European Union Aviation Safety Agency

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PROJECT: SAMPLE IV [EASA.2020.FC05]

DELIVERABLE: FPR

Final Project Report

An Agency of the European Union

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EXECUTIVE SUMMARY

In recent years, scientists have been working to understand the detrimental impact of Particulate Matter (PM) on local air quality, public health and the wider global environment. The SAMPLE IV study was therefore initiated to further investigate civil aviation's newly adopted regulation of non-volatile Particulate Matter (nvPM), towards understanding its current uncertainties and hence potential for improvement moving forwards.

Civil Aviation nvPM largely consists of carbonaceous Ultra Fine Particles (UFP), with a number weighted mobility diameter <100 nm. Given significant concentrations of these small particles are emitted from aircraft gas turbine engines, there are obvious concerns in terms of their potential adverse health impacts for the demographics surrounding airports and their potential to adversely impact the climate when emitted at altitude.

Different studies have shown that nvPM when emitted from the engine exhaust, interact with other pollutants (e.g. organic gases and sulphates) which act as secondary organic aerosol precursors, resulting in a complex mixture of volatile and non-volatile aerosol in the evolving plume [1] [2]. Historically, only Smoke Number (SN) regulation limited particle emissions from civil aircraft. However, it was recognised that this visibility criterion metric did not necessarily control the number concentrations of PM emitted from aircraft and hence their potential health impact. As such as of the 1st January 2020, as part of CAEP/10, ICAO introduced a new maximum nvPM mass standard, which was further improved by the adoption of regulatory limits of nvPM mass and number and came into force as of 1st January 2023 (CAEP/11). However, it is noted that these new standards only apply to large civil aviation engines (>26.7 kN) and do not regulate emissions from: i) engines with maximum certified thrust lower than 26.7 kN; ii) propeller type engines and iii) APU, all of which are known to contribute to air pollution in and around airports.

Members of the SAMPLE IV consortium sit on the SAE E31 technical committee, responsible for the development of Aerospace Recommended Practices (ARPs) which outline how nvPM should be sampled and measured along with the relevant corrections required to estimate the loss of particles within the sampling and measurement system. Similarly, consortium members contribute to the ICAO CAEP WG3 committee with responsibility to advise on the adoption of recommended practices into a regulatory framework. As such the SAMPLE IV consortium were well placed to document the development of nvPM regulations, whilst also offering insight into the current levels of uncertainty in the nvPM standards and ways that these uncertainties may be reduced moving forwards.

Within the SAMPLE IV consortium, there was also the expertise of the developers and operators of both the European and Swiss reference nvPM systems, which for over a decade have collected a large nvPM database covering a wide range of aircraft engines, through numerous domestic, EU, industrial and collaborative internationally funded measurement campaigns.

In this context the SAMPLE IV Project was funded with the aim to understand current limitations in the nvPM regulation, towards suggesting potential future improvements to the ICAO Annex

16 Volume II nvPM emissions standards. It is perceived that such work will facilitate simplified and more accurate regulation of nvPM mass and number in the future.

Commented [li1]: measurement?

Commented [AC2R1]: I was thinking regulation as the loss corrections and fuel corrections etc are beyond measurement, however happy to change

The SAMPLE IV Project is an EU Project, funded and managed by EASA, is part of the Horizon 2020 Work Programme Societal Challenge 4 'Smart, green and integrated transport'. This project was divided into two Specific Contracts (SC01 March 2021 – March 2022; SC02 April 2023 – March 2025), both encompassed in a Framework Contract (EASA.2020.FC05, lot 1) signed by the parties on 23rd September 2020.

As an outcome of the SAMPLE IV work programme, several publicly available deliverable reports have been published concerned with:

1. Potential Improvements to current ICAO nvPM sampling & measurement system
2. Solutions for regulatory aviation nvPM mass and number measurements
3. Improving nvPM sampling and measurement system uncertainties
4. Impact assessment of nvPM emissions from non-regulated engines
5. Small and non-regulated engine emission testing
6. Refining methodologies for estimating nvPM emissions from reported Smoke Number
7. ICAO fuel specifications and nvPM emissions fuel correction

This Final Project Report (FPR) presents a summary of the research activities, and the research results from the two Specific Contracts. This document therefore complements the aforementioned project deliverables submitted and approved by EASA.

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LIST OF ABBREVIATIONS

AFR	Air-Fuel Ratio
APU	Auxiliary Power Unit
ARP	Aerospace Recommended Practice
ASTM	American Society for Testing and Materials
BPR	Bypass Ratio
CAEP	Committee on Aviation Environmental Protection
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon dioxide
CPC	Condensation Particle Counter
CS	Catalytic Stripper
DFCAS	Diffusion Flame Combustion Aerosol Source
EASA	European Union Aviation Safety Agency
EED	Engine Emissions Databank
EI	Emission Index
FPR	Final Project Report
GCxGC	Comprehensive two-dimensional Gas Chromatography
GMD	Geometric Mean Diameter
GSD	Geometric Standard Deviation

GTRC	Gas Turbine Research Centre
HC	Hydrocarbon
ICAO	International Civil Aviation Organisation
LII	Laser Induced Incandescence
LOD	Limit Of Detection
LOQ	Limit Of Quantification
LTO	Landing and Take-Off cycle
MSS	Micro Soot Sensor
MTF	Mixed Turbofan Engines
N/M	Number to Mass ratio
NCB	Nebulised Carbon Black
NOx	Nitrogen Oxides
NPL	National Physical Laboratory
nvPM	Non-Volatile Particle Matter
OD	Outer Diameter
OEM	Original Engine Manufacturer
PM	Particle Matter
PMP	Project Management Plan
PSD	Particle Size Distribution
SAE	Society of Automotive Engineers
SAF	Sustainable Aviation Fuel
SC	Specific Contract
SMPS	Scanning Mobility Particle Sizer
SN	Smoke Number
SPG	Silver Particle Generator
tPM	Total Particle Matter
UDAC	Unipolar Diffusion Aerosol Charger
UFP	Ultra-Fine Particle
VFR	Visual Flight Regime
vPM	Volatile Particle Matter Concentration
VPR	Volatile Particle Remover

Moreover, the next abbreviations will be used for each SAMPLEIV Consortium Partner:

Table 1: SAMPLEIV Consortium Partners Abbreviations

SAMPLEIV Consortium Partner	Abbreviation
INSTITUTO NACIONAL DE TÉCNICA AEROESPACIAL "ESTEBAN TERRADAS"	INTA
ROLLS-ROYCE PLC	RR
THE UNIVERSITY OF MANCHESTER	UoM
CARDIFF UNIVERSITY	CU
ZHAW ZURICH UNIVERSITY OF APPLIED SCIENCES	ZHAW
UNIVERSIDAD POLITÉCNICA DE MADRID	UPM

1. OVERVIEW OF THE PROGRESS

The objective of the SAMPLE IV Project was to further understand the current uncertainties of and contribute to the potential improvement of the ICAO Annex 16 Volume II requirements for engine emissions sampling, measurement and correction for nvPM mass and number. This research supports the work of the ICAO Committee on Aviation Environmental Protection (CAEP) and the Society of Aerospace Engineers (SAE) Aircraft Engine Gas and Particulate Emissions technical Committee (E-31).

