

# Dynamic Downsizing Gasoline Demonstrator

Michael Bassett, Jonathan Hall, Tony Cains, and Mark Underwood  
MAHLE Powertrain Ltd.

Richard Wall  
Aeristech Ltd.

Bryn Richards  
Consultant

## ABSTRACT

Gasoline engine downsizing is already established as a technology for reducing vehicle CO<sub>2</sub> emissions. Further benefits are possible through more aggressive downsizing, however, the tradeoff between the CO<sub>2</sub> reduction achieved and vehicle drivability limits the level of engine downsizing currently adopted by vehicle manufacturers. This paper will present the latest results achieved from a very heavily downsized engine, and resulting demonstrator vehicle, featuring eSupercharging in combination with a conventional turbocharger.

The original 1.2 litre, 3-cylinder, MAHLE downsizing engine has been re-configured to enable a specific power output in excess of 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 has been installed into a demonstrator vehicle that also features an advanced 48 V lead-carbon battery pack and a 48 V belt-driven 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 fuel consumption of the resulting demonstrator vehicle has been analysed over a number of drive-cycles and the benefits of the downsized engine in conjunction with the complete mild-hybrid system have been assessed.

**CITATION:** Bassett, M., Hall, J., Cains, T., Underwood, M. et al., "Dynamic Downsizing Gasoline Demonstrator," *SAE Int. J. Engines* 10(3):2017, doi:10.4271/2017-01-0646.

## INTRODUCTION

The European Environment Agency (EEA) has recently released the provisional data for the CO<sub>2</sub> emissions of passenger cars registered in the European Union in 2014 [1]. This data shows that all manufacturers have achieved their 2015 targets ahead of time, with average emissions of 123.3 grams per kilometre (g/km) in 2014, a decrease of 3 % compared to 2013 [2]. However, Mock *et al.* [3] 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 CO<sub>2</sub> 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 CO<sub>2</sub> values established via type-approval testing form a basis for consumer information, CO<sub>2</sub> regulation, and CO<sub>2</sub> 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].

48 V mild-hybrid architectures, currently receiving increasing attention, pave the way for increased levels of engine downsizing. This is facilitated through the ability to achieve a virtually instantaneous and continuous supply of boost air for the engine, even at low engine speeds, via the addition of an electrically powered supercharger (eSupercharger). 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 meeting these stringent new CO<sub>2</sub> 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 CO<sub>2</sub> reductions via 48 V micro-hybridisation and system control are also discussed.

## GASOLINE ENGINE DOWNSIZING

Gasoline engine downsizing has long been recognised as an effective technology for engine CO<sub>2</sub> reduction [6, 7, 8] and is firmly established as a technology for assisting in achieving fleet CO<sub>2</sub> 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 [6, 7, 8, 9, 10]. However, as specific output increases so too do the technical challenges, which include abnormal combustion (pre-ignition and detonation), low speed torque, transient response and engine durability.

### 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 [11]. The resulting engine was a direct injection, 1.2 litre, 3-cylinder inline, turbocharged, gasoline engine, as shown in Figure 1. 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 (100 kW/litre) from 5000 min<sup>-1</sup>. Stoichiometric fuelling ( $\lambda = 1.0$ ) could be maintained over a wide proportion of the engine operating map [11]. 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.



Figure 1. MAHLE Downsizing demonstrator engine.

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 (CO<sub>2</sub> emissions of 135 g/km) over the NEDC. The MAHLE downsizing engine achieves very high BMEP levels and the BMEP curve achieved is shown in Figure 2.

Table 1. Specifications of the MAHLE Downsizing 3-cylinder (Di3) demonstrator engine.

|                     |                           |
|---------------------|---------------------------|
| 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     |
| Turbocharger        | Bosch Mahle Turbo Systems |

## FURTHER ENGINE DOWNSIZING

Recently, MAHLE Powertrain has also investigated the possibility of further increasing the level of engine downsizing. With a revised turbocharger and charge cooling, the low-speed torque characteristics of the engine have been enhanced further. The high specific power output has been achieved through the use of a carefully selected larger turbocharger which, unassisted, has a detrimental effect upon the low-speed torque and transient response of the engine. An electrically powered supercharger (eSupercharger) has therefore been specified to enable the transient response and low speed torque to be at least recovered.

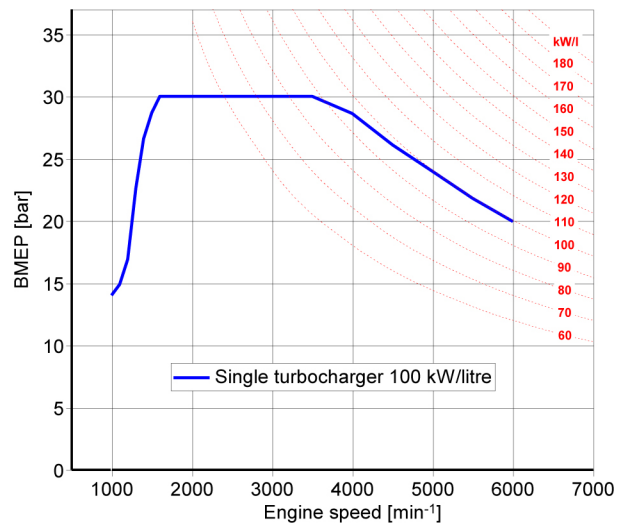


Figure 2. Downsizing demonstrator engine performance.

The eSupercharger, manufactured by Aeristech and shown in Figure 3, was found to be well suited to this application, having a compressor which can provide the desired pressure ratio and mass-flow rate, and a motor capable of continuous operation. The specifications of the Aeristech eSupercharger are summarised in Table 2.

