

# A review of the requirements for injection systems and the effects of fuel quality on particulate emissions from GDI engines

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## Abstract

Particulate emissions from Gasoline Direct Injection (GDI) engines have been an important topic of recent research interest due to their known environmental effects. This review paper will characterise the influence of different gasoline direct injection fuel systems on particle number (PN) emissions. The findings will be reviewed for engine and vehicle measurements with appropriate driving cycles (especially real driving cycles) to evaluate effects of the fuel injection systems on PN emissions. Recent technological developments alongside the trends of the influence of system pressure and nozzle design on injector tip wetting and deposits will be considered. Besides the engine and fuel system it is known that fuel composition will have an important effect on GDI engine PN emissions. The evaporation qualities of fuels have a substantial influence on mixture preparation, as does the composition of the fuel itself. Recently a number of studies have attempted to link fuel composition with PN emissions, developing a variety of indices including the PM index (Aikawa *et al.*) and the PN index (Leach *et al.*). An extensive literature search has been carried out and the PN index evaluated against these data. In addition the PM index and PN index are compared. The results of the review show that the Aikawa index should be applied when the fuel quality is known by lab reports, whereas the Leach index is relevant when only minimal information about a fuel is known, even the latter giving a relatively good prediction of PN emission trends from fuels in GDI engines.

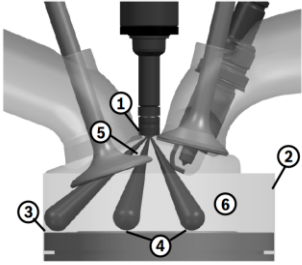
## Introduction

Vehicle electrification is widely seen as a path to low tailpipe emission and lower CO<sub>2</sub> mobility in the future. Many electrified vehicles will, however, still contain a combustion engine, as either mild hybrid engine vehicles or plug-in hybrid engine vehicles. Gasoline Direct Injection (GDI) engine technologies have proven themselves as a lower CO<sub>2</sub> path for gasoline engines, however such engines are known to emit more particle number (PN) emissions compared to their port fuel injected (PFI) counterparts [1].

Generally the most significant influence on PN emissions from gasoline engines is the air fuel ratio (AFR), where a rich mixture is often observed to give approximately an order of magnitude larger number of particles, compared to the stoichiometric case [1]. This is due to the reduction in soot oxidation that is possible with less air

present than would be sufficient to burn all of the fuel. Such effects are dependent on the local AFR in the cylinder, rather than the global AFR necessarily, which is relevant particularly to stratified operation modes [2].

A detailed understanding of the origin of particulate formation in the combustion chamber is of high importance. In Figure 1 the different locations for the production of PN and HC are depicted. The picture shows a combustion concept with central mounted injector. The sources in the engine for PN and HC would be the same for side-mounted concepts. The table in Figure 1 shows the weighting of PN and HC emissions based on current knowledge for multi-hole injectors in homogenous ("regular" rather than stratified) operation mode [3].



PN & HC raw emissions* homogeneous mode multi hole injectors	PN		HC (raw)	
	cold	warm	cold	warm
1 injector	+	+++	+	0
2 liner	++	+	++	+
3 fireland	+	0	+++	++
4 piston	+++	++	++	0
5 intake valves	++	+	+	0
6 gas phases	0	0	+	0

\*regular mode, not catalyst heating or engine start

Figure 1 Main sources for PN and HC raw emissions (0 = minor impact, +++ = highest impact) [3]

From Figure 1 it can be seen that the key issue in the formation of PN emissions is the wetting of components in the combustion chamber – mainly piston and the liner. Component wetting is such a key issue because liquid fuel films will form. These fuel films may not have time to evaporate before ignition occurs; this might be due to cold in-cylinder temperatures, or low volatility components in the fuel. If these liquid films have not evaporated at ignition, they will likely burn as so-called pool fires – heavily sooting diffusion flames – which will lead to high PN emissions. Although not the focus of this review, besides the reduction of PN emissions from the combustion process a further measure of PN control is the introduction of a gasoline particulate filter, which is expected to be state-of-the-art in the future for example in Europe [4].

The best way to reduce wall wetting (and hence PN emissions) is to reduce the chance of the spray impinging any combustion surfaces. This is best done by reducing the spray penetration. This may be achieved by combining a number of measures:

- Reduced spray penetration by increased spreading of spray plumes, thereby enhancing mixing of the spray with the cylinder charge (often this can be done by increasing the number of injector holes)
- Optimised spray direction including individual mass distribution
- Particle optimised engine calibration for whole operation map (cold and warm)
- Improved fuel metering, capability of short injection pulses and multi injection

Frottier *et al.* [5] achieved all of the above by increasing the number of injector holes and operating at high injection pressures. This resulted in each spray plume being shorter, decreasing the wall impingement probability. In addition they oriented the spray beams in respect to the moving parts and the charge motion to avoid impingement. However it should be noted that this should be done while maintaining sufficient charge motion for good combustion.

A number of other GDI engine operating parameters are known to be significant for PN emission formation. These include engine load, ignition timing, injection timing, inlet air temperature, exhaust back pressure, and EGR. These have all been studied extensively in the literature [6-12], including – recently – for highly boosted engines [13].

Overall, given the number of influences on PN emissions from GDI engines, system optimisation is essential - injection systems can only be assessed for their PN reduction potential in combination with the combustion concept and together these will show different optimisation criteria to those that might have been seen had they been considered individually [14].

## Fuel injection system requirements

Most of the parameters mentioned above – fuel-air ratio, engine load, ignition timing, injection timing, inlet air temperature, exhaust backpressure, and EGR are parameters that can be controlled either by vehicle calibration or are necessary drive parameters (load etc). Therefore to further reduce PN emissions from GDI engines a more detailed study of parameters that can be controlled and optimised would be helpful. In this work we will consider tip-wetting, injector fouling, and system pressure.

### Tip wetting

A common source of PN emissions from GDI combustion systems can be injector tip wetting. This occurs in particular at the end of injection, where liquid fuel can dribble out over the end of the fuel injector. This liquid fuel will then (like the wetting of other surfaces in the combustion chamber) not evaporate before ignition, and burn as a diffusion flame (pool fire) leading to a source of PN emissions during the combustion process. Pauer *et al.* [15] show that optimized injector tip geometry reduces injector tip-wetting leading to a decrease in PN emissions.