The main objectives of the SAMPLE IV Project were as follows:

1. **Assessment of non-regulated engine emissions** – Evaluating the proportion of aircraft fitted with engines that are not currently subject to nvPM regulations and analysing their contribution to operations and emissions at individual European airports.
2. **Advancement of sampling, measurement and correction techniques** – Developing and testing novel sampling designs and measurement techniques based on the latest advancements in the field. This objective also included improving correlation methods between Smoke Number (SN) and nvPM, as well as assessing the validity of current fuel correction methodologies.
3. **Expanding the aircraft engine emissions database** – Collecting and analysing emissions data for small and non-regulated engines that do not have publicly available data. This includes the reporting of gaseous emissions (e.g., NO_x, HC, CO, CO_2), smoke emissions, nvPM mass and number emissions, and nvPM particle size.

To achieve these objectives, a series of tasks were defined within the SAMPLE IV contract, which formed the basis of the work required to complete the deliverables (see Table 2 - Table 4). The work was conducted under two specific contracts, with the work of the first contract guiding the final requirements and deliverables, which were to be made publicly available as deliverables by the end of the second contract. Further details of the specific tasks are presented in Section **Error! Reference source not found.**.

Objective 1: Assessment of non-regulated engine emissions

Table 2: Progress towards Objective 1

Specific Contract	Task Ref.	Task title
SC01	Task 4.1	Activity of aircraft with non-regulated engine emissions at European Airports
SC01	Task 4.2	Candidate non-regulated engines to be measured
SC02	Task 4	Impact assessment of nvPM emissions from non-regulated engines and selection of engines for emission measurement

<u>Objective 2:</u> Advancement of sampling, measurement and correction techniques

Table 3: Progress towards Objective 2

Specific Contract	Task Ref.	Task title
SC01	Task 1.1	Current status of the measurement methodology for nvPM mass and number
SC01	Task 1.2	The scientific optimum nvPM mass and number measurement
SC01	Task 1.3	Measurement compromises in ICAO Annex 16 Volume II
SC02	Task 1.2	Novel existing measurement equipment
SC02	Task 1.3	Identification of gaps in the technical work necessary to progress SAE E31
SC01	Task 2.1	Compromises and ICAO Annex 16 Vol. II
SC01	Task 2.2	Improvements, which are not covered in the list of compromises
SC01	Task 2.3	Conclusion for the selection of measurement improvements to be further investigated
SC02	Task 2	Review of the contents, chosen approaches and compromises made
SC02	Task 3.1	Quantification of drift uncertainties of the nvPM number instruments based on “as found” calibrations
SC02	Task 3.2	Penetration comparison between current and alternative existing VPR technologies (including smaller particles sizes)
SC02	Task 3.3	Improvements in calibration protocols
SC02	Task 3.4	Standardised mass calibration sources
SC02	Task 3.5	Advancement of PSD measurement for system loss correction in CAEP timescales including support of SAE E31 loss team
SC02	Task 6.1	Review of current correlation methods and their limitations
SC02	Task 6.2	Proposals for improving the existing correlation and calculation methods between SN and nvPM mass and number
SC02	Task 7.2	Effects of different blending ratios of Jet A1 with SAF on emission levels. The base Jet A1 fuel used for blending should represent a fossil fuel medium level or aromatics and sulphur content
SC02	Task 7.3	Assessment of current fuel correction methods and potential limitations or improvements
SC02	Task 7.4	Proposal for improvements as necessary

<u>Objective 3:</u> Expanding the aircraft engine emissions database

Table 4: Progress towards Objective 3

Specific Contract	Task Ref.	Task title
SC02	Task 1.1	Maintaining and calibrating [European nvPM] reference system
SC02	Task 3.6	Measurement of relevant parameters through lab/rib/engine testing to prove novel measurement and correction techniques
SC02	Task 5.1	EASA agreed test plan [for SAMPLE IV engine tests]
SC02	Task 5.2	Potential deviations or adaptations from and to Annex 16 described methods as necessary
SC02	Task 5.3	Measurement of gaseous emissions, SN and nvPM (mass & number) representative of selected unregulated engines
SC02	Task 5.4	Proposal for measurement and sampling procedures that could be included to ICAO Annex 16 in the future

2. DESCRIPTION OF WORK CONDUCTED BY THE SAMPLE IV CONSORTIUM MEMBERS

2.1. Task 1

Task 1's scope was to assess the current nvPM sampling and measurement standard, collecting background information from relevant stakeholders (e.g. SAE E-31, ICAO, and other relevant actions) and review approaches and compromises made in the development of the existing nvPM standard. Using this gained knowledge, it was then the aim to identify and recommend solutions to reduce both uncertainties in measurement and uncorrected losses of particles within the sampling and measurement system, leading to a more efficient and accurate nvPM sampling and measurement standard, considering improved and novel approaches (e.g., nvPM size measurements, nvPM density determination, efficient calibration techniques etc.).

The purpose of the initial exercise was to understand and document the rationale of the nvPM standards development, highlighting scientific compromises that were historically made and any known operability issues that have been observed to date. This assessment enabled a more thorough assessment of potential improvements, that could be achieved in the current ICAO Annex 16 Vol II nvPM sampling and measurement system (see Figure 1) and future system loss correction methodologies.

