Whitepaper

Characterisation of Gasoline Fuels in a DISI Engine

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Summary

The importance of direct injection for gasoline has been described and demonstrated on numerous occasions in many articles and technical papers. Similarly, the impact of deposits forming on the injector and the subsequent effect on efficiency and emissions is also well documented and many oil and fuel additive companies have developed their own methodologies. However, until now there has not been an industry test available to compare deposit forming tendencies of different fuels or deposit control additives to clean them up.

This paper looks at a recently proposed CEC direct injection gasoline fuels test based on the VW 1.4 'twin-charger' engine. SGS laboratories secured access to a surrogate engine sharing most of the key hardware and software components common with that proposed for the CEC test. This allowed early work to be conducted between SGS and Afton Chemical to study a range of engine, fuel and deposit control additive effects.

The impact of fuel properties on injector deposit formation was found to be significant. Previous studies have shown there is almost no consensus of 'bad actors' with regard to fuel properties and deposit formation. This seems likely to be due to the fact that each engine and test cycle has its own specific characteristics, and in this regard, this proposed CEC test currently appears to be no different.

1. Introduction

During the last two decades, the automobile industry has made impressive technological steps forward. Modern combustion technology, high pressure direct injection fuel systems and advanced exhaust after-treatment systems have defined more stringent requirements for modern automotive fuels.

Since the introduction of in-use compliance legislation, the role of the fuel has been brought into focus for car manufacturers. The pressure for more detailed fuel specifications is increasing, as is the need for advanced test methods.

In Europe the Coordinating European Council for the development of Performance Tests for Fuels, Lubricants and Other Fluid (CEC) is responsible for the introduction and development of new performance based test methods.

1.1 Overview of Gasoline Tests - SGS

Test parameters and specifications - some of which are not defined by the European fuel standard EN228, but are required by car manufacturers - are listed in the ACEA World Wide Fuel Charter. These tests focus on the specification of engine cleanliness and the definition of the deposit forming tendency of fuels.

ASTM standards are the North American counterparts of the CEC standards. Figure 1 gives an overview of existing ASTM standards which define engine cleanliness and deposit formation in gasoline engines.

US Test Methods

ASTM D5500
- BMW 318i (1985) 4-speed automatic transmission
- On-Road test profile 16.090km / 16.250km (10.000 mi)
- Intake valve weight and rating of valve deposits and photos

ASTM D6201
- Ford Ranger 2.3L 4-cylinder engine
- 100 hours at the engine test stand (~462 cycles)
- Intake valve weight and induction system rating and photos

ASTM D5598
- Chrysler 2.2L 4-cylinder vehicle (MJ1985 – MJ1987)
- 16.100km (cycle: 15 min @ 88km/h + 45 min soak)
- Evaluation of flow rate before and after test (Bosch EV1.1A)

ASTM D6241
- Rig test comparable to ASTM 5598

Figure 1: ASTM Test Methods

All engines and vehicles used in these tests were produced in the 1980s. The engine technologies are not representative for the current vehicle fleet in developed markets.

EU Test Methods

CEC-F-05-93
- MB M102e 2.3L OHC 4-cylinder (mechanical/electrical injector system)
- 60 hours low load test profile at engine test stand
- Intake valve weight and rating of valve deposits and photos

CEC-F-16-96
- VW 1.9L water-cooled boxer Otto engine type 2 series
- Drive cycles, cool-down, soak, compression test
- Sticking tendency of intake valve at low temperatures

CEC-F-20-98
- MB M111 2.0L 4-cylinder engine with 4 valve / cylinders
- 60 hours low load test profile at engine test stand
- Intake valve weight, combustion chamber deposit weight, piston top deposit weight

Figure 2: CEC Test Methods

The situation in Europe is comparable to the US. The CEC tests were developed in the 1990s and earlier. Mainly, Port Fuel Injection (PFI) engines are in use for the fuel deposit characterisation of gasoline fuels. Figure 2 shows the CEC methods to determine engine cleanliness and deposit formation in gasoline engines.

2. DISI Test

As this situation is not satisfactory, most car manufacturers and many companies from the additive and fuels industry have defined in-house tests, using direct injection spark ignition (DISI) engines. To address this gap, VW has proposed a new CEC test using a DISI engine.

The SGS test procedure is in principle based on the VW test procedure which is under development as CEC-TDG-113 test method.

2.1 Test Hardware

The SGS test engine is a VW EA111 1.4 litre 4-cylinder CAVE engine from SKODA. The engine has a compressor and a turbo charger with waste gate which produces a maximum power of 132 kW at 6.200 rpm.

The maximum fuel pressure is 200 bars, limited to 175 bars for the CAVE engine type. The fuel injectors are six hole injectors from Magneti Marelli. The EA111 Twincharger variant has been produced since 2005 in different versions with power output from 90 kW to 132kW for mostly VW models - from the VW Polo to the VW Sharan Model 2010.

