Institution: Loughborough University		
Unit of Assessment: B12 - Engineering		
Title of case study: Reducing Fuel Burn and CO_2 Emissions in Rolls-Royce Turbofans through Improved Integrated Compressor Duct Technologies		
Period when the underpinning research was undertaken: 2004 – 2020		
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:**
A. D. Walker J. F. Carrotte	Reader in Applied Aerodynamics Professor of Aerothermal Technology	1997 – present 1996 – present
Period when the claimed impact occurred: 2014 to present		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact (indicative maximum 100 words)

Climate change is a global issue and in 2017 the International Air Transport Association estimated aviation generated 859m tonnes of CO_2. Given the current growth rate in air travel, this is unsustainable. Research at Loughborough and Cambridge Universities has led to significant advances in compressor duct technologies used in Rolls-Royce large civil aero engines (turbofans). These advances represent a paradigm shift in engine architecture and have led to 1) a fuel burn saving of 0.25%, equivalent to an annual saving of ~£14,600,000 in fuel and thus economic benefit; 2) reduced emissions of ~71,000,000 kg in CO_2 for the current fleet of 379 aircraft operating the Trent XWB, and, collectively, resulted in 3) the transformation and improvement of duct design for the Rolls-Royce Trent XWB.

2. Underpinning research (indicative maximum 500 words)

Modern aero engines employ annular s-shaped transition ducts to connect the low- and high-pressure compressors. Reducing the duct length and hence engine weight has a direct benefit on fuel savings and emissions. However, the design of these transition ducts is challenging due to their conflicting aerodynamic and structural requirements.

From 2004-2011 research conducted, in collaboration with Cambridge University, within the EU-FP6 projects AIDA[i] and NEWAC[ii] generated improved understanding of duct aerodynamics. This enabled Loughborough to develop new numerical methodologies, new innovate designs, and rapidly evaluate these on a bespoke test facility. The Loughborough test facility provided a rapidly reconfigurable test vehicle able to reproduce engine representative aerodynamics at a fraction of the cost of engine tests. Within this framework Loughborough conceived and demonstrated a new technique that integrated compressor outlet vanes into the duct achieving a 21% reduction in length **[R1].**

Subsequently, research undertaken between 2011-2015, within the EU-FP7 LEMCOTEC[iii] project, concentrated on further improving the aerodynamic integration of neighbouring components within large turbofan engines **[R2]**. This allowed for previously parasitic and weight adding struts to be redesigned to remove compressor swirl without detrimental effect on the complex flow field **[R3]**. Patented designs **[R4]** physically integrated these struts into the compressor outlet vanes whilst masking any undesirable component interaction. Merging these components realised a further ~10% reduction in system length.

From 2016-2019, within the Innovate UK iCORE[iv] programme, focus moved to the duct immediately downstream of the fan feeding the engine core. The inclusion of a gearbox, for example in the UltraFan^{TM} engine, increases the challenge for this duct as it is required to undertake increased aerodynamic turning in addition to being fed by the poor-quality flow emanating from the fan root. This was quantified using a combination of computational and experimental methods **[R5]** and the subsequent improved understanding led to Loughborough developing new integrated designs. These addressed the trade-off between aerodynamically and structurally optimised solutions **[R6]**. For example, employing a structural vane with a clean duct as opposed to an aerodynamically optimised vane integrated with a separate strut.

In parallel (2018-2020) work was also undertaken by Loughborough, in collaboration with GKN Aerospace, as part of the EU Clean Sky 2 project IDA[v]. The Loughborough research investigated the impact of a bleed at the exit of the compressor immediately upstream of the transition duct. This bleed is used to allow the engine to operate more efficiently when not at the design condition. Using computational predictions failure mechanisms and bleed limits were identified providing clear boundaries to the design space.