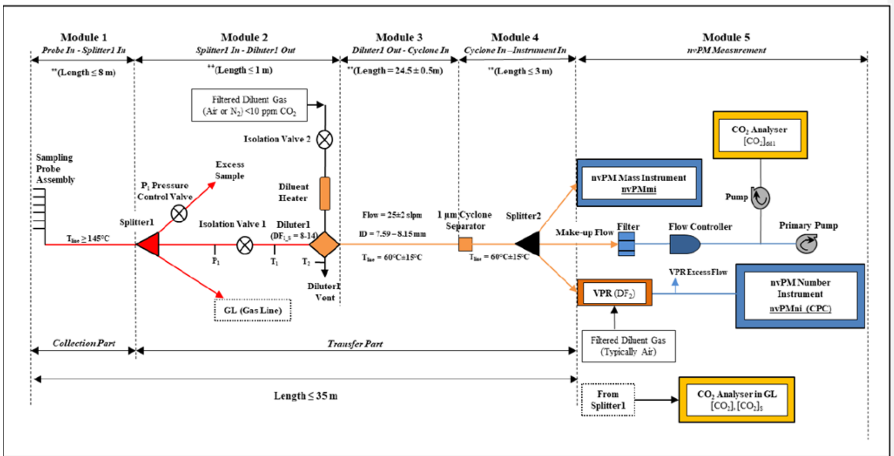

Figure 1: ICAO Annex 16 Vol. II nvPM sampling and measurement system [3]

Towards improving reported issues in the sampling system definition, a series of experiments were designed and conducted at both Rolls-Royce Derby and Cardiff University's Gas Turbine Research Centre (GTRC) in 2021/22. These were carried out in consultation with EASA and the SAE E31P committee. The primary experiments aimed to assess:

1. <u>A reported issue of adverse temperature gradients (thermophoretic loss) and compliance in meeting the 145°C minimum temperature at T_1 in the dilution box (Module 2) of nvPM sampling systems</u>

Towards understanding this issue, three different experiments were conducted, assessing three different ICAO A16V2 'compliant' nvPM sampling systems, namely the European (EUR) nvPM reference system, Swiss nvPM reference system (SMARTEMIS) and the Rolls Royce nvPM system. This new SAMPLE IV data was supported by equivalent work carried out by Missouri University of Science & Technology, which assessed the North American nvPM Reference System[1], and provided the insight necessary to guide an interim change in the specified T_1 location, which was adopted in SAE ARP6320B and then into ICAO Annex 16 Vol II.

This interim solution was required to standardise the thermophoretic loss correction applied by all engine OEMs as required in regulatory EI nvPM reporting (Probe to Splitter1), whilst ensuring the consistency of existing nvPM data already published in the ICAO Aircraft Engine Emissions Databank, prior to this change.

Furthermore, the particle loss observed due to the thermophoretic losses between Splitter1 and Diluter1 inlet have subsequently been added as a part of a recommended practice for calculating system loss correction factors during the revision of SAE ARP6481A. It is noted that this is an interim solution until further work is performed. Depending on the specific nvPM system design, being employed, this interim solution may currently lead to a slight overestimation or underestimation of particle loss in Module 2.

As a result of this work, additional wording concerning 'negative temperature gradients' has also been added to both SAE ARP6320B and ICAO Doc 9501, towards minimising the chance of additional unintentional thermophoretic loss, being witnessed in a given sample system design.

2. Impact of cleanliness of Cyclone on uncertainty of nvPM measurements

It was observed, during combustor testing, that increasing the frequency of cyclone cleaning improved the operability of both the Swiss and EUR nvPM reference systems, particularly when measuring at low mass concentrations. It was observed that 'shedding' from uncleaned sharp-cut-point cyclone traps, resulted in increased measured mass concentrations, and hence a bias in reported mass of the order of the quoted limit of detection of the mass analysers. This study found that more frequent cleaning of the cyclone 'pot', particularly if measuring low mass concentrations after a high mass loading test point, significantly enhanced system performance compared to the current ICAO Annex 16, Volume II requirement, which only mandates a cleanliness check before the start of an engine test series.

Based on this study, it was recommended that advisory guidance on cyclone cleaning be included in SAE ARP 6320 and ICAO Annex 16, Volume II.

3. Intercomparison studies of nvPM mass, number & size instruments using 'novel' particle sources

Since no commercially available 'standardised' gas turbine aerosol calibration source exists, and the significant costs associated with operating a gas turbine engine, several 'size relevant' laboratory-scale particle generation sources were evaluated, towards assessing their suitability for calibrating and performing 'in-field' checks of nvPM sampling and measurement systems. It was noted that high particle concentrations were achieved, allowing for a detailed assessment of system losses (including VPR) and number counter performance <15 nm.

When investigating very small surrogate aerosols at low particle concentrations, significant increases in measurement uncertainty were observed when comparing two nominally identical number counting devices. The use of these 'novel' particle generators enabled the comparison of different particle size analysers, showing general agreement within a coefficient of variation (i.e., standard deviation/average) of 8.3% for GMD across all test points and 3.4% for GSD within a size ranging from 8 to 75 nm. This result provided confidence that improved system loss correction may be achievable by employing well-characterised real-time particle sizers.

[1] DP34 SAE 31 Annual Meeting: On-line (January 2021)

Nebulised Carbon Black colloids were successfully demonstrated as a potential 'field-check' source for number, mass and size instruments. However, further work is needed to more fully characterise stable concentration limits, charge state, reproducibility of manufacture, and repeatability over time. Laser fluence measurements were obtained on multiple particle sources, highlighting that nebulised Carbon Black colloids may have potential to become a traceable calibration source for Laser Induced Incandescence analysers.

4. Understanding Charge potential of aerosols and their impact on particle size measurement

It was observed that the charge state of an aerosol can influence some fast-sizing instruments which rely on a single unipolar charger. Therefore, further research is needed to better understand the charge potential of aircraft exhaust and hence the uncertainty this may have on future size measurements. However, the findings from this study indicated that adding a neutraliser at the inlet of the particle size instrument effectively mitigates the impact of high particle charge.

5. Characterisation of particle loss in Splitter 1

Unequal flows in Splitter 1 have been noted to cause additional particle losses due to inertial and diffusional effects. As part of a combustor rig trial, this impact was briefly empirically investigated using the Swiss and EUR nvPM systems. It was observed that operating Splitter 1, within a limited range of flow split velocities, resulted in only a 3% difference in mass and number concentrations. However, it was noted that an experimental setup capable of simulating a full range of split velocities, as would be witnessed on a large engine test, with a stable source is ideally required to fully assess the impact of unequal flow splitting.

The dissemination level of the deliverables resulting from Task 1 are shown in Table 5.

Table 5: Task 1 – Deliverable status

Specific contract	Deliverable	Title	Dissemination level
SC01	D-1	Final Report on Task 1 and Task 2.	Consortium Only
SC02	D-1	Potential Improvements to Current ICAO nvPM Sampling & Measurement System	Public

Commented [AC3]: I think this table is now more useful as it indicates that the public can only find D1 report from SC02 - it is not available from SC01, rather than just stating all reports are 100% complete??

