Department of Engineering Science
University of Oxford

Felix Leach, Richard Stone – University of Oxford
Derek Fennell, David Hayden, Dave Richardson,
Nick Wicks – Jaguar Land Rover
felix.leach@eng.ox.ac.uk

Predicting Particulate Matter Emissions from Gasoline Direct Injection Spark Ignition Engines – the PN index

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Outline

- **Introduction**
  - **Previous work**
  - **The PN index**
- **Engines**
- **Fuels**
- **Results**
  - **Model fuels**
  - **EN228 fuels**
  - **NEDC**
  - **EU5 Reference fuels**
- **Conclusions**

What effect do aromatic content and fuel volatility have on particulate emissions?

- "Development of a predictive model for gasoline vehicle particulate matter emissions" (Aikawa et al.)

Aikawa, Sakurai, and Jetter, SAE 2010-01-2115

- PM number index: $I(VP, DBE) = \sum_{i=1}^{n} \left[\frac{DBE_i + 1}{VP_i} W_{ti} \right]$
- DBE: Double bond equivalent
  - A measure of how unsaturated a Hydrocarbon is
  - $DBE = \frac{2C - H + 2}{2}$
- No independent control of volatility and DBE. PFI engine only.
- Aim:
  - Verify index and extend to SGDI combustion system

PM index to PN index

- Unable to calculate PM index without detailed compositional breakdown of fuels
- Need to use industry standard measurements
  - DVPE
  - Blending by volume

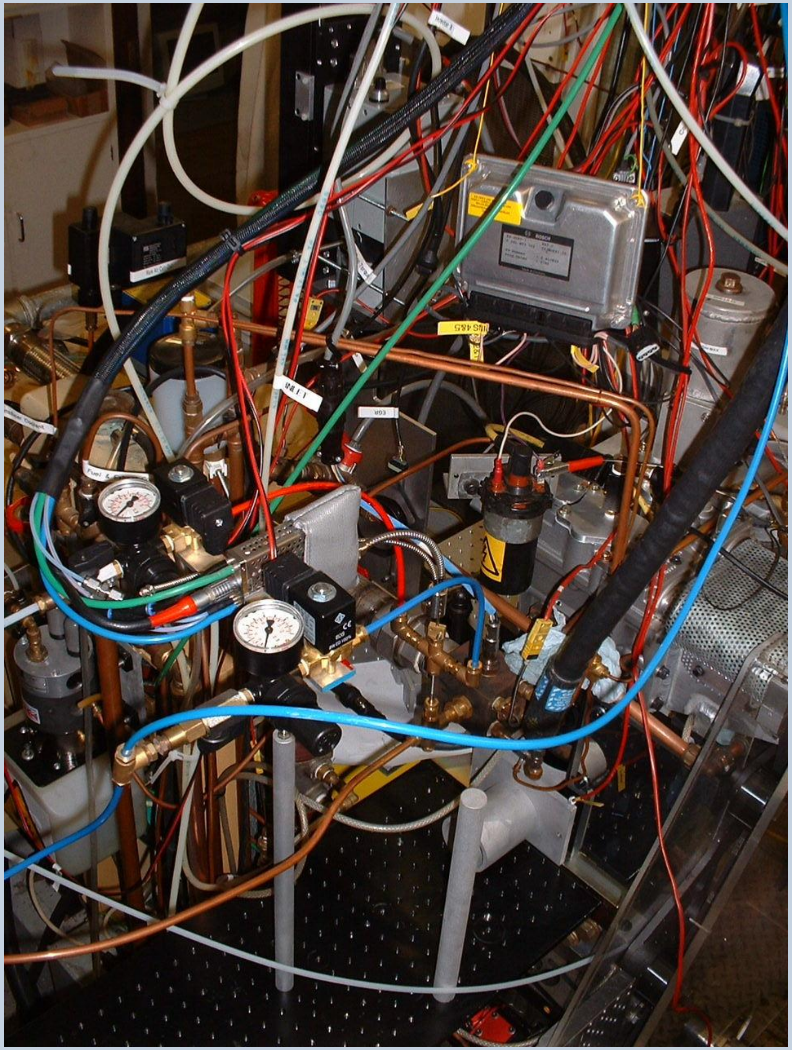
$$\text{PM index (Honda)} = \sum_{i=1}^{n} \left[\frac{DBE_i + 1}{VP_i} W_{ti} \right]$$

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

Single Cylinder Engine with optical access

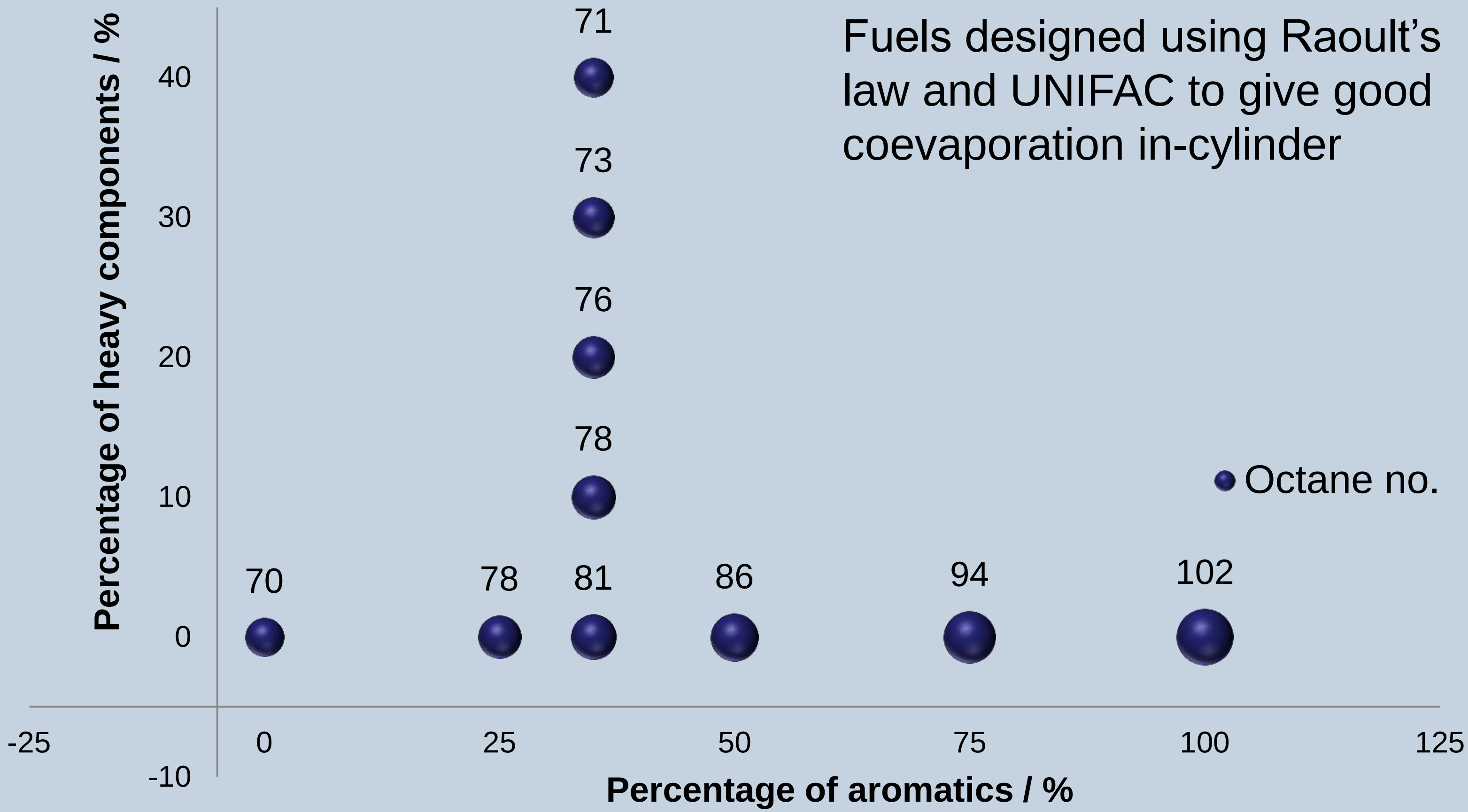
- **Bore** **89 mm**
- **Stroke** **90 mm**
- **Capacity** **562 cc**
- **Compression Ratio 11.1**
- **Injection Pressure 150 bar**

- **GDI**
- **IMEP 1.8bar**
- **Mixture inlet 40ºC**
- **Coolant 60ºC**
- **λ 0.9 & 1.01**
- **1500 rpm**



