

Dedicated GTL Vehicle: A Calibration Optimization Study

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Michael Kind
FEV Motorentechnik GmbH

Dorothea Liebig
Shell Global Solutions (Deutschland) GmbH

Rene Van Doorn
AUDI AG

Matthias Lamping
FEV Motorentechnik GmbH

Andrew Harrison and Richard Clark
Shell Global Solutions UK

Andreas Kolbeck
FEV Motorentechnik GmbH

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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 CO₂ 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 CO₂ output. The two routes to reduce local emissions are re-designing the engine and adding after-treatment devices. For reduction of CO₂ 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.

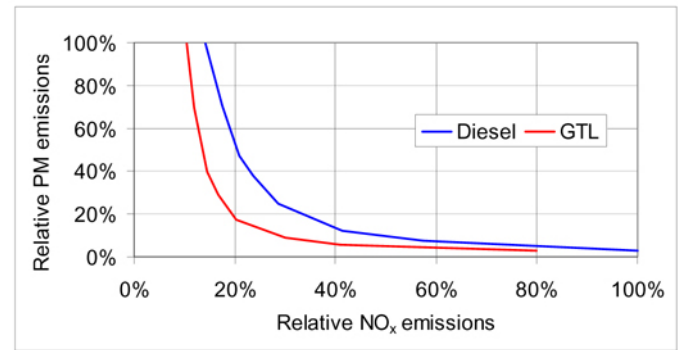


Figure 1. Typical improvement of the PM-NO_x trade-off curve with GTL fuel in a non-adapted engine

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 °C)	kg/m ³	830	775
Viscosity (40 °C)	mm ² /s	2.9	2.45
Cetane Number CFR	-	56	> 70
IBP	°C	170	200
FBP	°C	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	42.9	44.0
	MJ/l	35.6	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 CO₂ 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 dynamometer by NEDC vehicle tests.