Institution: University of Bath		
Unit of Assessment: B12 Engineering		
Title of case study: Delivering new development processes resulting in reductions in CO_2 and pollutants from the global Ford vehicle fleet		
Period when the underpinning research was undertaken: 2012 - 2017		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Sam Akehurst	Professor, previously Reader, Lecturer	January 2000 - present
Colin Copeland	Reader, previously Lecturer	September 2012 - January 2020
Chris Brace	Professor, previously Reader, Senior Lecturer	September 1992 - present
Jamie Turner	Professor	January 2015 - January 2021
Period when the claimed impact occurred: 2018 - 27 October 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The development of novel experimental and simulation techniques at the University of Bath has enabled Ford Motor Company to implement faster and better product development practice (Impact 1) that allows design decisions to be made safely much earlier in the development process. This can identify and resolve serious problems a year earlier than the established method, an outstanding impact in terms of reach and significance.

This process was developed at the University of Bath as part of a research project that resulted in a decrease of 9% CO_2 emissions of the UK's best-selling car (Impact 2) – the Ford Fiesta - alongside substantial reductions in pollutant emissions. The technology that the University of Bath helped to develop has also been deployed in a range of other Ford vehicles, delivering similar improvements.

Since 2018 Ford has produced 1,400,000 new vehicles each year which emit less CO_2 and pollutants because of Bath's research, delivering an annual cumulative saving of 200,000tCO_2/year of production, equivalent to taking 109,000 average cars off the road every year since 2018. Hence the total saving in the period 2018 to 31 July 2020 is 700,000tCO_2. 94% of these engines are exported outside the UK and used in Ford's global fleet of vehicles.

2. Underpinning research

In 2013, while planning the development of its revised EcoBoost engine to meet new CO_2 and performance targets, Ford asked the University of Bath to apply their expertise in highly downsized engine systems [1, 2, 3, 4] to better understand and model the complex engine boosting system. The research at Bath began in 2014. Specifically, the Bath team studied how non-steady energy transfers from a highly pulsating exhaust flow affect the performance of a novel mixed-flow turbocharger [5]. A subsequent aim was to incorporate the new techniques into an improved development process.

Novel Experimental and Simulation System Development

Existing design techniques for engine development use simple models of turbocharger performance based on datasets captured experimentally under steady flow conditions. True dynamic performance cannot be assessed until much later in the development process when the engine and turbocharger are fitted into a vehicle.

To provide greater insight into dynamic performance at an early stage in the process, the Bath team designed a technique to move from steady state to dynamic real-time data. They developed a novel experimental system that could be used to study the behaviour of the turbocharger under pulsed air mass flow and high-speed pressure fluctuations, realistically recreating the phenomena seen on-engine. The University of Bath team, led by Professor Sam Akehurst and Dr Colin Copeland, designed, built and demonstrated the first facility of this type in the world [6].

The exhaust pressure pulses caused by individual engine cylinder firing events were recreated by a novel hot gas pulse generator. Changing the frequency of the valve events simulates changing engine speed. To achieve robust, high fidelity measurement of the critical temperature and pressure fluctuations at the turbine inlet required the development of a high-speed mass flow sensing system using a novel, 3D printed, metal pitot tube architecture, complementing data from more traditional sensors. Similar challenges were overcome when quantifying unsteady turbine efficiency, which required the ability to measure the time-resolved mass flow rate at high speed. Full-scale engine experiments studies further refined the technique to ensure correlation of the process with real-world behaviour across all operating conditions.

The data and insight gained were used to develop new dynamic simulation methods that predict the behaviour of the complete engine/turbocharger system under realistic dynamic conditions. The simulation was used to model system behaviour, demonstrating that the required dynamic performance was achievable. Additionally, the simulation provided an early warning of a control instability leading to flow disturbances that would render vehicle performance unacceptable. This was achieved at a point in the programme at least a year in advance of when such issues would normally be evident in vehicle testing.