2.2. Task 2

The scope of task 2 supported the maintenance and development of nvPM sampling and measurement protocols defined in SAE ARP6320 and ICAO Annex 16 Volume II Appendix 7, whilst also investigating practicable solutions which may lead to more efficient and/or accurate future sampling and measurement system designs. Noting that reducing measurement uncertainty may assist with increasing regulatory stringency, hence enabling a real-world reduction of future engine particle emissions.

Task 2 detailed the evolution of 'standardised' nvPM sampling and measurement systems, considering the evolution of scientific thoughts, compromises considered (within SAE E31 & CAEP) and data that was available at the time to understand the impact of the measures adopted. Using this knowledge potential improvements to the current nvPM sampling and measurement system, were then proposed and assessed towards simplifying practices and reducing the uncertainties in reported aircraft engine emissions.

A brief summary of the historical development of the relevant 'modules' (see Figure 1) of the nvPM sampling system is presented below.

- Module 1 – Probe inlet to Splitter 1 inlet

This module encompasses the initial collection of engine exhaust emission with probes. A compromise carried out during the development of the standard, was to use existing Annex 16 Vol II sampling probes and rakes, since OEMs developed a variety of different probes, designed and optimised for specific engine exhaust designs. It was considered early in the nvPM standard development process (2010) that the time to develop new probes for all engine types would have added a significant delay to implementing a new nvPM standard.

Several compromises have been made in terms of nvPM measurement as a consequence of using the existing probe designs. For example, the sample velocity is not consistent or measured in the sample line from probe inlet to splitter 1 across different engines and/or power conditions, meaning that any calculation of particle loss requires an unsubstantiated assumption of residence time. It is now understood that this likely impacts nvPM number measurements more than nvPM mass measurements in terms of both diffusion particle loss to the sample line walls and coagulation.

At the time of the early nvPM sampling system development, it was perceived that 'tip dilution' probes were scientifically optimal for extractive sampling, because early dilution was thought to both limit, 'coagulation', nucleation of volatile fractions and thermophoretic loss through quenching of the sample. Given new understanding of particle loss correction and recently cited volatile nucleation/line contamination experiences[2], nvPM specific probe specification may be an area to reconsider moving forwards.

Another compromise for the existing probes, is the requirement to reduce and keep the sample at a temperature > 145 °C. This reduced temperature, potentially allows volatile matter to condense onto particles or nucleate prior to dilution. This mandated temperature reduction, may not be optimal in the case on nvPM measurement, since it may result in not all of the volatiles remaining in the gas phase prior to dilution, potentially leading to nucleated particles or coatings onto nvPM. Similarly, not reducing the gas temperature, prior to dilution, may potentially offer the ability to reduce thermophoretic loss.

- Module 2 – Splitter 1 inlet to diluter 1 outlet

[2] DP18 SAE E31 annual meeting, Saclay 2019

This module contains splitter 1 and dilutor 1. Initially it was assumed that particle loss up to and within the eductor dilutor were negligible, attributed to the fact that the exhaust gas cooling is brought about by dilution and the walls of the diluter mixing chamber are a significant distance from the centreline of the mixing zone. However, laboratory studies [4] have suggested there are potential size dependant losses or size dependant dilution uncertainties experienced in eductor diluters, which may need to be better accounted for.

Similarly, probe design, splitter geometry, engine thrust range and gaseous raw line flowrates result in non-standardised, unquantified and variable unbalanced flow splits in splitter 1. It is known that highly variable and unbalanced flow splitting leads to size dependant variations in particle penetration along the different flow paths. It is thought that typical gas turbine particles, which exhibit small (10 – 100 nm) number weighted size distributions, should not be significantly affected by these unequal flow splits, given small particles are assumed to follow streamlines, whereas larger particles have more potential to be lost via impaction from relatively lower flow splits. However, a recent OEM laboratory-based study[2] has indicated that imbalance in splitters may lead to increased uncertainty in nvPM mass measurements, which are dominated by the larger particles in the exhausts size distribution.

At present, further research (CFD) is being carried out to determine 'real-world' witnessed system loss in Module 2. Until this data is fully assessed, it is currently still recommended to report nvPM data using a T_1 thermophoretic correction only.

- Module 3 – Diluter 1 outlet to cyclone inlet

This is a single length of heated anti-static PTFE line, which connects module 2 to module 3. To facilitate all the different OEM's test-cell geometries (given the initial wish for a somewhat 'standardised' sampling geometry) the dimensions deemed necessary for this sample line were 25 m length and 3/8'' OD. The flowrate along this sample line (25±2 sLPM), was also specified in-light of the chosen dilution strategy and was specified to prevent 'over-pulling' of the diluted exhaust sample, resulting in additional pressure drop and the potential of ingesting ambient air through the diluter 1 vent.

As for the sample line temperature (60±15 °C), this was defined as the lowest temperature which could be standardised across global testbed locations and somewhat aligned with the minimum temperature requirement defined in the established SN standards. Higher sample line temperatures were initially dismissed. However, given the nvPM number system now typically employs a heated CS and the aforementioned issues of the diluter temperature gradient in module 2, revisiting this decision may warrant further investigation towards reducing the overall thermophoretic loss.

- Module 4 – Cyclone inlet to measurement analyser inlets

This module includes the cyclone, splitter 2 and the sampling lines to the instruments. The cyclone was initially deemed necessary as it was observed that relatively few large 'shed' particles could impact mass measurements, hence a D_{50} diameter of 1 µm at 25 sLPM was specified. However, as discussed earlier the cyclone has been witnessed to shed particles if it is not suitably clean, hence further work on the cyclone 'pot' design and cut point are still on-going. Splitter 2 is also not currently fully optimised for the known variations in flowrate between different measurement analysers.

- Instruments

ICAO A16V2 [3] defines instruments for the measurement of mass and number, based on technology and performance specifications. However, at present nvPM size instruments are not described or mandated, although recent data indicates system loss correction using measured particle size is potentially beneficial over the current A16V2 (N/M) methodologies, particularly at low mass loadings. Initially size measurement was discarded due to issues associated with the definition of nvPM size, representativeness of the highly fractal nvPM witnessed in gas turbine exhaust and traceable calibration of size measurements and particle count.

However, in light of the known bias that particle loss has on reported EI's, currently, particle size measurement is again being reconsidered with a view to reduce the uncertainty of the current system loss correction methodologies, which requires numerous assumptions (particle lognormality, GSD, particle density and particle cut-off size). Initially it was thought the 'standardised' sampling approach would adequately control the uncertainty associated with size dependant particle loss, however with the large variations in particle sizes witnessed across engine powers, engine technologies and fuels it is being considered as to whether significant reductions in system loss correction uncertainty may be brought about by defining a size measurement.

