3 A 110kW/L, 200Nm/L Downsized Gasoline Engine with a High-Speed, Permanent Magnet Electric Supercharger

Bryn Richards, **Tran Hoang Hiep**, Aeristech Ltd., Coventry, UK, **Oliver Porter**, **Mark Parrett**, **Petr Matajsz**, Ricardo UK Ltd., Shoreham-by-Sea, UK

Abstract

Engine downsizing is a proven approach to reduce CO_2 emissions and improve fuel economy, but the approach is predicated on achieving high specific power without compromising reliability, drivability, or cost. One approach to engine downsizing is advanced pressure charging, placing challenging demands upon the pressure charging system.

This paper addresses engine downsizing in the embodiment of a high performance and high specific power 2.0L gasoline engine simulated using Ricardo WAVE software. With best available conventional, single-stage turbocharger technology, the boosting system requires augmentation to maintain the same steady-state torque profile as a naturally aspirated engine of the same power and also to maintain an acceptable transient response, particularly at lower engine speeds.

Having specified the requirements for the boosting system in a demanding engine downsizing application, the simulation incorporated an Aeristech 48V high speed permanent magnet electric supercharger, connected in series with the conventional turbocharger, to augment the performance of the boosting system. The engine and boosting system was then tuned to produce a relatively consistent torque delivery of the engine across a range of engine speeds, in steady-state and transient conditions, indicating that the downsized engine with the electric supercharger would likely exhibit acceptable levels of responsiveness and desirability.

1. Background

Automobile emission regulations are becoming increasingly stringent across much of the world. In the European Union, for example, the CO_2 fleet average to be achieved by all new cars is 130g CO_2/km (grams of CO_2 produced per kilometre driven) by 2015 and 95g CO_2/km by 2021, phased in from 2020. [1] This equates approximately to 50mpg (miles per gallon) fuel consumption average by 2015 and 69mpg by 2021. The 2015 and 2021 targets represent reductions of 18% and 40% respectively compared with the 2007 fleet average of 158.7g CO_2/km (41mpg). In terms of fuel consumption, the 2015 target is approximately equivalent to 5.6 litres of petrol or 4.9 litres of diesel per 100 km driven. The 2021 target is approximately 4.1 litres of petrol or 3.6 litres of diesel per 100 km driven. Japan has enacted target of 105 g CO_2/km by 2020, representing a 15% reduction from Japan's 2010 average and equating to approximately 62mpg fuel consumption. [2] Legislation has been proposed in other countries as follows: USA [3]: 109 g CO_2/km (60mpg) by 2025, a 50% reduction from the country's 2010 average; China [2]: 117 g CO_2/km (56mpg) by 2020, a 30% reduction from 2010; India [2]: 113 g CO_2/km (58mpg), a 20% reduction from 2010.

To achieve lower CO_2 emissions, a well-established technical approach is to use smaller engines with better average emissions in real-world driving conditions and legislative driving cycles, all of which tend to entail a significant amount of engine usage at part load. [4,5,6] The smaller engine can be pressure charged to maintain the peak power of the original engine, hence engine downsizing with pressure charging. To be fit for purpose and also viable commercially, downsized engines must exhibit (1) acceptable levels of steady-state torque at every engine speed, and (2) the ability to produce steady-state torque or a substantial fraction thereof within a reasonable time frame (transient response). [7] The above requirements can stretch the limitations of conventional pressure charging systems.

2. Baseline Engine Model

The baseline engine model was a 4-cylinder inline 2.0L gasoline engine boosted with a single stage, wastegated turbocharger. The base engine produced 220kW peak power at 5500 RPM (revolutions per minute) and was considered by Ricardo UK Ltd. to be a realistic contemporary or next-generation baseline engine. The engine model uses a turbine wastegate only in full-load conditions. Turbine inlet temperature is maintained at 950C by controlling air/fuel ratio. The engine model was implemented in Ricardo WAVE [8] 1D simulation suite. The Wave representation of baseline model is shown in Figure 1.

