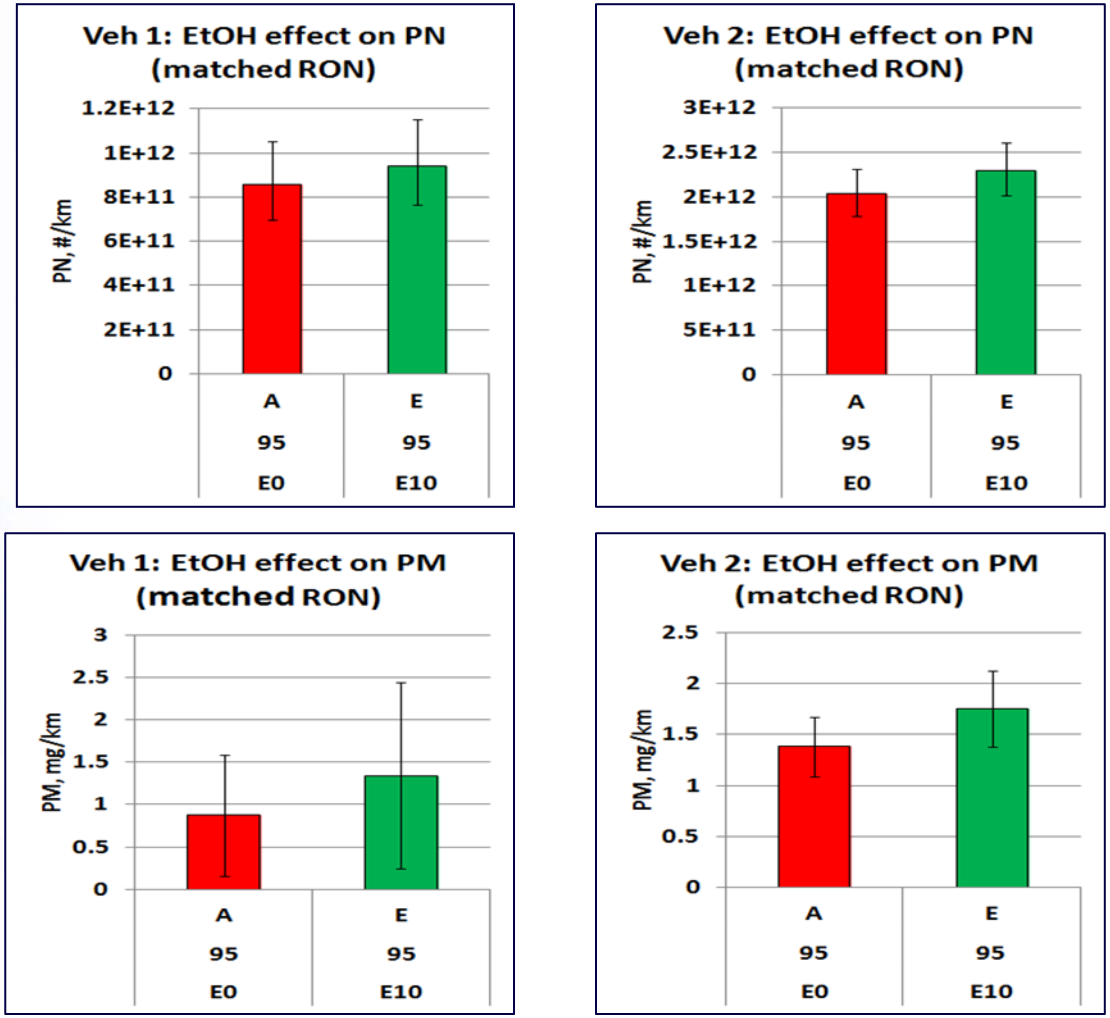
	Vehicle 1	Vehicle 2
Test 1	Reference	Reference
Test 2	Fuel A	Fuel F
Test 3	Fuel D	Fuel B
Test 4	Fuel C	Fuel E
Test 5	Reference	Reference
Test 6	Fuel E	Fuel G
Test 7	Fuel F	Fuel A
Test 8	Fuel B	Fuel C
Test 9	Fuel G	Fuel D
Test 10	Reference	Reference
Test 11	Fuel D	Fuel C
Test 12	Fuel F	Fuel A
Test 13	Fuel B	Fuel G
Test 14	Fuel C	Fuel F
Test 15	Reference	Reference
Test 16	Fuel A	Fuel D
Test 17	Fuel G	Fuel E
Test 18	Fuel E	Fuel B
Test 19	Reference	Reference

Results of Splash Blending Ethanol up to E20



- Splash blending gave directional reduction in PN as ethanol content increases, only significant in one vehicle but no significant effect on PM

Ethanol Effects on PN and PM matched at RON95



- No significant effects - directional increase in PM and PN with increased ethanol