As briefly discussed above, it is understood that there is the potential for the nvPM sampling and measurement system and its operation and calibration procedures, as defined in ICAO A16V2 [3], to be further optimised and improved. Table 6 documents specific details of potential improvements that the SAE E31 currently perceive as having the biggest impact in reducing uncertainties of the existing nvPM regulatory practices.

Table 6: Highest priority nvPM system improvements (as agreed by SAE E31P, Albuquerque 2024)

Task
Reduce nvPM mass calibration uncertainty
Reduce system loss correction factor uncertainty
Reduce nvPM number uncertainty & size dependent particle losses in VPR
Reduce nvPM number uncertainty
Reduce system loss correction factors uncertainty by reducing particle losses in sampling system Understand/Improve Module 2 thermophoretic and diffusion loss Minimise Splitter 1 particle loss by recommending design rules
Measure nvPM at or near current Limit of Detection (LOD)/Limit of Quantification (LOQ) Minimise re-entrainment of particles caught in the cyclone, frequency and timing of system zero/cleanliness tests PSD system loss correction methods
Understanding limitations of historic gas and smoke probes Document historical approach to gas & smoke sampling Future nvPM probe concepts
Large (>250/300 nm) particles understanding Understand composition/source generations Impact on PSD method
Reduce system loss correction factor uncertainty Improve nvPM density assumption Diluter 1 penetration

In the Task 2 deliverables, the status of the nvPM (mass and number) measuring methodology has been documented. Further discussion and consideration of the uncertainty of system loss correction calculations, using measured particle sizes are also further considered. However, at present the full uncertainty benefit of these new methods have not yet been quantified.

Finally, optimum sampling and measurement design concepts are considered towards reducing overall nvPM uncertainties, compared to the existing regulatory nvPM measurement system.

The dissemination level of the deliverables resulting from Task 2 are shown in Table 7.

Table 7: Task 2 – Deliverable details

Specific contract	Deliverable	Title	Dissemination level
SC01	D-1	Final Report on Task 1 and Task 2.	Consortium Only
SC02	D-2	Updated report on solutions for nvPM mass and number measurements.	Public

2.3. Task 3

The scope of Task 3 aimed to quantify and address the main uncertainties within the nvPM standard, including the representativeness of reported EIs in characterising nvPM concentrations witnessed at the engine exhaust. Specifically, Task 3 focused on instrument calibration and drift, refining methodologies for calculating size-dependent nvPM losses within the standardised sampling system, and exploring recent technical advancements which offer potential improvements to the sampling and measurement system, towards simplifying measurements and reducing particle loss.

A summary of the different subtasks is provided below:

- Uncertainty and potential improvements in regulatory nvPM number measurement

Several laboratory experiments were conducted to assess the impact of VPR penetration efficiency and CPC counting efficiency uncertainty on reported nvPM number. While VPR losses are not expected to change over time, these investigations revealed significant uncertainty in the reported VPR penetration efficiency across different calibration laboratories, with particle pre-conditioning methods significantly influencing the reported penetration efficiencies. Notably, different commercially available compliant VPRs exhibited substantial variations in penetration performance, approximately 15–20% across GMDs representative of nvPM, highlighting the need for further standardisation of VPR calibration protocols towards minimising this uncertainty. Additionally, the type of particle used during calibration was found to affect CPC counting efficiency. However, it is noted that no statistically significant drift in nvPM number measurement instruments was observed over a 12-month calibration period.

By adopting stricter specifications for VPR and CPC calibrations and implementing corrections for size-dependent VPR particle loss and CPC counting efficiency, the accuracy and reproducibility of nvPM number reporting can be improved.

- Novel nvPM mass calibration sources

Calibration aerosol sources are known to significantly impact nvPM mass uncertainty, directly influencing the uncertainty in reported EIs. To better understand and mitigate this uncertainty, novel laboratory-generated nvPM mass sources were explored. Specifically, stable aqueous colloids were produced by Cardiff University, using commercially available carbonaceous powder or ‘real’ aircraft-engine soot, which was collected from the exhaust system of an engine certification test cell. These colloids were subsequently nebulised to generate carbonaceous aerosols at concentrations representative of aircraft exhaust.

The resulting aerosols were characterised in terms of nvPM number, mass, size, and morphology, demonstrating their potential as an in-field check for mass, number, and sizing instruments. The aerosol properties were influenced by the choice of carbonaceous powder, the nebuliser’s droplet size distribution, and the colloid preparation process. While current regulations mandate the use of a diffusion flame combustion aerosol source (DFCAS) for calibration, it was proposed that further research could establish these colloids as viable mass calibration sources in the future.

- Advancement of particle size measurement for system loss correction

An assessment of measured-PSD-based system loss correction methods was conducted using contemporary certification-like data, demonstrating a reduction in uncertainty in the reported system loss correction fraction (k_{SL}) compared to the current N/M-based ICAO regulatory method. The findings indicate that measured-PSD-based methods are particularly beneficial at low nvPM mass concentrations, typically associated with smaller particle sizes, where diffusion losses in the sampling system are most pronounced.

Additionally, recommendations were provided to SAE E31 on the best practices for sampling and measuring particle size, as well as the current uncertainties associated with sizing instruments (DMS500, EEPS, ELPI+, and SMPS), supporting the future adoption of measured-PSD-based system loss correction standards.

This work has significantly contributed to the development of an SAE Aerospace Information Report (AIR) on nvPM PSD measurement and has informed recent improvements to an Aerospace Recommended Practice (ARP) related to system loss correction.

- <u>Novel advanced measurement techniques for nvPM number and mass</u>

As part of SAMPLE IV Task 3, novel measurement techniques for nvPM number and mass were developed and demonstrated, highlighting their potential to reduce sampling and measurement complexity and cost.

Commercially available dilution systems, with controllable dilution factors, were successfully tested on raw aircraft exhaust across the full range of engine power settings (dynamic probe pressures). These systems offer the potential to reduce uncertainties associated with low particle counts while eliminating the need for a pressure dump line. This minimises loss or bias in Splitter 1 and could provide greater operational flexibility for engine manufacturers.

Additionally, diffusion-based particle counters were successfully deployed near the probe exit during aircraft engine testing, showing good agreement with reference nvPM number instruments and number concentrations derived from PSDs. However, further research is required to quantify the uncertainty in nvPM number, mass, and size measurements obtained from diffusion-chargers and other emerging techniques.

