Case study

Innovation in engines –
New Full Electric Turbocharger
enabling higher control and power
whilst lowering emissions
Abstract

This project set out to show the potential for improved engine performance combined with lower CO₂ emissions in heavy diesel engines subjected to the stringent requirements of quarry vehicles. The project demonstrated a potential for significant turbo-lag reduction and exhaust energy recovery, through a series of tests and comparisons around a 4l-quarry engine at Birmingham City University. It appears feasible to develop product applications for specific engine families and to expect high-level control opportunity, performance improvement and reduction in CO₂ emissions across the quarry sector and other highly transient diesel engine sectors. Aeristech Full Electric Turbocharger enables vehicle manufacturers to deploy vehicles with smaller, more efficient engines without loss of performance.
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1 Executive Summary

Increasingly stringent emissions regulations have led to extensive research within the automotive industry to improve engine performance and fuel consumption, most notably through engine downsizing and forced induction.

This Carbon Trust sponsored project focused on improving engine performance without compromising gas emissions performance by using a Full Electric Turbocharger developed by Aeristech. This technology can be applied to both on-road and off-road vehicles. In this project, the system’s performance was compared against a conventionally turbocharged (fixed geometry turbocharger) 4l diesel test engine running at medium load, 1200 rpm under steady-state and transient conditions.

Aeristech’s technology provides electrically-driven compressors and turbine generator units with high-speed direct drive. This type of technology typically offers significant efficiency improvements, as well as opportunity for size and cost reductions, compared to gear-driven electric turbomachines. Aeristech’s Full Electric Turbocharger was able to almost eliminate the turbo-lag and gain 14.3% more power in transient operation. Furthermore, Aeristech’s permanent magnet technology enables additional improvement in efficiency, a 75% reduction in size (per kilowatt), and a 50% reduction in cost (per kW) compared to high-speed switched reluctance machines.

The engine applications are improved air handling, turbocompounding, and engine performance enhancement. Electric turbomachinery has advantages in several segments:

- Passenger car market, where it supports engine downsizing to achieve CO₂ emissions reductions
- Heavy diesel on-road market, where it supports turbocompounding and efficiency improvement
- Heavy diesel off-road sector, where it supports rapid air delivery for soot reduction and turbocompounding for CO₂ reduction.

The UK aggregates sector accounts for approximately 2.7 million tonnes of carbon emissions each year with the off-road vehicles, used for transport on-site, accounting for 15% of this industry total (BCG, 2009). The UK aggregates sector aims to reduce carbon emissions by 15-20% by 2020. In order to achieve this, one approach is to improve the efficiency of quarry vehicle engines.

Aeristech has built a prototype of the Full Electric Turbocharger, adapted for the arduous duty cycles of quarry vehicles and completed testing the integration of the technology with a quarry vehicle engine at Birmingham City University’s engine test facility. The technology is designed to substantially eliminate turbo-lag to enable vehicle manufacturers to deploy vehicles with smaller, more efficient engines without loss of performance. Incorporating Aeristech’s technology into quarry vehicles could improve efficiency through: (i) exhaust gas energy recovery; (ii) improved combustion; and (iii) eliminating exhaust filtration.
This case study details the work undertaken to develop the turbocharger, the challenges faced, brief technical details, and the impact that successful replication of the technology across the UK could have on the aggregate sector’s carbon emissions.

2 The Project

This project was led by Aeristech and part of the Industrial Energy Efficiency Accelerator Programme funded by the Carbon Trust that helped identify innovations across 14 mid-energy intense sectors. Initial funding was provided by the Department of Energy & Climate Change (DECC), with follow-on funding by the Department of Business Innovation & Skills (BIS) through the Regional Growth Fund (RGF).

Aeristech applied and developed its background IP in the Full Electric Turbocharger to the latest embodiment/application/sector of heavy diesel engines and off-road quarry vehicles. This involved considerable modification of the underpinning technology and also an element of engine integration work, engine testing, and simulation analysis of engine and vehicle responses.

Aeristech, a technology development company, has developed its Full Electric Turbocharger for the automotive sector as well as the off-road sector. Likely interested companies include the main turbocharger companies, or other entities such as OEMs. The industry will need to invest in production capability and tooling to deliver the technology in its final form.

3 Development

As a precursor to this project, Aeristech approached leading manufacturers of off-road vehicles, Drax Power station (a user of off-road vehicles), and others to gain an understanding of the technical and commercial challenges surrounding the project. To achieve a technically and commercially useful result, it was agreed that the project would focus on a ‘real’ engine and would incorporate an element of integration with the engine’s ECU (on-board computer). The decision was taken to bring in Birmingham City University (BCU), as the owner/operator of a 4l diesel engine.

