E-supercharging for Heavily Downsized Gasoline Engines

M. Bassett[1], J. Hall[1], P. Freeland[1], K. Gray[2], B. Richards[2]

1: MAHLE Powertrain Limited, Costin House, St. James Mill Road, Northampton, NN5 5TZ, UK.
2: Aeristech Limited, Unit G, Princes Drive Industrial Est, Coventry Rd, Kenilworth, CV8 2FD, UK.

Abstract: The next generation of heavily downsized-gasoline engines will demand advanced charge-delivery systems. High-pressure charge-air is required across a broad engine speed range, and to meet driveability requirements, this high pressure charge-air needs to be available almost instantly. Gasoline engine downsizing is already established as a proven technology for reducing CO_2 emissions by up to 25 %.

Further benefits are possible through greater downsizing. However, there is a trade-off between the CO_2 reduction achieved and vehicle driveability, which currently limits the level of engine downsizing adopted. The key objective of this project is to demonstrate the highest specific power and torque output combination of any gasoline engine for the road car market, whilst retaining an excellent drivability and fuel economy.

Keywords: Downsizing, eBoosting, eSupercharging, TGDI, high-specific output.

1. Introduction

CO_2 emissions from road transport have increased by 21 % between 1990 and 2011 [1]. Clearly the total greenhouse gas emissions of the transport sector are still increasing, and are predicted to grow further in the coming years [2]. This is driven by the rapidly expanding global vehicle fleet which is anticipated to increase by over 63 % during the next 20 years [3]. Thus, present automobile development efforts are keenly focused on measures to reduce the CO_2 output of vehicles.

The current method for establishing the fuel consumption, and hence CO_2 emission values, for new cars in Europe today is via the vehicle type-approval process, which involves testing vehicles on a chassis dynamometer over a prescribed vehicle speed profile, known as the new European Driving Cycle (NEDC), following the strict procedure laid down in Regulation 101 [4]. However, Mock *et al.* [5] have analysed data gathered from real world driving and compared the reported fuel consumption to the type-approval value. Their analysis makes use of several large sets of on-road driving data, for both private and company cars, from various European countries. The analysis of Mock *et al.* [5] reveals a clear trend: while the average discrepancy between type-approval and on-road CO_2 emissions was below 10 % in 2001, by 2011 it had increased to around 25 %. However, this should not be allowed to detract from the real strides that manufacturers have made in greatly reducing the CO_2 emitted by vehicles, as type-approval based emissions figures have decreased by almost 20 %, from 164.9 g/km in 2007 to 133.1 g/km in 2012 [6]. This, coupled with the results of the study by Mock *et al.* [5], would suggest that the 'real-world' emissions levels have dropped by about 14 % in the 5 years from 2007 to 2012, which is a very significant reduction.

The vehicle CO_2 values established via type-approval testing form the basis for consumer information, CO_2 regulation, and CO_2-based vehicle taxation and therefore ought to provide a reliable and stable indication of fuel consumption and emission levels observed, on average, under 'real-world' conditions on the road [5]. Partly to bridge the gap between 'real-world' and type-approval figures, and partly to align the differing type-approval procedures used for testing vehicle fuel consumption around the world, the worldwide harmonized light vehicles test procedure (WLTP) is being developed and is anticipated to replace the NEDC in Europe after 2017 [7].

To meet the aggressive targets for fleet-average CO_2, the next generation of heavily downsized-gasoline engines will demand advanced charge-delivery systems. High-pressure charge-air is required across a broad engine speed range, and to meet driveability requirements, this high pressure charge-air needs to be available almost instantly. As the degree of downsizing is increased so do the requirements placed on the engine systems for the optimum benefits to be realised. Further benefits are possible through more aggressive downsizing, however, the trade-off between the CO_2 reduction achieved and vehicle driveability limits the level of engine downsizing currently adopted by vehicle manufacturers.

This paper presents results from a 1.2 litre, 3-cylinder, engine fitted with an eSupercharger in addition to a conventional turbocharger. The results clearly show the potential of eSupercharging as a technology enabler for extreme engine downsizing. Additionally, the compatibility with 48 V micro-hybridisation offers potential for further CO_2 emissions reduction.

2. Downsizing

Gasoline engine downsizing is firmly established as one of the main technologies for achieving the fleet CO_2 reduction targets, with increasing degrees of downsizing being applied in the market place. 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. It has long been recognised as an effective technology for engine CO_2 reduction [8].

