

Heavily Downsized Gasoline Demonstrator

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ABSTRACT

Gasoline engine downsizing is already established as a proven technology to reduce automotive fleet CO₂ emissions by as much as 25 %. 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. This paper presents results showing the benefits of adding an eSupercharger to a very heavily downsized engine. Measurements are presented from a 1.2 litre, 3-cylinder, engine fitted with an eSupercharger in addition to a conventional turbocharger.

The original MAHLE downsizing engine has been re-configured to enable a specific power output that exceeds 160 kW/litre. Of key importance is a cost effective, efficient and flexible boosting system. The Aeristech eSupercharger, operating at 48 V, enables the transient response and low speed torque to be more than recovered, enabling both very high specific output and specific torque characteristic with excellent transient response and drive-ability characteristics, clearly demonstrating eSupercharging as a key technology for enabling further engine downsizing.

The resulting heavily downsized engine is to be installed into a demonstrator vehicle. The vehicle will feature an advanced 48 V lead-carbon battery pack and a 48 V belt-integrated starter generator (BiSG). The battery and BiSG have been selected to enable the continuous high-output (>6 kW) operation of the eSupercharger to support prolonged operation of the engine at low-speed and high-torque output. The 48 V architecture also enables the use of electrical machines and energy storage systems to reduce drive-cycle CO₂ through the recuperation of energy during deceleration events.

The eSupercharging concept described in this paper also provides the potential to enable greater ability to operate with low levels of valve overlap, to help minimise emissions at low engine speeds. The resulting engine layout achieves 193 kW from a 1.2 litre swept volume and 317 Nm torque is available from 1250 min⁻¹, whilst excellent fuel economy and drivability characteristics are retained.

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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.

On a total fleet basis, manufacturers have made significant improvements to reduce type-approval emissions figures by almost 20 %, from 164.9 g/km in 2007 to 133.1 g/km in 2012 [4]. However, in a recent study, Mock *et al.* [5] analysed data gathered from real world driving and compared the reported fuel consumption to the

type-approval value. This analysis revealed that while the average discrepancy between type-approval and on-road CO₂ emissions was below 10 % in 2001, by 2011 it had increased to around 25 %. Several reasons were discussed for this, including the trend for downsizing which was purported to allow tangible reductions in fuel consumption at light loads, but could lead to a worsening of fuel consumption under higher load conditions.

The vehicle CO₂ values established via type-approval testing form a basis for consumer information, CO₂ regulation, and CO₂-based vehicle taxation [6]. 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 [7]. The fleet average emissions levels in the EU are due to

severely over the coming years and by 2019 manufacturers will have to pay an excess emissions premium for each car registered of €95 for each g/km that they are over the fleet target [7].

The ability to 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.

This paper presents results from a 1.2 litre, 3-cylinder, engine fitted with an eSupercharger in addition to a conventional turbocharger. The results show the potential of eSupercharging as a technology enabler for extreme engine downsizing. Engine structural durability considerations and the potential for further CO₂ reductions via 48 V micro-hybridisation and system control are also discussed.

2. EFFICIENT DOWNSIZING

Gasoline engine downsizing has long been recognised as an effective technology for engine CO₂ reduction [8, 9, 10] and is firmly established as a technology for assisting in achieving fleet CO₂ reduction targets. Gasoline engine downsizing is the process whereby the engine operating load point is shifted to a higher, more efficient region, through the reduction of engine swept volume, whilst maintaining the full load performance of the original engine, via pressure charging.