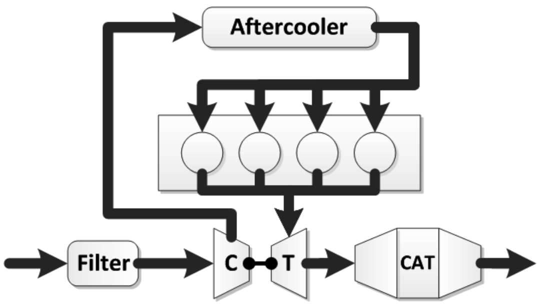

Figure 1: *WAVE representation of baseline engine*

3. Aeristech's High-Speed Permanent Magnet Electric Supercharger

3.1 Specifications

Aeristech's high-speed, permanent magnet electric supercharger is rated to produce 2.2 bar boost in less than 0.5 seconds (worst case load step) and deliver over 5kW continuous power (higher power available in transient) to a centrifugal compressor with a maximum speed of 120kRPM. Aeristech's electric supercharger is being built at the time of writing for first testing in May 2015. The present study was based on calculated performance data, derived from design simulations, actual subsystem test results, and Aeristech's extensive library of test results from similar permanent magnet electric turbomachines at a range of speed and power levels. Aeristech's electric supercharger incorporates power electronics into a fully integrated package with interfaces for 48V power supply and CAN Bus communication. (See Figure 2)

Figure 2: *CAD rendering of Aeristech's electric supercharger*

The compressor map used for the simulation is shown in Figure 3.

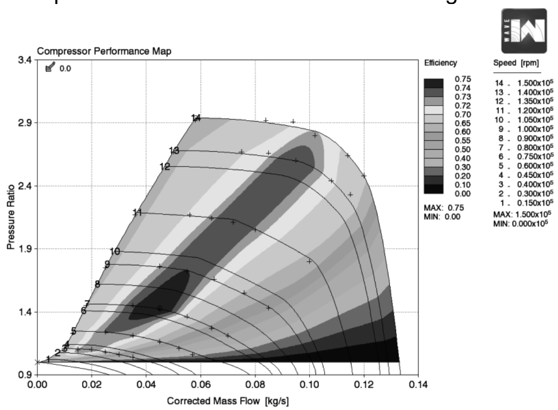

Figure 3: *Electric supercharger compressor map*

Aeristech's electric turbomachines are rated to supply high power levels continuously, as well as to supply rapid transient response. Aeristech's fuel cell compressor [9] and full electric turbocharger (FETT) compressor [10] are examples of still higher continuous power devices. The 48V supercharger has been rated at a relatively modest power level to limit current draw from the vehicle. However, Aeristech's electric supercharger is rated for engines from approximately 1.2L to 2.2L size, where the main turbochargers are specified to maximise total power. The electric supercharger provides boost at low and intermediate engine speeds where such peak-power turbochargers exhibit turbo lag and boost threshold limitations.

3.2 Implementation with the Engine Model

The electric supercharger was simulated both downstream of and upstream of the main turbocharger compressor (low-pressure and high-pressure configurations, respectively). An additional charge air cooler (water-to-air type) was implemented in the model so that the air was cooled after each stage of compression. A bypass valve was included, allowing inlet air to bypass the electric supercharger at higher flow rates, where the supercharger would have provided a restriction. Figure 4 shows a representation of the model in Ricardo WAVE.

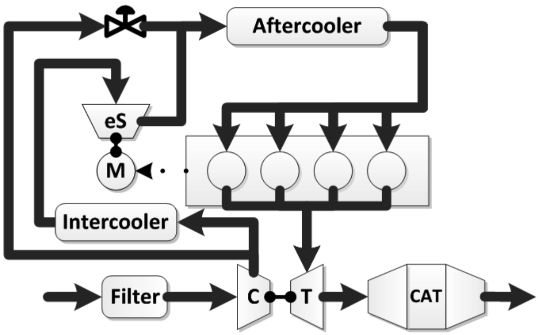

Figure 4: *Implement electric supercharger on Ricardo WAVE model*

The boost configuration with the electric supercharger in the high-pressure position was the preferred configuration in initial simulations, because it allowed for more dense air to enter the electric supercharger, improving compressor efficiency and enabling the electric supercharger to function at higher engine speeds (and greater air flow rates) than it was capable of achieving in a low-pressure configuration.

The engine's intake manifold pressure was controlled by the throttle valve and by a compressor speed target request generated by the model ECU. The model ECU would limit compressor speed (and therefore engine manifold pressure) as required to limit peak cylinder pressure and/or knocking intensity. Nowhere was the model limited by boost system capability. In other words, the capability of the boosting system met or exceeded the boost requirement of the engine, in each steady-state operating condition.