The technical data of the CAVE test engine is shown in Table 1.

Engine Model	VW EA 111	-
Engine Type	CAVE	-
Introduction	05.2010	Polo 2010
Emission standard	EU5	-
Capacity	1.390	ccm
Power	132 kW	@62000 rpm
Torque	250 Nm	2000-4500 rpm
Bore Dm	78,5	mm
Stroke	75,8	mm
Compression Ratio	10	-
RON min.	95	-
Mixture Formation	Homogenous	-

Table 1: Technical Data VW EA111 CAVE Engine

2.2 Test Procedure

The test procedure was selected in accordance with the likely proposed CEC test method TDG-F-113.The engine showed extremely high nozzle coking potential under low load conditions.

A steady state test cycle with a constant engine speed of 2000 rpm and a constant torque of 56 Nm has been selected. Engine parameters, such as fuel temperature and charge air temperature are controlled during the test cycle.

Speed	2 000	RPM
Load	56	Nm
Fuel Pressure	77	Bar
DU phase	48	hours
CU phase	24	hours

Table 2: Test Conditions

All tests are performed with new injectors. Each set of injectors is run in for 4 hours at the test set point and then ultrasonically cleaned prior to the main test. The test procedure has two phases. The first phase is a 48 hour dirty up (DU) test performed with base fuel without performance additives to produce nozzle coking. The second phase is a 24 hour clean up (CU) test, performed with a test fuel with clean up capabilities.

The primary test parameter to describe the nozzle coking is the injection length. Additional parameters are the short term fuel trim and the long term fuel trim. The product of the trim factors is directly proportional to the injection length. These values are available as ECU parameters.

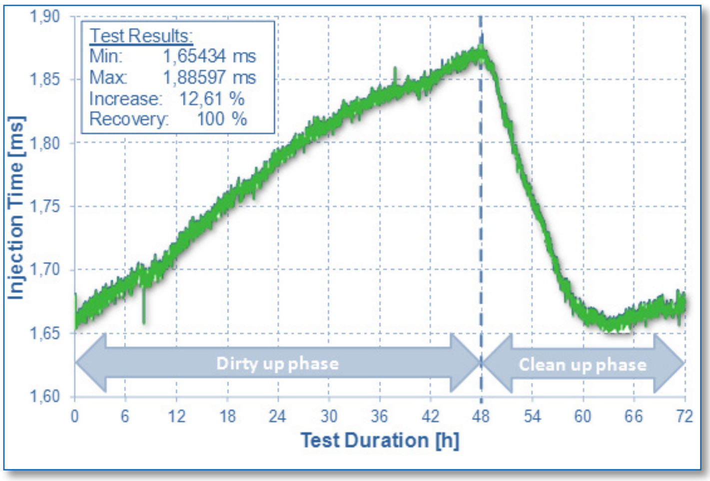


Figure 3: Change of Injection Timing During Test

Figure 3 shows a typical test result with a CEC reference fuel RF-83-91 as the test fuel for the whole test. To demonstrate clean up performance during the second test phase, a VW service additive was added.

2.3 Test Results

Initial trials with different test fuels have been performed. Significant nozzle fouling has been observed for all market fuels without performance additives. Typical test results range from a 5% increase of injection length to a 50% increase of injection length over the 48 hours.

The RF-83-91 test fuel is not EN228 compliant, containing 170 mg/kg sulfur and up to 40% aromatic content. All other test fuels are EN 228 compliant refinery fuels with or without ethanol. Two tests with a EN228 compliant refinery fuel

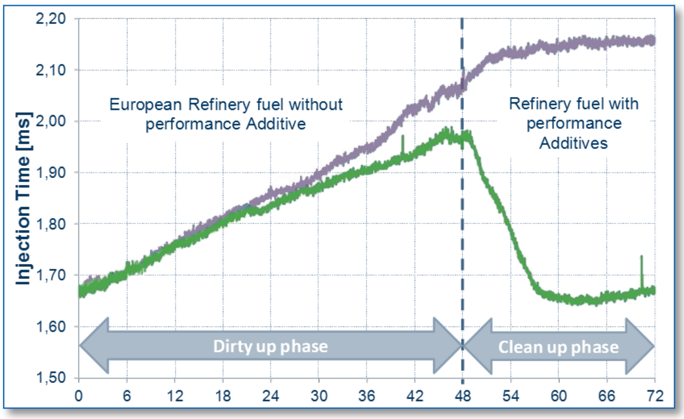


Figure 4: Tests with different performance additives

without ethanol for the DU phase are shown in Figure 4. For the CU phase different performance additives were added to the base fuel.