Further improvements in fuel economy have been shown to be possible through increased levels of engine downsizing [8, 9, 10, 11, 12, 13]. However, as specific output increases so too do the technical challenges, these include:

- A robust combustion system that allows a high compression ratio to maintain part load efficiency, with minimal requirement for over-fuelling to maintain safe exhaust gas temperatures
- Good low speed torque and transient performance
- Fuel consumption benefits achievable over a wide range of driving styles and road characteristics
- Base engine robustness and durability

An estimation of effect of engine downsizing upon drive-cycle fuel economy over the NEDC, for the case of a 3.2 litre naturally aspirated D-segment vehicle, is shown in Figure 1. The analysis results presented in Figure 1 have been based on data taken from the MAHLE Downsizing Demonstrator vehicle [14]. In Figure 1 the degree of downsizing is defined as

$$\text{Degree of downsizing} = \frac{(SV_0 - SV_{DS})}{SV_0} \quad (1)$$

Where SV_0 represents the swept volume of the original engine and SV_{DS} represents the swept volume of the downsized engine that it is being replaced by.

It can be seen that as the degree of downsizing of the engine increases, the specific power output and brake mean effective pressure (BMEP) required to maintain equivalent performance to that of the original engine increases drastically. Mass market current production engines do not have specific outputs of more than 120 kW/litre or 24 bar BMEP (50 % downsizing in Figure 1), as to go beyond this point and retain acceptable transient performance would require complex multi-stage charging systems. There are an increasing number of production engines that do exceed these values with a single turbocharger, for example the Mercedes AMG A45 [15] which achieves 140 kW/litre, or the BMW i8 [16] which achieves almost 27 bar BMEP, however, these are not mainstream products and rely either on semi-automatic transmissions or significant hybrid motor assist, to maintain acceptable low speed driveability and transient response characteristics.

The "downsizing effect" in Figure 1 shows how the drive-cycle fuel consumption would reduce purely by reducing the swept volume of the engine. This curve can be seen to plateau beyond 75 % degree of downsizing, which is brought about by the fact that at this level of downsizing the bulk of the engine operation has been raised into the peak efficiency region of the engine operating map. Further downsizing will begin to move the higher load cycle operating beyond the peak efficiency region of the engine map.

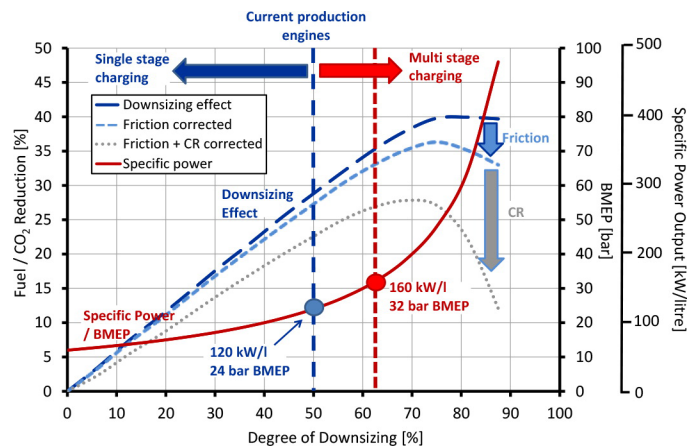


Figure 1. Impact of advanced degrees of downsizing (based on analysis of a 3.2 litre naturally aspirated engine in a D-segment vehicle, over the NEDC).

However, as the level of downsizing of the engine is increased the relative sizes of the bearings have to be increased to cope with the higher specific output of the engine, leading to an increased influence of engine friction on the engines brake specific fuel consumption (BSFC). This effect causes the estimated effect of the CO₂ reduction for the "friction corrected" case, for the example depicted in Figure 1, to peak at around 75 % downsizing.

The benefits of downsizing are further degraded due to the reduction in the compression ratio (CR) of the engine to achieve the high level of specific power and BMEP required for maintaining equivalent performance to that of the original engine. When this is also taken into consideration, it can be seen that the resulting CO₂ reduction effect beyond ~60% downsizing is less pronounced and peaks at ~70 % downsizing. It should be stressed that the results shown in Figure 1 represent an estimate based on a specific case and could vary

significantly for different vehicles, engine technologies and drive-cycles. It does indicate, however, that further benefits can be achieved beyond the 120 kW/l downsizing demonstrator already successfully trialled [14], without a CO₂ penalty, up to specific power levels of around 160 kW/l. Even towards this 160 kW/l target, drivability limitations restrict manufacturers' progress. Instantly available, high pressure charge air, available across the entire engine operating range, is essential to overcome these limitations, alongside other specific measures to maintain high-load efficiency. Even for engines below the notional 160 kW/l inflection point of efficiency, the advanced boosting systems discussed in this paper have the potential to recycle energy otherwise wasted across real-world drive cycles. They may also introduce more flexibility for engine charging that can aid in minimising the engine-out emissions (for example, using boosted air to offset the lack of low speed intake air scavenging).

