Comparison of Standardized Sampling and Measurement Reference Systems for Aircraft Engine Non-volatile Particulate Matter Emissions

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Abstract

The International Civil Aviation Organization has established new regulatory standards for emissions certification of non-volatile particulate matter (nvPM) from aircraft turbine engines. The adoption of the nvPM emissions regulatory standards required development of a standardized sampling and measurement methodology, and rigorous testing. Three reference systems for aircraft engine nvPM emissions measurement, compliant with the specifications for the standardized methodology, were independently developed. This paper reports the results of the first inter-comparison of these three reference systems using a CFM56-7B26/3 aircraft engine to establish repeatability and intermediate precision of the sampling and measurement systems as part of the multi-agency international collaborative projects: Aviation-Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE) 5/ Studying, sAmpling and Measuring of aircraft ParticuLate Emissions (SAMPLE) III - SC03. The instruments used in the three reference systems recorded nvPM mass and number concentration, which were converted to their respective emission indices for comparison. The reference systems generally agreed to within 15% of the average nvPM number emission index and 30% of the average nvPM mass emission index. The only exception was for the nvPM mass instruments, which exhibited a higher variation as the concentration levels approached the limit of detection. The additional measured particle size distributions could be approximated to lognormal distributions with the geometric mean diameter ranging from 15 nm to 38 nm, and the geometric standard deviation varying between 1.53 and 1.92. The results from this study are a benchmark for the variability in standardized sampling and measurement systems for measuring aircraft engine nvPM emissions.

Highlights

- Comparison of three reference systems for measuring aircraft engine nvPM emissions
- The nvPM number emission index was generally within 15% of the average value
- The nvPM mass emission index was generally within 30% of the average value
- Mass-based emissions exhibited high variability towards the instrument limit of detection

Keywords

Aircraft engines, non-volatile particulate matter, aviation emissions, black carbon, particle number, size distributions

1 Introduction

Aircraft engine gaseous and particulate matter (PM) emissions are a unique source of pollution compared to other sources in the urban environment. The public awareness about aviation emissions has grown since the rapid increase in demand for commercial air travel in the 1960s, which led to the introduction of emission standards by the International Civil Aviation Organization (ICAO). Prior to 2010, the ICAO Committee on Aviation Environmental Protection (CAEP) developed emission standards and recommended practices (SARPs) limited to the emissions of gaseous pollutants such as oxides of nitrogen (NO_x), carbon monoxide (CO), and unburnt hydrocarbons (UHC), and emissions of smoke (reported in terms of smoke number, SN). The SARPs are applicable to turbojet and turbofan engines with maximum sea-level static rated thrust >26.7 kN for gaseous emissions and to all engine sizes for smoke emissions. The SARPs, intended to mitigate the impact of aircraft engine emissions on local air quality, have been established for the type certification of aircraft engines and are documented with approved test and measurement procedures in ICAO Annex 16 to the Convention on International Civil Aviation, Volume II (ICAO, 2017). The type certification process involves operating one or multiple representative engines of a specific model on a test stand at combustor inlet temperatures corresponding to the four thrust settings of the standardized Landing and Take-off (LTO) cycle – 7% (taxi), 30% (approach), 85% (climb), and 100% (take-off) – corrected to International Standard Atmosphere (ISA) conditions (ICAO, 1993). The engine manufacturers submit emissions data, acquired during these engine type certification tests to the certificating authority for approval and subsequently for inclusion in the ICAO Aircraft Engine Emissions Databank (EEDB) maintained by the European Union Aviation Safety Agency (EASA) (EASA, 2019a).

Since aircraft engine emissions regulatory standards were first adopted in 1981, ICAO/CAEP has developed increasingly stringent standards for NO_x emissions. This, along with the introduction of newer, more fuel-efficient engine technologies, has resulted in lower aircraft engine emissions over time (Wey & Lee, 2018). However, with the growth of commercial and cargo air traffic at a rate of ~4.5% per year (Airbus, 2018; Boeing, 2018; IATA, 2019) the absolute emissions from the aviation sector have increased, including PM emissions which are forecast to increase over the next twenty years if current engine technology continues to be used (EASA, 2019b). This in turn has led to several studies to measure, model, and ultimately develop solutions to mitigate aviation-related emissions (Masiol and Harrison, 2014).