The dissemination level of the deliverables from Task 3 is shown in Table 8.

Table 8: Task 3 – Deliverable details

Specific contract	Deliverable	Title	Dissemination level
SC02	D-3	Report on improved nvPM measuring concepts.	Public

2.4. Task 4

The scope of Task 4 was evaluated the relevance of non-regulated engine emissions across European civil airports, towards recommending 'representative' candidate non-regulated engines which would be of particular interest to acquire emissions data for. The following civil engine categories were investigated: i) Turbofan engines with a maximum certified rated thrust lower than 26.7 kN; b) Turboprop engines; c) Helicopter turboshaft engines and d) Auxiliary Power Units (APU) installed in civil aircrafts.

The main study was conducted in two phases, firstly an examination of the prevalence (in terms of number of movements) of different engine models at several specifically selected airports. Secondly, calculations were performed to approximate the levels of nvPM emitted by each type of engine at the selected airports.

To enable the study, traffic quantification was assessed for a representative week (intermediate week of June) in 2019, which was considered as the most representative year for which recent data was available, whilst avoiding the traffic irregularities created by COVID disruptions/ lockdowns. Three Spanish airports of different sizes and operating different types of air traffic were analysed, concluding that Visual Flight Regime (VFR) and piston aircraft operations were a negligible part of the total traffic.

The geographical area assessed in the study, included the 31 EASA members and associated countries, with 12 airports selected to adequately cover the full range of airport sizes witnessed across Europe. The test airports were divided so as four different 'representative' airports were assessed in three size categories, with their locations provided in Table 9. The sizes of airports were defined as Large, with more than 15 million passengers per year, Medium, witnessing between 6 and 15 passengers per year, and Small, having less than 6 million passengers per year. The selection of airports ensured a wide diversity in both geographical zones and types of air traffic.

Table 9: Airports assessed in Task 4

Size	Airports
Large	Frankfurt (Germany), Rome Fiumicino (Italy), Zurich (Switzerland), Stockholm Arlanda (Sweeden)
Medium	Porto (Portugal), Riga (Latvia), Sofia (Bulgaria), Hannover (Germany)
Small	Trondheim (Norway), Rodhes (Greece), Eindhoven (Netherlands), Bratislava (Slovakia)

The results of the first phase of analysis showed that piston engines and non-regulated jets composed only a small fraction of the total flight movements, while regulated jets were seen to form a large majority at all airports. It was found that turboprops were numerous in some of the airports which served a lot of local flights. It was seen that these engines were therefore particularly prevalent at airports in the 'Small' category. The case of the APUs was more complicated because it was not possible to accurately determine when a given airline is using an APU or taking advantage of the energy provided by ground equipment.

Considering the findings of the first part of the study, it was proposed that representative engines to consider for the SAMPLE IV project would be a turboprop and an APU. Assessing prevalence of these engines across the different airports it was found that a Pratt & Whitney PW100 family would be most 'representative' of the turboprop fleet, while in the case of APUs both the Pratt & Whitney APS3200 and Honeywell GTCP 131 are highly prevalent.

The second part of the study was carried out using existing datasets and correlations to estimate the amount of nvPM produced by non-regulated engines across the 12 selected airports and confirm the 'representativeness' of the suggested engines.

Source term nvPM emissions data was not available for all the engines included in the study. For turboprops, the main source available for emissions data was the Federal Office of Civil Aviation of Switzerland's database. For engines not included in the database, it was assumed that emissions were proportional to the rated power, with emissions loadings estimated using data from other engine models of the same family or from engine models with similar technological designs. The same approach was applied to non-regulated jet emissions.

The lack of information was more pronounced for APUs. In this case, it was decided to apply the general approach of the ICAO Airport Local Air Quality Design Manual. Uncertainty over specific APU usage at airports, coupled with a lack of traceable emissions data meant it was very difficult to quantify the relevance of APU's when compared with other non-regulated engines.

Following the full analysis, confirming earlier thoughts, leading candidates for 'representative' non-regulated engines were proposed as the Pratt & Whitney PW127 and PW150 covering turboprops, the Honeywell TFE 731 as a small jet and either Pratt & Whitney APS3200 or a Honeywell GTCP 131 as an APUs.

The dissemination level of the deliverables in Task 4 are shown in Table 10.

Table 10: Task 4 – Deliverable details

Specific contract	Deliverable	Title	Dissemination level
SC01	D-2	Final Report on Task 4.	Consortium Only
SC02	D-4	Report on impact assessment of nvPM emissions from non-regulated engines.	Public

2.5. Task 5

As part of Task 5, nvPM, smoke, and gaseous emissions were characterised for two small legacy turbofan engines (ALF502-R5 and LF507-1H) and following the guidance of Task 4 a non-regulated turboprop engine (PW127G), for which currently there is not publicly available nvPM emissions data reported. Measurements were conducted on the ALF502-R5 and LF507-1H at CFS Aero (Hawarden Airport, UK) in September 2023, using the European reference nvPM system. Additionally, a Pratt & Whitney PW127G turboprop engine was tested at INTA facilities (Spain), in October 2024, using a non-compliant 'novel' sampling and measurement system, developed based on the data generated at the ALF502/LF507 tests. Within the SAMPLE IV Deliverable 5 report, full descriptions of the specific experimental setups are provided for each test campaign, including details of the custom-designed exhaust probes, sampling and measurement systems, and data analysis methods.

The emissions data from the three tested engines, along with nvPM measurements from three additional non-regulated turbofan engines in the 16-22 kN thrust range – previously collected using the Swiss SMARTEMIS nvPM system - revealed that small and non-regulated engines produce nvPM and gaseous emissions comparable to those of regulated engines. With it observed that emission levels of all these engines, were generally well below the ICAO regulatory thresholds for in-production engines. Notably, nvPM emissions varied significantly among the tested engines. The ALF502 and LF507 emitted relatively low concentrations of small nvPM, whereas the tested turboprop (PW127G) exhibited higher concentrations of larger PM emissions across the entire power range.

These full- engine test experiments were used to develop and validate the 'novel' simplified sampling and measurement approaches, as discussed in Task 3, to further assess methodologies for estimating nvPM emissions from smoke number, as presented in Task 6, and to evaluate the impact of fuel composition on observed nvPM emissions, as detailed in Task 7.

The dissemination level of the relevant deliverable for Task 5 is shown in Table 11.