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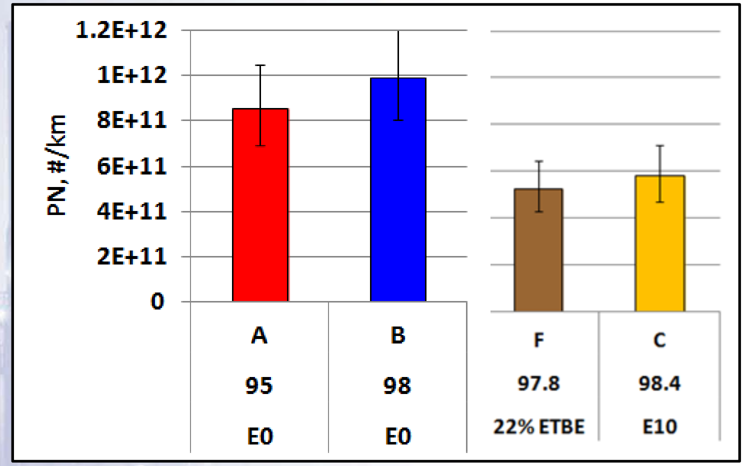
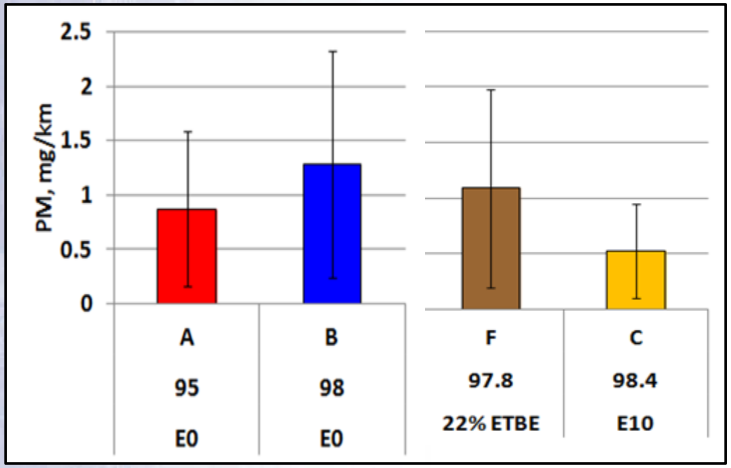
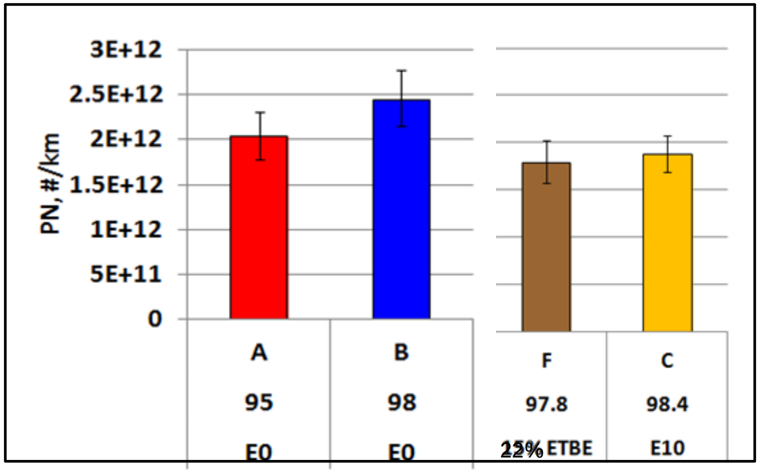
Matched RON98 blends with and without oxygenates