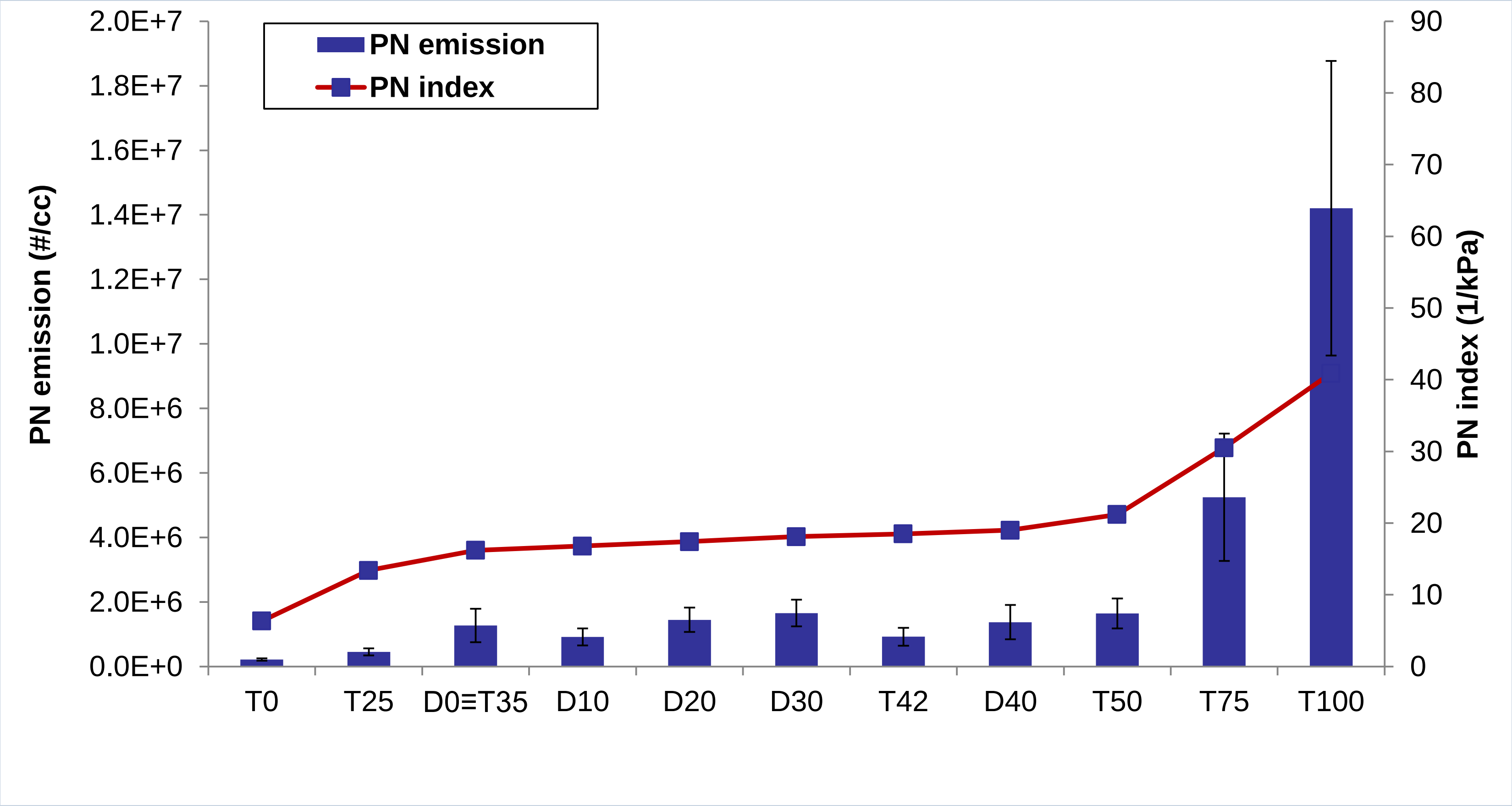
Fuels

Model fuels

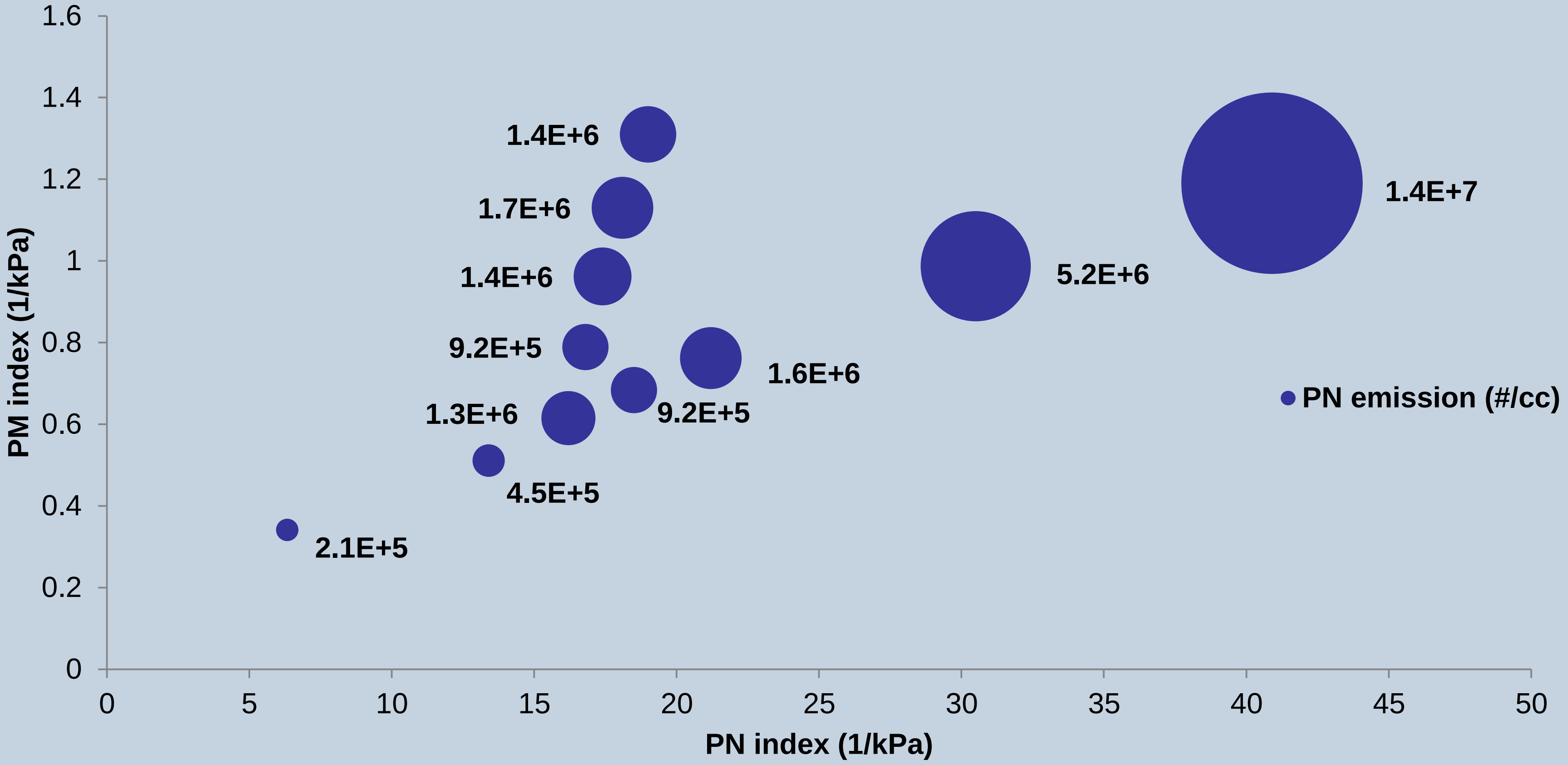


Fuels designed using Raoult's law and UNIFAC to give good coevaporation in-cylinder

Model fuels (DMS500 results)



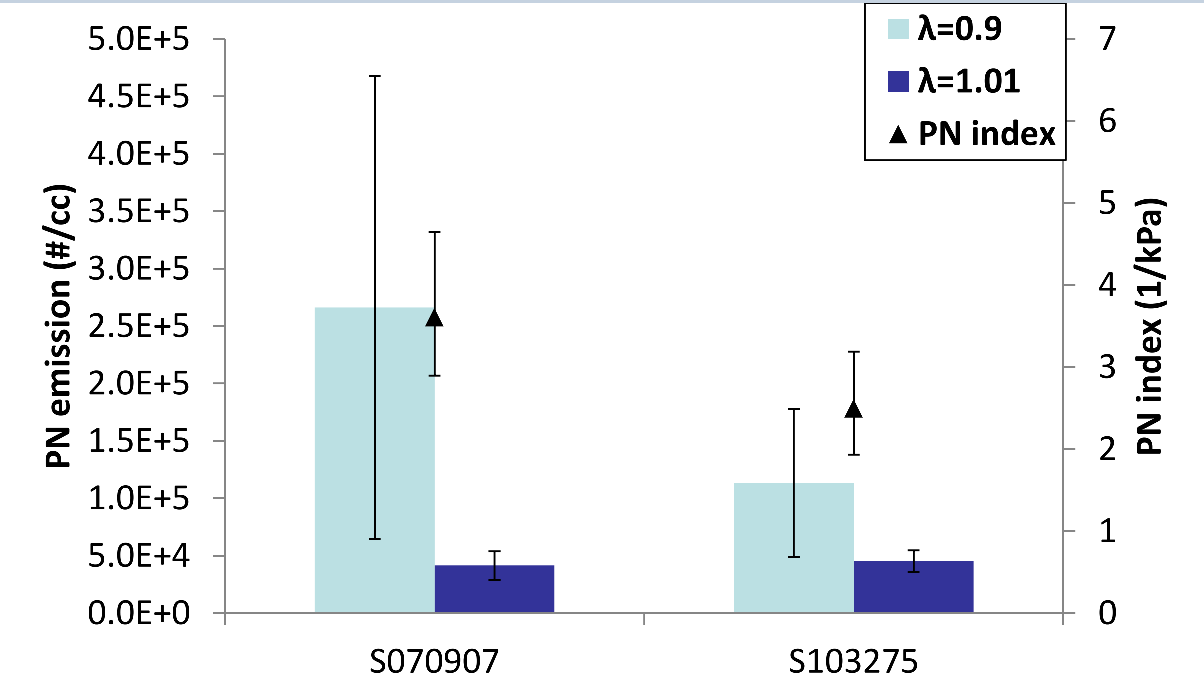
PM index vs PN index



EN228 fuels (DMS500 results)

