The Effect of Fuel Volatility and Aromatic Content on Particulate Emissions from GDI Engines

Felix Leach[1], Richard Stone[1], Dave Richardson[2]

1. Department of Engineering Science, University of Oxford, Parks Rd, OXFORD, OX1 3PJ
2. Powertrain Research, Jaguar Land Rover, Whitley Engineering Centre, COVENTRY, CV3 4LF
Corresponding email: felix.leach@eng.ox.ac.uk

Gasoline Direct Injection (GDI) engines have become the preferred standard for gasoline light-duty vehicles in the worldwide market. Advantages of GDI engines over Port Fuel Injected (PFI) engines include greater specific output and lower CO_2 emissions. However GDI engines emit more Particulate Matter (PM) than PFI engines [1]. Increasingly stringent EU emissions legislation has led to increased interest in Particulate emissions and concern that modern GDI engines will not meet coming legislation unless they are optimised for reducing particulate emissions [2]. Forthcoming European emissions legislation, EU6 – effective 1 January 2012, mandates a particle limit of 6×10^{12} #/km reducing to 6×10^{11} #/km within 3 years [3].

Aikawa et al. [4] conducted tests with a Port Fuel Injection (PFI) engine and developed a model linking fuel composition with PM emissions. It links PM emissions with the Vapour Pressure (*VP*) and Double Bond Equivalent (*DBE*) of the components in the fuel weighted by Mass Fraction (W_t):

Equation 1

$$I(VP, DBE) = \sum_{i=1}^{n} \left[\frac{DBE_i + 1}{VP_i}\right] W_{ti}$$

DBE is a measure of how unsaturated a hydrocarbon is, and can be easily calculated from Equation 2, where C, H, and N are the number of Carbon, Hydrogen, and Nitrogen atoms respectively present in an organic compound.

Equation 2

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

The aim of this work is to review this index and extend the PM Number (PN) measurements to a modern Spray Guided Direct Injection (SGDI) combustion system. To avoid confusion in the current work the term PN Index is used here, with the Vapour Pressure being evaluated as Dry Vapour Pressure Equivalent (DVPE) with units of kPa and as a minor simplification the use of volume fraction (V_i):

Equation 3

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

Engine

The engine for this work is a single-cylinder optical access SGDI engine supplied by Jaguar. The combustion system is essentially the same as that used in the Jaguar AJ133 engine, which has been comprehensively described by Sandford et al [5]. Table 1 shows the engine details and the valve timings.

Table 1: Specifications of the single-cylinder optical access SGDI engine

Bore × Stroke	89 × 90.3 mm
Displacement	562 cm^3
Valves per Cylinder	2 intake, 2 exhaust
Compression Ratio	11.1
Fuel Pressure	150 bar
Injector	Bosch Multi-hole Nozzle
Valve Timing (°CA aTDC)	IVO 34°, IVC 242°, EVO 475°, EVC 5°

Instrumentation

Particulate emissions were measured using a Cambustion DMS500 Differential Mobility Spectrometer (DMS) [6]. In accordance with the DMS Manuals and Braisher et al. [2] only the accumulation mode output was used as this has been shown to replicate the PMP measurement protocol [7] that effectively discounts nucleation mode particles. The engine was not fitted with a catalyst, and nor was hot air dilution of the exhaust gas used, so these would both lead to misleadingly high values of Particulate Matter emissions in the nucleation mode.

Fuels

Both unleaded gasolines and model fuels blended from pure components were used in this work. The fuel composition is shown in Figure 1, and it can be seen that there is full independent control over the Double Bond Equivalent (DBE) and Vapour Pressure (VP) of the fuel. Toluene and 1,3,5-Trimethylbenzene were chosen as aromatic components having medium and high boiling points (both with a DBE of 4), and then their paraffin counterparts were selected on the basis of having adjacent boiling points, with blends selected to give co-evaporation with the corresponding aromatic component. Pentane was used to provide a volatile 'front end'. When the volatility was varied, the aromatic content was kept at 35%, as it is the upper limit for the aromatic content in European gasoline and it maintains the octane number at above 70. Modelling of the fuel properties is described below. The index was also tested against fuels which reflected the EU5 reference fuel specification for emissions testing [3]; the specifications are shown in Table 2.

