Evaluation of a PN Index on SGDI Engines at Steady State and over the NEDC

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

1. Department of Engineering Science, University of Oxford, Parks Rd, OXFORD, OX1 3PJ, UK
2. Powertrain Research, Jaguar Land Rover, Whitley Engineering Centre, COVENTRY, CV3 4LF, UK
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 $6\text{x}10^{11}$ #/km with a derogation to $6\text{x}10^{12}$ #/km for 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

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

DBE is a measure of how unsaturated a hydrocarbon is, and can be easily calculated from Equation 2.

Equation 2

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

A PN Index for a modern Spray Guided Direct Injection (SGDI) combustion system was developed by Leach et al (2013) [5]. The PN Index uses Vapour Pressure 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

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

The aim of this work is to extend the PN Index and compare it to the PM Index.

Steady state tests

Model fuels [5] were tested in a single-cylinder optical access Spray Guided Direct Injection (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 [6]. Particulate emissions were measured using a Cambustion DMS500 Differential Mobility Spectrometer (DMS) [7].

Results

Results for model fuels tested in the single cylinder optical access engine are shown in Figure 1. It can be seen that the PN emission follows the trend of the index. Unfortunately the variation in PN index for fuels with fixed DBE and varying volatility is small, and as such the effects are difficult to discern amid the normal variations in particles emitted (the error bars here represent one standard deviation).

The results shown in Figure 1 have been plotted again in Figure 2, this time comparing the PM Index and PN Index value of each of these fuels, the PN emission is shown as proportional to the area of the "bubbles" displayed (no error is plotted here for clarity, but the error can be seen on Figure 1). It can be clearly seen that the PN Index appears to provide a better indication of the PN emission compared to the PM Index, indeed two fuels with the same PN index, but very different PM indices give almost the same PN emission (within the error), and not the factor of 2 difference predicted by the PM Index.

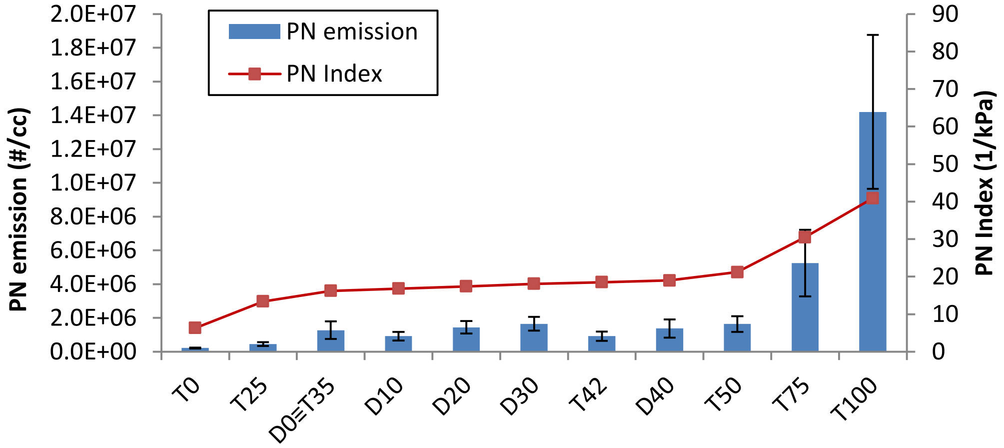


Figure 1: Accumulation mode Particulate Number emissions and PN Index variation for model fuels (independent control of DBE and VP)

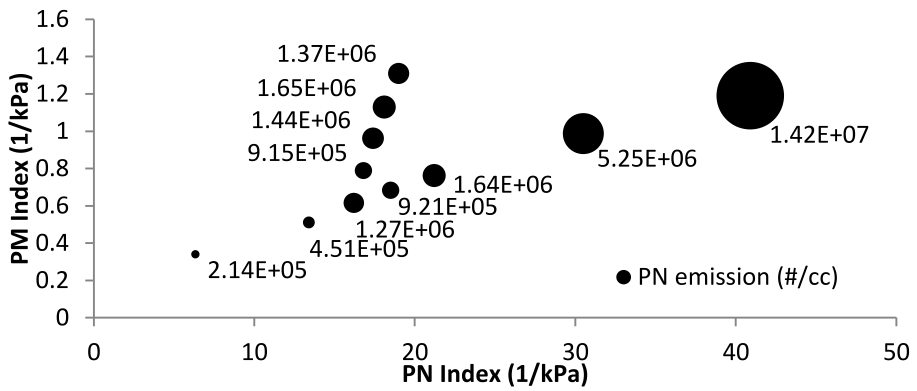


Figure 2: Comparison of PN Index and PM Index with the measured PN emission (represented by the 'bubble' size)

