report no. 10/10

Advanced combustion for low emissions and high efficiency
Part 2: Impact of fuel properties on HCCI combustion

Advanced combustion for low emissions and high efficiency Part 2: Impact of fuel properties on HCCI combustion

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Brussels
December 2010

ABSTRACT

A broad range of diesel, kerosene, and gasoline-like fuels has been tested in a single-cylinder diesel engine optimized for advanced combustion performance. These fuels were selected in order to better understand the effects of ignition quality, volatility, and molecular composition on engine-out emissions, performance, and noise levels. Low-level biofuel blends, both biodiesel and ethanol, were included in the fuel set in order to test for short-term advantages or disadvantages.

The diesel engine optimized in Part 1 of this study included practical and cumulative engine hardware enhancements that are likely to be used to meet Euro 6 emissions limits and beyond, in part by operating under conditions of Homogeneous Charge Compression Ignition, at least over some portions of the speed and load map.

The centre of combustion was matched for each fuel by adjusting the fuel injection timing. This simulates the performance of a future advanced engine operating with closed loop combustion control using an in-cylinder pressure sensor. The warmed-up engine could be run successfully on a wide range of diesel, kerosene, and gasoline-like fuels, including part-load and full-load operation, with diesel-like efficiency.

NOx emissions at or below Euro 6 emissions limits were achieved without the use of a NOx aftertreatment system. PM emissions were also low but a diesel particulate filter would be needed to reach Euro 6 limits and below. HC and CO emissions increased but were within the range that could be treated with a diesel oxidation catalyst.

Fuel properties had a substantial effect on PM emissions, consistent with the wide range of fuels investigated. In general, PM emissions decreased with increasing ignition delay, higher volatility, and lower aromatics levels of the fuel but the relative effects varied depending upon the engine operating conditions.

This study has investigated engine performance and emissions for a warmed-up single-cylinder bench engine only. Additional work would be needed to investigate engine performance under transient and cold start conditions.

KEYWORDS

Internal combustion engine technology, diesel, gasoline, fuel, combustion, Homogeneous Charge Compression Ignition (HCCI), Controlled Auto-Ignition (CAI), exhaust emissions, cetane number, octane number, RON, MON, biofuels, alternative fuels, aromatics, volatility, kerosene, particulate matter (PM), exhaust gas recirculation (EGR)

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SUMMARY

An experimental programme has been completed to explore the potential to reduce engine-out emissions while maintaining engine efficiency and acceptable noise levels. To do this, we have investigated a range of advanced engine hardware and fuel properties to enable optimum engine performance.

The single-cylinder bench engine evaluated in this study included cumulative engine hardware enhancements that are likely to be used to meet Euro 6 emissions limits and beyond, in part by operating under conditions of Homogeneous Charge Compression Ignition, at least over some portions of the speed and load map.

In this paper, we focus on the impact of fuel properties on engine-out emissions and performance using an optimized engine configuration developed in Part 1 of this study. Four part-load and full-load operating conditions were evaluated, representing a wide range of engine operation including the load points important to the European regulatory emissions cycle (New European Driving Cycle (NEDC)).

Fourteen fuels were tested in this Part 2 study that included a range of diesel, kerosene, and gasoline-like fuels. These fuels were selected in order to better understand the effects of ignition quality, volatility, and molecular composition on emissions and performance in an engine that had already been optimized for advanced combustion performance through hardware enhancements. Biofuel blends were also included in order to test for short-term advantages or disadvantages.

Operation of the engine was optimised for each fuel. It was found that the fuel injection pressure and boost pressure could be harmonized and optimized combustion achieved by matching the centre of combustion (CA50[1]) for each fuel by adjusting the fuel injection timing. This simulates the performance of a future advanced combustion engine operating with closed-loop combustion control (CLCC).

The warmed-up engine could be run successfully on a wide range of diesel, kerosene, and gasoline-like fuels, including part-load and full load operation, with approximately the same efficiency on all fuels.

Nitrogen oxides (NOx) emissions consistent with Euro 6 and below were achieved without the use of NOx aftertreatment. Particulate matter (PM) emissions were also low but a diesel particulate filter (DPF) is needed to reach limits at Euro 6 and below. Hydrocarbon (HC) and carbon monoxide (CO) emissions increased but were within the range that could be treated with a diesel oxidation catalyst (DOC).

Fuel properties had a substantial effect on PM emissions, consistent with the wide range of fuels investigated. In general, PM emissions decreased with increased ignition delay, higher volatility, and lower aromatic levels but the relative effects varied depending on the operating conditions.

This study has investigated engine performance and emissions for a warmed-up engine only. Additional work would be needed to investigate engine performance under transient and cold start conditions.

[1] CA50 is the point in the combustion cycle where 50% of the injected fuel has been converted to energy.

1. INTRODUCTION

Air pollutant emissions from motor vehicles have fallen dramatically as a result of continuing improvements in vehicle engine and aftertreatment technologies to meet lower regulated emissions limits. As a result, attention is increasingly focused on vehicle efficiency and fuel consumption in order to address concerns related to future energy supplies and Greenhouse Gas (GHG) emissions while maintaining and further reducing air pollutant emissions. Light-duty vehicle technology is evolving rapidly to respond to these new challenges.

Exhaust catalyst systems are an important factor in controlling air pollutant emissions, and fuel sulphur levels have been dramatically reduced to enable these to work effectively. Gasoline and diesel fuels that are effectively sulphur-free (<10ppm) now provide 100% of liquid road transport fuel demand from 2009. Although other changes to fuel properties have been introduced, their effects on emissions are small compared to that of advanced catalyst systems coupled with sulphur-free fuels. The existing sulphur-free fuels meet the needs of the vehicles expected to be introduced over the next several years [20].

In the search for both improved emissions and reduced fuel consumption, research and development are concentrating more closely on advanced combustion systems. Compression-ignition engines are already very efficient compared to spark-ignition engines and today's challenge is to maintain or improve this efficiency while further reducing air pollutant emissions. For the longer term, engines using advanced combustion systems are being developed which, if successful, could combine improved efficiency with lower air pollutant emissions from the engine, thus reducing the demand on exhaust aftertreatment systems and potentially costs. Because these advanced combustion concepts combine features of both spark-ignition and compression-ignition combustion, the optimum fuel characteristics could be quite different from those needed by today's conventional gasoline and diesel engines [1,2,3,4].

These advanced combustion concepts, often called Homogeneous Charge Compression Ignition (HCCI) or Controlled Auto Ignition (CAI), are the subject of this report. Broadly speaking, HCCI and CAI describe advanced combustion sequences in which fuel and air are substantially premixed before combustion and the fuel is burned without spark initiation at relatively low temperatures. This approach helps to reduce both soot and NOx formation [5,6].

The search for practical systems has inevitably led to many new acronyms describing different variations of engine and fuel injection strategies. In this study, we use the term HCCI in the most generic sense, to describe all of these advanced combustion concepts that seek to provide:

- low engine-out emissions (especially NOx and PM),
- low fuel consumption (comparable to or better than today's compression-ignition engines), and
- stable engine operation over a wide load range.

A recent literature review [7] has found that the technology already largely exists to produce combustion with very low soot and NOx emissions over a significant part of the engine load range. One study even reports HCCI combustion up to full load conditions [8]. Although progress is being made in gasoline CAI, the incentives to reduce engine-out emissions without performance losses are probably greater for diesel engines. Diesel engine developments are also well aligned with the requirements for combustion with low engine-out emissions, because the higher fuel injection pressures, exhaust gas recirculation (EGR) rates, and boost pressures that aid conventional compression-ignition combustion will also help to enable future advanced combustion. Many of the hardware enhancements needed to enable HCCI engines already exist today although they may be expensive to implement in production engines. Engine pressure sensors and a robust engine management system will also be required in order to better control the combustion process and timing. Nonetheless, HCCI engines are rapidly moving from research into the engine development phase.

'True' HCCI combustion involves fuel injection very early in the engine cycle so that there is sufficient time to achieve good fuel-air mixing. Although this approach achieves good fuel dispersion, it also makes it more difficult to control the ignition process. Most researchers now favour fuel injection later in the engine cycle in order to retain most of the benefits of HCCI combustion while achieving better control of the auto-ignition process [9,10]**.** Such low emission combustion can be achieved most easily at light engine loads and becomes increasingly difficult as power increases. The first production engines may therefore be 'part time' HCCI engines, reverting to conventional diesel or gasoline operation at higher load conditions, either progressively, or by a step change in operating mode [11] as long as this is the case, fuels must be compatible with both operating modes.

Many engineering groups are working on practical ways to achieve this combustion concept. These technologies are comparatively new and it is not possible to predict precisely how they will develop. Because of their potential importance for future fuel needs, however, CONCAWE and FEV Motorentechnik GmbH have investigated what can be achieved by practical future engine technologies and how fuel properties could influence their effectiveness.

Part 1 of this study [12,22] investigated how engine hardware developments could reduce engine-out emissions while retaining acceptable engine efficiency and noise levels. Four diesel-like fuels were tested with the engine calibrations optimised for each fuel. These tests demonstrated the potential of a late injection strategy to simultaneously deliver both low NOx and low PM emissions. In Part 2 of this study, reported here and in [21], a more diverse set of fuels has been tested on one of the two engine configurations optimised in Part 1.

The fuels tested in Part 2 included a wide range of practical and experimental fuels that were designed to investigate the impact of ignition quality, volatility, and molecular composition on engine-out emissions and performance. Experimental fuels in the gasoline boiling range were included that are not traditionally associated with diesel engines. Two low-level biofuel blends and a blend of commercial gasoline and diesel were also tested to look for short-term advantages and disadvantages. In each case, the combustion timing was adjusted to the same optimum position, simulating the behaviour of a future engine operating with in-cylinder pressure sensors and closed-loop control.

2. METHODOLOGY

The engine hardware enhancements in this programme were selected to achieve optimised combustion behaviour for lowest engine-out emissions and highest fuel efficiency. With this approach, HCCI combustion is possible especially at lower engine loads but the combustion process becomes progressively more like conventional diesel combustion as the load increases. The concept applied in this study was to allow as much premixing of fuel and air as possible before combustion occurred but the overall success criterion was the performance of the engine (in terms of efficiency, emissions, and noise) rather than the exact nature of the combustion process. Engine hardware enhancements were used that are practical for future engines, including high fuel injection pressures for improved mixture formation, high EGR levels, and intensified charge air and EGR cooling to lower the temperature in the combustion chamber for a cooler combustion.

Because of the wide range of fuels studied, the engine calibration was adjusted in order to optimise the performance on each fuel. An important finding from the Part 1 study was that this optimisation could be achieved by controlling the timing of the combustion event so that the CA50 occurred at the same crank angle position regardless of the fuel properties. When this was achieved, the same fuel injection pressure, boost pressure and pilot injection quantity and offset could be used for all of the fuels tested. For future production engines, this suggests that CLCC timing will be an important capability and a simulation of this approach has been used in this study.

The research engine was capable of achieving low NOx levels compatible with Euro 6 emissions limits and beyond through the use of high EGR levels. While PM emissions could also be substantially reduced in some cases, it was assumed that a DPF will be used to meet Euro 5 PM emissions limits and beyond and that a DOC will be used to reduce HC and CO emissions to regulated limits.

In this report, results are presented from Part 2 of this study. An engine configuration optimised in Part 1 of this study [12,22] was tested under steady-state condition on a wide range of practical and experimental fuels.

The overall objectives of this Part 2 study were to:

- define the potential for advanced combustion to reduce engine-out emissions while maintaining efficiency, noise, and engine performance and
- investigate the influence of fuel properties on engine performance.

Measurements were made at four part-load conditions covering and extending beyond the range of the NEDC as well as at four full-load conditions. The fuels selected for this study were designed to investigate the impact of ignition quality, volatility, and molecular composition on efficiency, engine-out emissions, and noise. Fuels in the gasoline boiling range were also evaluated that are not traditionally associated with diesel engines. In addition, two low-level biofuel blends and a blend of commercial gasoline and diesel were also tested to look for short-term advantages and disadvantages. In each case, the combustion timing was adjusted to the same optimum position, simulating the behaviour of a future engine operating with in-cylinder pressure sensors and closed-loop control.

The purpose of this fuel study was not to recommend future fuel properties, but to provide performance data on a range of fuels in an advanced combustion engine and to relate performance to that required to meet future emission regulations and customer expectations. It is recognised that this work, covering hot steady-state engine conditions, does not answer all of the questions regarding HCCI engines. More work is needed, particularly on transients and cold engine operation, before a commercial engine could be produced. Nevertheless, this report provides a valuable contribution to the discussion regarding future engine developments and their fuel requirements.

2.1. TEST ENGINE

Two different single-cylinder engine configurations were evaluated in Part 1 of this study [12,22], a Phase A engine benchmarked to achieve Euro 5 emissions performance and a Phase B engine benchmarked to achieve Euro 6 emissions performance. The Phase B engine was then used in this Part 2 study with the hardware specifications shown in **Table 1**.

Table 1 Hardware specifications for the Phase B engine used in this study

	Units	**Phase B Engine**
Emissions Benchmark	[-]	Euro 6
Single-cylinder swept volume	[cm^3]	390
Stroke	[mm]	88.3
Bore diameter	[mm]	75
Compression ratio	[-]	15
Valves per cylinder	[-]	4
Maximum peak pressure	[bar]	220
Fuel injection system specifications:	[-]	Bosch Piezo Common Rail System
Maximum injection pressure	[bar]	2000
Nozzle	[-]	8 x 153°
Nozzle hole diameter	[µm]	109
Hydraulic Flow Rate (HFR)	[cm^3/30s]	310
Charge air cooling level	[-]	Euro 6

The Phase B engine represented a downsized concept since the swept volume of would permit the construction of a 1.6L 4-cylinder engine equivalent in power to a 2.0-2.2L engine of today. In addition, the engine was designed with a reduced compression ratio, a higher maximum cylinder peak pressure, and better in-cylinder swirl through valve seats with chamfers [10] to aid pre-mixed combustion. The injection pressure was increased to give a maximum rail pressure of 2000 bar. In order to take advantage of this higher rail pressure, a nozzle with a lower hydraulic flow rate (smaller nozzle hole diameter) was used to improve mixture preparation.

Finally, this engine was equipped with an external 3-stage boosting device that was capable of generating a maximum absolute boost pressure of 3.5 bar. By using an external boosting system, the boost pressure generation on the test engine could be varied independently of the engine load point.

Most experiments were conducted with pilot injection but the effect of switching off the pilot injection was also studied and the results are summarized in **Appendix 2**. Most of the results shown in this report have been obtained with pilot injection except where noted.

Tests on the Phase B engine simulated CLCC. This was done by adjusting the fuel injection timing on each fuel so that the CA50 was always at the same point in the engine cycle, chosen to maximise engine efficiency. Fuels with lower cetane numbers (CN) and therefore longer ignition delays required earlier fuel injection timing to maintain the centre of combustion at the desired crank angle position.

To achieve low NOx emissions, the engine was also capable of high levels of EGR delivered through an intercooler to reduce charge temperatures.

These engine enhancements are expected to be commonly used on advanced Euro 6 combustion engines including those operating in HCCI mode over some portions of the speed/load cycle. As such, the testing possibilities on the Phase B engine exceeded that of today’s production engines.

During the optimization of the engine calibration, the maximum levels of boost pressure and EGR were constrained to limits that are achievable by production engines. As mentioned before, the Phase B engine was equipped with valve seats with chamfers. This modification meant that different swirl levels could be achieved by using intake camshafts with different cam lifts. Using in-cylinder air flow modelling, it was determined that camshafts which open the valve with smaller lifts over the opening event duration resulted in a higher swirl level in the combustion chamber. Although the impact of increased swirl levels was investigated and reported in the Part 1 study, all of the measurements in this Part 2 study used a standard valve lift in order to reduce the test time and maximize the number of fuels that could be evaluated.

In summary, the Phase B engine hardware was enhanced and benchmarked to achieve Euro 6 emissions performance by means of a lower compression ratio, a higher maximum cylinder peak pressure, a maximum rail pressure of 2000 bar, adjustment of fuel injection to achieve a constant centre of combustion, and intensified EGR. These engine enhancements are expected to be commonly used on advanced diesel engines including those operating in HCCI mode over some portions of the speed/load cycle. The Phase B engine used in this Part 2 study is equivalent to Configuration 2 in the Part 1 study [22].

2.2. TEST FUELS

Previous studies have suggested that three fuel properties are especially important to promote HCCI combustion [7]:

- Lower CN in order to lengthen the ignition delay and provide time for more fuel-air mixing,
- Increased volatility, in order to reduce the time needed to achieve fuel-air mixing before auto-ignition occurs, and
- Fuel composition, to promote combustion and reduce engine-out emissions.

The ignition quality of diesel fuels is routinely characterised by its CN, as measured in the CFR Cetane Engine (ASTM D613). In this measurement, the cetane number of an unknown diesel fuel is measured by comparing its ignition quality with two reference fuels of known cetane number. The cetane number is directly related to the ignition delay of the fuel under specified engine conditions.

In recent years, a laboratory device, called the Ignition Quality Tester (IQT) [13], has found widespread use as an alternative to the CFR engine method. In the IQT device, a small sample of unknown fuel is injected into a constant volume chamber that has previously been filled with air at a specified temperature and pressure. After injection, the test fuel auto-ignites and the Derived Cetane Number (DCN) is determined by comparing the ignition delay of the unknown fuel to that of a correlation curve derived from reference samples. For diesel-like fuels, the agreement between DCN measured in the IQT and the CN measured in the CFR engine is very good [13].

The ignition quality of gasoline-like fuels is generally described by two different parameters: Research Octane Number (RON) and Motor Octane Number (MON) [13]. Relative to a primary reference fuel containing iso-octane and n-heptane, the ignition quality of production gasoline fuels is known to vary with temperature and pressure. This observation explains why the RON and MON of production gasolines usually differ by about 10 octane numbers.

Kalghatgi et al. [15] have shown, however, that there is a remarkably good correlation between DCN and RON (**Equation 1**) for a wide range of fuels:

$$DCN = -0.4208 * RON + 54.633 \qquad \textbf{Equation 1}$$

In order to compare the ignition qualities of all the diesel and gasoline-like fuels on the same basis, the DCN is reported in **Table 2**, either measured directly in an IQT or determined from the Research Octane Number (RON) using **Equation 1**.

Under HCCI combustion conditions, ignition delays are expected to be longer than in a CFR engine and fuel will be injected earlier in the compression stroke where temperatures and pressures are lower. For this reason, the conditions in an IQT or a CFR engine may differ from those found in an advanced combustion engine running in HCCI mode. The way in which ignition delay varied with cetane number in this study is discussed later.

The test fuels in this study were designed to investigate ignition delay, volatility, and molecular composition over as wide a range as possible. Both practical and experimental fuels were included in this study. Because fuel parameters tend to be correlated, it was not possible to produce an orthogonal fuel matrix for all fuel properties of interest. Instead, fuel properties were changed one at a time, keeping the other properties of interest as constant as possible. The effects of fuel property changes could therefore be evaluated by comparing selected pairs of fuels.

The fuel set was anchored by the Baseline Diesel fuel, an ultralow sulphur, EN590 production diesel fuel (DCN53). A Low Cetane Diesel (DCN44) with an aromatics content similar to the Baseline Diesel was tested to evaluate the impact of cetane in production diesel-like fuels. A Low Aromatics Diesel (DCN53) with a cetane similar to the Baseline Diesel but with a lower aromatics content was specially blended for this study to evaluate the impact of aromatic content in diesel-like fuels.

In order to evaluate the impact of fuel volatility, two kerosene boiling range fuels were included, having two different levels of aromatics. The Kerosene fuel (DCN47) is typical of current production kerosene while the Low Aromatics Kerosene (DCN48) was specially blended and is similar to the fuel proposed previously by Volkswagen for HCCI engines [3].

Some studies [1,2] have suggested that fuels in the gasoline boiling range may be particularly well suited for HCCI combustion. For this reason, we also tested a number of experimental gasoline-like fuels that varied in ignition quality and aromatics content. These gasoline-like fuels were either Primary Reference Fuels (PRF, mixtures of n-heptane and iso-octane) or Toluene Reference Fuels (TRF, mixtures of toluene and n-heptane) and covered a range of DCN values from 47 to below 25.

Initial tests showed that PRF gasoline-like fuels that had a DCN lower than 30, including a standard European 95RON gasoline, would not run at all load points in the Phase B engine without further modifying the optimized engine configuration. For this reason, the very low DCN fuels are not discussed further in this paper. A commercial ester-type lubricity additive was added to all of the gasoline-like fuels to minimize wear in the fuel injection system.

