

Heavily Downsized Demonstrator Engine Optimised for CNG Operation

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ABSTRACT

The complexity of modern powertrain development is demonstrated by the combination of requirements to meet future emission regulations and test procedures such as Real Driving Emissions (RDE), reduction of fuel consumption and CO₂ emissions as well as customer expectations for good driving performance. Gasoline engine downsizing is already established as a proven technology to reduce automotive fleet CO₂ emissions. Additionally, alternative fuels such as natural gas, offer the potential to significantly reduce both tailpipe CO₂ and other regulated exhaust gas emissions without compromising driving performance and driving range.

This paper presents results showing how the positive fuel properties of natural gas can be fully utilised in a heavily downsized engine. The engine has been modified to cope with the significantly higher mechanical and thermal loads when operating at high specific outputs on compressed natural gas (CNG). In this study, peak cylinder pressures of up to 180 bar and specific power output levels of 110 kW/litre have been realised. It is also shown that having cylinder components specific to natural gas can yield significant reductions in fuel consumption, and, in conjunction with a variable geometry turbine, a port-fuelled CNG engine can achieve impressive low-speed torque (27 bar BMEP at 1500 rpm) and good transient response characteristics.

The results achieved from the test engine whilst operating on CNG are compared to measurements from the baseline, gasoline-fueled, direct injection (GDI) engine. The potential CO₂ savings offered by this heavily downsized CNG engine, of up to 50% at peak power and 20-40% for the drive-cycle region (including real driving emissions (RDE) testing), are presented and discussed.

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1. INTRODUCTION

Between 1990 and 2011, the total CO₂ emissions from road transport have increased by 21 % [1]. Greenhouse gas emissions of the transport sector are still increasing, and this figure is predicted to grow further during the coming years [2], driven by the rapidly expanding global vehicle fleet which is anticipated to increase by over 63 % during the next 20 years [3]. For this reason, world-wide automobile development effort is keenly focused on measures to reduce the CO₂ output of vehicles.

The vehicle CO₂ values established via type-approval testing form a basis for consumer information, CO₂ regulation, and CO₂-based vehicle taxation [4]. In order to bridge the gap between current type approval and real-world results, as well as align the various approaches used across the globe, the worldwide harmonized light vehicles test procedure (WLTP) is being developed and is anticipated to replace the new European drive cycle (NEDC) in Europe after 2017 [5].

Gasoline engine downsizing is already established as a proven technology to reduce automotive fleet CO₂ emissions. Further benefits are possible through more aggressive downsizing, however, the trade-off between the CO₂ reduction achieved and vehicle drive-ability limits the level of engine downsizing currently adopted [6].

The ability to maintain or increase the level of engine downsizing, while retaining good fuel efficiency across the majority of the engine operating map, would provide manufacturers with a transferable, and scalable, means for assisting in meeting these stringent new CO₂ targets across their entire fleet. CNG, is with more than 20 million vehicles currently the most common alternative fuel to diesel fuel and gasoline and consists mainly of methane, CH₄ [7]. Even when from fossil origin, purely because of its high H/C ratio, it can theoretically provide a reduction of around 25% CO₂ during vehicle operation compared to fossil diesel fuel or gasoline [6, 7].

This paper presents results from a 1.2 litre, 3-cylinder engine which has been re-optimised for operation using CNG as the primary fuel. The specific characteristics of CNG combustion have been considered and the engine components redesigned to better utilise the properties of the fuel. Results are presented from engine tests and compared to a version of the same engine, which has been comparably optimised for gasoline-fuelled operation. Engine tests were carried out at MAHLE Powetrain in Northampton, UK.

2. CNG FUEL PROPERTIES

Natural gas, as an alternative to gasoline, offers specific benefits due to its higher knock resistance, H/C ratio and specific energy content (Table 1).

Table 1. Comparison of Natural Gas and Gasoline properties [8, 9]

	Natural Gas	Gasoline
H/C Ratio	3.9:1	2.0:1
Specific energy content	46.5 MJ/kg	43 MJ/kg
Octane number	>120	95
Density	0.79 kg/m ³	730 kg/m ³

Methane, the prime constituent of natural gas, provides a theoretical CO₂ advantage of as much as 26% as a result of the higher H/C ratio and specific energy content. Supplied natural gas from a national grid contains slightly lower methane content of typically 90-95%, which reduces the theoretical benefit to around 20%. Further CO₂ improvements may be possible through fuel consumption reductions enabled by the higher knock resistance, which could lead to less compromised combustion phasing and greater thermal efficiency at high loads. A higher compression ratio (CR) may also be enabled by these same characteristics, further improving efficiency.

