Institution: University of Manchester		
Unit of Assessment: 7 (Earth Systems and Environmental Sciences)		
Title of case study: The development of new international regulatory standards deliver global engine emission limits and reduction in aviation soot		
Period when the underpinning research was undertaken: 1 Jan 2009 – 31 Dec 2019		
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:**
Paul I Williams	Senior Lecturer (2019 – present) Research Fellow (2009 – 2019) Research Associate (2004 – 2009)	2009 – present
Period when the claimed impact occurred: 1 August 2013 – 31 July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The University of Manchester has developed research-led methods to quantify and standardise the measurement of non-volatile particulate matter (nvPM) from aircraft engines, impacting an industry worth approximately USD10Billion per annum. These methods were adopted by the International Civil Aviation Organisation (ICAO) to update aircraft emissions regulations, which affect local air quality across the globe. New international measurement and emission standards for large aircraft engines were introduced. This research enabled:

i) two new international standards for nvPM emissions measurement;
ii) subsequent technical contribution and drafting of the ICAO regulatory documents; and
iii) the introduction of nvPM mass and number concentration emission limits for new aircraft engines, to reduce global aviation soot.

2. Underpinning research

In 2009, ICAO recognised the requirement for a new metric and emissions standard for aircraft engines above 26.7 kN of thrust (the entire global commercial, non-propeller air fleet). This was driven by the need to address the environmental impact of the global air industry. Prior to this, standardised processes existed to measure both gaseous emissions (NO_x, HC, CO), and an outdated visibility metric called smoke number, but not for non-volatile particulate matter (nvPM, or soot) number and mass concentrations.

Research undertaken by Williams at the University of Manchester (UoM) formed an integral part of the body of work that informed these regulatory standards on emissions of nvPM. As an expert in aerosol measurement and aircraft emissions, Williams was instrumental in all stages of the research and provided key aerosol measurements, quantified the number and size data, and evaluated the aerosol losses and uncertainty in the systems.

The UoM research was funded by the European Aviation Safety Agency (EASA) through a series of international programmes involving academic and industry partners (SAMPLE I-III, 2008-2014; EASA specialist support I–IV, 2014–2019).

The EASA funded research progressed through a series of key components needed to produce the standards:

i. Identification of suitable measurement technologies and sampling protocols

In 2010, the EASA funded SAMPLE team evaluated methods for measuring nvPM emissions from gas turbines in order to identify suitable technologies for emission measurement. Williams' research activities in aerosol counting and sizing made a key contribution by providing equipment and analysis of the data contained in [1]. This research [1] identified that condensation particle counter (CPC) instruments proved highly robust tools for measuring aerosol number concentrations; and due to the much smaller scatter in data, were preferred over instruments that indirectly measured aerosol concentrations.

ii. Validation of proposed methodologies and development of software and procedures for correcting data.

Following the identification of aerosol measurement technologies, research was undertaken to develop measurement strategies and methodologies to sample all gas turbine engines with >26.7 kN of thrust, whilst simultaneously developing software and procedures that quality-assure and correct the data collected [2]. All aerosol sampling systems are subject to particle losses, such as diffusional losses, electrostatic losses and thermophoretic losses, which are modelled and verified in the proposed standards. This involved testing the proposed nvPM sampling system in small scale combustor rigs and the exhaust of aircraft turbine engines [1,2].

iii. Measurement of real engine emissions using the new methodology and data handling procedures, to allow ICAO to set appropriate current and future emission limits

In 2013, research progressed to develop the EU emission regulatory reference system that would provide data to ICAO to set appropriate emissions limits [3]. Engine manufacturers are required to ensure their own systems are compliant with one of three regulatory reference systems; there are three reference systems, and manufacturers must show equivalence to one (EU, North American and Switzerland).