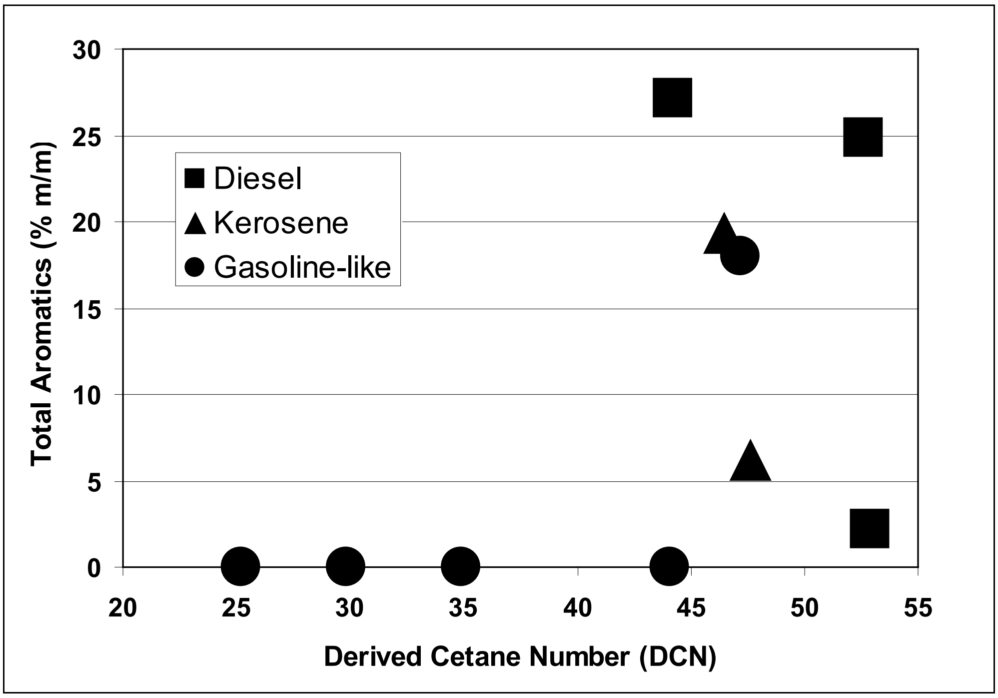
The PRF and TRF gasoline-like fuels were selected for this study to more easily separate the effects of DCN and aromatics content among fuels of very similar volatility. For example, PRF25 and PRF47 allowed a comparison between DCN44 and 35 fuels of similar volatility without changing the aromatics content. Similarly, PRF25 and TRF18 allowed a comparison on the basis of aromatics content without substantially changing the volatility and DCN.

A blend of commercial gasoline and diesel, called ‘Dieseline’ (DCN44), was also tested. This concept fuel has been suggested as a potentially practical HCCI fuel by Collings and Weall [16] and by Zhong et al. [17] as long as issues associated with the blend’s flash point and evaporative emissions can be resolved.

Finally, two biofuel blends were tested to investigate short-term advantages and disadvantages for advanced combustion performance. These fuels included a gasoline-like fuel (E10PRF) consisting of 81% n-heptane, 9% iso-octane, and 10% v/v ethanol and a diesel fuel (B10) consisting of 90% of the Baseline Diesel and 10% v/v Fatty Acid Methyl Ester (FAME). The FAME used in this study was a Rapeseed Methyl Ester (RME) that complied with EN14214 specifications. The DCNs for these biofuel blends were 43 and 52, respectively.

Relevant chemical and physical properties for all of the fuels in this study are summarised in **Table 2**, and a full list of measured chemical and physical properties is provided in **Appendix 1**.The fuel matrix is illustrated in **Figure 1** where the DCN is plotted versus the total aromatics content.

Figure 1 DCN versus Total Aromatics Content for selected test fuels[1]



[1] The 'Dieseline', E10PRF, and B10 fuels are not shown in **Figure 1**.

Table 2 Selected properties of the diesel, kerosene, and gasoline-like test fuels

	Baseline Diesel (DCN53)	Low Cetane Diesel (DCN44)	Low Aromatics Diesel (DCN53)	Kerosene (DCN47)	Low Aromatics Kerosene (DCN48)	TRF18 (DCN47)	PRF25 (DCN44)	PRF47 (DCN35)	PRF59 (DCN30)	PRF70 (DCN25)	PRF95 (DCN15)	EN228 Gasoline (DCN14)	Dieseline (DCN44)	E10PRF (DCN43)	B10 (DCN52)
Derived Cetane Number [DCN]	52.6	44.2	52.9	46.5	47.6	47.2	44.1	34.9	29.8	25.2	14.7	14.1	43.6	43.4	51.8
Aromatics Content [% m/m]	24.9	27.1	2.2	19.3	6.2	18.0	0.0	0.0	0.0	0.0	0.0	34.4	37.5	0.0	28.0
Lower Heating Value (LHV) [MJ/kg]	43.0	42.9	43.5	43.0	43.7	44.3	44.2	44.1	44.0	43.9	43.7	43.3	42.8	40.6	42.5
T10 [°C]	195.4	184.0	205.5	165.6	168.1	98.5	97.9	97.9	97.9	98.3	98.1	49.7	108.6	71.7	202.8
T50 [°C]	274.9	241.0	227.1	199.0	176.0	98.7	97.9	97.9	97.9	98.3	98.3	98.5	256.2	97.7	283.7
T90 [°C]	328.9	338.6	329.3	253.1	188.7	99.2	98.0	97.9	97.9	98.3	98.3	152.8	331.1	97.7	333.5

2.3. MEASUREMENTS

For each test fuel, engine measurements were taken at each of the four part-load points, varying the EGR levels over a wide range and maintaining a constant centre of combustion at each condition. Similar measurements were also made at the four full load points. Evaluation of a single fuel at all load points took about 3 days, so it was not practical to carry out multiple repeat tests on each fuel. However, to provide an estimate of test repeatability, three tests were performed at intervals on the Baseline Diesel and results from all three of these tests are reported in the charts that follow. These tests provide reassurance that engine drift was not an issue and a context within which the effects of fuel changes can be evaluated.

Gaseous emissions of total HC, CO, and NOx were measured directly at the engine-out exhaust. Smoke emissions were measured using an AVL 415S Smoke Meter, which also provided a read-out of PM emissions using an internal conversion formula. These emissions are shown as “indicated specific” (g/kWh) in the figures.

3. TEST PROCEDURE AND METHODOLOGY

3.1. PERFORMANCE CRITERIA

The bench engine was optimized based on the following considerations. The success criteria of the optimisation included low PM, HC, and CO emissions, an acceptable engine noise, and a fuel efficiency that was at least as good as the base configuration of the engine. It was assumed that future production engines will use a DOC and a DPF. Therefore for HC, CO, and soot/particulate emissions, the bench engine was optimized for engine-out emission levels that can be effectively treated with these aftertreatment devices.

For meeting NOx emissions, active deNOx aftertreatment systems, such as Selective Catalytic Reduction (SCR) or NOx-storage catalysts, are likely to be avoided due to their complexity and cost. To realize this simplification, sufficient levels of EGR must be used in order to achieve very low engine-out NOx emissions. Based on the NEDC regulatory cycle, maximum Indicated Specific NOx emissions ($ISNO_x$) targets were estimated for each load point and different emission levels.

3.2. EXPERIMENTAL APPROACH TO ENGINE OPTIMIZATION

In Part 1 of this study, the engine calibration was optimized for each fuel using a Design of Experiments (DOE) approach. This was done to define the optimum injection pressure, boost pressure, and pilot injection strategy. As the study progressed, it was found that a full DOE optimization was not needed for every fuel and the optimized calibrations for the Base Diesel fuel could be used for all fuels, provided that the injection timing was adjusted for each fuel to give the same CA50. This approach was also used in this Part 2 study.

3.3. TEST POINTS

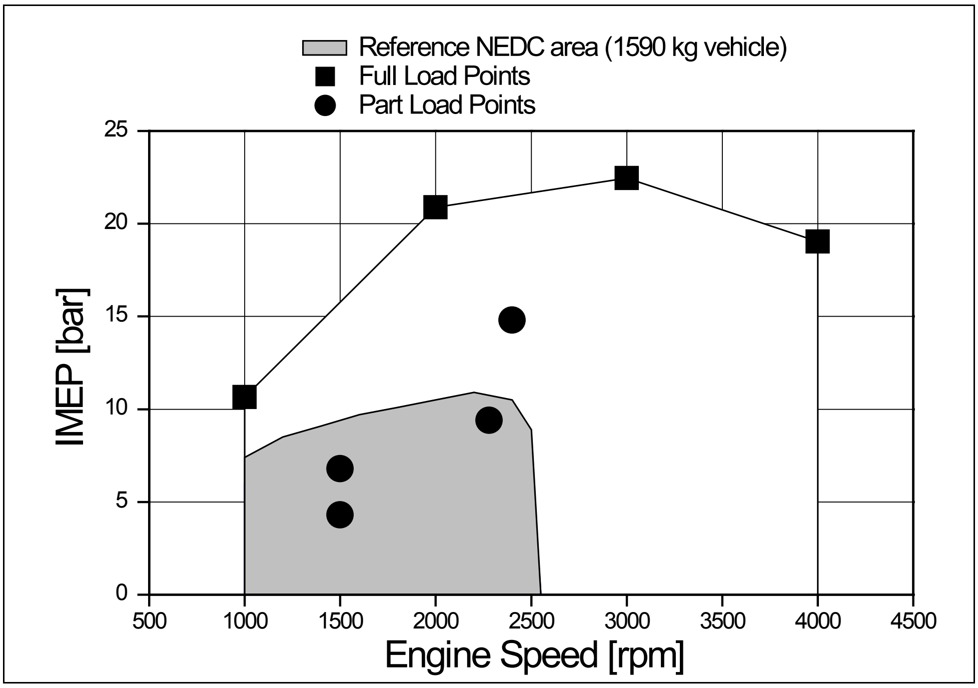
The investigations included the analysis of the engine performance and the fuel influence at 4 part-load and 4 full-load conditions. All load points tested within this programme are summarized in **Table 3** and displayed in **Figure 2**.

Table 3 Phase B engine part-load and full-load operating points

Part-load Operating Points			Full-load Operating Points		
Speed (min^{-1})	IMEP (bar)		Speed (min^{-1})	Smoke Limit (FSN[1])	Exhaust Gas Temperature Limit (°C)
1500	4.3		1000	2.6	820
1500	6.8		2000	1.7	820
2280	9.4		3000	2.2	820
2400	14.8		4000	2.4	820

[1] Filter Smoke Number

Figure 2 Engine speed and load points selected for this study



At the beginning of this study, it was decided to investigate three part-load points: 1500 rpm/4.3 bar IMEP, 2280 rpm/9.4 bar IMEP, and 2400 rpm/14.8 bar IMEP. A fourth part-load operating point (1500 rpm/6.8 bar) was added at the start of testing on the Phase B engine. At this condition, other researchers have reported very low soot and NOx emissions for a fuel having a very narrow boiling point range with a gasoline-like endpoint, a cetane number of 45, and a very low aromatics level of 2.1% [3].

Typically, HCCI-like combustion can only be sustained at lower loads but it is important to consider the whole engine operating envelope in order to judge emissions and performance at the highest loads as well. The three lowest part-load points are within the range of the NEDC (based on a typical vehicle configuration, for example, 1.6-litre engine, 1590kg vehicle mass). The highest part-load point is outside the NEDC and was added as a reference for possible future driving cycles or additional engine downsizing.

The full load behaviour was tested at four engine speeds. This was done to ensure acceptable operation over the full range of engine speed and load conditions and demonstrate that the engine could meet the required performance. Operation at full load is typically limited by either the smoke emissions (FSN) or exhaust gas temperature limit for turbochargers on production engines. The full-load points tested in this study are listed in **Table 3**.

At each part-load point and Euro emissions level, the maximum ISNOx and Indicated Specific PM (ISPM) emissions were estimated that would be needed to meet the required overall performance in the NEDC and at the highest part-load point just outside of the NEDC range. These estimated target levels are summarized in **Tables 4** and **5** and take into account the expected impact of transient operation and cold start and include an appropriate engineering margin.

Table 4 Estimated ISNOx targets needed to meet different Euro emissions limits at the four part-load operating points

ISNOx (in g/kWh)	1500 rpm, 4.3 bar IMEP	1500 rpm, 6.8 bar IMEP	2280 rpm, 9.4 bar IMEP	2400 rpm, 14.8 bar IMEP
Euro 4	0.6	0.6	1.8	2.25
Euro 5	0.4	0.4	1.2	1.50
Euro 6	0.2	0.2	0.6	0.75
50% Euro 6[2]	0.1	0.1	0.3	0.38

Table 5 Estimated ISPM targets needed to meet different Euro emissions limits at the four part-load operating points

ISPM (in g/kWh)	1500 rpm, 4.3 bar IMEP	1500 rpm, 6.8 bar IMEP	2280 rpm, 9.4 bar IMEP	2400 rpm, 14.8 bar IMEP
Euro 4	0.0030	0.0279	0.0706	0.2129
Euro 5	0.0006	0.0056	0.0141	0.0426
Euro 6	0.0006	0.0056	0.0141	0.0426
50% Euro 6	0.0006	0.0056	0.0141	0.0426

For NOx emissions, it was assumed that the vehicle would not be equipped with any special aftertreatment system for NOx abatement and that engine-out NOx levels would be sufficiently low through the use of high EGR levels to meet the prevailing NOx specifications. It was also assumed that future production engines will require a DOC and DPF in order to meet Euro 5 emissions limits and beyond. For this reason, the Phase B engine was optimized for engine-out HC/CO and PM emissions that could reasonably be converted or trapped by means of these aftertreatment devices.

At each part-load point, maximum design limits were also set on noise outside the engine (estimated from pressure traces as described in **Part 1** and **Section 3.4**) in order to keep noise within acceptable limits from a driver's perspective.

The success criteria for the optimization at each operating point included acceptably low PM, HC, CO, and noise emissions and an engine efficiency at least as good as the base configuration of the engine.

3.4. WHAT WAS MEASURED

For each test fuel, measurements were taken at each of the four part-load points, varying the EGR levels over a wide range and maintaining a constant centre of combustion at each condition. Similar measurements were also made at the four full load points.

Gaseous emissions of total HC, CO, and NOx were measured directly at the engine-out exhaust. Smoke emissions were also measured and used to estimate total PM emissions using a formula that takes into account the expected contribution of the volatile organic fraction.

[2] Also called "Euro 6+" in this study.

The fuel consumption was measured volumetrically by determining the engine runtime needed to consume a defined volume of fuel. Then, by using the density of the fuel, the gravimetric fuel consumption could be calculated. Because fuels with different energy contents were tested in this study, the engine efficiency was considered to be more important than the fuel consumption and was calculated by taking into account the energy content of the fuel.

Combustion noise is related to the maximum rate of pressure rise in the engine cylinder and was calculated from the cylinder pressure trace using an average of about 50 cycles. The methodology is described in [18]. The overall noise outside of the engine was then calculated taking into account attenuation through the engine structure and including mechanical noise. This overall engine-out noise is reported here as the Combustion Sound Level (CSL).

3.5. REPEATABILITY OF ENGINE TEST RESULTS

Engine optimization and evaluation at each load point was a time-consuming process. Evaluation of a single fuel at all load points took about 3 days so it was not practical to carry out multiple repeat tests on each fuel. However, to provide an estimate of test repeatability, three tests were performed at intervals on the Baseline Diesel fuel and the results from all three of these tests are reported. These three results are displayed in the Figures in **Section 4** and provided reassurance that engine drift was not an issue. Based on these results, a comparison of the different engine configurations and fuels could be made with confidence.

To improve the reliability of the fuel comparisons, short-term “back-to-back” tests were performed at the end of the study using the optimized calibrations where the fuels are compared at a constant centre of combustion.

4. RESULTS

Although much attention naturally focuses on the part-load test conditions that influence performance on the NEDC regulatory cycle, a practical engine must provide acceptable performance over the entire speed/load operating range. For this reason, measurements were made at four full-load conditions as well as the four part-load conditions. Even though the properties of the test fuels varied over a wide range, the Phase B engine was able to match the full-load power achieved on the Baseline Diesel for all test fuels, within the constraints imposed by smoke level and exhaust temperature and with very little impact on engine efficiency or CSL.

For the part-load conditions, NOx emissions from the engine were adjusted by varying the EGR rate and sufficient measurements were taken to produce a complete EGR sweep. The amounts of EGR needed to achieve a given NOx level were similar but not identical for the different fuels.

Other emissions and performance parameters were then compared at constant levels of engine-out NOx emissions required to meet light-duty vehicle Euro 4, Euro 5, Euro 6, and 50% of Euro 6 limits (called the ‘Euro 6+’ condition) without the use of exhaust NOx aftertreatment.

The tests evaluated four part-load engine conditions covering and extending beyond the load range expected in the NEDC. The target emission levels identified for the four part-load points are engineering targets (**Tables 3** and **4**) that take into account the effects of transient operation and an allowance for cold start emissions. It should be recalled, however, that a limited number of hot engine conditions can only give an approximation of the full NEDC.

In this study, we found that the engine ran well on a wide range of fuels under hot engine conditions, including fuels in the diesel, kerosene, and gasoline boiling ranges and with DCN values from 53 to 30. Although the engine could be run on gasoline-like PRF fuels having DCN values less than 30, it was necessary to increase the boost pressure at the lowest load point.

The lower viscosity fuels in the gasoline boiling range could not achieve the same high fuel injection rail pressures as the diesel and kerosene fuels because of leakage within the pump. This did not significantly impact their performance, however. In addition, the fuel injection system was not optimized for gasoline-like fuels and further improvements may be possible if this were done.

As reported in the Part 1 study, the optimum fuel injection pressure and boost pressure could be harmonized for a wide range of fuels and optimized combustion could be achieved by adjusting the centre of combustion. In this Part 2 study, fuels were compared at the same fuel injection and boost pressures, subject to the limitations noted above. The combustion timing was adjusted in all cases to give a centre of combustion about 6-9 degrees crank angle (^{o}CA) after top dead centre (ATDC) and close to the optimum for efficiency (see **Table 6**). The results therefore simulate the performance of an engine with CLCC timing. This means that the fuel injection timing varied depending upon the ignition quality of the fuel with those fuels having a lower DCN value (longer ignition delay) needing an earlier fuel injection timing to achieve the desired combustion phasing. The pilot injection quantity and advance relative to the main injection were held constant as shown in **Table 6**.

Table 6 Indicated Specific Fuel Consumption (ISFC) optimisation conditions for the Phase B engine

	BOI-Main	Centre of Combustion	Pilot Offset	DOI-Pilot	Rail Pressure	Boost Pressure
	[°CA BTDC]	[°CA ATDC]	[°CA]	[µs]	[bar]	[bar abs]
1500 rpm, 4.3 bar IMEP	Variable	6.6 @ 0.5 g/kWh ISNOx	10	180	720	1.07
1500 rpm, 6.8 bar IMEP	Variable	5.8 @ 0.5 g/kWh ISNOx	11	140	904	1.5
2280 rpm, 9.4 bar IMEP	Variable	9.2 @ 0.5 g/kWh ISNOx	20	120	1399	2.29
2400 rpm, 14.8 bar IMEP	Variable	9.2 @ 0.5 g/kWh ISNOx	20	120	1399	2.29

BTDC = Before Top Dead Centre
ATDC = After Top Dead Centre
BOI-Main = Beginning of Injection-Main Injection
DOI-Pilot = Duration of Injection-Pilot Injection

Key results are presented in the following sections and a full tabulation appears in **Appendix 3**.

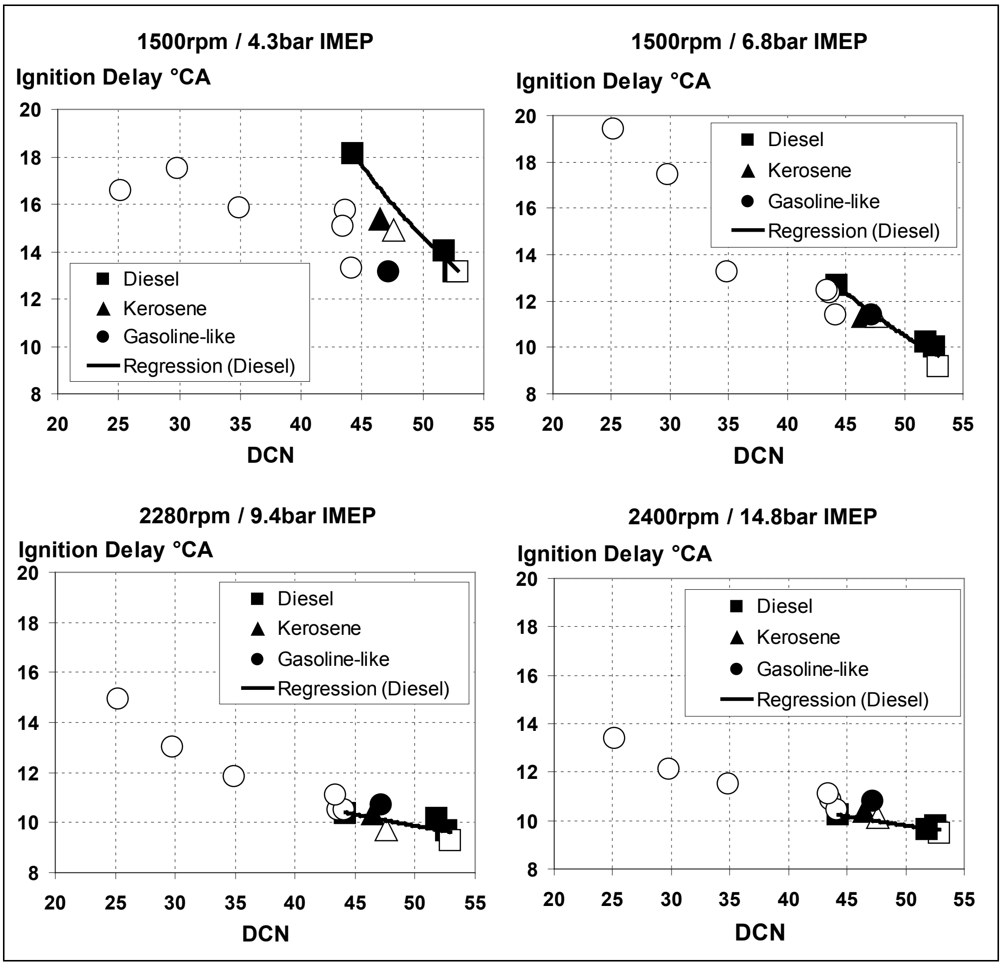
4.1. IGNITION DELAY

The ignition delay (in ^{o}CA) was calculated from the BOI-Main to the point where 5% of the total heat release had occurred as indicated by the cylinder pressure traces. The ignition quality of the test fuels was characterised by their DCN values based on direct measurements of ignition delay in the ASTM D6890-07a test [13]. In compression ignition engines using conventional diesel or kerosene type fuels, ignition delay is well known to increase as the CN of the fuel decreases. However, the relationship between CN and ignition delay may change under the cooler conditions and longer ignition delays associated with HCCI combustion, particularly for gasoline fuels where the ignition chemistry is more complex.

