

The Effect of Near-Zero Aromatic Fuels on Internal Diesel Injector Deposit Test Methods

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ABSTRACT

Internal diesel injector deposits (IDID) are now a well understood phenomenon and a standard test procedure has been developed and partially approved by the Coordinating European Council (CEC). The engine test procedure has been approved for simulation of sodium soap deposits by dosing the test fuel with a sodium salt and dodeceny succinic acid (DDSA), whilst amide lacquer deposits simulation by dosing the test fuel with a low molecular weight (MWt) polyisobutylene succinimide (PIBSI) is still under development. The solubility of these contaminants in the base fuel should be reasonably constant to achieve consistent results. With the introduction of diesel from varying sources, this study focused on the effect of near-zero aromatics EN 15940 compliant gas-to-liquids GTL diesel, very similar to hydrotreated vegetable oil (HVO), on IDID severity across two different engine platforms, and the response of a modern deposit control additive.

The test results showed that, with the same level of contaminants, IDID severity did differ significantly when comparing GTL diesel to a petroleum diesel reference fuel. The IDID effects also differed across engine platforms. In a previous study, it was found that the effect of zinc solvency in the base fuel had a dramatic effect on the CEC F-98-08 DW10 injector nozzle fouling test results. For the IDID test procedure used in this study, the effect of base fuel solvency was less pronounced on IDID formation. It was also found that some degree of nozzle fouling does take place with typical IDID contaminants. The deposit control additive tested proved to be effective in preventing both IDID formation and nozzle fouling for GTL diesel and petroleum diesel.

In conclusion, it was highlighted again that base fuel solvency can influence the results of a test procedure where contaminants are dosed into the fuel, and these effects need to be considered where such fuels are tested.

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INTRODUCTION

The introduction of common rail diesel engines and the move to higher injection pressures, smaller injector holes and advanced injection strategies were significant steps towards reducing fuel consumption and exhaust emissions. These changes were required to ensure very precise and repeatable metering of fuel quantities [1]. However, given the small clearances present in a typical common rail injector, e.g. between the injector body and the needle / piston, and the smaller nozzle channels and injector holes, these

injectors are potentially more sensitive to deposits compared to older generation injectors. In older injection systems, clearances were typically significantly higher than in these modern technology injectors. Another main difference between these older type injectors and modern technology injectors is in the method of actuation- in older type injectors, these were frequently mechanically actuated, while modern injectors use piezo-electrical or solenoid actuation. The first type of injector deposits that was extensively studied was injector nozzle tip deposits, which form on

the injector nozzle surface and in spray channels. Indirect injection engines were particularly prone to this type of deposit, and a CEC test method, based on a Peugeot XUD9 engine, was developed to quantify the propensity of a fuel to form deposits in these engines [2]. Also in direct injection common rail engines, nozzle channel deposits and deposits on the external surface of the injector have been studied extensively. Zinc and biodiesel are two examples of chemistries that could result in injector deposits in common rail diesel engines [1].

The CEC F-98-08 engine test, based on the Peugeot DW10 engine, was developed and accepted in March 2008 to predict the injector fouling behaviour of fuels in modern generation common rail engines [3]. The nozzle fouling propensity is assessed in terms of a loss in power over a fixed test cycle. In this test, the fuel is typically doped with a zinc salt (zinc neodecanoate) contaminant, although tests may be conducted with or without zinc depending on the requirements. Barbour [4] showed that the fouling found for a given fuel in the DW10 test is comparable to that experienced in the field. On treatment with an advanced deposit control additive, it was possible to regain the original power output of the engine [1]. These advanced additives have been extensively proven to prevent nozzle coking and are also able to “clean up” deposits once they have been formed.