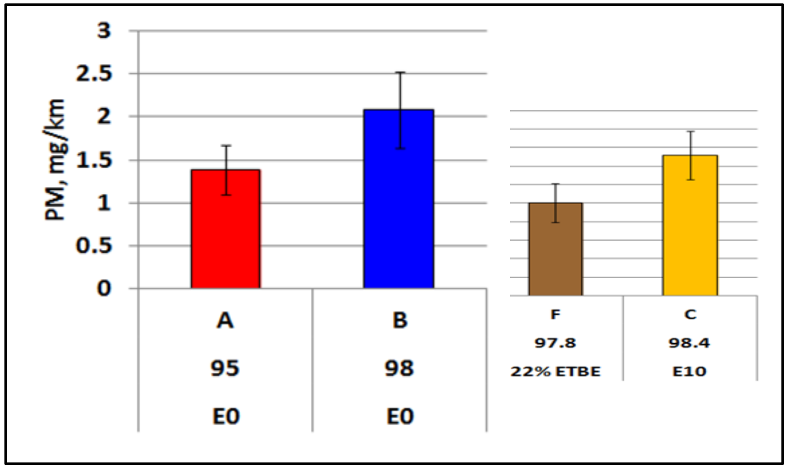
Vehicle 1





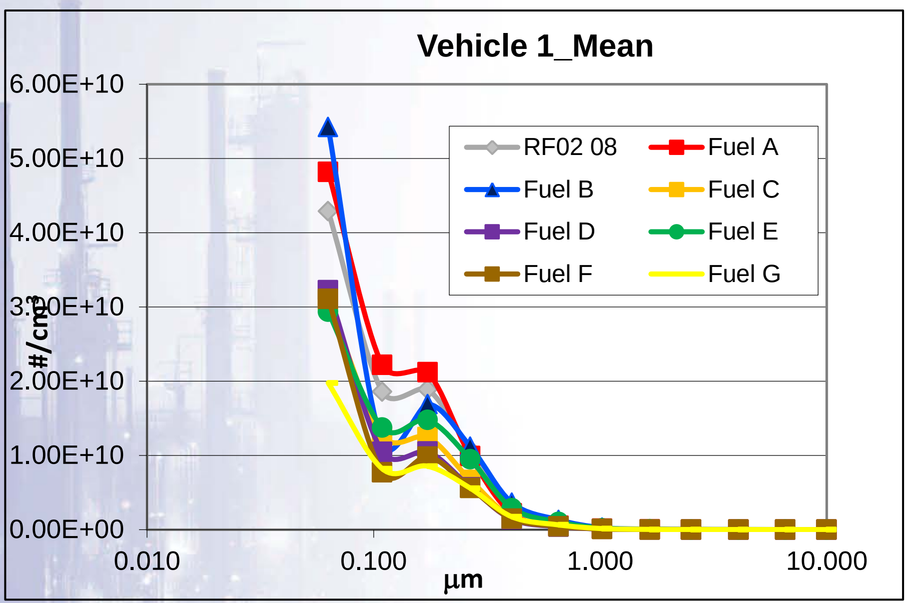
Vehicle 2

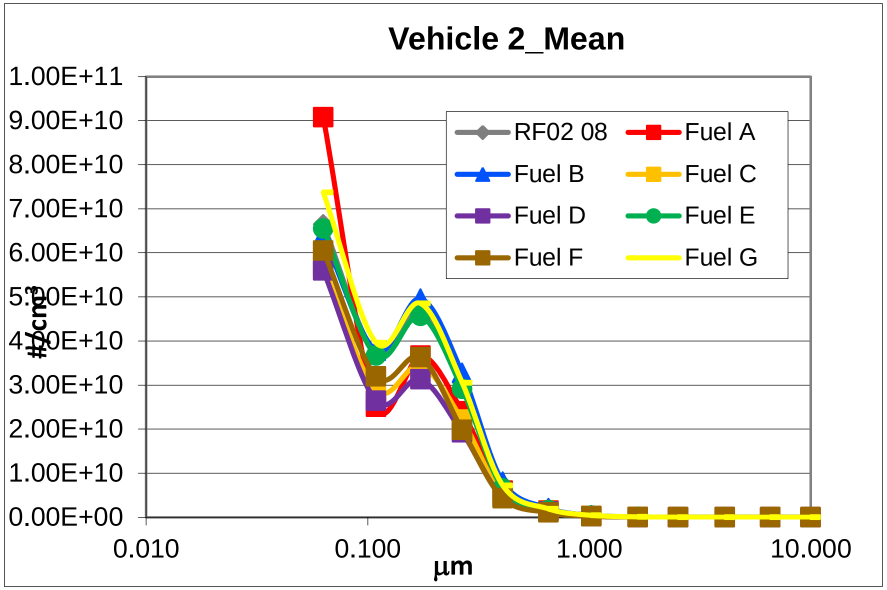




- Oxygenate blends showed lower PN at similar octane in both vehicles but only ETBE PM result on one vehicle was significant

Particle Number Distribution





- Vehicle 2 has higher PN than Vehicle 1 for all fuels
- Indication of bi-modal distribution although limitations on the detection limit of the equipment for nano-particulate detection
- Error bars (not shown) too great to distinguish trends between fuels

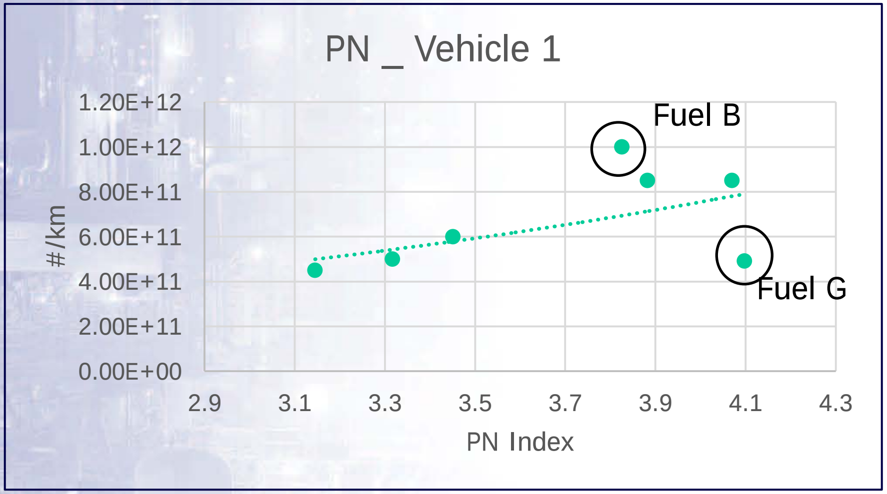
Jaguar Landrover PN Index

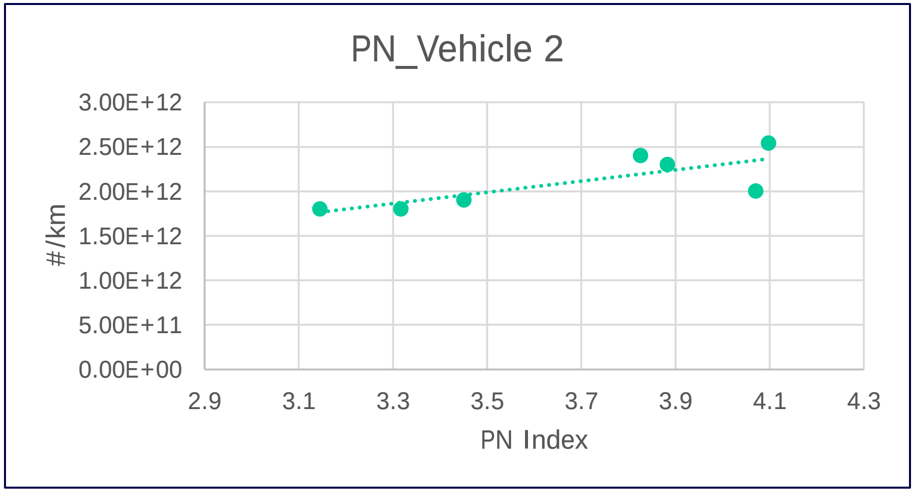
- Various indices exist which try to correlate fuel properties with particulates
- One of the simpler of these was developed by Jaguar Landrover
- Calculated from the % of paraffins, olefins, aromatics, oxygenates, DVPE

$$\text{PN Index} = \frac{\sum_{i=1}^{n}[DBE_i+1]V_i}{DVPE\ (\text{kPa})}\ (\text{kPa}^{-1})$$