Dageförde *et al.* [16] reduced tip wetting by modifying the hole design and internal flow of the injector tip. Through these measures the lateral flow velocity in the spray holes is reduced which leads to less fuel flowing orthogonally (to the spray direction) out on the injector tip during the injection. This was verified by measurements with a high speed camera and a long distance microscope at a spray chamber. Although this might reduce the spray plume area, investigations on-engine confirmed the improvement: the new tip design led to a reduction of the PN emission by around 66 % during an injector ageing endurance test compared to the unimproved tip design.

Knorsch *et al.* [17] state that the PN behaviour of an injector partly depends on tip wetting, which can be influenced by momentum distribution within the spray nozzle. The paper shows that it is crucial to understand the limitation of three different measurement techniques, in particular for spray measurement close to the injector nozzle where tip wetting is likely to occur. Robust optical measurement techniques are used alongside CFD tools to make the right decisions and conclusions during the design process for platform development.

### Injector fouling – PN-drift

Many studies have found links between injector fouling (or deposit formation on injector tips and in-nozzle) and an increase in PN emissions [18, 19]. Wen *et al.* [20] report that injector deposits lead to increased PN emissions can be explained that three main sources:

1. longer spray penetration resulting in wall impingement;
2. deteriorated spray quality causing incomplete combustion and an increase in fuel leakage during injector closing;
3. fuel adsorbed by porous deposits leading to a diffusion flame after the combustion period.

Henkel *et al.* [21] concurred, finding that PN emissions from coked injectors increased by around two orders of magnitude. They attributed this to coking causing a narrower spray angle, leading to increased spray penetration and combustion surface impingement – hence higher PN emissions. They also reported that detergents in the fuel were effective in reducing these deposits, with a corresponding decrease in PN emissions. Miura *et al.* [22] also consider the use of detergents to remove deposits from GDI injectors. They also report vehicle results which show that EURO 6 targets can be met by GDI engines by further optimisation of relevant hardware and calibration without adding after treatment systems.

These effects often result in aged injectors showing increased PN emissions compared to clean or new injectors. This phenomenon is known as PN-drift. Figure 2 shows a significant increase of PN emission within a couple of hours for an engine endurance run at a stationary operating point (it should be noted that this operating point is designed to “age” the injector and is not representative of “normal” driving). There is a clear correlation between PN increase, the change to a coked injector tip and the appearance of soot thermal radiation close to the injector tip. This phenomenon will occur with a non-optimised system during normal engine operation in a vehicle and contributes significantly to total PN emissions. Thus the reduction of PN-drift is currently one major focus in the development of next generation injectors.

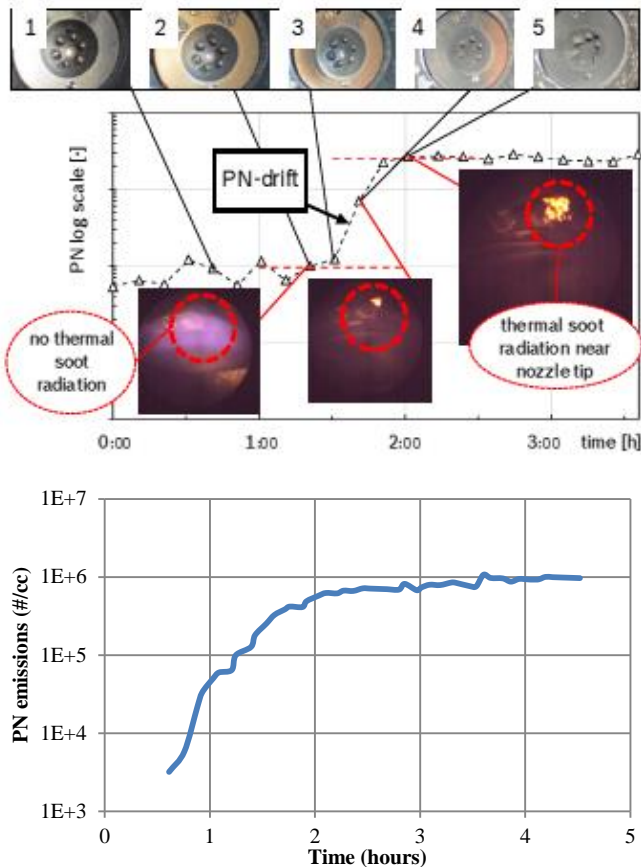


Figure 2: PN-drift examples from Kufferath [3] (upper) and Henkel [21] (lower)

Like most PN sources in GDI engines the PN-drift phenomenon is also driven by surface wetting. However, the mechanism of injector tip wetting is completely different to the wetting process of other parts in the combustion chamber due to spray impingement. Surfaces around injector spray holes are wetted at the end of injection. This wet surface is in effect an injector fuel wall film. Deposit build up is caused by a cracking process of non-evaporating high boiling components of the fuel that remain on the injector tip surface until next injection and hence combustion. These act like an initial layer for the further fast build-up of deposits, visible in the fast PN increase in Figure 2. After some time equilibrium between deposit build up and reduction will be reached. Once an injector tip is coked, the deposits act like a sponge leading to increased storage capacities and elongated evaporation times of this wall film leading to PN emissions.

The phenomenon of a PN-drift can also be observed in cases where other parts of the combustion chamber are consecutively wetted due to spray impingement. This can happen e.g. at intake valves, combustion chamber roof and on the piston surface. With an optimised nozzle tip design PN-drift due to deposits build up on the injector tip (the sponge effect) can normally be avoided (in particular, an increase in system pressure, discussed in the next section, can help with this) [3]. Combustion surface temperatures are also important for such fuel film evaporation – with higher temperatures promoting evaporation. This becomes significant particularly during cold start when the engine is at a low temperature. This low engine surface

temperatures result in the presence of significant wall films and hence the high PN emissions associated with cold start.

## System pressure

Fuel injection system pressure is recognised as a key parameter in reducing PN emissions from GDI engines. The system pressure of GDI injection systems in the market is currently around 20 MPa. The next generation will feature pressures up to 35 MPa [23]. The main reason to increase the system pressure is to reduce PN emissions. This reduction in PN emissions can be explained with an increased air entrainment because of higher fuel velocities with increased system pressure. In addition greater system pressure can also lead to smaller fuel droplet sizes upon injection. Both of these effects lead to greater mixture homogeneity due to the greater fuel/air mixing and improved evaporation (smaller droplets will evaporate faster than larger ones all other things being equal) and hence reduced PN emissions.