As the nozzle fouling test procedure required the dosing of zinc into the test fuel, the solubility of the zinc in the test fuel became a variable in the test procedure. Near-zero aromatic fuels, such as GTL diesel and HVO, were found to have considerably lower solvency power of zinc than more conventional petroleum diesels. The consequence of this was substantially higher deposit formation in the CEC F-98-08 test for near-zero aromatic fuels when dosed with zinc. However, it was found that the uptake of zinc in market logistic systems for this type of fuel was substantially reduced [5]. This referenced study gave rise to awareness of the base fuel solvency effects when using test procedures requiring the dosing of contaminants. The zinc analysis technique used in the referenced study was very accurate and conclusively showed vast differences in solvency between GTL and EN590 diesel, as well as the solvency effect of a DCA. The solvency of sodium and PIBSI in diesel is less easy to measure; nevertheless it has been attempted in the current study. However, discussions on solvency should be read considering the current solvency results together with the very conclusive solvency results of this reference [5].

More recently, there were several reports indicating that a ‘new type’ of injector deposit problem was being experienced by all original equipment manufacturers (OEMs). Conventional coking deposits typically form on the nozzle tips or in the fuel spray holes [6]. These “new types” of deposits, referred to as internal diesel injector deposits (IDID), form within the injector body, e.g. on the armature group, on the piston, nozzle needle and control valve. In 2009, *Hart's Diesel Fuel News* gave two short reports on the issue [7, 8], indicating that the Engine Manufacturer's Association (EMA) was unsure about the reasons for this phenomenon.

IDIDs are distinctly different from conventional nozzle deposits in several aspects, including:

- Traditional nozzle tip deposits form external to the injector body while IDID form on the internal fuel supply surfaces.
- Typically IDID cause sticking of the internal moving parts of the fuel injector while nozzle deposits typically cause a physical blockage in the channel.
- Different contaminant chemistries may be responsible although this is still not fully understood.

IDID are seen as especially troublesome as they may lead to unacceptable engine and emission performance. These IDID problems were found during the testing of developmental engines during dynamometer tests and also in failed injectors returned from the field [9].

Problems are mostly attributed to a slowing in the injector response by sticking of the internal components of the injector.

The following definition of IDID [10] seems to be a good description of the problem:

“These deposits can slow the response of the fuel injector, or cause sticking of internal parts, which may result in loss of control of injection event timing, as well as the quantity of fuel delivered per injection. Hence, a build-up of these deposits can lead to a loss in vehicle driveability and rough engine running, as well as unwanted variations in power and loss in fuel economy.”

The advent of IDID has been said to coincide with the introduction of ultra-low sulphur diesel (ULSD) [11] in the US and the introduction of Euro 4 compliant fuel injection equipment. There are numerous postulated causes for these deposits including the injector designs, the fuel and additive factors [12]. These problems were not noted in all regions in the USA. In California, for example, no such problems were experienced.

Ullmann [13] in 2008 reported that there are two possible types of IDID:

1. Metal ion-based, in particular sodium, and
2. Organic polymer based.

The phenomenon was reported to be sporadic in occurrence, but was widespread globally [6]. Reports indicated that the issue arose in light duty and heavy duty engines, in on-road, off road and marine applications [6].

The US Coordinating Research Council (CRC) and others further differentiated IDID and classed deposits as 1) carboxylate soaps, 2) amide lacquer, 3) inorganic salts and 4) carbonaceous deposits. [11]

Metal Ion Based Deposits (Waxy or Soapy Deposits)

In the US (although not limited to this location), typically the IDID are ‘waxy’ or soapy in nature. These deposits are typically metal-ion based and primarily suspected to be due to sodium contamination, although calcium may also be present [11]. Sodium nitrite pipeline corrosion inhibitors, reacting with monomer fatty acid type lubricity improvers or other acidic components, were postulated to be a

possible pathway to soap formation [13]. The reaction of sodium with dodecenyl succinic acid (DDSA) was also identified as a possible avenue to the formation of IDID [11].