Further improvements in fuel economy have been shown to be possible through increased levels of engine downsizing [9-10] However, as specific output increases so too do the technical challenges; the foremost of these being:

- A robust combustion system that allows a high compression ratio to maintain part load efficiency
- Good low speed torque and transient performance
- Real world fuel consumption benefits through a reduction in full load fuel enrichment
- Base engine robustness and durability

These challenges require unique engine design solutions to enable the significant efficiency improvements of an aggressively downsized engine to be realized.

2.1 MAHLE Downsizing Demonstrator Engine

In order to conduct research into the requirements for advanced downsizing engines and their components, MAHLE previously developed a demonstrator engine and installed it into a vehicle [11]. The resulting engine developed by MAHLE was a direct injection, 1.2 litre, 3-cylinder inline, turbocharged, gasoline engine, shown in Figure 1.

Figure 1: MAHLE Downsizing demonstrator engine.

The initial work focussed on developing a high specific torque and high-specific output engine which featured two-stage turbocharging [12-13]. The two-stage turbocharging system was developed to enable good transient response along with the high torque levels at all engine speeds demanded by a downsizing approach. A schematic of the two-stage turbocharging arrangement used is shown in Figure 2.

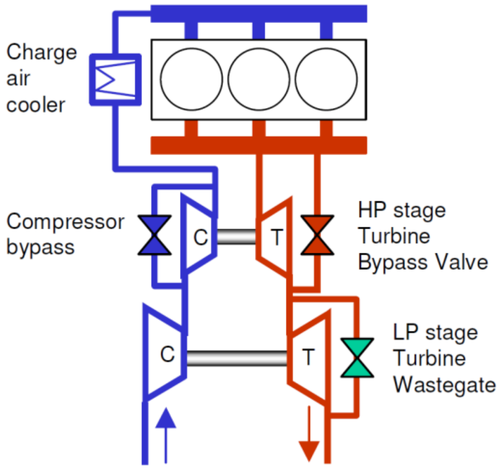

Figure 2: Schematic of the twin-turbocharger arrangement.

The resulting engine exceeded 30 bar peak brake mean effective pressure (BMEP). The peak power output of the engine was 144 kW (120 kW/litre) at 6000 rev/min. Stoichiometric fuelling (lambda = 1.0) could be maintained over the majority of the full-load line.

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

When implemented into the MAHLE downsizing demonstrator vehicle, shown in Figure 3, the engine was modified to have a single turbocharger in order to demonstrate a cost effective concept which could realise significant market share. The single turbocharger derivative has been developed to achieve 30 bar peak BMEP, and 100 kW/litre, to maintain excellent vehicle dynamic performance, whilst still providing significant CO_2 reductions [11]. The specifications of the single turbocharger derivative are summarised in Table 1. A key feature of the development of the single-stage turbocharged engine was to ensure that the transient response of the engine remained acceptable.

Figure 3: MAHLE Downsizing demonstrator vehicle.

The engine was installed into the D-segment demonstrator, which features stop-start capability, and testing has confirmed that the vehicle achieves a fuel consumption figure of 5.8 l/100 km (CO_2 emissions of 135 g/km) over the new European Drivecycle (NEDC).

The MAHLE downsizing engine has a higher BMEP level than any gasoline engine currently in mass production. A comparison of the BMEP curves =, for both the single and two-stage turbocharged derivatives, is shown in Figure 4. Also shown in Figure 4 are the BMEP of typical production engines.

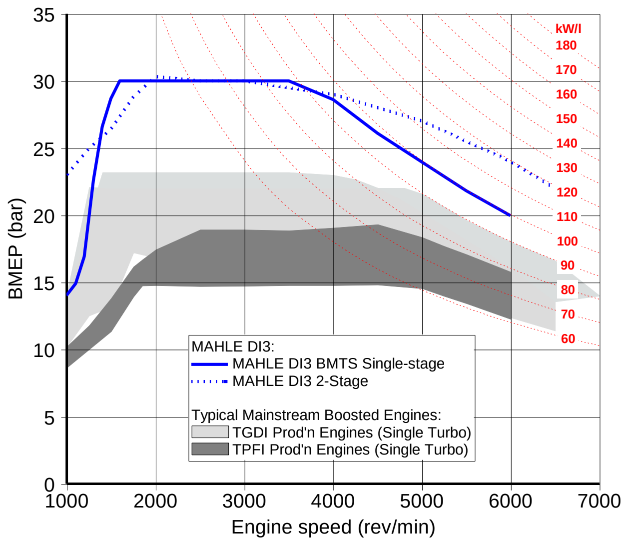

Figure 4: MAHLE Downsizing demonstrator engine perfromance.