Aeristech contracted the services of Dr Manjit Srai, an expert in engine control strategy at BCU, who cultivated a relationship with Delphi - a major contributor to the implementation of engine control codes on the engine manufacturer’s production engines.

Aeristech came to the project from a position of having demonstrated the technical feasibility of the Full Electric Turbocharger’s constituent components. For this project, Aeristech had to
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develop a system with the properties needed to turbocharge the engine on a typical quarry duty cycle. This required scaling up the technology in terms of power, as well as operating the turbine and compressor at higher speeds and with higher voltages than in previous trials. Aeristech took on several members of staff in order to move the technology to the next level and produced a system ready for engine testing in Q2 2012. The system was commissioned in-house at Aeristech and produced favourable performance.

The project then continued with integration and testing at BCU. A significant setback was encountered when attempting to reprogram the engine’s ECU. After much effort, discussion, and further simulation analysis, the ECU was recalibrated into accepting the Full Electric Turbocharger, producing test results that were not completely optimised but acceptable within the margin of error designated as tolerable for the project (e.g. lack of redesigned and fully optimised turbomachinery and valve timing systems). Tests were completed in Q3 2012, with analysis and post processing continuing to the present day.

The results showed that for the same fuelling rate, the hybrid system produced 6.3% more torque (675 Nm) than the conventional system (635 Nm) with no increase in NOx emissions and substantial reductions in particulates. During a 10sec duty cycle, the hybrid produces 14.3% more power, providing an opportunity for downsizing the engine by a similar amount. The time to full torque output was reduced to 1.25sec from 4.75sec resulting in nearly 75% reduction in turbo lag. The faster transient response enables the engine to achieve steady-state exhaust flow at a faster rate, providing an opportunity to extract more energy from the exhaust gases. This would facilitate further reduction in CO₂ emissions and reduced use of the diesel particulate filter, with potentially further fuel saving.

Note:

The project started in 2009, when the EU Stage 3a emissions legislation was the current standard and the engine technology of the day reflected this legislative requirement. Since then, the emissions legislation has moved forward with EU Stage 3b being introduced in January 2012, which required around 90% reduction in particulate emissions alongside a new transient test cycle. To meet this new requirement the engine technology had to change from that used on the Stage 3a engines. This means that the engine technology today has moved on from the engine type used in the testing phase.
4 The Full Electric Turbocharger

Aeristech’s high speed motor and control technology enables a compact 35kW motor compressor to be accelerated to 150,000 RPM in 0.5 seconds. This enables air to be compressed into an engine almost instantaneously at any point in the engine cycle to greatly enhance the combustion process. This enables a quarry vehicle to burn less fuel and to reduce the fouling of its exhaust gas filter when in service, particularly in the challenging start-stop duty cycles that typify the quarry sector and differentiate it from the on-road heavy diesel sector.

The power to drive Aeristech’s high speed motor is derived from a turbine-generator powered by exhaust gas. This is an efficient power source, in the sense that air compression necessarily increases the amount of usable waste energy in the exhaust gas. Energy storage, in the form of a small and simple capacitor or battery, allows the turbine and the compressor to be mis-matched when the engine responds to dynamic changes in load, such as the action of powerful hydraulic systems and ancillaries found on quarry vehicles. Thus, Aeristech’s approach turns the turbocharger into a Full Electric Turbocharger, although the quantities of energy storage and battery capacity required for the Full Electric Turbocharger are far less (typically 1/5) than that required for a conventionally-understood hybrid powertrain. This makes the Full Electric Turbocharger uniquely feasible for powerful, utility vehicle applications.

Figure 1 shows a schematic of the full Electric turbocharger concept, with the turbine and compressor being independent machines with an electrical connection between them, rather than a conventional turbocharger with a shaft connecting the turbine to the compressor.

![Figure 1: Schematic of the Full Electric Turbocharger](image-url)
5 Technology Applications

The applications of the Full Electric Turbocharger are all applications of the mechanical turbocharger, minus certain highly-steady applications, plus certain highly-unsteady applications.

Highly-steady applications include certain types of power generators, where not only the speed but the torque output remains constant [e.g. base loaded generators]. In these applications, the mechanical turbocharger can be designed to exactly match the requirements of the engine in its steady-state operating point, so there is little or no benefit of adding a Full Electric Turbocharger. An electric turbine generator (part of the Full Electric Turbocharger) may still have a use in such an application. Highly-unsteady applications include many passenger car applications, where a mechanical turbocharger might provide an unacceptable amount of lag, leading the vehicle operator to prefer a Full Electric Turbocharger. In between these two extremes, either a mechanical or a Full Electric Turbocharger might serve, but the Full Electric Turbocharger will offer superior CO₂ performance.