[i] Aggressive Intermediate Duct Aerodynamics, https://cordis.europa.eu/project/id/502836
[ii] New Aero Engine Core Concepts, https://cordis.europa.eu/project/id/30876
[iii] Low Emission Core-Engine Technologies, https://cordis.europa.eu/project/id/283216
[iv] Integrated Core Technologies, https://gtr.ukri.org/projects?ref=113076
[v] Intermediate Compressor Case Duct Aerodynamics, https://cordis.europa.eu/project/id/785317

3. References to the research (indicative maximum of six references)

The underpinning research was funded via competitive grants totalling more than £2.5m. This included grants from the EU (Framework Programmes 6 and 7, Horizon 2020, Clean Sky), the UK Government (ATI, Innovate UK, EPSRC). It included collaboration with academic partners (Cambridge University) and with industry (Rolls-Royce, GKN Aerospace). The work generated several patent applications and high-quality papers published in peer-reviewed journals and at global conferences. This has guaranteed wide-spread dissemination of the work to both academia and industry.

[R5] also received the Best Paper Award from the ASME Turbo Expo Turbomachinery Committee.

R1 Walker, A. D., Barker, A. G., Carrotte, J. F., Bolger, J. J., and Green, M. J. (2012). Integrated Outlet Guide Vane Design for an Aggressive S-Shaped Compressor Transition Duct. *ASME Journal of Turbomachinery*, 135 (1), 011035. DOI: https://doi.org/10.1115/1.4006331.

R2 Walker, A. D., Regunath, G. S., Carrotte, J. F. and Denman P. A. (2012). Intercooled Aero Gas Turbine Duct Aerodynamics: Core Air Delivery Ducts. *AIAA Journal of Propulsion and Power*, 28 (6), pp. 1188-1200. DOI: https://arc.aiaa.org/doi/10.2514/1.B34450.

R3 Walker, A. D., Barker, A. G., Mariah, I., Peacock, G. L., Carrotte, J. F., and Northall, R. M. (2014). An Aggressive S-Shaped Compressor Transition Duct with Swirling Flow and Aerodynamic Lifting Struts. *Proceedings of the ASME Turbo Expo*, 2A, V02AT40A002. DOI: https://doi.org/10.1115/GT2014-25844.

R4 Northall, R., Mariah, I., Carrotte, J. F., Krautheim, S., Rae, A., and Walker, A. D. (2018). "Gas Turbine Engine Vanes", Patents US20180252231A1, EP2269893A1, GB210703422D0, US20180252113A1, EP2269891A1, GP201703423D0.

R5 Walker, A. D., Mariah, I., Tsakmakidou, D., Vadhvana, H., and Hall, C. (2019). The Influence of Fan Root Flow on the Aerodynamic of a Low-Pressure Compressor Transition Duct. *ASME Journal of Turbomachinery*, 142 (1), 011002. DOI: https://doi.org/10.1115/1.4045272.

R6 Walker, A. D., Mariah, I., and Hall, C., 2020, "An Experimental Aerodynamic Evaluation of Design Choices for a Low-Pressure Compressor Transition Duct", Paper GT2020-16318, presented at the ASME Turbo Expo 2020: Turbine Technical Conference and Exposition, London, UK, September 21-25, 2020, https://doi.org/10.1115/GT2020-16318

4. Details of the impact (indicative maximum 750 words)

Aviation contributes 2-3% of human generated CO_2 emissions and in 2017 the IATA estimated this amounted to 859m tonnes of CO_2. Given that passenger numbers are expected to double by 2037 the increasing impact of aviation is unsustainable. Motivated by this, research at Loughborough has produced substantial advances in compressor duct technologies. This has produced shorter ducts with more aggressive turning which has enabled a more efficient and lighter compression system. This has led to the following research-based impacts.

Impact 1: Reduced fuel consumption led to commercial benefits for industry

a) to Rolls-Royce – Trent XWB

Rolls-Royce applied the new duct technologies **[R1]** to the compressor duct in their Trent XWB engine which "*reduced the specific fuel consumption of the engine by 0.25%*" **[S1]** (Dr John Bolger, Engineering Fellow, Rolls-Royce). The Loughborough research is therefore integral to the success of Rolls-Royce's fastest selling widebody engine. Entering service in 2014, the Trent XWB is marketed as the "*world's most efficient large aero-engine*" **[S2]**. It has record orders of over 1600 and is the sole option for the Airbus A350. In 2019 the XWB accounted for over half of the civil aero engines delivered by Rolls-Royce who are currently the world's second-largest manufacturer of aircraft engines.