3.3 Implementation of a Larger Main Turbocharger Turbine

Having implemented the electric supercharger to achieve torque fill and improved transient response relative to the baseline engine, the next step was to increase the size of the main turbocharger, aggravating its turbo lag and boost threshold problems and maximising the capability of the electric supercharger to supplement and support the main turbocharger. Any increase in the size of the main turbocharger is limited by (1) the amount of specific power (engine speed and cylinder pressure) that the engine is capable of supporting and (2) the amount of power that the vehicle and electric supercharger are capable of supplying to complement the main turbocharger to achieve acceptable levels of steady-state and transient torque at low and moderate engine speeds. In this study, the high power capability of Aeristech's electric turbocharger (with over 5 kW steady state mechanical power) and high speed (over 120 kRPM enabling a wide and efficient compressor map) allowed the electric supercharger to boost through a relatively wide range of engine speeds (up to 2250 RPM). Because low-end boost was handled by the electric compressor, it was possible to specify a larger main mechanical turbocharger than in the baseline engine. The larger turbocharger was implemented in the model by scaling mass flow and maintaining efficiency constant. The mass flow in the mainstream turbocharger turbine and compressor were both increased by 80%.

However, the larger main mechanical turbocharger was not used to achieve significant a power increase in the present study. Boosting overall engine specific power is mainly achieved by increasing the peak cylinder pressure and density to achieve more torque on the crankshaft. In this study, the baseline engine was not capable of accommodating higher peak cylinder pressures. Therefore, the larger turbine and compressor of the main turbocharger were useful mainly to improve BSFC (Brake Specific Fuel Consumption). Overall specific power was increased only modestly from 110 kW/L to 120 kW/L. More importantly for this study, BSFC was improved in the critical part-load area, indicating potential CO_2 savings on standard driving cycles.

4. Steady-State Results

4.1 Full Load Results

Figure 5 shows a torque improvement of the model with electric supercharge and with scaled turbine against baseline. When the main turbocharger was enlarged to take maximum advantage of the performance capability of the supporting electric supercharger, steady-state torque at 1500 RPM rose to 329 Nm from the base engine's 272 Nm, torque at 2000 RPM rose to 412 Nm from the base engine's 403 Nm, and torque at 2500 RPM rose to 416 Nm from the base engine's 404 Nm.

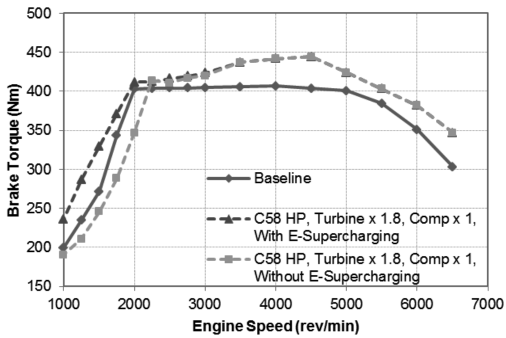

Figure 5: *Engine torque of electric supercharger with 80% larger turbine and the baseline engine*

As can be seen from Figure 5, the larger turbine was not used to achieve any substantial improvement in specific power but only to reduce engine exhaust manifold pressure and improve BSFC. The larger turbine reduced the torque available in steady-state at low RPM, and this torque was recovered (and further augmented beyond the baseline torque) using the electric supercharger with its steady-state capability.

The engine configured with a larger main turbocharger exhibited lower exhaust manifold pressures, illustrated on the Figure 6. The exhaust manifold pressure drop of full load is 65 mbar at 1500 RPM, 365 mbar at 2000 RPM, 856 mbar at 5500 RPM. The exhaust manifold pressure drops roughly on high and middle and gently on low engine speed range.

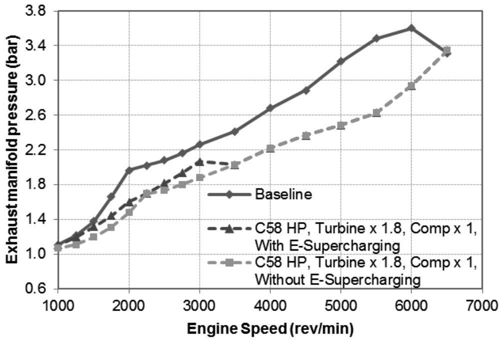

Figure 6: *Full load exhaust manifold pressure cross whole RPM range*

BSFC is shown on the Figure 7 with and without the larger turbine. Results show 9.4% improvement at 5500 RPM, 7.3% at 3500 RPM, 2.6% at 1500 RPM, and 1.9% at 2000 RPM. Results are greatest in the high engine speed range but still significant at lower engine speeds. BSFC results are net of supercharger power draw from the crankshaft.