The smoke standard was introduced at a time when the visibility of exhaust plumes from aircraft engines was of significant concern for airport safety. Smoke number is determined by measuring the reduction in reflectance of a Whatman #4 filter used to sample a prescribed mass of exhaust per unit area of the filter, i.e. 16.2 kg of exhaust gas/m^2. The precision of the SN measurement method is reported as ±3 SN (SAE, 2011), which in some cases is higher than the recorded SN for modern turbofan engines. Also, the SN does not provide any information about the number, size, and composition of the PM emissions that are required for environmental impact assessments. In the absence of fleet-wide aircraft engine PM emissions data, the First Order Approximation (FOA) methodology was developed based on correlations between SN reported in the ICAO EEDB and available data for non-volatile particulate matter (nvPM) mass emissions (Wayson, Fleming, & Iovinelli, 2009). FOA and subsequent updates (current version FOA 4.0) have been used to estimate PM emissions from certified commercial aircraft engines during the LTO cycle at airports (Rissman et al., 2013; Winther et al., 2015; Woody et al., 2016).

The eighth meeting of CAEP (ICAO, 2010) recognized the need for PM emissions regulation in addition to the existing set of regulated pollutants. The first new regulatory standard for aircraft engine nvPM emissions was adopted by CAEP in 2016 (CAEP/10). It included reporting requirements and a nvPM mass emissions standard for in-production aircraft engines with rated thrust >26.7 kN on or after 1 January 2020. The CAEP/10 standard was set at a regulatory level that matched the existing smoke number visibility standard. The regulatory level for the CAEP/10 maximum nvPM mass concentration was developed based on a statistical relationship between nvPM mass concentration and smoke number (Agarwal et al., 2019). This ensured that any aircraft engine that would have met the certification requirements for smoke number would also meet the nvPM mass emissions level (all-pass standard). From 1 January 2023, regulatory limits for mass and number-based nvPM emissions will become applicable for in-production and new commercial aircraft engine types with a maximum rated thrust > 26.7 kN (CAEP/11 standard) (ICAO, 2019). Along with this new standard and since the CAEP/10 standard includes control of exhaust plumes visibility, CAEP agreed that the smoke number standard will no longer be applicable for these engines from 1 January 2023.

Before regulatory standards for nvPM mass and number emissions could be defined, a standardized sampling and measurement methodology was required for aircraft engine emissions certification tests. The Society of Automotive Engineers (SAE) Aircraft Engine Gas and Particulate Emissions Measurement Committee (E-31) was tasked with recommending a standardized protocol for aircraft engine nvPM mass- and number-based emissions. The development of this standardized protocol for aircraft engine nvPM emissions was the culmination of several years of effort to investigate sampling methods, evaluate measurement technologies, and assess engine type and fuel composition differences on nvPM emissions during the PARTEMIS (Petzold et al., 2003), APEX (Lobo et al., 2007; Timko et al., 2010; Kinsey et al., 2010), AAFEX (Kinsey et al., 2012), SAMPLE (Petzold et al., 2011; Crayford et al., 2012; Crayford et al., 2013; Boies et al., 2015), A-PRIDE (Durdina et al., 2014; Lobo et al., 2015a; Brem et al., 2015), and MERMOSE (Delhaye et al., 2017) projects, in addition to other studies (Lobo et al., 2015b). The results informed the development and publication of Aerospace Information Report (AIR) 6241 (SAE, 2013) and Aerospace Recommended Practice (ARP) 6320 (SAE, 2018). The standardized protocol is limited to only nvPM emissions, defined as particles that exist at the aircraft engine exhaust nozzle exit plane that do not volatilize at temperatures greater than 350°C (ICAO, 2017). Controlling aircraft engine nvPM emissions at the source will lead to lower emissions on local, regional, and global scales. Total PM emissions downstream of aircraft engines are not currently considered since they have been shown to vary in space and time as the exhaust plume cools and expands (Lobo et al., 2012; Timko et al., 2013; Beyersdorf et al., 2014), making it complicated to develop a standardized sampling and measurement protocol that reports repeatable concentrations, and to enforce through a certification requirement. The approach to limit the sampling and measurement system to nvPM was similar to that adopted by the Particle Measurement Programme (PMP) for the regulation of the number concentration of solid (non-volatile) particles with a diameter >23 nm emitted from automotive engines (Giechaskiel et al., 2012).

