2010-01-0737

Dedicated GTL vehicle: a calibration optimization study

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ABSTRACT

GTL (Gas-To-Liquid) fuel is well known to improve tailpipe emissions when fuelling a conventional diesel vehicle, that is, one optimized to conventional fuel. This investigation assesses the additional potential for GTL fuel in a GTL dedicated vehicle.

This potential for GTL fuel was quantified in an EU 4 6-cylinder serial production engine. In the first stage, a comparison of engine performance was made of GTL fuel against conventional diesel, using identical engine calibrations. Next, adaptations enabled the full potential of GTL fuel within a dedicated calibration to be assessed. For this stage, two optimization goals were investigated:

- Minimization of NO_x emissions
- Minimization of fuel consumption

For each optimization the boundary condition was that emissions should be within the EU5 level. An additional constraint on the latter strategy required noise levels to remain within the baseline reference.

Optimizing the calibration for GTL fuel led to further substantial reductions of regulated emissions, i.e. achieving EU 5 levels with a former EU 4 vehicle, as well as significantly reduced exhaust CO_2 emissions.

The use of GTL fuel in combination with a dedicated calibration already achieves a significant benefit, even before consideration of potential hardware modifications. This would allow an improved emissions level for compliance with required local legislation.

INTRODUCTION

Light duty vehicle development faces two main challenges: the need to reduce regulated emissions to meet the progressively tightening standards as well as the requirement to reduce the CO_2 output. The two routes to reduce local emissions are re-designing the engine and adding after-treatment devices. For reduction of CO_2 emissions a large number of measures compete with regard to the cost-effectiveness trade-off, ranging from extreme light-weight vehicles to electrification, to the use of bio-fuels.

BACKGROUND TO GTL FUEL

The basic technology behind GTL was developed in Germany during the 1920's and is known as the Fischer Tropsch process after its inventors. In essence, it uses catalytic reactions to synthesize complex hydrocarbons from simpler organic chemicals.

Shell has more than 30 years of experience in this area. Work started on their proprietary GTL process in the Group's Amsterdam laboratories in the 1970s, and by 1993, a small commercial plant (14,700 barrels/day) in Bintulu, Malaysia had been opened. This was the world's first commercial low-temperature Fischer Tropsch GTL plant. Then, in 2007, Shell commenced construction of Pearl GTL in Qatar. Pearl GTL will be the world's largest plant, converting natural gas into 140,000 barrels a day of GTL products - gasoil, naphtha, kerosene, normal paraffin and lubricants base oils - as well as 120,000 barrels of oil equivalent a day of ethane, liquefied petroleum gas (LPG) and condensate.

Technical Attributes of GTL fuel

GTL fuel, the product of the Fischer Tropsch process, is of a distinctly different nature to crude derived diesel fuel. Indeed, even its appearance as a crystal clear liquid makes it readily distinguishable from diesel. Its composition is paraffinic, leading to a high cetane number and higher hydrogen to carbon ratio compared with diesel. In addition, it is virtually free of sulphur and poly-aromatic hydrocarbons (PAH).

GTL fuel is often referred to as a "clean fuel", because a key technical feature is its ability to reduce engine exhaust emissions. A wealth of studies demonstrates this emissions reduction potential. Fuelling a car with GTL fuel instead of conventional diesel, has the potential to give an immediate emissions benefit of up to 40% less particulate mass [1,2,3].

Figure 1 illustrates schematically the form of PM - NO_x trade-off curves, in particular the distinct difference for GTL fuel curve, which is significantly closer to the origin.

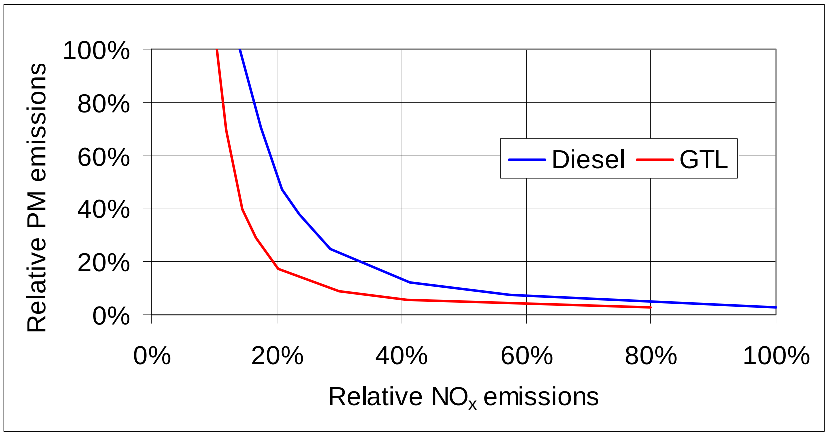

Figure 1 Typical improvement of the PM-NO_x trade-off curve with GTL fuel in a non-adapted engine

However, while there is already quite a substantial emissions reduction with non-adapted engines, there is a strong expectation that the potential of synthetic fuels will not be fully exploited in engines, which have been designed and calibrated for conventional diesel. This belief stems from the differences between GTL fuel and diesel for a number of properties, for example the high cetane number. Indeed it would seem logical that the emissions benefits that result from these differences would relax the constraints and give greater flexibility to the engine design process. Consequently, many groups have varied engine parameter settings in order to adjust the operating points to better exploit the benefits of GTL fuel. Overall goals were either increased emissions reduction or increased engine efficiency, and thus decreased fuel consumption [4, 5, 6].

For the emissions reduction target, then moving along the PM – NO_x trade-off curve by varying EGR rates may be used to trade the inherent particulates emissions benefit for further NO_x reduction. For example, a EU3 engine on a test bench [7], initially gave a 60% benefit in PM emissions combined with 15% NO_x in the non-adapted engine, subsequent trade-offs changed this to an emissions benefit of 45% for both, NO_x and PM.

Additional adaptation possibilities for the engine includes changes to the hardware, such as lowering the compression ratio, which is made possible by the high cetane number of GTL fuel. This enables further emissions reduction [8,9,10].