NEDC tests

Five commercially representative fuels with a spread of the PN Index were run on an AJ126 3.0L V6 supercharged SGDI engine, fitted with a three-way catalyst mounted on a transient dynamometer set to run a simulated cold-start New European Drive Cycle (NEDC) with stop-start enabled. The PN was measured with a Cambustion DMS500 and AVL Particle Counter [8] in parallel. Fuels were selected that had a low (or high) PN Index due to either a high (or low) Vapour Pressure or DBE, giving some form of independent control over these parameters. The composition of these fuels is shown in Table 1.

Table 1: Fuels tested over NEDC

	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 (EU5 reference fuel)	2.32	56.2	4.07
Fuel 4	2.28	47.8	4.77
Fuel 5 (TRIAS certification fuel)	2.95	57.3	5.14

Results

The results of the V6 drive cycle tests are shown in Figure 3. Each fuel was tested three times; with Fuel 3 being the first fuel tested (three times), and then repeated at the end a further three times. It can be seen that the repeat of Fuel 3 has given a highly repeatable result; reassuring that no drift effects have been present. It can be seen that there is some impact of the PN index, but much less than was predicted. Breaking the cycle down into its constituent parts however reveals more detail. Here, the first 100 s of the cycle is referred to as the "Cold start", 100-800 s as the "Urban", and 800-1180 s as "Extra Urban". Fuel 4 has the lowest VP of all the fuels, and so will take the longest to evaporate upon injection. This fuel also has the highest emission in the Extra Urban portion of the cycle, which requires the highest load from the engine, suggesting perhaps that some spray impingement is taking place – leading to higher PN emissions, while leaving emissions where full evaporation has taken place constant. Likewise the Urban portion of the cycle correlates better with the DBE of the fuel, Fuel 5 having the highest DBE, and the highest Urban emission. The Cold Start part of the cycle again seems to correlate best with VP, unsurprising perhaps given the dependence of this part of the cycle on fuel evaporation. The cold start, and use of stop start, may also cause deviation from the results observed on the single cylinder, optical access engine, which was run fully warm.

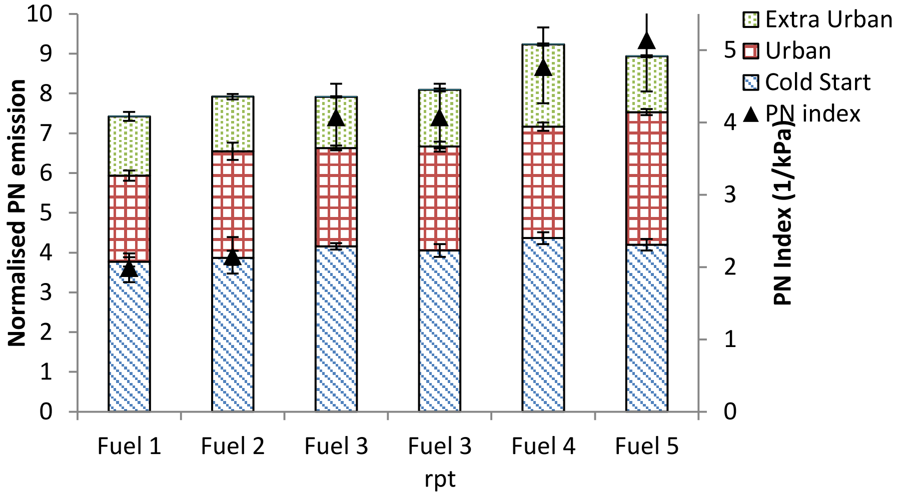


Figure 3: PN emissions over NEDC (APC results)

Conclusions

A range of fuels have been tested on two different Spray Guided Direct Injection gasoline engines. The PN results from a single cylinder, optical access engine validate previously observed results suggesting that the PN Index is a useful tool in predicting PN emissions. Drive cycle results have been more mixed, with other factors masking the effect of the PN Index. In addition it has been seen that different parameters in the PN Index have differing impacts on the PN emission from different parts of the NEDC.