The gaseous nature of the fuel can also provide theoretical emissions benefits, especially when considering particulate matter. This is due to the lack of liquid fuel droplets in the charge air, which is a significant source for particulate formation. The highly homogeneous air fuel mixture achievable with gaseous fuels also assists the consistency of combustion across the chamber. It should also be noted, however, that methane has 21 times higher Global Warming Potential (GWP) than CO₂ (1kg of methane causes 21 times more warming over a 100 year period compared to 1 kg of CO₂) [10]. This means that unburned or escaped methane (methane slip) that gets into the atmosphere may offset the benefits already described. This effect can be mitigated in combustion engines through valve timing optimisation and use of a three-way catalyst. These aspects are investigated during this study and discussed in more detail in later sections.

Natural gas has a low density due to its gaseous nature and therefore a high volume of fuel is required to achieve a stoichiometric mixture relative to liquid gasoline. If CNG is injected into the intake ports, or

even further upstream, the volumetric efficiency of the engine will be reduced due to the air volume displacement effect and engine performance will reduce proportionally. This can be compensated with elevated boost levels, but this is not without disadvantages. The gaseous fuel also needs to be stored at elevated pressures (typically around 200 bar), which requires the use of high pressure storage tanks. These can be challenging to package on a passenger vehicle and add extra mass when compared to gasoline storage tanks providing a similar driving range.

Storing the gas at high pressures also leads to some challenges when regulating the high pressure down to the desired injection pressures (typically 5-10 bar G for port injection). To achieve this, the gas must be expanded through a high pressure ratio, which results in a decrease in the gas temperature, even to below 0° C under some conditions (high fuel flow rates and high tank pressures). This can bring challenges in the design of the pressure regulators to provide the consistent control behaviour needed to achieve stable fuel rail pressures. These issues can result in restrictions in the minimum operating temperature of the engines when using CNG. It is common to restrict the operation of the engines at cold starting temperatures until the engine coolant has warmed, as this is used to warm the gas regulator valve. An example of this is the VW Golf 1.4TSI Bluemotion CNG [11], which will start using the gasoline back-up fuel tank at temperatures below -10°C. It is therefore common for CNG equipped vehicles to also have an on-board secondary gasoline fuel system for cold starting.

3. MAHLE DI3 TEST ENGINE

The engine used throughout this study is the MAHLE Di3 1.2L, 3 cylinder downsized engine. This engine has been the focus of previous papers [12-13] and has, thus far, been configured as a gasoline fuelled, direct injected, turbocharged unit. Single and twin boosted variants have been developed with power outputs ranging from 120 to 190 kW. All gasoline variants have a minimum of 30 bar BMEP, with up to 35 bar BMEP being achieved in the highest specification variant [14].



Fig. 1. MAHLE CNG Di3 engine installed in a demonstrator vehicle

For this study, the engine was adapted to run with CNG as the primary fuel. This was done in two development stages, the initial stage saw the application of a Port Fuel Injection (PFI) CNG system to the engine, whilst retaining the standard Gasoline Direct Injection (GDI) system for gasoline backup. The original power cell unit (PCU) was used, which has a maximum in-cylinder pressure capability of 125 bar. During gasoline operation, this is rarely a practical limitation, even in the highest specific output variants of the engine. It was found, however, that the cylinder pressure limit became a restriction to performance when running on CNG. The 125 bar pressure limit restricted engine BMEP output to 24 bar. The gasoline injectors also became a limiting factor when not in use during CNG operation. Without the cooling effect of the gasoline flowing through them, the temperature of the injectors, especially at the tip seals, became too high and power output was restricted to 108 kW (against a target of 120 kW) to keep the injector temperature within critical limits.

Table 2. Comparison of the specification of engines used during this study

	Gasoline Baseline	CNG Baseline	CNG Optimised
Engine layout	3 cylinder in-line		
Displacement	1200 cc		
Bore/Stroke	83.0 / 73.9 mm		
Compression ratio	11.3:1	12.5:1	13.3:1
Fuel system	Gasoline DI	CNG PFI & Gasoline DI	CNG PFI
Nominal Power	120 kW	108 kW	120-130 kW
Nominal Torque	286 Nm (30 bar BMEP)	231 Nm (24 bar BMEP)	286Nm (30 bar BMEP)
Max. allowable Cylinder Pressure	125 bar	125 bar	180 bar
Turbocharger	BMTS WG-TC	BMTS WG-TC	BMTS WG-TC / BMTS VTG-TC

Based on the experience gained during this initial investigation, MAHLE re-optimised certain engine components to increase the maximum allowable cylinder pressure to 180 bar, which is more in line with diesel engine technology than typical current production gasoline engines. Unlike diesel engines, the combustion characteristics of a gasoline or CNG engine do not prevent operation at high engine speeds. Automotive diesel engines are typically restricted to maximum operating speeds of 5000 rpm, with many achieving peak power at lower speeds (4000-4500 rpm). The CNG version of the Di3 engine can run at speeds of up to 6500 rpm, enabling a high specific power output (100 kW/L). For this “CNG optimised” variant, the drillings for the GDI injectors were left

unmachined, and port injected CNG was employed as the primary fuel system. A back-up gasoline PFI system was also added, but this has a limited performance envelope due to the very high CR of 13.3:1, which was selected for best part load efficiency and was enabled by the very high knock resistance properties of CNG.

