A Study of Diesel Fuel Injector Deposit Effects on Power and Fuel Economy Performance

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Abstract

Injector cleanliness is well characterised in the literature [1,2,3,4] as a key factor for maintained engine performance in modern diesel cars. Injector deposits have been shown to reduce injector flow capacity resulting in power loss under full load; however, deposit effects on fuel economy are less well characterised.

A study was conducted with the aim of developing an understanding of the impact of diesel injector nozzle deposits on fuel economy. A series of tests were run using a previously published chassis dynamometer test method. The test method was designed to evaluate injector deposit effects on performance under driving conditions more representative of real world driving than the high intensity test cycle of the industry standard, CEC DW10B engine test, [1]. The efficacy of different additive levels in maintaining injector cleanliness and therefore power and fuel economy was compared in a light duty Euro 5 certified vehicle.

Full load power loss in low or non-additised fuels was observed (~3%), whereas a keep-clean dose of a deposit control additive (DCA) fully maintained performance. Furthermore, a statistically robust link between injector fouling and an increase in specific fuel consumption (~0.7%) at steady state was established.

In addition, mechanisms were proposed for the link between injector fouling and changes in fuel consumption derived from in-cylinder measurements throughout the test duration, as well as exploration of how fuel consumption effects change across the operating range outside of the test cycle.

Introduction

The formation of deposits within the nozzle holes of modern direct-injection diesel engines can reduce the quantity and disrupt the spray pattern of fuel injected into the combustion chamber. The reduced or less efficient combustion that results affords lower power

at the expense of increased fuel consumption and emissions [1,2]; therefore, studying the formation, removal and control of these deposits is of great interest [3,4].

Modern diesel engines have undergone extensive evolution in order to comply with ever more stringent emissions standards whilst also providing: high power density, low fuel consumption, reduced Noise, Vibration and Harshness (NVH). As part of this design process, engine downsizing and increasingly complex exhaust after treatment processes have been adopted, as well as strict control of combustion enabled by high precision fuel injection hardware and strategies.

The need for accurate control of the combustion process to comply with emerging emissions regulations (Euro 6 & Tier 2 bin 5) has driven fuel injection equipment manufacturers to employ increasingly high pressure common rail systems with multiple injection events to deliver meticulous control and metering of injected fuel quantity.

High hydraulic efficiency fuel injector nozzles featuring an increased number of smaller diameter high hydraulic efficiency nozzle holes have also been adopted to deliver mixture preparation benefits. However, the result improved hydraulic efficiency within the nozzle is likely to be reduced cavitation, and thus a reduction in the self-cleaning propensity of deposits in these injector nozzle designs, thus adding further potential for injector fouling in the latest FIE designs.

In addition to changes in engine and fuel injector designs, earlier work in this field [5,9] has shown that drive cycle intensity (i.e. an individual's driving style and requirements) and fuel composition (presence of trace elements, such as zinc), can affect the formation of injector nozzle deposits as well as the general observation that higher engine temperatures increase deposit severity [8,10,11,12].

Objectives

Previous data from our own testing has [10,11] shown a strong correlation between reduced fuel economy (FE) and power loss when fuel injector fouling occurred; which was partially reversed when a new additive was used to clean-up the deposits. The objectives of the program outlined in this paper, were to:

1. Reproduce the observed link between changes in power and fuel consumption that result from injector fouling in an additional vehicle, in a statistically robust test design;
2. Study the link between changes in power and fuel consumption that result from injector fouling across the full operating range of engine speed and loads, using data from injected fuel quantity, injector strategy and in-cylinder pressure measurements as diagnostic aids.

Part 1: Statistically Robust Investigation of the Link between Injector Cleanliness and Fuel Economy

The test programme was designed to provide a statistically robust investigation of the proposed link between changes in power and fuel economy arising from injector fouling. This was achieved through the comparison of the results of multiple tests in a single vehicle, of three fuel/additive formulations hypothesised to provide differing levels of injector cleanliness during a keep-clean chassis dynamometer test.

Experimental

Test Vehicle

A pick-up truck was chosen as the test vehicle. The model chosen was selected to be representative of US and global markets, which engine technology typical of many modern diesel vehicles.

Table 1. Particulars of the test vehicle

Peak Output:	>105 kW at 3400 r/min
Peak Torque:	>340 N·m (>250 lb·ft) at 1600-2800 r/min
Displacement / layout:	2.5L / I4 with intercooler and variable nozzle turbo-charger
Injection system:	Common rail, 1800 Bar peak pressure, Solenoid actuated injectors
Compression ratio	18.5:1
Emissions class:	Euro 5 via Exhaust Gas Recirculation (EGR) and Diesel Particulate Filter (DPF)

Test Fluids

The base fuel for all test fuels was CEC RF-79-07, which is an EN590 compliant B0 fuel used as the official reference fuel of the CEC DW10B injector nozzle deposit engine test, CEC F-98-08 [1]. The fuel has a cloud point of a winter grade diesel (approximately -18° C) and does not contain any FAME.

As per CEC F-98-08, pro-foulant zinc neodecanoate was added to the test fuels, A-C, at a nominal concentration of 1 mg/kg zinc, to provide a deposit formation rate that would be consistently measureable during moderate test duration; circa. 24 hours [1].

Although this level of metal contamination is not representative of real world conditions, it is known that metal contamination of the fuel can occur in vehicle systems [13,14].

To provide varying levels of injector cleanliness, three fuels were tested; one with a deposit control additive, a second with a lower performance additive and a third containing no performance additive. To assess the performance of these additive packages, the power output and fuel consumption were recorded.