Ignition delays at the four part-load points are shown in **Figure 3**. Diesel, kerosene, and gasoline-like fuels are distinguished by different symbols. Open symbols indicate low- or zero-aromatic fuels, while solid points are fuels containing higher-levels of aromatics. Since the DCN measurement is an empirical method calibrated for diesel fuels, the power curve has been plotted based on regression of the diesel fuel results only as a basis for comparing the behaviour of the kerosene and gasoline-like fuels.

Since there were no diesel fuels in this study having DCN values less than 44, the regression lines cannot be continued to the very low DCN values exhibited by some of the gasoline blends.

Figure 3 Ignition delay (in °CA) versus DCN at the four part-load operating points. Data are for the Euro 6 condition with pilot injection.



At the two higher part-load points, the ignition delays appear to follow a common trend for all fuels with ignition delay depending only on the DCN value. Because of the high pressures and temperatures at these higher loads, the increase in ignition delay is relatively modest, even for the DCN25 (PRF70) fuel. This behaviour suggests that the combustion process at these higher loads is essentially characteristic of diesel compression ignition combustion.

At the two lower part-load points, however, a different picture is seen. The gasoline-like blends and to some extent the kerosene blends gave shorter ignition delays than expected based on their DCN values. This effect is most evident at the lowest part-load point (1500 rpm/4.3 bar) where PRF blends having DCN values of 25 (PRF70) and 30 (PRF59) produced shorter ignition delays than the Low Cetane Diesel (DCN44) fuel. It is possible that cool flame reactions of these largely paraffinic fuels caused earlier ignition than would have occurred with a diesel fuel of similar DCN. However, the presence of aromatics in the gasoline blend did not influence the ignition delay so some other mechanism may be responsible. This deviation from conventional diesel combustion behaviour suggests that the combustion process is moving into a different mode at these lower part-load conditions.

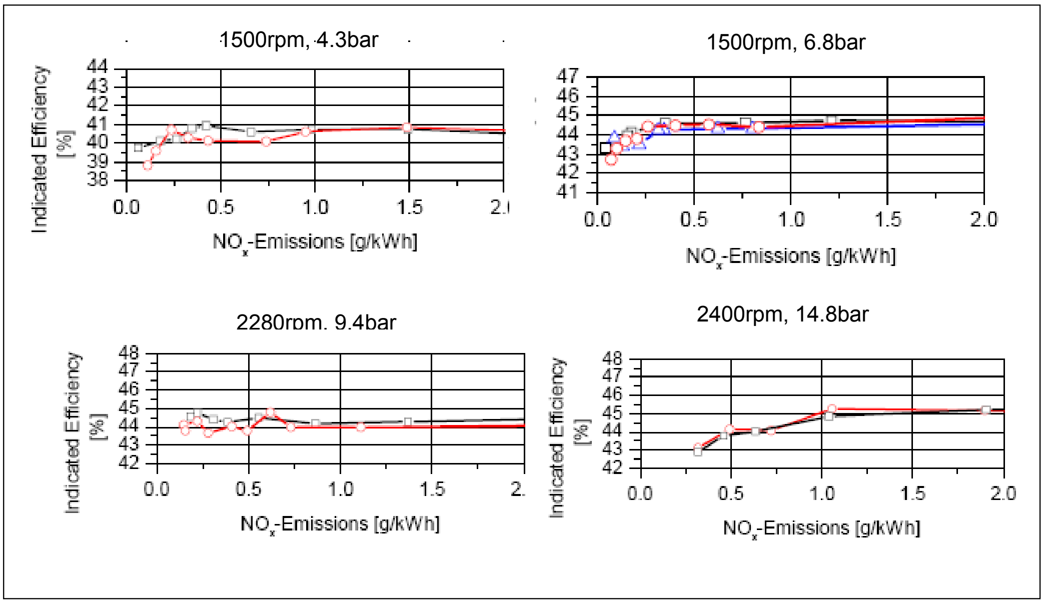
The ignition delay behaviour may explain why good engine operation could be achieved with such low DCN fuels in the gasoline boiling range. However, it cannot be inferred that such DCN levels would be acceptable in the kerosene or diesel boiling range.

4.2. ENGINE EFFICIENCY

Very low NOx levels could be achieved at all four part-load operating points while maintaining good engine efficiency but an effect was seen on changing the NOx level. On average, for all fuels over the four part-load points, the indicated engine efficiency decreased from 44.3% at the Euro 4 NOx level, to 43.8% at the Euro 6 NOx level, and to 43.2% at the Euro 6+ NOx level.

For practical reasons, the fuels were compared by harmonising the centre of combustion only at the Euro 5 NOx level and maintaining the same injection timing as the NOx level was then varied. Under these conditions, increasing EGR levels to further reduce NOx would be expected to slow down the combustion process delaying the combustion phasing slightly with a corresponding small loss in engine efficiency. Additional tests were therefore carried out on the Baseline Diesel fuel to evaluate the effect of readjusting the timing to the optimum condition at each NOx level. Results are shown in **Figure 4**.

Figure 4 Evaluation of engine efficiency as the EGR rate was increased to reduce NOx emissions (tests on the Baseline Diesel fuel)



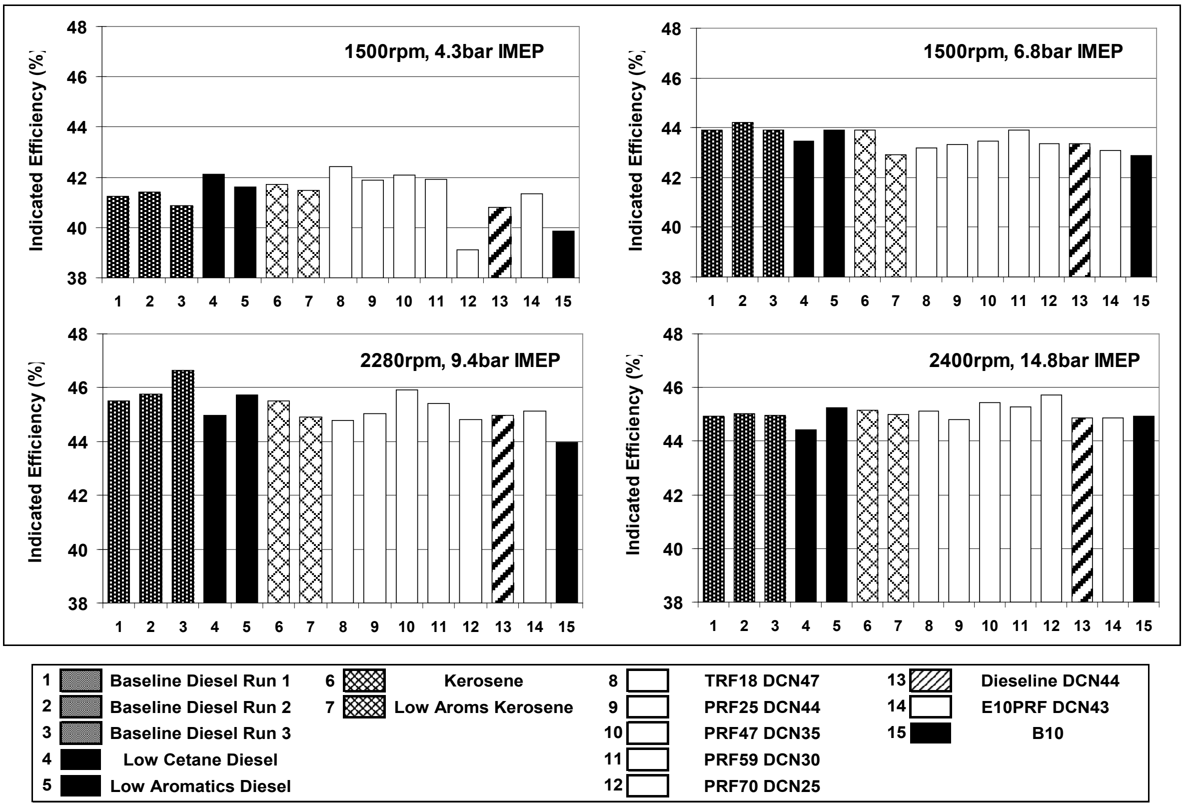
Optimization of the combustion timing did improve efficiency at the lowest NOx levels for the 1500 rpm/4.3 bar and 2280 rpm/9.4 bar test conditions although there was no clear effect at the other two conditions. At 2280 rpm/9.4 bar, the efficiency was the same down to the very lowest NOx levels achieved. For the other test conditions, there was a clear decrease in efficiency even with perfectly optimized combustion timing as the NOx levels decreased below Euro 5 levels.

Emission levels were not significantly affected by the small changes in combustion timing with the exception of HC and CO emissions at 1500 rpm/4.3 bar. For these emissions, optimization of the combustion timing decreased emissions at the lowest NOx levels.

The indicated engine efficiencies for all test fuels are shown in **Figure 5** for the four part-load operating points and the Euro 6 NOx emissions target. The order of fuels in this and subsequent figures are the same as in **Table 2**. The Baseline Diesel fuel was tested three times at intervals and the results on each of these runs are shown as the first three bars in these figures.

As seen in **Figure 5**, there were some differences in engine efficiency among the different test fuels at each part-load condition but there were no consistent trends. For example, the engine efficiency for the Low Cetane Diesel was among the highest at 1500 rpm/6.8 bar IMEP but among the lowest at 2400 rpm/14.8 bar IMEP. When comparing individual fuels, efficiency measurements tended to show increases at some conditions and decreases at others which suggested that test variability could be a contributing factor. None of the fuels tested offered a particular advantage with respect to efficiency at all part-load conditions in this engine. The PRF70 (DCN25) fuel gave lower efficiency at 1500 rpm/4.3 bar IMEP illustrating that a higher cetane number is needed to achieve stable combustion at this light load condition.

Figure 5 Indicated engine efficiency at the Euro 6 NOx emissions target for all test fuels and four part-load operating points. The centre of combustion was harmonized only at the Euro 5 NOx emissions level for each fuel.



4.3. PARTICULATE EMISSIONS

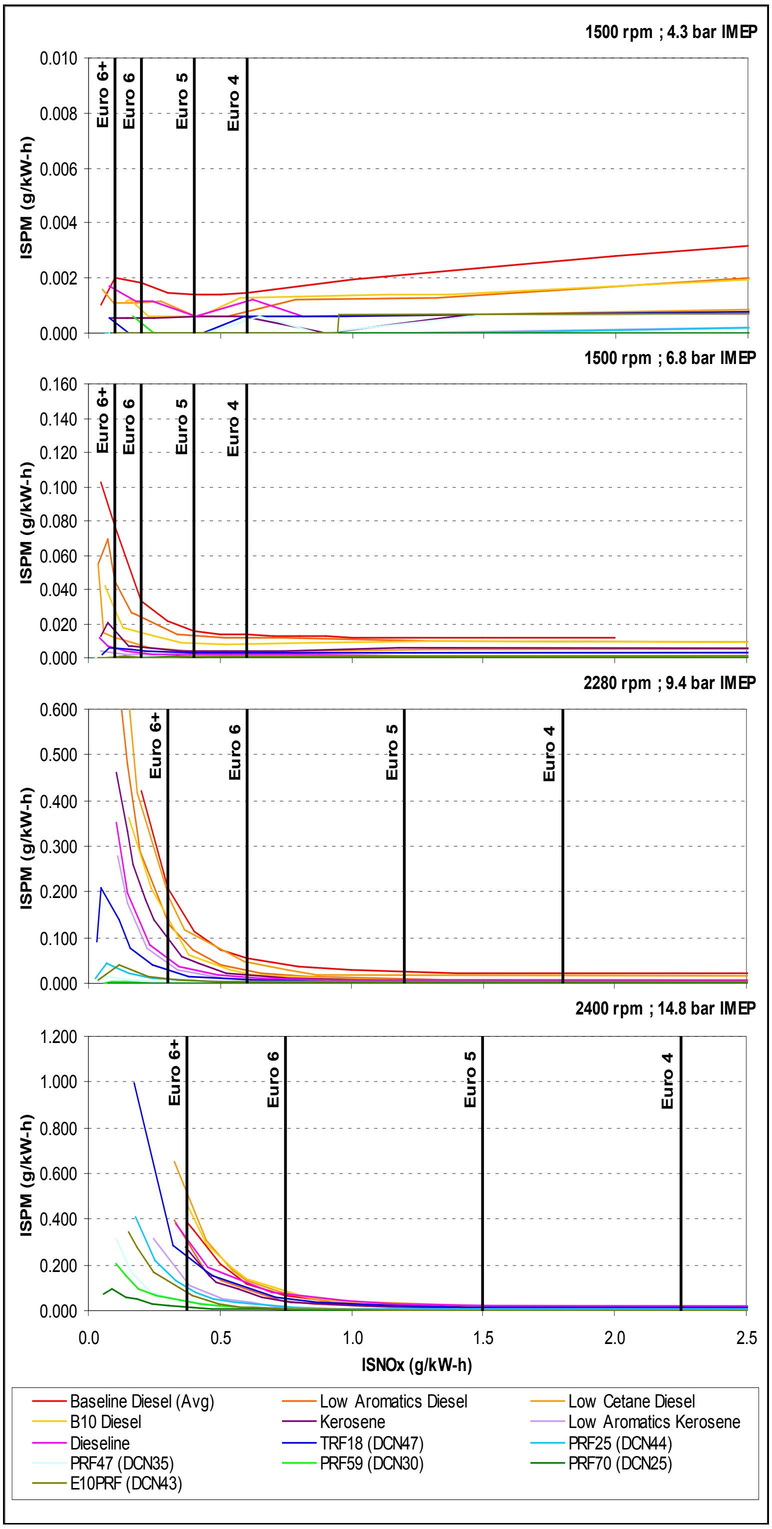
In conventional compression ignition engines, a characteristic 'PM-NOx trade-off curve' is typically observed, where PM emissions increase as EGR is increased with the objective of reducing NOx emissions. At the higher part-load points, this type of behaviour was seen in the Phase B engine [22], although the advanced engine design meant that significant increases in PM emissions were only seen below 0.5-0.7 g/kWh NOx.

The type of fuel also affects PM emissions and a wide variation in PM versus NOx emissions was seen, reflecting the wide range of fuels tested in this study **(Figure 6)**. For some fuels, the NOx/PM curve turned down at very low NOx levels. This behaviour is characteristic of HCCI combustion and indicates the onset of sootless combustion. At the 4.3 bar part-load point, PM emissions remained very low regardless of NOx level. At the 6.8 bar part-load point, the same behaviour was seen for some fuels with others showing a more typical NOx/PM trade-off. As engine load increased to 9.4 and 14.8 bar, some fuels maintained the flat or turned-down NOx/PM curve but the majority reverted to a typical diesel NOx/PM trade-off curve.

The results therefore show essentially sootless combustion at low load and a gradual reversion to more diesel-like combustion behaviour as the load increases with the transition influenced to some extent by the fuel type.

At all four part-load points, the NOx target levels for Euro 4 and Euro 5 performance were on the flat part of the curves while the NOx levels required for Euro 6 and Euro 6+ were in the area where PM emissions tended to increase. However, the PM emissions on all fuels were well within the range that can be effectively treated using a DPF.

Figure 6 ISPM emissions versus ISNOx emissions for all test fuels at the four part-load operating points



At the lower NOx levels, a wide range of PM emissions was seen for the different fuels. In general, the Baseline Diesel fuel, which is typical of a current European EN590 diesel fuel, gave the highest PM emissions. **Figure 7** shows an example of how the ISPM emissions varied for all fuels at the Euro 6 NOx emissions target. For convenience, the data are plotted against DCN but it is clear that volatility and aromatics content also influence PM emissions. **Figure 8** shows a summary of the same data in chart format.

Figure 7 DCN versus ISPM emissions for all test fuels at the Euro 6 NOx emissions target

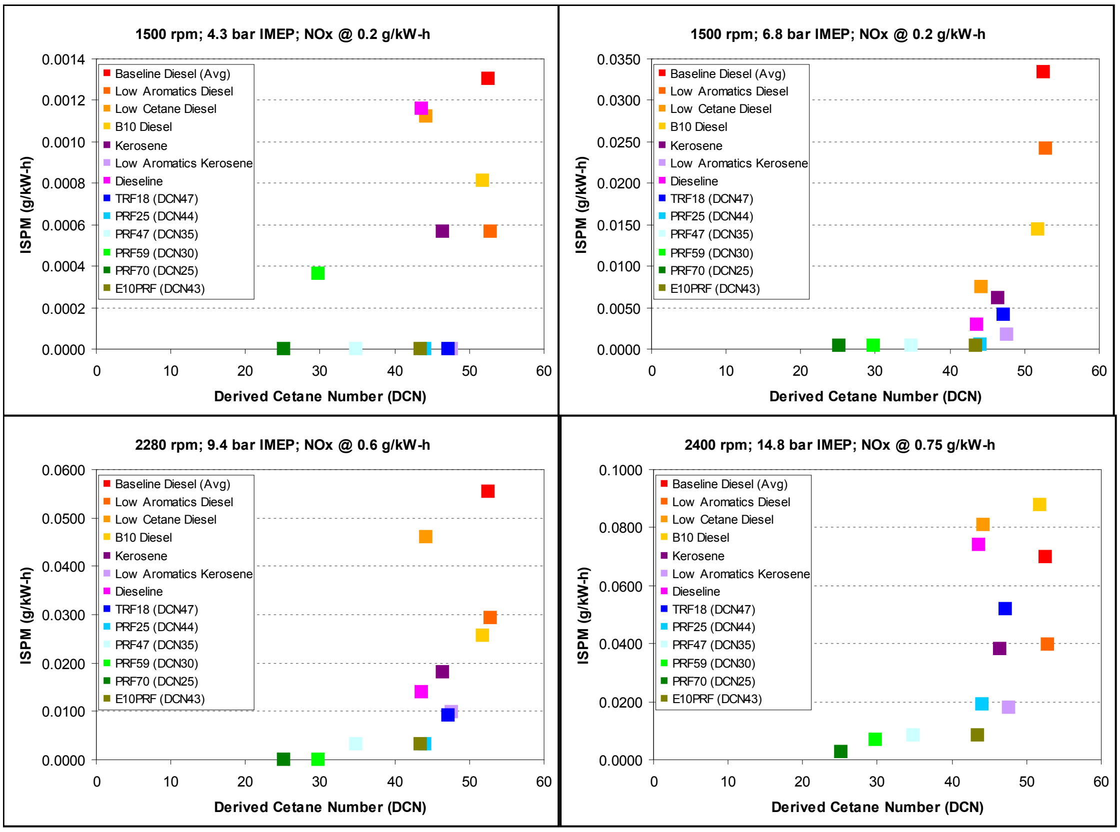
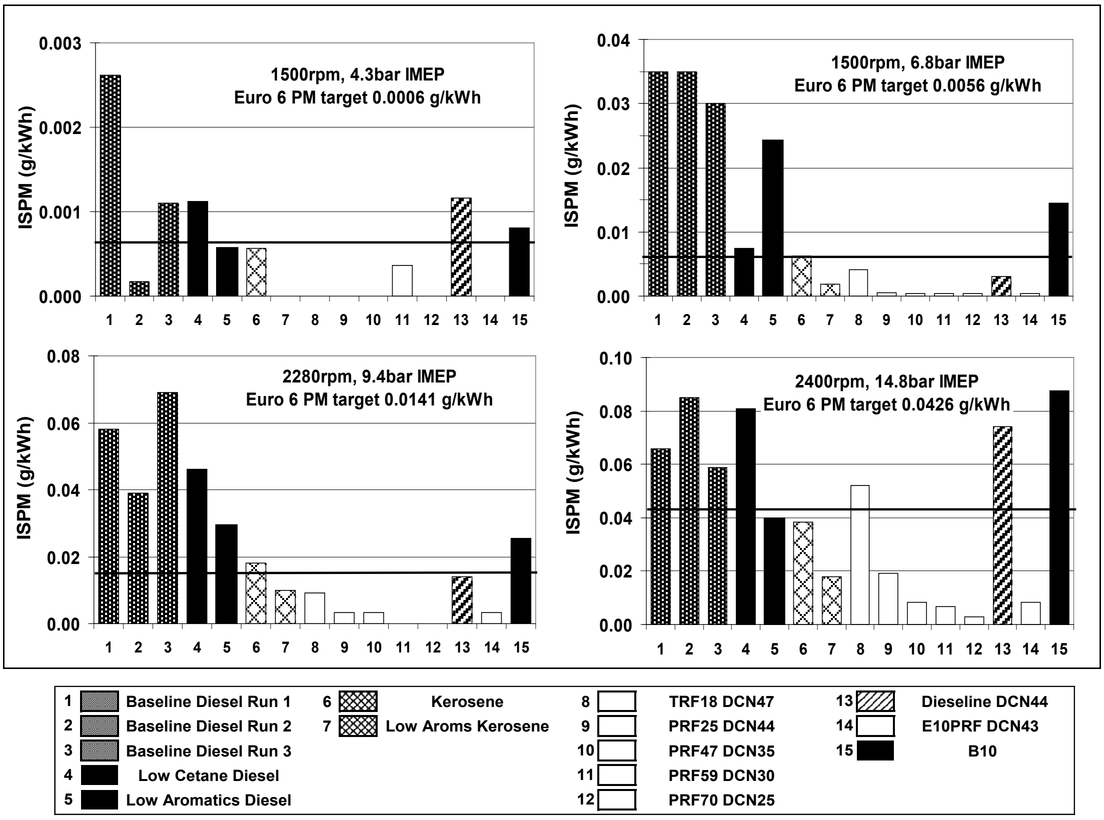


Figure 8 ISPM emissions at the Euro 6 NOx emissions target level for all test fuels at the four part-load operating points. The ISPM targets at the Euro 6 NOx emissions level are also shown.