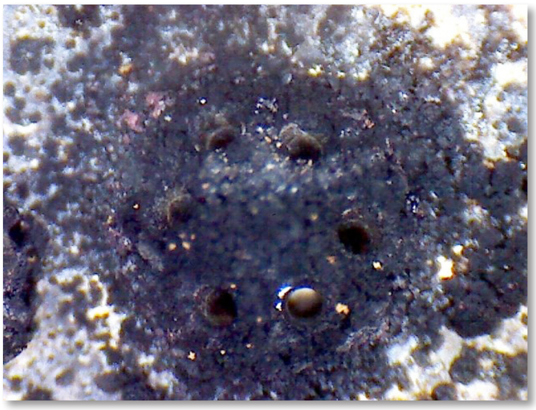


Figure 5: Nozzle holes after successful clean up

The initial injection length of 1,65 ms at the start of test is a good validation test criterion. For EN 228 compliant fuels without ethanol, a limitation of 1,65 ms +/- 0,05 ms has been defined as the limitation during start of the DU test.

After a 48 hour test time, the fuels were changed for both tests. The performance of both fuel additives differs significantly. The green curve shows a complete recovery of the injection timing. Nozzle holes have been cleaned

DISI Test continued...

completely by the additive. The picture of the nozzle at end of test is displayed in Figure 5. Deposits at the injector tip are still present, but the nozzle holes are visibly clear.

No clean up effect is visible for the purple curve. The injection timing has not decreased during clean up. The nozzle deposits at the holes of the injector have not been removed, as seen in Figure 6.

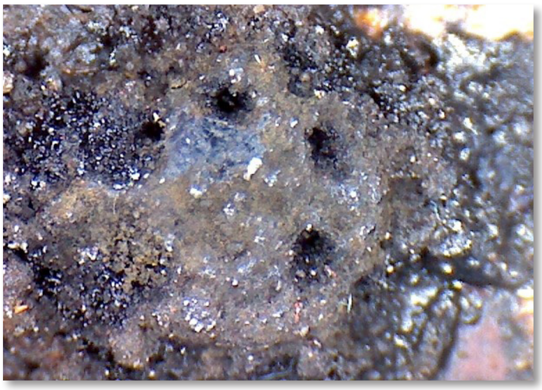


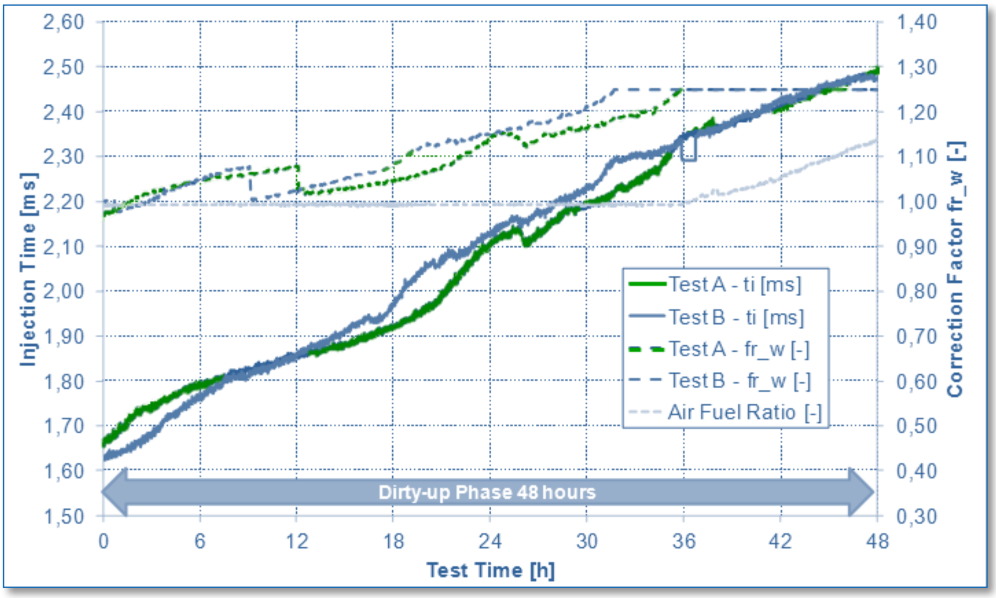
Figure 6: Nozzle holes after failed clean up

2.4 Test Limitations

The tendency of the test engine to build nozzle deposits is the key factor for differentiation between fuels and fuel additives.

However, at very high deposit levels, inconsistencies of engine parameters are observable. Two test examples, DU phases only, are shown in Figure 7.

Figure 7 (right): Injection Timing During Test Procedure, High Fouling Fuel - DU phase



Both tests are performed with EN228 compliant refinery quality fuel without ethanol, resulting in more than 50% increase of injection timing in both.

The test operation is stable as long as nozzle coking is corrected by the fuel trim values. The short term trim reflects the immediate change of injection timing and is displayed in the graph for both tests and is labelled fr_w.

