

Comprehensive Evaluation of Exhaust Emissions with Diesel Fuel from a Commercial Scale Gas-to-Liquids Plant

2010-01-1512

Published
05/05/2010Paul Schaberg and Arthur Bell
Sasol Technology

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ABSTRACT

The world's first large scale commercial Gas-to-Liquids (GTL) fuel production plant using low temperature Fischer-Tropsch (LTFT) technology, Oryx GTL, has been in operation in Qatar since 2007. The first on-specification diesel fuel produced by this plant was subjected to a comprehensive fit-for-purpose validation programme, part of which comprised exhaust emission tests which were conducted with two different passenger cars and two different heavy-duty engines. Three neat GTL diesel fuels were included in the study: commercial GTL diesel fuel, an equivalent full boiling range GTL diesel fuel produced in a pilot plant, and a GTL diesel fuel with a narrower distillation range. Commercial sulphur-free (<10 mg/kg) European EN590 diesel fuel was used as the reference fuel. In addition, tests were performed with two different blending ratios (20% and 50%) of GTL diesel in the EN590 diesel.

The neat GTL fuels showed reductions in PM, THC, and CO, while NO_x emissions were either neutral or reduced, depending on the engine technology, when compared to the EN590 diesel. The blended fuels generally showed reductions in emissions or a neutral response, in some cases with a distinct non-linear characteristic in relation to the blending ratio. The narrower cut of pilot plant GTL diesel fuel also showed a varied response relative to the full boiling range GTL diesel fuel, depending on the engine technology. The results of the tests demonstrated that the commercial GTL diesel fuel shows the same favourable exhaust emissions performance that has come to be expected from extensive testing conducted previously with GTL fuel produced in pilot plants. Interactions with engine technology, specifically in terms of fuel injection equipment, were also highlighted.

INTRODUCTION

The last decade or more has seen publications on the subject of GTL fuels (also referred to as Fisher-Tropsch or synthetic fuels) become a regular feature at technical conferences and in journals. The first publications focused on the properties and performance of these fuels [1,2,3], particularly in terms of exhaust emissions. In addition to highlighting beneficial properties, it was also confirmed that, despite having certain properties which differ substantially from refinery diesel fuels, complete compatibility is maintained with conventional diesel systems. Attention was also drawn to the fact that Fischer-Tropsch synthesis can be applied to a wide variety of carbon-containing feedstocks, and this spawned the terminology "XTL", with "X" denoting, amongst others, natural gas, coal, and biomass. These aspects of LTFT (Low Temperature Fischer-Tropsch) diesel fuel are considered to be relatively unique amongst alternative fuels for CI engines. It was also realised that certain of the properties of LTFT GTL fuels, notably the high cetane number, negligible sulphur, and lower soot formation, could be leveraged to further optimise engines, in terms of both combustion and exhaust gas aftertreatment systems, for operation with these fuels [4,5,6].

It is therefore clear that XTL fuels can play a beneficial role in the global mobility landscape, should significant volumes of this product become available. The commissioning of the Oryx GTL plant in Ras Laffan, Qatar, represents an important milestone in the development of the synthetic fuels industry, in that it is the first commercial scale plant using LTFT technology and producing diesel fuel as its primary product. A comprehensive fit-for-purpose validation programme of the first volumes of on-specification fuel produced by this plant was conducted and is reported on in a companion paper [7].

This paper reports in more detail on one aspect of this programme, namely exhaust emission tests.

OBJECTIVES

The primary objectives of the study were to:

- Evaluate the emissions performance of the commercial diesel fuel from the Oryx GTL plant and selected blends of this fuel with European EN590 diesel.
- Assess whether there are any significant differences in the emissions performance of the commercial GTL fuel, and GTL fuel produced in a pilot plant and used extensively in a variety of GTL fuel studies, including emissions tests, in the past, for example refs [5,6,17,18,21].

The experimental programme was structured in such a way so as to also allow the following comparisons to be made:

- Emissions response with GTL fuels and blends in different technology vehicles and engines, specifically in terms of their fuel injection systems.
- Emissions response of a narrow distillation range GTL diesel fuel with a reduced T95, with the full boiling range GTL diesel fuel.
- Performance of GTL fuels in steady-state and transient test cycles (heavy-duty engine only).