IMEP: 1.8bar
Mixture inlet: 40ºC
Coolant: 60ºC
***λ:* 0.9 & 1.01**
1500 rpm

	S070907	S103275
DVPE	70.6	88.6
DBE+1	2.58	2.25
PN index	3.66	2.54



Drive cycle testing
Jaguar AJ126 3.0L V6 Supercharged

- **Transient dynamometer**
- **Set up to run as ‘SUV’ over NEDC**
- **Tailpipe sampling post-cat**
  - **Approximately 5m downstream of catalysts and silencer**

Fuels

Drive cycle test fuels

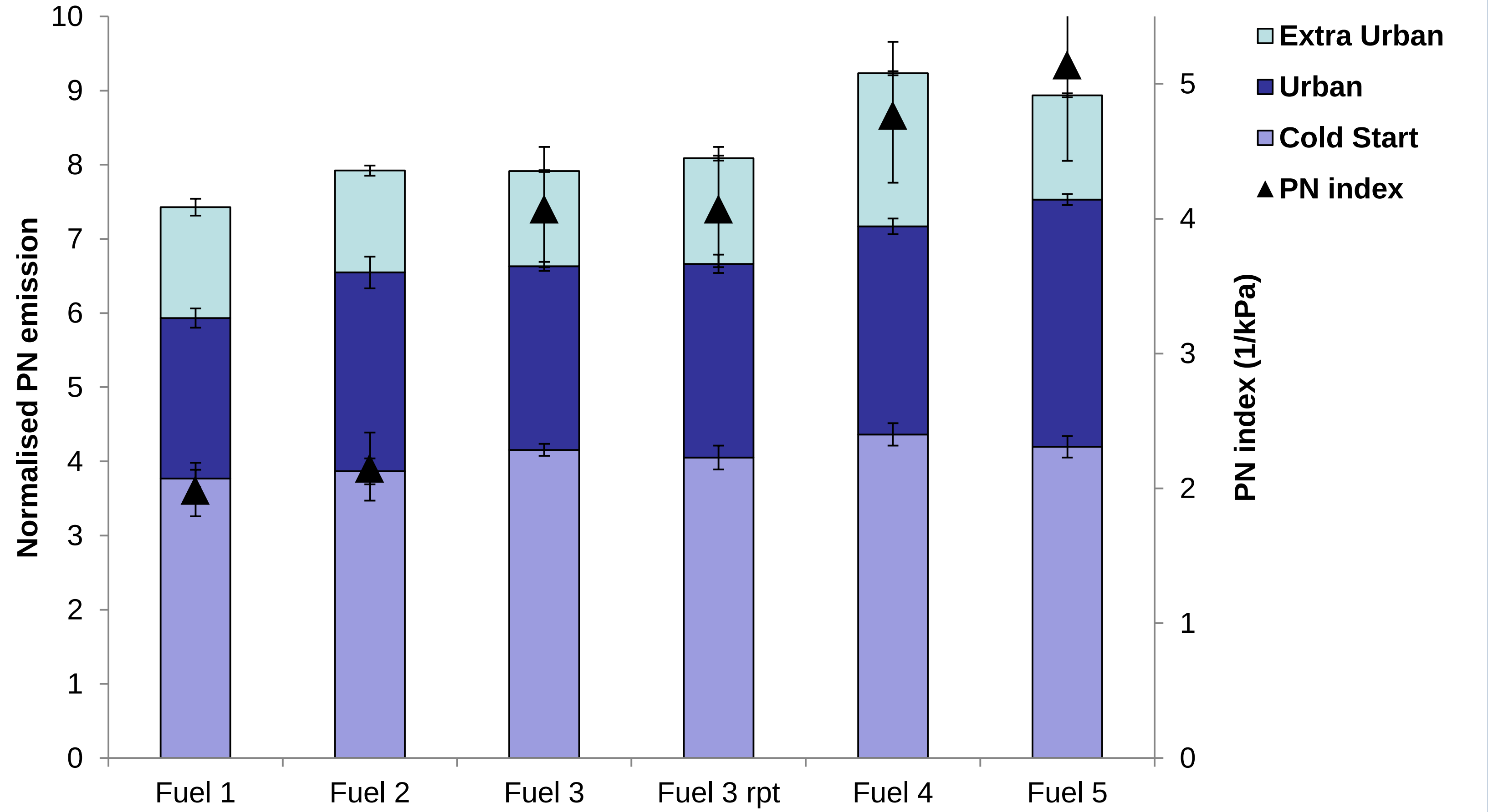
- 5 fuels chosen from those available to give good spread of PN index

	DBE+1 (%v/v)	VP* (kPa)	PN index (1/kPa)
Fuel 1	2.11	106.1	1.99
Fuel 2	1.98	92.9	2.15
Fuel 3	2.32	56.2	4.07
Fuel 4	2.28	47.8	4.77
Fuel 5	2.95	57.3	5.14

* either DVPE or RVP depending on fuel analysis method

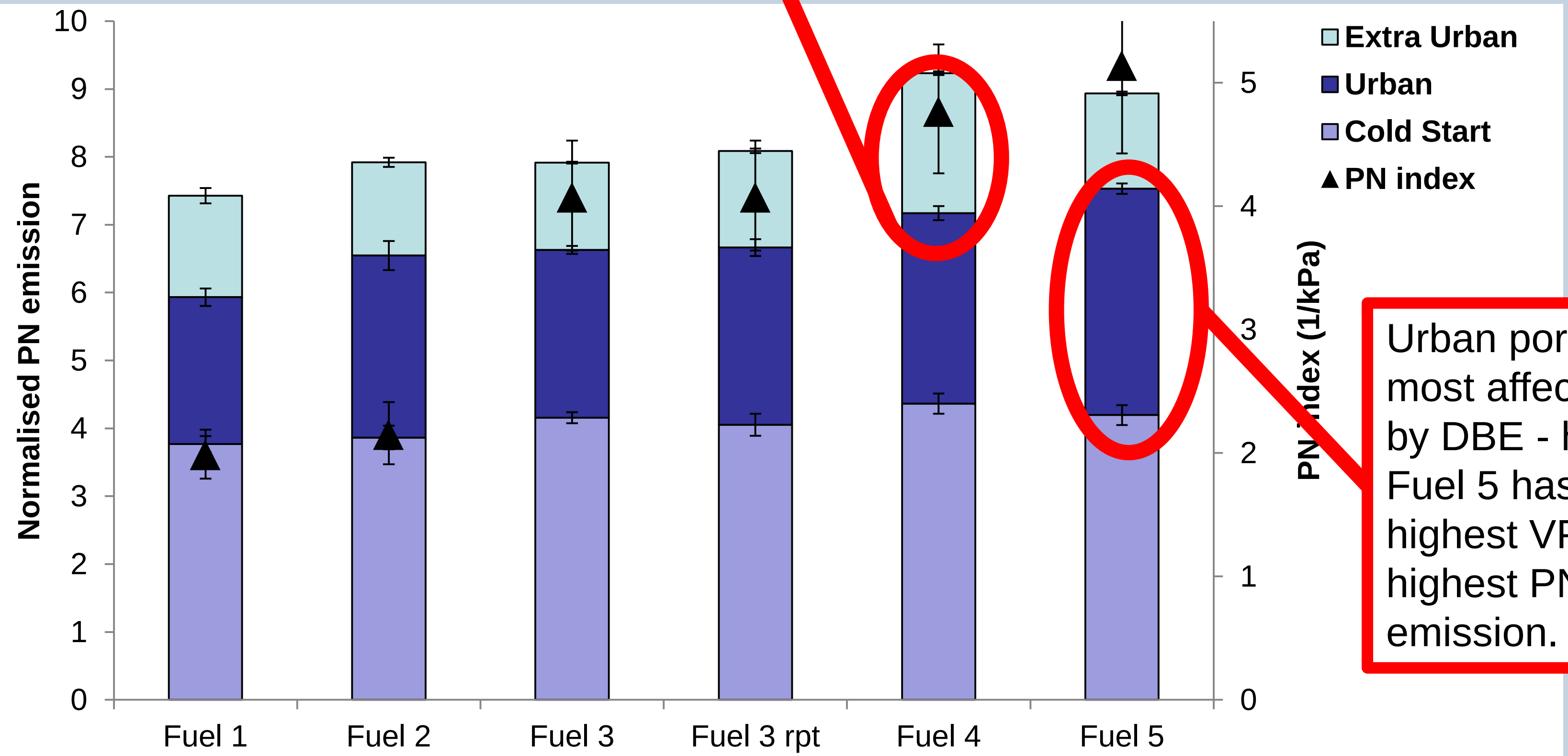
PN emissions over NEDC (APC results)

APC: AVL Particle Counter



PN emissions over NEDC (APC results)

Extra Urban portions most affected by *VP* - here, Fuel 4 has the lowest *VP*, and highest PN emission.