At an increase of injection timing of 40%, no further fuel trim correction is available. The additional increase of injection timing leads to an adjustment of the air fuel ratio and a significant change of the pedal position.

This lean engine operation results in a change of the operational conditions, such as exhaust temperatures.

The effect is completely reversible during a successful clean up.

2.5 Fuel Characterisation

All other currently used CEC test methods are defined as a Keep Clean (KC) test. This new DISI test method will be defined as KC test and as Dirty-up/Clean-up (DU/CU) test procedure. The challenge is to establish precision data for both tests and for both test parts of the DU/CU procedure.

Figure 8 (below) shows two repeated tests, using the recommended VW aftermarket gasoline additive, and used and cleaned injectors.

To compensate for the variation in DU performance, the result of the DU stage is normalized to 100% and the CU phase is displayed in the graph, showing the relative clean up performance of the additive.

In order to characterize clean up fuels or additives, significant performance criteria are defined. One such example is the absolute clean up potential. Another - in the case of very responsive additives - is the time for the maximum clean up performance to occur.

Using identical base fuels and identical additives, this approach to compare normalized test results indicates the precision of the test method is comparable to other CEC tests.

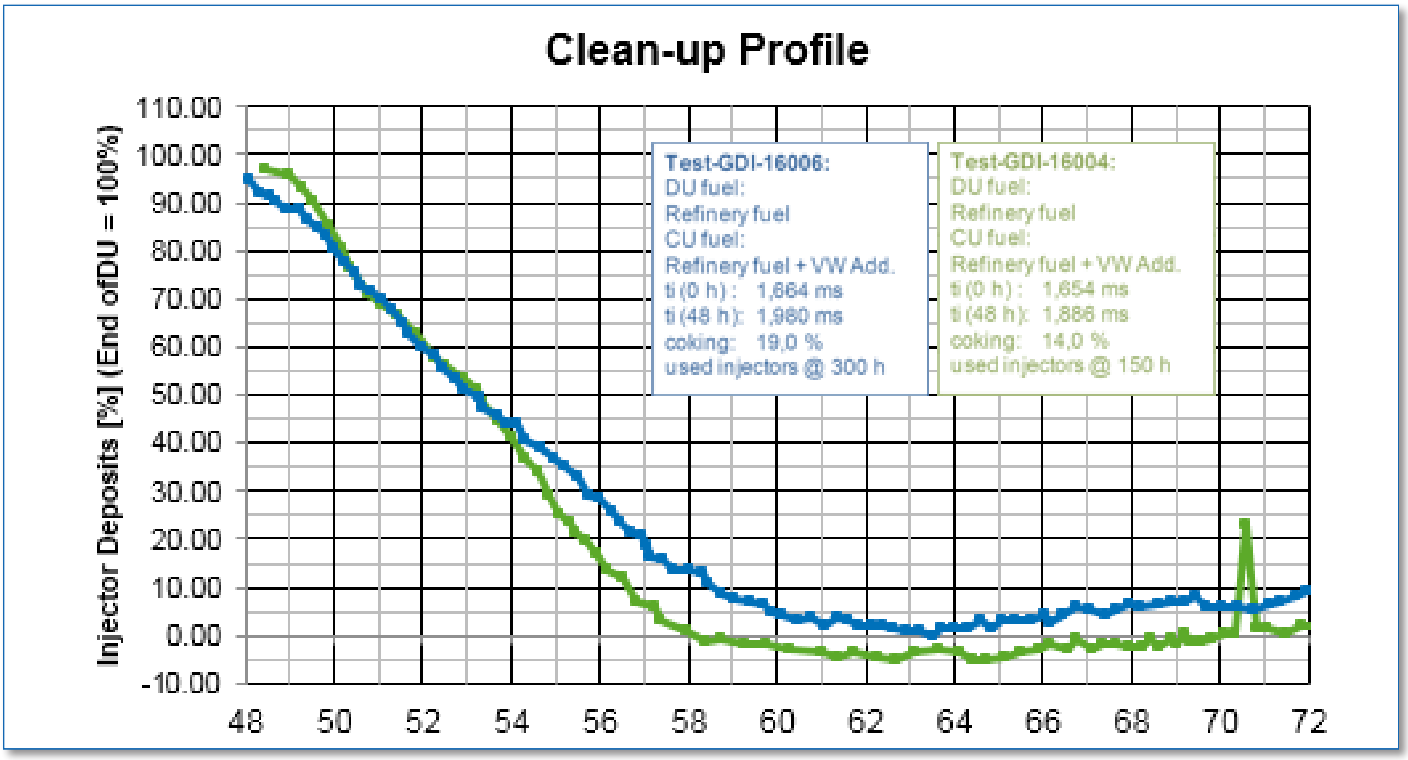


Figure 8: Evaluation of Clean Up Phase - Clean up Profile

3. Fuel Additive Response

As described previously, SGS performed an initial study of the test method, fuels and Deposit Control Additives (DCA). This early work enabled a repeatable test method which could then be used for customer projects.