EXPERIMENTAL OUTLINE

The experimental programme encompassed two different vehicles, two different heavy-duty engines, and a total of six different fuels, although not all of the fuels were tested in each application. The passenger car and heavy-duty engine studies are now described in detail.

PASSENGER CAR STUDY

Test Vehicles

Both passenger cars selected for the study were four-door sedans meeting Euro 4 emission standards. The distinguishing factor of interest between the two vehicles in this study is that different fuel injection technologies were employed: one vehicle was equipped with unit injectors, while the other used the more prevalent common-rail technology. Both vehicles were equipped with cooled EGR and oxidation catalysts. Detailed specifications of both vehicles are provided in [Table 1](#).

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

Vehicle Emission Test Procedure

Both vehicles were tested according to the ECE R83.05 procedure using the NEDC 2000 test cycle. Vehicle A was tested at the Volkswagen of South Africa (VWSA) test facility in Uitenhage, South Africa, while Vehicle B was

tested at the South African Bureau of Standards (SABS) test facility in East London, South Africa. With each vehicle, three sets of tests were performed, each comprising a randomized sequence of single, cold-start, emission tests with each of the test fuels. The sequence in which the tests with both vehicles were performed is provided in tabular form in the [Appendix](#). After each test the vehicle's fuel tank was drained, flushed, and charged with the new test fuel. The vehicle was then operated at high speed and load for approximately 10 minutes before being pre-conditioned for the next emission test. Pre-conditioning consisted of three consecutive EUDC cycles followed by a soak of at least 12 hours.

HEAVY DUTY ENGINE STUDY

The two heavy-duty engines selected for the study both had six cylinders and a nominal displacement of two liters per cylinder. As with the passenger car study, the two engines differ fundamentally in terms of their fuel injection equipment. Engine A is equipped with a unit pump system, while Engine B is equipped with a common-rail system. A further fundamental difference is that Engine A is certified to the US EPA 2004 emission standards while Engine B is certified to the Euro V EEV standards. Accordingly, the engines also differ in terms of turbocharging equipment and exhaust gas aftertreatment, as detailed in [Table 2](#). In both cases NOx limits are achieved with the aid of cooled EGR. The exhaust gas aftertreatment system on Engine B comprises an oxidation catalyst and a continuously regenerating particle separator.

(See [Table 2](#) after last section of paper.)

Engine Emission Test Procedures

Engine A was tested at the Sasol Advanced Fuels Laboratory at the University of Cape Town, South Africa. Emission tests were performed using the ESC test procedure (EU Directive 1999/96/EC). NOx, THC, CO, and CO₂ were sampled directly from the exhaust pipe, and a partial flow dilution system was used for particulate sampling. Three successive emission tests were performed with each test fuel, and the first fuel tested was repeated at the end of the test sequence in order to check that excessive drift had not occurred over the duration of the tests. The complete sequence of tests is provided in the [Appendix](#). The engine torque set points used were the same for all fuels, and were determined using the fuel with the lowest density so that the maximum torque demand could be attained with all test fuels. While this implies a marginal de-rating of the engine with the higher density fuels, it ensures that all fuels are tested under the same conditions. The A, B, and C speeds and 100% torque values for the ESC test are listed in [Table 3](#). In addition to the usual test-bed instrumentation, the engine was fitted with pressure transducers in the no. 1 cylinder and the corresponding injector line, to enable crank-angle resolved

comparisons of cylinder and injection pressures and the associated combustion parameters.

It was recognised that the reference fuel (commercial European EN590 diesel rather than US 2D diesel), and the test procedure used are not those which would be applicable to this engine for certification purposes. The test facility was, however, not equipped for performing transient FTP tests, and the use of the same reference fuel for all tests in the programme was considered to be of overriding importance

Engine B was tested at the Sasol Fuels Application Center in Cape Town, South Africa. Both steady state (ESC) and transient (ETC) emission tests (EU Directive 2005/78/EC) were performed in a transient-enabled test cell equipped with a full-flow dilution tunnel and CVS system. In addition to the dilute and bag samples, NO_x, THC, CO, and CO₂ were also sampled directly before and after the exhaust catalyst. A double dilution system with conditioned primary and secondary dilution air and single, heated sample filters was used for particulate sampling. Three sets of tests were performed, each comprising a randomized sequence of ESC + ETC tests with each test fuel. The complete sequence of tests is provided in the [Appendix](#). The speed and torque set points for both the ESC and ETC tests were the same for all fuels, and were determined using the fuel with the lowest density. The ESC speed and load details are provided in [Table 3](#). As with Engine A, the engine was instrumented for cylinder pressure-based combustion analysis.