Urban portion most affected by DBE - here, Fuel 5 has the highest VP, and highest PN emission.

Cold Start dependent on other factors. Stop-start and other transient factors may also stop other areas from showing such strong trends as predicted.

Fuels

EU5 Reference Fuel for emissions testing

CEC RF-02-08 fuel spec.

	Min	Max
DVPE (kPa)	56.0	60.0
Olefins (% v/v)	3.0	13.0
Aromatics (% v/v)	29.0	35.0
Ethanol (% v/v)	4.7	5.3

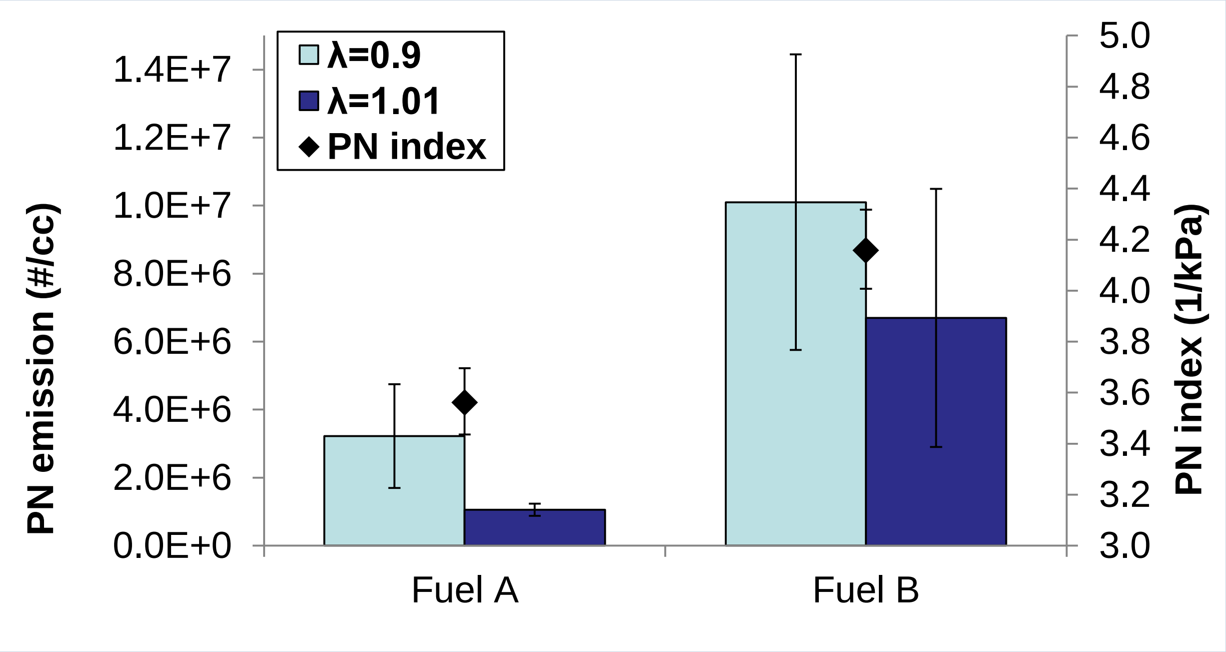
EU5	Min index	Max index
DVPE (kPa)	60.0	56.0
DBE+1	2.19	2.53
PN index	3.65	4.52

	Fuel A	Fuel B
DVPE	61.7	59.9
DBE+1	2.20	2.49
PN index	3.56	4.16

EU5 Reference fuels (DMS500 results)

IMEP: 1.8bar
Mixture inlet: 40ºC
Coolant: 60ºC
***λ:* 0.9 & 1.01**
1500 rpm

	Fuel A	Fuel B
DVPE	61.7	59.9
DBE+1	2.20	2.49
PN index	3.56	4.16



Steady state testing Jaguar AJ133 5.0L V8

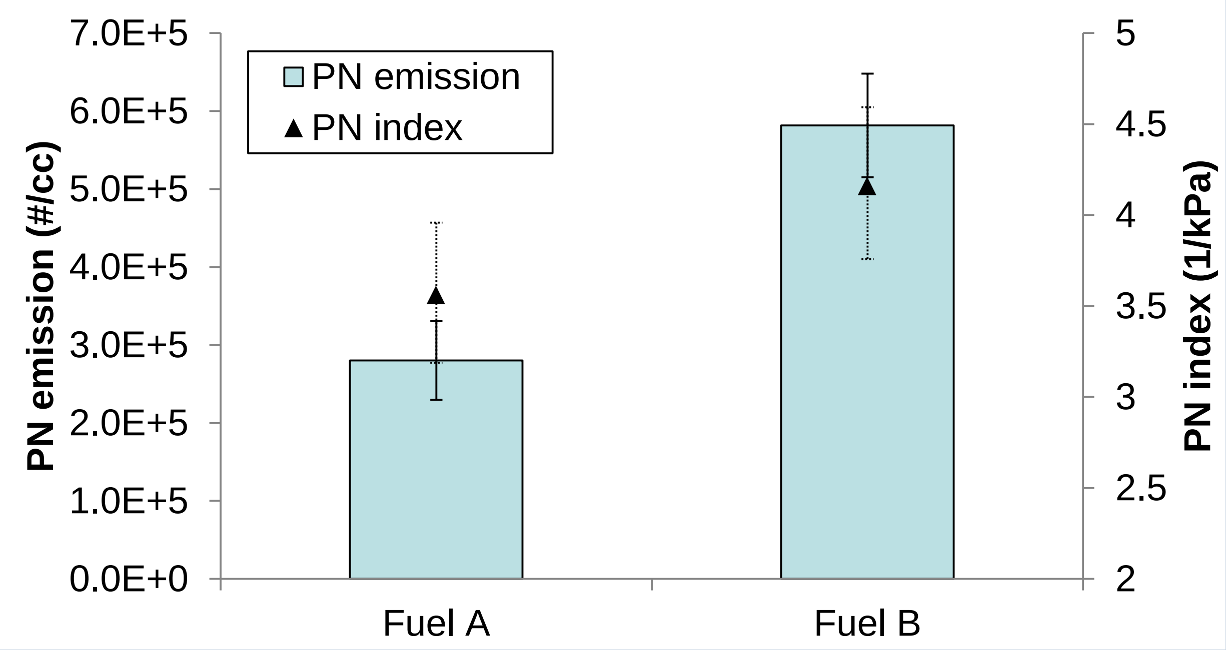
▪ Bore	92.5 mm
▪ Stroke	93 mm
▪ Capacity	4999 cc
▪ Compression Ratio	11.5
▪ Injection Pressure	150 bar

- Tailpipe sampling post-cat

EU5 Reference fuels (DMS500 results)