b) to Airbus

Airbus, the world's largest airliner manufacturer, state **[S3]** that the A350 "*will shape the future of aviation*" and "*burns 25% less fuel and generate 25% less CO_2 emissions compared to the long-range aircraft it replaces*". Fuel accounts for approximately a quarter of an airlines' operating cost. As of Sept 2020, Airbus's published figures **[S4]** stated there were 379 A350 aircraft in service with 36 different airlines and there were a further 591 aircraft on order. Aviation experts estimate **[S5]** that an A350 flies an average of 13 hours per day with a fuel cost of ~£3250/hr. Based on these data a simple calculation shows that the 0.25% reduction in fuel consumption equates to a ~£14,600,000 per year fuel cost saving for the current A350 fleet**.** This will more than double when the remaining aircraft are delivered.

Impact 2: The environment benefited from reduced emissions of CO_2

A long-range aircraft such as the A350 will burn ~5000kg of fuel per hour generating three times that in CO_2. Based on the data from the aviation industry **[S4, S5]** a 0.25% saving in fuel equates to an annual reduction of ~71,000,000 kg CO_2 for the current A350 fleet**.** Again, this will more than double when the remaining aircraft are delivered.

Impact 3: Duct design for Rolls-Royce has been transformed and improved

The new duct technologies **[R2-R6]** have also played an essential role **[S1]** in development of the Rolls-Royce Advance3 and UltraFan^{TM} engines. These new engines represent a paradigm shift in engine architecture and, according to Rolls-Royce **[S6]**, are crucial to the company's future strategy for an environmentally and economically sustainable large civil engine programme. Loughborough has provided new, computational design methodologies **[R2-R6]** which have significantly speeded up the design process reducing development time and cost.

This led to new, knowledge-based, and patented design solutions **[R4]** for the Advance3 and UltraFan^{TM} engines which have been validated on the unique Loughborough test facility **[R6]** reducing the need for costly full-scale engine testing. An integrated design strategy has led to further fuel burn and CO_2 savings of approximately 0.1% **[S7]**. Again, this equates to many millions of pounds over the life of an engine product. The Loughborough design philosophy is now embedded in best practice methods at Rolls-Royce. As Dr Hall, a Compressor Aerodynamics Specialist at Rolls-Royce stated **[S7]**, Loughborough research had direct impact on engine development programmes and has "*provided the foundation for the Advance 3 duct design*" and "*de-risked the novel UltraFan engine demonstrator design and has enabled us to optimise duct length*".

New understanding of compressor duct aerodynamics generated by Loughborough has also been crucial to GKN Aerospace **[S8]**, a major supplier to global engine manufactures. Dr Wallin, R&T Program Manager at GKN **[S8]** states that Loughborough research has "*developed product-specific solutions*", and "next generation CFD tools" for GKN. This has allowed GKN Aerospace to improve their market position – GKN are now responsible for suppling compressor ducts to SAFRAN, MTU, Rolls-Royce and General Electric.

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1 Dr John Bolger, Engineering Fellow - Aerodynamics, Rolls-Royce plc.
S2 Rolls-Royce plc., "Trent XWB", September 2020. www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-xwb.aspx#section-overview
S3 Airbus, "A350 XWB Family: Shaping the Future of Air Travel", August 2019. https://www.airbus.com/content/dam/corporate-topics/publications/backgrounders/Backgrounder-Airbus-Commercial-Aircraft-A350-XWB-Family-E.pdf
S4 Airbus Orders and Deliveries, September 2020, https://www.airbus.com/aircraft/market/orders-deliveries.html
S5 Reported Operating Cost and Utilization of Wide-body Jets, https://www.planestats.com/bhsw_2019sep
S6 Rolls-Royce plc., "Future of Flight", https://www.rolls-royce.com/media/our-stories/innovation/2016/advance-and-ultrafan.aspx#overview
S7 Dr Chris Hall, Compressor Aerodynamics Specialist, Rolls-Royce plc.
S8 Dr Fredrik Wallin, R&T Program Manager, GKN Aerospace, Sweden.