

## Comprehensive Applications Testing of Diesel from a Commercial Scale Gas-to-Liquids Plant

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Andre Swarts, Arthur Bell, Konrad Mokheseng, Marie Pretorius and Paul Schaberg  
Sasol Technology

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### ABSTRACT

This paper reports on the comprehensive applications testing of the first commercial volumes of Gas-to-Liquids (GTL) diesel produced via the Sasol Slurry Phase Distillate™ (Sasol SPD™) process, a Low Temperature Fischer-Tropsch (LTFT) process, at the Oryx GTL plant in Qatar. The technical literature is well populated with results of emissions and applications studies of GTL diesel, however, these results have been limited to product produced at pilot plant and relatively small commercial scale. To ensure that diesel produced commercially not only matches the performance of material previously produced at pilot plant scale using the same technology, but is also fit-for-purpose in the broader sense, a series of chemical assessments and applications testing was performed using both neat and blended diesel fuels. These included emissions tests in passenger cars and heavy duty applications, engine durability, injector fouling performance and a passenger car fleet trial. The evaluation found that the product from the commercial plant was fit-for-purpose in both neat and blended form and validated all claims made to date on GTL diesel from a pilot plant.

### INTRODUCTION

The process to produce Gas-to-Liquids (GTL) diesel, an alternative, non-crude oil derived diesel, has been studied extensively by various companies including Sasol, PetroSA, Shell, Exxon, Statoil, Syntroleum and Rentech. In such processes, natural gas is used as a feedstock to produce a high quality diesel as the main product. Common features of GTL diesel produced via a Low Temperature Fischer-Tropsch (LTFT) process include near zero aromatics, a high cetane number and very low levels of sulphur.

As far back as 1999, the unique properties and emissions performance of GTL diesel were shared in the technical literature [1]. GTL diesel was able to show immediate emissions reduction when applied in unmodified compression ignition engines [2,3], with even greater benefits becoming evident when applied in engines particularly adapted and optimised for the properties of the synthesised fuel [4,5,6,7].

A variety of no-harm testing [8,9,10] has confirmed not only the in-service performance of GTL diesel, but also the continued real-life emissions benefits. As a result, GTL diesel has been reported to improve emissions performance in vehicles while it can be used without any modifications in existing engines. It has most recently been shown to deliver further emissions benefits, even for vehicles fitted with diesel particulate filters [11].

The application of GTL diesel may find its way to end users either as a blend component or in a neat form. The conclusion of the CEN\* Workshop 38 - "XTL Gasoil for use in automotive diesel engines" has now firmly put the legislative framework in place for XTL (X-to-Liquids where X could include biomass, gas or coal) fuel to be taken up into the EN590 diesel specification and for it to be sold and applied in neat form. The stated objective of the workshop was that *"the specification should be based on EN 590 and will highlight the differences between GTL and the fuels covered in that EN. The Workshop Agreement will be based on GTL experience, aspects of it may also be applied to BTL and CTL since these are identical with respect to chemical composition. The CWA will be usable on a voluntary basis for engine clearance, fuel acceptance and fuelling station allowance, supporting both local regulations and international trade"*[12].

\*CEN - European Committee for Standardization

The resulting standard “CWA 15940: Automotive fuels - Paraffinic diesel from synthesis or hydrotreatment - Requirements and test methods” is now available to legislators to call upon for inclusion in local application of the EN590 diesel fuel specification.

A similar initiative within the ASTM is looking at developing an XTL specification for inclusion in the ASTM diesel fuel specification in the USA [13] with work-item WK23320 currently being considered [14], although this specification will be specific to Fisher-Tropsch derived diesel fuel oils.

Oryx GTL, a joint venture between Qatar Petroleum and Sasol, started with commercial production of GTL diesel in 2007. Whilst substantial research was conducted in the last two decades to understand the properties and application benefits of GTL diesel produced at pilot plant scale, it was required with the start-up of Oryx GTL, to verify the validity of previous results to ensure that the product produced by the new plant would be fit-for-purpose. A comprehensive study was designed to answer the key question of whether the characteristics, properties and performance of GTL diesel from a commercial facility is similar to that which was produced at pilot scale and by extension, whether the various claims made over the years, using pilot plant product, are still valid. Physical and chemical properties of the GTL diesel were analysed and compared to previous data, whilst an extensive application testing programme was employed to answer real-life application questions by performing a fleet trial and bench durability, vehicle performance, injector fouling and emissions tests. This paper describes the results obtained during this study.