Frottier *et al.* [5] showed the effect of fuel rail pressure increase, they demonstrated a clear improvement in atomization, which led to clearly reduced PN emissions in the highway driving part of the NEDC. Kramer *et al.* [24] found that reduced spray penetration is possible by using shorter injection durations, at a higher fuel pressure. Sabathil *et al.* [25] also found a close link between system pressure and PN, with low fuel pressure leading to increased PN emissions due to worse mixture preparation.

System pressure can also help to reduce tip wetting (and hence PN emissions as discussed above). Piock *et al.* [26] illustrated the influence of the fuel system pressure increase on two mechanisms of particulate emissions reduction: (a) an improvement of mixture homogeneity due to the enhancement of spray atomization and mixture preparation, and (b) reduction of the injector tip diffusion flame (often the result of tip wetting). Dageförde *et al.* [16] showed that an increase in injection pressure not only improves spray break up, but can also improve PN emissions through reduced tip wetting. Both papers report that this is mainly due to the reduced lateral flow out of the injector nozzle at higher pressures.

An increased system pressure also works as a robustness measure to minimise PN-drift and further helps to reduce PN emissions especially in the early phase of a test cycle by reducing fuel wall films inside the combustion chamber. Xu *et al.* [27] showed that an increase in system pressure could reduce PN emissions from a fouled injector by approximately 70 %. Figure 3 shows the effect of system pressure on tip wetting at the end of injection, clearly showing a positive impact. By using LIF to measure the fuel mass of the wall film the right hand graph was derived. There is still a significant reduction from 10 to 20 MPa indicating a possible further advantage for pressures higher than 20 MPa.

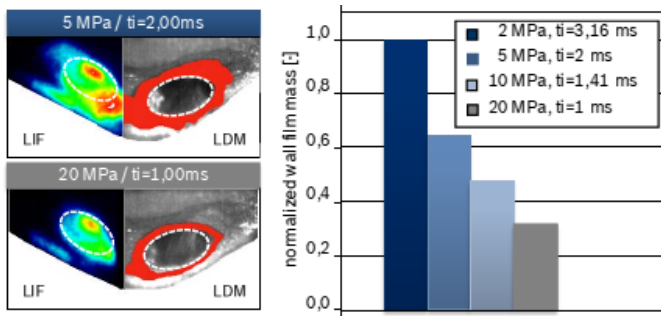


Figure 3: Impact of system pressure on injector tip wetting

Kazour *et al.* [28] show that increased system pressure can clean injector nozzles – leading to lower PN emissions. Jiang *et al.* [18] also report a similar effect – with a tripling of system pressure leading to a decrease in PN emissions of a factor of three with a fouled injector. Kufferath *et al.* [3] show that there is a clear positive effect of increased system pressure in terms of robustness and overall PN emissions. They also show that the gap between a clean and coked injector is significantly reduced with 35 MPa. A summary of these three studies showing the reduction in PN emissions from coked injectors with increased system pressure is shown in Figure 4 (although of course these data are taken from different engines with different injection systems so absolute comparisons between them at a given pressure should not be made).

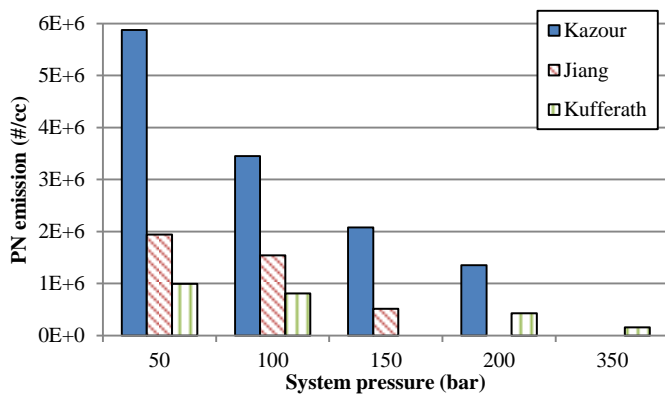


Figure 4: Impact of system pressure on PN emissions with coked injectors from different engines and combustion systems (data from Kazour [28], Jiang [18], and Kufferath [3]).

Overall increased system pressure causes increased air entrainment leading to improved fuel-air mixing and hence lowers PN emissions. Lower droplet sizes (caused by increased system pressure) also enhances mixture preparation and evaporation resulting in the droplets better following the charge motion, reducing wall wetting, and reducing PN emissions.

Care must be taken with increased system pressure to ensure an optimised fuel injection strategy and fuel injector, as such optimisation, an increase in system pressure can lead to increased spray penetration lengths, and possibly fuel impingement on the piston or walls, and hence an unexpected increase in PN emissions [13].

## RDE effects on PN emissions

RDE (real driving emissions) would be expected to increase PN emissions measured from GDI vehicles relative to other test cycles such as NEDC or WLTP. This increase will be due to the harsher accelerations likely to be experienced in RDE, as well as the more variable atmospheric conditions that would be seen. In particular the most challenging RDE conditions from a PN emissions perspective would be a cold start (in say sub-zero temperatures) followed by some hard accelerations. This would result in a large quantity of fuel being injected into a cold engine, and would likely lead to significantly reduced fuel evaporation, hence mixture preparation, and hence higher PN emissions.

Ogata *et al.* [29] show an increase in PN emissions from a GDI vehicle not equipped with a Gasoline Particulate Filter (GPF) of approximately a factor of two over an RDE cycle relative to an NEDC. Interestingly, Ogata *et al.* show a similar increase from a vehicle that is equipped with a GPF. Pauer *et al.* [15] show that approximately 80 % lower PN emissions can be achieved under RDE conditions through injector optimisation and calibration, in particular by reducing injector tip wetting.

## Effect of fuel quality

### Fuel influences on PN emissions

It is not surprising that different fuels have different levels of particulate matter emissions, and it is almost inevitable that even a single engine will not always be tested with the same fuel. Accounting for the influence of different fuel properties on PM emissions is very important in order to be able to compare tests, as well as to work towards an overall reduction in particulate emissions.

It has been recognised that the coalescence during combustion of PAHs is responsible for the initiation of soot [30, 31]. Therefore it is expected that a high level of aromatic compounds in the combustion fuel would lead to a higher level of PM emissions, and indeed the literature supports this both for gasoline and Diesel engines [32, 33]. Hydrocarbons present in fuel that are close to benzene rings are therefore expected to have an increased effect on PM emissions, a summary of the likely dependence on PM emissions [34] from common components is shown in Table 1. A more detailed discussion of sooting potentials of common hydrocarbons is outside the scope of this work, but is included for example in [35].