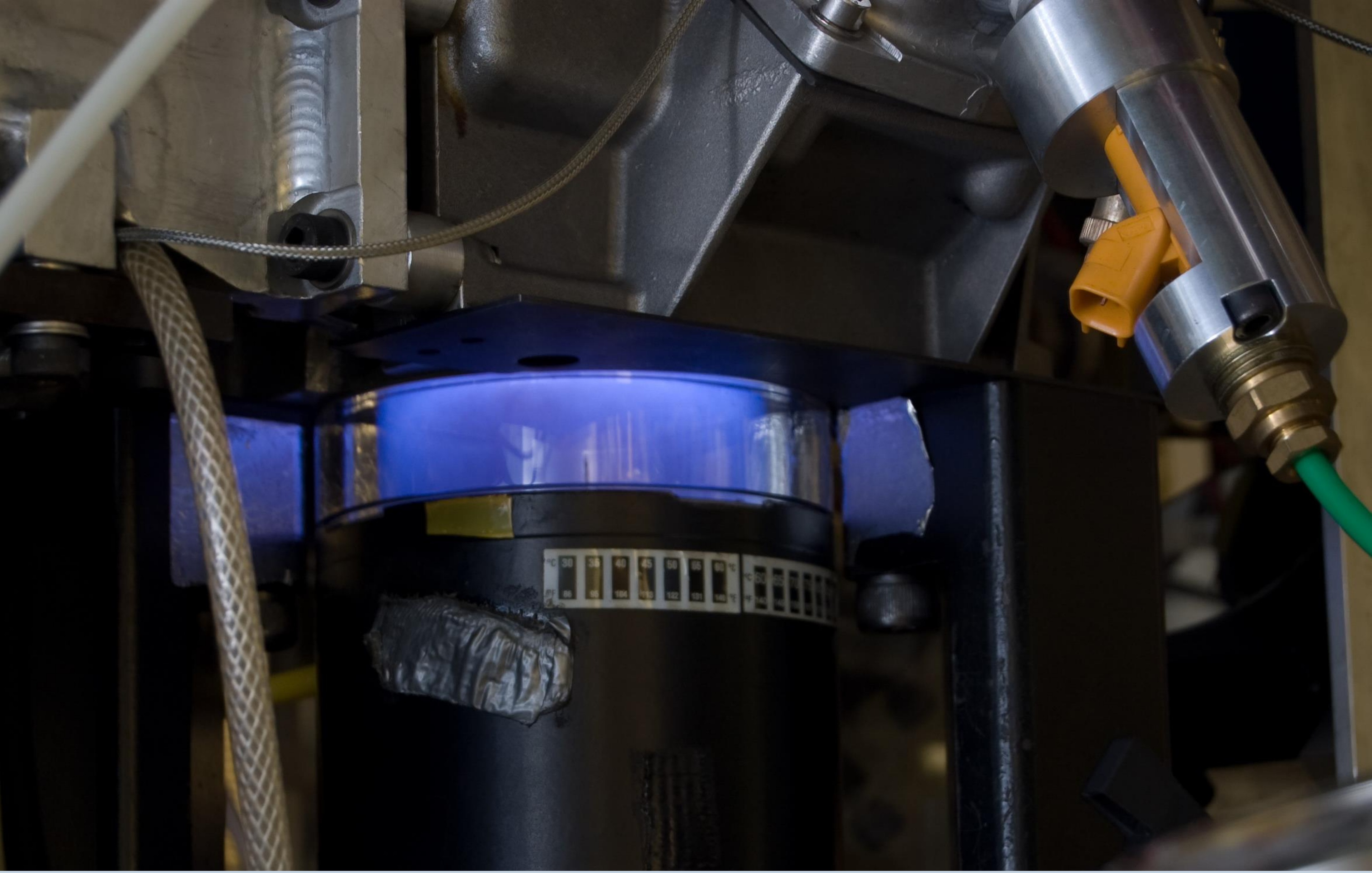
IMEP: 1.8bar
Mixture inlet: 40ºC
Coolant: 60ºC
***λ:* 1.0**
1500 rpm

	Fuel A	Fuel B
DVPE	61.7	59.9
DBE+1	2.20	2.49
PN index	3.56	4.16



Conclusions

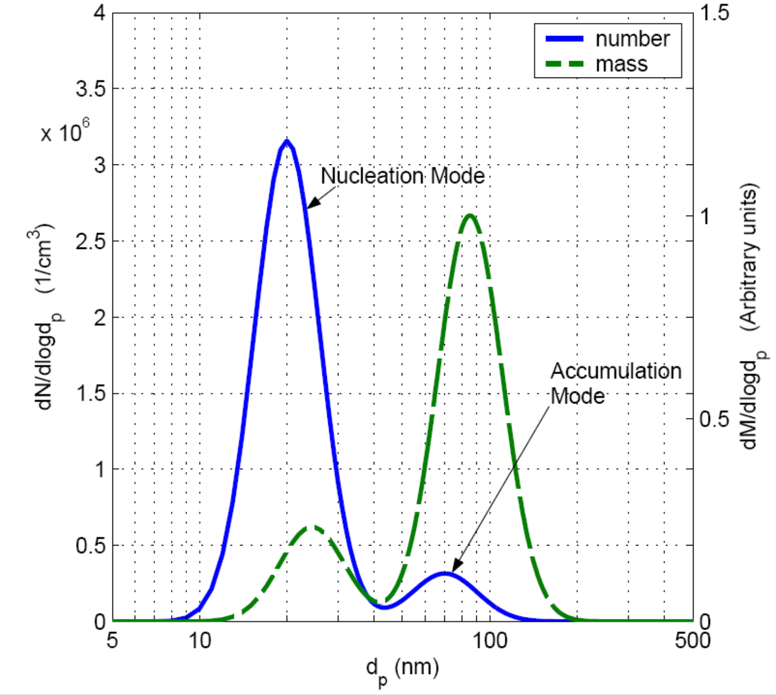
- Fuels blends have been devised that have independent control of volatility and aromatic content
- UNIFAC needs to be used for modelling co-evaporation of aromatics
- Trends reported by Honda replicated in SGDI engines using model fuels and real fuels
- Trends also observed in transient testing
- Implications for reference fuels
- A new Particle Number (PN) index has been devised
    - More tests and non-linear forms of the index to be investigated

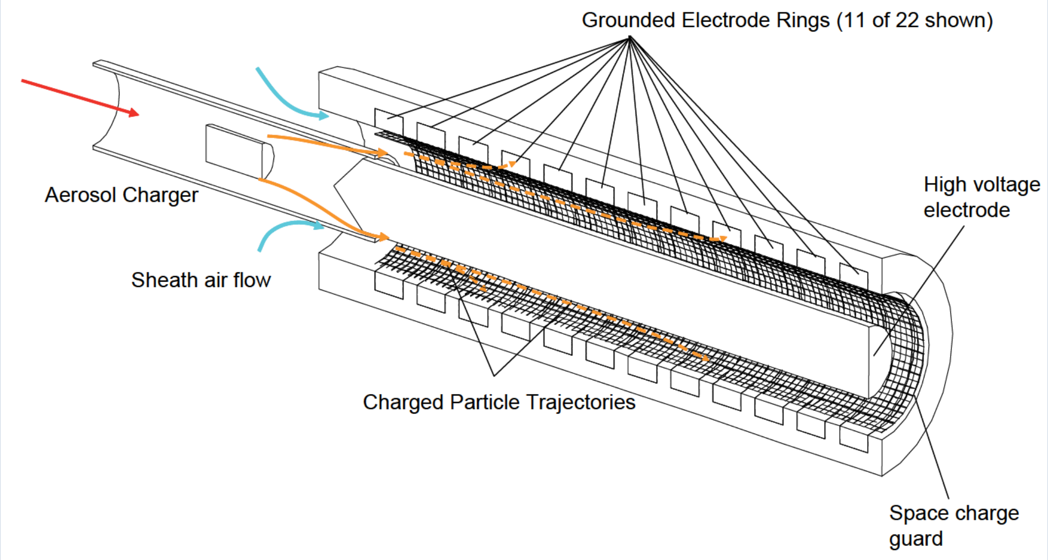


Particulate matter measurements

Cambustion DMS500

Number counts and size distributions



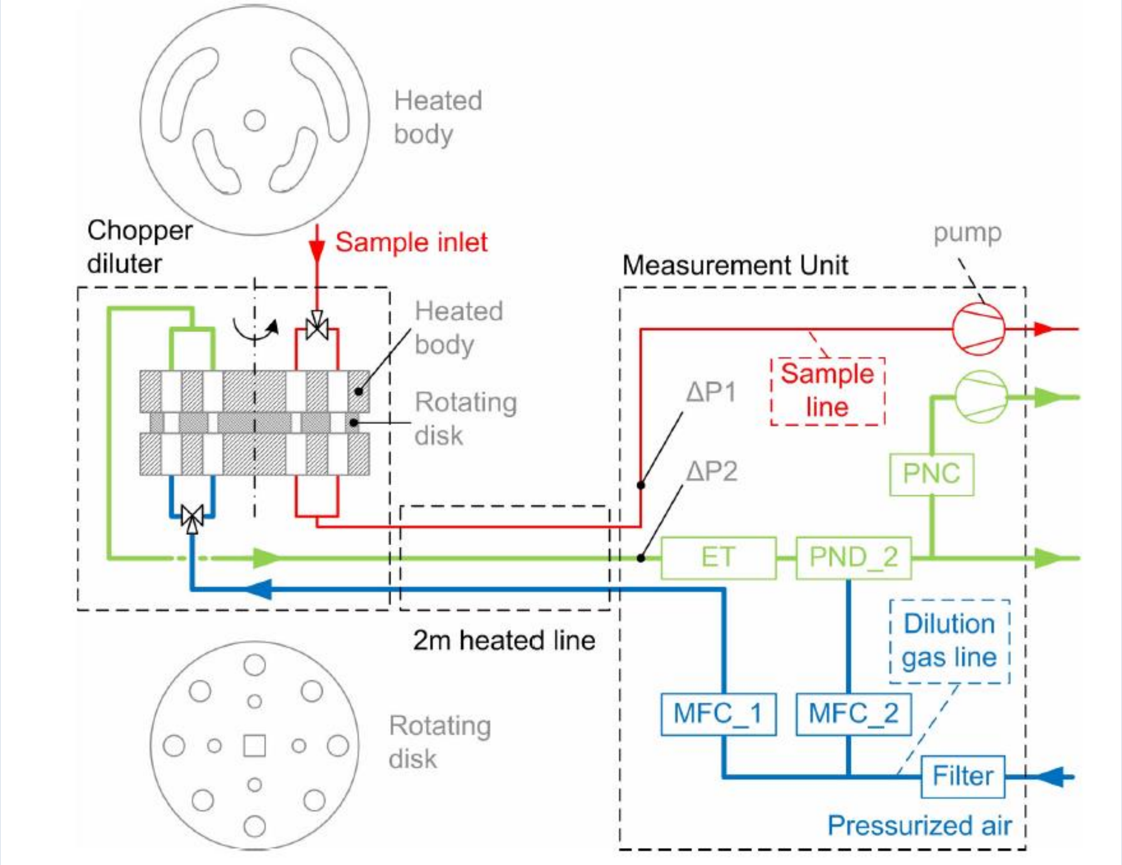


Reavell et al. SAE 2002-01-2714

Results digitally filtered to replicates PMP measurement protocol

Particulate matter measurements

AVL Particle Counter



Legally compliant counter

APC Product Guide AT2858E, Rev. 05 (2010)