Analogous to the reference “golden” particle number measurement system used in PMP (Martini, Giechaskiel, & Dilara, 2009), three reference systems for aircraft engine nvPM emissions measurement were independently developed - the Swiss (CHE) fixed (later mobile) system by

Empa, the European (EUR) mobile system by Cardiff University, and the North American (NAM) mobile system by Missouri University of Science and Technology. All three reference systems were compliant with the specifications for the standardized system detailed in AIR6241, but not identical since AIR6241 permits tolerances for different components and specification ranges. It was essential to inter-compare the three reference systems using a common aircraft engine source to establish repeatability and intermediate precision of the sampling and measurement systems, and to estimate some of the uncertainties associated with the measurements of aircraft engine nvPM emissions.

In this paper, we present results of the Aviation-Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE) 5/ Studying, sAmpling and Measuring of aircraft ParticuLate Emissions (SAMPLE) III - SC03 campaign, the first multi-agency international collaborative project to inter-compare and evaluate the robustness of the Swiss, European, and North American standardized reference systems for the sampling and measurement of aircraft engine nvPM emissions. The measurements were performed from 28 July to 25 August 2013, on a leased CFM56-7B26/3 engine used during dedicated engine testing at the SR Technics engine test facility in Zürich, Switzerland.

2 Methods

*2.1 **CFM56-7B26/3 engine***

The engine used for the dedicated tests was a CFM56-7B26/3, which was leased for the duration of the campaign. The CFM56-7B engine is the sole powerplant for the Boeing 737NG family, and it is the most widely used engine in commercial aviation. The “/3” configuration (improved durability and emissions) was emissions-certified for gaseous pollutants and smoke in 2006. The specific engine used during this campaign had accumulated 5009 flight hours during 2000 flight cycles. The engine had representative operating and performance characteristics with minimal degradation and negligible oil consumption in the range of a brand-new engine. This engine was declared to be a representative reference engine to be used as a source of nvPM to inter-compare the standardized reference systems. Aircraft engine emissions certification-like tests for nvPM emissions were also performed with a single system (Durdina et al., 2017).

2.2 Fuel

The Jet A-1 fuel used for the emissions tests was provided by SR Technics. Seven fuel samples were collected during the measurement campaign, and the results of the fuel analysis performed by Intertek AG (Schlieren, Switzerland) for selected properties are presented in Table 1. The properties of the Jet A-1 fuel were all within the allowable range specified by ASTM D1655 (ASTM, 2019). The fuel also met all the specifications for emissions certification tests (ICAO, 2008) except that for naphthalenes content, which was below the lower limit requirement at the time (1%). This was also the case for a previous campaign conducted at SR Technics (Lobo et al., 2015a). The lower limit for naphthalenes specification was subsequently changed to 0% (ICAO, 2017). Overall, the different batches of Jet A-1 fuel used for the emissions tests had similar properties, thus eliminating fuel composition as a variable in the calculation of emission indices (EIs) and inter-comparison of the reference systems. An average hydrogen to carbon (H/C) ratio of 1.95 was used for the calculation of the number and mass emission indices for all three reference systems.

Table 1: Properties of Jet A-1 fuel used during the A-PRIDE 5/SAMPLE III-SC03 campaign