The commercial operation of the Oryx GTL plant in Qatar and the smaller Shell plant in Bintulu in Malaysia, described as a “medium-scale, commercial low temperature Fischer Tropsch GTL plant” [11], together with the imminent start-up of the Shell Pearl GTL plant, also in Qatar, makes it clear that LTFT diesel will become an increasingly important player in future mobility as one of the few large scale, feed-stock flexible alternative liquid fuel options in the world. As such, it is important for the synthetic diesel industry that the reputation of GTL diesel as an excellent quality, alternative fuel is reinforced.

## FUEL SELECTION

To reach the objectives set out above, it was necessary to compare both neat GTL diesel and blends thereof to a relevant reference diesel. To achieve this, the following fuels were evaluated in the project<sup>†</sup>:

- **CGTL** - GTL diesel produced on commercial scale via the Sasol Slurry Phase Distillate™ (SPD™) process at the Oryx GTL plant in Qatar. Tests were performed on a representative

commercial operation sample of fuel from the Oryx plant, received in 2008.

- **EN590 diesel** - a representative European EN590 specification diesel fuel acquired in 2005. The quality of this product has been diligently monitored to ensure that the product remains within specification and adheres to the EN590:2009 specification in all respects.

- **PGTL** - GTL diesel produced on pilot plant scale at the Sasol Hydrocracker Demonstration Unit (HCR-DU) in conjunction with the Sasol SPD™ process. This plant is situated in Sasolburg, South Africa and is operated by Sasol Technology.

- Blends of the above two GTL diesel fuels with the EN590 diesel. The blends, by volume, of 20% GTL diesel and 80% EN590 diesel was utilised as this approximates the highest GTL diesel content possible in blends with typical crude derived diesels without violating the minimum density requirement stipulated in the EN590 specification of 0.820 kg/l at 15 °C. **CGTL20** and **PGTL20** refer to blends with GTL diesel sourced from commercial and pilot scale, respectively.

Despite being the subject of significant research in the technical community, blends with FAME (fatty acid methyl ester) or other bio-fuels were not considered for this project.

## CHEMICAL/PHYSICAL EVALUATION

As part of the fit-for-purpose study, it was important to evaluate the chemical integrity of the CGTL diesel fuel and establish how this material compared with typical European EN590 diesel which was chosen given Europe's close proximity to the production plant.

Selected key bulk properties that were evaluated for the above mentioned diesel fuels are given in [Table 1](#) below.

(See [Table 1](#) after last section of paper.)

With the exception of density in the case of the neat GTL diesel, all tests fuels practically met all of the EN590:2009 specifications. Some of the important fuel properties are discussed under the relevant headings below.

## LUBRICITY AND VISCOSITY

In order to avoid excessive wear, diesel fuels must have some minimum measure of lubricity characteristic which is related to the ability to reduce friction between solid surfaces in relative motion [15]. GTL diesel is normally highly paraffinic, containing only small quantities of compounds which naturally provide lubricity to diesel fuels, resulting in

<sup>†</sup>For the remainder of this publication, the terms as defined will be used without further reference to the proprietary technology used to produce the diesel

reduced lubricity characteristics of these diesel fuels [16]. Conventional lubricity additives were employed in order to provide the required lubricity characteristics to all test fuels which then met the maximum EN590 lubricity specification of 460  $\mu\text{m}$  wear scar diameter (WSD) as measured by the High Frequency Reciprocating Rig (HFRR - ASTM D6079) test method. The viscosity of a diesel fuel is also important as it impacts the ability of the fuel to confer some lubrication to the engine in which it is used, i.e. higher viscosity provides better hydrodynamic lubrication [15]. All fuels investigated met the EN590 viscosity specification range of 2.0 - 4.5 cSt at 40 °C.