Beginning with fuels in the diesel boiling range, reducing the DCN from 53 (Baseline Diesel) to 44 (Low Cetane Diesel) reduced the PM emissions by 71-85% at 6.8 bar. Lower PM emissions were also seen at 4.3 bar (14-57% reduction) and at 9.4 bar (4-27% reduction) but PM emissions increased at 14.8 bar (16-50%). Reducing the aromatics levels from 24.9% m/m (Baseline Diesel) to 2.2% m/m (Low Aromatics Diesel) reduced the PM emissions at all four part-load points. At 6.8 bar and 14.8 bar, PM emissions reductions were in the range 14-43% and larger reductions were seen at the other two part-load points (35-78%).

Increasing the fuel volatility into the kerosene boiling range reduced PM emissions at all four part-load points. Comparing the Kerosene with the Low Cetane Diesel (both fuels having similar DCNs and aromatics contents), the PM levels at 4.3 bar were very low on both fuels at the Euro 4 and Euro 5 NOx levels. At the Euro 6 NOx level, the PM emissions on Kerosene remained low while those on the Low Cetane Diesel almost doubled. At 6.8 bar, PM emissions on the Low Cetane Diesel were much lower than on the Baseline Diesel and the Kerosene fuel gave little further improvement. At the two higher part-load points, PM emissions reductions for Kerosene ranged between 48 and 72% compared with the Low Cetane Diesel.

Compared with the Baseline Diesel, reductions from 23-87% in PM emissions were seen at all part-load points for the Kerosene fuel. The Low Aromatics Kerosene gave further reductions in PM emissions. Compared with the Kerosene fuel, reductions between 26% and 77% were seen at the three higher part-load points. At 4.3 bar, soot emissions were too low to be measured.

Interpretation of these results only on the basis of aromatic effects presents some problems, however. This is because the T50 for the Low Aromatics Diesel was 47.8°C lower than that of the Baseline Diesel while the density of the Low Aromatics Diesel (812.3 kg/m^3) was lower than that of the Baseline Diesel (832.9 kg/m^3). It is therefore possible that some of the difference in emissions between these fuels is due to volatility or density effects. A similar situation exists for the kerosene fuels, where the T50 for the Low Aromatics Kerosene was 23°C lower than that of the Kerosene and the density was 23.2 kg/m^3 also lower. Separating out the aromatics effects from volatility and density is clearly difficult with the data that are available but an analysis is presented in **Appendix 4**.

The conclusion from this analysis is that a large fraction of the PM effects attributed to aromatics in fuels in the diesel range may be due to lower T50 and density for the fuel pairs compared above. For this reason, the aromatics effects reported above should be considered as upper values for the diesel fuels. For fuels in the kerosene boiling range, the effect of aromatics on PM emissions appears to be more clearer associated with the aromatics contents of the fuels.

An EN228 commercial gasoline (95RON and DCN14) was also tested but this fuel could not be run at all conditions in the Phase B engine without additional hardware modifications such as using a higher boost pressure. Therefore, gasoline fuels were modelled mainly using PRFs which allowed a range of octane/cetane numbers to be evaluated. To provide a comparison to the diesel and kerosene fuels, a PRF25 (DCN44) was first tested. PM emissions for this fuel were essentially zero at 4.3 bar and 6.8 bar and very low at the two higher part-load conditions. Compared with the Low Aromatics Kerosene, the PRF25 (DCN44) fuel reduced PM emissions by 41-82% at 9.4 bar and up to 25% at 14.8 bar.

Reducing the cetane number still further, using PRF fuels equivalent to DCN35 (PRF47), DCN30 (PRF59), and DCN25 (PRF70), reduced the PM emissions even more although, as noted above, higher boost pressure was needed to operate the DCN25 fuel. These results confirm findings of other studies that gasoline-like fuels may be suitable for use in HCCI engines [1,21] although PRF fuels cannot be considered fully representative of commercial gasolines.

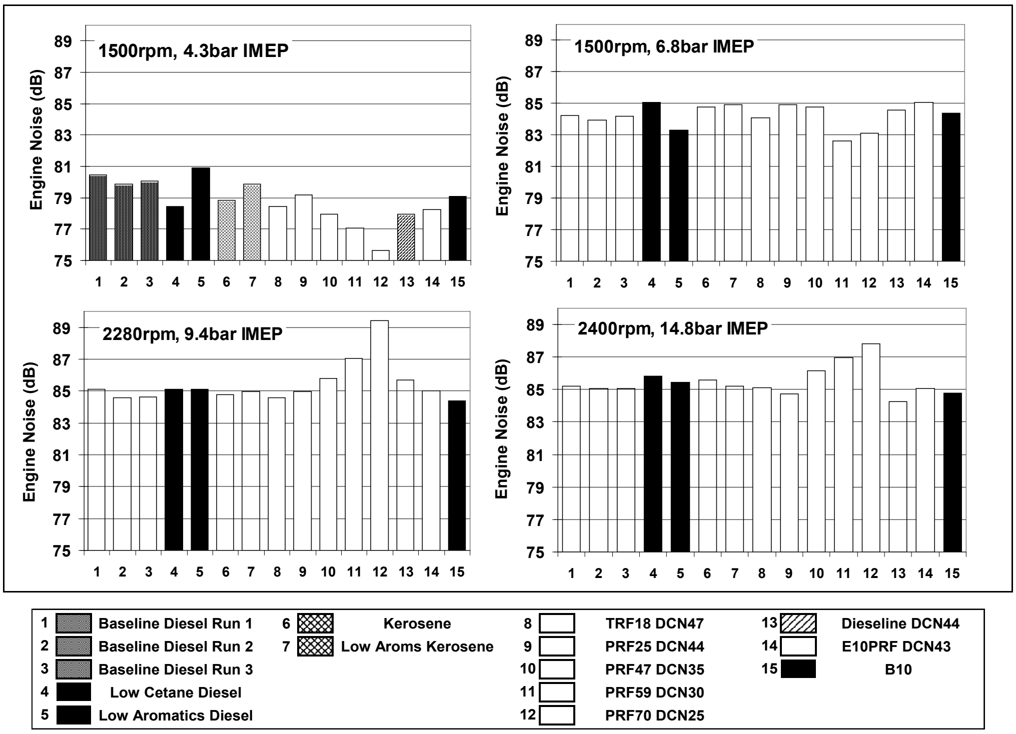
To test the effect of aromatic content, TRF18 (DCN47) was also tested. Comparing this fuel with the PRF25 (DCN44), the PM emissions increased were essentially zero at the 4.3 bar part-load point but increased at the three higher part-load points. The PM emissions were lower than for the non-gasoline fuels except at the 14.8 bar condition where a larger increase in PM emissions was seen. On a percentage basis, the PM emission reductions from TRF18 to PRF25 were large, ranging from 58% to 100% at the three higher part-load points. In this case, the T50s of the TRF18 and PRF25 fuels were matched so the PM effect is largely due to the difference in aromatics content. However, the PRF fuels did show rapidly increasing PM emissions as the DCN increased at the 4.8 bar test condition. For this reason, there is a possibility that some of the increase in PM emissions for the TRF18 fuel is due to its higher CN.

PM emissions on the ‘dieseline’ blend (DCN 44) varied depending upon the part-load point. At 4.3 bar, 6.8 bar, and 9.4 bar, PM emissions were low but higher PM emissions, similar to the diesel fuels, were seen at 14.8 bar. Nevertheless, even at 14.8 bar, the ‘PM-NOx trade-off curve’ indicated that the PM emissions for the ‘dieseline’ fuel improved compared to the Baseline Diesel and tended toward those of the kerosene or gasoline-like fuels as NOx levels decreased to the Euro 6+ target.

4.4. ENGINE NOISE

In the experimental design, limits were set on engine noise to maintain a level that is considered acceptable by diesel vehicle designers. The engine noise, as measured by CSL[3] did prove to be a critical parameter in the engine optimization and imposed a constraint on engine efficiency improvements for some engine options considered in the Part 1 study.

Figure 8 Engine noise at the Euro 6 NOx emissions target for all test fuels and the four part-load operating points



As seen in **Figure 8**, at the 9.4 bar and 14.8 bar part-load points, a reduction in DCN (and hence a longer ignition delay in the engine) led to an increase in CSL as would be expected for conventional diesel combustion. For a given fuel, increasing the EGR level to reduce NOx emissions resulted in a small increase in CSL.

For the 4.3 bar load point, the noise levels were generally well within the acceptable range but an increase in DCN (and a decreasing ignition delay) led to an increase in CSL. For a given fuel, increasing the EGR level to reduce the NOx gave a reduction in noise. Both of these trends are opposite to those observed at the higher part-load points. The results suggest that different combustion regimes may be operating at the highest and lowest part-load points.

Engine noise at the 6.8 bar part-load condition was acceptable for all fuels and the combustion behaviour seemed to be intermediate between the two combustion

[3] The CSL as used here refers to the calculated overall sound level outside of the engine and includes estimates of both combustion and mechanical noise. However, the differences observed between different fuels are a result of differences in the combustion noise level.

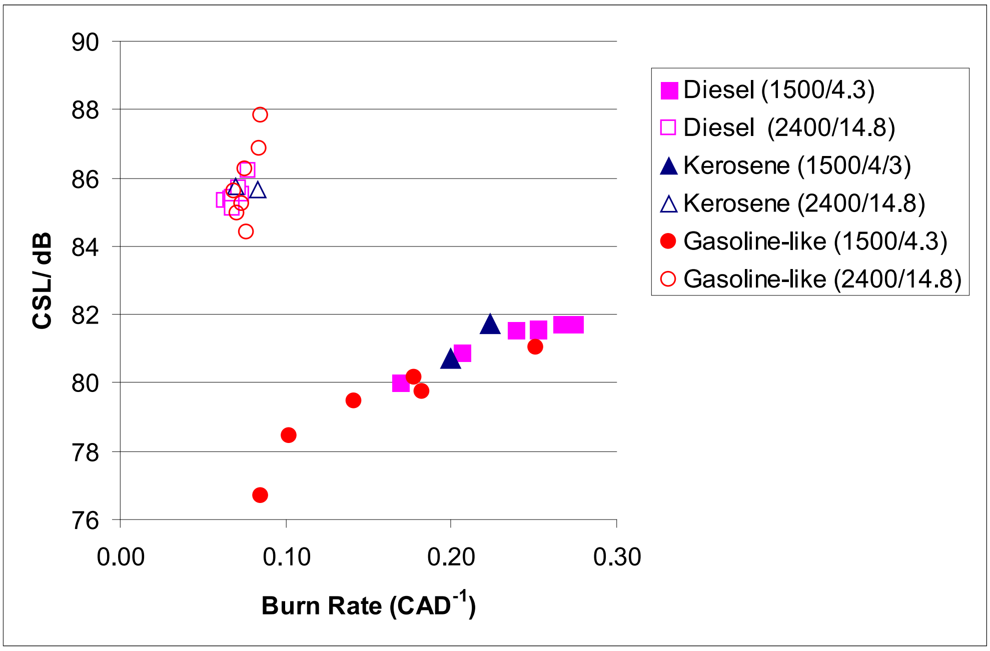
regimes. No clear trends were observed with fuel type or EGR level at this part-load condition.

At the two higher part-load conditions, noise level was fairly constant for different fuels except for the lowest DCN PRF blends. As the DCN decreased below 44, the noise level increased at both the 9.4 bar and 14.8 bar IMEP conditions.

The CSL is expected to depend on the maximum rate of pressure rise in the engine which is proportional to the burn rate. **Figure 10** shows that this is the case for the Phase B engine as well since the CSL increases proportional to the burn rate.

In conventional diesel combustion, the burn rate increases with ignition delay, because more fuel is available for pre-mixed burning. However, the relationship between burn rate and ignition delay is more complex here. At the higher loads (9.4 bar and 14.8 bar), the behaviour is similar to a conventional diesel engine, with burn rate and CSL increasing with longer ignition delay. However, under HCCI-like conditions at 4.3 bar, and to some extent at 6.8 bar, the CSL decreased as the ignition delay increased.

Figure 10 Relationship between burning rate and CSL for the highest and lowest part-load points and Euro 5 NOx levels

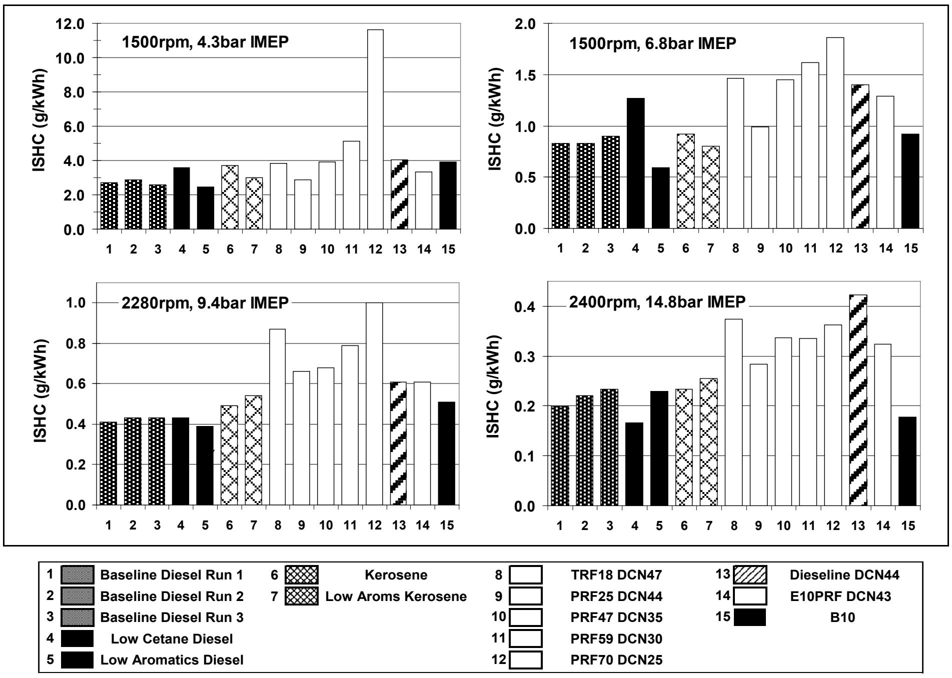


4.5. HC AND CO EMISSIONS

Other HCCI studies have shown that the combustion conditions producing low NOx and PM emissions also tend to increase emissions of HC and CO [7]. These emissions are not considered to be a major concern, however, since DOCs are effective for removing these pollutants from the tailpipe as long as the exhaust temperature is sufficiently high. Nevertheless, any measures that can reduce engine-out HC and CO emissions will reduce the demand on exhaust aftertreatment and, to some extent, improve efficiency.

Fuel properties had some effect on HC and CO emissions, although the effects were much smaller than for PM emissions. The trends are illustrated in **Figure 11** for Indicated Specific HC (ISHC) emissions at Euro 6 NOx levels.

Figure 11 ISHC emissions at the Euro 6 NOx emissions target for all test fuels and four part-load operating points



With the exception of the DCN25 (PRF70) fuel which was at the limit of engine operation, HC emissions for all fuels at 4.3 bar were only about a factor of two different. A similar trend was seen at 6.8 bar and 9.4 bar although the increases in HC emissions was more marked for the gasoline-like fuels. At 14.8 bar, the difference between fuels was small.

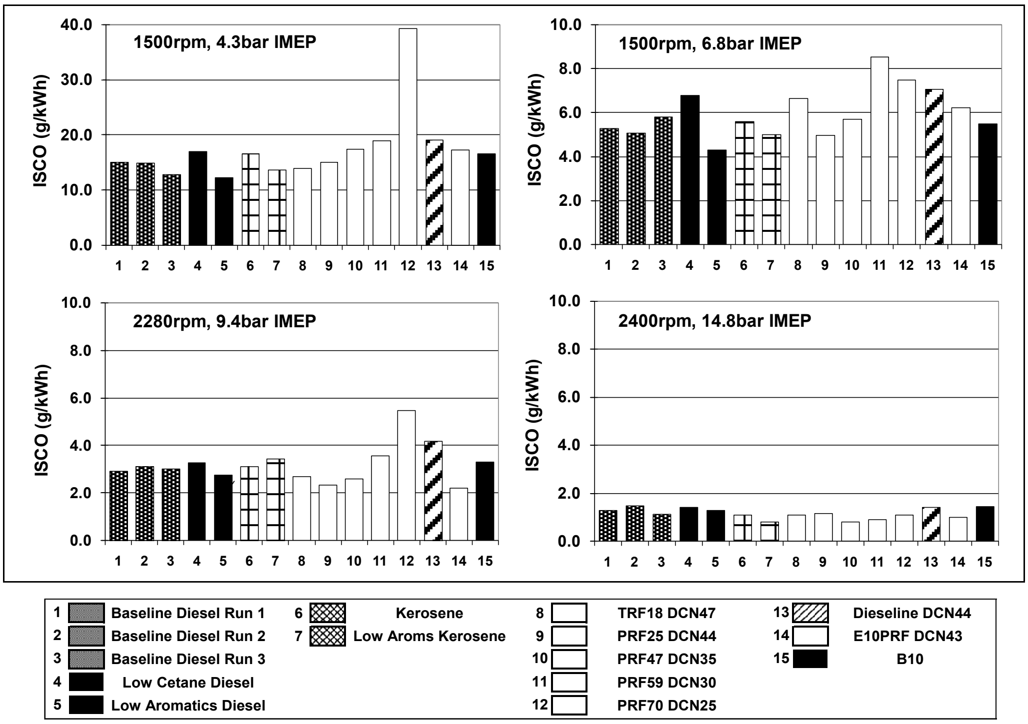
Reducing DCN from 53 to 44 in the diesel boiling range increased HC emissions at 4.3 bar and 6.8 bar by 32-53%, but had little effect at 9.4 bar and reduced emissions by 22-36% at 14.8 bar. A similar picture was seen on reducing DCN from 44 to 35 in the gasoline boiling range.

Reducing aromatics in the diesel boiling range lowered HC emissions by 8-31% at the two lower part-load points and had a small or neutral effect at higher part-load points. In the kerosene boiling range, reducing aromatics decreased HC emissions by up to 26% at 4.3 bar but higher HC emissions were seen at higher part-load loads. In the gasoline boiling range, reducing aromatics lowered the HC emissions at all part-load points by 20-32%.

Compared with the Low Cetane Diesel, the HC emissions were about the same for the Kerosene fuel at 4.3 bar. Lower HC emissions (by 21-31%) were observed at 6.8 bar and higher HC emissions (by 11-41%) were observed at the higher part-load conditions. Increasing volatility from the kerosene to the gasoline boiling range increased HC emissions at all four part-load points for the fuels that contained aromatics and either increased or had little effect for the fuels that contained low aromatics levels at the same DCN level.

Similar results are shown for CO emissions in **Figure 12**. Indicated Specific CO (ISCO) emissions are shown in this figure.

Figure 12 ISCO emissions at the Euro 6 NOx emissions target level for all test fuels and four part-load operating points

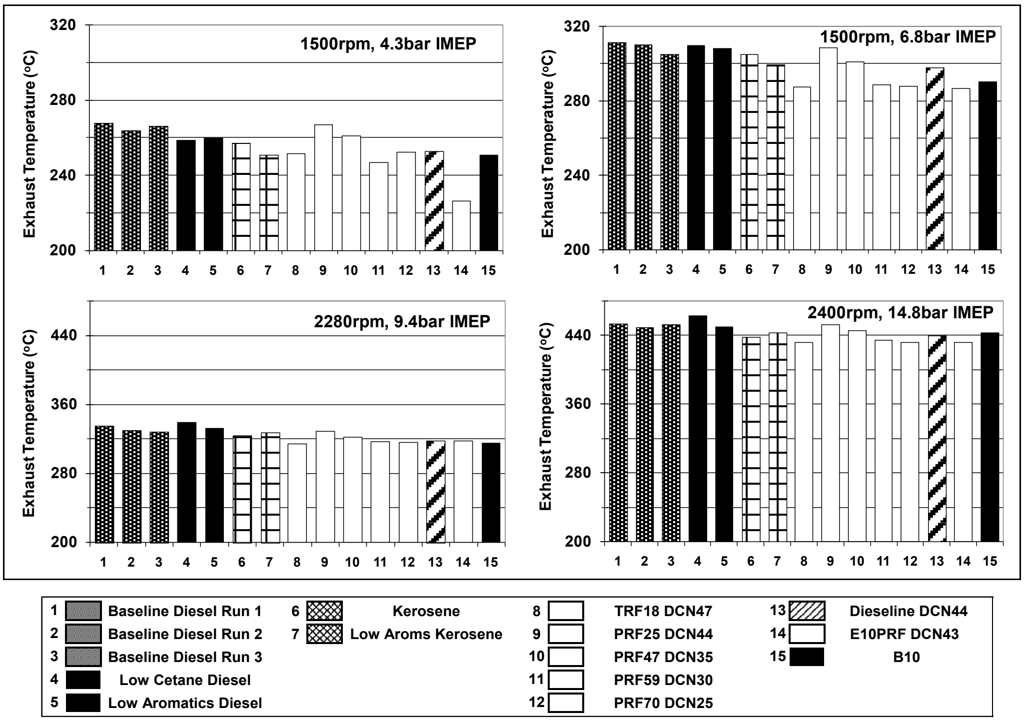


The trends for CO emissions with different fuels were similar to those for HC emissions with the highest CO emissions observed at the lower part-load points. Overall, there was less variation in the CO emissions compared to the HC emissions. The highest CO emissions were seen for the PRF70 fuel where combustion was marginal.