Market Applications

The ability to convert natural gas into liquid fuels opens up opportunities within the more flexible liquid fuels market. GTL fuels have market potential when used either neat or in blends with conventional diesel fuel. Indeed, fuels containing a proportion of GTL fuel are already available for the private motorist within some areas of the retail fuels market.

However, in those areas which are sensitive to air quality issues (e.g. inner cities), the use of neat GTL fuel in dedicated fleets is an attractive option, because of the profound effect that GTL fuel can have on vehicle emissions. Indeed trials of pure GTL have already taken place in heavily-congested cities like London, Berlin and Shanghai. Attendant emissions tests have shown that the trial vehicles (buses and taxis) have produced significantly lower levels (than those powered by conventional diesel) of the key regulated emissions, which directly affect local air quality.

The progression from using neat GTL in conventional vehicles towards the possibilities of optimizing engines to GTL fuel would seem to be the natural evolution required in order to find and achieve the maximum potential of such fuels.

CURRENT STUDY

Motivation

The preceding section covering the background to GTL fuel, including technical attributes and potential applications, gives excellent indications that increased benefits may ensue when engines are optimized to GTL fuel. This current study was motivated by a strong desire to explore such characteristics in a sound technical study, which would be comprehensive enough to explore both, engine software and hardware routes. The ultimate technical aim is to find the full potential of the fuel, with respect to both emissions reduction and also fuel consumption. The goal of the program was twofold: to appraise the technical possibilities and challenges for GTL fuel dedicated vehicles as well as to produce a demonstrator vehicle that tangibly shows the benefits to stakeholders.

Outline study design

A key feature of this study was the unique nature of the study team, which brought together the disparate expertise of three different industrial players:

- Shell, a global leading oil company, commissioned the work and provided insights into GTL fuel and conventional diesel
- Audi, a premium automotive OEM with latest TDI diesel technology, provided the baseline vehicle and insights into its design and potential
- FEV, world-wide operating engineering consultancy, provided expertise on implementing such projects.

To explore the full potential of GTL fuel in a dedicated vehicle, the study group agreed on three phases for the program:

1. Comparing the behavior of the series-production baseline engine with GTL fuel and conventional diesel
2. Optimizing the calibration to GTL fuel
3. Optimizing the hardware and the calibration to GTL fuel

This paper discusses and presents the results of phases 1 and 2, phase 3 will be subject of a future publication.

METHODOLOGY

EXPERIMENTAL DESIGN

Test fuels – For this optimization program a GTL fuel, with the properties outlined in Table 1, was used. In order to provide a comparative baseline, initially the behavior of the non-adapted engine was assessed with a standard EN 590 diesel fuel.

Due to the length of the optimization program, several batches of each fuel were used, Table 1 gives values representative of all batches.

Table 1 Typical Properties of EN 590 Diesel Fuel and GTL Fuel

Property	Units	EN 590 Diesel	GTL Fuel
Density (15 ºC)	kg/m^3	830	775
Viscosity (40 ºC)	mm^2/s	2.9	2.45
Cetane Number CFR	-	56	> 70
IBP	ºC	170	200
FBP	ºC	360	310
Sulfur	mg/kg	< 10	0
Hydrogen content	%w	13.6	14.7
Carbon content	%w	86.3	85.2
Calorific value	MJ/kg MJ/l	42.9 35.6	44.0 34.1
FAME content	Vol.%	0	0

BASELINE VEHICLE

The baseline vehicle was a series production Audi A4 Avant, equipped with a series production Audi 2.7 TDI V6 engine and a 6 gear manual shift The key parameters for the engine are summarized in Table 2. At the time of production this engine was certified as EU 4.

Table 2 Engine data

Property	Unit	Value
Displacement	Liter	2.698
Compression ratio		16.8
Bore	Mm	83
Stroke	Mm	83.1
Max. combustion pressure	bar	150
Max. Torque	Nm	380 @ 1400 – 3250 rpm
Power	kW	140 @ 3500 -4400 rpm

Prior to testing, the vehicle received a run in of over 5000 km, and EU4 emissions compliance was confirmed. Moreover, apart from NO_x, all emissions were at or below the EU5 level.

Apart from the normal measurement equipment required for these type of experiments, no modifications were applied to the vehicle.

For test bench experiments (see below) a second identical engine was used.

EXPERIMENTAL SETUP

The investigations of emissions and fuel consumption potential from GTL fuelling were performed on:

- steady-state test bench
- vehicle chassis dynamometer

The steady state test bench was equipped with an eddy-current dynamometer. For conditioning oil and water, special conditioning devices were installed which enabled a variation of oil and water temperature between 35°C and 90°C. Inlet air was conditioned to 1013 mbar and 25°C. The serial intercooler was replaced by an air / water cooler to ensure a precise conditioning of the inlet air temperature in the intake plenum (T_2’).

The engine has been equipped with un-cooled piezo resistive pressure transducers for each cylinder, which were mounted in the glow plug bore. Within the system, typical temperature and pressure measurements were recorded. The raw exhaust gas sampling was conducted downstream of the turbo but upstream of the DOC (diesel oxidation catalyst). Additionally the CO_2 content in the intake manifold was measured in order to make an exact determination of the EGR rate. For the PM emissions measurements, the DPF was removed from its housing. Exhaust backpressure was then simulated by an additional exhaust flap.

The vehicle tests were performed on a chassis dynamometer Schenk EMDY 48 AC/LC. The roller dyno was conditioned to 22°C. For the conditioning of the vehicle a separate conditioning room was available. The exhaust gas analysis was performed employing a Pierburg AMA 4000. Weighing of the particulate collectors was performed at 22°C and 47% humidity.

Monitoring of the tailpipe emissions during the vehicle investigations was performed downstream of the DOC. In addition to the serial ECU (electronic control unit) sensors, further pressure and temperature measurement points were installed in the intake and exhaust line, which were to enable a good comparison between the engine operating conditions of vehicle and test bench.