Table 1: PN forming potential of common HCs in fuels (0 = minor impact, +++ = highest impact)

Common name	IUPAC name	PN forming potential
Paraffins	Alkanes	0
Olefins	Alkenes	+
Napthenes	Cycloalkanes	+
Aromatics	Arenes	+++

Given the importance of mixture preparation on particulate emissions already seen, in particular the dependence of mixture preparation (and hence PN emissions) on temperature, it is to be expected that some measure of the evaporative performance of the fuel will play an important role in PN emissions formation. Vapour pressure is a common measure of a fuel's evaporative performance. A high vapour pressure means that a fuel is more likely to evaporate at a given temperature, and hence should be a better prepared mixture and give lower particulate emissions. Vapour pressure of gasoline is often presented as Reid vapour pressure (RVP) or dry vapour pressure equivalent (DVPE).

Vapour pressure is not the only measure of evaporative performance of a fuel, and can be skewed by the presence of components at the extremes, e.g. a large amount of 'light-end' components such as butanes. Such presence may give a fuel with a high vapour pressure, but some components with a very high boiling point may also be present that are being masked by the presence of large numbers of low boiling point components. This can be taken into account by looking at the distillation curve of the fuel, and values such as the final boiling point (FBP), E150 (proportion of the fuel evaporated at 150 °C), or the T90 (the temperature at which 90 % by volume of the fuel has evaporated) can be used as an alternative measure of the fuels evaporative performance. T90 may be preferable so that the presence of a small amount of very high boiling point components does not skew results. A high T90 means that a fuel is less likely to have evaporated at a given temperature, and hence should be a less well prepared mixture and give higher particulate emissions.

Recent work suggests that "heavy" aromatic components - say C9 and above - lead to an increase in PN emissions proportionally significantly more than C8 and lower aromatics – in particular this is thought to be due to their prominence in the formation of injector tip deposits and hence increased PN emissions [4, 36, 37].

In general, however, these fuel effects are often minor compared to the impact of other engine parameters on PN emissions, such as air-fuel ratio, or combustion chamber surface wetting [13, 38]. This may result in these fuel effects being masked by other more significant effects. Prakash *et al.* demonstrated clearly that injection technology can have a much more significant effect than fuel composition [36].

## Particulates indices

Aikawa *et al* [39] conducted tests with a PFI engine and developed a model linking fuel composition with PM emissions. Their model – the PM index - links PM emissions with the vapour pressure (VP) and DBE of each individual component in the fuel weighted by mass fraction ( $W_i$ ). Their PM index is shown below:

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

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

DBE is a measure of how unsaturated a particular hydrocarbon is, and is calculated from the chemical formula of a particular hydrocarbon where  $C$  and  $H$  are the number of carbon and hydrogen atoms respectively.

In their work, Aikawa *et al* [50] evaluate the vapour pressure of each component at 443 K by means of an empirical correlation with boiling point. 443 K was chosen as it gave the best correlation between particulate emissions and their PM index. A very strong correlation ( $R^2 = 0.95$ ) was found between the PM index and measured particulate emissions, this can be seen in Figure 5.

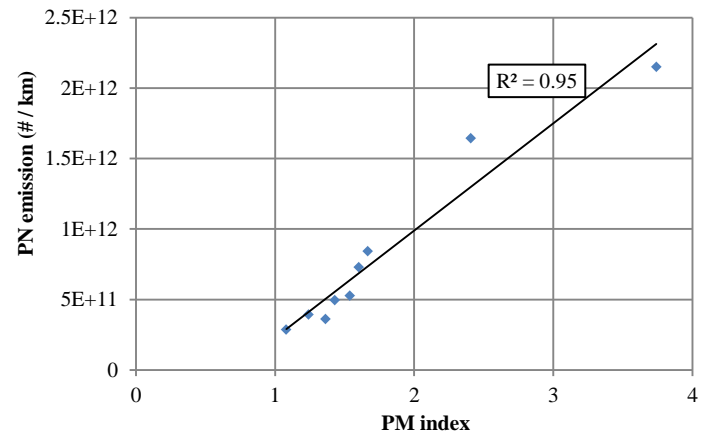


Figure 5: Relationship between PN (# / km) and PM index over NEDC (data from [39])

The Aikawa *et al.* PM index [39, 40] and subsequent developments of indices such as the Particulate Evaluation Index (PEI) [41] and the Menger/Wittmann (MW) index [42] have shown very good correlations between PN emissions and their respective indices – indeed mostly superior correlations to the PN index. However all of these indices require tests which are not typically performed and often expensive and are therefore best suited to laboratories or other specialist uses. The PN index requires only two tests ASTM D1319 [43] and DVPE [44] both of which are typically undertaken for test gasolines used in R&D and so is potentially more widely usable as a comparator between fuels.

The PN index (with units of  $\text{kPa}^{-1}$ ) is a simplified metric to evaluate fuels' propensity to emit particulate emissions from GDI engines. It was developed by Leach *et al.* [38, 45] as a modification of the PM index in order that it might be applied without having to conduct expensive detailed hydrocarbon analyses (DHA) which are not typically undertaken for gasolines.

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

In the PN index the DBE is calculated for each subset of components in the gasoline (typically split out in the industry standard ASTM D1319 [43] test into aromatics ( $DBE = 4$ ), olefins ( $DBE = 1$ ), and saturates ( $DBE = 0$ )) by volume ( $V_i$ ) – as is industry standard. Dry Vapour Pressure Equivalent (DVPE) with units of kPa is the European standard for vapour pressure measurement of gasolines [44].

## PN index as a predictor of PN emissions

Given that one of the aims of the PN index in its development was to provide a simple index characterizing the fuel effects on PN emissions from GDI engines this paper presents the results of a



literature survey presenting the PN index against the PN emissions for all data found for which the PN index could be calculated.

An extensive survey of published works has been undertaken. The PN index has only been validated on GDI engines (and indeed these are the engine type for which PN emissions is of the greatest interest) so in evaluating the literature all other engine types were excluded. The PN index has only been validated as an indication of the particulate number emissions from fuels, so papers presenting results solely in terms of particulate mass were excluded. Likewise only data which were taken from legislatively compliant tests (eg EU PMP testing procedure [46]) or equivalent were included.