The exhaust temperature at the four part-load conditions increased slightly as the EGR levels increased and the NOx emissions decreased. At the Euro 6 NOx levels, the mean exhaust temperatures were 257°C at 4.3 bar, 299°C at 6.8 bar, 324°C at 9.4 bar and 443°C at 14.8 bar. Although the range across all fuels was 25-32°C at the three higher part-load points, the range was 42°C at the 4.3 bar condition which is especially critical for DOC operation (see **Figure 13**). At this part-load condition, the exhaust temperatures were 256°C on average for the gasoline-like fuels and 263°C on average for the diesel fuels. The E10PRF blend, however, gave the lowest exhaust temperature of 226°C at the 4.3 bar condition. At the higher part-load points, the gasoline-like fuels again gave slightly lower exhaust temperatures but the E10PRF blend was not different from the PRF/TRF fuels at these conditions.

Although these exhaust temperatures are low at the lowest part-load condition, they are still thought to be high enough to ensure light-off of the DOC [19]. A full consideration of catalyst effectiveness under transient and cold engine operation would be needed, however, which was beyond the scope of this study.

Figure 13 Exhaust temperatures at the Euro 6 NOx emissions target level for all fuels and four part-load operating points



4.6. SHORT-TERM IMPACT OF BIOFUELS

The introduction of low levels of biofuels into diesel and gasoline fuels presents several challenges that are being addressed by the motor and fuel industries and are beyond the scope of this study. However, ‘part time’ HCCI engines are likely to be introduced when gasoline or diesel fuels containing bio-components are already widely available in the market. Regulations are increasingly requiring biofuels to be added as components of these conventional fuels, so in the context of this HCCI study it was useful to ask whether the presence of biofuel in the blend offered any advantages or disadvantages in terms of maintaining low emissions and good efficiency.

Tests were performed using a 10% v/v blend of Fatty Acid Methyl Ester (FAME) in the Baseline Diesel fuel (B10) and 10% v/v ethanol in a gasoline-like fuel (E10PRF). The target DCN for E10PRF was 44, so that it could be compared with the hydrocarbon-only PRF25 (DCN44) fuel.

The B10 blend gave lower PM emissions than the Baseline Diesel at the three lower part-load points. This is in line with expectations, because the presence of oxygen in the fuel tends to improve soot oxidation. However, PM emissions were slightly higher at the 14.8 bar IMEP test condition. It should be remembered that the soluble organic fraction of PM may increase with the use of FAME, especially under cold and transient conditions, and this was not tested in this study. This trend was seen, however, in increased HC emissions at the lower load points, especially at 4.3 bar where the increases ranged from 33-45%. In contrast, at 14.8 bar, addition of FAME reduced HC emissions by 15-31%.

There was no consistent impact of FAME on CSL.

In terms of PM emissions, the E10PRF blend (DCN43) gave similar emissions to the pure hydrocarbon PRF with DCN44 at the three lower part-load points and reduced PM emissions at the 14.8 bar IMEP condition. The PM emissions were essentially zero on both fuels at the two lower part-load points. The effect on HC and CO emissions was overall neutral with increases up to 32% seen under some conditions but decreases in other cases. There was no consistent trend on efficiency or noise levels with the E10PRF fuel.

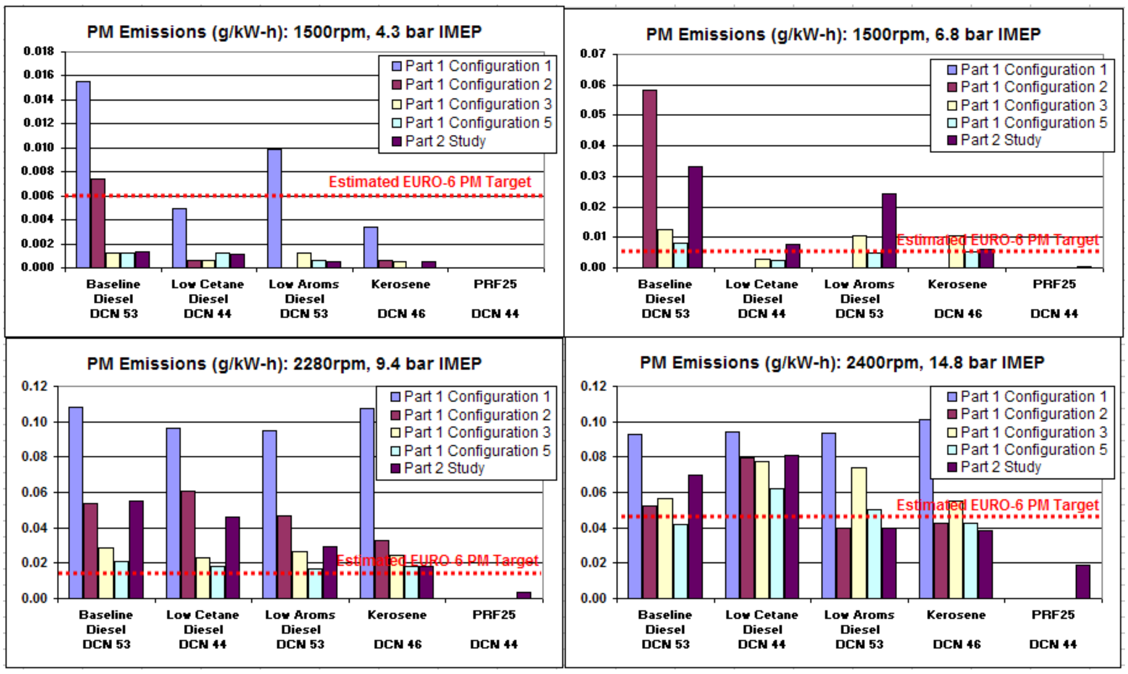
Overall, the addition of small (10% v/v) amounts of bio-components had mixed effects on emissions, sometimes increasing emissions and sometimes decreasing. These effects should not compromise efforts to achieve practical advanced combustion engines with fuels containing bio-components. Since increased exhaust catalyst conversion may be needed in some cases, the use of biofuel blends needs to be considered at the vehicle design stage.

4.7. SYNTHESIS OF ENGINE AND FUEL EFFECTS

In Part 1 of this study, the impact of engine hardware on performance, emissions, and noise was investigated using four diesel fuels. In **Figure 14**, the PM emissions from these Part 1 fuels are compared to those from the gasoline-like fuel, PRF25 (DCN44), that was tested only in Part 2 in order to evaluate the relative importance of large engine and fuel changes. The PRF25 fuel was selected for this comparison because its DCN is similar to those of the Low Cetane Diesel and Kerosene.

ISPM emissions at the Euro 6 targets for ISNOx are shown at each of the four part-load points. The estimated Euro 6 PM targets are also indicated (see also **Table 4**).

Figure 14 Comparison of ISPM emissions at Euro 6 NOx emissions targets for five fuels and four part-load operating points[4]



Part 1 Configuration 1: Phase A engine (Euro 5 hardware)
Part 1 Configuration 2: Phase B engine with lower CR and standard swirl (Euro 6 hardware)
Part 1 Configuration 3: Phase B engine with lower CR and optimised swirl by Variable Valve Timing (VVT)
Part 1 Configuration 5: Phase B engine with lower CR, optimised in-cylinder swirl, and no pilot injection
Part 2 Study: Equivalent to Part 1 Configuration 2

These results suggest that the NOx and PM Euro 6 targets can be achieved at all part-load points with conventional diesel fuels, kerosene, and gasoline-like fuels and without extraordinary aftertreatment systems. The NOx emission targets can be reached without special NOx aftertreatment and relatively modest reductions of PM would be needed by the DPF to meet the targets. The relative impact of engine configuration and fuel is clearly different at different part-load conditions. For this reason, the relative contribution of engine and fuel to an overall driving cycle is also expected to be different although this was not investigated in these studies.

At three of the four part-load conditions, the engine configuration makes a larger contribution to PM reduction than do the fuel variations studied in Part 1, with reductions typically greater than five times from Configuration 1 to Configuration 5. Addition of VVT (Configuration 3) to the engine tested in the Part 2 study would be expected to provide additional reductions in emissions.

Relative to the diesel and kerosene fuels, the PRF25 (DCN44) showed virtually sootless combustion at three of the four part-load conditions and much reduced emissions even at the highest part-load point.

[4] Data were not collected for the Part 1 Configuration 1 engine at the 1500 rpm/6.8 bar IMEP condition.

5. CONCLUSIONS

This study investigated the impact of a broad range of fuel properties on engine efficiency, engine-out emissions, and noise using a Euro 6 benchmarked optimized single-cylinder engine equivalent to Configuration 2 in Part 1 of this study [12,22].

- The warmed-up engine could be run successfully on a wide range of diesel, kerosene, and gasoline-like fuels at all part-load and full-load conditions.
- For the range of fuels tested here, the fuel injection pressure and boost pressure could be harmonized and optimized combustion achieved by matching the centre of combustion (CA50) for each fuel. This is an important observation and could translate into a strategy for future closed loop combustion control (CLCC) based on in-cylinder pressure sensing.
- When the CA50 was adjusted to a constant value for each fuel, that is, to the same centre of combustion as for the Baseline Diesel, all fuels gave approximately the same engine efficiency at the same speed and load conditions.
- Engine efficiency was equal to or better than conventional diesel engines. However, at the very lowest NOx levels there was some decrease in efficiency as a consequence of higher EGR levels.
- For several fuels and at certain speeds and loads, the breaking of the ‘NOx/PM trade-off curve’ was observed. This observation is characteristic of HCCI-like combustion and demonstrated that the hardware configuration used in this study could achieve HCCI combustion behaviour especially at the lower part-load operating points.
- In general, as load increased to 9.4 bar and 14.8 bar IMEP, all fuels tended to revert to a classic diesel NOx/PM trade-off curve.
- Very low NOx emission levels were achieved on a range of fuels while maintaining low levels of PM, HC, and CO that could be acceptably treated by DOC and DPF aftertreatment. Other parameters of interest (noise and efficiency) were also at acceptable levels for all fuels and part-load points.
- The engine hardware needed to achieve this performance is available today and includes high pressure injection, higher boost pressures, high and low pressure cooled EGR, and in-cylinder pressure sensing coupled with a sophisticated combustion control system. A DPF would be needed to reduce PM emissions and a DOC would be needed to control HC and CO emissions. Optimised in-cylinder swirl would be expected to provide additional performance improvements.
- No clear advantage was found by switching off the pilot injection. Lower PM emissions and higher noise were observed at the higher part-load points while HC and CO emissions increased at the lower part-load points.
- The relative importance of the fuel’s ignition delay (CN), volatility, and molecular composition on PM emissions appears to be different at different speed/load points. In general, increasing ignition delay had a beneficial effect at the lower part-load points for diesel fuels but only a moderate effect for the gasoline-like fuels. At these conditions, the PM emissions for the gasoline-like fuels were already very low, typically an order of magnitude lower than for the diesel fuels. Increasing volatility from the diesel fuel range to kerosene generally reduced PM emissions. Further volatility reductions from kerosene to

gasoline-like fuels reduced PM emissions at the lower part-load points but gave some increases at the highest part-load point. Reducing aromatics in the fuel consistently reduced the PM emissions, although some of the effect seen was probably due to volatility effects.

- Although the absolute PM emissions were very low for all fuels, sizeable differences were found between the relative PM emissions for different fuels at high EGR levels.
- Although the engine could be run on gasoline-like PRF fuels having DCNs less than 30, it was necessary to increase the boost pressure which also resulted in higher HC and CO emissions.
- The Part 1 study showed that further improvements in engine performance beyond that of the Part 2 engine could be achieved by optimizing in-cylinder swirl. Part 2 of the study has also shown that dramatic fuel changes, for example to a gasoline PRF with DCN44, can further reduce emissions.
- Including small amounts of ethanol or FAME into the test fuel blends had no short-term detrimental effect on the combustion process.
- Although the fuel matrix tested in this study was extensive, some areas of the fuel map were not studied. For example, we are not able to draw conclusions for fuels below DCN44 in the diesel and kerosene boiling ranges nor have we evaluated ‘real’ gasoline blends with higher cetane number/lower octane number than conventional gasoline. In addition, this study has investigated engine performance and emissions for a warmed-up engine only. Additional work would be needed to investigate engine performance under transient and cold start conditions.

6. GLOSSARY

ASTM	American Society for Testing and Materials
ATDC	After Top Dead Centre
BMEP	Brake Mean Effective Pressure
BTDC	Before Top Dead Centre
^{o}CA	Degrees Crank Angle
CA10	Point in the combustion process where 10% of the injected fuel mass has been converted
CA50	Point in the combustion process where 50% of the injected fuel mass has been converted, also called the centre of combustion
CAI	Controlled Auto Ignition
CFR	Cooperative Fuel Research
CLCC	Closed Loop Combustion Control
CN	Cetane Number
CO	Carbon Monoxide
CR	Compression Ratio
CSL	Combustion Sound Level
DCN	Derived Cetane Number
DOE	Design of Experiments
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EN228	Standard European CEN specification for gasoline
EN590	Standard European CEN specification for diesel
FAME	Fatty Acid Methyl Ester
FSN	Filter Smoke Number
HC	Hydrocarbon
HCCI	Homogeneous Charge Compression Ignition
IMEP	Indicated Mean Effective Pressure
IQT	Ignition Quality Test or Tester

ISCO	Indicated Specific Carbon Monoxide Emissions
ISHC	Indicated Specific Hydrocarbon Emissions
ISPM	Indicated Specific Particulate Mass Emissions
ISNOx	Indicated Specific NOx Emissions
MON	Motor Octane Number
NEDC	New European Driving Cycle
NOx	Nitrogen Oxides
PM	Particulate Matter or Mass
PRF	Primary Reference Fuel
RME	Rapeseed Methyl Ester
RON	Research Octane Number
SCR	Selective Catalytic Reduction
TRF	Toluene Reference Fuel
VVT	Variable Valve Timing

7. ACKNOWLEDGMENTS

The authors wish to thank Shell Global Solutions UK, Total, Repsol YPF, and ExxonMobil for providing the fuels, components, and analytical data used in this study.

8. REFERENCES

1. Kalghatgi, G.T. et al (2006) Advantages of fuels with high resistance to auto-ignition in late-injection, low-temperature, compression ignition combustion. SAE Paper No. 2006-01-3385. Warrendale PA: Society of Automotive Engineers

2. Ryan, T. (2006) HCCI – update of progress 2005. 12th Diesel Engine-Efficiency and Emissions Research (DEER) Conference, August 20-24, 2006, Detroit MI

3. Steiger, W. (2006) Future powertrains and fuels for sustainable mobility. IMechE Conference on cost effective low carbon powertrains for future vehicles, 6-7 November 2006, London

4. Farrell, J.T. and Bunting, B.G. (2006) Fuel composition effects at constant RON and MON in an HCCI engine operated with negative valve overlap. SAE Paper No. 2006-01-3275. Warrendale PA: Society of Automotive Engineers

5. Akihama, K. et al (2001) Mechanism of the smokeless rich diesel combustion by reducing temperature. SAE Paper No. 2001-01-0655. Warrendale PA: Society of Automotive Engineers

6. Kimura, S. et al (1999) New combustion concept for ultra-clean and high-efficiency small DI diesel engines. SAE Paper No. 1999-01-3681. Warrendale PA: Society of Automotive Engineers

7. CONCAWE (2008) Advanced combustion for low emissions and high efficiency: a literature review of HCCI combustion concepts. Report No. 4/08. Brussels: CONCAWE

8. Duffy, K. et al (2006) Heavy duty HCCI development activities - DOE High Efficiency Clean Combustion (HECC). DOE Contract DE-FC26-05NT42412. 12th Diesel Engine-Efficiency and Emissions Research (DEER) Conference, August 20-24, 2006, Detroit MI

9. Kalghatgi, G.T. et al (2007) Partially pre-mixed auto-ignition of gasoline to attain low smoke and low NOx at high load in a compression ignition engine and comparison with a diesel fuel. SAE Paper No. 2007-01-0006. Warrendale PA: Society of Automotive Engineers

10. Weissbäck, M. et al (2003) Alternative Brennverfarhren – ein Ansatz für den zukünftigen Pkw-Dieselmotor. *MTZ Worldwide 64, 9, 718-727*

11. Duret, P. et al (2004) Progress in diesel HCCI combustion within the European SPACE LIGHT project. SAE Paper No. 2004-01-1904. Warrendale PA: Society of Automotive Engineers

12. Muether, M. et al (2008) Advanced combustion for low emissions and high efficiency. Part 1: Impact of engine hardware on HCCI combustion. SAE Paper No. 2008-01-2405. Warrendale PA: Society of Automotive Engineers

13. ASTM (2007) Standard test method for determination of ignition delay and Derived Cetane Number (DCN) of diesel fuel oils by combustion in a constant volume chamber. ASTM Standard D6890-07a. West Conshohocken PA: ASTM International

14. ASTM (2003) Standard test method for research octane number of spark-ignition engine fuel. ASTM Standard D2699–03a. West Conshohocken PA: ASTM International

15. Kalghatgi, G.T. et al (2005) Auto-ignition quality of practical fuels and implications for fuel requirements of future SI and HCCI engines. SAE Paper No. 2005-01-0239. Warrendale PA: Society of Automotive Engineers

16. Weall, A.J. and Collings, N. (2007) Investigation into partially premixed combustion in a light-duty multi-cylinder diesel engine fuelled with a mixture of gasoline and diesel. SAE Paper no. 2007-01-4058. Warrendale PA: Society of Automotive Engineers

17. Zhong, S. et al (2005) Experimental investigation into HCCI combustion using gasoline and diesel blended fuels. SAE Paper no. 2005-01-3733. Warrendale, PA: Society of Automotive Engineers

18. Alt, N. et al (2005) Combustion sound prediction within combustion system development. SIA article technique R-2004-07-07. Suresnes: Société des Ingénieurs de l'Automobile

19. Majewski, W.A. and Khair, M.K. (2006) Diesel emissions and their control. Part V, Chapter 18, Emission control catalysts, p. 369. Warrendale PA: Society of Automotive Engineers

20. Thompson, N.D. and Larivé, J.-F. (2003) Regulations to control emissions and fuel implications. Proceedings of the 4th International Colloquium on fuels, 15-16 January 2003, Esslingen

21. Cracknell, R.F. et al (2008) Advanced combustion for low emissions and high efficiency. Part 2: Impact of fuel properties on HCCI combustion. SAE Paper No. 2008-01-2404. Warrendale PA: Society of Automotive Engineers

22. CONCAWE (2010) Advanced combustion for low emissions and high efficiency. Part 1: Impact of engine hardware on HCCI combustion. Report No. 09/10. Brussels: CONCAWE