Possible sources of sodium are sodium nitrite pipeline corrosion inhibitors, sodium chloride, used as a drying agent for diesel and sodium hydroxide or sulphate which can be present in the diesel fuel due to the carry-over from the refinery processes [8]. Sodium chloride from sea water, used as ballast on ships, may also contribute to this phenomenon. Sodium hydroxide is commonly used as a catalyst in the production of fatty acid methyl ester (FAME). Sodium fatty acid salts are known to be insoluble in diesel fuel. Other metals, e.g. calcium, have also been found in deposits in failed injectors.

Schwab et al [9] carried out an extensive testing program to characterise sodium type deposits on failed injectors, received from the field. Advanced analytical characterisation of sodium type (waxy / soapy) deposits showed the potential involvement of alkenyl succinic acids (like DDSA and hexadecenyl succinic acids (HDSA)) in the formation of sodium containing deposits [9]. DDSA and HDSA traditionally have been used as pipeline corrosion inhibitors.

Schwab et al [9] developed an engine test to show the propensity of a fuel, containing sodium and DDSA to form IDID. It was also shown that both sodium and DDSA were required for the IDID to form. The causes for these sodium soap IDID are now well understood. One specific recommendation that came from a CEN workgroup (TC19/WG24) was to recommend the removal of sodium based pipeline corrosion inhibitors [11].

Carbonaceous Deposits

There are several proposed causes of carbonaceous or 'amide lacquer type' deposits [11]. These deposits appear to consist of polymeric fuel borne material coating the metal surfaces and typically do not contain metals. These deposits are non-soluble in normal solvents of different chain lengths, and typically appear to be sticky and brownish in appearance. The mechanism for the formation of this type of deposit is not as well understood as the sodium soap deposits [6].

There are two postulated causes for the formation of lacquer type deposits. One of the early suspected causes of these deposits is the reaction of polyisobutylene succinimide (PIBSI) and acidic fuel components. Initial work to try and understand the mechanisms for IDID were carried out in the laboratory. Using glassware experiments, Ullmann et al [13, 14] showed that the reaction of PIBSI with a dimer acid could result in deposit formation. The Fourier Transform Infrared (FTIR) spectra of these deposits appeared similar to the FTIR spectra of deposits, detected on injectors. The work also indicated that mono-acid lubricity additives may participate in the formation of IDID, however, this has been disputed later by other authors. Further experiments into the possible causes of these deposits were carried out by several additive suppliers using mono acidic fatty acids, glycerol fatty acids and dimer acids in combination with PIBSI. Although commonly used in the past before year 2000, dimer acids are no longer used as lubricity additives due to concerns regarding compatibility with

lubricating oil additives. Several authors questioned this mechanism for IDID formation, and suggested that low MWt PIBSI [6, 11] is more likely to be the cause of the problem. It is however difficult to prove this mechanism, as PIBSI, by its very nature, is designed to surface absorb to metal surfaces, and would therefore, by default, be present on metal surfaces analysed.

Subsequently several other authors tried to reproduce the reaction of acids and PIBSI in dynamometer engine testing [9, 16] with no or limited success.

Fuel Effects on the Formation of IDID

Although there are several fuel related factors that could potentially influence the formation of IDID, most of the investigations up to now have focused on the effect of additives and contaminants [13, 14]. Alternative fuels like GTL diesel and HVO differ from conventional diesel in that they contain near-zero aromatics, sulphur and have a high cetane number (typically >70). These properties result in less harmful exhaust emissions and lower toxicity, which make them desirable from a blending perspective. These fuels can also be used as neat fuels. Recently, a specification was approved in Europe to enable the sale of paraffinic fuels (GTL, biomass-to-liquid (BTL) and HVO) as a neat fuel [15].

Aromatics are known to aid with solubilisation of additives and trace components, but also potentially contaminants and deposits. As paraffinic diesels contain no aromatics, it is essential that the differences in the solubility between GTL diesel and conventional diesel fuels be understood. Velaers et al [5] showed that zinc precipitated faster from GTL diesel (no aromatics) than from a higher aromatic fuel. The lower solvency of GTL diesel was postulated to result in higher observed fouling in the DW10 test. However, GTL diesel is also less likely to pick up zinc in the logistical chain due to this lower solvency. Deposit control additives were also shown to be very effective in controlling these deposits.