Property	Units	Method	Allowable Range	Test Fuel Samples[†]						
				29 Jul 2013	2 Aug 2013	5 Aug 2013	12 Aug 2013	17 Aug 2013	18 Aug 2013	25 Aug 2013
Density at 15°C	kg/m^3	ASTM D4052	780-820	797.6	797.6	797.8	797.8	797.8	797.8	797.2
Kinematic viscosity at -20°C	mm^2/s	ASTM D445	2.5-6.5	3.591	3.618	3.598	3.596	3.599	3.599	3.618
Distillation temperature 10% boiling point	°C	ASTM D86	155-201	169	168	168	168	167	168	169
Final boiling point			235-285	265	265	265	261	263	264	264
Net heat of combustion	MJ/kg	ASTM D3338	42.86-43.50	43.3	43.3	43.3	43.3	43.3	43.3	43.3
Aromatics	volume %	ASTM D1319	15-23	17.7	17.7	17.4	18.0	17.7	17.7	17.5
Naphthalenes	volume %	ASTM D1840	0-3%[‡]	0.68	0.72	0.71	0.71	0.74	0.75	0.70

[†] All fuel samples were collected from the fuel line in the test cell except the on 5 Aug 13, which was collected directly from the fuel tanker

[‡] Original allowable range 1.0-3.5%, subsequently updated to 0-3%

Smoke point	mm	ASTM D1322	20-28	21	21	21	21	22	21	22
Hydrogen content	mass %	ASTM D5291	13.4-14.3	14.18	14.18	14.28	14.04	13.96	14.00	13.76
Sulphur content	mass %	ASTM D5453	< 0.3%	0.053	0.033	0.039	0.039	0.042	0.042	0.042
H/C ratio (calculated)			1.84-1.99	1.97	1.97	1.99	1.95	1.93	1.94	1.90

2.4 *Experimental Setup*

A schematic of the experimental setup is shown in Fig. 1. Details of the various sections of the sampling and measurement systems are provided in the following sections.