APPENDIX 1 FUEL PROPERTIES

	Fuels Tested in Part 1 Study				Additional Fuels Tested in Part 2 Study										
	Baseline Diesel (DCN53)	Low Cetane Diesel (DCN44)	Low Aromatics Diesel (DCN53)	Kerosene (DCN47)	Low Aromatics Kerosene (DCN48)	TRF18 (DCN47)	PRF25 (DCN44)	PRF47 (DCN35)	PRF59 (DCN30)	PRF70 (DCN25)	PRF95 (DCN15)	EN228 Gasoline (DCN14)	"Dieseline" (DCN44)	E10PRF (DCN43)	B10 (DCN52)
Research Octane Number (RON)	4.8 [A]	24.8 [A]	4.1 [A]	19.3 [A]	16.7 [A]	17.7 [A]	25.0 [B]	47.0 [B]	59.0 [B]	70.0 [B]	95.0 [B]	96.4 [D]	26.2 [A]	26.6 [A]	6.7 [A]
Derived Cetane Number	52.6 [C]	44.2 [C]	52.9 [C]	46.5 [C]	47.6 [C]	47.2 [C]	44.1 [E]	34.9 [E]	29.8 [E]	25.2 [E]	14.7 [E]	14.1 [E]	43.6 [C]	43.4 [C]	51.8 [C]
Density @ 15°C	0.8329 [F]	0.8418 [F]	0.8123 [F]	0.8011 [F]	0.7779 [F]	0.7206 [F]	0.6901 [F]	0.6919 [F]	0.6928 [F]	0.6937 [F]	0.6955 [F]	0.7459 [F]	0.8200 [F]	0.6976 [F]	0.8381 [F]
Distillation															
IBP	147.9 [G]	161.0 [G]	192.9 [G]	151.0 [G]	159.1 [G]	98.2 [G]	97.8 [G]	97.7 [G]	97.6 [G]	98 [G]	98.1 [G]	31.8 [G]	46.0 [G]	70.8 [G]	166.1 [G]
10% rec	195.4 [G]	184.0 [G]	205.5 [G]	165.6 [G]	168.1 [G]	98.5 [G]	97.9 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	49.7 [G]	108.6 [G]	71.7 [G]	202.8 [G]
20% rec	221.7 [G]	193.2 [G]	211.1 [G]	171.8 [G]	170.4 [G]	98.5 [G]	97.9 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	62.4 [G]	154.6 [G]	73.1 [G]	229.6 [G]
30% rec	243.6 [G]	204.6 [G]	216.2 [G]	180.1 [G]		98.6 [G]	97.9 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	74.7 [G]	191.8 [G]	93.2 [G]	251.4 [G]
40% rec	261.4 [G]	220.5 [G]	221.0 [G]	189.2 [G]		98.6 [G]	97.9 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	86.9 [G]	226.8 [G]	97.5 [G]	270.6 [G]
50% rec	274.9 [G]	241.0 [G]	227.1 [G]	199.0 [G]	176.0 [G]	98.7 [G]	97.9 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	98.5 [G]	256.2 [G]	97.7 [G]	283.7 [G]
60% rec	287.2 [G]	266.7 [G]	233.8 [G]	210.1 [G]		98.7 [G]	97.9 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	108.9 [G]	278.2 [G]	97.7 [G]	296.6 [G]
70% rec	298.7 [G]	294.0 [G]	244.8 [G]	222.7 [G]		98.8 [G]	97.9 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	119.6 [G]	294.5 [G]	97.7 [G]	308.7 [G]
80% rec	311.9 [G]	316.6 [G]	266.3 [G]	236.0 [G]		98.9 [G]	97.9 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	134.1 [G]	311.0 [G]	97.7 [G]	320.7 [G]
90% rec	328.9 [G]	338.6 [G]	329.3 [G]	253.1 [G]	188.7 [G]	99.2 [G]	98.0 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	152.8 [G]	331.1 [G]	97.7 [G]	333.5 [G]
95% rec	344.0 [G]	354.5 [G]	360.0 [G]	268.5 [G]		99.7 [G]	98.0 [G]	97.9 [G]	97.9 [G]	98.3 [G]	98.3 [G]	169.3 [G]	346.8 [G]	97.7 [G]	343.5 [G]
FBP	356.4 [G]	369.3 [G]	369.1 [G]	291.5 [G]	206.2 [G]	107.0 [G]	104.4 [G]	103.9 [G]	102.9 [G]	99.6 [G]	102.6 [G]	198.9 [G]	360.6 [G]	102.9 [G]	354.2 [G]
Sulphur - WD XRF	7.3 [J]	39.0 [J]	41.0 [J]	226.0 [J]	<3.0 [H]	0.0 [K]	0.0 [K]	0.0 [K]	0.0 [K]	0.0 [K]	0.0 [K]	21.8 [H]	11.2 [L]	0.0 [K]	7.0 [H]
Aromatics															
Mono	21.0 [M]	25.2 [M]	2.2 [M]	16.5 [M]	5.9 [M]	18.0 [R]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [Q]	34.4 [X]	33.5 [P]	0.0 [Q]	24.3 [N]
Di	3.3 [M]	1.7 [M]	0.1 [M]	2.6 [M]	0.3 [M]	0.0 [R]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [X]	3.6 [P]	0.0 [Q]	3.4 [N]
Tri	0.6 [M]	0.2 [M]	0.1 [M]	0.2 [M]	<0.1 [M]	0.0 [R]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [X]	0.4 [P]	0.0 [Q]	0.3 [N]
Total	24.9 [M]	27.1 [M]	2.2 [M]	19.3 [M]	6.2 [M, V]	0.0 [R]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [Q]	0.0 [Q]	34.4 [X]	37.5 [P]	0.0 [Q]	28 [N]
Lower Heating value	43.0 [S]	42.9 [S]	43.5 [S]	43.0 [S]	43.7 [S]	44.3 [U]	44.2 [S]	44.1 [U]	44.0 [U]	43.9 [U]	43.7 [U]	43.3 [Y]	42.8 [T]	40.6 [S]	42.5 [W]

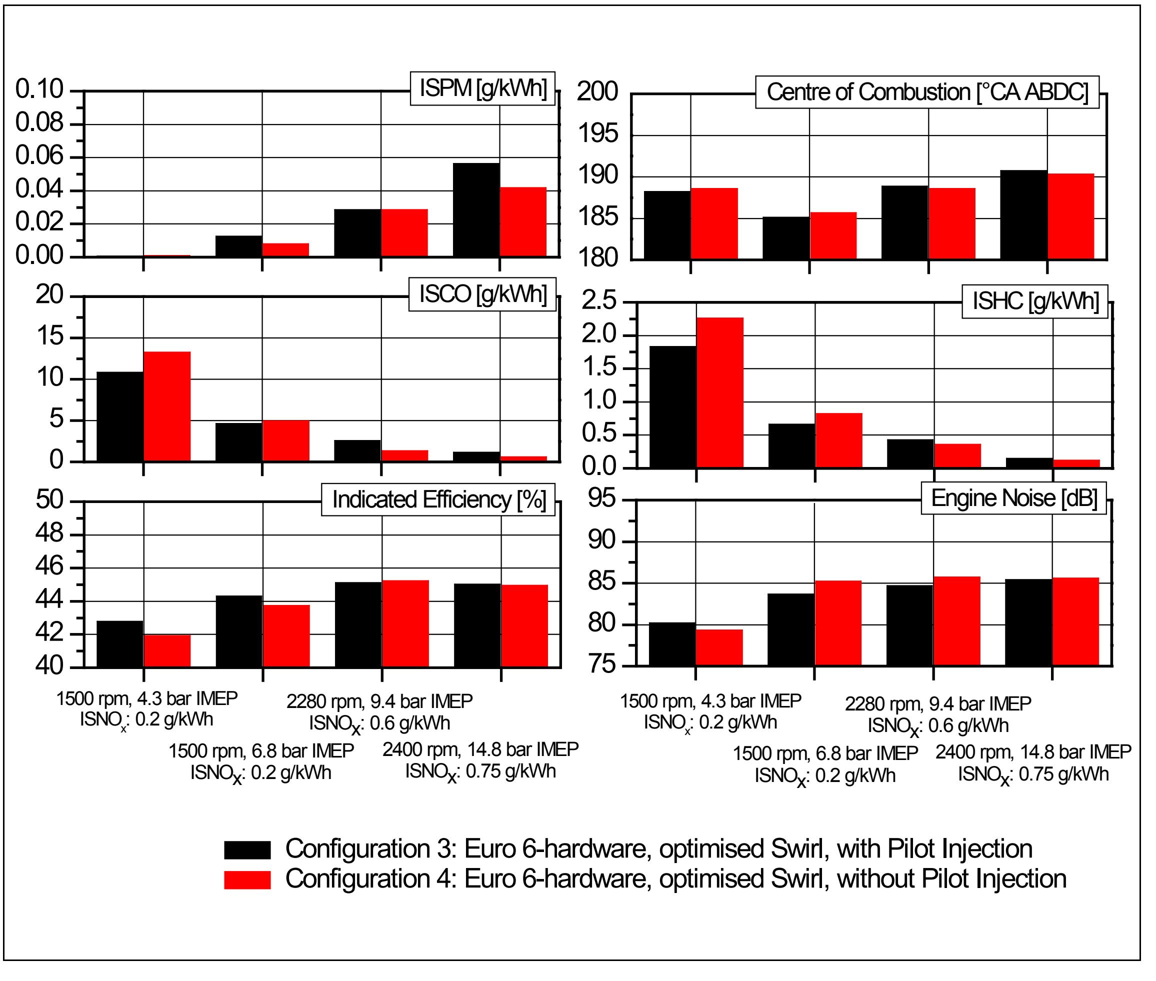
	Units
A) RON calculated from measured cetane number	-
B) RON taken as volume fraction of iso-octane	-
C) Derived Cetane number measured using IP 498/06 method	-
D) RON calculated using ASTM D2699 method	
E) Cetane number calculated from RON value	-
F) Density measured using IP 365 method	g cm^{-3}
G) Distillation measured using IP 123 method	^oC
H) Sulphur value measured using ISO 20884 method	mg/kg
J) Sulphur value measured using ASTM D2622 method	mg/kg
K) Sulphur value is 0 as pure component	mg/kg
L) Sulphur value calculated from sulphur values of diesel and gasoline	mg/kg
M) Aromatic content measured using IP 391/01 / IP 548/07 methods	% m/m
N) Aromatic content measured using IP 391/06 method	% m/m
P) Aromatic content calculated from aromatic contents of diesel and gasoline	% m/m
Q) Aromatic content is 0	% m/m
R) All aromatic content is mono in toluene	% m/m
S) Lower heating value calculated using IP 12 method	MJ/kg
T) Lower heating value calculated from values for diesel and gasoline	MJ/kg
U) Lower heating value calculated using calorific values of iso-octane and n-heptane	MJ/kg
V) Analyst for IP548/07 suggested that mono and di aromatic values may be overstated because of the influence of the saturate peak in the HPLC	
W) Lower heating value calculated from lower heating value of baseline diesel and RME	MJ/kg
X) Total aromatics from HPLC DIN 51448-2. Di and tri aromatics can seen to be close to 0 from GC trace	MJ/kg
Y) Predicted from GC trace	MJ/kg

APPENDIX 2 INJECTION STRATEGIES

The effect of switching off the pilot injection was also investigated in Part 1 of this study (Configuration 5). The centre of combustion was kept constant for these tests and the results are shown in **Figure A2-1**. At the highest part-load point, switching off the pilot injection helped reduce the PM emissions. The HC and CO emissions were slightly lower and the noise level was unchanged. At the two intermediate part-load points, switching off the pilot injection increased the noise emissions without any apparent benefits in the other parameters. At the lowest part-load point, switching off the pilot injection increased the HC and CO emissions. Because of the low temperatures at this lowest part-load point, the DOC temperature could be too low to efficiently convert the HC/CO emissions and an increase in these emissions should be avoided. For this reason, the pilot injection is probably needed to stabilize the combustion at the lowest part-load point.

Since no clear advantage was found by switching off the pilot injection, the results presented in this report refer primarily to the tests with pilot injection switched on.

Figure A2-1 Effects of switching off the pilot injection for the Baseline Diesel fuel



APPENDIX 3 SUMMARY TABLES COVERING ALL OPERATING POINTS

SUMMARY TABLE, 1500RPM, 4.3 BAR IMEP

Test Fuel	NOx	Smoke No	ISPM	CSL	ISHC	ISCO	Indicated Efficiency	Ign Delay	Center of Combustion	Combustion Duration Max	Burning Rate	Exhaust Temp
	[g/kWh]	[FSN]	[g/kWh]	[dB]	[g/kWh]	[g/kWh]	[%]	°CA	°CA ATDC	°CA	1/°CA	°C
Euro 4 NOx Level - target 0.6g/kWh												
Diesel Base 1	0.6	0.03	0.0018	82.0	1.84	11.14	42.34	12.02	186.10	23.07	0.2786	260
Diesel Base 2	0.6	0.02	0.0012	82.1	2.04	11.14	42.06	12.02	186.23	18.50	0.2641	259
Diesel Base 3	0.6	0.02	0.0012	81.9	2.00	10.11	42.35	12.02	186.17	20.78	0.2714	258
Diesel Base Avg	0.6	0.02	0.0014	82.0	1.96	10.80	42.25	12.02	186.17	20.78	0.2714	259
Diesel Low Aromatics	0.6	0.01	0.0006	82.3	1.61	9.52	42.51	11.61	185.10	26.77	0.3082	250
Diesel Low CN	0.6	0.01	0.0006	81.1	2.86	12.60	42.12	16.98	185.30	20.54	0.1930	254
Diesel B10	0.6	0.02	0.0013	81.8	2.60	12.80	40.56	12.38	186.87	19.94	0.2403	244
Kerosene	0.6	0.01	0.0006	81.3	2.86	12.60	42.39	14.39	185.12	19.97	0.2212	249
Kerosene Low Aromatics	0.6	0.00	0.0000	82.1	2.39	10.50	41.61	14.05	185.01	14.91	0.2434	247
Dieseline	0.6	0.02	0.0011	80.4	2.93	14.18	41.79	14.67	185.94	28.21	0.1768	247
TRF CN47	0.6	0.01	0.0006	80.9	3.14	10.76	42.51	12.75	186.04	28.63	0.2049	248
PRF CN44	0.6	0.00	0.0000	81.5	2.18	10.76	41.69	12.62	186.18	16.09	0.2679	261
PRF CN35	0.6	0.01	0.0005	79.6	3.06	11.14	43.12	14.75	184.78	23.07	0.1507	252
PRF CN30	0.6	0.00	0.0000	79.2	3.60	15.58	42.99	16.25	185.55	26.52	0.1189	242
PRF CN25	0.6	0.00	0.0000	77.6	4.86	29.38	41.24	14.96	185.86	23.57	0.0953	244
E10 CN43	0.6	0.00	0.0000	80.6	2.67	13.60	41.51	14.20	186.14	22.74	0.2049	213
Euro 5 NOx Level - target 0.4g/kWh												
Diesel Base 1	0.4	0.03	0.0018	81.7	2.12	12.60	41.73	12.30	186.54	22.30	0.2664	263
Diesel Base 2	0.4	0.02	0.0012	81.6	2.29	12.31	42.00	12.45	186.99	18.97	0.2384	261
Diesel Base 3	0.4	0.02	0.0011	81.6	2.19	10.98	41.68	12.38	186.77	20.64	0.2524	260
Diesel Base Avg	0.4	0.02	0.0014	81.6	2.20	11.96	41.80	12.38	186.77	20.64	0.2524	261
Diesel Low Aromatics	0.4	0.01	0.0006	81.7	1.98	10.88	41.73	12.11	185.93	26.26	0.2742	252
Diesel Low CN	0.4	0.01	0.0006	80.0	3.14	14.41	41.68	17.27	186.23	18.97	0.1691	255
Diesel B10	0.4	0.01	0.0006	80.9	3.07	14.33	40.52	12.95	188.02	20.23	0.2064	245
Kerosene	0.4	0.01	0.0006	80.7	3.08	13.63	42.45	14.80	185.98	19.23	0.1993	252
Kerosene Low Aromatics	0.4	0.00	0.0000	81.7	2.50	10.98	42.19	14.42	185.73	15.27	0.2239	250
Dieseline	0.4	0.01	0.0006	79.5	3.19	15.61	41.53	14.74	186.85	26.26	0.1572	248
TRF CN47	0.4	0.00	0.0000	80.2	3.38	11.79	42.52	12.87	186.79	25.81	0.1773	250
PRF CN44	0.4	0.00	0.0000	81.1	2.41	12.31	41.87	12.75	186.61	17.09	0.2514	262
PRF CN35	0.4	0.00	0.0000	79.5	3.25	12.93	42.83	14.86	185.47	22.30	0.1415	255
PRF CN30	0.4	0.00	0.0000	78.5	4.05	17.09	42.74	16.69	186.80	25.97	0.1019	245
PRF CN25	0.4	0.00	0.0000	76.7	5.93	34.13	40.93	15.50	187.09	24.83	0.0853	247
E10 CN43	0.4	0.00	0.0000	79.8	2.81	14.41	41.53	14.42	186.79	22.46	0.1829	216
Euro 6 NOx Level - target 0.2g/kWh												
Diesel Base 1	0.2	0.05	0.0026	80.4	2.70	15.11	41.25	13.14	188.10	25.72	0.1991	268
Diesel Base 2	0.2	0.03	0.0002	79.9	2.88	15.05	41.41	13.14	188.68	21.63	0.1872	264
Diesel Base 3	0.2	0.02	0.0011	80.1	2.57	12.94	40.88	13.14	188.39	23.68	0.1932	266
Diesel Base Avg	0.2	0.03	0.0013	80.1	2.72	14.37	41.18	13.14	188.39	23.68	0.1932	266
Diesel Low Aromatics	0.2	0.01	0.0006	80.9	2.45	12.33	41.62	13.14	187.54	28.21	0.2217	260
Diesel Low CN	0.2	0.02	0.0011	78.4	3.60	17.03	42.13	18.16	187.88	22.36	0.1379	258
Diesel B10	0.2	0.01	0.0008	79.1	3.93	16.58	39.86	14.04	189.81	23.68	0.1561	251
Kerosene	0.2	0.01	0.0006	78.8	3.69	16.75	41.70	15.40	187.77	22.36	0.1539	257
Kerosene Low Aromatics	0.2	0.00	0.0000	79.9	3.02	13.72	41.48	14.92	187.19	16.26	0.1779	251
Dieseline	0.2	0.02	0.0012	78.0	4.05	19.16	40.79	15.74	188.64	28.63	0.1287	253
TRF CN47	0.2	0.00	0.0000	78.4	3.83	14.01	42.44	13.14	188.45	25.18	0.1431	251
PRF CN44	0.2	0.00	0.0000	79.2	2.88	15.05	41.88	13.31	188.22	19.36	0.1872	267
PRF CN35	0.2	0.00	0.0000	78.0	3.93	17.44	42.08	15.85	187.54	26.20	0.1111	261
PRF CN30	0.2	0.01	0.0004	77.1	5.14	18.99	41.93	17.50	189.02	25.04	0.1003	247
PRF CN25	0.2	0.00	0.0000	75.7	11.63	39.43	39.12	16.58	189.44	27.77	0.0754	252
E10 CN43	0.2	0.00	0.0000	78.2	3.33	17.32	41.33	15.06	188.45	23.79	0.1459	226
Euro 6+ NOx Level - target 0.1g/kWh												
Diesel Base 1	0.1	0.06	0.0033	78.6	3.44	18.23	40.68	14.02	190.12	27.50	0.1552	275
Diesel Base 2	0.1	0.04	0.0024	78.2	3.58	17.72	40.91	13.85	190.56	26.00	0.1408	268
Diesel Base 3	0.1	0.04	0.0019	78.0	2.98	15.65	41.08	13.93	190.34	26.75	0.1480	265
Diesel Base Avg	0.1	0.05	0.0025	78.3	3.33	17.20	40.89	13.93	190.34	26.75	0.1480	269
Diesel Low Aromatics	0.1	0.01	0.0006	79.2	3.08	14.56	41.08	14.02	189.42	28.98	0.1724	267
Diesel Low CN	0.1	0.02	0.0011	76.9	4.41	21.04	41.08	18.82	189.65	24.75	0.1152	266
Diesel B10	0.1	0.02	0.0016	77.7	4.58	19.63	39.85	14.46	191.69	23.97	0.1163	258
Kerosene	0.1	0.01	0.0006	76.9	4.86	21.73	40.68	15.96	189.59	26.19	0.1184	259
Kerosene Low Aromatics	0.1	0.00	0.0000	78.1	3.58	16.69	41.36	15.74	188.70	18.43	0.1430	253
Dieseline	0.1	0.00	0.0000	77.0	4.14	19.36	41.21	16.45	190.75	31.92	0.1047	262
TRF CN47	0.1	0.01	0.0006	76.6	5.40	18.27	41.08	13.66	191.17	28.37	0.1017	257
PRF CN44	0.1	0.00	0.0000	77.9	4.14	19.36	41.21	13.78	188.70	21.73	0.1430	275
PRF CN35	0.1	0.00	0.0000	76.6	5.24	21.23	41.36	17.07	190.06	27.88	0.0905	269
PRF CN30	0.1	0.02	0.0012	76.2	5.71	18.36	41.99	18.38	190.19	24.60	0.0941	256
PRF CN25	0.1	0.00	0.0000	75.0	16.54	42.09	37.51	17.13	192.58	34.59	0.0646	257
E10 CN43	0.1	0.00	0.0000	77.1	4.49	22.26	40.44	15.74	190.59	27.56	0.1112	236