Table 2. Particulars of the test fuels

Fuel label	Fuel Description	Zinc Concentration[1]
A	CEC Reference + deposit control additive	1.0 mg/kg
B	CEC Reference + low additised	1.0 mg/kg
C	CEC Reference	1.0 mg/kg
D	CEC Reference + Premium Dose of deposit control additive to ensure complete keep clean performance for stabilisation and clean power and BSFC datum	0 mg/kg

Test Cycle

Table 3. Test cycle segments

Stage	Description	Duration of repeating 30 minute test cycle
1	Maximum accelerator pedal position (APP) for power measurement[2]	20 s
2	Road load	15 min
3	80% load	13 min 50 s
	Transients between stages	50 s (total)

Test Procedure

Prior to testing, the test cycle load set points were derived and then a 6 hour shake down test was completed, with the purpose being to;

*   Ensure that any potential running issues were eliminated before test commencement.
*   Measure the rate of oil consumption so that an automated system of engine oil top-up could be employed during testing if required.

[1.] Zinc concentration determined by ICP-AMS - repeatability 0.0579x+0.0295, reproducibility 0.1273x+0.0648
[2.] A single power measurement was taken for each 30 minute test cycle; the mean of stage 1

The 6 hour shakedown was completed on fuel D to ensure that there was no build-up of deposit prior to the start of the test.

The test injectors were ultrasonically cleaned prior to commencement of each test, to ensure a stable baseline.

30 Min Warm-Up & 100% APP Power Test

To warm up the engine, it was run at the test road load condition for 30 minutes.

The maximum engine power at 100% APP and 3300 r/min was determined at this point and used to define the load of the 80% load stage.

The main test run then commenced immediately.

1st Stage - Stabilisation & Keep Clean

The car ran 12 hours stabilisation and keep clean (24 repetitions of the test cycle listed in Table 3) using fuel D. Earlier data [11] has shown that the first 6 hours of this stage is sufficient duration to allow for the vehicle to stabilise, and the remaining 6 hours provide a stable baseline to obtain a power and BSFC datum point for comparison to subsequent measurements.

Testing was continued without stopping into the next stage.

2nd Stage - Keep-Clean

24 hour keep-clean (48 repetitions of the test cycle listed in Table 3) using fuel A-C (see Table 2).

After completing testing with the first fuel, the vehicle remained in-situ in the CD for ultrasonic cleaning of the injectors and a fresh refill of crankcase lubricant.

In the interest of statistical robustness, a repeat of the test procedure on each fuel was run so that the precision of the test could be established.

Data Analysis

For the calculation of percent change in a given response (e.g. BSFC or Power), the following methodology was applied to determine the "zero datum" at the end of the 12 hour stabilisation & keep clean stage.

A linear regression model was fitted to the last five data points of this stage and used to estimate the value of the response at 12 hours - the "zero datum". This approach reduces bias by avoiding dependence on the final data point.

In a similar manner, a linear regression model is fitted to the last five data points of the second keep clean stage and used to estimate the value of the response at the end of the test (36 hours). The office test result is the percent change in Power and BSFC from the "zero datum" to the end of test.

For graphical display purposes, all test data points are converted to percentages relative to the "zero datum" as shown in Figures 1 and 2.

Differences in the Power and BSFC changes of the three test fuels A, B & C were assessed using Tukeys multiple comparison test, which was applied simultaneously to all pairwise comparisons. The error bars on the results charts (Figures 5 & 6) are half the least significant difference at 95% confidence, i.e. these can be interpreted that the difference is significant at 95% confidence if the error bars do not overlap.

Test Results

The following colour scheme (Table 4) is used throughout the results section. Note that Fuel D was only used stabilisation purposes, and the performance of this fuel was not within the scope of this paper:

Table 4. Test fuels

A	Deposit control additive (orange)
B	Low additised fuel (yellow)
C	No additive / Dirty-Up (red)

Example Dataset - Fuel C

As an example, Figure 1 plots the power data for a single run, throughout the test duration, using the additive free base fuel (fuel C). As expected for an additive free fuel containing zinc, the results show a substantial reduction in power over the test duration, which can be attributed to the reduction in injector cleanliness.
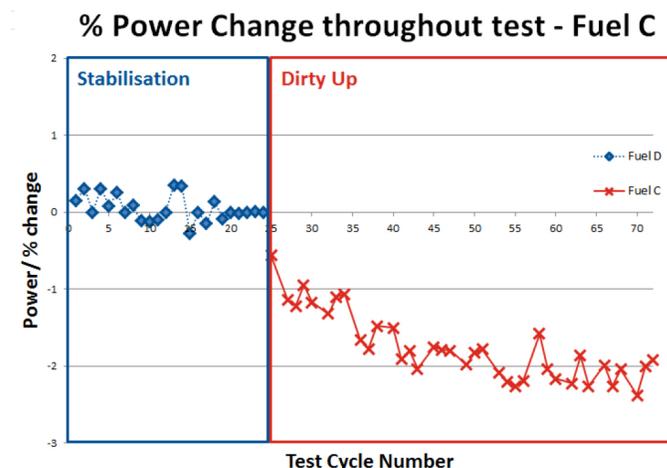

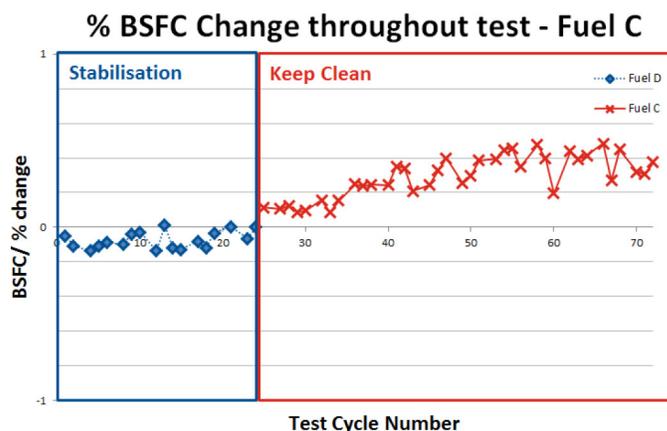Figure 1. Power data for fuel C, at 100% APP and 3300 r/min:

Figure 2. BSFC data for fuel C, at 100% APP and 3300 r/min:

As an example, Figure 2 plots the BSFC data throughout the test duration, using the additive free base fuel (fuel C). BSFC remains stable during the initial 12 hours, followed by a measurable increase in BSFC over the following 24 hours when power loss due to injector fouling had been shown to occur in Figure 1.