The characterization of engine noise was performed with the help of the FEV combustion sound level method (CSL), which provides a correlation between cylinder pressure traces and the (expected) engine noise. The definition and theoretical background of the CSL method has been described in the literature [11].

INTRODUCTION TO PRINCIPLES OF OPTIMIZATION

In general, processes searching for the best possible solution for a goal under given boundary conditions are called optimization. The free variables (optimization variables) are determined in a way that one or more target functions are satisfied in the best possible way, while still complying with pre-defined boundary conditions.

The methodologies employed for the optimization of this engine were: (1) design-of-experiments methods (DoE) and (2) FEV's in-house software tools [12]. In the context of engine optimization, the calibration parameters are the free variables, the optimization goal is defined as an emissions reduction target, and the boundary conditions are set as limits of acceptable emissions and noise.

The reason for using the DoE method for the software adaptation was firstly the reduction of the calibration effort. Secondly, that the settings of the investigated calibration parameters can be varied arbitrarily within the experimental area. The latter is a prime benefit of the DoE methodology. In essence, the DoE software calculates for chosen settings a prediction for defined output values, e.g. emissions, fuel consumption and engine noise. Moreover, the advanced DoE software enables an automatic optimization function. Consequently, the user can define the aims of the optimization and set different constraints. Based on this user-defined set-up, the software determines several calibrations, which fulfill the requirements.

First a re-calibration of the ECU software settings was performed with DoE, in a subsequent step, the recalibrated engine maps were smoothed and fine-tuning of the maps was conducted. This ensured a good compromise between drivability and emissions performance. Finally, the potential that was identified on the engine test bench, was then verified on a chassis dynanometer by NEDC vehicle tests.

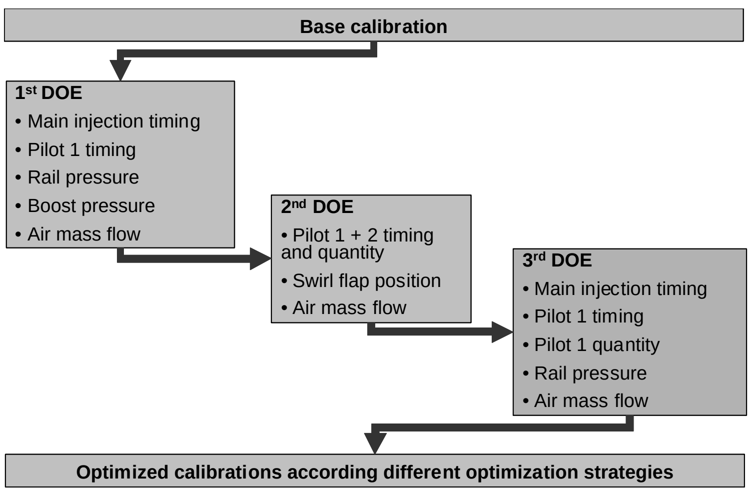

Figure 2: Optimization procedure

For each load point, three DoE investigations were performed as it is illustrated in Figure 2. Within every step of the DoE optimization procedure, different calibration parameters were varied in different combinations.

Between each of the single DoE steps, the DoE predictions were verified by tailored EGR sweeps on the test bench.

Using the above functionality in this current project, several calibrations were derived according to the different optimization strategies, which are described in the subsequent section.

The optimization on the steady state test bench required the definition of a 14-mode replacement test, which was based on the on-line measurement data from NEDC tests with the vehicle. Within each of the 14 points of this replacement test (illustrated in Figure 3), the calibration parameters were optimized by DoE methodology.

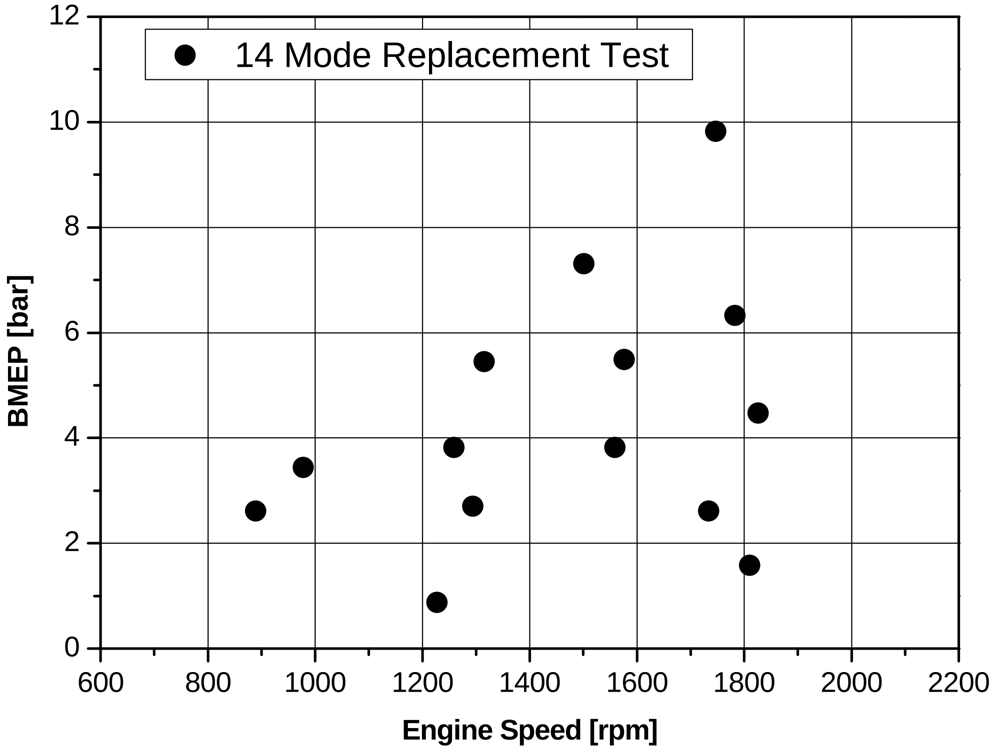

Figure 3: 14-mode NEDC replacement test

OPTIMIZATION STRATEGIES

Three different optimization strategies were defined for the recalibration of the ECU software. The main focus of strategy A was the reduction of NO_x emissions, whereas strategies B and C focused on both the reduction of fuel consumption and hence CO_2 emissions. The difference between these latter two strategies was that for B the re-calibration was performed without regard to engine noise, whereas for C, the engine noise was constrained to the baseline levels.