SUMMARY TABLE, 1500 RPM, 6.8 BAR IMEP

Test Fuel	NOx	Smoke Number	ISPM	CSL	ISHC	ISCO	Indicated Efficiency	Ign Delay	Center of Combustion	Combustion Duration Max	Burning Rate	Exhaust Temp
	[g/kWh]	[FSN]	[g/kWh]	[dB]	[g/kWh]	[g/kWh]	[%]	°CA	°CA ATDC	°CA	1/°CA	°C
Euro 4 NOx Level - target 0.6g/kWh												
Diesel Base 1	0.6	0.27	0.0126	83.4	0.56	3.27	44.44	8.69	185.11	30.71	0.1909	299
Diesel Base 2	0.6	0.24	0.0140	83.1	0.61	3.27	44.61	8.52	185.21	28.92	0.1806	300
Diesel Base 3	0.6	0.23	0.0136	83.4	0.58	3.27	44.23	8.34	185.31	27.13	0.1702	295
Diesel Base Avg	0.6	0.25	0.0134	83.3	0.58	3.27	44.43	8.52	185.21	28.92	0.1806	298
Diesel Low Aromatics	0.6	0.19	0.0115	82.3	0.44	2.58	44.55	8.01	185.07	29.05	0.1635	297
Diesel Low CN	0.6	0.07	0.0039	86.1	0.89	4.71	44.59	11.19	184.81	30.93	0.2975	297
Diesel B10	0.6	0.14	0.0084	84.1	0.61	3.60	43.50	8.70	185.16	25.40	0.2176	285
Kerosene	0.6	0.08	0.0042	84.8	0.61	3.65	44.88	9.66	185.07	26.79	0.2442	296
Kerosene Low Aromatics	0.6	0.04	0.0023	85.0	0.64	3.37	43.35	9.66	185.11	20.94	0.2108	292
Dieseline	0.6	0.03	0.0017	85.9	1.04	5.41	43.72	11.44	185.01	31.35	0.2821	289
TRF CN47	0.6	0.05	0.0028	84.5	1.26	4.35	43.68	10.02	184.76	32.40	0.2008	280
PRF CN44	0.6	0.00	0.0000	85.5	0.97	3.79	43.57	10.37	184.34	32.78	0.2352	296
PRF CN35	0.6	0.00	0.0004	86.2	1.34	4.52	43.89	12.50	184.29	26.79	0.3024	291
PRF CN30	0.6	0.01	0.0004	85.3	1.34	5.73	43.79	14.19	185.91	23.35	0.2669	284
PRF CN25	0.6	0.00	0.0000	85.5	1.59	5.21	43.35	17.81	184.88	18.43	0.2208	282
E10 CN43	0.6	0.01	0.0006	85.9	1.10	4.82	43.39	11.52	185.25	29.34	0.2925	281
Euro 5 NOx Level - target 0.4g/kWh												
Diesel Base 1	0.4	0.27	0.0151	83.8	0.64	3.84	44.44	9.23	185.50	31.25	0.2108	303
Diesel Base 2	0.4	0.26	0.0149	83.6	0.68	3.77	44.59	9.23	185.74	26.21	0.2108	301
Diesel Base 3	0.4	0.27	0.0154	84.0	0.67	3.79	44.28	8.86	185.58	26.64	0.1869	298
Diesel Base Avg	0.4	0.27	0.0151	83.8	0.66	3.80	44.44	9.11	185.61	28.03	0.2028	301
Diesel Low Aromatics	0.4	0.23	0.0129	82.9	0.49	3.12	44.21	8.48	185.22	29.56	0.1890	300
Diesel Low CN	0.4	0.07	0.0042	86.0	0.99	5.29	44.37	11.75	185.43	32.14	0.2908	302
Diesel B10	0.4	0.14	0.0082	84.4	0.71	4.14	43.42	9.24	185.59	26.04	0.2278	287
Kerosene	0.4	0.07	0.0042	85.1	0.73	4.25	44.44	10.30	185.66	26.64	0.2514	300
Kerosene Low Aromatics	0.4	0.03	0.0019	85.3	0.68	3.84	43.41	10.30	185.58	20.94	0.2216	294
Dieseline	0.4	0.04	0.0019	85.6	1.20	6.05	43.37	11.59	185.22	31.88	0.2789	290
TRF CN47	0.4	0.05	0.0029	84.4	1.32	5.15	43.33	10.74	185.50	31.03	0.2108	281
PRF CN44	0.4	0.01	0.0003	85.3	0.94	4.13	43.54	10.74	184.90	32.88	0.2352	299
PRF CN35	0.4	0.01	0.0003	85.7	1.39	4.88	43.75	12.83	185.04	27.42	0.2789	295
PRF CN30	0.4	0.01	0.0003	84.8	1.45	6.71	43.45	14.50	186.57	22.77	0.2353	286
PRF CN25	0.4	0.00	0.0003	84.6	1.68	5.94	43.54	18.39	185.81	18.66	0.1954	284
E10 CN43	0.4	0.00	0.0003	85.6	1.19	5.46	43.15	12.00	185.81	30.86	0.2872	282
Euro 6 NOx Level - target 0.2g/kWh												
Diesel Base 1	0.2	0.59	0.0350	84.2	0.83	5.30	43.89	10.18	186.39	31.74	0.2216	312
Diesel Base 2	0.2	0.59	0.0350	83.9	0.83	5.08	44.21	9.66	186.22	26.56	0.2136	311
Diesel Base 3	0.2	0.53	0.0300	84.2	0.90	5.84	43.90	10.18	186.71	33.49	0.2053	305
Diesel Base Avg	0.2	0.57	0.0333	84.1	0.85	5.41	44.00	10.01	186.44	30.60	0.2135	309
Diesel Low Aromatics	0.2	0.43	0.0242	83.3	0.59	4.31	43.89	9.19	185.77	29.05	0.1909	308
Diesel Low CN	0.2	0.15	0.0075	85.1	1.27	6.81	43.45	12.66	187.00	29.50	0.2495	310
Diesel B10	0.2	0.27	0.0144	84.4	0.92	5.51	42.89	10.21	186.57	26.48	0.2371	290
Kerosene	0.2	0.12	0.0062	84.8	0.92	5.62	43.90	11.33	186.81	25.82	0.2495	305
Kerosene Low Aromatics	0.2	0.04	0.0018	84.9	0.80	5.03	42.92	11.33	186.62	21.11	0.2311	300
Dieseline	0.2	0.05	0.0030	84.6	1.40	7.08	43.36	12.37	187.00	32.14	0.2261	298
TRF CN47	0.2	0.08	0.0041	84.1	1.46	6.65	43.18	11.38	186.54	33.49	0.2053	287
PRF CN44	0.2	0.02	0.0005	84.9	0.99	4.97	43.31	11.38	185.77	33.01	0.2311	309
PRF CN35	0.2	0.01	0.0004	84.8	1.45	5.70	43.45	13.28	186.22	23.18	0.2356	301
PRF CN30	0.2	0.00	0.0004	82.6	1.62	8.54	43.90	17.46	188.23	21.40	0.1719	289
PRF CN25	0.2	0.00	0.0004	83.1	1.86	7.50	43.36	19.42	187.44	19.03	0.1619	288
E10 CN43	0.2	0.00	0.0004	85.1	1.29	6.24	43.09	12.48	186.71	27.93	0.2559	287
Euro 6+ NOx Level - target 0.1g/kWh												
Diesel Base 1	0.1	1.32	0.0896	83.6	1.03	8.70	43.28	10.97	187.56	33.21	0.2104	319
Diesel Base 2	0.1	1.17	0.0785	83.6	1.06	8.46	43.53	10.79	187.56	29.32	0.2124	316
Diesel Base 3	0.1	0.99	0.0645	82.9	1.19	11.88	43.01	11.42	188.88	32.47	0.1818	317
Diesel Base Avg	0.1	1.16	0.0775	83.3	1.09	9.68	43.27	11.06	188.00	31.67	0.2015	317
Diesel Low Aromatics	0.1	0.76	0.0446	83.4	0.75	6.88	43.37	10.24	186.71	30.52	0.2050	314
Diesel Low CN	0.1	0.24	0.0120	83.9	1.55	9.32	42.40	13.49	188.48	28.38	0.1971	320
Diesel B10	0.1	0.52	0.0280	84.1	1.11	8.24	42.46	11.12	187.79	27.72	0.2306	298
Kerosene	0.1	0.21	0.0103	83.4	1.23	8.19	43.59	12.03	188.48	25.74	0.2104	313
Kerosene Low Aromatics	0.1	0.05	0.0024	84.1	0.93	6.50	42.56	12.03	187.90	22.40	0.2133	307
Dieseline	0.1	0.12	0.0058	82.6	1.68	9.48	42.76	13.23	189.22	32.47	0.1735	307
TRF CN47	0.1	0.11	0.0053	83.2	1.68	10.06	42.83	12.31	188.05	34.28	0.1923	298
PRF CN44	0.1	0.01	0.0000	82.2	1.27	10.28	42.40	11.94	187.06	32.76	0.2143	315
PRF CN35	0.1	0.01	0.0000	83.0	1.60	7.20	43.33	13.89	188.02	23.40	0.1841	309
PRF CN30	0.1	0.01	0.0005	80.3	2.11	11.43	43.33	15.73	190.47	23.40	0.1263	293
PRF CN25	0.1	0.00	0.0000	81.1	2.30	9.66	43.08	20.59	189.82	20.52	0.1292	297
E10 CN43	0.1	0.01	0.0000	83.6	1.40	7.61	43.00	13.28	188.30	26.04	0.2157	295

SUMMARY TABLE, 2280 RPM, 9.4 BAR IMEP

Test Fuel	NOx	Smoke Number	ISPM	CSL	ISHC	ISCO	Indicated Efficiency	Ign Delay	Center of Combustion	Combustion Duration Max	Burning Rate	Exhaust Temp
	[g/kWh]	[FSN]	[g/kWh]	[dB]	[g/kWh]	[g/kWh]	[%]	°CA	°CA ATDC	°CA	1/°CA	°C
Euro 4 NOx Level - target 1.8g/kWh												
Diesel Base 1	1.8	0.13	0.0089	85.0	0.39	2.52	45.82	9.29	188.40	34.10	0.0937	320
Diesel Base 2	1.8	0.13	0.0089	84.8	0.43	2.88	46.17	9.51	188.63	26.08	0.0927	318
Diesel Base 3	1.8	0.18	0.0265	84.7	0.43	2.52	46.06	9.51	188.75	32.11	0.1076	316
Diesel Base Avg	1.8	0.15	0.0148	84.8	0.42	2.64	46.02	9.44	188.59	30.76	0.0980	318
Diesel Low Aromatics	1.8	0.10	0.0066	85.4	0.41	2.62	45.82	9.00	188.16	32.11	0.0984	317
Diesel Low CN	1.8	0.25	0.0167	85.1	0.44	3.19	44.94	10.01	188.50	34.33	0.1074	327
Diesel B10	1.8	0.01	0.0018	84.9	0.60	3.23	44.35	9.70	188.83	28.17	0.1069	301
Kerosene	1.8	0.07	0.0046	84.9	0.51	2.98	46.12	9.87	188.63	31.35	0.1010	313
Kerosene Low Aromatics	1.8	0.04	0.0034	85.2	0.54	3.09	44.94	9.51	188.21	25.39	0.0936	314
Dieseline	1.8	0.10	0.0066	85.9	0.56	3.59	45.48	10.21	188.16	35.17	0.1257	306
TRF CN47	1.8	0.06	0.0038	85.1	0.89	2.02	45.33	10.43	188.86	32.80	0.1130	305
PRF CN44	1.8	0.03	0.0020	85.8	0.69	2.11	45.08	10.01	188.35	35.17	0.0966	313
PRF CN35	1.8	0.02	0.0012	86.0	0.79	2.16	45.43	11.28	187.87	35.32	0.1065	311
PRF CN30	1.8	0.01	0.0007	87.3	0.79	2.70	45.75	12.64	188.42	31.35	0.1350	306
PRF CN25	1.8	0.01	0.0007	89.1	0.89	4.19	45.43	14.02	187.08	32.11	0.1377	306
E10 CN43	1.8	0.06	0.0041	85.6	0.56	1.83	45.43	10.78	188.65	37.51	0.1141	309
Euro 5 NOx Level - target 1.2g/kWh												
Diesel Base 1	1.2	0.14	0.0093	84.9	0.39	2.50	45.79	9.34	188.45	34.22	0.0921	322
Diesel Base 2	1.2	0.15	0.0104	84.8	0.42	2.81	46.10	9.58	188.71	26.52	0.0897	320
Diesel Base 3	1.2	0.20	0.0227	84.7	0.42	2.55	45.93	9.58	188.85	32.19	0.1040	319
Diesel Base Avg	1.2	0.16	0.0141	84.8	0.41	2.62	45.94	9.50	188.67	30.98	0.0953	320
Diesel Low Aromatics	1.2	0.13	0.0087	85.4	0.40	2.62	45.74	9.07	188.32	32.74	0.0933	320
Diesel Low CN	1.2	0.26	0.0175	85.1	0.44	3.19	44.91	10.11	188.59	34.50	0.1056	328
Diesel B10	1.2	0.13	0.0189	84.8	0.57	3.21	44.20	9.63	188.76	28.44	0.1058	304
Kerosene	1.2	0.10	0.0065	84.8	0.50	3.00	46.01	9.94	188.71	31.84	0.0998	316
Kerosene Low Aromatics	1.2	0.06	0.0039	85.1	0.53	3.12	44.82	9.58	188.32	25.80	0.0938	317
Dieseline	1.2	0.11	0.0071	85.8	0.57	3.64	45.45	10.25	188.23	35.45	0.1212	309
TRF CN47	1.2	0.69	0.0440	84.9	0.88	2.16	45.28	10.45	188.90	33.18	0.1078	307
PRF CN44	1.2	0.03	0.0020	85.6	0.68	2.16	45.12	10.13	188.45	35.29	0.0928	318
PRF CN35	1.2	0.02	0.0014	86.0	0.78	2.27	45.41	11.48	188.02	35.45	0.0994	313
PRF CN30	1.2	0.01	0.0007	87.3	0.78	2.90	45.74	12.77	188.59	32.19	0.1268	309
PRF CN25	1.2	0.01	0.0007	89.2	0.90	4.35	45.41	14.19	187.23	31.55	0.1361	308
E10 CN43	1.2	0.57	0.0370	85.5	0.58	1.91	45.41	10.83	188.78	37.83	0.1097	310
Euro 6 NOx Level - target 0.6g/kWh												
Diesel Base 1	0.6	0.78	0.0581	85.1	0.41	2.93	45.50	9.58	188.80	35.09	0.0777	335
Diesel Base 2	0.6	0.58	0.0390	84.6	0.43	3.12	45.77	9.72	189.02	28.90	0.0898	330
Diesel Base 3	0.6	0.53	0.0691	84.6	0.43	3.02	46.65	9.72	189.09	33.08	0.0849	328
Diesel Base Avg	0.6	0.63	0.0554	84.8	0.42	3.02	45.97	9.67	188.97	32.36	0.0841	331
Diesel Low Aromatics	0.6	0.44	0.0293	85.1	0.39	2.75	45.72	9.27	188.71	34.38	0.0866	332
Diesel Low CN	0.6	0.65	0.0460	85.1	0.43	3.27	44.96	10.35	188.92	35.09	0.1061	339
Diesel B10	0.6	0.33	0.0256	84.4	0.51	3.31	43.96	10.14	189.12	30.34	0.0962	315
Kerosene	0.6	0.29	0.0181	84.8	0.49	3.12	45.50	10.35	189.02	33.61	0.0956	324
Kerosene Low Aromatics	0.6	0.15	0.0099	85.0	0.54	3.44	44.91	9.72	188.71	28.17	0.0859	328
Dieseline	0.6	0.23	0.0140	85.7	0.61	4.19	44.96	10.49	188.55	37.56	0.1162	318
TRF CN47	0.6	0.15	0.0091	84.6	0.87	2.68	44.77	10.71	189.26	34.18	0.0995	314
PRF CN44	0.6	0.05	0.0033	85.0	0.66	2.35	45.02	10.49	188.85	35.37	0.0991	329
PRF CN35	0.6	0.05	0.0033	85.8	0.68	2.59	45.92	11.82	188.49	35.49	0.0900	322
PRF CN30	0.6	0.01	0.0000	87.1	0.79	3.57	45.41	12.99	189.08	31.53	0.1002	317
PRF CN25	0.6	0.01	0.0000	89.4	1.00	5.48	44.82	14.93	188.13	32.27	0.1473	316
E10 CN43	0.6	0.05	0.0033	85.0	0.61	2.20	45.12	11.09	189.26	38.29	0.0921	318
Euro 6+ NOx Level - target 0.3g/kWh												
Diesel Base 1	0.3	2.31	0.2452	84.6	0.40	3.88	45.19	9.95	189.29	37.39	0.0734	349
Diesel Base 2	0.3	1.97	0.2027	84.1	0.44	4.05	45.42	10.09	189.42	31.34	0.0765	340
Diesel Base 3	0.3	1.79	0.1863	84.3	0.44	3.94	45.35	10.04	189.60	34.53	0.0775	342
Diesel Base Avg	0.3	2.03	0.2114	84.3	0.42	3.96	45.32	10.02	189.44	34.42	0.0758	344
Diesel Low Aromatics	0.3	1.61	0.1384	84.9	0.39	3.50	45.33	9.58	189.18	36.76	0.0829	344
Diesel Low CN	0.3	2.02	0.2027	85.1	0.44	4.44	44.59	10.71	189.25	37.36	0.0858	349
Diesel B10	0.3	1.48	0.1342	84.4	0.52	4.38	43.85	10.42	189.63	33.96	0.0886	324
Kerosene	0.3	1.23	0.0986	84.8	0.49	4.06	45.28	10.71	189.40	36.04	0.0906	335
Kerosene Low Aromatics	0.3	0.65	0.0459	84.5	0.51	4.09	44.73	10.09	189.01	30.19	0.0906	336
Dieseline	0.3	0.79	0.0548	85.7	0.61	4.81	45.08	10.89	189.08	39.59	0.1079	325
TRF CN47	0.3	0.47	0.0288	84.5	0.84	3.39	45.00	11.16	189.71	36.23	0.0949	321
PRF CN44	0.3	0.15	0.0082	84.7	0.67	2.89	44.33	10.96	189.35	36.76	0.0896	341
PRF CN35	0.3	0.08	0.0055	85.9	0.78	3.58	44.81	12.60	189.13	37.46	0.0855	333
PRF CN30	0.3	0.03	0.0000	86.9	0.87	4.72	44.76	13.60	189.78	32.57	0.1079	326
PRF CN25	0.3	0.01	0.0000	89.3	1.26	7.21	44.17	15.95	189.22	33.18	0.1542	324
E10 CN43	0.3	0.18	0.0110	84.8	0.65	3.14	44.62	11.50	190.01	41.13	0.0896	326

SUMMARY TABLE, 2400 RPM, 14.8 BAR IMEP

Test Fuel	Euro Leve	NOx	Smoke Number	ISPM	CSL	ISHC	ISCO	Indicated Efficiency	Ign Delay	Center of Combustio n	Combustio n Duration Max	Burning Rate	Exhaust Temp
		[g/kWh]	[FSN]	[g/kWh]	[dB]	[g/kWh]	[g/kWh]	[%]	°CA	°CA ATDC	°CA	1/°CA	°C
Euro 4 NOx Level - target 2.25g/kWh													
Diesel Base 1	E4	2.25	0.26	0.0151	85.6	0.35	0.92	45.62	9.58	189.96	37.80	0.0745	427
Diesel Base 2	E4	2.25	0.34	0.0205	85.4	0.45	1.24	45.26	9.63	190.08	36.17	0.0652	428
Diesel Base 3	E4	2.25	0.19	0.0110	85.4	0.28	0.82	45.63	9.62	190.10	34.71	0.0686	434
Diesel Base Avg	E4	2.25	0.26	0.0155	85.5	0.36	0.99	45.50	9.61	190.05	36.23	0.0694	430
Diesel Low Aromatics	E4	2.25	0.18	0.0110	85.8	0.33	0.97	45.98	9.45	189.75	36.53	0.0730	424
Diesel Low CN	E4	2.25	0.38	0.0219	86.3	0.23	1.05	45.36	9.88	190.06	38.44	0.0791	438
Diesel B10	E4	2.25	0.32	0.0137	85.2	0.25	1.23	46.25	9.63	189.97	33.67	0.0668	424
Kerosene	E4	2.25	0.15	0.0082	85.9	0.29	0.82	45.50	10.13	190.35	37.22	0.0731	419
Kerosene Low Aromatics	E4	2.25	0.09	0.0055	85.7	0.32	0.61	45.48	10.10	190.44	35.41	0.0844	419
Dieseline	E4	2.25	0.30	0.0178	84.5	0.59	1.06	45.12	10.54	190.28	37.84	0.0776	426
TRF CN47	E4	2.25	0.22	0.0123	85.3	0.38	0.83	45.56	10.59	188.92	40.48	0.0737	413
PRF CN44	E4	2.25	0.08	0.0041	85.0	0.31	0.99	45.51	10.08	189.91	35.15	0.0712	428
PRF CN35	E4	2.25	0.04	0.0014	86.4	0.36	0.61	46.13	11.22	189.98	40.66	0.0766	426
PRF CN30	E4	2.25	0.04	0.0014	86.9	0.36	0.68	45.78	11.69	189.93	37.50	0.0875	417
PRF CN25	E4	2.25	0.03	0.0027	87.8	0.40	0.78	45.80	12.68	189.71	38.59	0.0880	419
E10 CN43	E4	2.25	0.02	0.0014	85.8	0.32	0.86	45.59	10.76	189.38	38.16	0.0700	416
Euro 5 NOx Level - target 1.5g/kWh													
Diesel Base 1	E5	1.50	0.26	0.0151	85.5	0.30	0.92	45.55	9.62	190.08	38.22	0.0740	430
Diesel Base 2	E5	1.50	0.35	0.0205	85.3	0.40	1.24	45.19	9.68	190.19	36.78	0.0635	431
Diesel Base 3	E5	1.50	0.20	0.0110	85.4	0.27	0.81	45.57	9.70	190.24	34.99	0.0670	436
Diesel Base Avg	E5	1.50	0.27	0.0155	85.4	0.32	0.99	45.44	9.67	190.17	36.66	0.0682	432
Diesel Low Aromatics	E5	1.50	0.19	0.0110	85.7	0.30	0.95	45.90	9.50	189.87	36.90	0.0719	427
Diesel Low CN	E5	1.50	0.40	0.0233	86.2	0.21	1.05	45.30	9.92	190.14	38.76	0.0777	441
Diesel B10	E5	1.50	0.27	0.0013	85.1	0.25	1.21	46.25	9.63	190.01	34.11	0.0680	427
Kerosene	E5	1.50	0.18	0.0096	85.8	0.27	0.85	45.41	10.16	190.46	37.64	0.0701	423
Kerosene Low Aromatics	E5	1.50	0.10	0.0055	85.6	0.31	0.62	45.43	10.17	190.61	36.06	0.0834	422
Dieseline	E5	1.50	0.33	0.0192	84.4	0.55	1.07	45.09	10.63	190.45	38.55	0.0763	428
TRF CN47	E5	1.50	0.23	0.0123	85.2	0.38	0.84	45.55	10.59	188.92	40.48	0.0737	415
PRF CN44	E5	1.50	0.08	0.0041	85.0	0.30	0.99	45.49	10.15	190.03	35.76	0.0706	430
PRF CN35	E5	1.50	0.04	0.0014	86.3	0.35	0.63	46.10	11.31	190.15	41.38	0.0757	429
PRF CN30	E5	1.50	0.04	0.0014	86.9	0.35	0.70	45.73	11.80	190.10	37.99	0.0842	419
PRF CN25	E5	1.50	0.03	0.0014	87.8	0.38	0.83	45.72	12.84	189.85	39.09	0.0853	421
E10 CN43	E5	1.50	0.02	0.0123	85.6	0.32	0.84	45.52	10.83	189.54	38.66	0.0688	419
Euro 6 NOx Level - target 0.75g/kWh													
Diesel Base 1	E6	0.75	1.05	0.0658	85.2	0.20	1.29	44.94	9.63	190.61	41.37	0.0618	454
Diesel Base 2	E6	0.75	1.17	0.0849	85.0	0.22	1.49	45.03	9.80	190.72	39.61	0.0611	450
Diesel Base 3	E6	0.75	0.90	0.0589	85.1	0.23	1.16	44.97	9.91	190.79	37.90	0.0667	453
Diesel Base Avg	E6	0.75	1.04	0.0699	85.1	0.22	1.31	44.98	9.78	190.71	39.63	0.0632	452
Diesel Low Aromatics	E6	0.75	0.74	0.0397	85.4	0.23	1.29	45.25	9.49	190.48	40.94	0.0625	450
Diesel Low CN	E6	0.75	1.16	0.0808	85.8	0.17	1.42	44.43	10.24	190.96	41.58	0.0710	463
Diesel B10	E6	0.75	1.17	0.0876	84.8	0.18	1.46	44.93	9.63	190.87	36.72	0.0591	443
Kerosene	E6	0.75	0.65	0.0384	85.6	0.23	1.13	45.14	10.40	191.04	40.36	0.0660	438
Kerosene Low Aromatics	E6	0.75	0.32	0.0178	85.2	0.25	0.81	45.00	10.16	191.28	39.37	0.0657	443
Dieseline	E6	0.75	1.09	0.0740	84.3	0.42	1.44	44.88	10.84	191.08	41.45	0.0665	440
TRF CN47	E6	0.75	0.83	0.0521	85.1	0.37	1.10	45.13	10.82	189.46	40.91	0.0723	432
PRF CN44	E6	0.75	0.34	0.0192	84.7	0.28	1.17	44.80	10.45	190.44	37.88	0.0683	452
PRF CN35	E6	0.75	0.15	0.0082	86.1	0.34	0.83	45.44	11.53	190.95	41.38	0.0731	446
PRF CN30	E6	0.75	0.14	0.0068	87.0	0.34	0.92	45.28	12.10	190.59	40.35	0.0785	435
PRF CN25	E6	0.75	0.08	0.0027	87.8	0.36	1.10	45.71	13.38	190.36	41.75	0.0760	431
E10 CN43	E6	0.75	0.15	0.0082	85.1	0.32	1.00	44.86	11.08	190.25	40.98	0.0669	432
Euro 6+ NOx Level - target 0.38g/kWh													
Diesel Base 1	E6+	0.38	3.03	0.3370	84.8	0.13	3.19	43.88	10.14	191.83	45.32	0.0640	469
Diesel Base 2	E6+	0.38	3.25	0.3370	84.8	0.17	3.00	44.31	10.03	191.69	45.01	0.0574	467
Diesel Base 3	E6+	0.38	3.13	0.3712	84.8	0.19	2.95	44.09	10.31	192.01	43.75	0.0608	474
Diesel Base Avg	E6+	0.38	3.14	0.3484	84.8	0.16	3.05	44.09	10.16	191.84	44.69	0.0607	470
Diesel Low Aromatics	E6+	0.38	2.78	0.3007	85.0	0.18	2.84	44.31	9.78	191.36	45.93	0.0584	471
Diesel Low CN	E6+	0.38	3.64	0.5171	85.4	0.13	3.38	43.35	10.75	192.07	46.86	0.0762	483
Diesel B10	E6+	0.38	3.50	0.4447	84.5	0.14	3.31	44.14	9.98	191.74	41.93	0.0538	469
Kerosene	E6+	0.38	2.65	0.2685	85.4	0.17	2.32	44.39	11.01	192.07	43.96	0.0741	460
Kerosene Low Aromatics	E6+	0.38	1.59	0.1219	85.0	0.22	1.64	44.42	10.88	192.32	43.92	0.0614	461
Dieseline	E6+	0.38	2.78	0.3123	83.9	0.35	3.05	44.14	11.23	192.39	46.42	0.0605	454
TRF CN47	E6+	0.38	2.44	0.2418	84.7	0.35	2.27	44.88	11.23	190.46	43.45	0.0650	447
PRF CN44	E6+	0.38	1.44	0.1021	84.4	0.27	2.02	44.68	10.79	191.26	41.40	0.0610	471
PRF CN35	E6+	0.38	0.75	0.0438	86.2	0.32	1.47	45.13	12.13	191.48	44.74	0.0693	465
PRF CN30	E6+	0.38	0.70	0.0397	86.9	0.33	1.69	45.21	12.77	191.66	44.77	0.0720	447
PRF CN25	E6+	0.38	0.32	0.0137	88.1	0.36	1.90	45.00	14.24	191.22	44.66	0.0671	449
E10 CN43	E6+	0.38	1.16	0.0795	84.9	0.32	2.10	43.76	11.42	191.90	46.95	0.0584	446