Figure 3 shows that the change in BSFC is linearly correlated (R^2=0.83) with power loss, and thus injector cleanliness.

Subsequent investigations into the loss of combustion efficiency due to injector fouling are detailed in the second half of this paper.
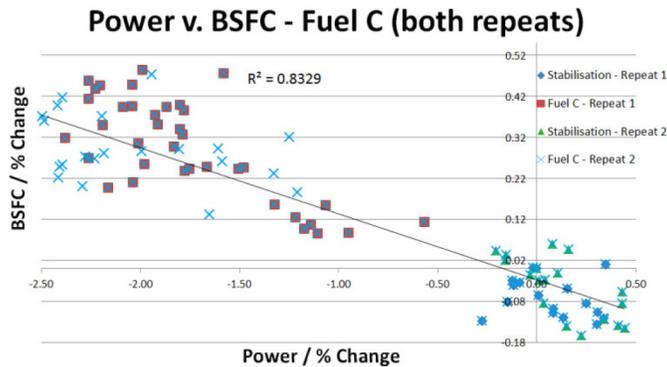
Figure 3. Power v. BSFC correlation for both repeats of Fuel C (at 100% APP and 3300 r/min)

Injector Cleanliness Results - % Power Change at Full-Load

The following figure shows the mean % power change for all test fuels.
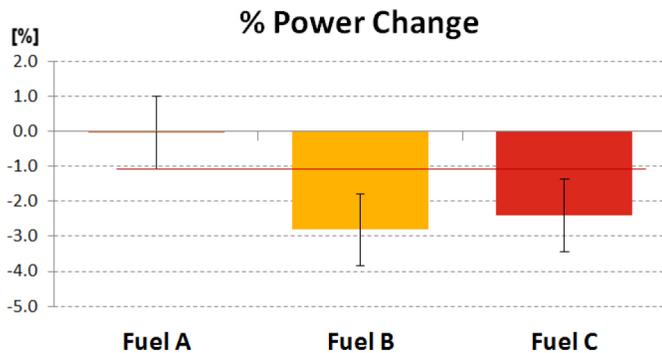
Figure 4. % Power change for all tests, at 100% APP and 3300 r/min.

Table 5. Average % Power change for each fuel, at 100% APP and 3300 r/min

Fuel	A	B	C
Deposit control additive	High	Low	None
Result (%)	-0.04	-2.82	-2.39
Standard Error	± 0.36	± 0.36	± 0.36

As shown in Figure 4 and Figure 5, only fuel A with the deposit control additive formulation was able to maintain engine performance and prevent any significant power loss from injector fouling.

Fuels B & C with low, or zero additive concentrations, could not be distinguished from each other, and showed significant power loss due to injector fouling.

Injector Cleanliness Results - % BSFC Change at Full-Load

The following figure shows the mean % BSFC change for all test fuels. Positive values indicate a BSFC increase.
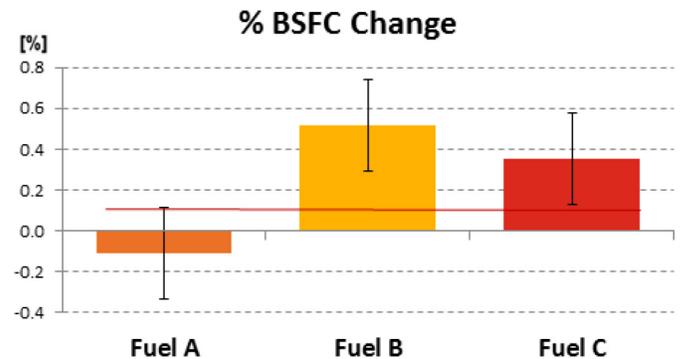

Figure 5. % BSFC Change, at 100% APP and 3300 r/min

Table 6. Average % BSFC change for each fuel, at 100% APP and 3300 r/min

Fuel	A	B	C
Deposit control additive	High	Low	None
Result	-0.11	0.52	0.35
Standard Error	± 0.08	± 0.08	± 0.08

As indicated by the data in Figure 5 and Table 6, only fuel A with the deposit control additive was able to maintain engine performance and prevent any significant change in BSFC as a result of injector fouling.

Fuels B & C with low, or zero additive concentrations, could not be distinguished from each other, and showed significant increases in BSFC as a result of injector fouling.

Part 1: Conclusions

Losses of power and fuel economy occur due to injector deposit formation when low or non-additised fuels used. There is a statistically significant reduction in these losses if a fuel containing the deposit control additive is used. Changes in power and fuel economy due to injector deposit formation correlate linearly.

Part 2: Investigating the Link between Injector Cleanliness and Fuel Economy across the Full Engine Operating Map

Following the investigation detailed in part 1 of this paper, the link established between injector cleanliness and fuel economy was investigated in further depth across a much wider range of engine speed and load points.

Experimental

Test Vehicle

The same vehicle was used as in the earlier testing, with additional fitment of thermo-couples, in-cylinder pressure measurement and data loggers to allow for a more critical investigation of properties linked to injector fouling and engine operating parameters.