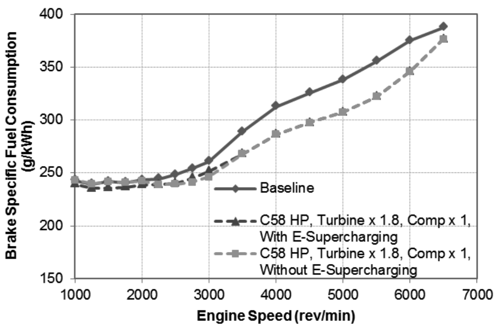

Figure 7: *Full load BSFC of baseline and 80% larger turbine*

4.2 Part Load Results

The part load key points were chosen from NEDC (New European Driving Cycle) for using a D-segment following the drive cycle with baseline engine. Part load points were defined at various engine speeds and torque levels to approximate the operating points of the drive cycle.

Figure 8 shows exhaust manifold pressure with and without the enlarged main turbocharger in three part load levels at various engine speeds from 1000 to 2500 RPM. Exhaust manifold pressure decreased approximately 100 mbar at 14 bar BMEP (Brake Mean Effective Pressure) and 2500 RPM, 40 mbar at 11 bar BMEP and 2500 RPM, 60 mbar at 13 bar BMEP and 2000 RPM, and 20 mbar at 9 bar BMEP and 2000 RPM. The results indicate an impact on exhaust manifold pressure within the range of part load operation relevant to NEDC.

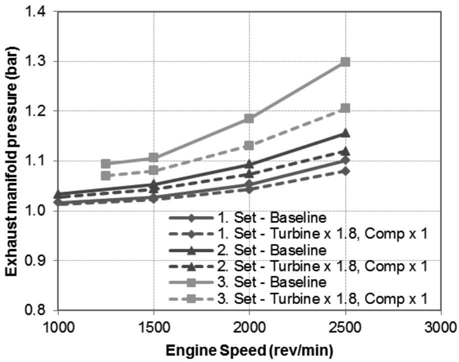

Figure 8: *Exhaust manifold pressure with 80% larger turbine and the baseline engine in part load conditions*

Lower exhaust manifold pressure leads to improved BSFC (Brake Specific Fuel Consumption). Figure 9 shows BSFC improvement the part load region, where the engine will tend to operate on legislative drive cycles. The BSFC improvement due to the larger turbocharger outweighs the energy cost of electricity to supply the electric supercharger (with associated inefficiencies). The total electrical power draw for the electric supercharger is presumed to be drawn form crankshaft power, and this is accounted for in the BSFC calculation. The net improvement in BSFC due to using electric boost rather than conventional turbocharger boost in these part-load points is 0.9% at 14 bar BMEP and 2500 RPM, 0.5% at 11 bar BMEP and 2500RPM, 0.6% at 13 bar BMEP and 2000RPM, and 0.3% at 9 bar BMEP and 2000RPM.

Overall, implementing an electric supercharger with a high continuous power rating, coupled with a larger main mechanical turbocharger, has improved torque and power at full load and BSFC at part load and full load.

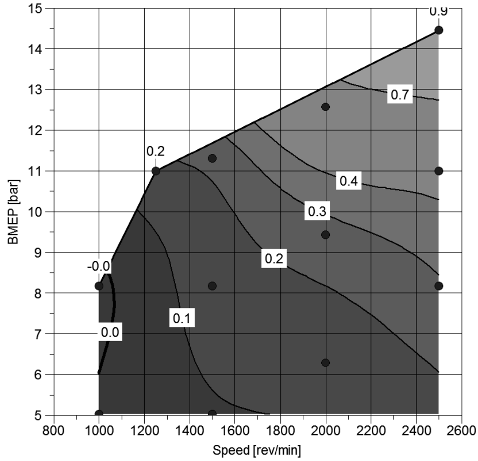

Figure 9: *Change in BSFC due to implementing the electric supercharger and 80% larger turbine in part load conditions*

5. Transient Results

The transient response of the electric supercharger was limited by the power available on the vehicle. The modelling assumption was that no more than 200A would be available from the vehicle, and that no supplemental energy storage would be provided to allow the electric supercharger a greater current draw, even instantaneously. Figures 10 and 11 show the transient response of the engine with electric supercharger and enlarged main turbocharger against baseline transient performance. Figure 10 shows results at 1200 RPM, and Figure 11 shows results at 1500 RPM.

1500 RPM was the most unresponsive operating speed for the baseline engine, and was also a challenging case for the electric supercharger due to the input power limitation of 200A. Results in Figure 11 include the electric supercharger's time to boost and the lag in the air system and engine, showing the total time to achieve a step change in engine torque output.