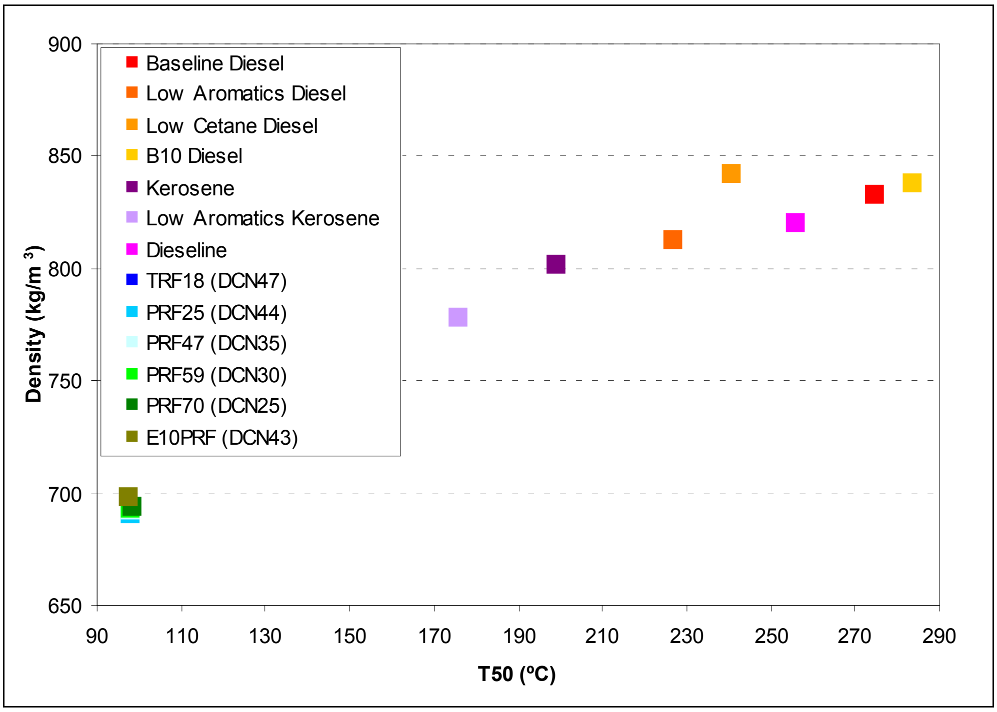
APPENDIX 4 SEPARATION OF AROMATICS AND VOLATILITY EFFECTS FOR FUELS IN THE DIESEL AND KEROSENE BOILING RANGES

INTRODUCTION

When comparing the Baseline Diesel and Low Aromatics Diesel fuels, the properties of the fuels made it difficult to attribute the reductions in PM emissions to a decrease in the aromatics content since the differences in T50 and density between these fuels were also large. A similar, although less critical, case arose when comparing the Kerosene and Low Aromatics Kerosene fuels.

Before discussing how to separate the effects of aromatics and other properties, however, it is first necessary to explore the relationship between density and T50. As might be expected, for the set of fuels used in this study, there was a clear correlation between density and T50, as is shown in **Figure A4-1**. Since it cannot be determined whether density or T50 is the governing variable and because these variables are correlated for this fuel set, the analysis below is presented in terms of T50 and aromatics content.

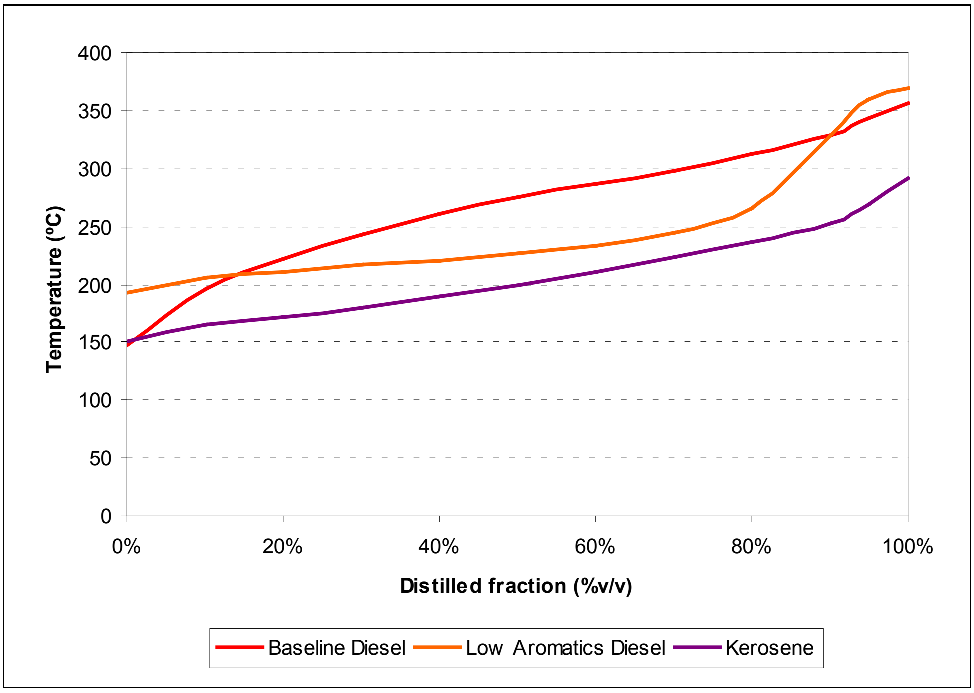
Figure A4-1 Density versus T50 for all fuels tested



DIESEL BOILING RANGE FUELS

The distillation curves for the Baseline Diesel and Low Aromatics Diesel fuels (**Figure A4-2**) show the difficulty in comparing these two fuels. Due to the shape of the Low Aromatics Diesel curve (with a steep rise in distilled fraction above 80% v/v), the difference in T50 between the Baseline Diesel and Low Aromatics Diesel is 47.8°C. The difference in density between these fuels is 20.6 kg/m^3.

Figure A4-2 Distillation curves for Baseline Diesel, Low Aromatics Diesel and Kerosene



In order to calculate the separate effects of aromatics content and T50 (or density), the simplest model is a linear model such as:

$$\Delta ISPM = a \times \Delta Aromatics + b \times \Delta T$$ **Equation A4-1**

Where Variable is the difference between the variable for the Baseline Diesel (in this case) and the other fuel considered.

Since there are two unknown coefficients in this equation, three fuels must be compared in order to solve the set of equations and calculate the coefficients. It must be noted that this is only a valid approach if two conditions are fulfilled: (1) other factors, such as CN, do not have a direct effect on PM emissions and (2) the dependence ( ) is linear. For these models and recalling that no extrapolation of the results will be done, it is sufficient to check these conditions within the range of values spanned by the independent variables used in the model.

Looking at the distillation curves for all of the fuels tested, the best set of fuels to compare is the Baseline Diesel, Low Aromatics Diesel, and Kerosene. Solving the set of equations provided by **Equation A4-1** for the three fuels and calculating the relative contributions of aromatics and T50 to the change in PM emissions for the Low Aromatics Diesel, gives the results shown in **Figures A4-3** and **A4-4**.

Figure A4-3 Relative contributions of the aromatics content and T50 for the Low Aromatics Diesel fuel to the change in PM emissions at 1500 rpm/4.3 bar IMEP

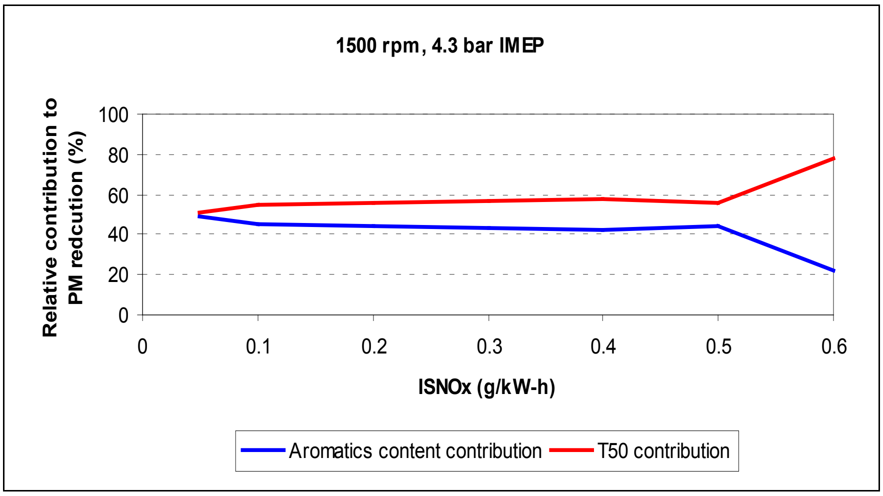
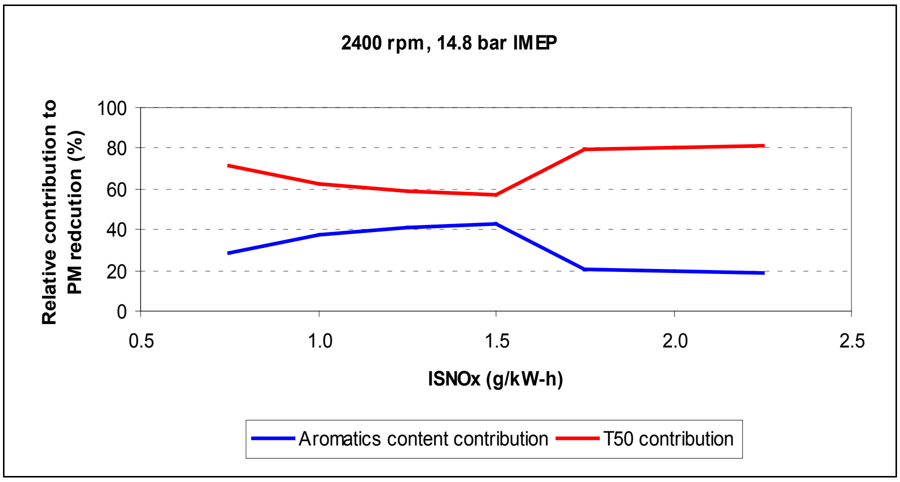


Figure A4-4 Relative contributions of the aromatics content and T50 for the Low Aromatics Diesel fuel to the change in PM emissions at 2400 rpm/14.8 bar IMEP



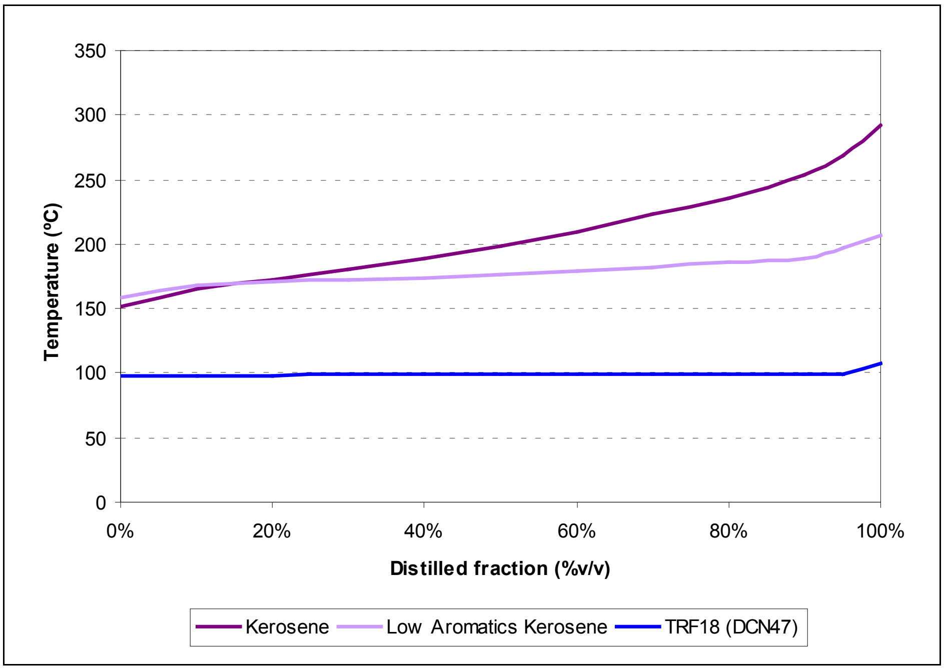
From these graphs, it is clear that, for the two experimental points shown here, the reduction in aromatics content in the Low Aromatics Diesel may only account for 20-50 % of the observed reduction in PM emissions between this fuel and the Baseline Diesel.

KEROSENE BOILING RANGE FUELS

The same approach is more difficult to apply to the kerosene boiling range fuels because the candidates available to establish the linear models are either PRFs or TRF. These fuels cannot really be considered as comparable to the diesel and kerosene fuels. Therefore, in order to establish whether the differences between the Kerosene and Low Aromatics Kerosene are due to the reductions in aromatics or to changes in other properties, some qualitative arguments will be used.

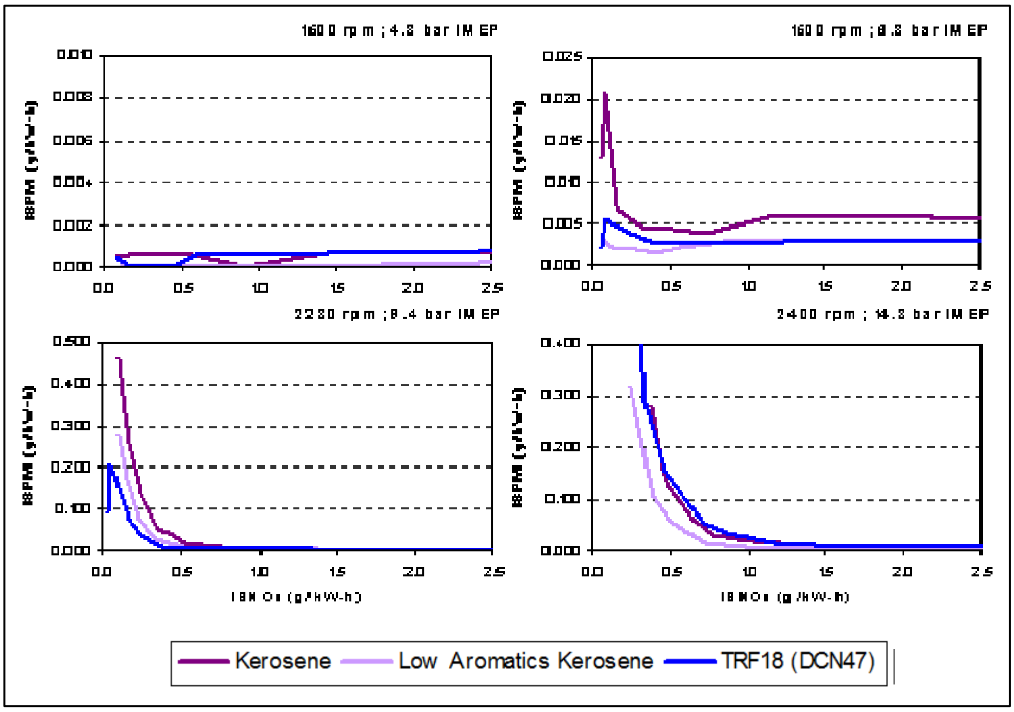
The most appropriate candidate to compare with both kerosene fuels is the TRF18 (DCN 47). As shown in **Figure A4-5**, the TRF18 distillation curve falls well below those of the two kerosene fuels. Furthermore, the density of the TRF18 is 57.3 kg/m^3 lower than that of the Low Aromatics Kerosene. On the other hand, its aromatics content (18% m/m) and DCN (47.2) are close to those of the Kerosene fuel (19.3% m/m and 46.5, respectively). Thus, TRF18 provides a reasonable reference for comparing the improvement in PM emissions due to lower T50 or density without additional complications from changes in CN or aromatics.

Figure A4-5 Distillation curves for Kerosene, Low Aromatics Kerosene and TRF18)



The ‘PM/NOx trade-off curve’ for the three fuels at the different testing points are shown in **Figure A4-6**.

Figure A4-6 PM/NOx trade-off curves for Kerosene, Low Aromatics Kerosene and TRF18



Starting with the 4.3 bar part-load point, the differences in PM emissions are so small that nothing may be concluded. At the 6.8 bar part-load point, the PM emissions for the Low Aromatics Kerosene are lower than those from the TRF18. Therefore, the aromatics content seems to play an important role at this part-load point.

At the 9.4 bar part-load point, PM emissions for TRF18 are lower than those from the Low Aromatics Kerosene and thus nothing may be concluded from this graph. Finally, at the 14.8 bar part-load point, PM emissions for TRF18 are similar to those from Kerosene and above those from the Low Aromatics Kerosene. Consequently, at this part-load point, the reductions in PM emissions between the Kerosene and Low Aromatics Kerosene fuels may be explained by the reduction in aromatics content.

Based on this limited evaluation, reduction in the aromatics contents for fuels in the kerosene boiling range seems to play an important role in reducing PM emissions.

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