The different strategies are summarized in Table 3.

Table 3: Optimization strategies

Strategy	Main focus	Boundary conditions
A	Minimization of NO_x emissions	Other emissions not to exceed the EU5 limits
B	Minimization of fuel consumption	Emissions not to exceed the EU5 limits
C	Minimization of fuel consumption	Emissions not to exceed the EU5 limits, engine noise levels at or below the base calibration

RESULTS

TEST BENCH RESULTS

The following sections discuss the results from the test bench investigations. In this context, all emissions results are compared with those from the baseline engine-out emissions using conventional diesel fuel. To aid the comparison, results are reported at a constant NO_x-level for each load point.

Investigation with baseline calibration

The evaluation of the emissions reduction potential of GTL fuel with the baseline calibration was performed by complete engine mappings as well as EGR variations within the 14 mode points of the NEDC replacement test.

Figure 4 illustrates the improvement of the raw emissions, illustrated with 2 different load points:

- 1200 rpm / 1 bar BMEP
- 1800 rpm / 4.5 bar BMEP

It can clearly be seen that the use of GTL fuel leads to a significant improvement in CO, HC and particulate emissions. The reduction of particulate emissions was better at higher load points, whereas the CO emissions showed more improvement at lower engine load.

The relative reduction of HC emissions was comparable for the two chosen load points. Key issue for the reduction of emissions especially particulates and hydrocarbons is the paraffinic nature of GTL fuel and its low polyaromatic content [7].

Specific fuel consumption of the two fuels was nearly identical. However, due to the higher heating value of GTL fuel, this means that the engine efficiency within this baseline application is slightly lower with GTL fuel.

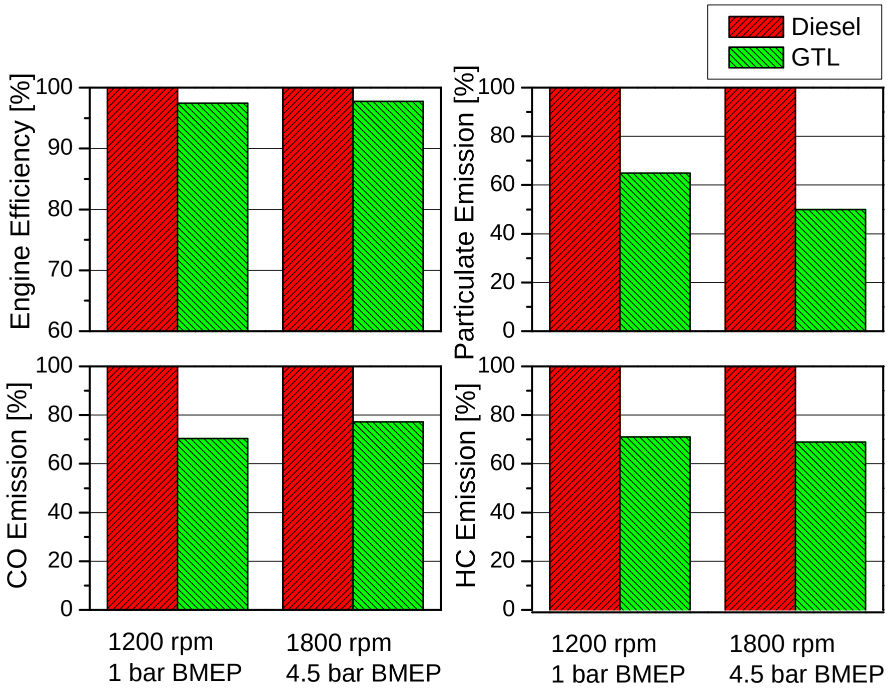

Figure 4: Emission performance with base calibration (compared at iso-NO_x)

In Figure 5 the results of a heat release calculation are illustrated for both load points. The burning rate shows that due to the higher cetane number of GTL fuel, the ignition delay of the pilot injection is reduced such that the combustion of pilot quantities starts earlier.

For both points, the ignition delay of the main injection is hardly influenced, but the share of premixed combustion is lower with GTL fuel compared to Diesel fuel. This leads to a slight retardation of the centre of combustion. Because of this, the engine efficiency with GTL fuel is slightly lower than with Diesel fuel.