Recognised as 'Globally Unique'

This new capability is recognised by the Government's Technology Strategy Board [C] as globally unique, and the technique has been patented (GB2536760A·2016-09-28). To make the improved understanding delivered by this research more widely available and to reduce the cost and time required to apply it, the University of Bath then used data and insights from the laboratory simulations to support the development of a high fidelity, computer-based dynamic model of airflow within a turbocharger.

3. References to the research

[1] Turner, JWG, Popplewell, A, Patel, R, Johnson, TR, Darnton, NJ, Richardson, S, Bredda, SW, Tudor, RJ, Bithell, CI, Jackson, R, Remmert, SM, Cracknell, RF, Fernandes, JX, Lewis, AGJ, Akehurst, S, Brace, CJ, Copeland, CD, Martinez-Botas, R, Romagnoli, A & Burluka, AA. 2014. 'Ultra boost for economy: extending the limits of extreme engine downsizing', *SAE International Journal of Engines*, vol. 7, no. 1, pp. 387-417. https://saemobilus.sae.org/content/2014-01-1185/

[2] Turner, JWG, Popplewell, A, Marshall, DJ, Johnson, TR, Barker, L, King, J, Martin, J, Lewis, AGJ, Akehurst, S, Brace, CJ & Copeland, CD. 2015. 'SuperGen on ultraboost: variable-speed centrifugal supercharging as an enabling technology for extreme engine downsizing', *SAE International Journal of Engines*, vol. 8, no. 4, pp. 1602-1615. https://doi.org/10.4271/2015-01-1282

[3] Turner, JWG, Popplewell, A, Richardson, S, Lewis, AGJ, Akehurst, S & Brace, CJ. 2013. 'The Ultraboost Extreme Downsizing Project: Direct Injection, Compound Charging, Variable Valve Timing and 60% Less Capacity', Paper presented at 22nd Aachen Colloquium Automobile and Engine Technology 2013, Aachen, Germany, 7/10/13 - 7/10/13. https://purehost.bath.ac.uk/ws/portalfiles/portal/218563759/A6.1_Turner_Jaguar_2013.pdf

[4] Lewis, AGJ, Brace, CJ, Akehurst, S, Turner, J, Popplewell, A, Richardson, S & Bredda, SW. 2013. 'Ultra boost for economy: realizing a 60% downsized engine concept', Paper presented at IMechE Internal Combustion Engines: Performance, Fuel Economy and Emissions Conference, London, UK United Kingdom, 19/11/13 - 19/11/13. (Available on request)

[5] Liu, Z & Copeland, C. 2020. 'Optimization of a Radial Turbine for Pulsating Flows', *Journal of Engineering for Gas Turbines and Power*, vol. 142, no. 5, GTP-19-1257, pp. 1-17. https://doi.org/10.1115/1.4046235

[6] Vijayakumar, R, Akehurst, S, Liu, Z, Reyes Belmonte, M, Brace, C, Liu, D & Copeland, C. 2019. 'Design and Testing a Bespoke Cylinder Head Pulsating Flow Generator for a Turbocharger Gas Stand', *Energy*, vol. 189, 116291, pp. 1-16. https://doi.org/10.1016/j.energy.2019.116291

4. Details of the impact

Impact 1 - Extending the use of digital development tools (change to practice)
As laid out by the Automotive Council, over the next decade the automotive industry needs to adopt new development practices to shorten product development from 5 years to 18 months, under increasing regulatory pressure. This will require a change from today's practice, where around 95% of product verification is achieved experimentally, to an end state where 95% of the process is digital. The challenge is enormous and will require much better digital models of complex powertrain systems.

A key obstacle is the lack of accuracy in simulation of the dynamic performance of turbochargers, commonly leading to overly optimistic design choices that later result in unacceptable performance deficiencies in real world use. As result the standard technique is to complete the evaluation of dynamic performance in vehicle, late in the vehicle development programme, when any changes are enormously expensive. This led to a strong pull through for the research from Ford, who wished to use the improved experimental methods and computer model to allow fast, accurate understanding of how airflow influences the behaviour of turbomachinery. This in turn allowed CO_2 and fuel economy benefits to be realised with lower risk of delays and changes late in the programme.