The PN index has only been validated with fuels containing low levels of oxygenates. Given recent work showing that the effect of levels of ethanol as low as E10 on PN emissions can be mixed depending on how the blending took place (splash vs matched blends) [36, 47] fuels with levels of ethanol higher than E5 were excluded. In addition fuels containing any oxygenate other than ethanol were excluded.

A number of published works have used some form of model or single component fuels. PN emissions can be very sensitive to exactly how these fuels were constructed [45, 48]. In addition such fuels frequently have vapour pressures significantly outside the market range [49] so all such fuels were excluded.

From the literature survey some 66 relevant published works were identified, 34 were excluded for being out of scope (e.g. being from a PFI engine or containing data solely from oxygenated fuels) leaving 32 which were directly relevant. Of these 23 contained data from which the PN index could be calculated. In this work, data from the following publications is included: [4, 36-38, 40, 42, 45, 50-65]. That over 70 % of the relevant papers identified had sufficient data to calculate the PN index demonstrates the utility of the index.

Figure 6 shows the PN index distribution of the fuels evaluated in this work. Here the PN index of all of the fuels included in this work has been calculated, and put into 'bins' of 0.5 PN index. Assuming a normal distribution of the data, the distribution is centred on the 3.5-4 PN index 'bin'. However, it can be seen in Figure 6 that the PN index of the fuels is not quite normally distributed but slightly skew, with the mode occurring in the 4-4.5 PN index 'bin'.

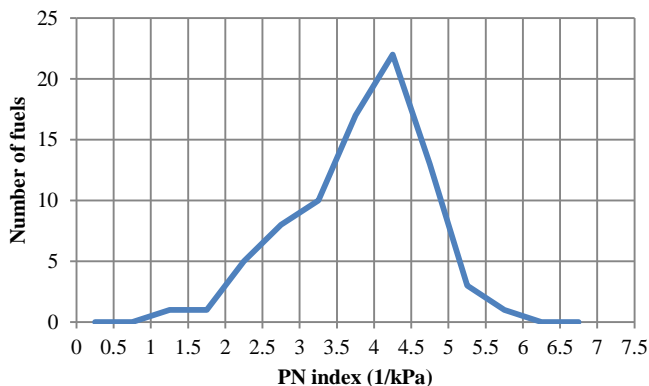


Figure 6: PN index distribution of all the fuels in this paper. A slight skew towards higher PN indices is observed compared to a normal distribution of the same data.

Aikawa *et al.* in their survey of global fuels [39] showed a roughly normal distribution of PM indices, centred on a value of approximately 1.6, shown in Figure 7 with a slight skew towards lower values – this is similar to the spread of PN indices shown in Figure 6.

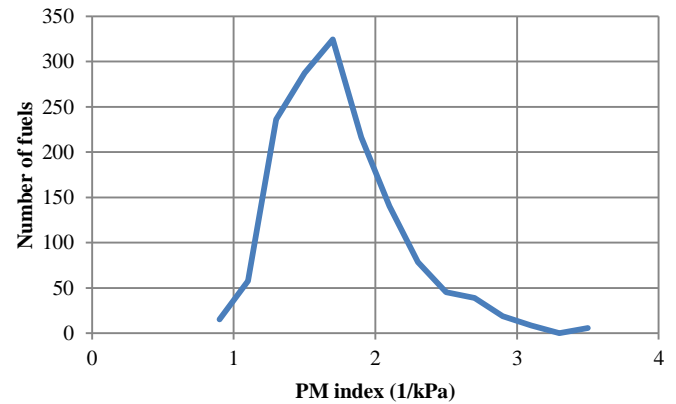


Figure 7: Range of PM indexes of a selection of commercially available fuels worldwide [39]. A slight skew towards lower PM indices is observed compared to a normal distribution of the same data.

It was important to ensure that the PN emissions data evaluated in this work was consistent with the spread of PN indices of fuels found in the literature. If this were not the case then an excessive number of data points from high or low PN index fuels might skew the results. The comparison between the PN indices of the fuels evaluated, and the PN emission data used is shown in Figure 8. It can be seen that the PN emission data used is a fair reflection of the PN indices of the fuels that were evaluated in this study.

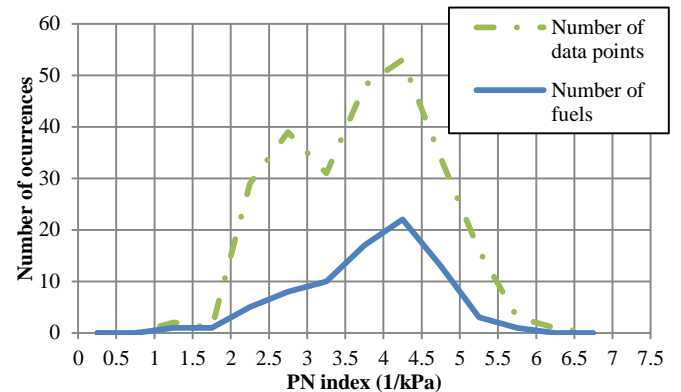


Figure 8: Comparison of PN indices of fuels and PN emission data evaluated in this work.

61 separate data series were identified in the literature survey. An overall comparison between the PN index and all of the PN emissions considered in the literature is shown in Figure 9. At once it can be seen that there is no significant information to be gained from this approach, because, as discussed in the previous section, fuel effects alone do not dominate, and so the spread of data and lack of correlation with the PN index is caused by other factors. The biggest factors include the reported unit of measurement (e.g. is the data from

a drive cycle (and hence #/km or mile) or steady state testing (and hence #/cc or kg of fuel)).

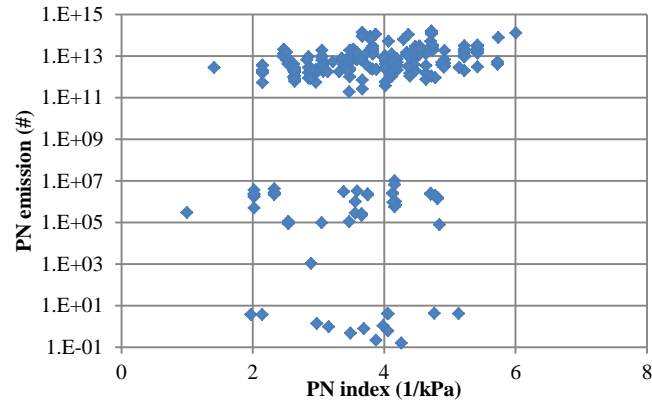


Figure 9: Comparison of PN emissions and PN index for all fuels.

greater than 0.75 (correlation coefficients of 1 from data series which only have two data points are excluded).