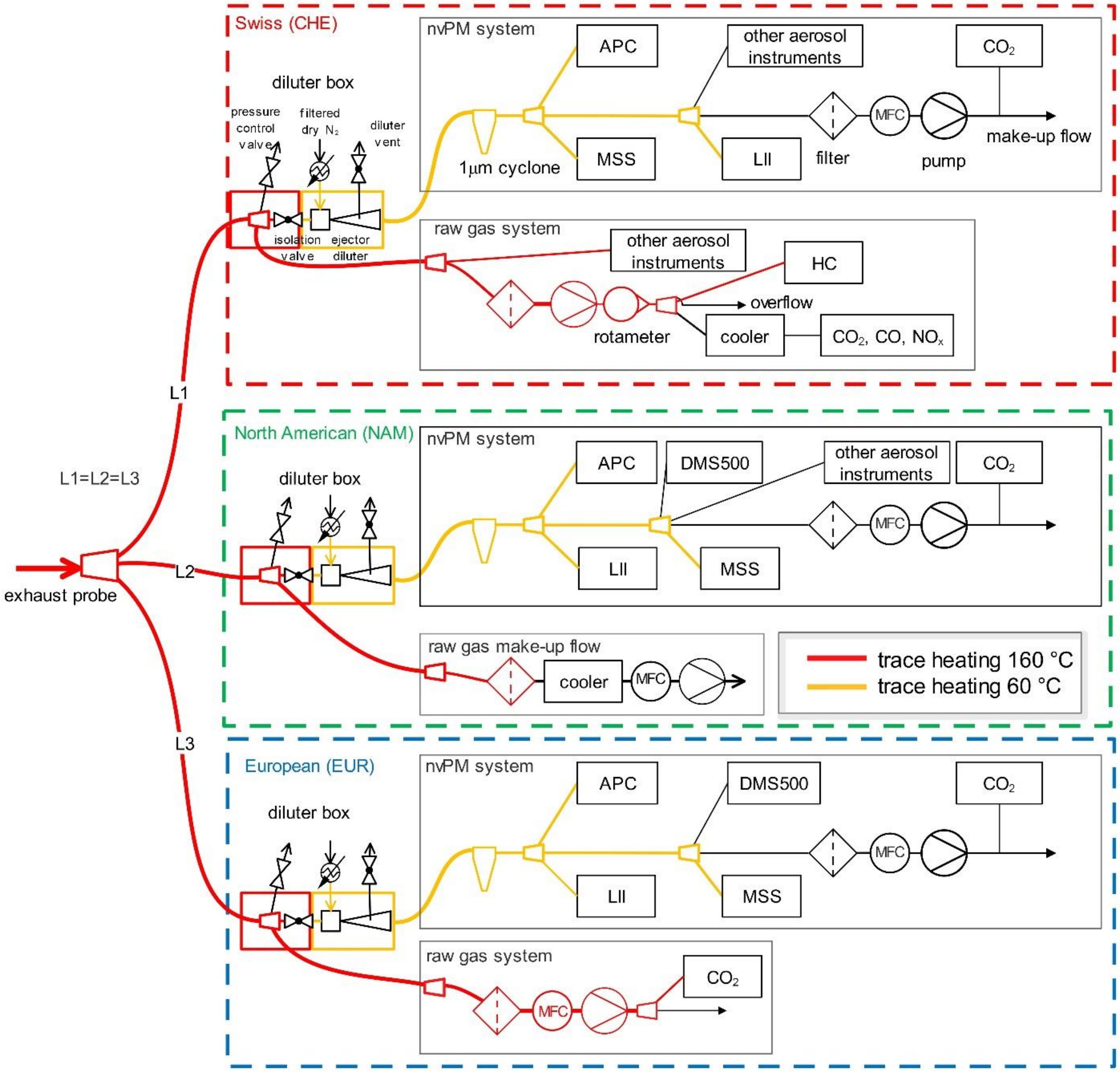

Figure 1: Experimental setup for CFM56-7B26/3 engine tests (not to scale)

2.4.1 Extractive sampling probes

Two exhaust sampling probe assemblies were used to extract emission samples within 1 m of the engine exit plane. A fixed multi-point probe made of Inconel 625 alloy compliant with the requirements for nvPM sampling and measurements for emissions certification (ICAO, 2017) was used during a subset of the dedicated engine tests. It consisted of a cruciform with six sampling orifices located on each of the four arms, from which three orifices per arm were used to comply with the carbon balance check (air/fuel ratio estimated from the exhaust sample total carbon concentration agrees with the estimate based on engine air/fuel ratio). The sampling orifices were symmetrically located on circular radii from the center of the cruciform. Various configurations of the number and position of sampling orifices on the multi-point probe were evaluated during the campaign. The primary goal of this assessment was to ensure that the three reference systems operating in parallel were adequately supplied with sample flow, while still providing an exhaust representative sample and complying with the carbon balance check.

A traversable single-point probe used during previous campaigns at SR Technics (Lobo et al., 2015a) was used during piggy-back measurements and a subset of dedicated engine tests. The probe with an 8 mm ID orifice was made of Inconel 600 alloy. The probe's vertical traverse capability afforded representative sampling at the exit plane of different engine types operated in the test cell (for the CFM56-7B26/3 engine, the distance from the probe to the exit plane was 0.8 m). The specific vertical sampling location was optimized during testing, ensuring the carbon balance of the single-point probe maintained satisfactory agreement (< 10%) with the multi-point probe at all similar test conditions.

2.4.2 Sampling and measurement systems

The probe was connected to a three-way splitter using a 5.2 m long, 8 mm ID thin-walled stainless steel tubing, electrically trace heated and insulated to maintain a temperature of 160°C ± 15°C. The exhaust samples were distributed to the three reference systems. Each reference system, while compliant with the specifications detailed in AIR6241, was independently assembled from non-identical components and evaluated prior to deployment in the campaign. Briefly, each system had a three-way splitter to distribute the exhaust sample to the line for raw gaseous emission measurements, the pressure control line to regulate the sample inlet pressure, and the nvPM line for nvPM mass- and number-based emission measurements (Fig. 1). Of the three reference systems, only the NAM system did not have measurements of raw gaseous emissions on the raw exhaust line. Instead, a pump was used to draw flow down the gaseous emissions line in order to achieve a prescribed flow velocity in each leg of the splitter, and to be consistent with the CHE and EUR system flowrates. The undiluted CO_2 concentration data from the CHE reference system were used to calculate dilution factors for all three systems. The variability in undiluted CO_2 concentrations measured by the CHE and the EUR reference systems was evaluated. The slope of a linear interpolation comparing the undiluted CO_2 concentrations in the EUR system to those from the CHE system was 0.993 (R^2=0.997). This variability is within the uncertainty of the CO_2 measurements, estimated to be less than 4% across all test points.