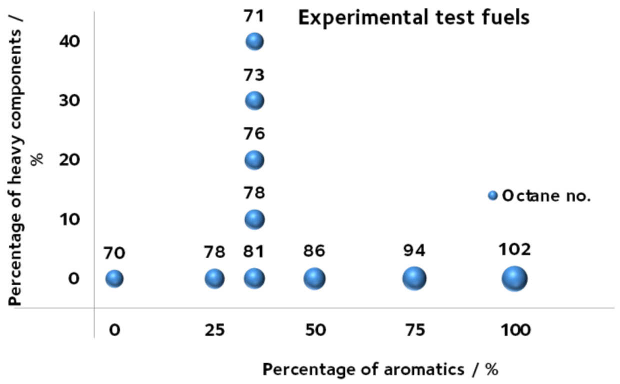


Figure 1: Research Octane Number (RON) of the model fuels with independent control of the aromatic content and volatility

Table 2: EU5 Reference Fuel Specification [8] and tested Reference Fuel Composition

	Reference Specification		Fuel blends tested	
	EU5 (Min I)	EU5 (Max I)	W12/185	W12/186
Vapour Pressure (DVPE, kPa)	60.0	56.0	61.7	59.9
Double Bond Equivalent (DBE)	2.19	2.53	2.20	2.49
Final Boiling Point (FBP, °C)	190	210	193.3	213.6
PN Index	2.74e-2	3.43e-2	2.67e-2	3.12e-2

Results

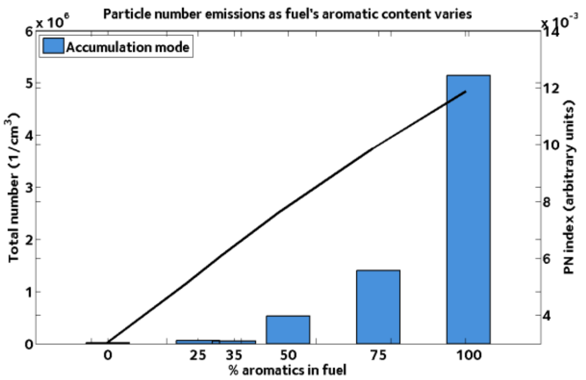


Figure 2: Particulate Number emissions and PN Index dependence on the fuel aromatic content

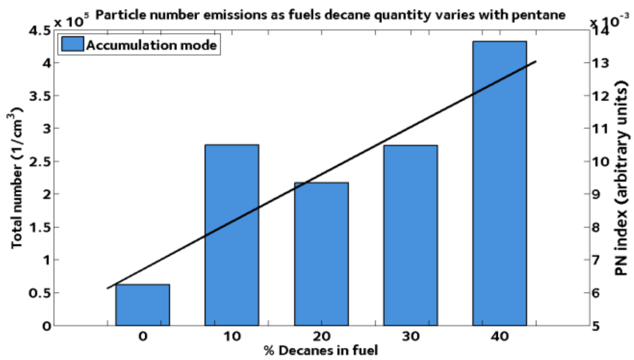


Figure 3: Particulate Number emissions and PN Index value variation as fuel Vapour Pressure is varied (fixed DBE)

Both Figure 2 and Figure 3display rich (λ = 0.9) data. This gives clearer trends, and rich mixture excursions have been shown to be the source of the majority of the PN emissions over the NEDC [9]. These fuels have full independent control over VP and DBE and validate the trends shown in the PM Index [4].

Figure 4 shows the PN emissions (in #/cm^3) for two fuels which represent the reference fuel specification for testing against EU5 emissions legislation. It can be seen that again the trends of the index are followed, with a difference in PN emissions of around 40%. This has implications for the forthcoming EU6 emissions legislation, where PN emissions from gasoline vehicles will be regulated for the first time, as unless the reference fuel specification is changed or an allowance is made for a PN Index, then batch to batch variations in PN emissions may be experienced with different fuels meeting the same specification.