Acknowledgements

This work was funded by the Engineering and Physical Sciences Research Council (EPSRC) and Jaguar Land Rover. The authors wish to thank Derek Fennell, David Hayden, Glyn Davies, and Mike Braisher of Jaguar Land Rover for their assistance in undertaking the Drive Cycle experiments.

References

1. Zhao, H., *Overview of Gasoline Direct Injection Engines*, in *Advanced direct injection combustion engine technologies and development: Gasoline and gas engines*. 2010, Woodhead Publishing Ltd.
2. Braisher, M., C.R. Stone, and P. Price, *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., T. Sakurai, and J.J. Jetter, *Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions.* SAE International Journal of Fuels and Lubricants, 2010. **3**(2): p. 610-622.
5. Leach, F., D. Richardson, and R. Stone, *The Influence of Fuel Properties on Particulate Number Emissions from a Direct Injection Spark Ignition Engine.* SAE 2013 World Congress & Exhibition, 2013. **2013-01-1558**.
6. Sandford, M., G. Page, and P. Crawford, *The All New AJV8*, in *SAE World Congress & Exhibition, April 2009*. 2009, SAE: Detroit, MI, USA.
7. Reavell, K., T. Hands, and N. Collings, *A Fast Response Particulate Spectrometer for Combustion Aerosols*, in *SAE Powertrain & Fluid Systems Conference & Exhibition, October 2002*. 2002, SAE: San Diego, CA, USA.
8. Giechaskiel, B., et al., *Calibration and accuracy of a particle number measurement system.* Measurement Science and Technology, 2010. **21**(4): p. 045102.

Evaluation of a PN Index on SGDI Engines at Steady State and over the NEDC

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

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

EPSRC
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 Particle Number (PN) emissions with fuel composition (Vapour Pressure and Double Bond Equivalent) on a PFI engine. The index was developed into the PN Index in [2] on a SGDI engine. The **aim** of the current work was to extend the PN Index and compare it to the PM Index.

$$\text{PM Index} = \sum_{i=1}^{n}\left[\frac{DBE_i + 1}{VP_i}\right] Wt_i$$

DBE (Double Bond Equivalent) is evaluated from: $DBE = \frac{2C - H - N + 2}{2}$
Aromatics (e.g. Toluene) have a *DBE* of 4.