3. Aeristech eSupercharger

In this study, the possibility of further increaseing the level of downsizing, via higher specific engine output, is invesigated. The MAHLE downsizing engine will be re-configured to achieve a very high specific output power, without compromising specific torque or transient response.

The high specific power output will be achieved through the use of a larger turbocharger which will inevitably have a detrimental effect upon the low-speed torque and transient response of the engine. An electrically powered supercharger (eSupercharger) will be used to enable the transient response and low speed torque to be recovered, resulting in a very high specific output and specific torque characteristic with excellent transient response for good drivability, allowing the downsizing effect to be maximised for minimised CO_2.

The eSupercharger manufactured by Aeristech, shown in Figure 5, was found to be suited to this application, having a compressor which can provide the desired pressure ratio and mass-flow rate. The specifications of the Aeristech eSupercharger are summarised in Table 2. MAHLE Powertrain has previously applied Aeristech's eSupercharger to increase the power output of a range extender engine from 30 kW to 50 kW [14].

Figure 5: Aeristech 2012 eSupercharger as used in the present study.

Aeristech has been developing a compact and cost effective electric machine, for variable high-speed applications, for the past 6 years. For this application, Aeristech has developed power electronics for 48 V operation, which is in-line with current automotive trends and is compatible with micro-hybridisation for further CO_2 emissions reduction. The unit is capable of running continuously at high boost pressures and high mass-flow rates. The capability to operate at full boost continuously sets the eSupercharger apart from so called eBoost systems [15], which only offer short duration boost assist for improvements in engine transient response.

Due to its impressively fast response time, the electric supercharger effectively addresses the low-speed turbo lag issues associated with downsized engines. Electric superchargers can provide the engine with high boost pressure at low flow rates, equating to both dramatically improved engine performance (with reduced CO_2 emissions) and response at low engine speed.

Table 2: Summary of eSupercharger specifications.

Parameter	Value
Compressor type	Centrifugal
Motor	High-speed PM
Max operating speed	120,000 rev/min
Lubrication	Greased for life
Cooling	Liquid
Input voltage	48 V nominal
Unit mass	4.2 kg

Conventional belt-driven mechanical superchargers consume some of the power the engine produces, in particular at low revolutions, whereas electric superchargers are decoupled from the engine and need only be activated when required. Furthermore, recuperation during vehicle deceleration events has the potential to enable the electricity required to power the eSupercharger to be generated without consuming any additional fuel. The degree to which this can be done will be dependent upon the storage capacity of the 48 V battery, the amount that the eSupercharger is required, and the whether the vehicle duty cycle provides the opportunity for regeneration events to take place.

Aeristech next generation eSupercharger development, shown in Figure 6, is due for completion in Q2 2015, and is intended to support market introduction in 2017. The 2015 unit includes fully integrated power electronics. Aeristech's proprietary electric motor and control technology supports low-cost electric boosting at all voltage levels, from 12 V and 48 V passenger car and off-highway applications to high voltage (200 V to 400 V) fuel cell and hybrid vehicle applications. As in the present study, the relatively high continuous boost pressures and flow rates offered by Aeristech's eSupercharger can offset the need for a multi-stage turbocharger arrangement and potentially provide a net reduction of cost and complexity in the boosting system of heavily downsized engines.

Figure 6: Aeristech 2015 eSupercharger development with integrated power electronics.

4. E-supercharging for Heavily Downsized Gasoline Engines

The eSupercharger could be located either downstream of the main turbocharger compressor, as shown schematically in Figure 7a, or upstream, as shown in Figure 7b. In order to provide high-pressure air at low engine speeds, at flow rates below where there is sufficient exhaust energy for the larger main turbocharger to provide high-pressure air, the eSupercharger is optimised for low flow rates. This means that the eSupercharger will not be capable of passing the full air flow required by the engine at higher power outputs. Thus the eSupercharger must be bypassed when high engine power is required. Additionally, there must be sufficient ovelap between the eSupercharger operation map and the main turbocharger map to enable a seamless handover between the two devices in operation, to aviod any torque interuption which would give an undesirable drive feel in the vehicle.