Afton undertook such a program with SGS looking at the performance of DCAs. During this project, several different fuels were used and as such it was necessary to repeat testing of some DCAs as a control. By doing this, a picture emerged of the response of specific additives in different fuels.

For a given DCA, the same can of material was used to minimize the influence of any batch to batch variation.

As mentioned previously, it became clear from testing that there was a wide difference in the DU performance of different fuels. The test method was kept constant as described previously. The engine parameters were well controlled, the fuel injectors were the same part number and sourced at the same time from the same supplier, to minimize part-to-part variability.

It is common in DU/CU tests to quote the overall relative CU in percent. In this case, the injector pulse width at the end of the CU relative to the pulse width at the end of the DU.

These values are taken after fixed periods of DU and CU (48 and 24 hours respectively).

This approach was not adopted, as complete CU was sometimes achieved before the end of the CU period. Calculating the CU value at 24hrs would underestimate the performance of these additives.

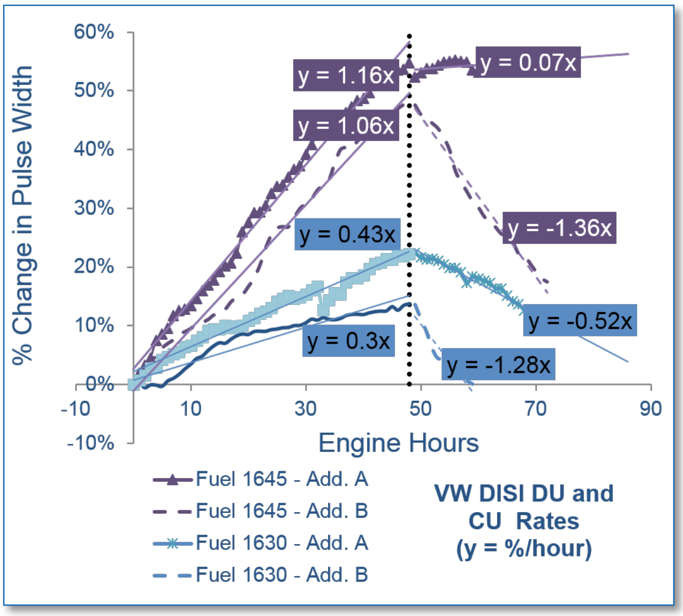


Figure 11: Graph showing impact of different DU fuels on CU rate

Therefore, it was more useful to look at the rate of DU and CU rather than absolute values - as shown in Figure 11 by the values in the colored boxes.

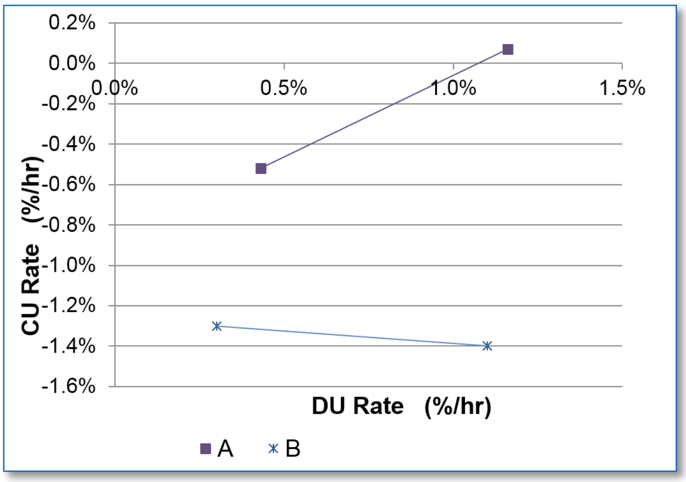


Figure 12: Graph Showing Difference in CU Response between two different types of chemistry in different base fuels. (Additive Clean Up Rate vs Dirty Up Rate)

The CU data set is limited with no replicates, but broad observations could be made. Additive A and Additive B were tested in two of the same fuels, as can be seen in Figure 12.

For Additive A, fuels with a higher DU rate appear to reduce the rate of CU. Additive B did not appear to be influenced by the DU rate of a given fuel.

In absolute terms, it can be seen that even though the performance of Additive A changes with DU fuel, it still has some ability to prevent further deposits being formed and it is anticipated that by increasing the concentration, it would be able to provide additional CU performance.

There was further analysis of the DU's from other fuel batches. To assist in the analysis, SGS shared additional DU data from other tests they had run in the same time period. Some in the same fuels tested by Afton, others in additional fuels from other testing.