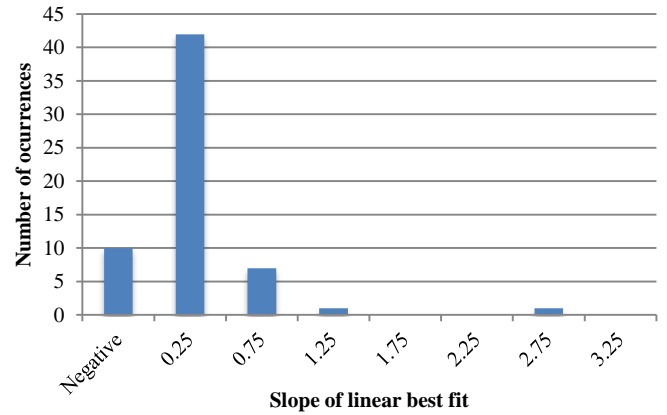


Figure 11: Slopes of trendlines for PN index vs PN emissions for all data

An attempt to consolidate all of the data can be seen in Figure 10, which shows the normalised PN index and normalised PN emission for almost all of the data points. To avoid cases where PN indices were very close together skewing the results (i.e. the PN index is sufficiently close that the measurement value might be subject to natural variation) data with PN indices within 5% have been excluded, as the normalization process is quite binary. The results show that although the correlation is not particularly strong, when considering 61 separate tests from 23 published works, there is a clear positive correlation between the PN index and PN emissions – a significant result given the relatively sparse information that is input into the PN index.

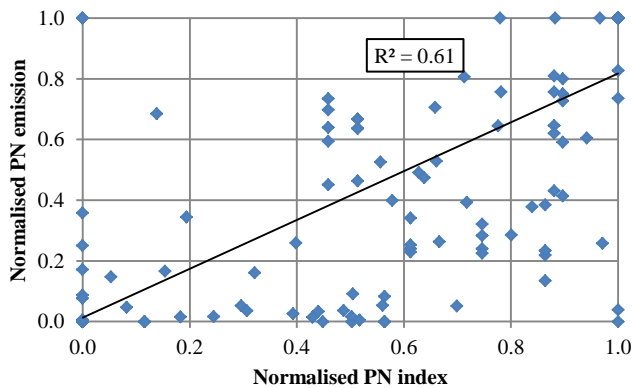


Figure 10: Normalised PN index vs normalised PN emission (data from the same publication with PN indices within 5% have been excluded). A strong positive correlation is seen.

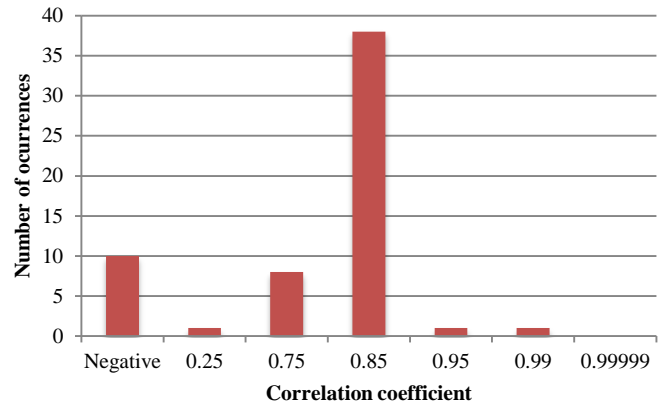


Figure 12: Correlation coefficients for PN index vs PN emissions for all data

On examining those data series which were not correctly predicted by the PN index, it was noted that several of those were cases where the PN indices of the two fuels tested were very close together (for example in [52] the two fuels tested have PN indices of 2.48 and 2.51 – and those fuels were tested multiple times). Where fuels have a very close PN index, it would be hoped that their PN emissions would be close together, and indeed they are; however when looking at whether a best-fit slope is positive or not, this is effectively a binary measure so many of these negative results occur because of noise or measurement error. It was therefore decided to exclude data points whose PN indices were within 5% of each other. These results are shown in Figure 13 and Figure 14. Now, the PN index correctly predicts the PN emissions trends from all but 3 fuels – nearly 95 %, the correlation coefficients have improved slightly as well.

Figure 11 and Figure 12 show the slope of linear best fit and correlation coefficients respectively for the 61 data series (best fits such as are plotted in the upper parts of Figures 16-18). A positive slope indicates that the PN index follows the trend of the PN emissions, the correlation coefficient shows how good the fit is. It can be seen that the trends of the PN emissions from all but 10 data series are correctly predicted by the PN index – and of those which are correctly predicted, all but one has a correlation coefficient

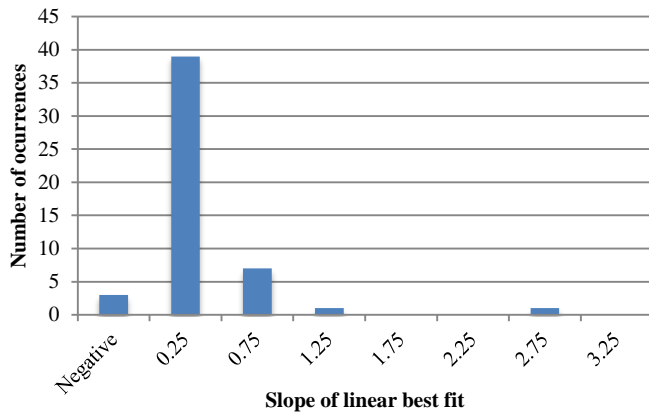


Figure 13: Slopes of trendlines for PN index vs PN emissions when fuels with PN indices with 5 % are excluded.

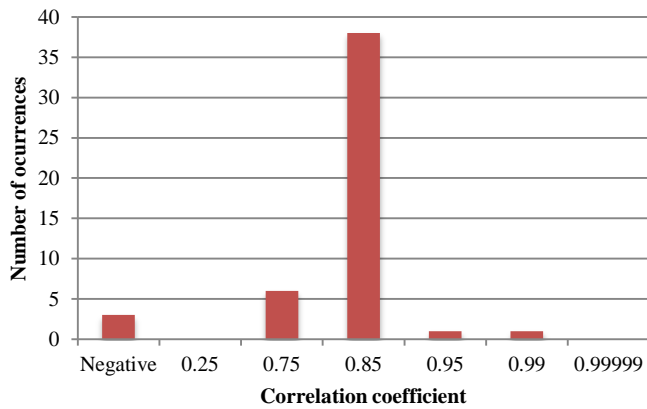


Figure 14: Correlation coefficients for PN index vs PN emissions when fuels with PN indices with 5 % are excluded.