$$DBE = C - \frac{H}{2} + \frac{N}{2} + 1$$

SAE 2013-01-1558





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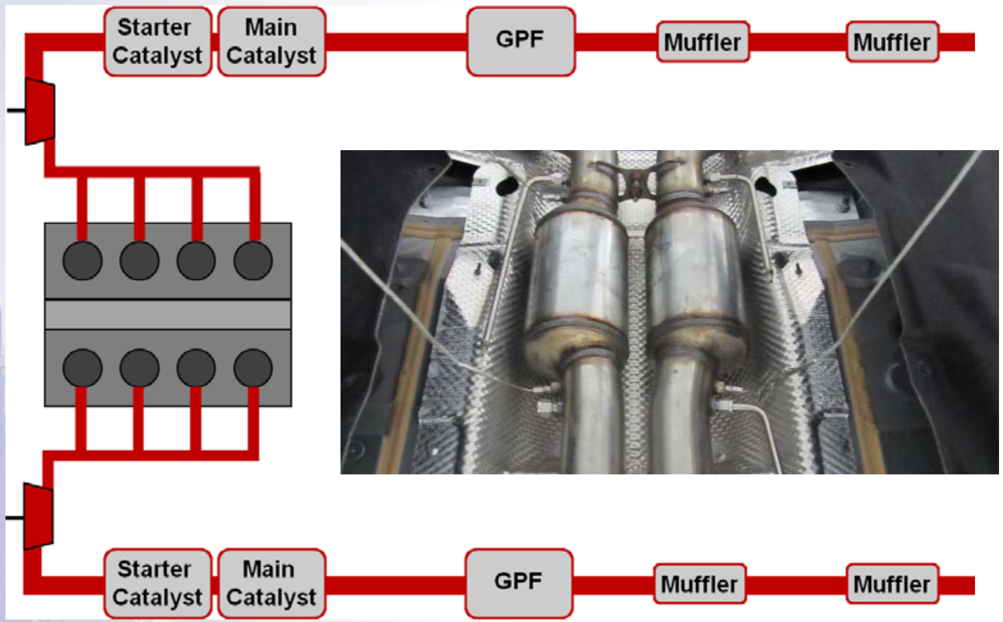
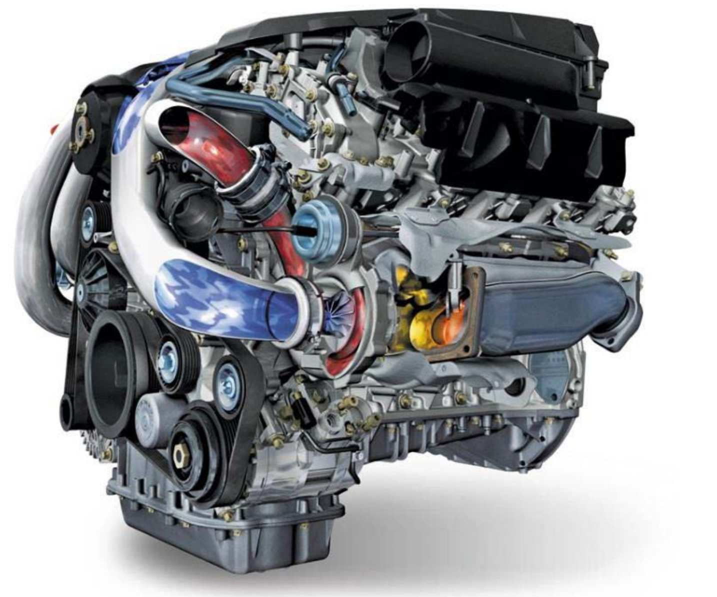
Concawe / AECC GDI Programme (1)