The exhaust sample for the nvPM line was diluted with particle-free synthetic air (purity 99.999%) using a Dekati DI-1000 ejector diluter. The dilution factors achieved using the DI-1000 ejector diluter are highly dependent on the sample inlet pressure and diluent air pressure (Giechaskiel, Ntziachristos, & Samaras, 2004). The dilution factor at nominal sample and diluent inlet pressures was 8-14 (as specified in the SARPs); however, the range extended from 7 to 20 for some of the dilution factor sensitivity tests performed during the campaign. The diluted sample was transferred to the real-time diagnostic instruments by a 24 - 25 m long, carbon-loaded, electrically grounded polytetrafluoroethylene (cPTFE) line maintained at a temperature of 60°C ± 15°C followed by a sharp cut cyclone with a 1 µm cut size. The sample lines for each reference system had slightly different internal diameters, but well within the range 7.59 - 8.15 mm as specified by AIR6241. The diluted exhaust sample flow rate in the cPTFE line was maintained at 25 slpm ± 2 slpm. Another three-way splitter distributed the particle-laden flow to the nvPM number instrument, the nvPM mass instruments, and the excess flow line for CO_2 concentration, and other ancillary measurements that were not a requirement of the standardized system.

All three reference systems measured nvPM number emissions using an AVL Particle Counter (APC) Advanced (Giechaskiel et al., 2010), which consists of a primary dilution stage with a rotating disk diluter, a catalytic stripper with a sulphur trap (volatile particle remover, VPR) maintained at 350°C, a secondary dilution stage with a porous tube diluter, and an n-butanol-based condensation particle counter (CPC; TSI 3790E), with a 50% cut-off diameter ≈10 nm and 90% count efficiency at ≈15 nm (Lobo et al., 2015a). All CPC's were operated in single count mode by increasing the APC dilution factor when CPC concentrations approached 10,000 particles/cm^3. The diluent used for the APC was synthetic air. The nvPM mass emissions were measured using both an Artium Laser Induced Incandescence LII 300 (LII) (Snelling et al., 2005) and an AVL Micro Soot Sensor (MSS) (Schindler et al., 2004) on all three reference systems. Additionally, two Cambustion DMS500 fast mobility spectrometers (Reavell et al. 2002) were installed on the excess flow/ancillary line, one each on the EUR and NAM reference systems to measure PM size distributions. A compact time of flight aerosol mass spectrometer (CToF-AMS) (Drewnick et al. 2005) to obtain chemical composition information, and a Cavity Attenuated Phase Shift (CAPS) PM extinction monitor (Yu et al., 2011) to measure nvPM mass were installed on the ancillary line on the NAM reference system. Further aerosol instrumentation was also deployed in the CHE reference system to measure particle effective density (Durdina et al., 2014) and chemical composition (Abegglen et al., 2016).

2.4.3 Instrument calibrations

The LII 300 and MSS instruments were calibrated to the NIOSH 5040 protocol (NIOSH, 2003) for EC using thermal optical analysis (TOA) in accordance with AIR6241 in two batches at NRC-Metrology, Ottawa, Canada one month prior to the start of the campaign. The NRC inverted-flame burner (Coderre et al., 2011) was used as the source of black carbon (BC) particles. The BC particles generated by the inverted-flame burner were diluted using filtered air, and the diluted sample was divided using a splitter and then directed to two 1μm cyclones – one was upstream of the dual-stage filter collection system, and the other upstream of the nvPM mass instruments to be calibrated. Equal length (2 m) heated cPTFE 3/8” OD tubing was used from splitters to all measurement devices. The entire sampling system was heated to 60°C. The MSSs from all three reference systems and the LII 300 from the NAM reference system were calibrated in the first batch with 6 or more repeats at target mass concentrations of 0, 50, 100, 500, and 1000 $\mu g/m^3$. The remaining two LII 300s were calibrated in the second batch with 3 or more repeats at target mass concentrations of 0, 100, 250, and 500 $\mu g/m^3$. The correlation of mass concentration measured by the instruments to NIOSH 5040 EC was >0.995 in all cases.