In addition to the above, the Full Electric Turbocharger will often operate at higher boost pressures than a conventional mechanical turbocharger. Because the Full Electric Turbocharger is subject to greater control, the engine designer can specify a higher boost pressure knowing that, [1] the boost will be available more often, due to the elimination of lag and [2] the turbocharger will have a high efficiency, because of the ability of the Full Electric Turbocharger to operate the turbine and compressor at independent speeds. By operating at higher pressures, the Hybrid Turbocharged engine will be “more turbocharged” than the equivalent mechanically turbocharged engine.

In other words, an engine with a Full Electric Turbocharger can be more downsized and recover more exhaust energy without the ill effects of a mechanical turbocharger, such as smoke production and lag. This will provide a benefit to customers in the form of fuel consumption and CO₂.
6 Impact

6.1 Transient response

The engine was tested with a mechanical and a hybrid system. As shown on figure 2, the hybrid system receives the boost quicker than the mechanical one on transient response. This means that more torque is produced earlier on the crankshaft. At 1200 rpm, the lag to full torque output is 1.25 seconds with the Full Electric Turbocharger compared to 4.75 seconds with the mechanical turbocharger, as shown by the two bottom lines of the graph below.

![Aeristech vs conventional load step](image)

*Figure 2: Torque response of mechanical and Full Electric Turbocharger*

The steady value of the hybrid system’s engine torque is higher than the mechanical turbocharger one. Moreover, the steady fuel demand of the hybrid and mechanical turbochargers are the same, as shown on figure 3. The Full Electric Turbocharger produces more torque with the same fuelling, due to lower exhaust back pressure. Both the transient and the steady state improvements allow potential engine downsizing.
Steady state: The torque value of the hybrid system is 675 Nm at 1200 rpm, whereas the mechanical turbocharger is at 635 Nm at 1200 rpm. The Full Electric Turbocharger can produce 6.3% more torque at the same fuelling.

**Figure 3: Fuel response of mechanical and Full Electric Turbocharger**

Transient: The machine is using a 4.4l diesel engine which is running at 1200 rpm speed and 655 Nm load. The engine power is 82 kW [max engine power at 1200 rpm].

To picture what this represents, consider a case where an item with a mass of 8000 kg is lifted from ground to a height of 10 metres. The energy deployed by the machine is:

\[ \text{Energy} = 8000 \text{ kg} \times 10 \text{ m/s}^2 \times 10 \text{ m} = 800 \text{ kJ}, \text{where } 10 \text{ m/s}^2 \text{ is the acceleration of gravity} \]

Assuming the machine has a duty cycle of 10s, the item is lifted up during 10s. The machine’s power for this cycle is simply the energy divided by time, hence:

\[ \text{Power} = \frac{800 \text{ kJ}}{10 \text{ s}} = 80 \text{ kW} \]

Therefore, the power produced by the machine is comparable to lifting 8 tonnes over 10 m. This image helps to measure the impact of turbo lag on the total energy consumption to achieve that task. The fuel energy consumed and soot emitted to achieve that result will consequently vary whether the electric turbo is used or not.
The Full Electric Turbocharger response is better than the mechanical turbocharger on transient operation. Figure 4 shows the green area where the Full Electric Turbocharger delivers more torque than the mechanical turbocharger. The Full Electric Turbocharger can produce 14.3% more power during this 10s cycle. The engine can run at 1200 rpm and 565 Nm with the Full Electric Turbocharger instead of 655 Nm, and still produce the same total energy during the cycle (lift the same load as the mechanical turbocharger lagging but ultimately producing 655 Nm).

The fuel demand of the engine at 1200 rpm and 655 Nm is 125 mg/stroke, and 113 mg/stroke at 1200 rpm and 565Nm. So the engine can save 9.6% of fuel (and CO₂) with the Full Electric Turbocharger and get a 14.3% engine downsizing effect when compared with the mechanical turbocharger. There is also less friction with small engines, namely less bore and stroke. That means less fuel burning which suggests a possible further saving in CO₂ using Aeristech’s technology. However, this comparison is only valid for simple fixed geometry turbocharger. A modern engine equipped with a variable geometry turbocharger and EGR is more efficient and would not benefit of similar fuel saving and downsizing effect using Aeristech’s technology.
Figure 5: Transient exhaust flow rate of mechanical and Full Electric Turbocharger

Figure 5 illustrates the quicker hybrid exhaust flow rate compared to the mechanical system. On the 10s duty cycle of the engine, the hybrid system can reach the steady state very quickly. As a result, there is more time to capture more power from the exhaust gas.

6.2 NOx and particulate emissions

6.2.1 NOx emissions

The hybrid system can achieve better combustion whilst reducing emissions. Figures 6 shows the NOx emissions using the Full Electric Turbocharger and the mechanical turbocharger. The steady-state is comparable across the two configurations; hence, the hybrid system can produce more torque during the transient condition without sacrificing emissions control.
6.2.2 Particulate emissions

In order to reduce particulate matter emissions, some vehicles use a diesel particulate filter. A regeneration process is used to remove the accumulated soot from the filter. On-board active regeneration processes introduce high heat into the exhaust system and therefore use extra fuel and generate CO₂ emissions. As the Full Electric Turbocharger reduces the turbo-lag, the production of particulate matter is reduced as well.