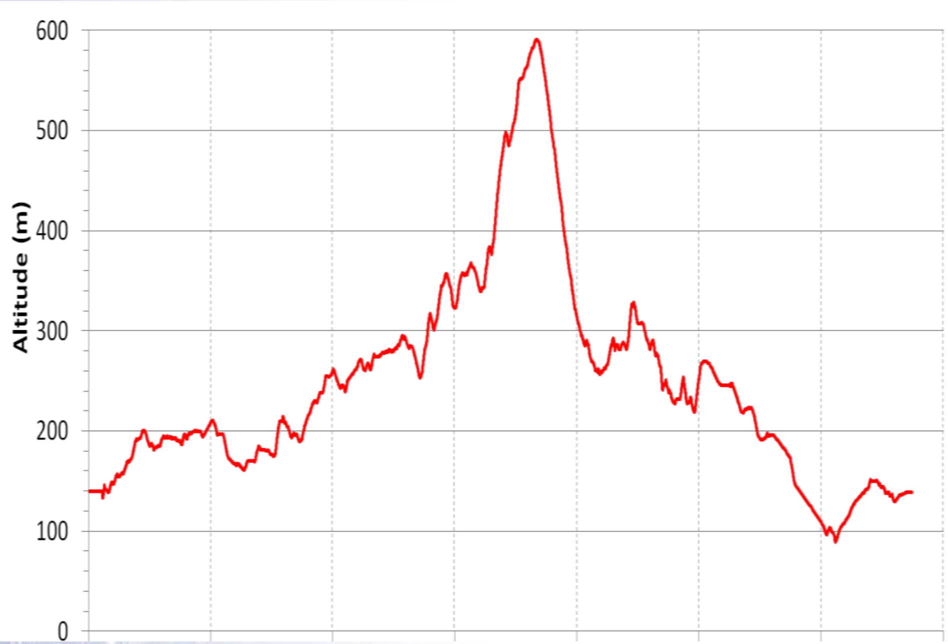


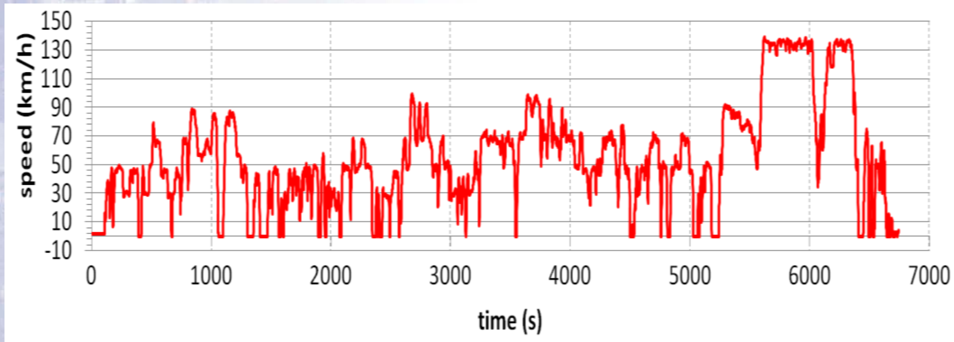


Engine Type	Capacity	Power	Emissions control
V8 Turbocharged	4.7 litres	335kW	2×TWC+GPF in each of 2 branches

- Commercial GPF-equipped vehicle was tested using NEDC, WLTC and RDE on the road
- Three repeats were carried out using each test cycle on a E5 market fuel
- Ecostar LDV PEMS for CO/CO2/NOx, Pegasor Mi3 for PN.

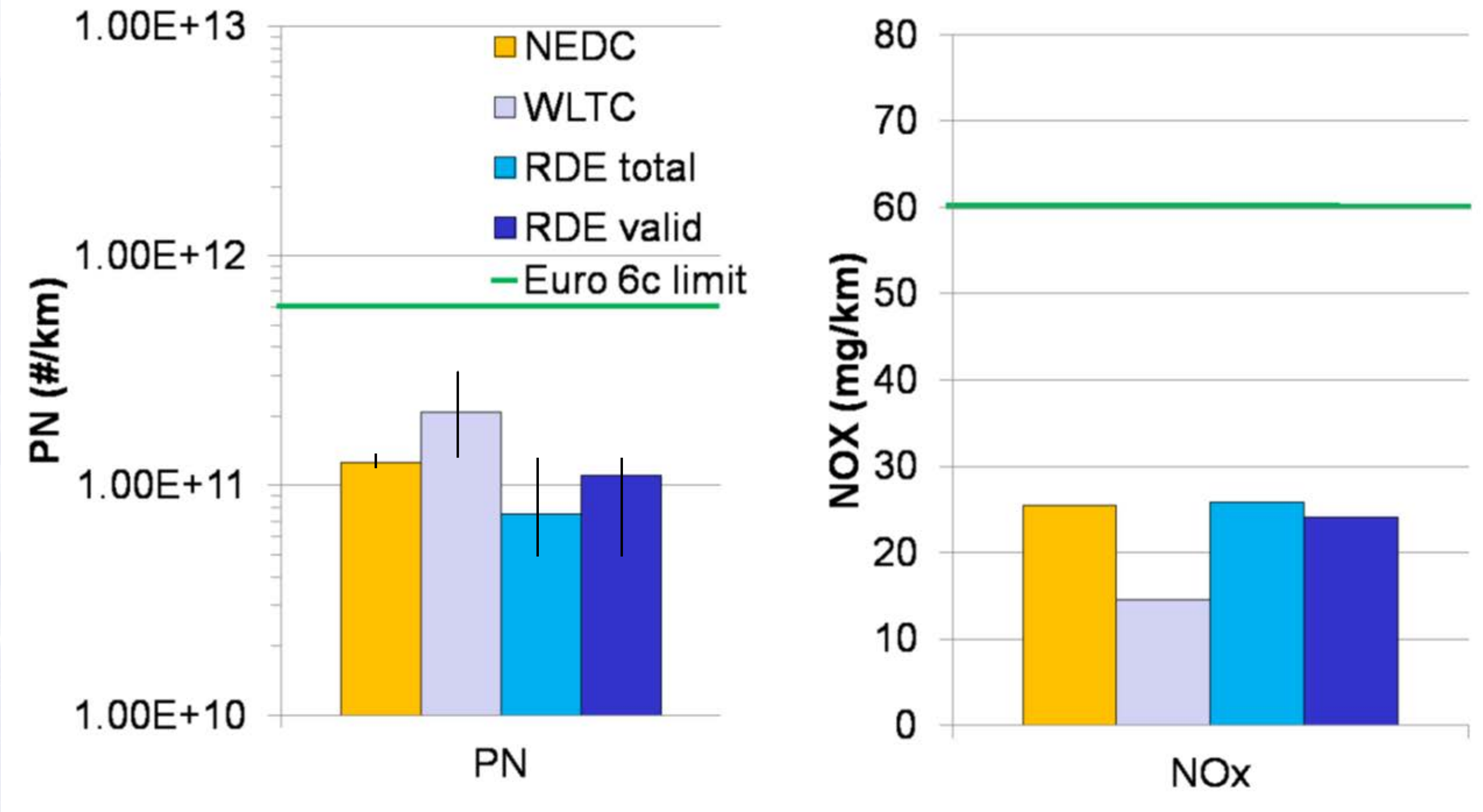
Concawe / AECC GDI Programme (1)