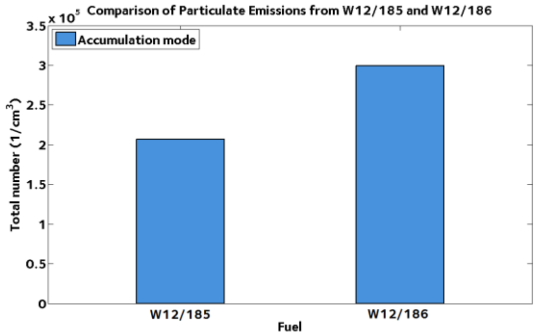


Figure 4: PN emissions from two fuels representing EU5 Reference fuel specification

Conclusions

Particulate emissions from a SGDI engine have been studied experimentally using a Cambustion DMS500 Differential Mobility Spectrometer. Fuel blends have been devised that have independent control of the fuel volatility and aromatic content, and these have been used to validate a PN Index. It has been shown that to model fuel evaporation with mixtures of aromatics and paraffins, Raoult's Law needs to be extended by use of the UNIFAC method. This model can be used to ensure co-evaporation of aromatic and paraffin components in a model fuel, to avoid stratification of the components in a fuel. The effect of low boiling point components on the fuel spray is significant, and the addition of pentane to fuels mixed from pure components is important in order to reflect real world evaporation behaviour. The PN index has been validated in a SGDI combustion system using both model fuels and reference fuels. The PN Index has also been shown to be an important parameter for reference fuel specification, with two fuels representing current specifications giving a 40% difference in PN emissions. This has important implications for policy makers.

Acknowledgements

The authors would like to thank EPSRC and Jaguar Cars Ltd for funding this research.

References

1 **Zhao, H.** Overview of Gasoline Direct Injection Engines. In Zhao, H., ed. *Advanced direct injection combustion engine technologies and development: Gasoline and gas engines* (Woodhead Publishing Ltd and CRC Press, 2010).

2 **Braisher, M., Stone, C.R. and Price, P.** Particle Number Emissions from a Range of European Vehicles. *SAE Technical Paper*, 2010, **2010-01-0786**.

3 Commission Regulation 692/2008, OJ L 199 of 18.7.2008, p.130.

4 **Aikawa, K., Sakurai, T. and Jetter, J.J.** Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions. *SAE International Journal of Fuels and Lubricants*, 2010, **3**(2), 610-622.

5 **Sandford, M., Page, G. and Crawford, P.** The All New AJV8. *SAE World Congress & Exhibition, April 2009* (SAE, Detroit, MI, USA, 2009).

6 **Reavell, K., Hands, T. and Collings, N.** A Fast Response Particulate Spectrometer for Combustion Aerosols. *SAE Powertrain & Fluid Systems Conference & Exhibition, October 2002* (SAE, San Diego, CA, USA, 2002).

7 **Andersson, J., Giechaskiel, B., Muñoz-Bueno, R., Sandbach, E. and Dilara, P.** Particle Measurement Programme (PMP) Light-duty Inter-laboratory Correlation Exercise (ILCE_LD) Final Report. (European Commission Joint Research Centre Institute for Environment and Sustainability, 2007).

8 Commission Regulation 692/2008, OJ L 199 of 18.7.2008, p.88.

9 **Peckham, M.S., Finch, A., Campbell, B.W., Price, P. and Davies, M.** Study of Particle Number Emissions from a Turbocharged Gasoline Direct Injection (GDI) Engine Including Data from a Fast-Response Particle Size Spectrometer. *SAE 2011 World Congress & Exhibition, April 2011* (SAE, Detroit, MI, USA, 2011).

 felix.leach@eng.ox.ac.uk

The Effect of Fuel Volatility and Aromatic Content on GDI Particulate Emissions

Felix Leach[1], Richard Stone[1], Dave Richardson[2]

1. Department of Engineering Science, University of Oxford, Parks Rd, OXFORD, OX1 3PJ
2. Powertrain Research, Jaguar Land Rover, Whitley Engineering Centre, COVENTRY, CV3 4LF

Corresponding email: felix.leach@eng.ox.ac.uk

Engineering and Physical Sciences Research Council

1. Introduction and Aims

Gasoline Direct Injection (GDI) engines produce a greater number of particulate matter (PM) emissions than Port Fuel Injected (PFI) engines, but their greater specific output and lower CO_2 emissions have led to their widespread use. Concern over the health effects of PM emissions, and forthcoming European legislation to regulate them from gasoline powered vehicles has led to an increased interest in the study of PM emissions. A model, PM Index, has been developed by Aikawa et al. [1] correlating PM emissions with fuel composition (Vapour Pressure and Double Bond Equivalent) on a PFI engine . However, there was no independent control of these parameters. The **aim** of the current work was to validate this index with GDI engines having full independent control of fuel volatility and DBE (by use of aromatic components). PM emissions from a Spray Guided Direct Injection (SGDI) engine have been analysed using the **Cambustion DMS500** Accumulation Mode fit (which has been shown to replicate well measurements made with a legally compliant counter [2]) to determine the effect of Vapour Pressure and the DBE of the components of the fuel on PM emissions.