A crucial part of the research was to determine the uncertainty in the sampling system and differences between the reference systems used by different aviation regulators (e.g. the US Federal Aviation Administration). Therefore, a comparison of the nvPM system with two other reference systems was needed [3,4]. This was to provide confidence that these reference systems deliver repeatable and comparable data when measuring the same engine at the same time, and to provide quantification of the measurement uncertainty for later modelling. The EU nvPM reference system, alongside the reference systems from North America and Switzerland, was tested against a range of engines to compare their performance. Williams' research contributed expertise in aerosol counting and sizing to help validate the comparison of the reference system and to determine and model the losses in the proposed measurement standard [3].

iv. Determination of uncertainties in the sampling framework and hence the values reported by engine manufacturers to ICAO

Throughout the SAMPLE projects, new understanding was generated around aerosol sampling loss and uncertainty modelling. From 2014, the research expanded into the losses and uncertainties in the proposed nvPM measurement methodology. Williams quantified the nvPM number and size data of real engines and evaluated the aerosol losses and uncertainty in the measurement systems [3,5]. This enabled bespoke loss and uncertainty models for the sampling system to be developed, which fed directly into the final recommended regulatory documentation.

3. References to the research

The research was published *via* International Standards, end of project technical reports, and peer reviewed journals, including one of the top journals in the field (*Environmental Science and Technology*). The research has secured EUR496,000 of funding (EUR242,000 from EASA and EUR227,000 under the OMEGA ALFA scheme).

[1] Petzold, A., Marsh, R., Johnson, M., Miller, M., Sevcenco, Y., Delhaye, D., Ibrahim, A., **Williams, P. I.**, Bauer, H., Crayford, A., Bachalo, W. D., and Raper, D. (2011) Evaluation of methods for measuring particulate matter emissions from gas turbines, *Environmental Science and Technology*, **45**(8), p3562 – 3568. DOI:10.1021/es103969v (Web of Science citation count 34 ;November 2020)

[2] Marsh, R., Sevcenco, Y., Walters, D., **Williams, P. I**., Petzold, A., Bowen, P., Wang, J., and Lister, D. SAMPLE III: Contribution to aircraft engine PM certification requirement and standard Second Specific Contract– Final Report, 2012. https://www.easa.europa.eu/document-library/research-projects/easa2010fc10-sc02

[3] Crayford, A., Johnson, M., Llamedo, A., **Williams, P. I**., Madden, P., Marsh, R., and Bowen, P. SAMPLE III: Contribution to aircraft engine PM certification requirement and standard Third Specific Contract– Final Report, 2013. https://www.easa.europa.eu/document-library/research-projects/easa2010fc10-sc03

[4] Lobo,P., Durdina, L., Brem, B.T., Crayford, A., Johnson, M., Smallwood, G., Siegerist, F., **Williams, P.I.,** Black, E., Llamedo, A., Thomson, K., Trueblood, B. Yu, Z., Hagen, D., Whitefield, P., Miake-Lye, R., and Rindlisbacher, T. (2020) Comparison of standardized sampling and measurement reference systems for aircraft engine non-volatile particulate matter emissions, *Journal of Aerosol Science*, **145**, DOI: 10.1016/j.jaerosci.2020.105557.

[5] Crayford, A., Johnson, M., Sevcenco, Y. A., **Williams, P. I**., Madden, P., Marsh, R., and Bowen, P. J. SAMPLE III: Contribution to aircraft engine PM certification requirement and standard Fifth Specific Contract– Final Report, 2014. https://www.easa.europa.eu/document-library/research-projects/easa2010fc10-sc05

4. Details of the impact
Context
Prior to this work, particulate emissions regulations from aircraft engines in the Landing and Take-Off (LTO) cycle were last updated in the 1970s. This previous regulation, based on a metric called “smoke number” (used as a measure of visibility), was not sufficient to address modern local air quality issues affecting human health [A]. In 2009, ICAO called for a new metric and emissions standard for engines rated above 26.7 kN of thrust. ICAO commissioned The Society of Automotive Engineers (SAE) Aircraft Engine Gas and Particulate Emissions Measurement Committee (E-31) to develop this international standard. In order for regulatory standards for nvPM mass and number emissions to be defined (and thus support future global efforts to improve air quality and public health, as part of the United Nations Millennium Development Goals), a standardised sampling and measurement methodology was required for aircraft engine emissions certification tests.