Table 3. ESC speed and load parameters

Mode	Speed (rev/min)	100% Torque (Nm)
Engine A		
Idle	590	-
A	1300	2050
B	1600	1850
C	1900	1600
Engine B		
Idle	600	-
A	1200	2300
B	1500	2200
C	1800	1880

There were some discrepancies between the certification emission levels and the levels measured in this test programme for both test vehicles as well as Engine B. These can probably be ascribed to small differences in the test procedures applied when compared to certification testing, as well as the fact that a commercial EN590 diesel fuel, rather than a certification diesel fuel, was used as the reference. Since the purpose of the study was to assess relative changes in emissions performance due to the use of GTL fuels and

their blends, these differences were adjudged not to detract from the validity of the results.

TEST FUELS

The test fuels used in this study were as follows:

EN590 : Sulphur-free (<10 mg/kg) diesel fuel meeting the EN590:2009 specification. This fuel was used as the reference fuel for all the emission tests performed during this study.

CGTL : Commercial GTL diesel fuel produced at the Oryx GTL facility in Ras Laffan, Qatar using the Sasol SPD™ LTFT process. This fuel meets all the requirements of the CEN Workshop Agreement 15940, and also meets all EN590:2009 specification limits except for the density which is below the minimum limit.

PGTL : GTL diesel fuel produced in a pilot plant facility, and used extensively in recent years to assess the performance of diesel fuel produced using the Sasol SPD™ LTFT process. This fuel was included in the test programme in order to assess whether there are any gross differences in performance between it and the commercial product. Substantially similar performance between the two fuels would provide confidence that the findings and conclusions from previous work are also applicable to the commercial product.

CGTL20 : Blend of 20% v/v CGTL diesel and 80% v/v EN590 diesel. This blending ratio for GTL diesel in EN590 diesel approximates the maximum which will not violate the minimum density specification for EN590 diesel.

PGTL20 : Blend of 20% v/v PGTL diesel in EN590 diesel, included to validate previous work done with this fuel by demonstrating substantially similar performance with the commercial fuel blend (CGTL20).

CGTL50 : Blend of 50% v/v CGTL diesel and 50% v/v EN590 diesel. This is an intermediate blend which was included in one set of tests to assess the emissions response to blending ratio.

LCPGTL : GTL diesel produced in a pilot plant facility with reduced T95, targeting a CFPP of < -15°C. The production process for this fuel differed from that of the PGTL diesel fuel only in terms of the back-end distillation temperature cut-point.

The properties of the test fuels are detailed in [Table 4](#). It can be seen that the three GTL diesel fuels display all of the properties that are normally associated with GTL diesel, namely: negligible aromatics and sulphur content, high cetane number, and high H/C ratio and the associated lower density and higher gravimetric heating value, relative to the EN590

diesel fuel. There is a small difference between the distillation profiles of the pilot plant and commercial GTL fuels (PGTL and CGTL) which is due to the more efficient distillation in the large-scale commercial plant, but this difference is too small to translate into a significant difference in the physical properties of the two fuels. The low CFPP fuel (LCPGTL) has a CFPP of -18°C (as opposed to -6°C for the full-boiling range PGTL fuel), and besides the distillation profile, the other major difference is that the viscosity is lower ($2.03\text{ mm}^2/\text{s}$ vs. $2.47\text{ mm}^2/\text{s}$, both at 40°C).

The EN590 fuel used as the reference fuel can be considered to have representative properties for a European sulphur-free ($<10\text{ mg/kg}$) diesel fuel, and for the most part, the properties of the blended fuels reflect the blending ratio. As expected, the densities of the two 20% GTL blends coincide with the EN590 minimum diesel density specification of 0.820 kg/l . Where required, fuels were dosed with an ester-based lubricity improver additive to ensure that a HFRR WSD (wear scar diameter) of $460\text{ }\mu\text{m}$ was not exceeded.