Table 2. Aeristech eSupercharger specification summary.

|                     |                           |
|---------------------|---------------------------|
| Compressor type     | Radial                    |
| Motor               | High-speed PM             |
| Max operating speed | 120,000 min <sup>-1</sup> |
| Cooling             | Liquid                    |
| Input voltage       | 48 V nominal              |
| Unit mass           | 4.2 kg                    |

Aeristech have developed a compact electric machine, for variable high-speed applications, the power electronics of which are configured for operation at 48 V, in-line with current automotive trends. The unit is capable of running continuously at high boost pressures and can also accelerate from an idle speed of  $\sim 30,000 \text{ min}^{-1}$  to its maximum speed of  $120,000 \text{ min}^{-1}$  in under 0.5 seconds [12], allowing it to address the low-speed turbo lag issues associated with heavily downsized engines.

Unlike conventional, belt driven, mechanical superchargers, which require some of the brake engine power to drive them when boost pressure is required, electronic boosting devices can use power that is generated during vehicle deceleration through brake power recuperation, in this case using the BISG. The degree to which this can be achieved is dependent upon the storage capacity of the 48 V battery, the amount of eSupercharger operation required, and the whether the vehicle operation provides the opportunity for recuperation events to take place.

In order to provide high-pressure air at low engine speeds, the eSupercharger is optimised for low flow rates. At higher engine air mass-flow rates there is sufficient exhaust energy for the larger main turbocharger to provide high-pressure air. Thus the eSupercharger is not capable of passing the full air flow required by the engine at higher power outputs and must be bypassed. Additionally, there must be sufficient overlap between the eSupercharger operation map and the main turbocharger map to enable a seamless handover between the two devices. This avoids a torque interruption, which would give an undesirable driving feel in the vehicle.

A completely new air intake system was designed, which included an eSupercharger bypass valve that remains closed when the eSupercharger is in operation and provides an alternative low-loss path, once the turbocharger alone is capable of maintaining the desired torque. New components were also designed for the mounting of the eSupercharger, the integration of the new turbocharger, the secondary charge cooler, and a high power BISG, as shown in Figure 3.



Figure 3. MAHLE engine with eSupercharger and revised intake system.

## ENGINE TEST RESULTS

The eSupercharged version of the engine has been configured with the same 9.3:1 compression ratio (CR) as the baseline 120 kW, single turbocharger, version of the engine. The ability to maintain the same CR as the base engine ensures that the part load fuel consumption

map will be unchanged, thus maintaining the drive-cycle fuel consumption benefits already achieved with this engine in the MAHLE downsizing demonstrator vehicle [11].

Figure 4 shows the BMEP and engine power measured during the engine testing, compared to the baseline. From Figure 4 the effects of the revised boosting system can be clearly seen. The peak performance achieved by the engine is summarised in Table 3. These results clearly demonstrate the significant improvement in peak power offered by the new turbocharger (increasing to 193 kW, from a baseline of 120 kW).

The penalty that this turbocharger imposes in terms of low speed BMEP output, when operated without the eSupercharger, is clearly illustrated in Figure 4a. Without the eSupercharger, the new turbocharger has little charging effect until engine speed is above  $1500 \text{ min}^{-1}$ , and peak torque is not achieved until  $2500 \text{ min}^{-1}$ . If this configuration were to be used in a vehicle, a negative effect on the driveability could be expected, particularly in heavier vehicle applications.

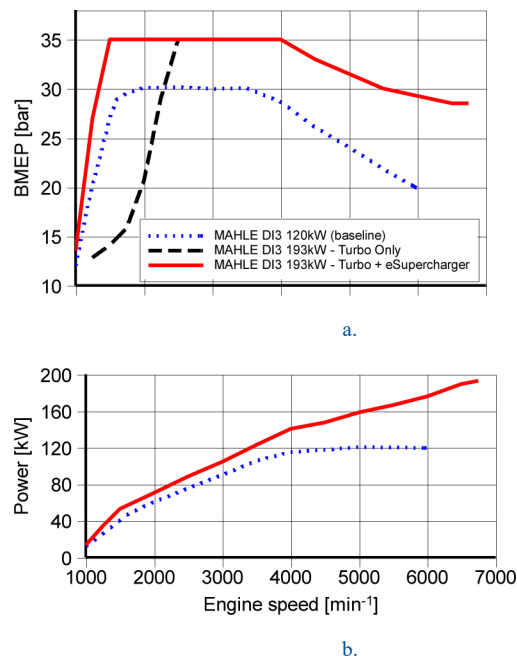


Figure 4. Test results from the MAHLE downsizing engine with combined eSupercharger and turbocharger; a) BMEP; b) Power.

Table 3. Performance summary for the eSupercharged Downsizing engine.

|                       |                                              |
|-----------------------|----------------------------------------------|
| Maximum power         | 193 kW                                       |
| Specific power output | 161 kW/litre                                 |
| Maximum BMEP          | 35 bar ( $1500$ to $4000 \text{ min}^{-1}$ ) |

When the eSupercharger is activated, the combined system not only restores the performance below  $3000 \text{ min}^{-1}$ , it exceeds the previous baseline torque levels at all engine speeds. Of particular note is the increase at  $1500 \text{ min}^{-1}$ , where the output of the engine is 35 bar. Furthermore, the BMEP level of the engine below  $1500 \text{ min}^{-1}$  has been limited to protect the main and big end bearings and the vehicle driveline. The operating speed of the eSupercharger is shown in Figure 5a, where it can be seen that the maximum eSupercharger