Test Fluids

The same base fuel as per part 1 (CEC RF-79-07) was used during this investigation, with the following blends used:

Table 7. Particulars of the test fuels

Fuel label	Fuel Description	Zinc Concentration
E	CEC Reference + a double premium dose of deposit control additive (2x fuel D) to provide high clean-up performance in a short window, before the stabilisation & keep clean stage.	0 mg/kg
F	CEC Reference + premium dose of deposit control additive to ensure complete keep clean performance for stabilisation and keep-clean power and BSFC datum (same as Fuel D in Part 1)	0 mg/kg
G	CEC Reference	1.0 mg/kg

Test Cycle

The same repeating 30 minute test cycle, as per part 1 (Table 3) was used during this investigation, with the following adaptations of the test detailed within Part 1:

Test Procedure

For this testing, the 6 hour shake down was eliminated as it had already been completed during part 1. In addition, ultrasonic cleaned injectors were not used; *in-situ* clean-up of the fitted injectors was completed through use of a very high DCA dose.

In addition to the normal speed, torque, fuel flow data, etc., collected by the chassis dyne, engine operating parameter and in-cylinder pressure data was collected by an independent system, and logged as the average of 500 engine revolutions.

Pre-Test Stage - Clean-Up

Prior to commencement of the test, to ensure that clean injectors were used, the test vehicle was run on a high DCA concentration fuel (fuel E) for 6 hours, (12 repetitions of the 30 minute test cycle).

Testing was continued without stopping into the next stage.

1st Stage - Stabilisation & Keep Clean

The test vehicle ran for 6 hours stabilisation and keep clean (12 repetitions of the 30 minute test cycle) using fuel F. It was assumed that the engine, injectors, vehicle driveline and dynamometer was fully stabilised after the 12 hours of the pre- and 1st stages, and after the 6 hours of the 1st stage, the recorded power and BSFC measures were used for comparison to subsequent measurements.

Testing was continued without stopping into the next stage.

Clean Injector Engine Performance Mapping

At this point the vehicle performance at an assumed clean and stable operating datum was appraised through the procedure detailed below.

Testing was continued without stopping into the next stage.

2nd Stage - Double Length Dirty-Up

48 hour running (96 repetitions of the 30 minute test cycle using detergent free fuel G. The increased duration over the earlier testing was chosen to maximise injector fouling and associated symptoms and deliver increased fidelity between supplementary measurements.

Testing was continued without stopping into the next stage.

Dirty Injector Engine Performance Mapping

Finally, a repeat of the vehicle performance mapping was completed for comparison to the clean datum.

Performance Mapping Procedure

Sequentially, the test vehicle was driven across the speed/load points described in Table 8 and Figure 6. Data was collected from the chassis dyne for 1 minute at each test point.

Table 8. Engine Mapping Points

		Speed / 1/min								
		1000	1500	2000	2500	3000	3300	3400	4000	4400
	Note:			3			4	5		6
Power / kW	10	x	x	x	x	x	x	x	x	x
	20	x	x	x	x	x	x	x	x	x
	30		x	x	x	x	x	x	x	x
	40		x	x	x	x	x	x	x	x
	50			x	x	x	x	x	x	x
	60			x	x	x	x	x	x	x
	70				x	x	x	x	x	
	80					x	x	x	x	
	90					x	x	x	x	
	100						x	x		
	Max	x	x	x	x	x	x	x	x	x

[3.] Max torque achievable from 1600 - 2800 r/min

[4.] Current test condition

[5.] Max rated power at 3400 r/min
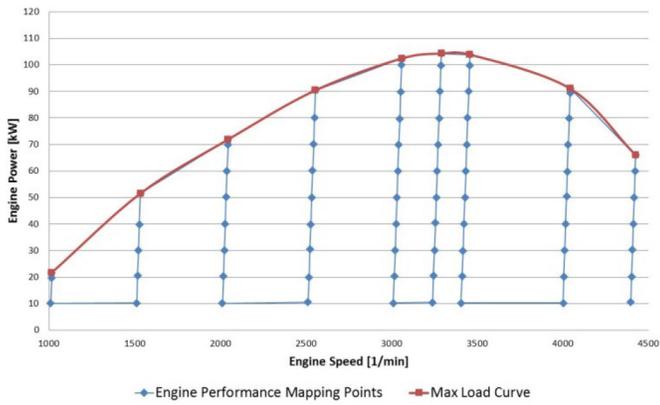
[6.] Max rated engine speed

Figure 6. Engine mapping points; tested sequentially from high speed, low load, to low speed, high load.

Engine operating parameters and in-cylinder pressure data was collected by an independent system, and logged as the average of 500 engine revolutions.

Test Results

The following colour scheme is used throughout the results section:

Table 9. Test fuels; Part 2

E	Double dose clean-up (blue)
F	Keep-clean & stabilisation (red)
G	No additive / Dirty-Up (green)

Injector Cleanliness Results - Power Change at Full-Load
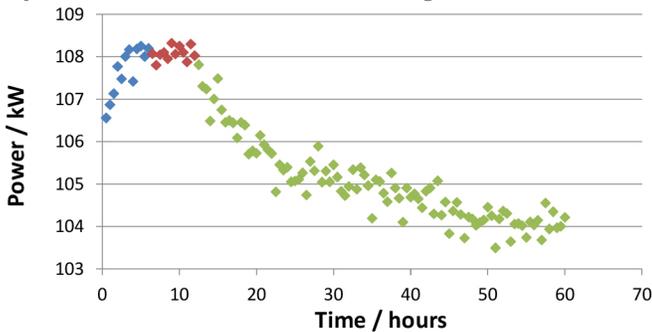
Figure 7. Full-load Power (100% APP at 3300 r/min) during the 60 hr test

Note the rapid and complete power recovery during the 6 hr clean-up using a double dose of deposit control additive, before the power output stabilises in the subsequent 6 hr stage, showing that the initial clean-up was complete and no further power recovery was possible.