(See [Table 4](#) after last section of paper.)

All the test fuels were not tested in each of the four applications studied. The PGTL20 fuel was only tested in Vehicle A, and the CGTL50 fuel was only tested in Engine B. The PGTL and PGTL20 fuels were omitted from the tests in Vehicle B because equivalent emissions performance to the CGTL and CGTL20 fuels was deemed to have been demonstrated in the tests with Vehicle A. [Table 5](#) provides an overview of which fuels were tested in each of the vehicles and engines.

Table 5. Fuel Test Matrix

	Vehicle		Engine	
	A	B	A	B
EN590	X	X	X	X
CGTL	X	X	X	X
CGTL20	X	X	X	X
CGTL50				X
PGTL	X		X	X
PGTL20	X			
LCPGTL	X	X	X	X

RESULTS

The results of the tests with the four vehicles and engines are presented in this section. In all cases, results are presented graphically (with numerical annotation), and are expressed in relative terms, as a percentage of the result obtained with the EN590 reference diesel fuel. Unless stated otherwise, “differences” referred to in the following sections refer to differences between the fuel/s under discussion and the

EN590 reference diesel. Each result represents the average of the three tests performed with each fuel, and the error bars depicted in the graphs indicate $\pm$ one standard deviation. In all cases the statistical significance of the measured differences was determined using Student's T-test, with a probability of 0.05 or less being deemed to indicate a statistically significant difference. Unless the contrary is specifically stated, quoted differences in results presented in the following sections are statistically significant.

PASSENGER CARS

The relative emissions of PM, NO_x, CO, and THC are shown in [Figures 1](#) and [3](#) for Vehicles A and B respectively. Relative CO₂ emissions and volumetric fuel consumption (i.e. l/100km) are shown in [Figures 2](#) and [4](#). The darker portion of each bar indicates the portion of the emission measured during the urban part of the test cycle (UDC), while the lighter portion indicates the contribution from the extra-urban portion (EUDC).

Vehicle A Test Results

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

The results show the following:

- Reductions in PM were obtained with all of the neat GTL diesel fuels, as well as the CGTL20 fuel. The reduction with the neat GTL fuels was greater than 40%, while the CGTL20 and PGTL20 blends showed reductions of 31% and 16%, respectively. While the reduction with the CGTL20 fuel is considerably greater than that with the PGTL20 fuel, the difference between these two results is not statistically significant. The LCPGTL fuel showed a smaller reduction (24%) than the CGTL and PGTL fuels (44% and 41% respectively). Comparison of the contributions from the urban and extra-urban phases of the test cycle indicate that with the neat GTL fuels, the reduction during the extra-urban phase was greater than that during the urban phase, while with the blended fuels the difference was smaller. In the case of the LCGTL fuel, the emitted PM level was higher than that of the EN590 fuel during the urban phase.
- NO_x emissions did not show statistically significant differences between the test fuels, but nevertheless showed a tendency to increase with the three neat GTL fuels, as well as with the PGTL20 fuel. The magnitude of the increases was between 3% and 6%. In all cases the increase is somewhat larger during the urban phase of the test, than during the extra-urban phase.
- CO was reduced by 70% or more with the three neat GTL diesel fuels, relative to the EN590 diesel fuel, and by 36% or more with the blended fuels. The majority of CO (93% in the case of the EN590 diesel) is emitted during the urban part of

the cycle which is not unexpected, given that the vehicle is equipped with an oxidation catalyst.

- THC emissions show a similar qualitative trend to those of CO, with the neat GTL fuels showing reductions of between 56% and 59%, and the GTL blends showing reductions of between 28% and 30%. The portion of THC emitted during the urban phase is smaller than for CO, however (76% in the case of the EN590 diesel), and the GTL fuels and blends show reductions during both phases.

(See [Figure 2](#) after last section of paper.)