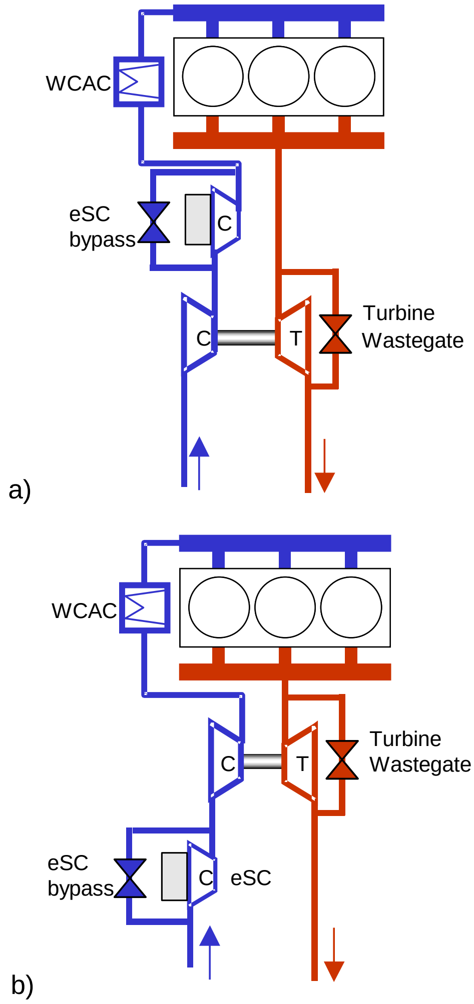

Figure 7: Schematic of the twin-turbocharger arrangement; a) Post turbocharger compressor; b) Pre-turbocharger compressor.

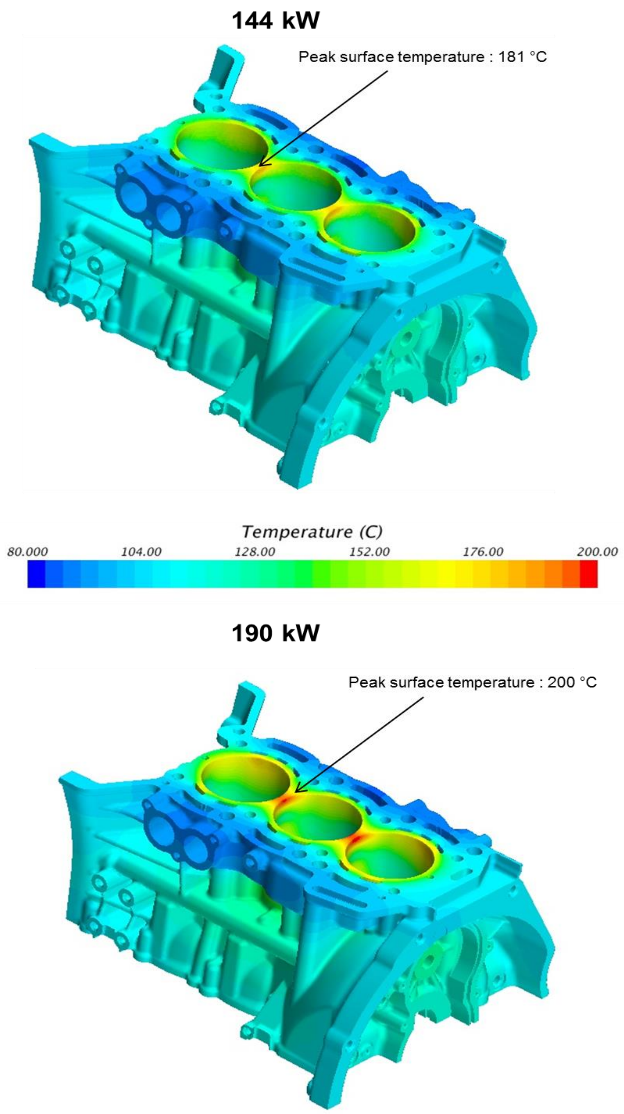

Figure 8: Calculated peak inter-bore cylinder block temperatures.