Pathways to impact
Williams became a key member of the EASA SAMPLE project as a result of his early work and reputation on characterising the chemical and physical properties of aerosol particles. Williams’ role was to collaborate on the technical design of a new nvPM sampling system and the production of a methodology to standardise nvPM measurement across the industry [B], and provide input to the SAE E-31. Following this, Williams was appointed a voting member of the SAE E-31 Committee, enabling him to help develop and subsequently approve the standards for nvPM measurement and reporting [C]. This position enabled Williams’ to directly contribute to the writing of the official ICAO regulatory documentation [B,D].

i) Technological impacts: new technical standards and revised industry regulation
Williams’ research in the SAMPLE project [2,3,5] was an essential component to the development of two new international standards, and to updating the associated regulatory documents, which all large engine manufacturers must now use to report their nvPM emissions to ICAO. These are:

- **ARP 6320:** Procedure for the Continuous Sampling and Measurement of Non-Volatile Particulate Matter Emissions from Aircraft Turbine Engines [E] (2016)
- **ARP 6481:** Procedure for the Calculation of Non-Volatile Particulate Matter Sampling and Measurement System Losses and System Loss Correction Factors [F] (2019)

- Contribution to the writing of ICAO regulatory documents Annex 16, Vol II, Appendices 7 & 8 [B,D]

Within the regulations, Williams' research was a key component to the setting of the new nvPM emission index limits (emission indices: corresponding to amount of nvPM per kg of fuel burnt) that ICAO approved. These emissions indices were for both aerosol mass of nvPM per kg of fuel burnt (EI_m) and reported number of nvPM per kg of fuel burnt (EI_n).

As corroborated by the EASA Environmental Protection Officer, for ARP6320, Williams' research [1-5] "*contributed to the design and build of the first prototype system, and ultimately to the development of the EASA mobile nvPM system…and developed a software package for EASA which mirrors the functionality of the software tools supported in the ARPs [enabling Williams] to contribute directly to ARP 6481."* [B]**.** Without this approved standardised measuring procedure, a regulated measurement standard would not have been possible.

In addition to underpinning the technology and methods for size and number concentration measurements, Williams' research directly contributed to validating the line losses and uncertainties in the sampling system [A,B]. In 2016, drawing on his work in [5] and as a result of his role on the SAE E-31 committee, Williams identified a fundamental flaw in the error analysis of the uncertainty calculations, where variables were being treated independently, but were in fact co-varying [B]. Failure to correctly account for the uncertainties would impact ICAO's ability to set realistic goals for reducing the emission standards. In addition, it would impact the emission inventories that scientists and air quality regulators use to assess the impacts on local air quality. Williams' model of the engine exit plane EI_n and EI_m (as developed as part of the work reported in [5] and subsequent EASA projects funded between 2014 and 2019), is currently the only full model in existence, and predicted smaller uncertainties than other approaches adopted within E-31.

Engine manufacturers are required to follow the ICAO Annex for reporting and emission standard compliance when they submit to ICAO for approval of the emissions data they record during engine certification tests. 192 countries are signed up to ICAO, and these new technological standards ensure that from 2020, all in-production engines over 26.7 kN of thrust (all commercial jet engines, excluding turboprop and small turbofan engines) operating in ICAO signatory national airspaces must conform to these standards of reporting EI_m and EI_n, limits.

ii) Environmental impacts: improved regulation standards leading to reduced emissions

Williams' work [2,3,5] in contributing to the measurement standards for measuring nvPM were fundamental in ICAO determining the limits of nvPM permissible by aircraft engines. As stated in the summary of [5], *"measurements were carried out at the exhaust of Rolls-Royce aircraft engines simultaneously with the EASA and Rolls-Royce nvPM systems for comparison. The data obtained will be used to start to fill in the nvPM data base for the setting of future ICAO mass and number nvPM standards*". These limits were approved by ICAO in February 2019 [G]. New regulatory mass concentrations were enforced in January 2020 for in-production engines, and ICAO mandated that EI_n and EI_m have to be reported, as per ARP6320. From 2023, the mass concentration regulation will be replaced with the EI_n and EI_m, metrics.