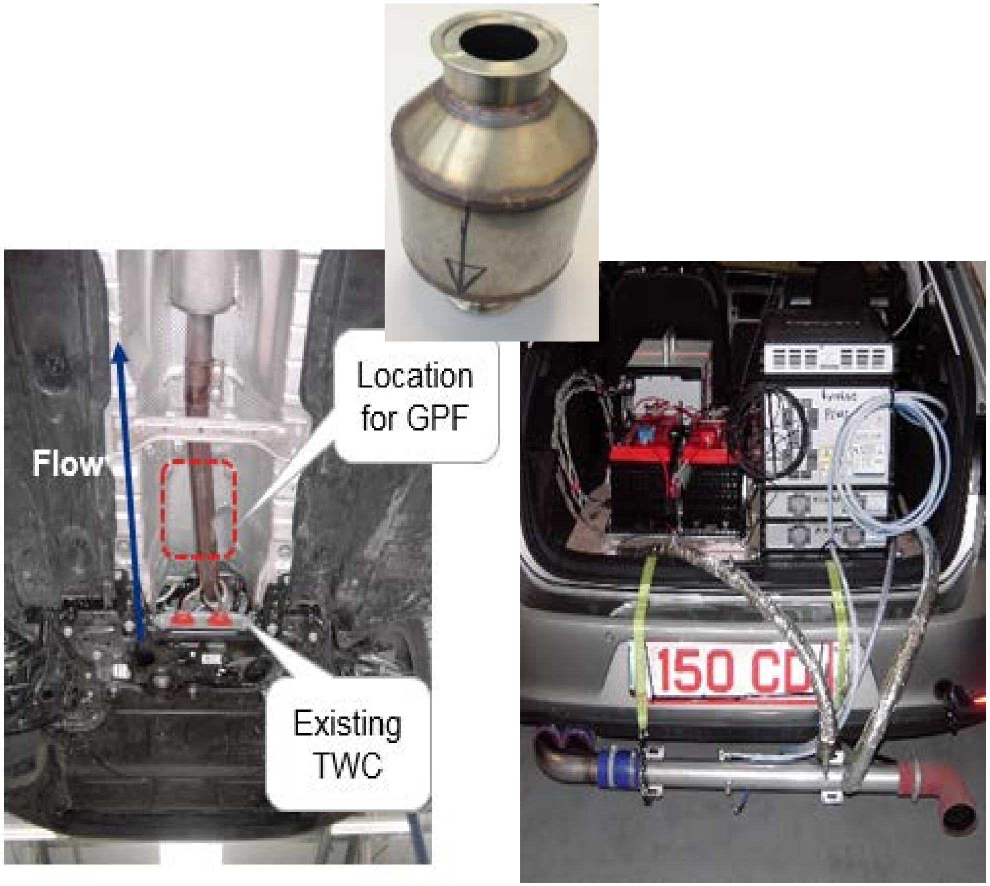
Concawe / AECC GDI Programme (1)

- Commercial GPF-equipped vehicle reduced PN well below the Euro 6c limit



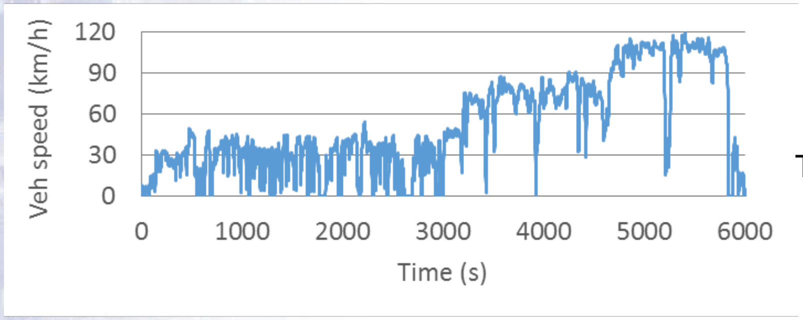
Concawe/AECC GDI (2) RDE PN test programme set-up

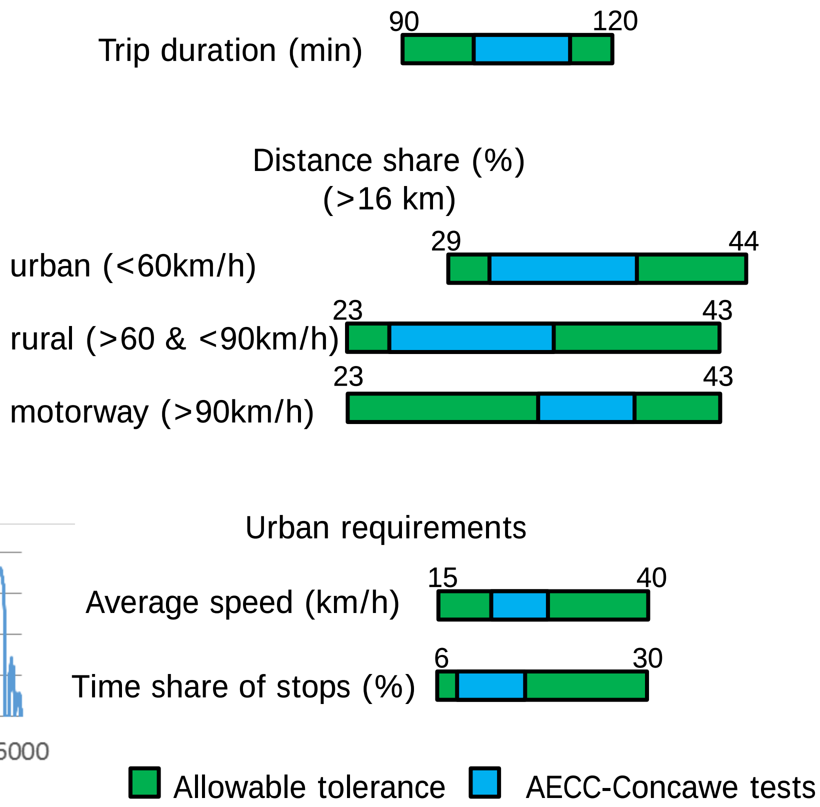
- Objective: investigate NOx & PN RDE without and with Gasoline Particulate Filter (GPF)
- Vehicle - C-segment, 1.4l engine
  - Market representative GDI technology targeting Euro 6c, only Euro 6b available
  - Original configuration w/o GPF
  - Add coated GPF demonstrator underfloor
- HORIBA PEMS equipment
  - Gaseous PEMS (CO_2, CO, NOx) + PEMS-PN demo unit
- Additional investigations (not discussed here)
  - Effect of severity of RDE
  - 7nm vs 23nm cut-off