During the extended, 48 hour dirty-up, a power loss of 3.8 kW due to injector fouling was recorded, which equates to 3.6%. Power loss did not occur linearly, with some reduction in fouling rate after ~15 hours testing.

Injector Cleanliness Results - BSFC Change at Full-Load

BSFC increased by 1.5 g/kWh (0.65%) in the 48 hour long fouling period, and the previously observed trend of loss of power and increased BSFC due to injector fouling is repeated (Figure 3).
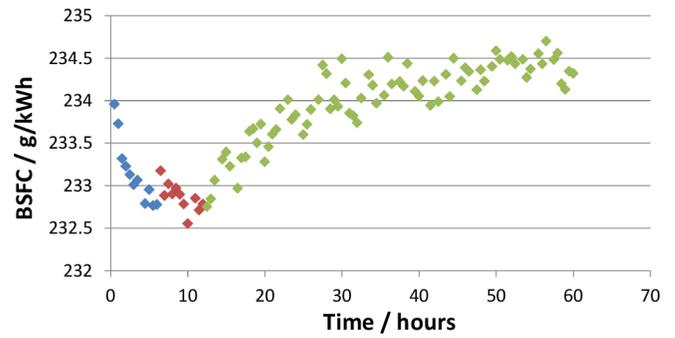
Figure 8. Full-load BSFC (100% APP at 3300 r/min) during the 60 hr test
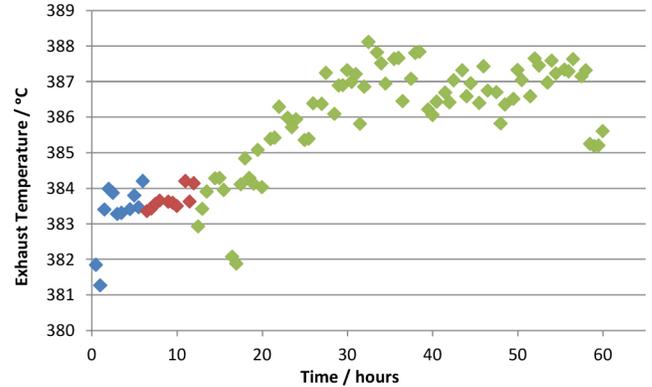
Full Load Data - Exhaust Temperatures

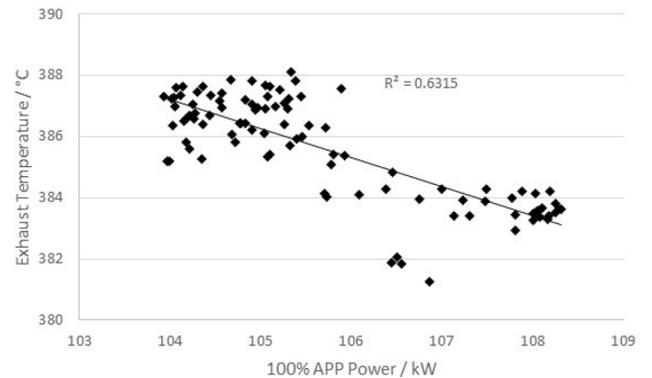Figure 9. Exhaust Temperature at 100% APP and 3300 r/min throughout the 60 hour test

Figure 10. Exhaust Temperature v. full-load power (100% APP at 3300 r/min) during the 60 hour test.
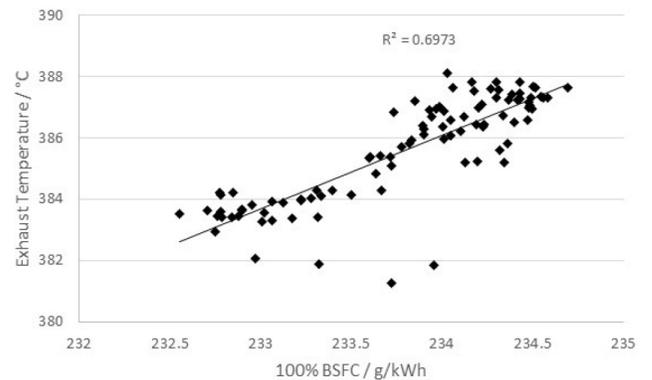

Figure 11. Exhaust Temperature v. full-load BSFC (100% APP at 3300 r/min) during the 60 hour test.

Figure 9, Figure 10, Figure 11, Figure 12 show the exhaust temperatures recorded during the 100% APP stage of testing, and how they correlate with power loss and increases in BSFC due to injector fouling.

Power loss is associated with increased heat in the exhaust indicating reduced thermal efficiency.

The opposite trend of increased exhaust gas temperature with increasing BSFC shows that that the combustion process or engine efficiency is compromised by injector fouling, which was explored in more depth through analysis of in-cylinder pressure and heat release measurements.

Full Load Data - In-Cylinder Data

A full suite of in-cylinder data was recorded throughout the 60 hour test, as well as during the engine performance mapping stages. Only the key results are discussed here:
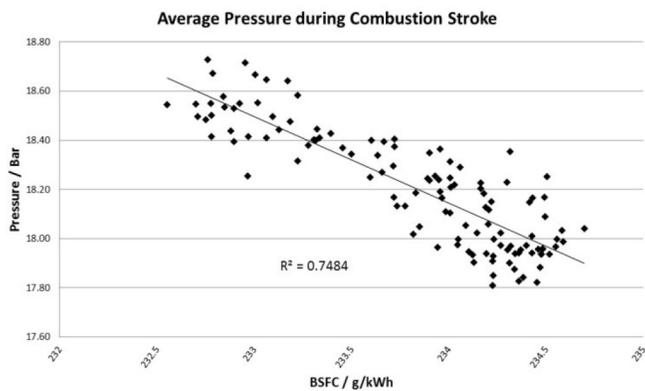
Figure 12. The Mean In-cylinder Pressure of the high pressure (combustion) cycle vs. full-load BSFC at 100% APP and 3300 r/min during the 60 hour test.