A comparison of CO₂ emissions ([Figure 2](#)) shows a reduction of approximately 5% with the neat GTL fuels, and a reduction of 1% or less with the blended fuels. The corresponding volumetric fuel consumption values are approximately 4% higher with the neat GTL fuels, and 1% higher with the blended fuels.

Vehicle B Test Results

The relative emissions measured with Vehicle B are shown in [Figure 3](#). As mentioned earlier, the PGTL and PGTL20 fuel were not tested in this vehicle, as the tests with Vehicle A were deemed to have adequately demonstrated that their performance was equivalent to that of the CGTL and CGTL20 fuels, respectively.

(See [Figure 3](#) after last section of paper.)

The results show the following:

- PM emissions showed reductions of 31% and 34% for the CGTL and LCPGTL fuels respectively, while the CGTL20 fuel showed no change from the EN590 diesel fuel. As was the case with Vehicle A, more PM was emitted during the extra-urban phase of the test cycle than during the urban phase, and larger reductions occurred with the GTL fuels during this phase.
- NOx emissions show a tendency for increased emissions of between 5% and 8% with the GTL fuels and blend, although differences are not statistically significant. There is no clear distinction between the two phases of the test cycle in terms of their contribution to the NOx emitted.
- Very large reductions of 88% and 85% in CO were recorded with the CGTL and LCPGTL fuels respectively, while the CGTL20 blend showed a reduction of some 34%. It can be seen that almost all the CO is produced in the urban part of the test cycle.
- Measured THC emissions with this vehicle were very close to ambient levels. Nonetheless, reductions of 60% and 72% were recorded with the CGTL and LCPGTL fuels, respectively. The blended fuel showed a reduction of some 18% although this difference was not statistically significant. As with CO, almost all of the THC is produced during the urban part of the driving cycle.

(See [Figure 4](#) after last section of paper.)

CO₂ emissions ([Figure 4](#)) with the two GTL fuels are some 4% lower than with the EN590 fuel, while that with the CGTL20 fuel is 1% lower than the EN590 fuel. The volumetric fuel consumption is higher by between 6% and 7% with the GTL fuels, and 1% with the blended fuel.

HEAVY-DUTY ENGINES

The results of the ESC tests performed with Engine A are presented in [Figures 5](#) and [6](#), and with Engine B in [Figures 7](#) and [8](#). ETC tests were also performed with Engine B, and the results are shown in [Figures 9](#) and [10](#). As mentioned earlier, the PGTL20 fuel was not tested in this engine, rather being replaced by the CGTL50 fuel.

Engine A ESC Test Results

(See [Figure 5](#) after last section of paper.)

The salient features of the results ([Figure 5](#)) are as follows:

- The neat GTL fuels all resulted in similar reductions in PM, of between 18% and 23%, when compared with the EN590 diesel. The blended fuel had a similar emission to the EN590 diesel.
- A similar fuel trend is evident in the NOx emissions, with reductions of the order of 11% being obtained with the neat fuels.
- Modest reductions in CO of between 6% and 11% were obtained with all the fuels, including the CGTL20 fuel.
- Similarly modest reductions in THC were obtained with the CGTL and the LCPGTL fuel, while the PGTL fuel showed a larger reduction of 19%, relative to the EN590 fuel. The CGTL20 fuel performed similarly to the EN590 fuel.

(See [Figure 6](#) after last section of paper.)

CO₂ emissions ([Figure 6](#)) were lower by between 3% and 4% with the neat GTL fuels, and by 1% with the CGTL20 blend. The corresponding BSFC values show a 2% decrease for the neat GTL fuels, and a 1% decrease for the CGTL20 fuel.

Engine B ESC Test Results

(See [Figure 7](#) after last section of paper.)

The ESC results from Engine B ([Figure 7](#)) show the following:

- The three neat GTL fuels showed reductions in PM of between 19% and 21%, compared with the EN590 diesel fuel. The CGTL50 fuel showed a reduction of 4% and the CGTL20 fuel showed an increase of 3%, although the latter two differences are not statistically significant.

- The three neat GTL fuels show reductions in NO_x of between 7% and 9%. The CGTL20 fuel shows no change from the EN590 diesel fuel, and the CGTL50 fuel shows a small reduction of 3% (not statistically significant).