The APC for all three reference systems had its annual calibration and maintenance performed by the manufacturer within nine months of the campaign. Combustion soot from a miniature combustion aerosol standard (miniCAST) generator was used as the source to establish penetration through the VPR. CO_2 calibration gas was used to verify dilution factors for the two-stage dilution of the APC. As part of the calibration procedure, VPR performance was evaluated in terms of volatile particle removal efficiency. The CPC linearity and counting efficiency were also determined and adjusted (counting efficiency at 10 nm > 50%). All three reference systems had similar particle penetration profiles for the VPR, and volatile particle removal efficiencies of 99.99%. The CHE and NAM reference systems had similar CPC counting efficiencies of 76% and 92% at 10 nm and 15 nm, respectively, while the EUR reference system had a much lower CPC counting efficiency of 53% at 10nm and slightly higher CPC counting efficiency of 98% at 15 nm.

*2.5 **Test Matrix***

The dedicated engine tests with the CFM56-7B26/3 engine started with a warm-up sequence used for conditioning the probe and the sampling systems. The warm-up sequence consisted of running the engine at five test points from ground idle to 85% sea-level static thrust for durations of 5 minutes each. The parameter used for setting the engine thrust was the combustor inlet temperature, T3. The T3 values were based on a correlation of sea-level static thrust with T3 corrected to ISA conditions (15°C, 1 atm). The full test matrix following the warm-up sequence consisted of 12 points on a descending power curve, starting at maximum continuous thrust (which was limited by the ambient conditions during the test) and ending at idle. These test points included the four thrust settings corresponding to the LTO cycle as well as an additional point at 65%. The duration of each test point was 10 minutes. A subset of the full test matrix was run during most dedicated engine tests. Table 2 lists the inter-comparison experiments performed during the measurement campaign, along with the range of ambient conditions recorded during each test.

Table 2: Overview of experiments performed for Reference Systems inter-comparison

Date	Ambient Condition Ranges			Engine/Source	Description	Sampling Probe	Reference System		
	T (° C)	P (kPa)	RH (%)				Swiss (CHE)	European (EUR)	North American (NAM)
28 Jul 2013	28.5-34.0	96.0-96.2	24-42	CFM56-7B26/3	AFR check (probe tips 1, 4, 6)	Multi-point	✓	✓	✗
29 Jul 2013	17.3-17.8	96.6-96.8	87-95	CFM56-7B26/3	AFR check (all 24 probe tips)	Multi-point	✓	✓	✗
2 Aug 2013				miniCAST 5201C	Instrument comparison	-	✓	✓	✓
3 Aug 2013	27.4-30.8	96.9-97.0	28-39	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✓	✓
4 Aug 2013	18.0-26.3	97.1-97.5	45-82	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✓	✓
5 Aug 2013	24.2-25.6	96.7-96.8	54-57	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✓	✓
10 Aug 2013	21.1-22.5	97.1-97.2	44-53	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✗	✓
11 Aug 2013	18.4-24.2	96.9-97.1	39-56	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✗	✓
12 Aug 2013	20.4-26.1	96.6-96.8	34-50	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✗	✓
24 Aug 2013	17.0-20.2	96.3-96.5	68-92	CFM56-7B26/3	Reference Systems comparison	Multi-point	✓	✓	✗

2.6 miniCAST

A miniCAST soot generator 5201C (Jing Ltd) was used as a surrogate emissions source to compare the nvPM mass and number diagnostic instruments used in the three reference systems prior to the dedicated engine tests. The miniCAST was operated at the following flowrates - propane: 0.06 lpm, N_2 mixing gas: 0 lpm, oxidation air: 1.55 lpm, N_2 quench air: 7 lpm, dilution air: 20 lpm, such that a high elemental carbon (EC) fraction (>80%), determined from TOA, was produced in the exhaust stream (Durdina et al., 2016). The mean size of particles at the miniCAST setting selected was ~130 nm. This test was performed to verify that the operation and performance of the instruments were optimal after transport to the SR Technics engine test facility. The configurations for the nvPM mass and number instrument comparisons using the miniCAST are presented in Figure 2.