As shown in earlier charts (e.g. Figure 3) the in-cylinder measurements confirm that reduced engine power (reduced average in-cylinder pressure at 100% APP and 3300 r/min) is correlated ($R^2=0.79$) with an increase in BSFC when injector fouling occurs.

As shown in earlier charts (e.g. Figure 3) the in-cylinder pressure measurements confirm that reduced engine power (reduced average in-cylinder pressure at 100% APP and 3300 r/min) is correlated ($R^2=0.79$) with an increase in BSFC when injector fouling occurs.

Figure 13 shows that the position of 5% mass burn fraction (MBF) is mildly correlated ($R^2=0.35$) with BSFC at 100% APP and 3300 r/min. The positions of 50% MBF ($R^2=0.08$) & 95% MBF ($R^2=0.06$) did not show any correlation with BSFC at the same engine conditions. Hence, it is suggested that at the 100% APP and 3300 r/min test condition, delays in the initial stages of combustion are the likely causes to changes in overall engine efficiency seen

due to injector fouling. Further investigation of combustion timing across a range of speed and load conditions are discussed in the following section.
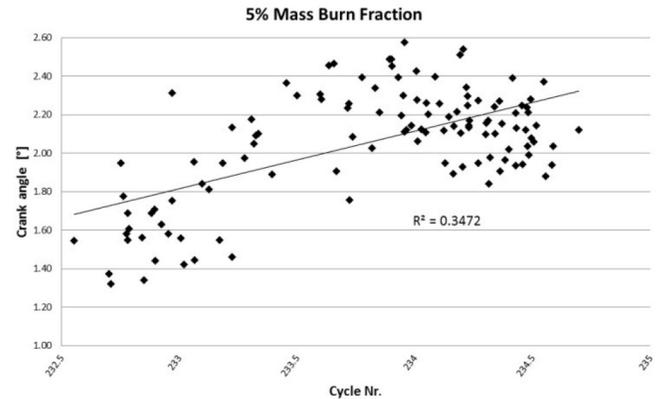

Figure 13. The position of 5% Mass Burn Fraction v. BSFC at 100% APP and 3300 r/min during the 60 hour.

Performance Mapping Procedure - Chassis Dyne BSFC Results

All results presented within this section are the difference between the average dirty injector performance, i.e. the end of test (EOT; mean of 60 s, 1 Hz data from the final test cycle, after running on Fuel G for 48 hours) minus the average clean injector performance, i.e. the start of test (SOT; mean of 60 s, 1 Hz data from the final test cycle before swapping to Fuel G).
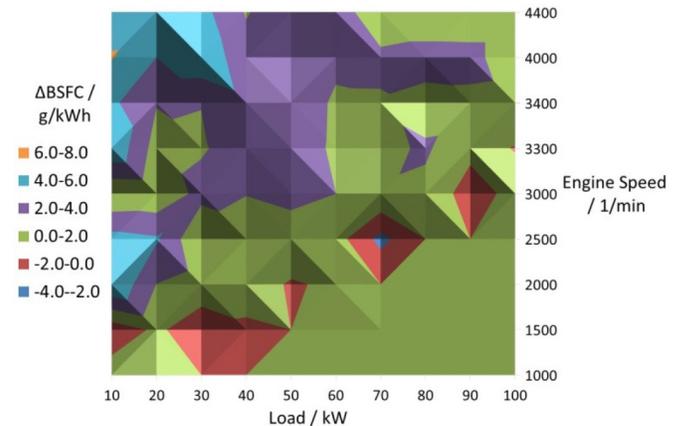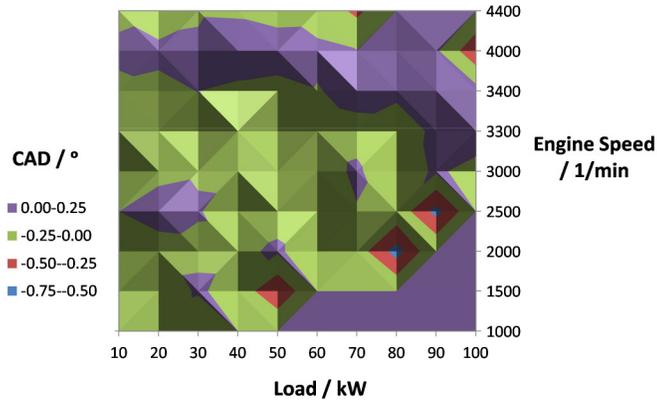

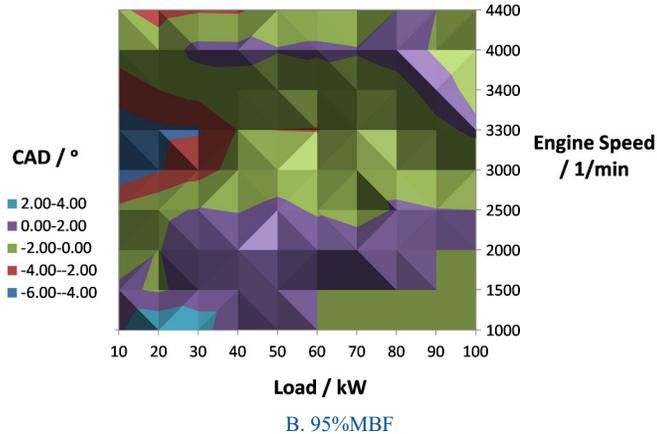Figure 14. ΔBSFC (EOT-SOT) for a range of engine speed and load conditions, displayed as a contour map

Note that the flat area in the lower right portion of the map (Figure 14) where the ΔBSFC is zero owing to the inability of the engine to operate in this range. This flat area is repeated in all subsequent charts.