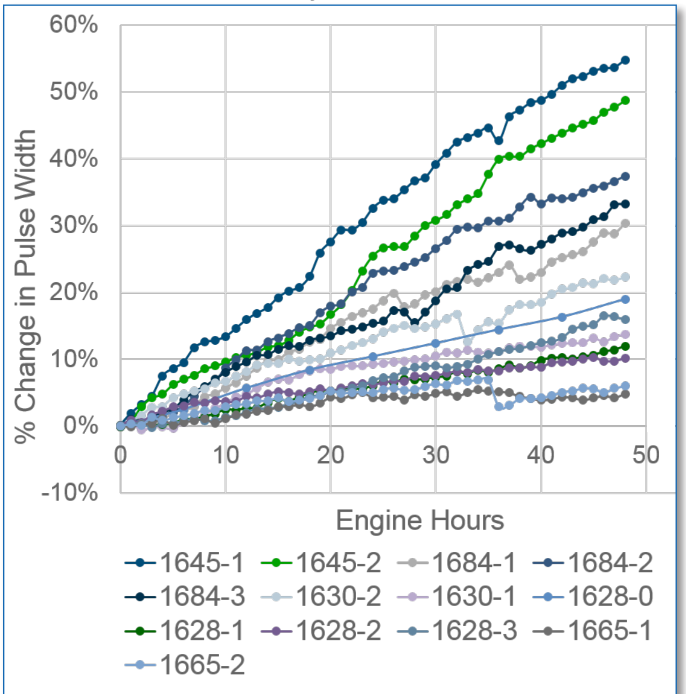


Figure 13: all DU data available from five different batches of fuel - VW DISI Results DU vs Fuel Batch (Each Color is a Different Batch)

Figure 13 shows all the DU data available from SGS for a total of five different batches of fuel. Different numbers of DUs were done with different batches of fuel. The four digit code refers to a specific batch of fuel, suffix '-n' denotes a repeat.

The repeat DU's for each of the batches was averaged and confidence intervals applied using a Student's T value. Figure 14 shows the average DU values of each batch along with confidence intervals at 90% confidence.

Figure 14 shows that, especially after 30hrs of DU, there is a statistical difference between some of the fuels. Fuels 1645, 1684 and 1665 are all significantly different.

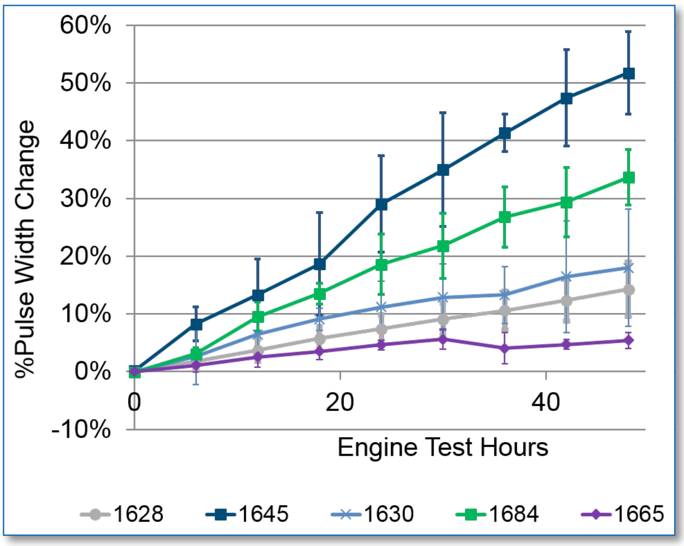


Figure 14: Average DU Curves for Different Fuel Batches plus Confidence Interval - Average Dirty Up of Different Fuels in SGS VW DISI Test

Batches 1628 and 1630 are not statistically

Fuel Additive Response cont...

different from one another but are different to the other batches.

At this point of the project, from this data, it was concluded that:

- The DU rate appears to to influence the CU rate of some types of additive.
- The DU rate was significanlty influenced by specific fuel batches.
- The test method and hardware was kept as constant as possible throughout this testing.
- There is significant variation within a specific batch of fuel but DU rates appear to be significantly influenced by the composition of specific fuel batches.
- The eventual CU rate for some additive types appears to be significantly influenced by the composition of specific fuels.