Table 11: Task 5 – Deliverable Details

Specific contract	Deliverable	Title	Dissemination Level
SC02	D-5	Report on Small and non-regulated engine emission testing	Public

2.6. Task 6

The scope of Task 6 targeted the future use of SN to derive nvPM mass and number emission indices for turbofan and turbojet engines that do not have relevant nvPM emissions data in the EDB. Such examples of these types of engines would include those with a rated thrust below 26.7 kN or legacy engines that are no longer in-production. As part of this work, improvements to the current nvPM mass and number calculation methods from SN values (e.g., ICAO Doc 9889) were recommended.

Task 6 evaluated the performance of the state-of-the-art methods for converting smoke number to nvPM mass and number EIs. The current conversion methods are detailed in SCOPE 11 (Agarwal et al [5]) and the first order approximation version 4 (FOA4) [7] methods. Assessments were based on combined measurements of nvPM (mass and number) and smoke number with the EU and Swiss nvPM reference emissions measurement systems. In addition, Task 6 set to propose refinements to these conversion methods, considering small engines.

The smoke number standard for large engines (max rated thrust greater than 26.7 kN) was finally retired at the start of the new nvPM standard for nvPM mass and number for large engines in 2023. However, for legacy regulated engines, which were out-of-production before the new nvPM standard, and for small engines (max rated thrust less than 26.7 kN), smoke number remains relevant. Therefore, to create continuity for the nvPM standards and for comparability between large and small engines, validation of the conversion from smoke number to nvPM mass and number is necessary.

In the assessment of the conversions to nvPM mass and number and their respective emission indices (EIs), the largest adjustable uncertainty was observed to correspond with the nvPM mass prediction, which is the basis for most other parameters in the EI estimation. The SCOPE 11 method for nvPM mass estimation from smoke number was adopted as the FOA4 method by ICAO Doc 9889 [7]. As noted in the SAMPLE IV Deliverable 6 report, this analysis suggested all measured nvPM mass were within the 90% prediction band of the SCOPE11 correlation.

However, the analysis indicated there were clear distinctions between mixed flow turbofan (MTF) engines and non-mixed flow engines. The MTF engines with high bypass ratio (BPR) were seen to exhibit lower nvPM mass for a given smoke number compared to similar unmixed engines. To account for this difference between MTF and non-MTF with high BPR, a new correlation was developed for MTF engines with BPR greater than 4. This refinement in the nvPM mass correlation, improved the prediction of follow-up parameters such as GMD and EIs of number and mass emissions for MTF engines with a BPR > 4.

For the prediction of nvPM number, the geometric mean diameter (GMD) of emitted particles is also relevant. While SCOPE 11 uses a parameterisation for GMD based on nvPM mass, the FOA4 method has fixed GMDs at the different thrusts in the ICAO landing take-off cycle (LTO cycle). By specifying alternative GMD parameterisations either directly as a function of thrust, using the findings of Durdina et al. [6] based on measured particle size distributions, or as a function of number to mass ratio, improvements were observed in the FOA4 estimates of nvPM number. Compared to the SCOPE 11 method, not much improvement was observed, with it noted the SCOPE 11 method generally estimated too low and unrealistic GMDs even for PSDs witnessed at the engine exit plane (e.g., predictions of GMD down to 4.5 nm).

Task 6 also assessed the possibility of direct correlations between smoke number and EIs of nvPM mass and number. Very good direct correlation was observed for EIs of mass, with distinct correlations for MTF (R^2 = 0.98) and non-MTF (R^2 = 0.95) engines. Such correlation was not possible for nvPM number.

To improve the performance of both SCOPE 11 and FOA4 methods, the following refinements to the present SN to nvPM correlations were recommended in the SAMPLE IV deliverable 6 report:

- SN to nvPM mass conversion could be improved with different correlations for MTF engines with BPR > 4, while the SCOPE correlation remains for other engines. This small, proposed change affects the calculation of other parameters for EI calculations, including particle loss correction factors and GMD.
- GMD in the FOA4 method in ICAO Doc 9889 [7] could be improved with more robust parameterisation using the data presented in Durdina et al. [6], see equation below (Eq. 1). This method allows for more accurate and easier implementation in emissions inventories, as nvPM mass is not readily available but needed in the SCOPE 11 method, and unrealistically small GMDs can be avoided.

$$GMD = 12.91 + 0.264\left(\frac{F}{F00}\right) \cdot 100 \qquad \text{Eq. 1}$$

- Large variability was also observed in the air-fuel-ratio (AFR) estimation, relevant for SCOPE 11 calculations, with larger variability at lower thrusts. Though only limited data are publicly available, interpolation of ICAO reference values was observed to provide reasonable estimates for most engines, including small engines. However, it is noted that Improvements to the AFR estimation will only be possible with more empirical data.

The status of the deliverable in Task 6 is shown in Table 12.

Table 12: Task 6 – Deliverable Details

Specific contract	Deliverable	Title	Dissemination Level
SC02	D-6	Report on refining methodologies for estimating nvPM emissions from reported Smoke Number for regulated and non-regulated aircraft turbine engines	Public

2.7. Task 7

The scope of Task 7 was concerned with detailing recommendations on updates to the ICAO fuel specifications and nvPM fuel correction methodology. Specifically, the work assessed the effects of different blending ratios of Jet A-1 with synthetic blending components on emission levels and assessed the current fuel correction methods and potential limitations or improvements that could be made. As part of the study new data concerning the relative agreement of laboratories and fuel analysis methodologies was generated along with an assessment of the relative accuracy of the current fuel correction method, using data collected on 2 engines (ALF502/LF 507) burning 4 different fuels (2 conventional Jet A-1 and 2 50% HEFA-SAF blends).

Literature review indicates that the fuel composition parameter that correlates most strongly with nvPM EI's is the fuel hydrogen content (FHC). However, this analysis indicates that at present, it is difficult to reach a high degree of confidence in reporting a FHC, due to observed in FHC analytical methods. This coupled with uncertainty in measured nvPM EIs, results in a major uncertainty in the fuel correction method.

However, the analysis conducted showed that the ICAO fuel composition nvPM correction performed relatively well for engine sizes ranging from 17 to 249 kN, with predicted nvPM EI reductions agreeing within ±20% of the measured ones at higher power conditions (>7% thrust), and within ±40% at idle/sub-idle conditions (≤7% thrust). It is noted that this analysis included fuels of up to 14.5% hydrogen content. However, the ICAO A16V2 [3] certification fuel specifications only permits FHCs in the range 13.4-14.3% (mass). With literature review indicating that conventional Jet A-1 fuels typically range from circa 13.6-14.2% (mass), SAF blends 13.6-14.7% and pure HEFA SAF from 15.1-15.4% (mass). Given, this disparity it was discussed whether the bounds of FHC, currently permitted in ICAO Annex 16 Volume II, should be changed to better align with available / future fuels. It is thought that a narrowing of the permittable allowance of FHC content for engine testing, would reduce the average uncertainty in correction, whilst also making it easier to acquire Jet-A1 fuel that meets the certification specification.