The PM Index has been modified to the PN index and takes the form:

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

DBE is calculated from the number of various types of atom in an organic molecule:

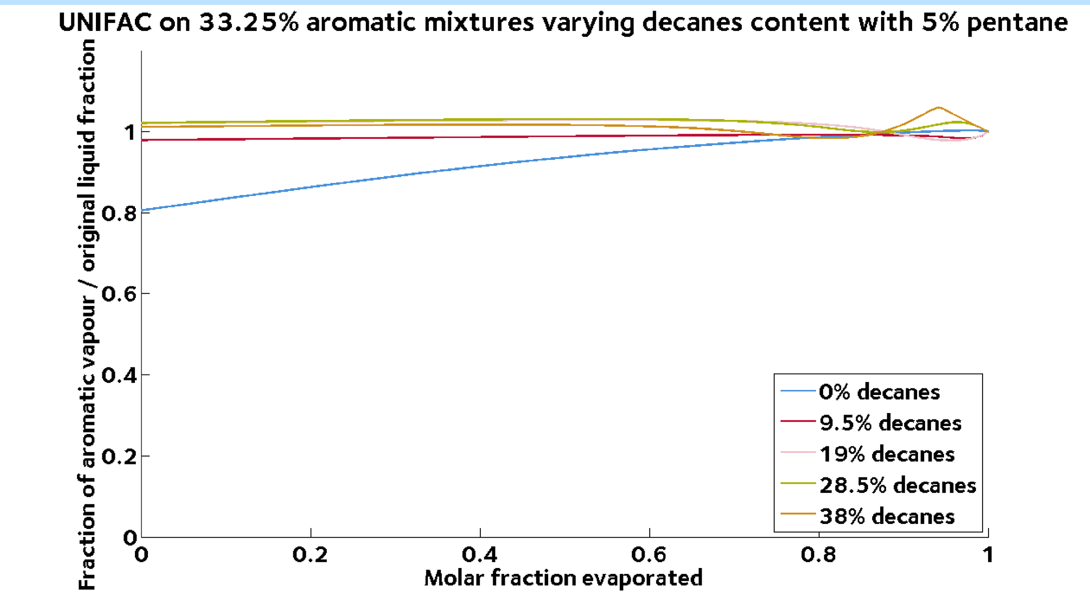
$$DBE = \frac{2C - H - N + 2}{2}$$

DVPE (Dry Vapour Pressure Equivalent) is the European Standard for measuring Vapour Pressure of fuels. V_i is the volume fraction of each component present in the fuel. This modification makes it easy to create an index from an industry standard fuel specification.