The CNG optimised engine was initially tested using the same specification of wastegate turbocharger (WG-TC) used on the single-turbo gasoline version of the engine, which is supplied by Bosch MAHLE Turbo Systems (BMTS). The same company also provided a prototype high temperature Variable Turbine Geometry turbocharger (VTG-TC) with the aim of realising improvements to low speed torque. The detail of the changes made for the CNG optimised engine components are now discussed in detail. The “CNG Baseline” engine and the “CNG Optimised” engine are compared to a gasoline variant of the same Di3 engine (“Gasoline Baseline”) to enable an assessment of the advantageous properties of CNG. The engine specifications are summarised in Table 2.

4. COMPONENT ADAPTATION FOR THE CNG OPTIMISED ENGINE

The particular characteristics of CNG lead to some requirements and opportunities to adapt the design of a spark-ignition gasoline engine for CNG operation. Some changes are required for functional and durability reasons and other changes can optionally be made to enable the CNG benefits to be accessed fully.

Port Fuel Injection and Valve Timing

The fuel injection system of the engine must be adapted or replaced to enable CNG operation. Most commonly, PFI systems are used with a supply pressure of between 5 and 10 bar G. Engines and vehicles are in series production with this solution and the injector technology is similar to common gasoline port injection hardware. As already mentioned, this results in a significant intake air displacement effect because of the low density of CNG. The intake air and the CNG must both flow through the intake port, leading to higher boost pressure requirements. This may require the re-matching and re-specification of the turbocharger or a small reduction in engine performance. MAHLE has tested an engine with this configuration and it was found that additional boost pressure of between 0.1 and 0.2 bar is required at high load conditions to maintain the same brake torque output.

When using port fuel injection of CNG it is also necessary to operate without exhaust to intake valve timing overlap. Utilising overlap can result in stronger low speed torque and improve run-up line performance; however unburned fuel will be passed through into the exhaust system. This unburned fuel cannot always be removed completely by a three way catalyst if flowing in sufficiently high quantities or when the catalyst is not yet up to operating temperature. As already mentioned, CNG has a high GWP and this “methane-slip” effect must be avoided for environmental and legislative reasons.

The testing conducted on the CNG engine variants show the effect of the removal of exhaust valve overlap on low speed torque output relative to the gasoline variant operating with higher levels of overlap. Figure 2 shows that this can displace the low speed torque

run-up line by as much as 500-700 rpm. This magnitude of low speed torque reduction will result in degradation in vehicle driveability and, in conjunction with significant engine downsizing, can cause issue with vehicle pull away in high kerb weight applications.

It is possible to mitigate the negative effects of the removal of overlap by the adoption of more advanced boosting and fuelling technologies. These are discussed in more detail later, but all are likely to increase the cost of the engine hardware.

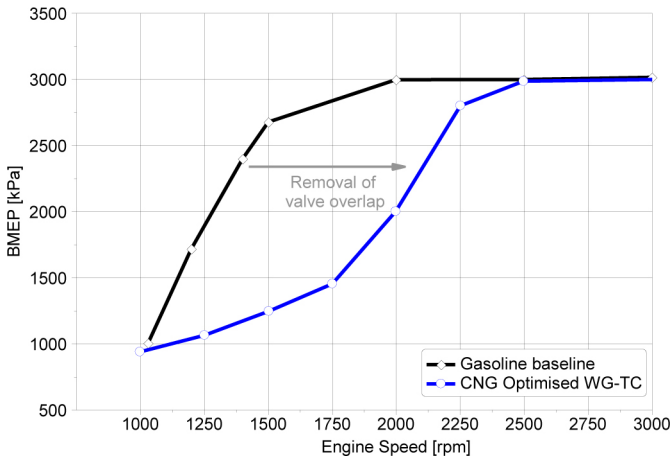


Fig. 2. Comparison of low speed torque output of Gasoline baseline and CNG optimised engines with WG-TC, showing the effect of removing valve overlap for cylinder scavenging