Placing the the eSupercharger downstream of the main compressor, as depuicted in Figure 7a, has the advantage of effectively broadening the eSupercharger map, towards higher-massflows, this arises due to the air exiting the main compressor being at a higher density as the turbocharger begins to provide boosted air, which potentially enhances the overlap of the operating maps for the two devices. However, placing the eSupercharger downstream of the main compressor means the the eSupercharger would be subjected to full boost pressure from the turbocharger compressor at full engine load. Additonally, unless an intercooler is placed between the main compressor outlet and the eSupercharger, the eSupercharger will also have to withstand the temperature of the compressor outlet air, which can reach 180 °C. To protect the prototype Aeristech eSupercharger used in this study it has been placed upstream of the turbocharger compressor, as depicted in Figure 7b.

5. MAHLE E-supercharged Downsized Engine

The significant increase in specific power output and BMEP (over the standard 30 bar) of the engine would put additional strain on the engine structure and components.
To establish whether the additional output would take the engine past its safe operational limits, analysis was carried out using both CFD and FEA. The analysis work undertaken included a cylinder head, block and valvetrain thermo-mechanical analysis (using models validated against previous experimental data), crankshaft and connecting rod strength simulation, plus an investigation into the oil film thickness of the main and big-end bearings at the higher loads. In addition, detailed analysis of specific components, such as the cylinder head gasket and bolts, was also carried out. Peak inter-bore cylinder block temperatures were predicted to rise by 10 %, as shown in Figure 8, cylinder head exhaust-valve bridge by 8 % and valve heads by 3 %. The results showed that the existing cooling system is capable of supporting this anticipated increase in heat flux and physical load.

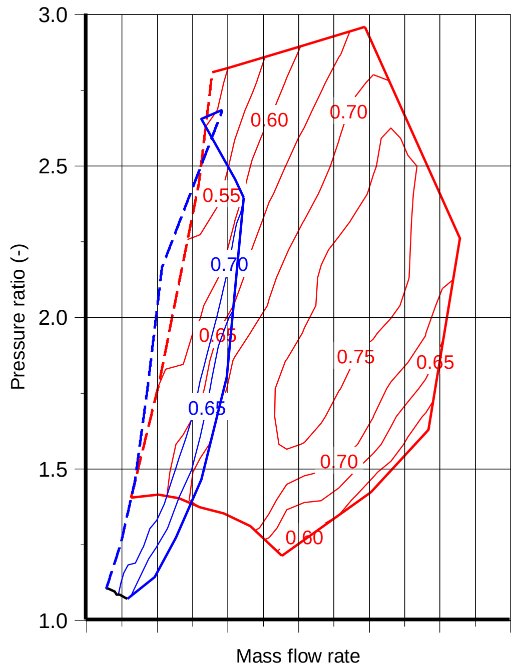

Figure 9: eSupercharger and main turbocharger compressor maps.

A detailed thermodynamic model of the MAHLE downsizing engine, developed within the commercial package GT-Power [16], has been used to enable the selection of a suitable turbocharger. The turbocharger unit has been selected to enable the peak power target for the engine to be achieved, whilst providing enough overlap with the supercharger operating map. The turbocharger compressor map, along with the eSupercharger compressor map, is shown in Figure 9.

With the analysis work completed and the turbocharger selected, MAHLE carried out a design study to package the Aeristech eSupercharger onto the engine. A completely new air intake system was required, that included an eSupercharger bypass valve, which remains closed when the eSupercharger is in operation and is opened when the turbocharger requires no assistance. New components were also designed for the mounting of the eSupercharger and the integration of the new turbocharger, as shown in Figure 10.

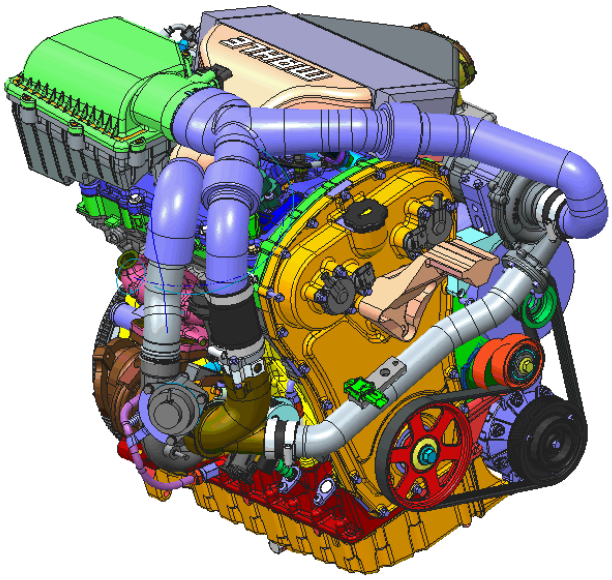

Figure 10: MAHLE engine with eSupercharger and revised intake system.