2. Evaporation Modelling

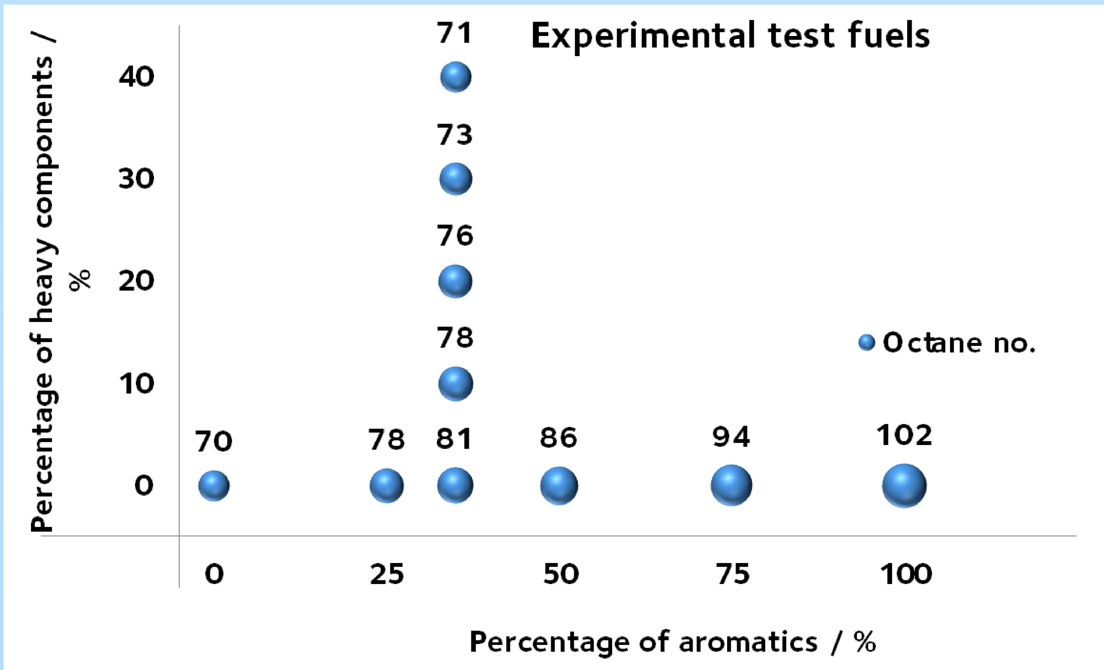
Model fuels are needed with low, medium, and high volatility components in which the aromatic and paraffin components will co-evaporate, so as to avoid segregation of the components. This was achieved using Raoult's Law with **UNIFAC** non-ideal mixing modifications. $y_i P = \gamma_i x_i P_{vpi}$ Where y_i / x_i are the component molar fractions of vapour/liquid γ_i is the UNIFAC activity coefficient P is the pressure of the system and P_{vp} Vapour Pressure of the component.

The results are presented such that a straight line at 1 on the ordinate gives an unsegregated mixture.