The techniques developed by the Bath team have been incorporated into the product development process used by Ford to develop the revised 1 litre EcoBoost and subsequent engines. The impact of this has been to improve the quality and speed of the development process when compared with the incumbent approach. The impact was to allow this evaluation at least a year earlier in the development process, a significant impact. As stated by Ford UK Innovation leader [A]:

> "*The Bath team developed a novel pulsating flow experimental test facility to characterise and optimise the turbocharger. This facility was so effective and unique that Ford Motor Company filed a patent to secure its IP, with Akehurst and Copeland as named inventors. (See DE102016121974 and GB2536760)*".

The adoption of this approach in the development process at Ford since 2015 has allowed outstanding reach for the impact, initially to include additional Ford engine programmes, and then to engine and system designers at other companies. Furthermore, this approach contributes towards the strategic goal for the industry - a more virtual product development process - by improving the fidelity of the analysis to a level not normally achieved until the physical hardware is available in a vehicle.

Impact 2 - Exceptional UK and Global CO_2 Reduction
Passenger cars represent 60.2% of EU road transport CO_2 emissions, themselves equivalent to 21.6% of all EU's CO_2 emissions [B]. The Ford Fiesta is the 4^{th} best-selling passenger car in

Europe, 1st in the UK. Therefore, any improvements that can be made have international reach due to the huge number of vehicles affected.

The primary impact of the University of Bath research was to develop and apply a novel research technique that allowed Ford's objectives to be met through precise but significant changes to turbocharger design and engine calibration, allowing their CO_2 reduction strategy to enter high volume production. The programme passed Ford's 'Judgement Gateway' in August 2016, meeting or exceeding all targets for fuel economy, CO_2, pollutant emissions and refinement. Engine production began in November 2017 with fitment planned for the Fiesta, the Focus (the UK's second best-selling vehicle) and seven other Ford models.

As noted by Ford [A]:

> "A*s a consequence of Bath's research... the ACTIVE programme* [C, D] *demonstrated a 13% improvement in vehicle fuel economy with 9% due to the engine technologies. The engine went into mass production in 2017 and is now available across a wide range of the Ford vehicle portfolio, to date more than 300,000 engines have been produced utilising the technology developed, peak demand for the engine family is expected to be around 1,400,000 vehicles per year. This would equate to approximately 200,000 tonnes of reduced CO_2 for a single year of production*." Furthermore, "*around 1,400,000 new Ford vehicles each year emit less CO_2 and pollutants because of this work, delivering an annual, cumulative CO_2 saving equivalent to taking 109,000 average cars off the road every year*".

This impact clearly has international significance in CO_2 terms alone. More efficient engines also offer the driver improved fuel economy, roughly equivalent to the percentage CO_2 reduction, saving money for the business or individual operating the vehicle and reducing the need for fossil fuels. The financial savings for a typical driver would be around GBP100 per annum.

The University of Bath work contributed to Ford winning the 2019 Global Engine of the Year award (under 150bhp category) following assessment by 70 specialist judges from 31 countries. The Ford of Britain Chairman stated that [A]:

> "*Bath directly contributed to fundamental research to improve the performance and integration of… our 1 Litre EcoBoost engine, which was voted engine of the year from 2012 to 2014 and best Sub 150PS engine in 2019*".

5. Sources to corroborate the impact

[A] Testimonial letter from Director of Ford UK Innovation and Ford of Britain Chairman, Ford Motor Company Limited, 27 October 2020.

[B] News European Parliament. 2019. 'CO_2 emissions from cars: Facts and figures (infographics). 22 March (updated 18 April). Available at: https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics

[C] Witt, D. and Chick, D. 2016. Project completion report: ACTIVE: Advanced combustion turbocharged inline variable valvetrain engine. Technology Strategy Board.

[D] UK Research and Innovation. Funded period: May 2014-October 2016. ACTIVE - Advanced Combustion Turbocharged Inline Variable valvetrain Engine. Project reference 101891, Funded by the Advanced Propulsion Centre call 'Building UK manufacturing strength in LCV'. Available at: https://gtr.ukri.org/projects?ref=101891