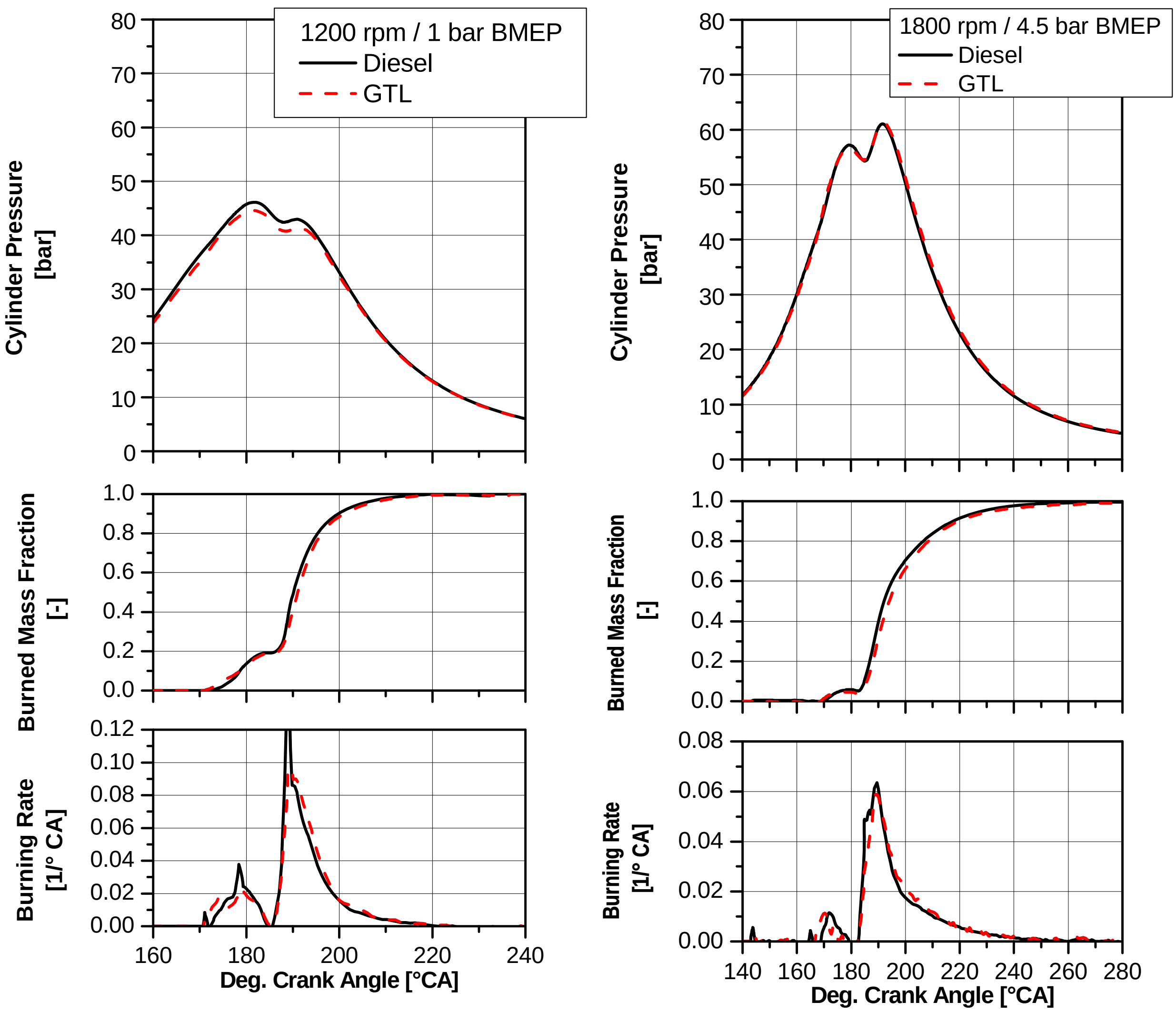

Figure 5: Heat release calculation 1200 rpm / 1 bar BMEP and 1800 rpm / 4.5 bar BMEP

In summary, when comparing GTL fuel with conventional diesel at constant NO_x levels throughout the whole emission-relevant area of the engine map, then the overall benefits are as follows:

- Particulate emissions are reduced in the between 30% and 55% with generally higher reduction rates at higher load points.
- The CO emissions benefit is from 10% to 40% with the highest reduction seen at low engine loads.
- HC emissions are reduced by 20% to 40 % with the highest reduction observed at low engine loads.
- No difference in engine noise level was detected within the main part of the engine map.
- The difference in terms of specific fuel consumption with both fuels was lower than 1 g/kWh for a wide map range.

Optimization of calibration

The results of the different optimizations are illustrated in Figure 6, using the load point 1260 rpm / 3.8 bar BMEP as an example.

To realize strategy A, minimum NO_x emissions, the drawback of the steeply increasing particulates evident at high EGR ratios needed to be overcome. Thus, the focus of optimization was to reduce the particulate emissions especially at these higher EGR rates. A substantial improvement was possible by using the calibration settings optimized within the DoE technique. The net result was a NO_x emissions reduction of 65% for an increased EGR rate, but simultaneously maintaining a reasonable level for the particulate emissions. Shortcomings in specific fuel consumption, CO and HC emissions were also avoided.

Strategy B, the minimization of fuel consumption, achieved a significant advantage over and above the baseline, especially at high EGR rates. A specific fuel consumption reduction of up to about 7% was possible. The NO_x / particulate trade-off was comparable to the baseline calibration. Although not the main focus of this strategy, CO and HC emissions were also slightly improved. However, the engine noise increased by 1 to 1.5 dB(A) depending on the NO_x emissions level

The improvement of fuel economy was also the aim of strategy C. However, with the additional constraint that engine noise was limited to or below the base calibration. This limitation at the higher EGR rates led to a reduction in the specific fuel consumption of ~2%. There was a concomitant reduction in engine noise of 2 dB(A). The emissions performance was not affected.