There is always a requirement to compare different additives tested in different fuels. So an attempt was made to mathematically normalize the CU performance.
The common baseline in this case was chosen

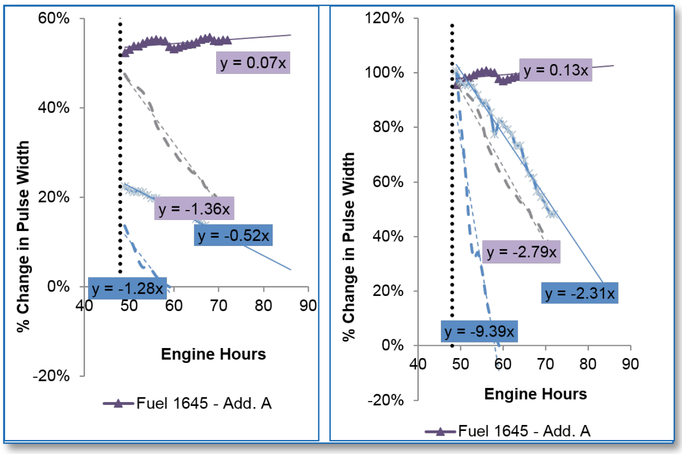


Figure 15: Comparison of same CU data as measured (left) and normalized (right) graph

to be 100%, as shown in Figure 15. This approach was taken by SGS in their early investigation but was not used to compare results from different fuel batches.

Whilst visually comparing the graphs in Figure 15 looks reasonable, when a mathematical comparison of the CU rates is carried out with the original data and normalized data, a different conclusion is drawn.

A comparison between the CU rate of additives A and B in different fuels shows that the CU rate changes differently before and after normalisation. In fuel 1630 the CU rate improved, whilst in fuel 1645 the CU rate remained constant (Table 3).
This means that normalising for different fuels

Additive	A		B	
Fuel	1630	1645	1630	1645
DU Rate (%/hr)	0.4%	1.2%	0.3%	1.1%
CU Rate	-0.5%	0.1%	-1.3%	-1.4%
CU rate of Add. B relative to Add. A	**Fuel 1630 is 2.5x better**		**Fuel 1645 is 19.4x better**	

Table 3: Comparison of Additive Performance before (above) and after (below) normalisation

Additive	A		B	
Fuel	1630	1645	1630	1645
DU Rate	2.1%	2.1%	2.1%	2.1%
CU Rate	-2.3%	0.1%	-9.4%	-2.8%
CU rate of Add. B relative to Add. A	**Fuel 1630 is 4.1x better**		**Fuel 1645 is 21.5x better**	

with different DU's does not allow a consistent comparison of additives.

From this work it can be seen that a test fuel with a reasonable average DU rate, and with consistent batch to batch DU is essential to providing a consistent test. This is necessary due to:

1. Some fuels exhibiting extreme values of DU, caused by excessive nozzle coking.
    - These levels of coking would require a higher concentration of DCA to achieve a given level of CU. That concentration may not be commercially attractive or viable.
    - As described earlier in this paper, excessive coking (>40%) forces the engine into a different operating regime where additional throttle opening is required to mainatin the torque set point.
2. Some fuels appear to provide very little DU which may not be sufficient to allow adequate discriminate between different CU additives.
3. As previously observed, the DU performance of some fuels appears to affect the CU performance of some types of additive.
    - This effect cannot be mitigated against with post processing of the data

The implications of different fuels affecting additive response will provide a challenge to the additive industry. In many cases, additive companies are asked to run their fuel additive candidates in the industry reference fuel of known performance.

Fresh batches of reference fuel are produced approximately every two years. For the existing industry fuels tests, the reference fuel properties are by now well enough defined to ensure consistency.

In the case of the proposed CEC test, if the SGS data is representative then the test is extremely sensitive to fuel formulation. This could be considered an advantage as it can make the test short in duration and low cost. In addition, coking is observed without resorting to contaminants or dopants and therefore fuels used will be more representative of market fuels.

To better define a consistent fuel specification with reasonable DU performance, an attempt was made to correlate the fuel properties of the different fuel batches used in the SGS testing with their engine test DU performance.

Each of the different fuel batches tested was analyzed and compared to its average DU value. There was a mix of EN228 and RF83 fuels tested as can be seen in Table 4 (overleaf). All fuels were summer grades except for the 'Severe EN228' which was a winter grade.

Based on previous literature (See 1,2,4 and 5 in

Fuel Additive Response cont...

Fuel Description	Mild EN228	Regular EN228	Regular EN228 adjusted to RF83	Severe EN228	RF83 Batch 1	RF83 Batch 2
DU @ 48hrs (%)	5.2	14.2	10.0	51.0	18.0	34.0
Density	0.744	0.754	0.760	0,736	0.757	0.755
DVPE (kPa)	60.4	58.8	51.6	81.4	58.2	60.2
IBP	34.7	36.1	35.2	28.6	31.9	32.1
10%	51.4	52.3	57.7	45.2	56.5	54.6
50%	103.7	98.3	109.8	97.3	104.8	104.6
90%	170.7	158.4	151.9	154.3	171.4	171.9
FBP	182.0	191.4	185.4	188.1	193.3	195.5
Paraffins	51.8	47.4	43.4	50.2	46.9	48.0
Olefins	12.4	10.3	10.2	14.6	13.4	12.5
Naphthenes	1.2	5.7	4.9	5.9	2.5	2.7
Aromatics	27.1	31.7	38.2	28.4	38.4	38.2
Benzne	Na	0.7	0.6	0.8	0.2	0.2
Sulfur (mg/kg)	6.4	7.4	186.0	4.4	168.0	186.0
Ethanol Content (%)	7.6	3.2	3.2	0.0	0.0	0.0
Ethers C5 (%v/v)	Na	3.3	3.0	0.6	0.0	0.0
Unwashed	1.0	32.0	0.0	3.0	0.0	1.0
Washed	0.0	0	0.0	1.0	0.0	0.0