- Due to the action of the oxidation catalyst on this engine, CO emissions are extremely low (of the order of 0.02 g/kWh). Differences in CO emissions between the fuels were not statistically significant, although there is a trend of increasing CO emissions with the GTL fuels and their blends. The largest difference was an increase of 8% with the LCPGTL fuel.

- Similar to CO, THC emissions are also very low (of the order of 0.01 g/kWh), and the measured differences between fuels were not statistically significant. In this case the neat GTL fuels and their blends show a general tendency to reduce emissions (up to 11%), although this reduction was not evident with the LCPGTL fuel.

(See [Figure 8](#) after last section of paper.)

CO₂ emissions and BSFC ([Figure 8](#)) show a similar fuel trend as with Engine A ([Figure 6](#)). CO₂ emissions are 4% lower with the neat GTL fuels, with the GTL blend emissions reflecting the blending ratio. Gravimetric fuel consumption is 3% lower with the neat GTL fuels.

Engine B ETC Test Results

(See [Figure 9](#) after last section of paper.)

Salient features of the ETC test results with Engine B ([Figure 9](#)) are as follows:

- There is a very clear trend of reducing PM emissions with the GTL blends and neat GTL fuels. The CGTL20 fuel shows a reduction of 5%, although the difference is not statistically significant. The CGTL50 fuel shows a reduction of 16%, and the neat GTL fuels show reductions of between 33% and 35%.

- NO_x emissions show reductions of 6% for the CGTL and PGTL fuels, 8% for the LCPGTL fuel, and 3% for the CGTL50 fuel.

- Differences in CO emissions are small and not statistically significant.

- Differences in THC emissions are also not statistically significant, although the trend is for a reduction with the CGTL and PGTL fuels and blends, and an increase with the LCPGTL fuel.

(See [Figure 10](#) after last section of paper.)

CO₂ emission and BSFC results ([Figure 10](#)) show a similar trend to that obtained in the steady-state ESC test, with reductions of between 5% and 6% with the neat GTL fuels in the former, and 3% to 4% in the latter.

ANALYSIS AND DISCUSSION OF RESULTS

The results from this study present a unique opportunity to examine the performance of three GTL diesel fuels and some blends thereof, in both passenger car and heavy-duty applications, with two different fuel injection technologies in each case, and also in steady state and transient operation in the case of one heavy-duty engine.

In a fuel study such as this one, a distinction can be drawn between changes in emissions which are due to differences in the inherent pollutant formation chemistry of the fuels, and differences which result from changes in the operating mode of the engine which arise out of the use of non-standard fuels. In addition to these two factors, there is the superposition of the effect of exhaust gas aftertreatment, with the end result being a combination, in varying degrees, of all of these factors.

NO formation in CI engine combustion occurs primarily at the periphery of the diffusion flame and in the hot post-flame gases [8]. The rate of NO formation is determined by the temperature and oxygen availability [9]. EGR reduces both of these parameters, and is employed in all of the engines tested in this study for NO_x control. Excluding EGR effects, fuel properties may influence NO_x formation via their influence on flame temperature, and combustion rate and phasing, which affect the bulk burned gas temperature. Fuel hydrogen to carbon (H/C) ratio has an effect on the adiabatic flame temperature [5], and, as shown in [Table 3](#), GTL fuels have a higher H/C ratio than fuels such as the EN590 diesel which contain unsaturated molecules such as aromatics. A higher H/C value results in a lower flame temperature.

A lower rate of heat release results in reduced bulk burned gas temperatures due to the additional time available for mixing and heat transfer [10]. Physical properties of the fuel which may affect the fuel injection rate may also affect the combustion rate. In this regard bulk modulus and viscosity are two fuel parameters which are likely to have a significant influence. Paraffinic fuels such as GTL diesel are known to have a lower bulk modulus of compression than conventional fuels which contain aromatics [11]. Density and heating value also have an effect, since fuel is metered volumetrically, with the result that, at equivalent engine load, injection durations will typically be longer with fuels which have a lower volumetric heating value.