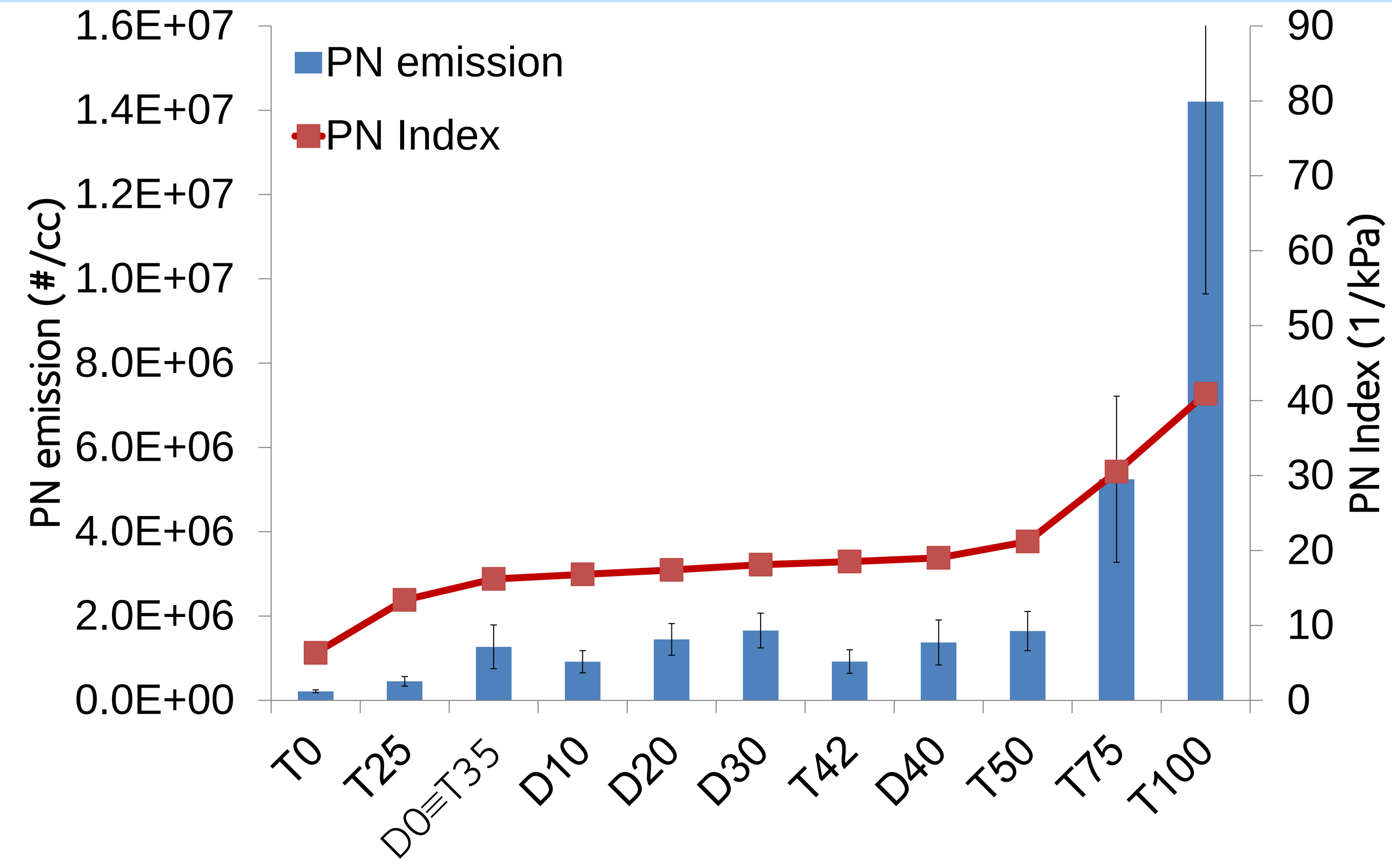
$$\text{PN Index} = \frac{\sum_{i=1}^{n}[DBE_i + 1]V_i}{DVPE\ (\text{kPa})}$$

VP_i is the Vapour Pressure of a component evaluated at 411K.
Wt_i is the mass fraction of each component present in the fuel.

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.