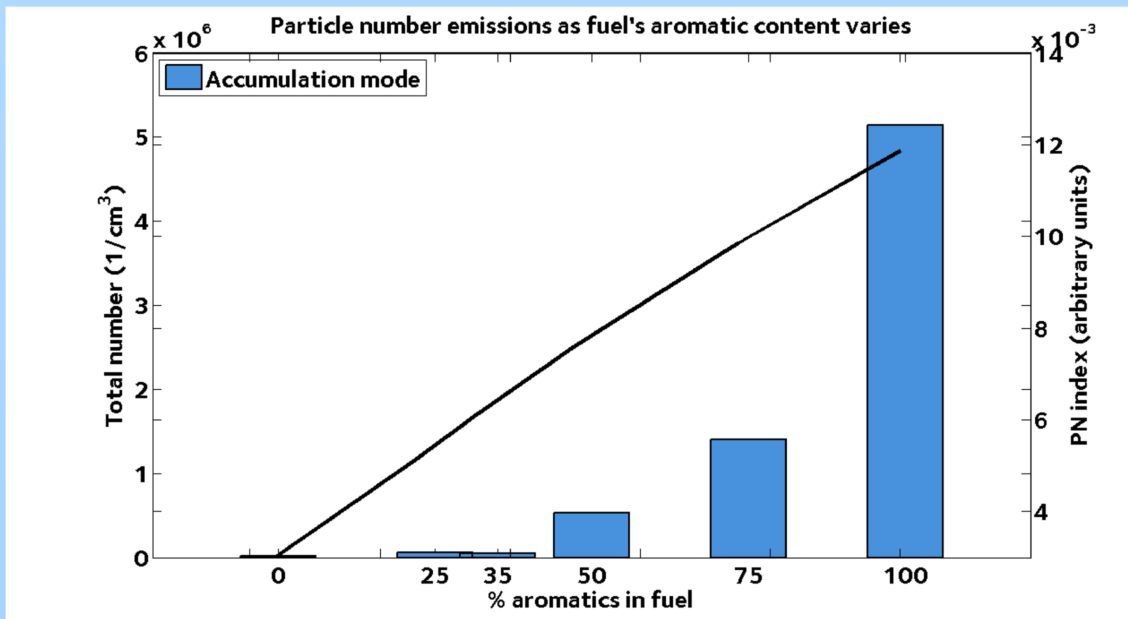


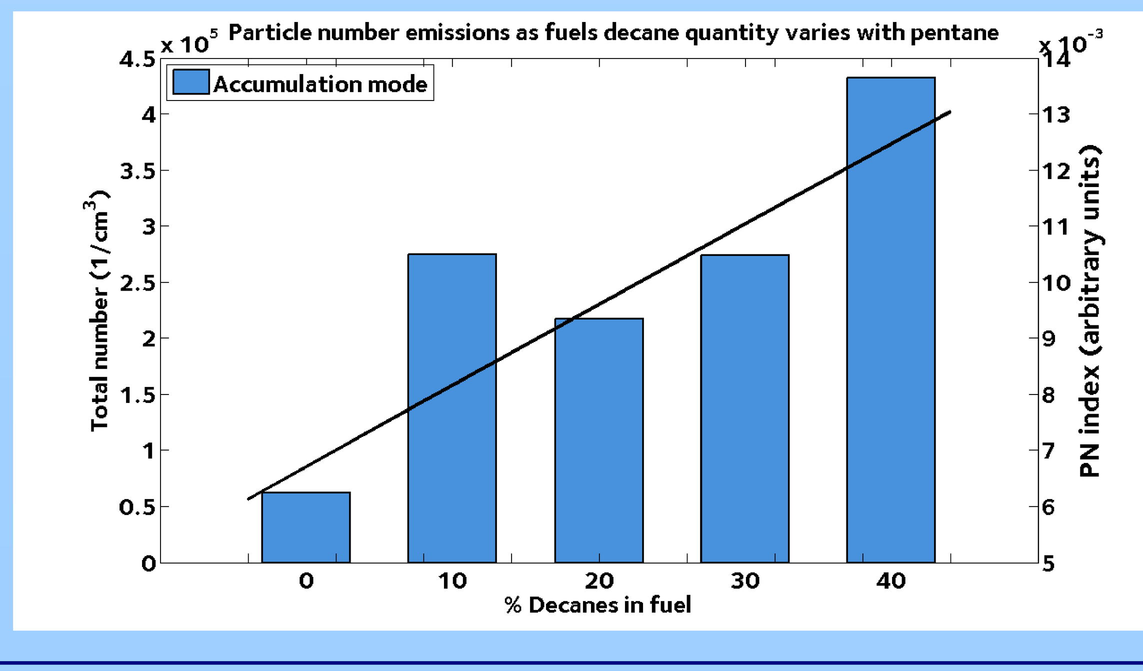
3a. Model Fuel Results

All results presented here are rich operation (λ=0.9) on a SGDI engine as this has been shown to be responsible for most of the PM emissions on the NEDC. It can be seen that full independent control over fuel volatility and aromatic content has been achieved.



The trends shown in the PN Index have been replicated experimentally, with the Particulate emissions increasing as the PN Index increases both with VP and DBE. The fuels tested all include 5%vv n-pentane, which is important for replicating the light end present in commercial gasoline.