Model fuel design
Raoult's law

- Raoult's law relates the vapour pressure of an ideal solution to the vapour pressure of each of its chemical components by the molar fraction of each component present

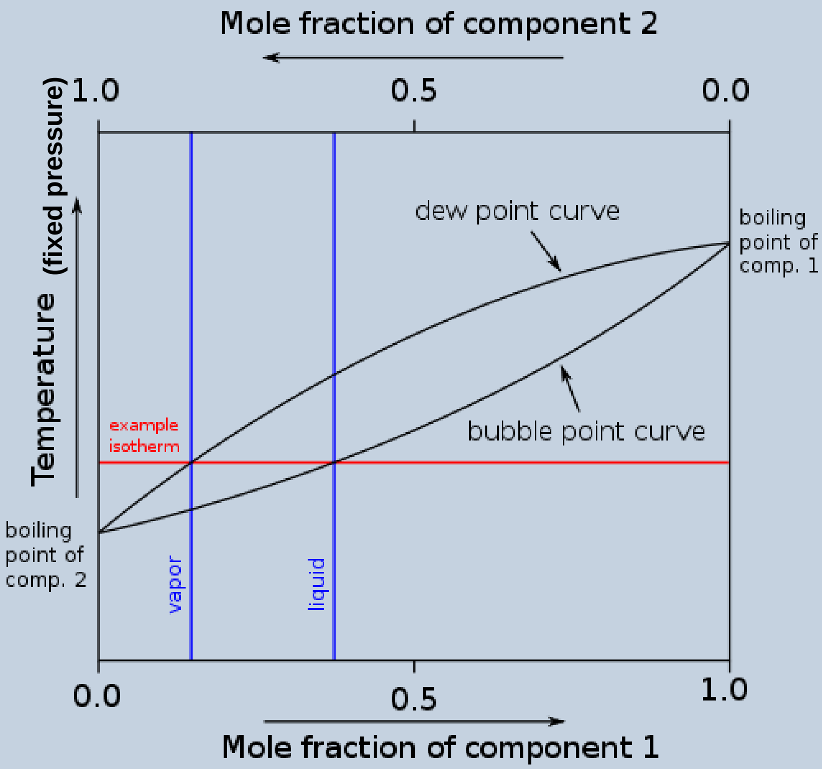
- $y_i P = x_i P_{vpi}$ [Poling, Prausnitz, & O'Connell]

  y_i: molar fraction of component *i* in vapour

  x_i the molar fraction of component *i* in liquid

  P_{vpi} the vapour pressure of component *i*

  P the partial pressure of the component.



- Assumptions:
  - Neglect effect of surface tension and any external conditions (electric/magnetic field)
  - Ideal mixing ➔ linear relationship

Model fuel design

UNIFAC*

- **UNIversal Functional Activity Coefficient (UNIFAC)**
- **Attempts to extend Raoult's Law to account for non-ideal mixing**
- **Semi-empirical model to predict non-ideal mixture behaviour based on molecular size and interactions**
- **Breaks molecules into functional groups to model interactions**
- **Cannot be used on electrolytes**

$$\ln\gamma_i = \ln\gamma_i^C + \ln\gamma_i^R$$

$$\ln\gamma_i^C = \ln\frac{\Phi_i}{x_i} + \frac{z}{2}q_i\ln\frac{\theta_i}{\Phi_i} + l_i - \frac{\Phi_i}{x_i}\sum x_j l_j$$

$$\ln\gamma_i^R = q_i\left[1 - \ln\left(\sum_j \theta_j\tau_{ji}\right) - \sum_j \frac{\theta_j\tau_{ji}}{\sum_k \theta_k\tau_{ki}}\right]$$

$$l_i = \frac{z}{2}(r_i - q_i) - (r_i - 1)$$

$$z = 10$$

$$\theta_i = \frac{q_i x_i}{\sum_j q_j x_j}$$

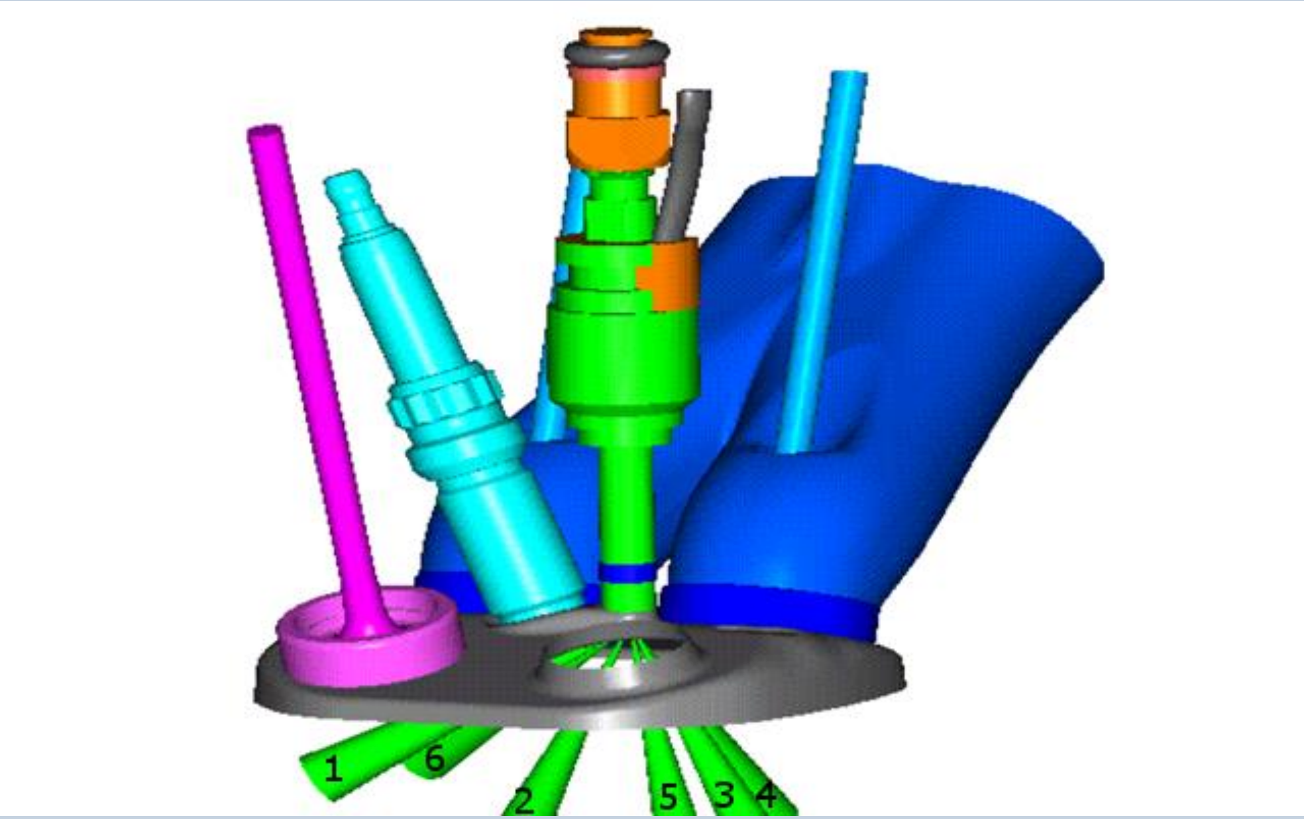
$$\Phi_i = \frac{r_i x_i}{\sum_j r_j x_j}$$

$$\tau_{ji} = \exp\left(-\frac{u_{ji} - u_{ii}}{RT}\right)$$

UNIFAC equations (Poling et al 2000)

* Reid, R. C., J. M. Prausnitz, et al. (1987). The properties of gases and liquids. McGraw-Hill.