Overfuelling

In gasoline-fuelled engines, it is possible to achieve an exhaust gas cooling effect by injecting a rich fuel mixture, which absorbs combustion gas heat when the excess liquid gasoline evaporates and changes phase to a gaseous state. This results in higher unburned hydrocarbon emissions, but the positive effect is to lower the temperature of the exhaust gas. This technique is commonly used in gasoline engines at high power outputs to keep exhaust valves, manifold and turbocharger temperatures within the limits required for durability. This usually occurs outside of the normal driving region, certainly outside of those measured using current legislative test procedures. As a result of the recent recommendations to move to real driving emissions (RDE) testing however, the over-fuelling region is likely to become of higher relevance, especially in highly downsized engines and emissions under these conditions will need to be controlled more tightly. Exhaust Gas Recirculation (EGR) [15] and water injection [16] are examples of technologies that can be used on gasoline engines to reduce the need for overfuelling, but additional boost pressure is required to drive EGR at high load and both systems will add cost.

Unlike gasoline, CNG is already in gaseous form and as such, no phase change can occur and little cooling effect can be achieved by running with a richer mixture. This means that the entire engine operating region can be run with an equivalence ratio of one. It has been found, during MAHLE's testing, that the combustion end-gas temperature is typically lower than with gasoline combustion (see Figure 3). This is thought to be due to the combination of high compression ratio, and therefore expansion ratio, and relatively advanced combustion phasing.

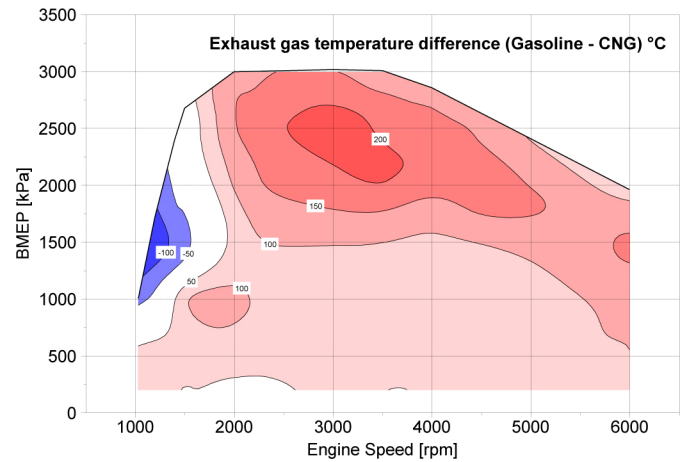


Fig. 3. Comparison of exhaust gas temperatures of Gasoline relative to CNG optimized engine

In addition, whilst exhaust gas lambda for the CNG engine is always one, the gasoline engine utilizes a rich mixture for component protection, as shown in fig 4. Without this, CNG exhaust gas temperatures would be cooler still by comparison.

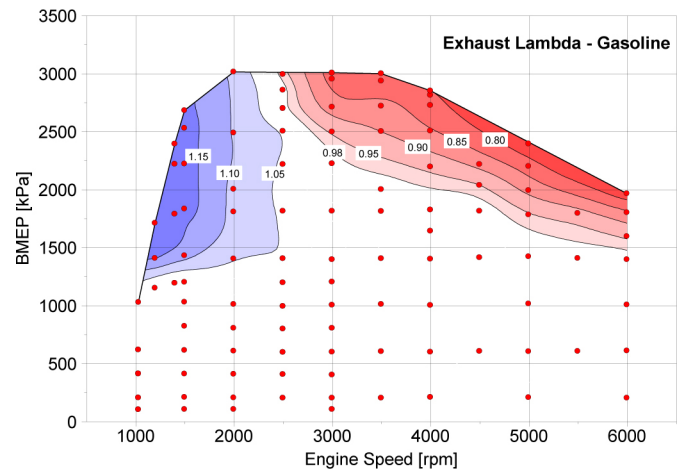


Fig. 4. Measured exhaust lambda for the gasoline engine variant

Combustion Pressures

CNG combustion is typically less retarded at high loads than gasoline and has a faster initial rate of combustion under these conditions. These factors combined lead to significantly higher in-cylinder pressures and temperatures than with gasoline combustion at the same MEP. If the engine is not able to cope with these conditions, then the torque output of the engine will be lower as the maximum cylinder pressure limit will be reached at a lower brake output. From MAHLE's experience with the Di3 engine, if the gasoline Pmax limit of 125 bar is maintained then a peak BMEP of 24 bar is achieved (relative to the gasoline performance of 30 bar BMEP using the same Pmax limit). Re-optimising for higher cylinder pressures, in this case up to 180 bar Pmax, enables 30 bar BMEP performance to be achieved using CNG whilst maintaining combustion efficiency.

To enable reliable operation at such high cylinder pressures, it was necessary to redesign the piston, pin, rings, connecting rod and bearings. The Di3 base engine was converted through the use of