This new standard meant ICAO completed all main environmental standards for the certification of aircraft and engines; namely for noise, local air quality (NO_x, HC, CO, nvPM) and climate change (CO_2). As of February 2019, the aviation industry was the only sector with environmental mandatory certification requirements at the global level for the operation of its equipment [G]. In addition, the new EI_n and EI_m metrics are summed over the entire LTO cycle, which means aviation is truly limiting emissions and not just concentrations [H]. Furthermore, from January 2023, all new aircraft engine designs will need to be certified to ICAO standards, but with a reduction of approximately 30% for both aerosol number and mass EI [H], thus greatly contributing to reduced global aviation soot emissions, and concentrations, especially near to major airports.

These emission standards will ensure a gradual reduction in the nVPM emissions of aircraft as the levels set by ICAO are periodically adjusted to reduce emissions [B]. Aircraft operate globally - hence the environmental benefits of this standard are global in reach, improving air quality for communities surrounding airports served by commercial jets. [Text removed for publication]. Without a standardised means to accurately measure nvPM engine emission samples [as now provided by William's contribution to Annex 16 Volume II], this setting and enforcement of limits would not have been possible.

iii) Economic impacts: commercial adoption of engine specification driving new products

This research has informed the environmental regulation of a globally important industry that is valued in excess of USD100,000,000,000. ICAO regulation cycles (and their standards) are typically in place for at least a decade. Failure to report as per the new ICAO regulation on engine emissions, or to meet the emission standards themselves, would prevent engine manufacturers from selling their engines. Therefore ensuring engines meet regulation and are operational is imperative for manufacturers.

To put this into context, two of the largest engine manufacturers are Rolls Royce, and GE Aviation. In 2019, Rolls Royce reported 'Large Engine' sales of GBP2,500,000,000 [I] (up from GBP1,600,000,000 in 2016) (approximately 31% of their underlying revenue). Likewise, GE Aviation 2019 annual report [J] gives a combined sales and service of USD24,200,000,000. Using a conservative estimate that 'Large Engine' sales at GE contributes 10-20% of this revenue, the value of new engine sales that have to meet the updated regulations is in the range USD2,400,000,000 to 4,800,000,000 (since sales figures are not reported separately).

5. Sources to corroborate the impact

[A] Letter of support from Assessment and Standards Division, US Environmental Protection Agency, July 2019
[B] Letter of support from Environmental Protection Officer, European Union Aviation Safety Agency, EASA, July 2019
[C] Letter of support from Aerospace Standards Specialist, SAE E-31 committee, February 2018
[D] Letter of invitation from ICAO, February 2015
[E] SAE Aerospace Recommended Practice ARP 6320: Procedure for the Continuous Sampling and Measurement of Non-Volatile Particulate Matter Emissions from Aircraft Turbine Engines, https://www.sae.org/standards/content/arp6320/
[F] SAE Aerospace Recommended Practice ARP 6481: Procedure for the Calculation of Non-Volatile Particulate Matter Sampling and Measurement System Losses and System Loss Correction Factors, https://www.sae.org/standards/content/arp6481/
[G] ICAO Press release confirming standard is approved, "*Sustainable aviation takes significant step forward at ICAO*" February 2019
[H] Presentation from the Swiss Federal Office of Civil Aviation (June 2019) "*The First Global Regulatory Limits for Aircraft Engine Particle Mass and Number Emissions*"
[I] Rolls Royce annual report 2019 (see page 25)
[J] GE annual report 2019 (see page 22)