## DENSITY

The density of a fuel impacts fuel consumption (volumetric) and performance related characteristics such as power and emissions of particulates and visible smoke [1]. Synthetically derived paraffinic diesel fuels have inherently lower densities than their crude derived counterparts as depicted in [Table 1](#) above. This is due to the paraffinic nature of synthetic FT fuels while the crude derived counterparts contain a significant amount of heavy components such as aromatics, resulting in higher density values. Due to this effect, the T95 of the GTL diesel fuels should be maximized (within the allowable specifications) in order to increase the yield and density of the GTL diesel. Although increasing T95 may assist with increasing the amount of heavy compounds which will, in turn, result in increased density, the impact on cold flow properties of the resultant fuel should also be taken into consideration as heavier, linear paraffinic compounds tend to crystallise more easily at low temperatures.

## HEATING VALUES

Although the heating value is not part of the EN590 specifications, it is still an important parameter of diesel fuels that warrants investigation as it influences fuel economy and performance. The paraffinic nature of GTL diesel fuels leads to significantly higher gravimetric heating values. It is apparent that, on a mass basis, the heating values of GTL diesel fuels are 2.0% to 2.4% higher than that of EN590 diesel, while on a volumetric basis, they are some 5.1% to 5.3% lower due to the inherently lower density of the GTL diesel fuels.

## OTHER PROPERTIES

Other important diesel properties worth mentioning include cold flow properties, cetane number and fuel stability. Although all GTL diesels reported on in [Table 1](#) met the minimum EN590 Cold Filter Plugging Point (CFPP) specification, the CFPP properties can further be improved by the use of cold flow additives. The necessity for this is dependent on climatic and geographical requirements. With

regards to the cetane number, all GTL diesel fuels had a higher cetane index (higher than 80) compared to the EN590 diesel (50). This is attributed to the paraffinic nature of GTL diesel and is in agreement with the literature [17]. Furthermore, in accordance with the literature, the cetane index of the crude derived diesel fuel was found to improve on blending with GTL diesel [18].

According to the thermal stability test method (Octel F21-61 which is comparable to ASTM D6468), all the fuels were found to have excellent thermal stability with GTL diesel performing better than an EN590 diesel. Similarly, good long term storage stability results were observed with all investigated diesel fuels with the GTL diesel again performing better than an EN590 diesel. This observation suggests that these GTL diesel fuels are less likely to undergo oxidative degradation during storage or form deposits during usage. Detailed analytical fingerprinting, utilising various gas-chromatographical methods, was also completed but this falls outside the scope of this paper.

Based on the above results and its chemical and physical properties, the CGTL diesel was considered to be fit-for-purpose.

## APPLICATIONS TESTING

Further to the chemical/physical evaluations, extensive application testing was executed to assess the performance of the neat and blended fuels in real-life and simulated real-life conditions.

## INJECTOR FOULING

Compression ignition engines rely on the fuel injection system for accurate and well-timed delivery of diesel fuel to ensure proper operation. The spray characteristics are particularly important to ensure effective atomization of fuel which, in turn, has performance and emissions impacts. Any deposits that may form either on the injector tip or inside the fuel delivery passages can upset the spray formation or, in extreme, cases reduce the amount of fuel injected, leading to a reduction of fuel flow and consequently engine power.

The fuel industry has long since realised the need to quantify this phenomenon and assess the effect of both fuel formulation and fuel additives on injector fouling. Various engine tests have been developed to evaluate the injector fouling propensity of diesel fuels and these were applied during this project.

### Peugeot XUD9

The long standing industry standard test method for evaluating injector fouling is the CEC<sup>‡</sup> F-23-01 test

<sup>‡</sup>CEC - Co-ordinating European Council

procedure. This utilises a Peugeot XUD9 test engine, equipped with indirect injection and pintle type, single hole injectors.

Figure 1 shows the results for CGTL, the CGTL20 and EN590, all unadditised and with typical dosage of a commercial detergency additive<sup>§</sup>, where average air flow loss at 0.1 mm needle lift is presented. It is clear that the unadditised CGTL diesel showed an immediate benefit in comparison to the EN590 or CGTL20 and with an excellent additive response and zero air flow loss at the recommended treat rate.