2.1. MAHLE Downsizing Demonstrator

In order to conduct research into the requirements for advanced downsizing engines and their components, MAHLE previously developed a demonstrator engine, which was intended to represent 50 % downsizing of a naturally aspirated 2.4 litre engine [12]. The resulting engine was a direct injection, 1.2 litre, 3-cylinder inline, turbocharged, gasoline engine, as shown in Figure 2.

Equipped with a single stage turbocharger, the resulting engine achieved a peak brake mean effective pressure (BMEP) of 30 bar. The peak power output of the engine was 120 kW (120 kW/litre) at 6000 min⁻¹. Stoichiometric fuelling ($\lambda = 1.0$) could be maintained over a wide proportion of the engine operating map [14].



Figure 2. MAHLE Downsizing demonstrator engine.

The engine was implemented into the MAHLE downsizing demonstrator vehicle in 2010, shown in Figure 3 [14]. A key target during the development of the single-stage turbocharged engine was to ensure that the transient response remained acceptable. The specifications of the single turbocharger derivative are summarised in Table 1.

The engine was installed into a D-segment demonstrator vehicle, which features stop-start capability. Testing confirmed that the vehicle achieves a fuel consumption figure of 5.8 l/100 km (CO₂

emissions of 135 g/km) over the NEDC - an improvement of 24 % over the baseline vehicle (an already downsized 1.8 litre turbocharged gasoline engine).

Table 1. Base engine specifications.

Parameter	Value
Engine displacement	1.2 litres
No. of cylinders	3 in-line
Bore/stroke	83.0 / 73.9 mm
Compression ratio	9.3:1
Fuel injection	Multi-hole central DI
Spark plug	M10
Engine control	MAHLE Flexible ECU
Turbocharger	Bosch Mahle Turbo System



Figure 3. Downsizing demonstrator vehicle.

The MAHLE downsizing engine achieves higher BMEP levels than any gasoline engine currently in mass production. A comparison of the BMEP curves, for both the single and two-stage turbocharged derivatives, as well as those of typical production engines taken from the MAHLE Powertrain engine database, is shown in Figure 4.

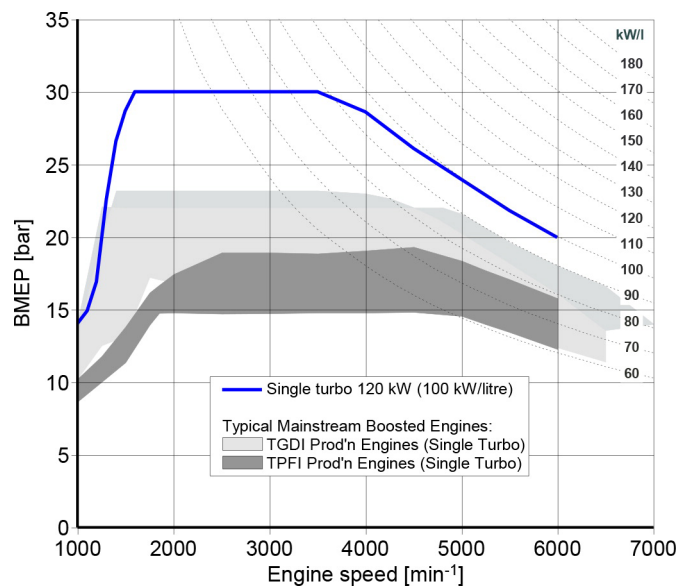


Figure 4. Downsizing demonstrator engine performance.