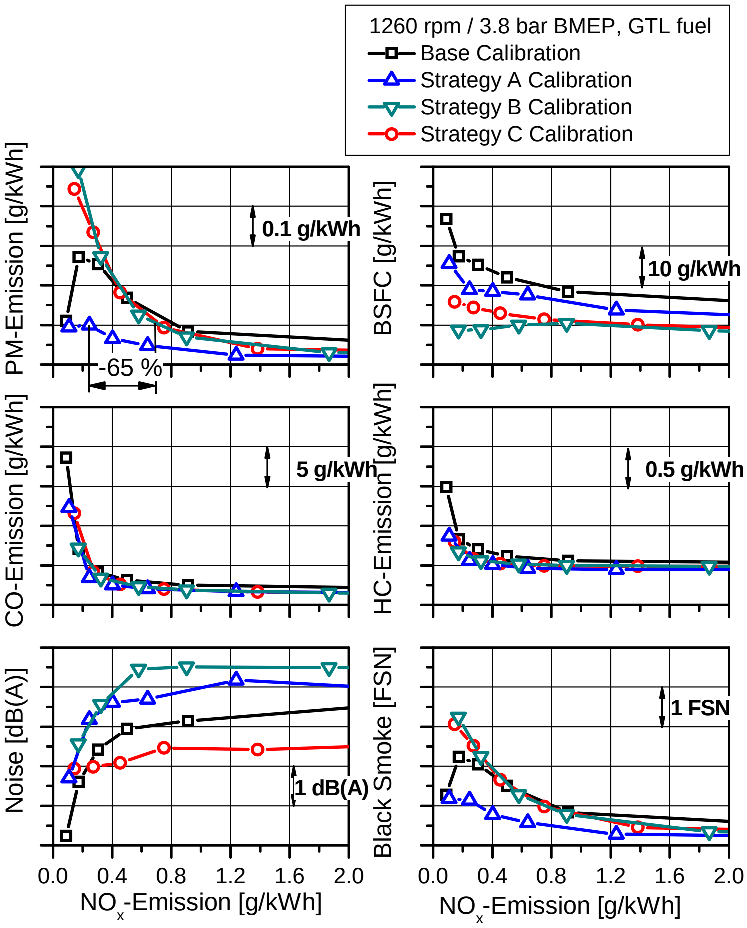

Figure 6: EGR variations with optimized calibration, 1260 rpm / 3.8 bar BMEP

<u>Key findings</u>

- With GTL fuel used in the baseline calibration, there was a substantial reduction of the engine emissions compared with conventional diesel fuel. Emissions reductions were in the following ranges: 30% to 55% for

PM, 10% to 40% for CO, and 20% to 40% for HC. Within the main part of the engine map, the engine noise level remained the same as with conventional diesel. The fuel consumption was near identical for both fuels

- Further significant improvements can be obtained for GTL fuel via a suitable recalibration of the ECU software. For the optimization goal of NO_x reduction, then an improved NO_x-PM trade-off curve was possible, equivalent to a PM engine out emissions reduction of up to 70%. The strategy of minimized fuel consumption realized benefits up to 7%. Adding to this recalibration the further constraint of the same noise level, resulted in the same emissions advantage, and a fuel consumption benefit of 5%.

VEHICLE TESTING

Investigation with baseline calibration

The test results for the base calibration are illustrated in Figure 7. The GTL fuel values are shown relative to those obtained with diesel fuel.

The vehicle testing with the base calibration fully confirmed the emissions reduction potential observed in the test bench investigations. Particulate emissions were reduced by 37% in the NEDC by usage of GTL fuel. CO emissions were lowered by 61%, HC was improved by 47%. NO_x emissions were increased by 2%. General experience is that GTL fuel gives a small NO_x benefit of ~5% in light-duty vehicles. The small difference observed here may have resulted from minor perturbation in EGR rates [13]. Due to the lower density of GTL fuel, the volumetric fuel consumption was 4.7% higher. Nevertheless the CO_2 emissions were 2% lower due to the lower C-content of GTL fuel.

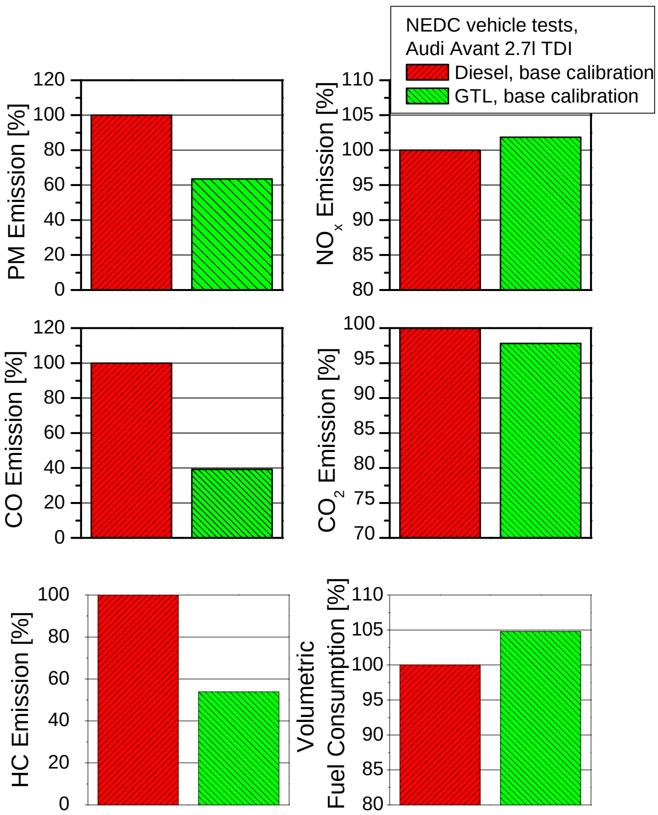

Figure 7: NEDC results with Diesel and GTL fuel with base calibration

Optimization of calibration

The modified engine maps, obtained from the steady state test bench optimization, were transferred to the vehicle. This was then tested on the roller dyno. Based on these results, there was further fine-tuning of the engine maps. The final results for each of the three strategies are illustrated in Figure 8.

With strategy A, a remarkable NO_x reduction of 52% was achieved, simultaneously there was an acceptable slight increase of the CO and particulate emissions of about 7% when compared to diesel. Moreover, the fuel consumption was significantly reduced compared to baseline calibration, resulting in a CO_2 benefit of 8.5%

The optimization from strategy B led to a significant improvement in the volumetric fuel consumption of about 7.5% when compared to the baseline with GTL fuel. Thus, any slight efficiency disadvantage of GTL fuel (relative to diesel) in the baseline calibration is more than compensated. Finally, in comparison to the baseline on diesel, the volumetric fuel consumption of GTL fuel was approximately 3% lower and CO_2 emissions show a 10% reduction. This final result is all the more remarkable, since it was obtained in parallel with NOx reductions of 24% and particulate reductions of 30%.

The additional noise constraint to the level of the base calibration (strategy C) led to a fuel penalty of less than 2%-points in comparison with strategy B. Nevertheless, even with this additional constraint, there still remained a benefit of approximately 1% for the volumetric fuel consumption of GTL fuel versus diesel, and consequently a CO_2 benefit of 7%.

Additional acoustic measurements have shown that the calibrations for strategies B and C were indistinguishable in terms of engine noise level within the vehicle cabin, even though the strategy B optimization was performed without a noise constraint. However, measurements inside the engine compartment indicated slight changes of the engine sound quality. Despite the comparable interior noise levels, the calibration changes resulting from strategy B clearly have led to a deterioration of the sound quality, which would be borderline with respect to the requirements of a premium car manufacturer.