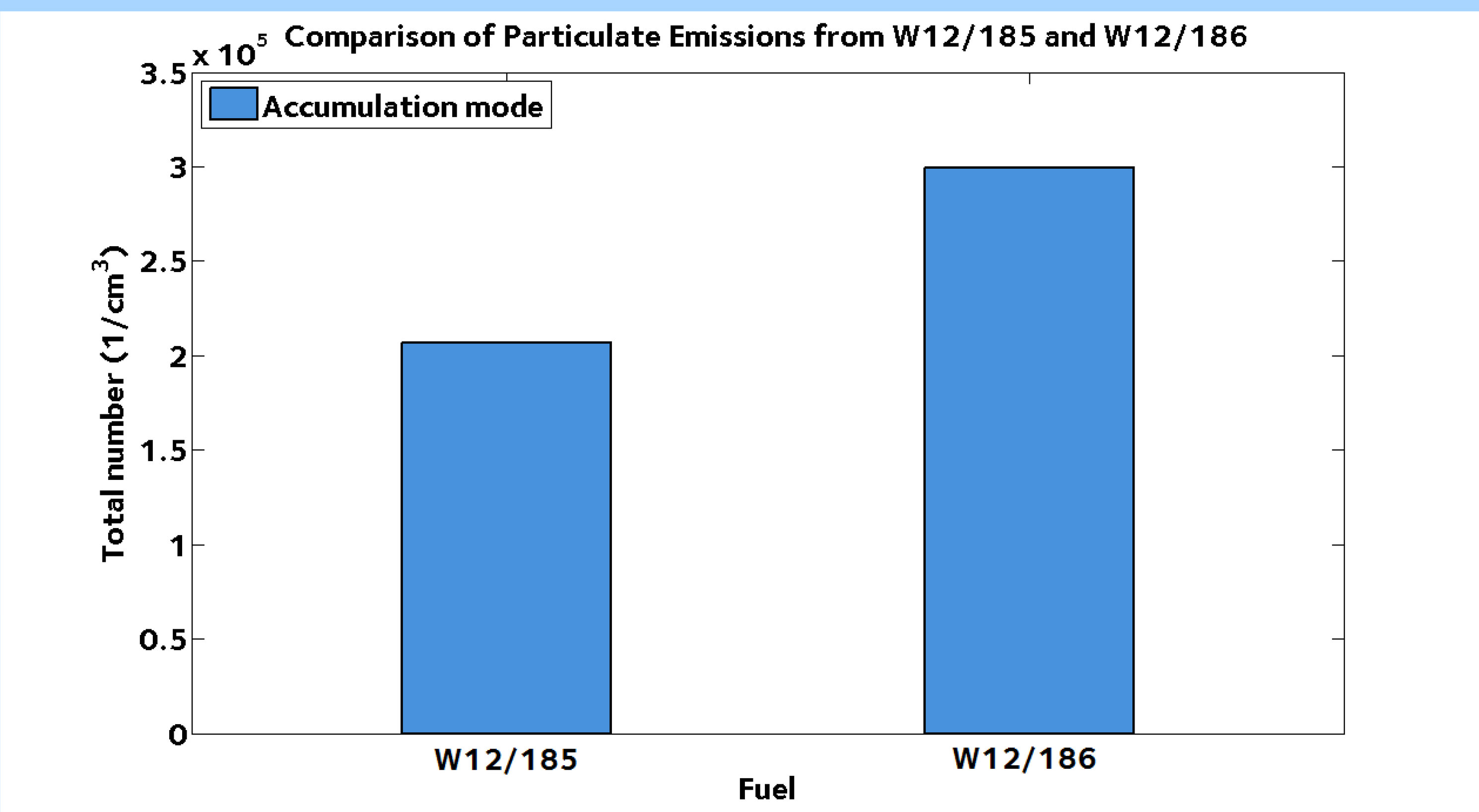




3b. EU5 Ref Fuel Results

Two fuels based on the EU5 reference fuel specification [3] but at the extremes of the PN Index were tested. Their specifications are shown in the table below and the results in the graph below. It can be seen that there is a 40% variation in Particulate Emissions from these fuels, and they follow the trends predicted in the PN Index.

	Reference Specification		Fuel Blends tested	
	EU5 (Min I)	EU5 (Max I)	W12/185 (Min I)	W12/186 (Max I)
Vapour Pressure (DVPE, kPa)	60.0	56.0	61.7	59.9
Double Bond Equivalent (DBE)	2.19	2.53	2.20	2.49
Final Boiling Point (FBP, ° C)	190	210	193.3	213.6
PN Index	2.74e-2	3.43e-2	2.67e-2	3.12e-2



4. Conclusions

Particulate emissions from a SGDI engine have been studied experimentally. Fuel blends have been devised that have independent control of the fuel volatility and aromatic content, and these have been used to validate a PN Index. It has been shown that to model fuel evaporation with mixtures of aromatics and paraffins, then Raoult's Law needs to be extended by use of the UNIFAC method. This model can be used to ensure co-evaporation of aromatic and paraffin components in a model fuel, to avoid stratification of the components. The **PN index has been validated in a SGDI combustion system using both model and reference fuels**. The PN Index has also been shown to be an important parameter for reference fuel specification, with **two fuels representing current specifications giving a 40% difference in PN emissions**. This has important implications for policy makers.

References

1. Aikawa, K., Sakurai, T. and Jetter, J.J. Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions. *SAE International Journal of Fuels and Lubricants*, 2010, **3**(2), 610-622.
2. **Braisher, M., Stone, C.R. and Price, P.** Particle Number Emissions from a Range of European Vehicles. *SAE Technical Paper*, 2010, **2010-01-0786**.
3. Commission Regulation 692/2008, OJ L 199 of 18.7.2008, p.88.