EXPERIMENTAL METHODS

This study aimed to quantify the differences in IDID formation behavior between GTL diesel and conventional petroleum diesel, using different engine platforms. The IDID performance of GTL diesel, adulterated with 1) sodium and DDSA and 2) a low MWt PIBSI was compared with the performance of petroleum diesel fuels, containing higher levels of aromatics.

Up until now many IDID studies have been conducted using the CEC reference fuel RF79 (RF-79-07), a petroleum diesel that complies with the EN590 fuel specification. The purpose of this study was to assess the effect of near-zero aromatic fuels on IDID formation. For this purpose, tests were conducted with a market relevant near-zero aromatics GTL as well as the RF79 petroleum reference fuel. Engine tests were conducted at two test laboratories; Laboratory 1 engine testing facility in Cape Town, South Africa and Laboratory 2 engine test facility in Hazelwood, Derby, UK. Laboratory 1 employed a VW 1.6 litre TDI engine that was equipped with piezo injectors (similar to the Bosch piezo injectors), that had previously been used to investigate fuel effects

on nozzle tip deposits. Laboratory 2 employed a Peugeot DW10C engine equipped with solenoid-type injectors, the technology adopted by the CEC group to develop the industry standard test. This allowed the effect of fuel composition to be assessed over two different engine platforms in order to obtain a broader perspective on any effects observed. While the test procedures were largely similar, there were some minor differences and these are described further in the “Engine Test Cycle and Protocol” and the “Engine Installation” sections.

Part of the current IDID study entailed the determination of the solubility of a sodium salt in different fuel matrices in order to enable any possible correlation with this aspect to IDID formation. One of the possibilities that had to be eliminated was the precipitation / poor solubility of sodium salt in a given base fuel, which could result in a false / artificial IDID result, i.e., no IDID formed due to the absence of sodium salt in the fuel solution. Sodium salt solubility studies were subsequently carried out, with the focus being on the GTL diesel.

Engine Test Cycle and Protocol

The engine test cycle used in the current study included extended periods of running at close to full load / maximum power, as the extreme temperatures experienced under such conditions are considered to promote the formation of IDID. A similar type of test cycle was employed by Bosch in the engine studies they published at Esslingen in 2013. [17]

The test cycle is severe, spending just over 80% of the time at near full load, and therefore generates significant heat inside the injectors. The 1 hour engine test cycle is shown in Figure 1. The engine runs in a torque control mode for 25 minute periods before ramping down to low speed for 5 minutes which is also torque controlled. It repeats this for the remaining 30 minutes. This represents a conventional IDID test cycle and was used at Laboratory 2.

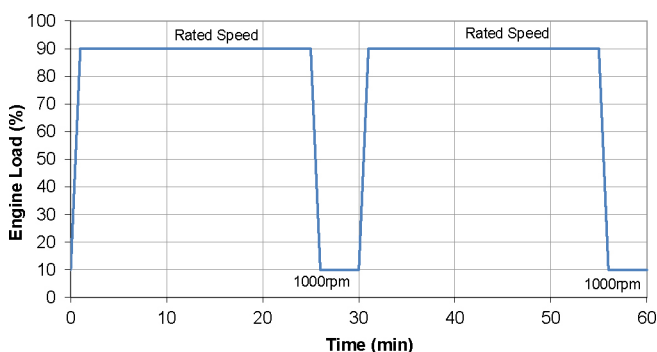


Figure 1. Laboratory 2: Test cycle, used in the evaluation of IDID

A subtle change was made to the same test cycle in Laboratory 1's testing to enable the measurement of maximum engine power at the end of each 25 minute high load run. After 22 minutes the dynamometer was programmed to switch to throttle control mode and ramp up to 100% open throttle for the remaining 3 minutes. In the 24th minute, power and fuel consumption were measured and