It is worth at this point briefly observing that these positive results might be subject to some confirmation bias from published data. The authors have no direct reason to suspect this, however PN emissions are naturally variable, and the published literature in general shows some positive correlation between an author's preferred metric and the PN emissions. Negative results in the literature are notable by their almost complete absence.

### Comparison between PM index and PN index

Where data has been available (specifically in [4, 37, 40, 52, 54, 56]) a comparison can be made between the PM index and the PN index. Data were available for 28 different fuels; in general it would be expected that, for a given fuel, the value of the PM index would be lower than the PN index as a fuel's DVPE (which is calculated at 100 °F or 310.95 K), used for the PN index, will be higher than the weighted sum of the VPs at 443 K, used for the PM index due to the lower evaluation temperature a more detailed discussion of this difference is included in [34]. A comparison between the PM and PN indices for these 28 fuels can be seen in Figure 15.

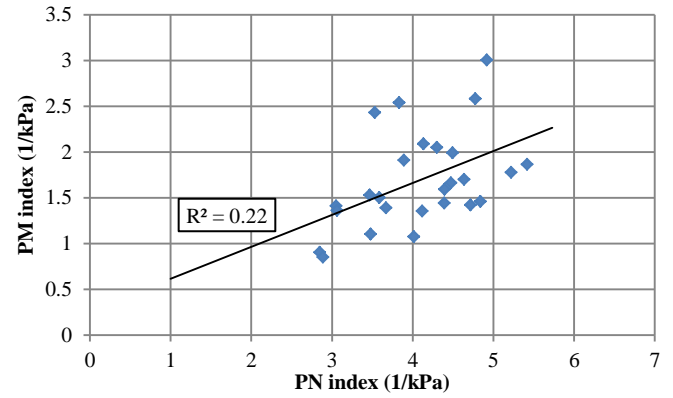


Figure 15: PN and PM index comparison it can be seen that there is a general positive, if weak, correlation

Comparing the PM and PN indices in Figure 15, it is clear that there is a positive correlation between the two indices but it is not particularly strong. Given the difference in calculation methods between the two indices, this is to be expected, but the positive trend is reassuring. As expected the magnitude of the PN index is higher than that of the PM index.

It is of great interest to understand which of the two indices might predict PN emissions from GDI engines better. Given the more rigorous calculation method, and greater detail of information that is input to the PM index, it would be expected that this index would provide a superior correlation, and this is what the literature suggests, however this paper presents this comparison for the first time.

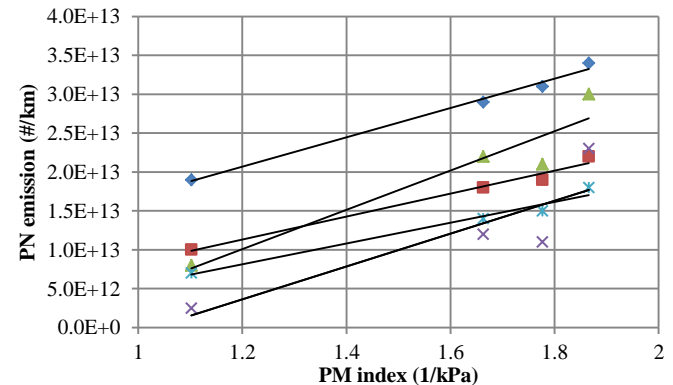
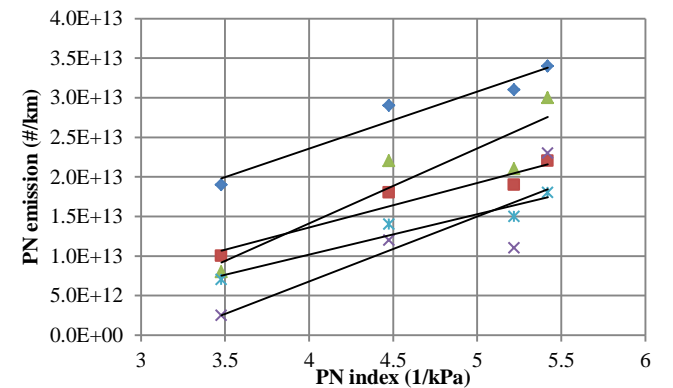


Figure 16: PN emissions vs PN index (upper) and PM index (upper) for data from [54].



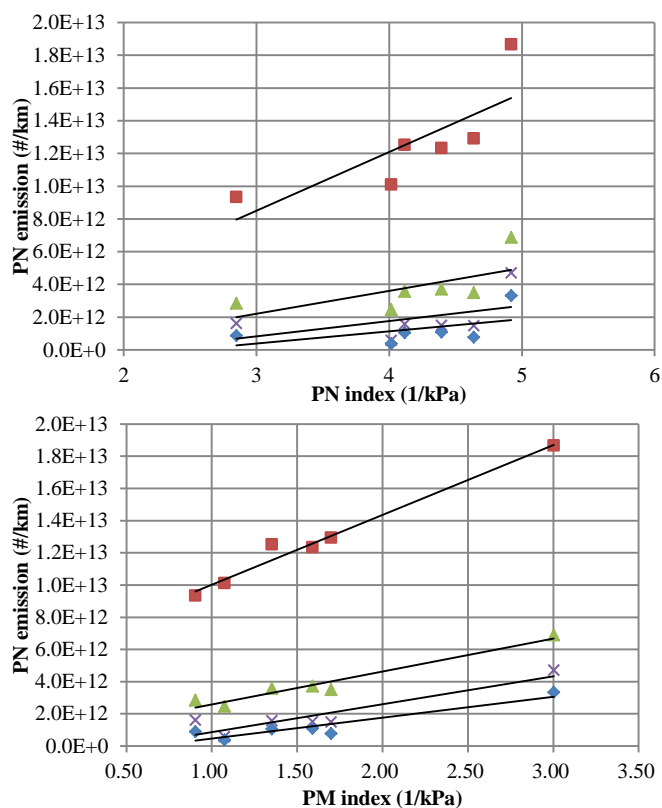


Figure 17: PN emissions vs PN index (upper) and PM index (upper) for data from [40].