Revised turbocharger service pipework was also designed to provide adequate water cooling and oil lubrication to the turbocharger. In addition, a simple Port Fuel Injection (PFI) system was designed to enable blended operation between Direct Injection (DI) and PFI and to increase the total system fuel flow capability to match the anticipated requirement, which is beyond the flow capacity of the existing DI system.

Following the completion of the design of the revised components, the prototype parts were manufactured. The engine was successfully assembled using the new components, and fully instrumented, prior to fitting to the testbed at MAHLE Powertrain's facility in Northampton. Additional functionality was added to the MAHLE Flexible ECU (MFE) system to enable control of the eSupercharger and bypass system during steady state and transient events. Modifications to the engine wiring harness were also designed and manufactured in-house.

6. Engine Test Results

During the testing, charge air temperature, engine oil temperature, engine coolant temperature and eSupercharger coolant temperature were all monitored and controlled to pre-defined values, intended to be representative of in vehicle operation.

The MAHLE downsizing demonstrator engine has undergone significant testing over recent years, which has resulted in a robust base engine operating map, which is typically used as a baseline for further optimisation of control parameters, especially following hardware changes. The base control map provided 'safe' values for the timing of the camshafts, ignition angle and fuelling timing and rate, which were subsequently manually optimised to give best performance at each operating site tested.

Initial testing was carried out using a lower compression ratio (CR) than used in the 120 kW, single turbocharger, version of the engine. The baseline CR is 9.3:1 and initial testing was carried out at 8.7:1. This CR change was implemented using a different piston. The results of the testing at the lower CR indicated that the low knock propensity of the MAHLE engine enabled the combustion phasing to be retained at a relatively advanced point within the cycle. Thus, the engine was reconfigured to run at the original 9.3:1 CR. The ability to maintain the same CR, as the base engine ensures that the part load fuel consumption map will be the same as that of the baseline engine, thus ensuring the drive-cycle fuel consumption benefits already achieved with this engine in the MAHLE downsizing demonstrator vehicle.

The engine following boosting system hardware combinations were investigated using these methods to understand the contribution of the individual components within the system and their interaction with each other:

- Turbocharger only;
- eSupercharger only;
- Combined eSupercharger and turbocharger.

Figure 11 shows the BMEP, power and eSupercharger power requirements measured during the engine testing, along with values for the baseline 120 kW single-turbocharger version of the engine. From Figure 11 the effects of the revised boosting system, in each of the three operating modes described above, can be clearly seen. The performance achieved by the engine is summarised in Table 3.

The results, shown in Figure 11b, clearly demonstrate the significant improvement in peak power offered by the new turbocharger (increasing to 193 kW, from a baseline maximum of 120 kW) but equally, the penalty that this turbocharger imposes in terms of BMEP output, when operated without the eSupercharger, at low speeds is evident from Figure 11a. Without the eSupercharger, the new turbocharger has almost no charging effect until engine speed is above 2,000 rev/min, and peak torque is not achieved, operating with the turbocharger alone, until 3,000 rev/min. If this configuration were to be used in a vehicle, a serious negative effect on the drivability would be anticipated, particularly in heavier vehicle applications.