averaged, in much the same way as during injector nozzle fouling tests as per CEC F-98-08. This was used to determine if the IDID contaminants also had an effect on nozzle fouling by resulting in flow and power loss. These measurements provided valuable additional data and also made the engine less prone to stalling during the ramp down when IDID were causing rough running. This was due to the throttle controlled mode instead of torque controlled allowing the engine to control the ramp down and avoid fluctuating braking influences of the dynamometer. Apart from this small difference, the test protocols between the two laboratories were exactly the same.

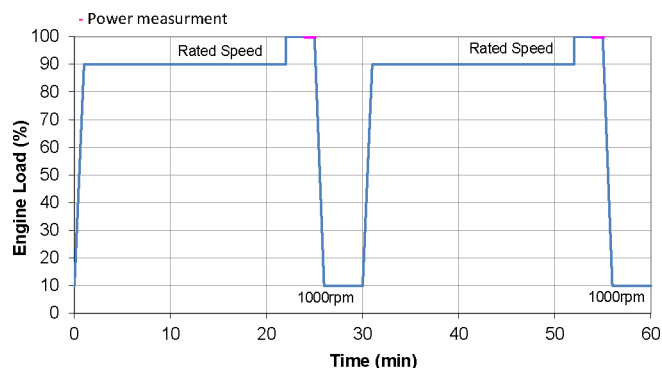


Figure 2. Laboratory 1: Test cycle, used in the evaluation of IDID

The 1 hour test cycle is repeated 6 times and the engine is then shut down to allow the system to cool and soak. The number of cycles is chosen so that one drum (210 litres) of fuel is sufficient to cover the running period between shutdowns. For IDID testing the soak period was extended to 8 hours to allow the fuel system to fully cool to ambient temperature and for the deposit to have sufficient opportunity to become sticky and to adhere to the injector surfaces. However, it should be noted no investigations were conducted to optimise the soak period. The overall protocol for the IDID testing used in this study by both laboratories is summarised in Table 1:

Table 1. Overall IDID test protocol

Test cycles	Cold soak time	Cold start number	Running hours	Main Run
Start of test (SOT)		CS 1		
1-6	6 hours		6	1
	8 hours	CS 2		
7-12	6 hours		12	2
	8 hours	CS 3		
13-18	6 hours		18	3
	8 hours	CS 4		
19-24	6 hours		24	4
	8 hours	CS 5		
25-30	6 hours		30	5
	8 hours	CS 6		
31-36	6 hours		36	6
	8 hours	CS 7		
End of test (EOT)				

Laboratory 2 Partial Rating System

Each cold start is followed by a 5 minute idle during which data are logged at high speed. This forms the basis of the partial rating system. Data during the main runs are also logged and the following factors are used in the rating system:

Cold Start Data

- Start - Yes/No
- Number of attempts to start
- Exhaust gas temperature deviations during 5 min idle

Main Run Data

- Number of ECU fault resets
- Stall - Yes/No
- Pedal Position correction at 1000 rpm point
- Maximum injector balancing co-efficient

Merits are assigned to successful aspects and demerits are deducted for deviations which exceed defined limits.

For the test, 5 merits are assigned for each successful cold start, each 5 minute idle period and each main run completed.

Demerits are deducted for each failed start attempt, each ECU reset and each stall during a main run, to a maximum of 5 demerits per category. Further deductions are determined using the data logged according to [Table 2](#):

Table 2. Additional demerit factors

	Condition	Demerits
1: Exhaust Gas Temp Deviation: (Deducted from the Cold start rating)	$T < 30\text{ }^{\circ}\text{C}$	0
	$30\text{ }^{\circ}\text{C} < T < 50\text{ }^{\circ}\text{C}$	3
	$50\text{ }^{\circ}\text{C} < T$	5
2: Pedal Position (Deducted from Main Run Rating - not below "0")	$P < 25\%$	0
	$25\% < P < 40\%$	3
	$40\% < P$	5
3: Injector Balancing: (Deducted from Main Run Rating - not below "0")	$\text{IBCcoeff} < 20$	0
	$20 < \text{IBCcoeff} < 30$	3
	$30 < \text{IBCcoeff}$	5