Underfloor view

RDE Route Within the Requirements





RDE legislation and AECC-Concawe GDI RDE PN test programme results

AECC-Concawe GDI RDE PN test programme set-up

- Identified parameters to evaluate
  - ☐ fuel type & quality
  - ☐ cold-start PN
  - ☐ driving dynamics (RDE on dyno)
  - ☐ cold ambient temperature
  - ☐ <23nm PN

Exhaust	Fuel	NEDC + WLTC	RDE on road	RDE on dyno
Original (without GPF)	Ref E5	1x	-	-
	Ref E10	1x	3x	-
	Market E5	1x	3x	6x
With coated GPF	Ref E10	1x	3x	-
	Market E5	1x	3x	6x

	RFE10	RFE05	EN228
Density 15°C kg/m3	747.7	749.5	736.5
I.B.Pt. °C	37.3	35.6	24.6
% Evaporated at 70°C, E70 %(V)	43.8	32.8	47.3
% Evaporated at 100°C, E100 %(V)	57.1	56.1	61.6
% Evaporated at 150°C, E150 % (V)	90.4	88.2	92.7
% Evaporated at 180°C, E180 % (V)	-	95.2	99.0
F.B.Pt. °C	181.2	193.4	179.8
R.O.N	97.4	95.5	96.8
M.O.N.	86.1	85.2	85.4
Aromatic content %(V)	28.3	33.5	32.6
Sulphur content mg/kg	4.5	3.5	4.9
Atomic H/C Ratio	1.799	1.845	1.861
Ethanol %(V)	9.9	5	4.8

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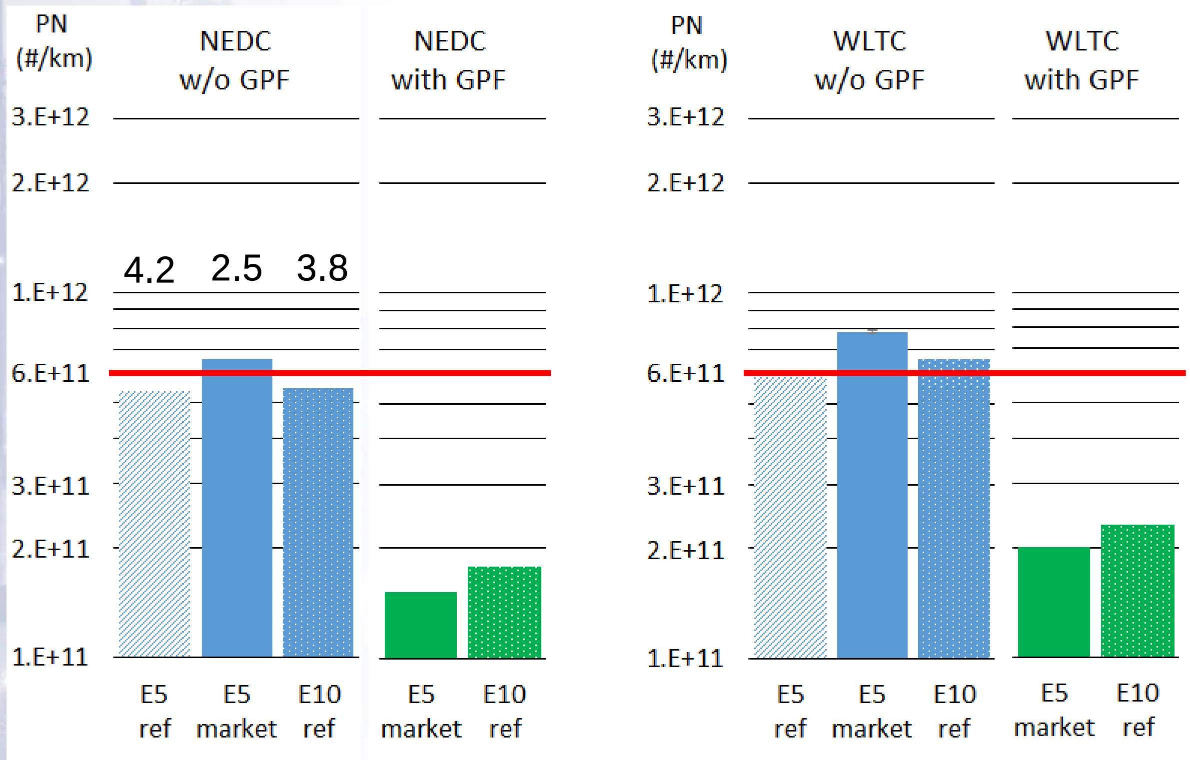
PN results with GPF are below Euro 6c limit on all dyno tests

$$\text{PN Index} = \frac{\sum_{i=1}^{n}[DBE_i+1]V_i}{DVPE\ (\text{kPa})}\ (\text{kPa}^{-1})$$