The trend shown in Figure 14 is that higher increases in ΔBSFC occur at lower engine speed and load conditions.
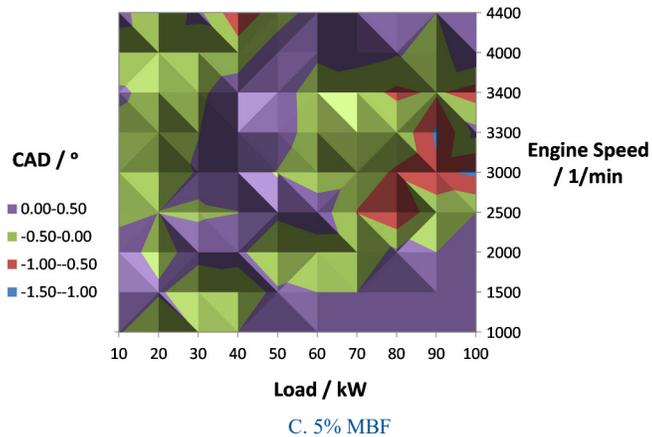
Performance Mapping Procedure - Engine Operating Parameters and In-Cylinder Pressure Data
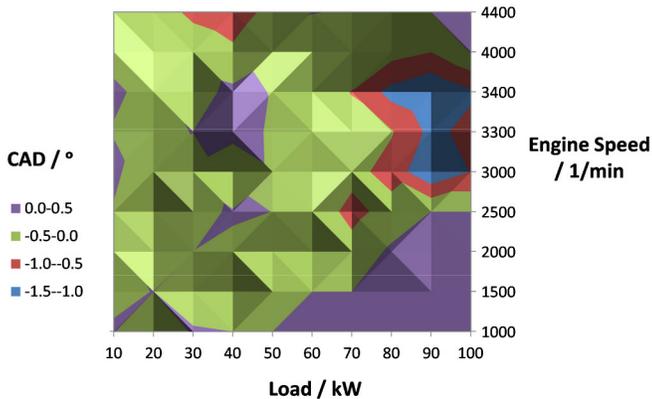
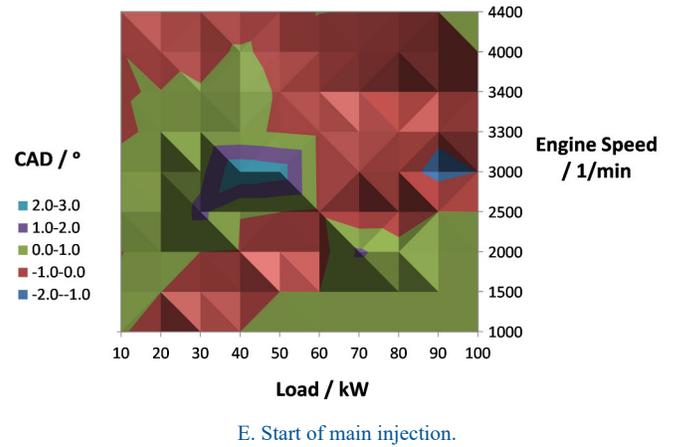A. The Mean In-cylinder Pressure of the high pressure (combustion) stroke

B. 95%MBF

C. 5% MBF

D. Start of first pilot injection

Figure 15.

E. Start of main injection.

Figure 15. (cont.) EOT-SOT data for a range of engine speed and load conditions, displayed as a contour map.

The charted data shows directional trends that have a level of significance, with the remaining parameters exhibiting zero change, or apparently random noise (see appendix for full list of parameters). It should be noted that the vehicle control systems may have compensated for some differences brought about from injector fouling, although the charted plots all display observed trends that directionally align with the observed change in BSFC.

Observations:

- At 4000 r/min engine speed, small increases to the Mean In-cylinder Pressure of the high pressure (combustion) stroke are correlated with an advance in 95%MBF due to injector fouling (A & B).
- With fouled injectors a 5%MBF (C) and the start of primary pilot injection (D) are both retarded at high loads (≥80 kW) and relatively high engine speeds (2500-3400 r/min).
- Retardation of the start of main injection is correlated with increases in BSFC (and thus injector fouling) for the majority of speed & load conditions, except for a small window between 40-50 kW at 3000 r/min where the injection is advanced (E). Whether this is an artefact, or if the engine control systems have altered injection strategy in this area of operation, perhaps for emissions control could be worthy of further investigation.

Performance Mapping Procedure - BSFC Results at 100% APP Only

The following data have been isolated from the performance mapping procedure to examine the full-load, 100% APP performance at varying engine speed.

Figure 16 indicates that there is a transition point at around 2500 r/min engine speed and 100% APP, above which there is an increase in ΔBSFC, and below, a decrease in ΔBSFC due to injector fouling.