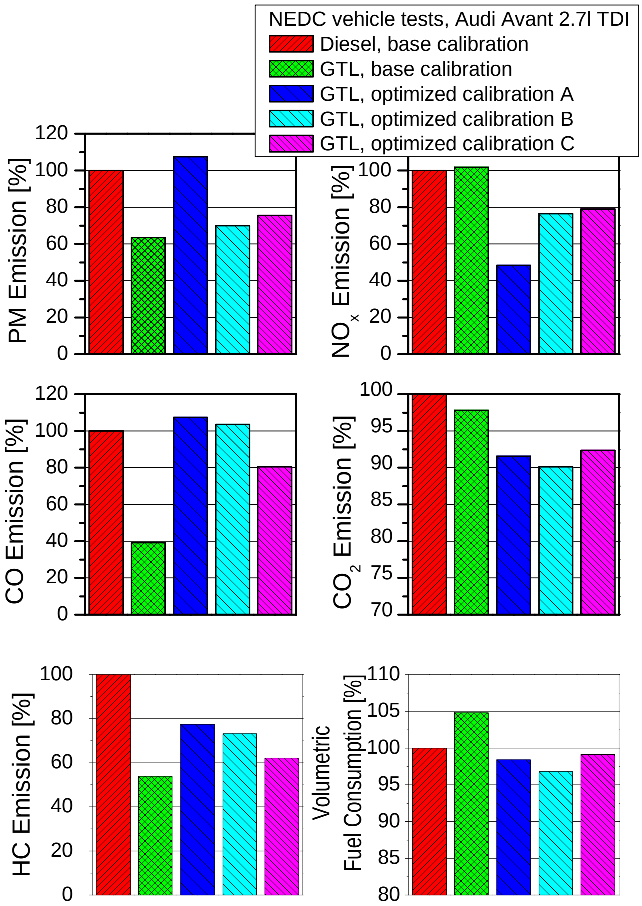

Figure 8: NEDC results with Diesel and GTL fuel with optimized calibrations

<u>Key findings</u>

- These vehicle investigations have confirmed the significant emissions reduction potential of GTL fuel that were already observed during the steady-state test bench operation.
- With baseline calibration, GTL fuel offers a significant emissions reduction, specifically for smoke, HC and CO emissions. A small NOx-penalty was observed, as opposed to the expected small benefit seen in previous investigations.
- GTL fuel’s full potential to improve NOx emissions was demonstrated with a 52% reduction in the NEDC.
- A significant improvement in fuel consumption could be realized, when the engine calibration was optimized to minimum fuel consumption. This resulted in a 10% benefit for CO_2 emissions.

DISCUSSION

IMPLICATIONS FOR EMISSIONS

Even without any recalibration of the ECU software, GTL fuel already offers a significant potential for emissions reductions.

Combining GTL fuel with a suitable software re-calibration (strategy B) enables simultaneous reductions of particulate, NO_x, CO and HC emissions, even though the actual focus of this optimization was the reduction of fuel consumption. Moreover, it was still possible to stay below the EU5 NO_x limits as illustrated in Figure 9.

In addition, the use of the strategy A calibration gives the possibility of a significant NO_x emissions reduction, while at the same time maintaining all other emissions at the diesel level. Thus, GTL fuel offers the potential to reach EU6 emissions in tandem with cost effective lean NO_x reduction technology, having relatively low efficiency.

For both strategies, CO_2 emissions were significantly lower than with conventional diesel as illustrated in Figure 10.

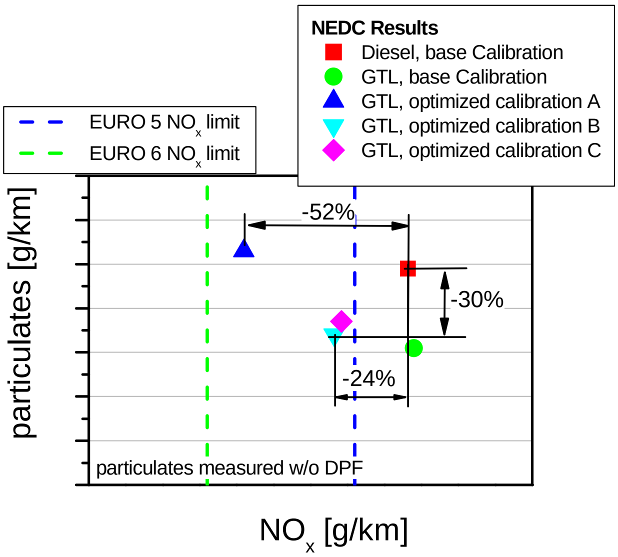

Figure 9: NO_x / particulate results of NEDC vehicle testing

IMPLICATIONS FOR FUEL CONSUMPTION

The vehicle tests demonstrated that CO_2 emissions can be reduced by 10% with GTL fuel in conjunction with an adequate software recalibration. The implication is that GTL fuel offers a very cost effective and significant potential for tailpipe greenhouse gas emission reduction. For a full evaluation of this scenario, it should be borne in mind that there was a parallel reduction in NOx emissions of 24%, but the noise quality as well as the noise levels were (slightly) increased. In addition, a slight increase in PM emissions was noted.

In terms of the customer's acceptance of GTL fuel, the observed reduction in volumetric fuel consumption is key. The initial downside in volumetric fuel consumption for GTL fuel was more than compensated by the recalibration measures, such that GTL fuel eventually gives a 3% advantage.

However, this gain is slightly reduced when the engine noise requirements (both quality and level) of a premium OEM are taken into account. This additional constraint from engine noise leads to an increase of volumetric fuel consumption of 2.5%, but nevertheless the fuel consumption remains slightly less than the baseline calibration.