Table 4: Fuel Properties

DU @ 48hrs (%)	RSQ
Density	28%
DVPE (kPa)	70%
IBP	79%
10%	40%
50%	24%
90%	3%
FBP	16%
Paraffins	7%
Olefins	48%
Naphthenes	17%
Aromatics	1%
Benzne	5%
Sulfur (mg/kg)	1%
Ethanol Content (%)	54%
Ethers C5 (%v/v)	38%
Unwashed	2%
Washed	68%

Table 5: Basic Correlation by Fuel Parameter

the Bibliography) the parameters of T90, aromatic content and Sulfur were studied first. There was no indication that any of these increase the fuels coking tendancy.

Noticeably, a ‘Regular’ EN228 was doped with additional sulfur and aromatic component to meet the RF83 specification. These two additions did not significantly alter the engine DU response (14.2% against 10%).
Table 5 shows a simple R-squared comparison of each fuel property against Engine DU result. This indicates that a cluster of properties describing ‘Front End‘ distillation (that is the distillation characteristics of the fuel at low temperatures) rank the highest.

An additional statistical multi-variate step-wise analysis using Minitab software indicates that Initial Boiling Point (IBP) is the only fuel property to significantly influence the engine test at a p-value of 0.018.
It is not clear at this time why ‘Front End’

distillation might affect the deposit formation so significantly. It is not mentioned in any previous technical literature.

Any vapor formation that might occur in the fuel system should be suppressed by fuel being held at high pressure.

One theory may be that if there is a significant volume of fuel held in the tip of the injector (the sac) there may be some effect of rapid vapor formation, forcing that fuel on to the injector surface.

Further work is required to confirm this relationship. It is clear from prior literature (see 1-8 in the Bibliography) that whilst there are occasional similarities, each engine design, combustion strategy and injector design has their own coking phenomenon. So it is perhaps not surprising that a new test might throw up a new phenomenon.

As previously mentioned, neither Sulfur, T90 or any specific hydrocarbon type appear to have any influence on engine DU. However, several previous papers (see 2 and 6 in the Bibliography) mention that higher ethanol content suppresses deposit formation.

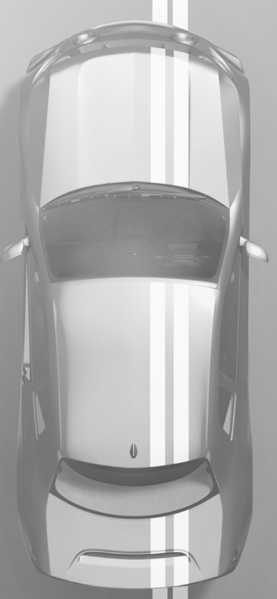
Whilst statistically it is impossible to correlate ethanol content to engine DU from this relatively small dataset, the three lowest fouling fuels all contained ethanol.

3. Conclusions

- A new CEC industry fuel test is being developed around the VW EA111 'Twin-Charger' engine. Early testing based on a surrogate engine at SGS in the Czech Republic indicates that the test method does create deposits.
- This phenomenon can be inferred from a change in injector pulse width change during the test.
- The test method in the state tested by SGS is extremely sensitive to coking. Even with retail EN228 fuels, coking in excess of 50% was observed. Test set point or conditions may need to be modified to reduce sensitivity.
- The test appears to respond to fuel additives, making it a potentially exteremly useful tool for the fuel and fuel additive industry.
- It was noted during testing of additive candidates that the 'Clean Up' rate of some additives is affected by the 'Dirty Up' rate.
- Pulse width changes during the 'Dirty Up' of between 5% and 50% have been seen depending on the batch of fuel tested.
- After comparing fuel properties to 'Dirty Up' values, it was observed that the distillation characteristics of the fuels at lower temperatures appear to be the main contributor to coking.
- It is not clear at this time why this might be the case and further investigation is required.

3.1 Next Steps

- Nozzle tip temperatures during the test should be investigated to compare to prior literature, in an attempt to understand the potential mechanisms leading to coking.
- Further testing to confirm or refute the relationship between front end distillation characteristics and coking should be carried out.
- A study will be made of the injector sac design to understand if vapor in the nozzle tips after injection might influence deposit formation.



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