The maximum rating is 12 - the rating scale can be considered as:

- **12** - Perfect score - No IDID effects
- **>6** - Completed more than half the test - IDID resulted in failure to start after some time
- **<6** severe and rapid IDID formation resulting in failure to start after a short running time.

This rating methodology of engine test results is still somewhat subjective but the system is reasonable given the varied effects of IDID. Note that any injector post analysis does not affect the rating score, even if IDID is visible. The score only represents IDID which influence engine operation. An example of a test rating is given in [Appendix A](#) for the Laboratory 1 EN590 + sodium + DDSA test.

The same rating system was applied to the results from both test laboratories in this study.

Laboratory 1: Engine Installation

Laboratory 1 used a VW 1.6 litre CAY engine with piezo-injectors, very similar to those used in the Peugeot DW10B engine test. An exploded view of the injector is shown in [Figure 3](#):



Figure 3. Laboratory 1: Piezo injector

The noteworthy features of this injector are a smooth needle without grooves, and a very basic control valve with large clearances. The engine was installed in a test cell with a Horiba eddy current dynamometer and a STARSTTM automation and data logging system. An AVL 735TM Coriolis fuel flow meter was used to accurately measure fuel consumption and control the fuel temperature. The test fuels were prepared in 210 litre drums and were placed in a fuel store adjacent to the test cell. Fuel was mixed during the tests using an automotive fuel pump which recirculated the fuel continuously while supplying a constant fuel pressure to the test cell.

Being a smaller engine, this engine used less fuel than the Peugeot DW10C engine, but its rated speed was 4400 rpm as opposed to 4000 rpm. It was decided to keep the test protocols the same between the two laboratories, so main runs were kept to 6×1 hour test cycles. 120 litres of fuel was required for each main run, and therefore a full length test of 6 main runs consumed 720 litres of test fuel.

Laboratory 2: Engine Installation

Laboratory 2 used a Peugeot DW10C engine, as per the CEC IDID test procedure. The engine was equipped with solenoid-type injectors, a view of which is shown in [Figure 4](#) where the needle and solenoid valve are magnified:

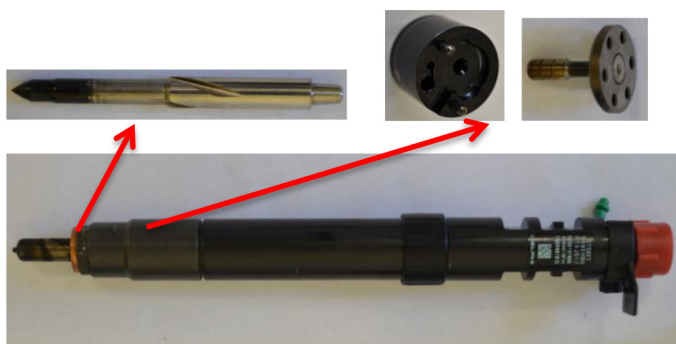


Figure 4. Laboratory 2: Solenoid injector

For ease of comparison, cutaways of both injector types are shown in Figure 5 to highlight the salient differences in design:

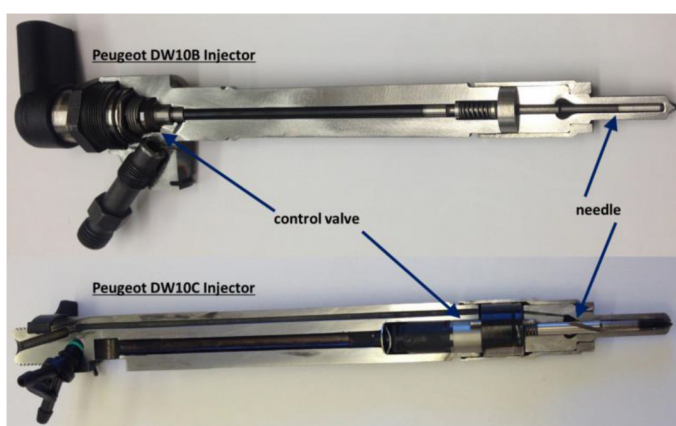


Figure 5. Comparison between the two injector types used

The Peugeot DW10B injector shown in Figure 5 is a piezo injector, which is almost identical to those used in the VW engine of Laboratory 1. The noteworthy features of the DW10C injector are the helical grooves in the needle which are designed to assist fuel flow. Around 200 litres of fuel was required for each main run, and therefore a full length test of 6 main runs consumed up to 1200 litres of test fuel.

Laboratory 1: Injector Test Rig

In an effort to try and establish possible alternative quantitative ways of rating the degree of IDID formation, an injector test rig was used by Laboratory 1. The rig was a Leitenberger DISU 6000™ which is capable of testing one common rail injector at a time. It can measure the following injector parameters:

- **Leak Test.** Checks the injector return valve for excessive leak.
- **Electrical Test.** Checks the condition of coil/coils or piezo crystal.
- **Injector Discharge (and Return) Mass Metering.** Measures the precise amount of fluid the injector discharges and returns on different parameters.
- **Nozzle Opening Pressure.** Measures what the minimum required pressure is for the needle to open.
- **Injector Mechanical Response Time.** Measures the time in microseconds between the electrical pulse and fluid discharge from the nozzle.



Figure 6. The injector test bench used by Laboratory 1

Both nozzle opening pressure and mechanical response time would theoretically be altered if IDID were present and had caused needle sticking. The measurement of these aspects before and after the engine test would reveal if these parameters can be used to quantitatively rate the degree of IDID formation.

Test Fuels

Base Fuels

Table 3. Selected properties of the base fuels, evaluated in the current study

Parameter	Commercial GTL diesel	EN590 diesel	RF79 diesel
Cetane Number	80.0	53.5	53.1
Density at 15 °C (kg/m ³)	0.770	0.836	0.834
Flash point (°C)	57	83	91
Viscosity at 40 °C (mm ² /s)	2.20	2.75	2.93
Lubricity, corrected wear scar at 60 °C (µm)	401	376	302
Total aromatics (Mass %)	<0.01	26.5	21.1
Sulphur (ppm)	1.0	1.2	<1.0
Carbon residue (Mass %)	0.01	<0.01	<0.10
Ash content (Mass %)	<0.01	<0.001	<0.001
Water content (ppm)	<250	70	40
Copper strip corrosion	1B	1A	1A
Oxidation stability (mg/mL)	0.2	0.3	0.002
CP (°C)	-5	-20	
CFPP (°C)	-7	-22	-20
Acid Number (mg KOH/g)	0.001	0	<0.01
Distillation: T90 (°C)	339	331	321
Distillation: T95 (°C)	357	347	346

The base fuels were selected to see if there is a significant difference in IDID formation potential of a near-zero aromatic (predominantly paraffinic) fuel such as GTL diesel, compared with a higher aromatics containing fuel. The same batch of GTL diesel was used in the testing in both laboratories. Laboratory 1 used a certified EN590 diesel as the

petroleum reference fuel, while Laboratory 2 used CEC RF79 for reference purposes. Critical properties of the test fuels are listed in [Table 3](#), while the full specification properties (including test methods used) of these fuels are shown in [Appendixes B and C](#). The full experimental fuel matrix is presented in [Table 4](#).