AJ133 Fuel Injection Pattern



Malcolm Sandford, Graham Page and Paul Crawford, SAE 2009-01-1060

6 fuel jets

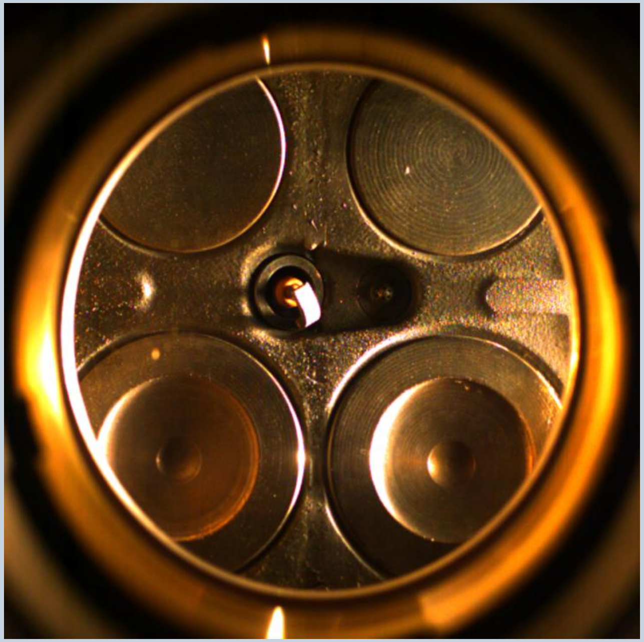
150 bar injection system

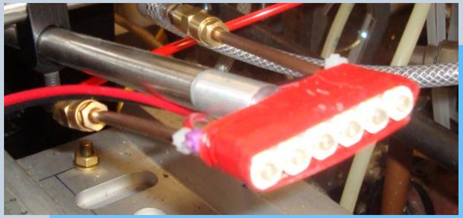
High Speed Imaging – Bowditch Piston

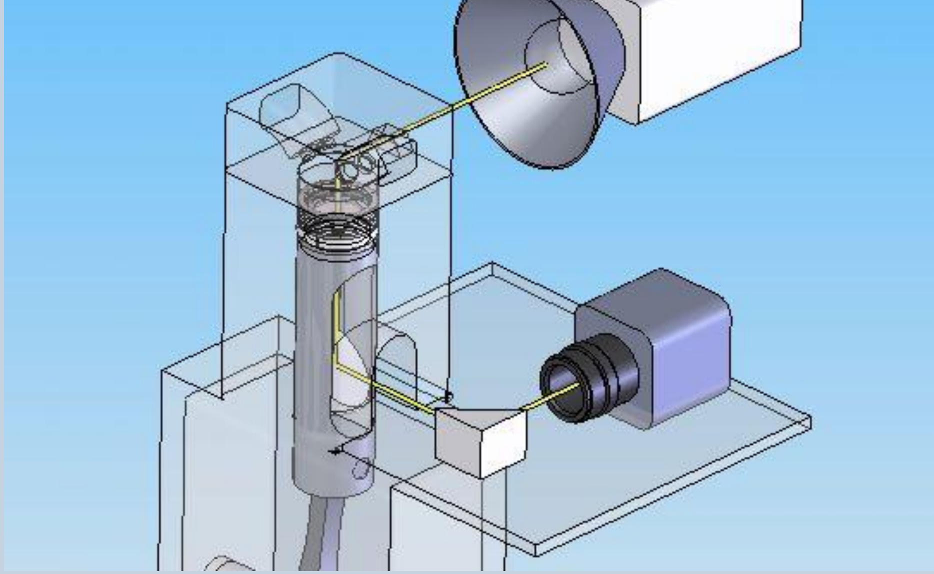
•Photron FASTCAM-1024PCI model

100K Colour Camera – 6000fps

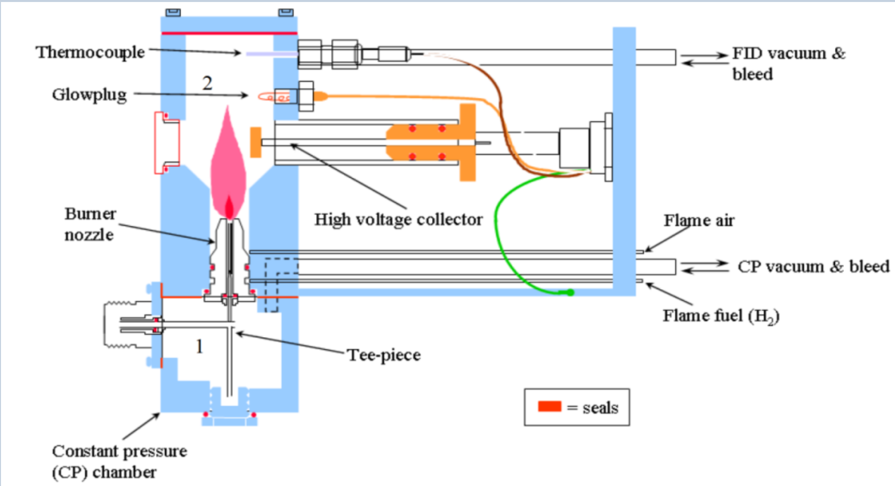
•Resolution: 384 x 352 pixels





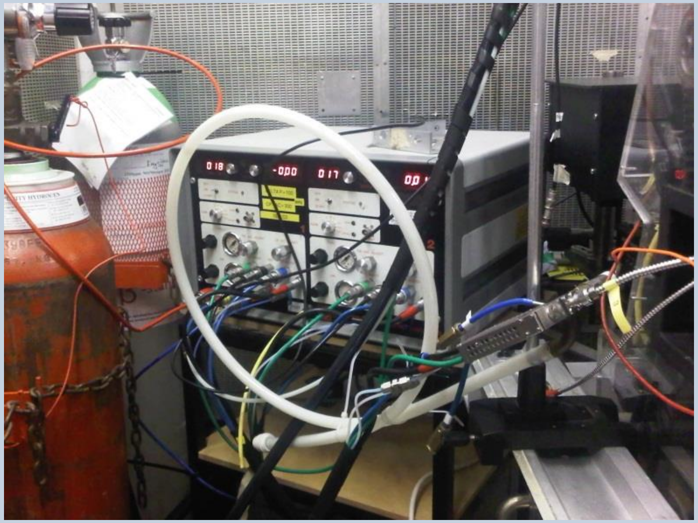


In-cylinder hydrocarbon sampling

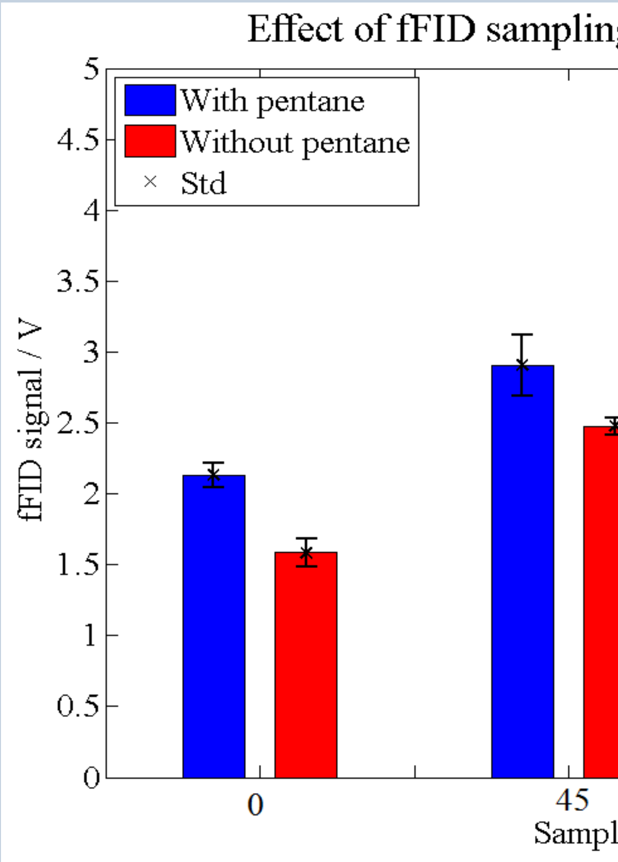