It was concluded that the main uncertainties in the ICAO fuel composition correction are likely currently concerned with the FHC measurement, and the repeatability of engine power condition at low thrust. As such it was recommended that further work is required towards reducing the uncertainty associated with FHC determination. With it stated that reproducibility rather than absolute accuracy of FHC is what would be required to optimise an improved nvPM fuel correction methodology. Two fuel analysis methods which may offer this high reproducibility are GCxGC and NMR. However, for both methods new internationally accepted standardised methods would need to be developed, in order there is confidence that there is no significant laboratory bias.

The dissemination of the deliverable report associated with Task 7 is shown in Table 13.

Table 13: Task 7 – Deliverable status

Specific contract	Deliverable	Title	Disemination Level
SC02	D-7	Report on fuel specifications and corrections – nvPM emissions	Public

2.8. Task 8

Task 8 related to activities concerned with the delivery of the SAMPLE IV project management, coordination actions, as well as communication and dissemination actions.

Throughout the SAMPLE IV project, regular meetings were organised to coordinate the project and discuss any ongoing technical issues. The meetings were required to underpin the SAMPLE IV framework, with details of their scheduling for the two specific contracts, detailed in Figure 2. As is seen, two Kick-Off Meetings (one per specific contract), nine management meetings with EASA (all of them during the SC02), ten quarterly Review Meetings (three in the SC01 and seven in the SC02), twenty two technical meetings with EASA Technical Leaders (one in the SC01 and twenty one in the SC02), four consortium meetings and a final project meeting were undertaken during the course of the SAMPLE IV project.

In addition to these official project meetings, the members of the consortium also arranged numerous teleconferences to discuss research plans and any technical issues related to the activities of the SAMPLE IV project.

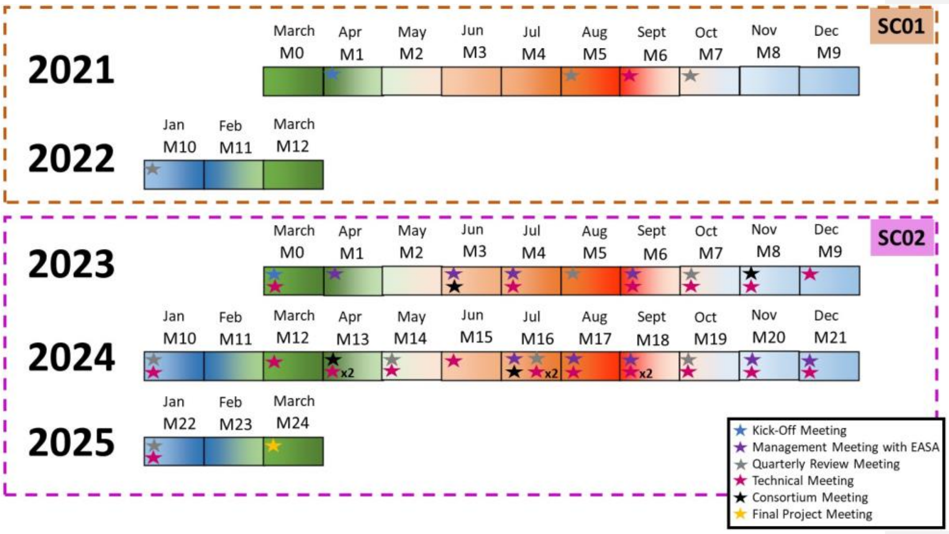

Figure 2: Meetings organised during the SAMPLE IV project

Regarding the project management, INTA, as project coordinator, together with the technical leads, continually monitored the projects progress, towards ensuring the objectives and goals of the project were achieved within the projects resources. A Project Management Plan (PMP) was developed and maintained to ensure that SAMPLEIV was delivered in accordance with the Specific Contract issued by EASA. This document describes the main project deliverables, the organisational structure, governance and decision-making structure, the project communication strategy, document management, reporting and financial management whilst also describing the project management processes and required documentation. Finally, an up-to-date Risk Management plan was maintained throughout the project duration. The risk status was monitored and presented at each Quarterly Review Meeting.

Continual progress monitoring was undertaken using a detailed Gantt chart, which was included in the PMP. This Gantt chart was used to track the progress of each of the individual tasks and deliverables on a quarterly basis, raising awareness of possible delays and their impact on the entire project.

As for communication and dissemination activities, these are summarised in the Communication and Dissemination Activities document (D-COM). In the D-COM the key stakeholders (including their interest and needs), are described, along with the key communication and dissemination goals and target audience to be reached. Finally, the elements needed to evaluate and measure the results of the communication and dissemination actions are explained. SAMPLE IV has developed a visual identity media (logos and reporting/presentation templates). News related to the project has been published on EASA's website, INTA's website and via a SAMPLE IV LinkedIn account. Finally, two articles related to the project have been published in a domestic (Actualidad Aeroespacial) and international magazine (Aerospace Testing International).

The SAMPLE IV consortium collectively, have delivered nine presentations at six different international conferences, technical committee meetings and workshop events. Moreover, a peer reviewed journal article has been published, with the consortium members continuing to significantly contribute and undertake leadership roles within E31 team discussions (novel, uncertainty, loss, size, etc.).

The status of the deliverables in Task 8 are shown in Table 14:

Table 14: Task 8 – Deliverable status

Specific contract	Deliverable	Title	Status
SC01	D-PMP	Project Management Plan	Approved
SC02			
SC02	D-COM	Communication and Dissemination Actions	Approved
SC01	D-QR1	1st Quarterly Report	Approved
SC01	D-QR2	2nd Quarterly Report	Approved
SC01	D-QR3	3rd Quarterly Report	Approved
SC01	D-QR4	4th Quarterly Report	Approved
SC02	D-QR1&2	1st and 2nd Quarterly Reports	Approved
SC02	D-QR3	3rd Quarterly Report	Approved
SC02	D-QR4	4th Quarterly Report	Approved
SC02	D-QR5	5th Quarterly Report	Approved
SC02	D-QR6	6th Quarterly Report	Approved
SC02	D-QR7	7th Quarterly Report	Approved
SC02	D-FPR	Final Project Report	Approved

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