The boost pressure profile versus time shown in Figures 10 and 11 illustrate transient overshoot. The electric supercharger overshoots in order to assist the mainstream turbocharger in spooling up faster, reducing overall time to torque. Without an overshoot capability, transient response of the engine (time to torque) would have suffered relative to the results shown. The electric supercharger improved transient response from baseline 1.71 to 0.64 seconds at 1200 RPM (stepping from 5% to 90% of full engine torque) and from baseline 1.44 seconds to 0.78 seconds at 1500 RPM.

The electric supercharger transient results incorporate the 80% larger turbine, with added inertia and turbo lag. The slower transient response time expected from the 80% larger turbine are more than counteracted by the transient capability of the electric supercharger. The electric supercharger's transient capability is limited only by the availability of electric power on the vehicle and the electric supercharger's corresponding maximum power rating. In this case, the electric supercharger was limited to 200A current consumption at 48V nominal vehicle voltage.

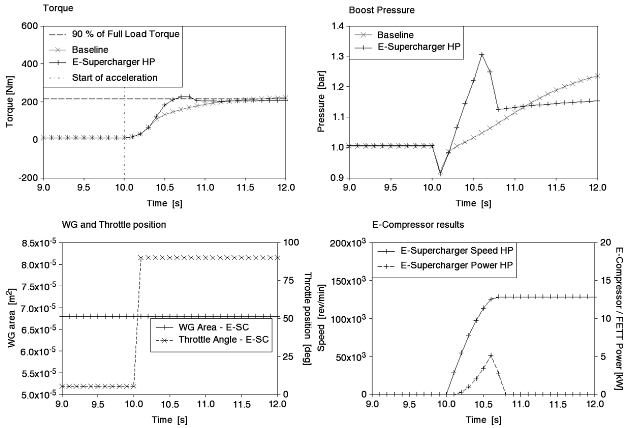

Figure 10: *Transient results of the electric supercharger with 80% larger turbine and the baseline engine at 1200 RPM*

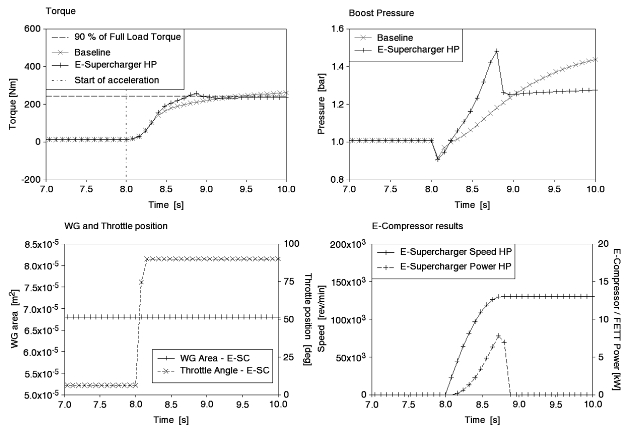

Figure 11: *Transient results of the electric supercharger with 80% larger turbine and the baseline engine at 1500 RPM*

6. Conclusions

The introduction of a high-speed, permanent magnet electric supercharger, with its associated high efficiency, high continuous power rating, and favourable map width, enabled the engine to use a larger main turbocharger, increase specific power, reduce net BSFC, and produce greater and more consistent torque across the full range of engine speeds, in both transient and steady-state conditions. These results indicate a strong potential for the electrically supercharged engine to serve in applications where only a larger engine would have met the requirements if relying on a conventional single-stage turbocharger. This supports the conclusion that electric supercharging supports engine downsizing. BSFC improvement, especially part-load BSFC improvement, achieved by implementing a larger turbocharger, indicates a direct case for CO2 reduction, even in applications such as the present study where the engine is not capable of further downsizing and/or significantly increased specific power. .

This study has further shown that the degree of engine downsizing (or main turbocharger enlargement) possible on a given engine is to some extent a function of the performance capability of the electric supercharger. Without accepting the cost and complexity of a multi-stage turbocharger system, the engine relies on the electric supercharger to produce significant continuous boost at low and intermediate engine speeds, freeing the single, main turbocharger to function efficiently at a high-power match point and offering a reduction in net BSFC across the range of engine operation, most importantly in part-load operating conditions consistent with legislative drive cycles. Despite improvements in specific power and BSFC, the resulting engine offers improved transient response relative to a conventionally boosted baseline engine because of the transient capability of the electric supercharger.

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