The power of the mechanical turbocharger for the regeneration cycle is 24 kW, which is 5% of duty cycle. Avoiding filter regeneration would save 1.2 kW, which is saving 1.4% on that cycle. Further to the above, there is a potential CO₂ saving from the elimination of the exhaust gas filter and its associated pressure, providing a further 5.5% CO₂ savings during an average operating life.
6.3 Additional exhaust gas energy recovery

The hybrid system offers tremendous control opportunity, which enables to extract more power from the exhaust gas. The hybrid turbine generation runs independently from the compressor, so the turbine can reach its own preferred steady-state operating speed, for maximum efficiency. Figure 8 illustrates the principle of a turbine running at higher speed at 0.7 velocity ratio; the efficiency is increasing to 70% instead of 55 % with the mechanical turbocharger constrained to operate at the speed of the compressor.

The turbine power is 35 kW at 2000 rpm, full load, and 120 kW engine power. So the hybrid system can recover an additional 5.25 kW at full engine power, which can contribute to the total output of the engine and allow further engine downsizing or reduced fuelling. In this case, CO₂ emissions are reduced by 4.4% at ideal conditions, steady speed and load. However, the reduction would tend to be lower in real operating conditions.

Figure 7: Total efficiency versus velocity ratio of turbine [Baines, 2008]
Additional power can be exploited from the exhaust gas considering the cooperation of variable vane geometry with an electric turbine generator. Turbine efficiency is increased by up to 15% with a variable geometry turbocharger (VGT) [Stafford, Mulloy, Yonushonis, Weber, & Patel]. On Figure 8, the red line shows the turbine efficiency of the present hybrid system. The hybrid system can capture over 15% more energy with a variable nozzle turbine - a 30% improvement in energy capture compared to a mechanical turbocharger operating without a variable nozzle turbine.

**Figure 8: Turbine efficiency of mechanical turbocharger with Variable Nozzle Turbine, Full Electric Turbocharger (FETT) and improved FETT with Variable Nozzle Turbine**

6.4 **CO₂ reduction**

In addition to 4.4% direct CO₂ saving from the high level of exhaust energy recovery, elimination of exhaust filtration and potential for further engine downsizing compared to other turbocharging technologies could generate higher CO₂ saving. Furthermore, Aeristech expect to achieve further improvements in efficiency in the future. It is difficult to put an exact number on the carbon saving as the technology is still in technical development stage and the above analysis does not include integration issues such as the interaction with valve timing systems, EGR, and other systems to enable additional electrical energy to be delivered to the crankshaft or the vehicle’s ancillary systems.

It will be appreciated that much of the CO₂ impact is available to other sectors as well as to the quarry sector. The duty cycle used in analysing engine downsizing, for example, is a quarry-
derived cycle, but it bears similarities to other off-road applications. However, it is unclear to what extent engine downsizing is applicable to diesels with ‘softer’ duty cycles. Passenger diesel cars are a relatively stringent cycle, but on-road transport and utility applications are relatively amenable to mechanical turbocharging. The reduction of CO₂ in these applications is entirely feasible through the elimination of exhaust gas filtration and/or turbine energy recovery, so these areas of CO₂ reduction can potentially apply to a very broad range of diesel engines.

The European Commission is preparing new legislations to limit CO₂ and NOx emissions. The hybrid system would typically be more in line with the European legislation. EU member states are also likely to introduce taxation before new legislations. This technology would certainly meet the new environmental criteria and therefore offer a competitive advantage compared to the standard or twin turbochargers.
7 Challenges

As described above, a major challenge arose in the integration of the Full Electric Turbocharger with the engine control computer. Birmingham City University found a solution to the problem, with the help of Aeristech and Delphi. However, manufacturer involvement would be useful for further stages of integration, refinement, and CO₂ reduction.

8 Next Steps

Aeristech has sought to progress the development of its technology through undertaking engine test projects with global car makers and other OEMs. Indeed Aeristech is involved in one such project at the moment and is in discussion regarding others.

Aeristech has provisionally agreed to work with a major vehicle manufacturer to demonstrate the capability of its Full Electric Turbocharger on a vehicle application project linked to enhanced engine downsizing. Aeristech is interested in bringing in key Tier 1s and Tier 2s to collaborate with Aeristech in this project.

Acknowledgement

We would like to thank James Tran, Asuquo Andah, Nicholas Gill and Bryn Richards for helping to write this case study. We would also like to thank Manjit Srai from Birmingham City University for expert input.

Further information

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