SAE 2013-01-1558



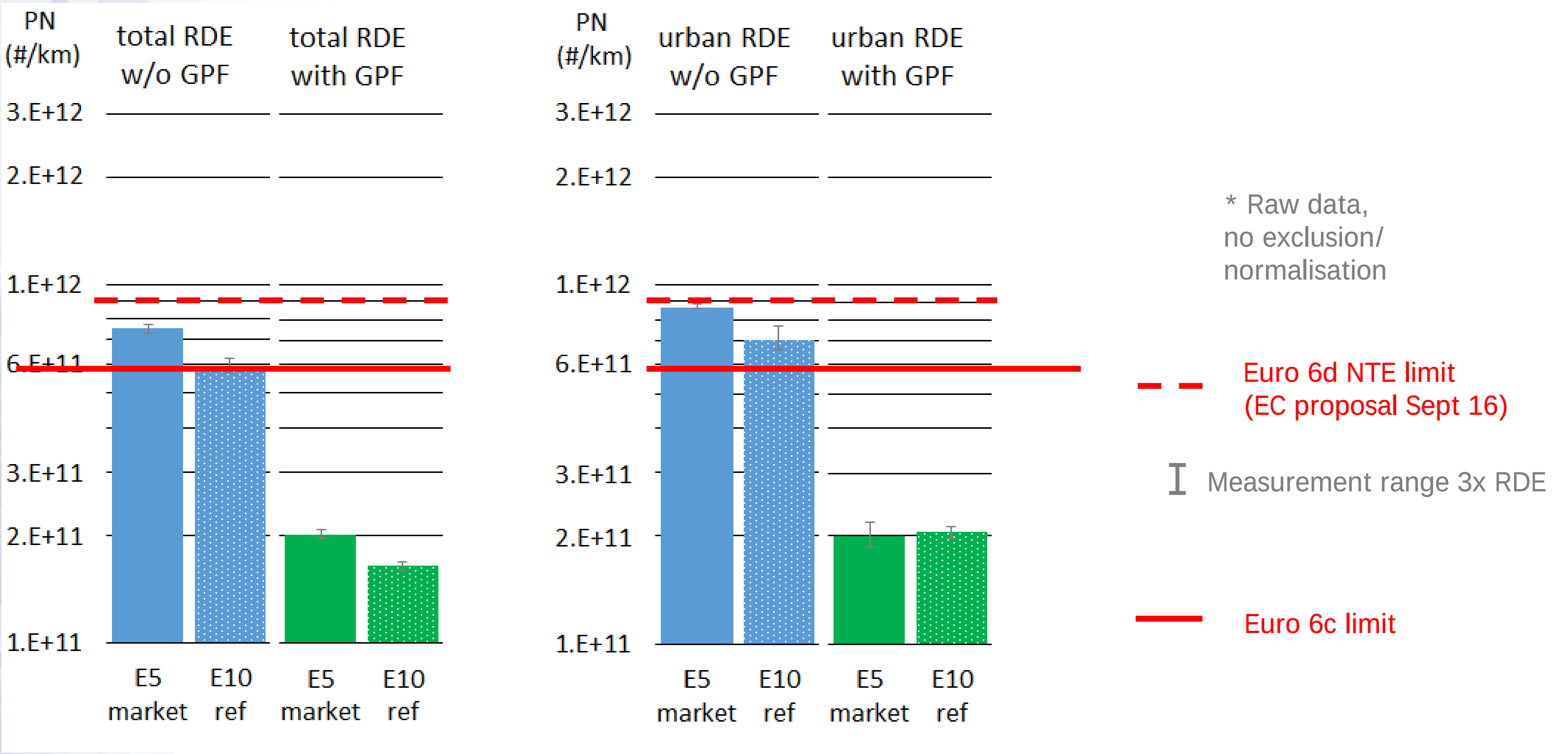
- JLR PN index has been calculated
- E5 market fuel gave much lower PNI than the reference fuels due to DVPE of the market fuel
- Few repeats so can't read too much into fuel to fuel differences

RDE legislation and AECC-Concawe GDI RDE PN test programme results

Euro 6c limit

Measurement range if repeated

PN results with GPF are well below Euro 6d NTE limit



RDE legislation and AECC-Concawe GDI RDE PN test programme results

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Conclusions

- In general fuel effects on emissions were fairly small compared to vehicle-vehicle differences
- Some indications that increasing oxygenates decreased PN emissions
  - Splash-blended fuels showed directional reduction but reductions were significant in only one vehicle in the Concawe study
  - Fuels matched at 95 RON showed no significant effects and directionally PN increased with increasing ethanol up to 10%
  - Fuels matched at 98 RON showed significant reduction mainly on PN
- The PM measurements are low and at the limit of the test capability which may explain why some effects were “seen” in PN but not PM
- Concawe/AECC study (2) gave mixed results comparing E5 market and E10 reference fuels
- PN index (JLR) showed some correlation with PN number – but fuels at extremes of vapor pressure did not correlate well
- Use of GPF was successful in reducing PN emissions below the Euro 6c and proposed 6d limits

Suggestions for Future Research

- The Concawe study showed different levels of correlation with PN Index in the two different vehicles studied
  - PM/PN indices are of interest but more work is needed to understand how they correlate with a wider range of vehicles
  - The indices proposed so far seem to rely heavily on the vapor pressure, other properties may be better predictors of PN number
- Recent Concawe work (unpublished) has suggested that GPF efficiency for filtration of smaller particulates (sub 23nm) is higher than larger particulates
  - More work is needed to understand numbers at these low particle sizes
  - Requires test development work before fuel effects can really be studied

Acknowledgements

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Thanks for Your Attention!