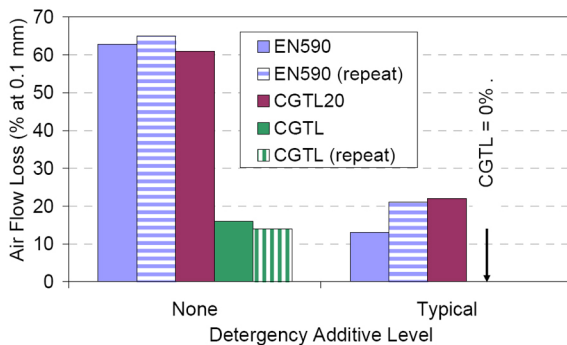


Figure 1. Additive dose response test in XUD9 for EN590, CGTL20 and the CGTL.

### In-house Common Rail Injector Fouling

The advent of high pressure, direct injection common rail fuel injection systems has raised concerns about the applicability of the XUD9 test and various companies developed in-house tests to assess common rail fouling performance.

Test fuels for this project were evaluated using an in-house test method which was adopted from Winter [19]. The principle of this common rail test method is to measure the actual fuel flow rate at the two maximum engine power stages of the sixty minute, multistage engine speed and load cycle. This cycle is repeated in eight hour blocks, separated by eight hour soak periods. A standard test specifies two eight hour engine cycles (16 hours of engine running) and the method allows for double tests (32 hours of engine operation). A Euro 4 emission level, 2.2 litre, four cylinder engine equipped with a modern high pressure common rail direct injection fuel system was used for the test. The maximum fuel pressure is 1600 bar and each injector has seven holes.

Zinc (Zn) is known to accelerate the formation of injector deposits significantly, even in trace amounts. The result of a Zn dosed fuel was used to ensure that the in-house test method was able to discriminate a worst case fuel [20], but

Zn was not added to any of the test fuels. Figure 2 shows the result of normalised change in fuel flow for CGTL, EN590 and the CGTL20 (all unadditised) as well as the CGTL20 with detergency additive, which represents a plausible final product. The graph also shows the fuel flow loss for a Zn doped EN590, designated a “Hazard fuel” (giving a 6% fuel flow loss at the end of the test). Fouling performance of the unadditised fuel is ranked from good to bad as CGTL, the CGTL20 and EN590 in the range 1% fuel flow gain to 2% fuel flow loss. The results also show that the additised blend gave similar results to that of its unadditised companion.

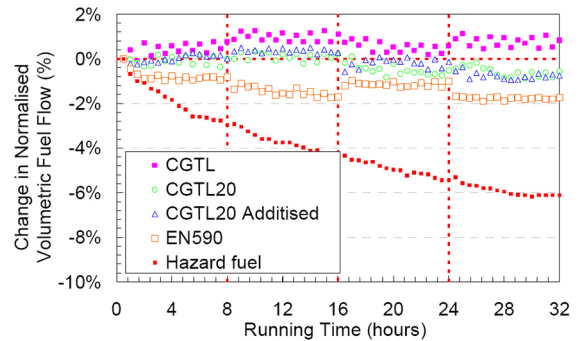


Figure 2. Normalised fuel flow loss in common rail fouling test. Results for CGTL, CGTL20 with and without detergency additive, EN590 reference and a Zn containing Hazard fuel.

The results show that, in relative terms, CGTL diesel has superior common rail injector fouling performance to EN590 or blended fuels when tested in the absence of Zn.

### Peugeot DW10

In addition to the in-house common rail fouling tests, selected test fuels were also evaluated using the new CEC F-98-08 test method utilising the Peugeot DW10 engine. The operating principles were very similar to that described in the section above, although the CEC method requires a 16 hour injector bedding period before starting power loss measurements. This test also reports power loss as a calculated weighted average of power measurements throughout the 32 hours engine running time and most importantly, the test practice requires all test fuels to be doped with 1 ppm of Zn.

Selected fuel evaluations were performed by a UK-based external laboratory and for these tests only, the CEC prescribed reference fuel, DF79-07, was used as the reference and blend component instead of the EN590 used elsewhere. Fuels that were evaluated are described in Table 2 and a solution of 90% Caromax 20 + 10% Zinc Neodecanoate was added to all the fuels to achieve approximately 1 ppm of Zn in the final fuel blend.

<sup>§</sup>It must be noted that the additive employed is of an older generation and even better results can be expected with the latest technology detergency additives on the market today.