Fuel Contaminants and Additives

Sodium Soap Contaminant

Sodium naphthenate was used as the sodium source. Sodium naphthenate is accepted by the CEC as the preferred source of sodium for IDID testing. The sodium naphthenate was obtained from TCI Chemicals (Product Number N0397, CAS Number 61790-13-4). To facilitate the dispersion of sodium naphthenate into the diesel it is first diluted with dry 2-ethyl hexanol (EHL). A 3% solution is prepared which contains 0.256 weight % sodium.

A 61% active sample of DDSA was the source of the DDSA for this test programme. To facilitate the dispersion of the DDSA and to improve the accuracy of the additisation, the DDSA component was diluted with EHL to 10%, giving a 6.1% active DDSA source for the work.

In a typical sodium soap IDID test the base fuel is doped with DDSA and then supplied for testing. Immediately before starting the test the sodium naphthenate solution is added and mixed for 1 hour prior to the start of test.

For all the sodium soap tests at each laboratory, the fuel was prepared in the same way. The fuels were dosed with 0.5 ppm sodium and 10 ppm DDSA.

Amide Lacquer Contaminant

Amide lacquer-type IDID were reproduced in the engine testing using a low MWt PIBSI product. This low MWt PIBSI product, supplied by Laboratory 2, was diluted with 2-ethylhexanol to give a solution that was 10% active. The sparingly soluble low MWt PIBSI was blended into the fuel immediately before the start of each test.

- The diluted low MWt PIBSI was added to a 1L sample of the test fuel and mixed in with a high shear blender. The resulting mixture was then immediately added to the drum of test fuel and mixed for 1 hour before the start of the test.

The test fuel was mixed continuously throughout the test. The only difference in the blending of the contaminants between the two laboratories was in the apparatus used to mix the fuel in the drum during the running of the test. At Laboratory 1 this was done by circulating the fuel through a regular 12 volt automotive fuel pump, whilst at Laboratory 2 the test fuel was mixed with an air driven blender continuously throughout the test. Both mixing protocols proved to be adequate for the sodium soap tests; however some questions are raised in the results section on the effect of this on the solubility of the low MWt PIBSI contaminants.

The low MWt PIBSI was dosed at 10 ppm (active content) at Laboratory 2, but at Laboratory 1 it was found that no IDID effects were observed at the 10 ppm contaminant treat rate. The low MWt

PIBSI concentration had to be increased to 25 ppm to realise measureable IDID effects on the VW engine in Laboratory 1. This was attributed to the control valve of the Laboratory 2 injector to be particularly sensitive to seizure effects caused by the low MWt PIBSI.

Deposit Control Additive

A commercially available, advanced diesel deposit control additive (DCA) was used in this study. A typical market treat rate representative of a high quality main grade fuel dose was used at both laboratories. The additive is known to be effective in reducing IDID formation; however, the purpose of this study was to determine how the aromatic content of the base fuel would affect the solubility of the contaminants and efficacy of the DCA.

Fuel Matrix

[Table 4](#) shows the test fuel matrix used in the current study.

Table 4. Test fuel matrix used in the current study

Sodium/DDSA blends						
	GTL diesel	EN590 diesel/ RF79	Na	DD SA	Low MWt PIBSI	DCA
Blend 1		✓	✓	✓		
Blend 2	✓		✓	✓		
Blend 3	✓		✓	✓		✓
Low MWt PIBSI blends						
Blend 4		✓			1) 25ppm 2) 10ppm	
Blend 5	✓				1) 25ppm 2) 10ppm	
Blend 6	✓				1) 25ppm 2) 10ppm	✓

- Laboratory 1
- Laboratory 2

In this investigation, the GTL diesel fuel effects were the main focus and not the EN590 diesel. The results of the EN590 diesel, containing the two contaminants, are included to show that IDID were created (as per the expectation) and were used as reference points to the response of the neat GTL diesel to these contaminants.

Injector Analysis Methodologies

Injector analysis was carried out using the following three methodologies:

- Light microscopy
- Scanning Electron Microscopy (SEM)
- Fourier Transform Infrared (FTIR) Microscopy