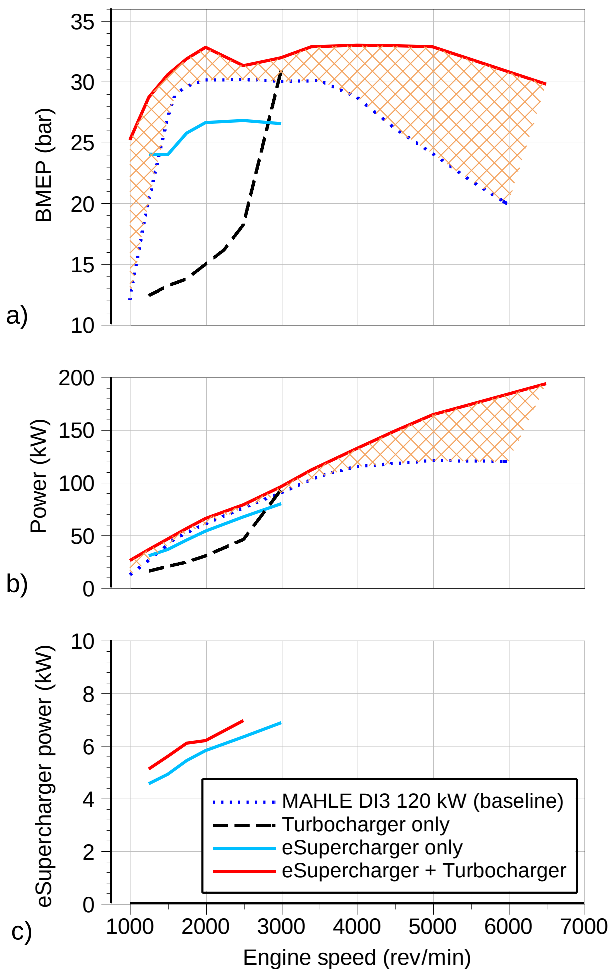

Figure 11: Test results from the MAHLE downsizing engine with combined eSupercharger and turbocharger; a) BMEP; b) Power; c) eSupercharger power requirement.

The test data presented in Figure 11 is for steady-state performance. The transient performance would be considerably worsened from the baseline case, in turbocharger only configuration. This test established that the revised turbocharger is able to offer considerably increased engine performance, but the results also highlight the need for an additional (assisting) boosting device to assist at low engine speeds.

When operated in isolation (turbocharger waste-gate fully open), the eSupercharger demonstrates strong performance enhancements at low engine speeds and can be used to achieve more than 26 bar BMEP. Measurement data is shown up to 3,000 rev/min, after which point the turbocharger operating alone gives significantly higher output than the eSupercharger. The power consumption of the eSupercharger system, including the losses from the power electronics, are shown in Figure 11c, resulting in a peak electrical power requirement at steady state conditions of less than 7 kW.

Finally, the eSupercharger and turbocharger were tested as a combined system, where the mass-flow provided by the eSupercharger passes through the turbine and aids in driving the main compressor. This combined system that offers significant performance advantages over the individual components. It can be seen from Figure 11a the test data that the combined system not only restored the performance below 3,000 rev/min, it actually allows the total system to exceed the previous baseline torque levels at all engine speeds. Of particular note is the increase at 1200 rev/min, where the output of the engine is raised from the baseline level of 20 bar BMEP, up to almost 29 bar. Furthermore, at 1000 rev/min the maximum engine output achieved was 25 bar BMEP.

The final overall torque curve offered by the combined system provides higher than baseline torque at all engine speeds, with a final power output of 193 kW (161 kW/l). On the 1.2 litre engine used for the testing, this results in a specific power output of 161 kW/litre and a BMEP output in excess of any gasoline engine currently available in series production.

These exceptionally high levels of steady state BMEP output clearly demonstrate the benefits enabled by the eSupercharger used in this investigation. It is also anticipated that the transient response benefits, which will be verified during future testing, are expected to offer a highly responsive driving experience, with impressive levels of available torque at any engine speed.

Table 3: Performance summary for the eSupercharged MAHLE Downsizing engine.

Parameter	Value
Maximum power	193 kW
Specific power output	161 kW/litre
Maximum torque	313 Nm at 2000 rev/min
Maximum BMEP	33 bar at 2000 rev/min

7. Conclusions

MAHLE Powertrain integrated a 48 V version of the Aeristech eSupercharger into the design of their downsized engine and built a prototype engine to enable testing.

The engine testing showed an increase in maximum power to 193 kW, resulting in specific power output increase from 100 kW/litre (with a single turbocharger) to 161 kW/litre. Furthermore, increases to low speed torque of 9 bar BMEP at

1200 rev/min were measured, as well as general increases in torque output at all engine speeds.

The concept of combining an eSupercharger and high-flow turbocharger has proved successful and the Aeristech eSupercharger was also demonstrated to enable continuous, high-pressure, operation on the engine dyno. This is a clear advantage over many of the competing technologies, which are typically limited to short bursts and are therefore not ideally suited to thiss types of very high specific output power application, where the eSupercharger will be relied upon for relatively high duty cycle operation.