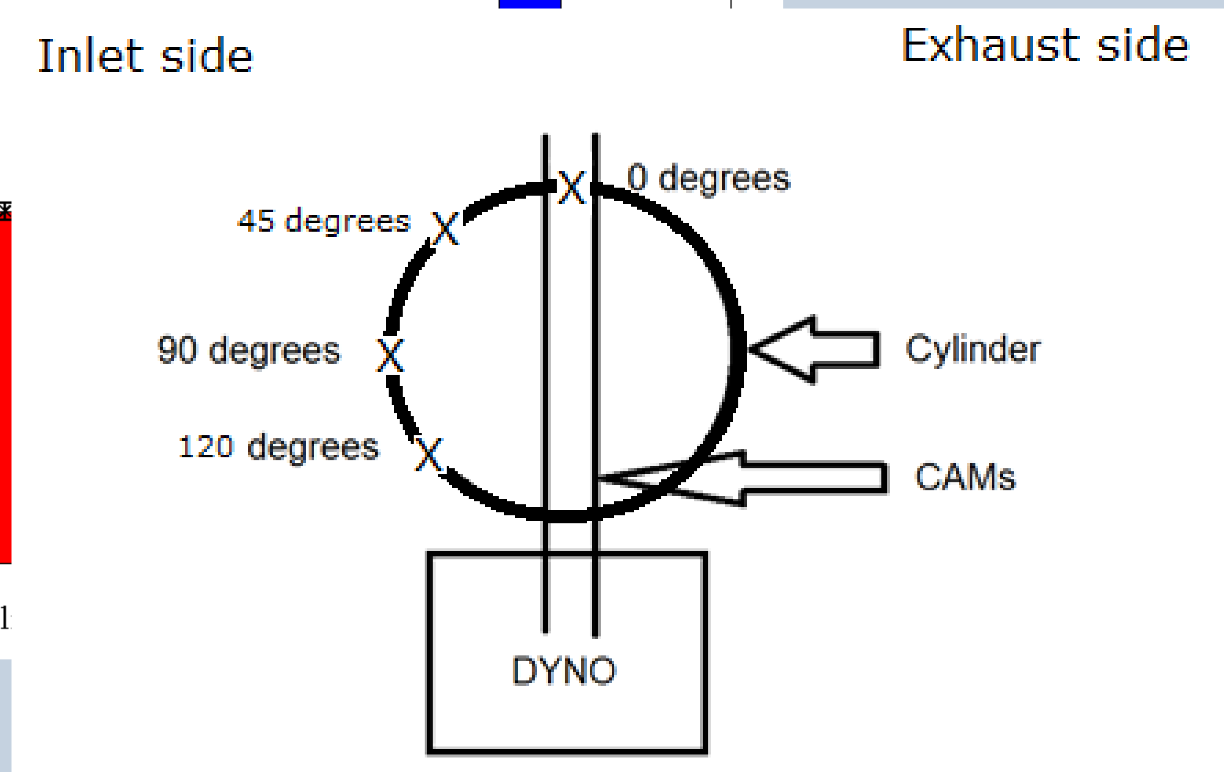
Cambustion HFR400 fast FID

- fFID measures hydrocarbon levels by chemi-ionization
- Response time ~ 4ms



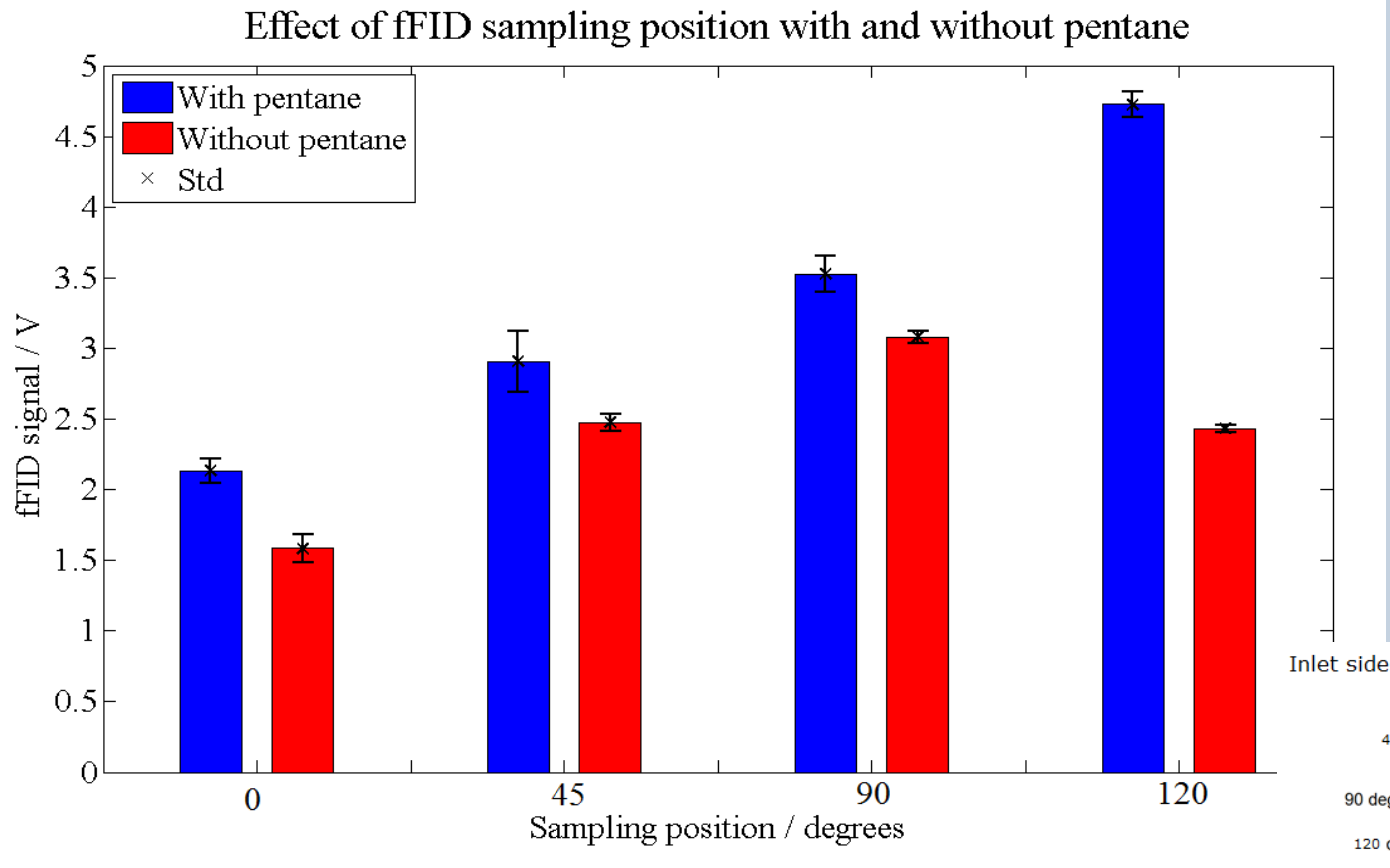
Effect of sampling position

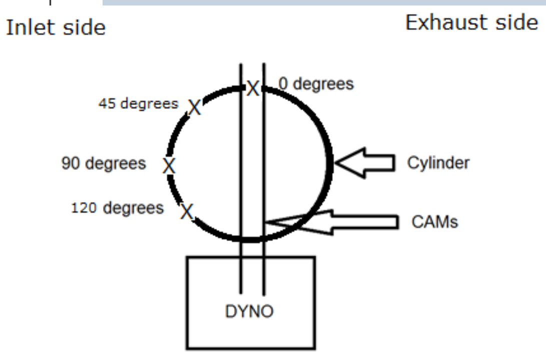




Leach et al, SAE 2013-01-1558

Effect of sampling position

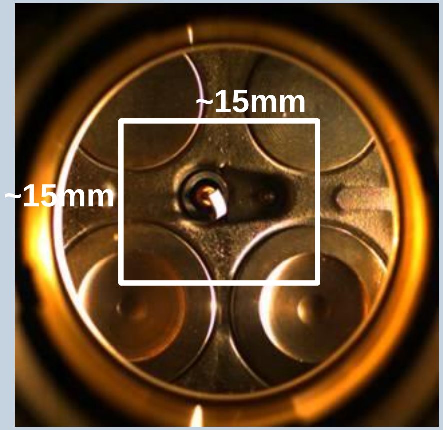


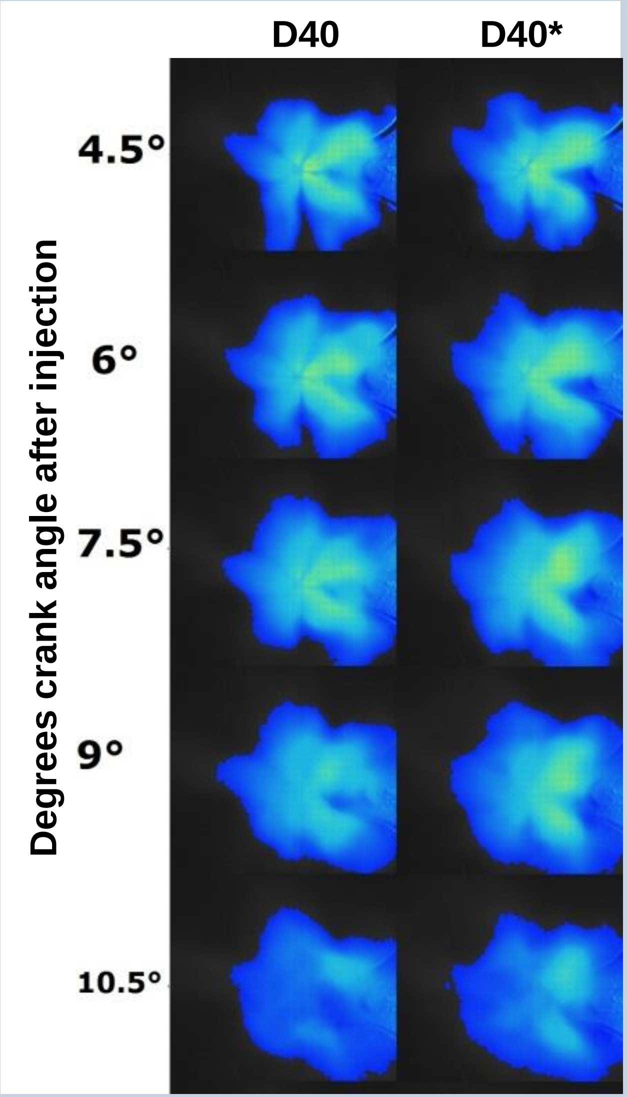


Leach et al, SAE 2013-01-1558

Spray penetration

False colour images





D40* is D40 fuel without 5% v/v n-pentane

PN index vs PN count (APC results)