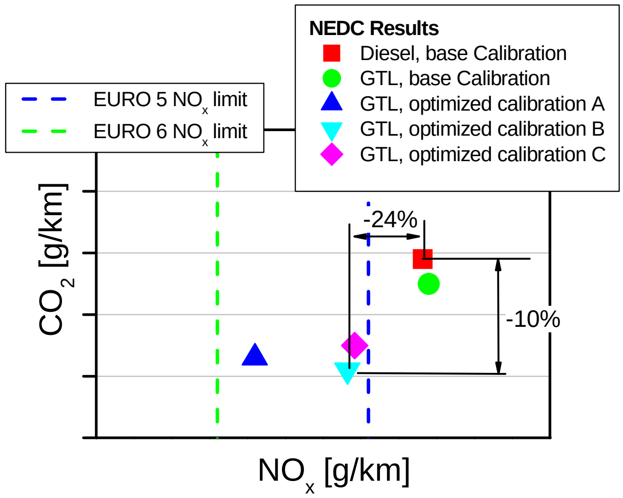

Figure 10: CO_2/NO_x emissions results of NEDC vehicle testing

Another effect that has an impact on fuel consumption is via the achieved reduction of particulate emissions: For example, the BSFC optimized calibration shows PM emissions could be lowered by 30%. Such a reduction could affect the performance of the DPF system. The average DPF back-pressure could be reduced and the time-interval between regeneration events stretched. Both these factors would result in further benefits for fuel consumption.

In interpreting the current results it needs to be borne in mind that the observed potential of an optimized vehicle is based on a demonstration calibration level. When considering the possibility of an actual serial application then a slight deterioration in the optimization potential might be expected. This would be due to a number of factors such as vehicle lifetime emission stabilities and manufacturing tolerances of the different parts.

IMPLICATIONS FOR FURTHER WORK

In the current study, NO_x emissions were reduced substantially below the EU5 engineering targets via a combination of GTL fuel and modification of the ECU software calibration, yet remaining with a series EU4 engine. The next logical step is to adapt the engine hardware to the characteristics of GTL fuel, in addition to software adaptation. The main focus of this hardware modification will be yet further reductions in NOx emissions, while maintaining all other emission improvements.

The high cetane number of GTL fuel would suggest that a first step might be the lowering in compression ratio. This is well known as having a positive impact on NOx reduction. Essentially, the lower compression ratio leads to lower cylinder peak pressure, which in turn results in reduced peak combustion temperatures and thereby a lower NO_x formation ratio. Moreover, the increased bowl volume enables a higher free spray length and thereby an improved mixing of air and fuel.

An important limitation on the lowering of the compression ratio is the need to satisfy cold start performance. However, because of the significantly higher cetane number of GTL fuel compared to diesel fuel, then it is expected to give improved cold start behavior. Thus it is anticipated that this hardware route would be feasible for GTL fuel.

Another factor to be addressed in the hardware project will be the reduction of the hydraulic flow rate of the injectors. At part load, this measure would lead to an improvement in mixture formation, and thus a reduction of emissions, especially particulate emissons. At full load, such a reduction in hydraulic flow rate would be expected to increase smoke emissions. However, the intrinsically low particulate emissions of GTL fuel will allow for greater flow reductions than with diesel fuel.

One final goal would be the adaption of the DPF regeneration calibration to GTL fuel. Strategies B and C have already shown that a particulate emissions reduction of 30% is achievable. This could be exploited via stretched regeneration intervals, which have an impact on reducing fuel consumption. In addition, this might offset the fuel consumption penalty of strategy C (versus strategy B), which arose because of the additional noise constraint.

CONCLUSIONS

A study has been conducted, which has enabled the assessment of the full potential of GTL fuel within a dedicated engine calibration. From an assessment of three different optimization goals (A) Minimization of NO_x emissions, (B) Minimization of fuel consumption and (C) Minimization of fuel consumption without increasing noise we conclude:

- GTL fuel has market potential both neat or in blends with conventional diesel. Neat GTL fuel offers substantial emissions advantages in existing engines and by engine optimization there is the opportunity to achieve the maximum potential of such fuels.

- For this study, the experimental setup included both bench engine tests as well as vehicle tests and NEDC measurements on the chassis dynamometer. First, a baseline comparison was performed between GTL fuel and standard European diesel. Secondly, the calibration was optimized using DoE methods to meet the goals described above.

- Using the baseline calibration, GTL fuel gave emissions reductions of 30-55% for PM, 10-40% for CO and 20-40% for HC. However, a small increase in NOx emissions of 2% was observed.

- Optimizing the calibration according to strategy A minimized the NO_x emissions, resulting in a reduction of up to 52%. Simultaneously, the HC and CO_2 emissions remained significantly below the levels observed with conventional diesel. Thus EU 5 emissions levels were achieved.

- With strategy B, the fuel consumption was minimized and yielded a reduction in TtW CO_2 emissions of 10%. Despite the focus on fuel consumption, all other emissions were also reduced in comparison with those achieved with diesel. Moreover, the reduction of PM emissions offers a further fuel consumption and CO_2 advantage via increased regeneration intervals of the DPF.

- When the boundary conditions were set to ensure noise was kept to the original level (strategy C), there still remained a TtW CO_2 emissions reduction of 7.5%.

- This successful optimization of the engine’s calibration has clearly indicated that the next logical step should be the additional adaption of the engine hardware. The high cetane number of GTL fuel suggests that further emissions benefits may be achieved with lowering the compression ratio. Also the inherent PM emissions reduction potential of GTL fuel would imply that injectors with lower hydraulic flow rate may be utilized to lower NO_x emissions even further.

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ABBREVIATIONS

BSFC Brake specific fuel consumption
BMEP Brake mean effective pressure
CO Carbon monoxide
CO_2 Carbon dioxide
DOC Diesel oxidation catalyst
DoE Design of experiment
DPF Diesel particulate filter

ECU	Electronic control unit
EGR	Exhaust gas recirculation
GTL	Gas-To-Liquids
NEDC	New European driving cycle
NO_x	Nitrogen oxide
PM	Particulate matter
HC	Hydrocarbons
TtW	Tank to wheel
T_2'	inlet air temperature in the intake plenum