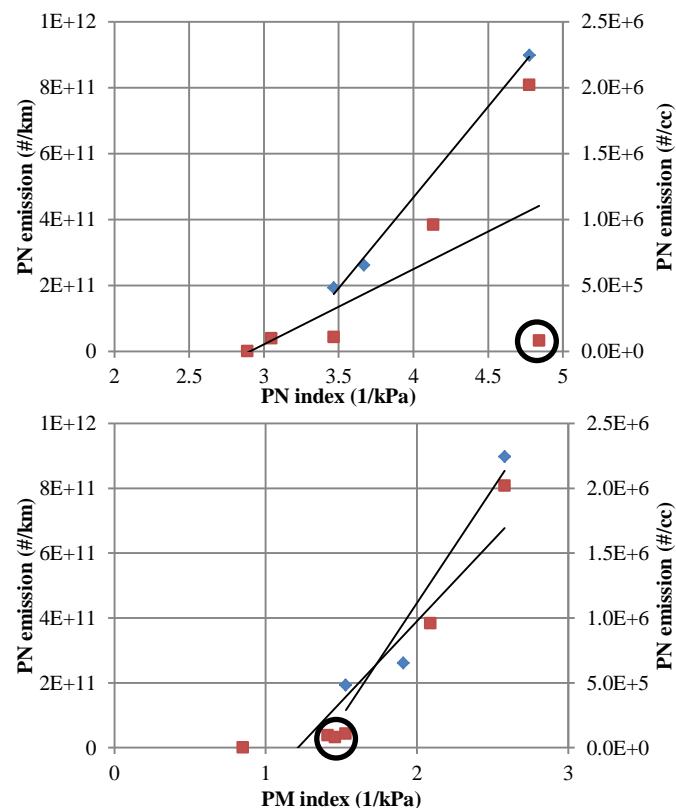


Figure 18: PN emissions vs PN index (upper) and PM index (upper) for data from [4]. The circled point plot is a fuel which the PN index predicts particularly poorly but the PM index predicts well.

Figure 16, Figure 17, and Figure 18 show a comparison between the PM and PN indices and PN emissions from three different sources in the literature. Both indices show positive correlations between the PN emissions and the index. However, with one exception, the correlation is stronger for every data set with the PM index. The correlation coefficients for the two indices are shown in Table 2. The one point where the PN index shows a slightly higher correlation (1.0 vs 0.93 for the PM index) only has three data points, so is not that significant.

Table 2: Comparison between correlation coefficients of PM and PN indices with PN emissions

PM index $R^2$	PN index $R^2$	Source
0.98	0.62	[40]
0.95	0.41	[40]
0.84	0.22	[40]
0.86	0.26	[40]
0.99	0.95	[54]
0.91	0.84	[54]
0.98	0.93	[54]
0.97	0.93	[54]
0.74	0.74	[54]
0.93	1.0	[4]
0.85	0.36	[4]
0.71	0.46	[37]

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There is one fuel, which particularly stands out in Figure 18 – this fuel (“light aromatics” from [4]) contains 35 % aromatic components, but only 11 % of those are C9/C9+ aromatics. This will lead the fuel to have a relatively high PN index, but because the methodology of the PM index will weight these light aromatic components less significantly in that index, the PM index value is significantly lower. This matches both the PN emissions observed and the literature that “heavy” aromatic components lead to an increase in injector tip deposits and hence higher PN emissions [4, 36, 37]. The PN index does not capture this feature.

## Summary/Conclusions

In this review paper, it has been found that the literature shows that a majority of PN emissions from a well-calibrated GDI engine will be due to liquid fuel films of one form or another. These may be due to films forming at the walls due to an aged injector, or even with a clean injector, films caused by impingement at higher engine loads and cold conditions. To avoid these, the literature indicates that two approaches are being used; on the one hand injector tip wetting must be reduced and on the other hand injector technology must minimise fuel wall films inside the combustion chamber. A key parameter for both of these features is the fuel injection system pressure - pressures of as high as 35 MPa are shown to have a significant effect in reducing PN from both generating paths – PN from aged injectors and from fuel wall films, for example on the piston surface.

Many studies show that injector coking is shown to be a significant source of PN emissions, with the PN-drift effect showing increases of two orders of magnitude in PN emissions after two hours of engine operation. RDE further emphasizes the impact of all of these effects, with cold, high load conditions, leading to high PN emissions, which injector technology – in particular an avoidance of surface wetting – must mitigate as much as possible.

There is a clear influence of fuel composition on PN emissions across the literature, however these effects are not as strong as many other engine parameters. In particular a fuels evaporative performance and the presence of aromatic components (notable those of C9 and above) has an impact of the PN emissions from a fuel. A number of particulate indices have been developed attempting to link fuel composition and PN emissions.

This work has considered two such indices in detail; the PM index of Aikawa *et al.* and the PN index of Leach *et al.* The results from this work show that the PN index can be more widely applied (requiring less detailed information than the PM index) but that in general PM index is a better predictor of PN emissions from GDI engines compared to the PN index. Notably the PN index correctly predicted the trend of PN emissions from 95 % of fuels when fuels with a PN index of within 5 % were excluded (such as would be masked by natural variations in PN emissions and measurement accuracy). It is possible alternative information commonly available about a fuel such as E100, E150, or T90 will improve the PN index and this will be considered in future work. Therefore when sufficient detailed information is available to calculate the PM index, it should be used, however in its absence, the PN index will prove a useful guide.

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## Definitions/Abbreviations

<b>AFR</b>	Air Fuel ratio
<b>DBE</b>	Double Bond Equivalent
<b>DHA</b>	Detailed Hydrocarbon Analysis
<b>DVPE</b>	Dry Vapour Pressure Equivalent
<b>EGR</b>	Exhaust Gas Recirculation
<b>E150</b>	Volume of fuel evaporation at 150 °C
<b>Exx</b>	Indicates a fuel containing xx % by volume ethanol

<b>FBP</b>	Final Boiling Point	<b>RVP</b>	Reid Vapour Pressure
<b>GDI</b>	Gasoline Direct Injection	<b>Txx</b>	The temperature at which xx % of a fuel has evaporated
<b>PAH</b>	Polycyclic Aromatic Hydrocarbon	<b>VP</b>	Vapour Pressure
<b>PM</b>	Particulate Matter		
<b>PN</b>	Particle Number		