However, as shown in Figure 17 there is no significance (90% confidence) to the decrease in BSFC at these lower engine speeds, or the differences observed below 3300 r/min.
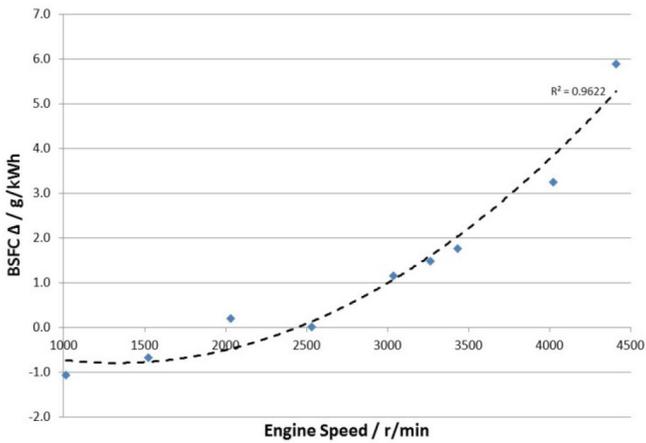
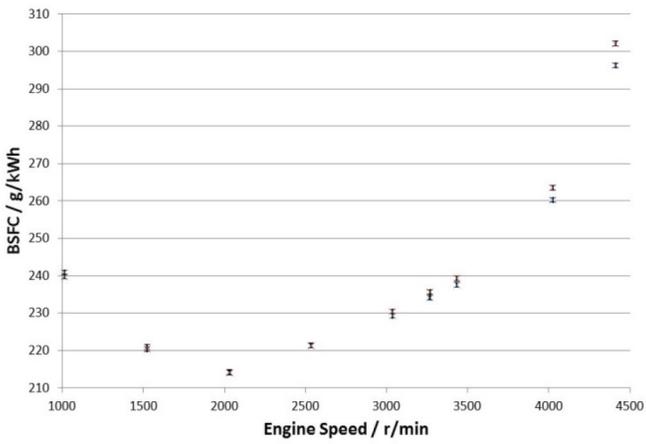Figure 16. ΔBSFC (EOT-SOT) for a range of engine speeds at 100% APP

Figure 17. Absolute BSFC values at each engine speed, with error bars equal to +/- 1.645σ.

Performance Mapping Procedure - Supplementary In-Cylinder Data at 100% APP

Only data with a marked trend with the observed changes in BSFC (Figure 16) are discussed in this section. All other data did not show any observable directional or statistically significant trends, and for the sake of brevity, is excluded from this paper.
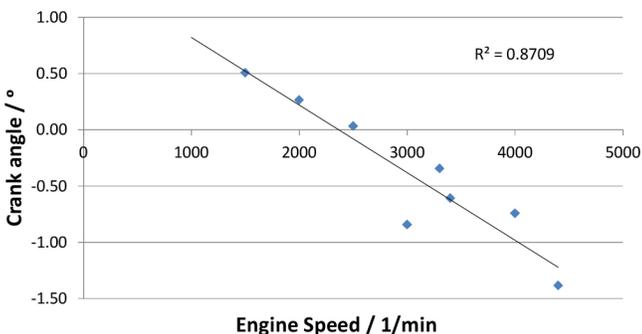

Figure 18. Change in 95%MBF (EOT-SOT) for a range of engine speeds at 100% APP

The timing of 95%MBF can be seen to be retarded at low engine speeds and advanced at engine speeds >2500 r/min after injector fouling occurs; this represents a cross-over point that matches the observations in suggesting that a strong link exists between late combustion and engine efficiency, especially at higher engine speeds where time for combustion is increasingly limited.

A possible explanation for this cross-over point is that injector fouling results in reduced fuel delivery, and a change in spray pattern. At low engine speeds, there is sufficient time remaining in the power stroke for the combustion to complete, and the retardation is observed. At higher engine speeds, and thus higher rail pressures, the effect of injector fouling on spray pattern is more accentuated, and results in an increased soot production, due to poorer mixing of the injected fuel. Hence, although the 95%MBF is seen to advance due to a reduction in the volume of fuel injected, there is an increase in BSFC as the last 5% of combustion is rich in slow burning soot, and is exhausted without providing useful work to the engine.

The single speed data displayed earlier (Figure 13) lies in the middle of this range, close to a zero change, hence explaining why the earlier data did not show any significant correlation between changes in combustion (MBF5%, 50% & 95%) due to injector fouling.

Part 2: Conclusions

Testing in this section delivered a full load (100% APP) power loss of 3.6% (at 3300 r/min) which was associated with a BSFC increase of 0.65% when using the same methodology as Part 1, albeit during a double duration (48 hour) dirty-up.

Insights into the link between injector fouling and changes in fuel economy were recorded via in-cylinder pressure measurements throughout the test duration, as well as additional mapping of engine performance across varied speed/load points before and after the "dirty-up" phase of the test. Highlights include:

*   Power loss and increases in BSFC due to injector fouling did not continue linearly throughout the test; slowing, but not halting beyond 15 hours dirty-up;
*   No consistent trend in BSFC changes was identified away from the full-load condition though BSFC tended to suffer most from injector deposits at high speed low load conditions;
*   The greatest losses in fuel economy were seen at high engine speeds and full-load (4400 r/min, 1.9%);
*   Changes in combustion timing and duration were investigated, with changes in timing of late combustion (MBF95%) the most strongly linked to the identified trend in increased BSFC with injector fouling as engine speed increases.

Summary and Overall Conclusions

A series of chassis dyne tests have been completed on a single vehicle, which have established:

*   A statistically significant (95% confidence) loss of power and increase in BSFC when injector cleanliness is not maintained through the use of fuel additives;
*   Power loss from injector fouling is linearly correlated to increases in BSFC, and the reasons for this have been investigated. The data shows that at full-load, changes in the final stages of combustion (MBF95%) are the most likely cause for the loss in combustion efficiency.

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APPENDIX

LIST OF MEASURED/DERIVED IN-CYLINDER MEASUREMENTS AND ENGINE PARAMETERS

Parameter	Unit
Average Pressure of complete engine cycle	Bar
Average Pressure of combustion stroke of engine cycle	Bar
Maximum In-cylinder Pressure	Bar
Maximum In-cylinder Pressure Timing	Crank Angle Degrees (CAD)
0% Mass Fraction Burn (Start of Combustion)	CAD
5% Mass Fraction Burn	CAD
50% Mass Fraction Burn	CAD
90% Mass Fraction Burn	CAD
95% Mass Fraction Burn	CAD
Start of Pilot Injection	CAD
Duration of Pilot Injection	CAD
End of Pilot Injection	CAD
Start of Secondary Pilot Injection (if present)	CAD
Start of Main Injection	CAD
Duration of Main Injection	CAD
End of Main Injection	CAD