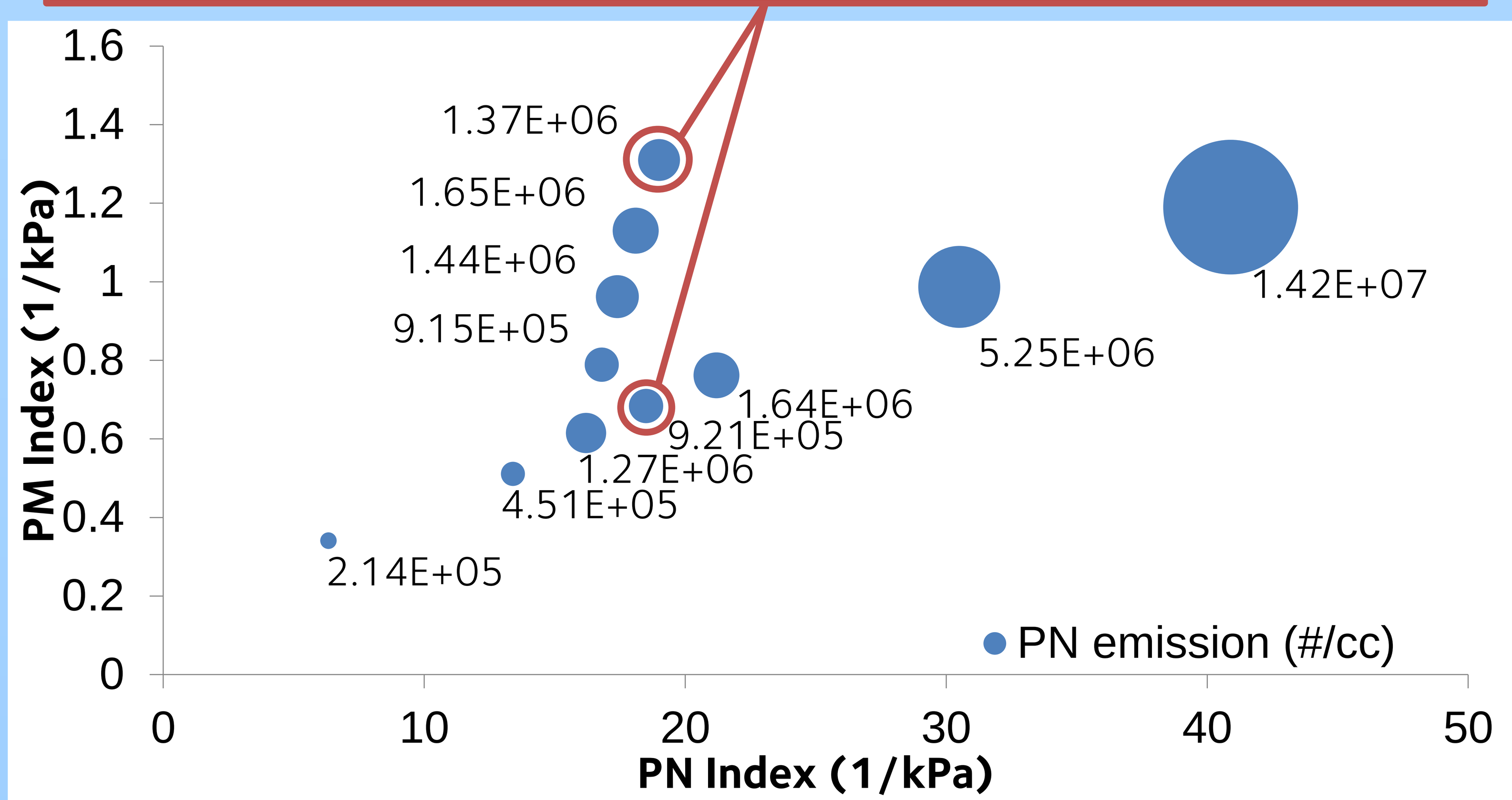
2. Steady State Results

Model fuels [2] were tested on a **single cylinder engine** at steady state (1.6 bar BMEP, 1500 rpm). The fuels were designed to give full independent control of *DBE* and *DVPE*. The particulate emission was measured with a **Cambustion DMS500**.



The PN emission follows the trend of the PN Index. Unfortunately the variation in PN Index for fuels with fixed *DBE* and varying *DVPE* is masked by the normal variations in particles emitted (error bars correspond to the standard deviation).

These two fuels have the same PN Index, but their PM Index differs by a factor of two. They give almost the same PN emission (within the error).



The PN Index can be seen to provide a better indication of the PN emission compared to the PM Index.