One of the most effective ways to reduce NO_x formation rates is to retard the injection timing and hence combustion, albeit at the expense of cycle efficiency and hence fuel consumption. The primary fuel effect on combustion phasing will be due to the fuel cetane number, with a higher cetane number advancing the start of combustion. This effect is, however, tempered by two factors:

- Almost all passenger car diesel engines, and many new heavy-duty engines (for example Engine B in this study), employ one or more pilot injections in their fuel injection strategy. This has the effect of greatly reducing the influence of cetane number on the ignition delay of the fuel injected during the main injection event [5].

- It has been shown that the difference in ignition delay between high cetane fuels such as GTL diesel and conventional diesel fuels diminishes as in-cylinder pressure and temperature increase [5]. Fuel cetane number effects can therefore be expected to play a smaller role during emission tests in heavy-duty engines than in passenger car engines due to the inclusion of a large proportion of high load operation in the former.

In certain engine technologies, notably passenger cars, it has been found that EGR rates are influenced by fuel density, in that lower density fuels require a higher fuelling rate to achieve the required engine load, and EGR demand rates are typically determined as a function of fuelling rate in the engine calibration. As a result, low density fuels result in lower EGR rates, with a concomitant increase in NOx emissions [12].

Soot formation in CI engines may be influenced by fuel properties via the following routes:

- The chemical composition of the fuel - highly aromatic fuels (with a lower H/C ratio) generally promote soot formation, while oxygenated fuels reduce soot formation rates.
- Combustion phasing - fuels with high cetane numbers may promote more advanced combustion, which usually results in lower soot formation (and increased NO formation).
- The amount of premixed combustion - premixed combustion has been shown to generate less soot than mixing controlled / diffusion flame combustion, and fuels with high cetane numbers may promote a reduction in the amount of premixed combustion.

In the present study, the passenger car emission tests were conducted using standard vehicles operated on chassis dynamometers, with no scope for making additional measurements which would assist in elucidating some of the mechanisms responsible for the observed differences in emissions. As a result, an analysis of the results inevitably involves hypothesis and some speculation. On the other hand, both heavy-duty engines in this study were instrumented for cylinder pressure-based combustion diagnostics, as well as various pressure, temperature, flow and other measurements. As will be seen in the ensuing discussion, these diagnostics have enabled considerable insight into engine operation, and for this reason, the results from the heavy-duty engine tests will be discussed first.

HEAVY-DUTY ENGINE RESULTS

Engine B Regulated Emissions

For reasons which will become apparent, it is convenient to discuss the results obtained with Engine B first. The results of the steady-state ESC tests with the neat GTL fuels fall well within the range which has been reported in literature [13], and are therefore not considered extraordinary. Two aspects are perhaps noteworthy, namely:

- The CGTL20 fuel did not provide any emission benefit when compared to the EN590 diesel. This is contrary to expectations based on many previous studies which have typically shown a benefit [1,5].
- The LCPGTL fuel did not show any PM emission benefit when compared to the full boiling range GTL fuels. Some previous studies have indicated a positive correlation between T95 and PM emissions [13], creating the expectation that the LCPGTL fuel might also show this characteristic. The result indicates either a lack of response to T95 in this engine, or that the high boiling point components in the GTL diesel fuels tested do not have the same deleterious effect on PM emissions as those in conventional diesel fuel, as suggested in [14].

In order to identify any possible contributing factors to the observed emission results, the following measured test data were scrutinised for differences:

- Measured EGR rates
- Combustion stoichiometry, as calculated from the measured exhaust gas composition, as well as measured using a wide-band exhaust lambda sensor
- Exhaust gas temperatures
- Combustion parameters, such as heat release rate, combustion phasing, rates of cylinder pressure rise, and maximum cylinder pressure
- Catalytic converter conversion efficiency, as determined from pre- and post catalyst exhaust gas analysis

No significant differences could be found in any of these parameters. To illustrate, the cylinder pressure traces and calculated heat release rates measured at the A100 and C25 modes with the CGTL and EN590 fuels, are shown in [Figure 11](#).

(See [Figure 11](#) after last section of paper.)

It can be seen that, with the exception of a slightly earlier start of combustion for the pilot injection charge during the high speed, low load C25 mode, differences in the data depicted for the two fuels are negligible. Although not shown here, it can further be confirmed that none of the test fuels showed discernable differences. This is considered somewhat remarkable, given the large differences in critical fuel