In conclusion, MAHLE Powertrain and Aeristech have demonstrated a concept engine with class-leading performance, which will enable fuel economy improvements through engine downsizing at specific power outputs not previously demonstrated. In doing so, the companies have pioneered a new development in engine boosting technology by hybridisation of the air intake system, making the electrical charging device a fundamental part of the enabling technology. The eSupercharger is, in this application, no longer simply a transient device, but also a key contributor to the steady state engine performance. In doing so, previously unachievable levels of specific power output have been realised.

MAHLE Powertrain will continue to develop the eSupercharged version of their downsizing engine and plan to have a fully functioning demonstration vehicle available before the end of 2015.

8. Acknowledgements

The authors acknowledge the contribution of their colleagues to this work, especially James Taylor and Ben Hibberd. This research was supported by a grant from the Niche Vehicle Research and Development programme.

9. References

[1] Monitoring CO_2 emissions from new passenger cars in the EU: summary of data for 2012, European Environment Agency, Copenhagen, Denmark.

[2] Kampman, B., Leguijt, C., Bennink, D., Wielders, L., Rijkee, X., de Buck, A., Braat, W.: “Green Power for Electric Cars - Development of policy recommendations to harvest the potential of electric vehicles”, Delft, CE Delft, January 2010.

[3] World Oil Outlook, 2008; Organization of Petroleum Exporting Countries, January 2009. http://www.opec.org/opec_web/static_files_project/media/downloads/publications/WOO%202009.pdf (last accessed 16th April 2015).

[4] E/ECE/324-E/ECE/TRANS/505 Regulation No 101 Rev 2, Annex 8. 29 April 2005.

[5] Mock, P., German, J., Bandivadekar, A., Riemersma, I., Ligterink, N., Lambrecht, U.: “From laboratory to road: A comparison of official and ‘real-world’ fuel consumption and CO2 values for cars in Europe and the United States”, International Council on Clean Transportation (ICCT), 2013.

[6] Kay, D., Hill, N., Newman, D., ‘Powering Ahead: The future of low-carbon cars and fuels’, Published by UKPIA and The RAC Foundation, April 2013.

[7] Report of the Working Party on Pollution and Energy (GRPE) on its 65th session (15-18th January 2013), ECE/TRANS/WP.29/GRPE/65, 7th February 2013.

[8] Atkins, J M and Koch, C R “A Well-to-Wheel Comparison of Several Powertrain Technologies” SAE paper 2003-01-0081, 2003.

[9] N Fraser, H Blaxill, “Engine Downsizing and the Application of Gasoline Direct Injection to a High Specific Output Turbocharged Engine”, Fuel Economy and Engine Downsizing Seminar Proceedings, 2004.

[10] Bandel, W. et al. “The Turbocharged GDI Engine: Boosted Synergies for High Fuel Economy Plus Ultra-low Emission” SAE paper 2006-01-1266, 2006.

[11] OudeNijeweme, D., Bisordi, A., Stansfield, P., Bassett, M., Korte, V., Mahr, B., Williams, J., Ali, R., Gold, M., Rogerson, J.: ‘Downsizing and Biofuels: Synergies for Significant CO_2 Reductions’, 20. Aachen Colloquium Automobile and Engine Technology, 2011.

[12] Hancock, D., Fraser, N., Jeremy, M., Sykes, R., Blaxill, H.: ‘A New 3 Cylinder 1.2l Advanced Downsizing Technology Demonstrator Engine”, SAE Paper 2008-01-0611, 2008.

[13] Lumsden, G., OudeNijeweme, D., Fraser, N., Blaxill, H.: ‘Development of a Turbocharged Direct Injection Downsizing Demonstrator Engine’, SAE Paper 2009-01-1503, 2009.

[14] Bassett, M., Hall;’ J., Warth, M., Mahr, B.: ‘Development of a range extender engine family’, Fisita World Congress, F2014-TMH-016, Maastrict, the Netherlands 2-6 June, 2014.

[15] SAE Automotive Engineering, ‘Testing Audi’s new e-booster reveals turbocharging's future’: http://articles.sae.org/13421/ (last accessed 14th April 2015).

[16] GT-Suite from Gamma Technologies: https://www.gtisoft.com/applications/a_Engine_Performance.php (last accessed 16th April 2015).