3. NEDC Results

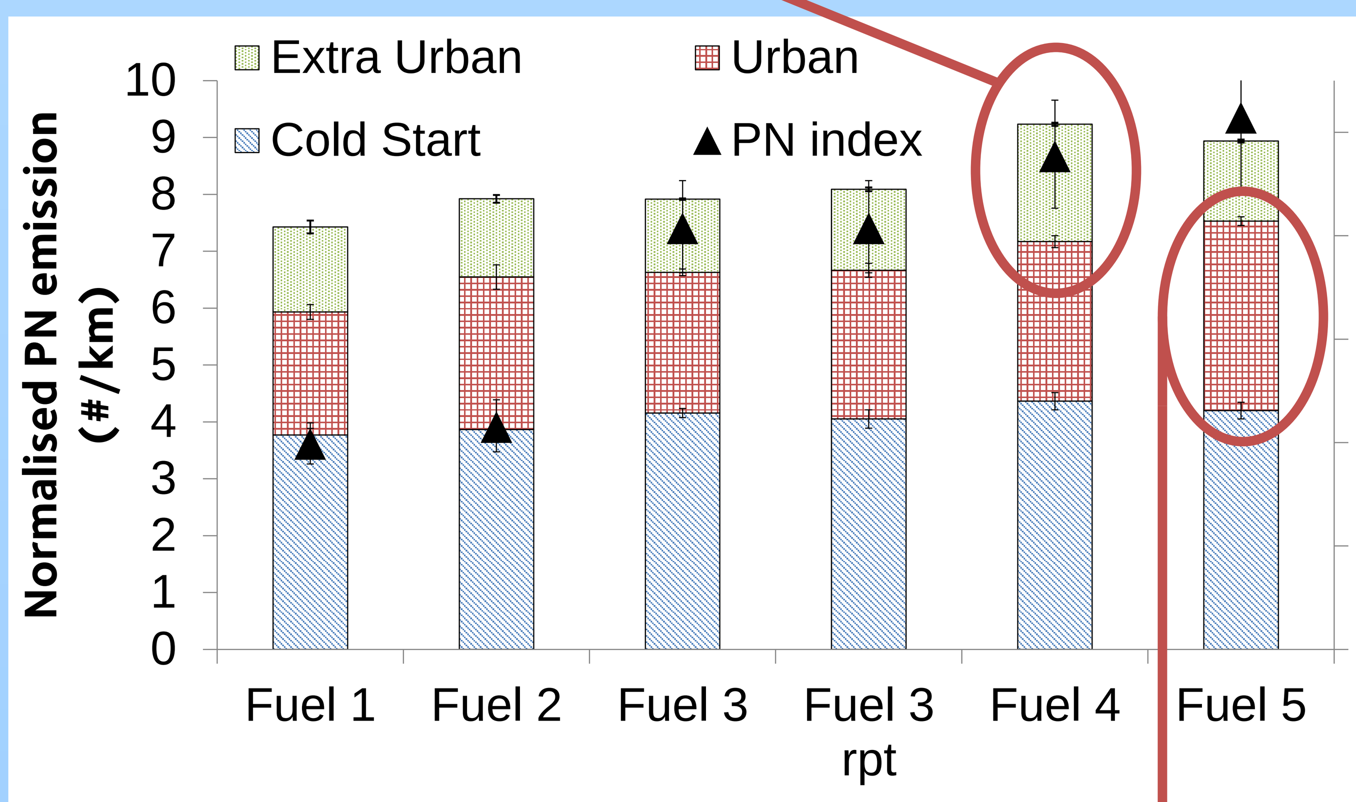
Five commercially representative fuels with a spread of the PN Index were run on an AJ126 3.0L **V6 supercharged engine**, fitted with a three-way catalyst mounted on a transient dynamometer set to run a simulated cold-start New European Drive Cycle (NEDC) with stop-start enabled. The PN was measured with a **Cambustion DMS500** and **AVL Particle Counter** in parallel.

Fuels were selected that had a low (or high) PN Index due to either a high (or low) Vapour Pressure or *DBE*, giving some form of independent control over these parameters.

	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 (EU5 reference fuel)	2.32	56.2	4.07
Fuel 4	2.28	47.8	4.77
Fuel 5 (TRIAS certification fuel)	2.95	57.3	5.14

The results follow the trend of the PN Index, but with less variation than was predicted. Looking at the constituent parts of the cycle reveals more detail.

The Extra Urban portion of the cycle is most affected by the *VP* of the fuel, here, Fuel 4 has the lowest *VP*, and highest PN emission.



The Urban portion of the cycle is most affected by the DBE of the fuel, here, Fuel 5 has the highest VP, and highest PN emission.

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

4. Conclusions

A range of fuels have been tested on two different Spray Guided Direct Injection gasoline engines. The PN results from a single cylinder, optical access engine validate previously observed results suggesting that the PN Index is a useful tool in predicting PN emissions, and is better for SGDI engines than the PM Index.

Drive cycle results have been more mixed, with other factors masking the effect of the PN Index. In addition it has been seen that different parameters in the PN Index have differing impacts on the PN emission from the various parts of the NEDC.

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. Leach, F., Richardson, D., and Stone, R. *The Influence of Fuel Properties on Particulate Number Emissions from a Direct Injection Spark Ignition Engine.* SAE 2013 World Congress & Exhibition. 2013-01-1558.