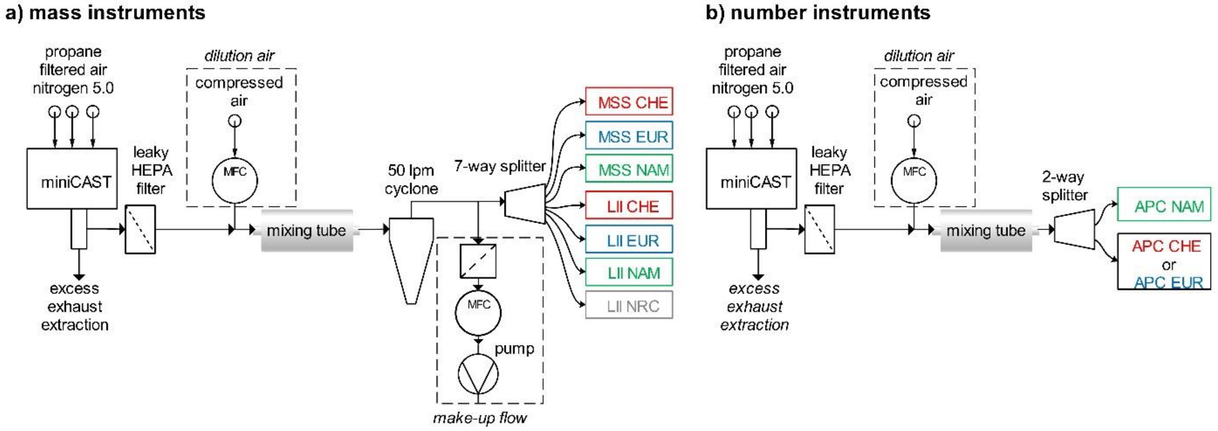

Figure 2: Configuration for the mass (a) and number (b) instrument comparisons using the miniCAST 5201C soot generator

For the nvPM mass instrument comparison, the miniCAST exhaust was passed through a HEPA filter dilution bridge and then diluted with compressed air to achieve target mass concentrations of 50, 100, 250, 500, 750, and 1000 μg/m^3. The diluted exhaust sample was then transferred through a mixing tube, a cyclone with a 1 μm cut-point at 50 lpm, and a 7-way splitter to the instruments under test – 6 instruments, (3 MSSs and 3 LII 300s) two from each reference system, and another LII 300 which was used to monitor source concentration levels during the course of the instrument comparisons. Only data from the instruments in the reference systems were used in the analysis. The calibration factors determined during the NRC-Metrology calibrations from the NIOSH 5040 EC protocol for all six nvPM mass instruments were applied prior to the comparison study. For the nvPM number instrument comparison, the miniCAST exhaust was diluted with compressed air and split into two legs – one providing a sample to the APC from the NAM reference system, and the other to the APC from either the CHE or EUR reference systems.

3 Results and Discussion

3.1 Instrument comparisons using the miniCAST

The results of the nvPM mass and number instrument comparisons conducted using the miniCAST as a source of nvPM are presented in Figure 3. The nvPM mass concentrations as measured by the MSS (Fig 3a) and LII 300 (Fig 3b) for each reference system were averaged for 60 seconds, and each instrument was then compared against the ensemble average. The data from the MSS and LII 300 instruments were tightly bound with a relative standard deviation (RSD) of 1.95% and 4.5%, respectively. A relatively higher degree of scatter (±10%) was observed with the LII 300 data for nvPM mass concentrations below 100 $\mu g/m^3$. Overall, the six nvPM mass instruments were within an RSD of 4.1% over the range of target nvPM mass concentrations explored. An RSD of 2.1% was observed between the 3 APCs used for the nvPM number measurements when the CHE and EUR reference system APCs were compared against the NAM reference system APC (Fig 3d). The repeatability of the miniCAST as reported by the manufacturer is ±5%. Larger differences have been observed from inter-day experiments (Moore et al. 2014), however, for the instrument comparison test the miniCAST settings were stable with RSDs in the mean nvPM mass and number concentrations <5%. Since the differences observed between the instruments were of a similar magnitude, the nvPM mass instruments and the nvPM number instruments were assessed as being in statistical agreement on the miniCAST source.

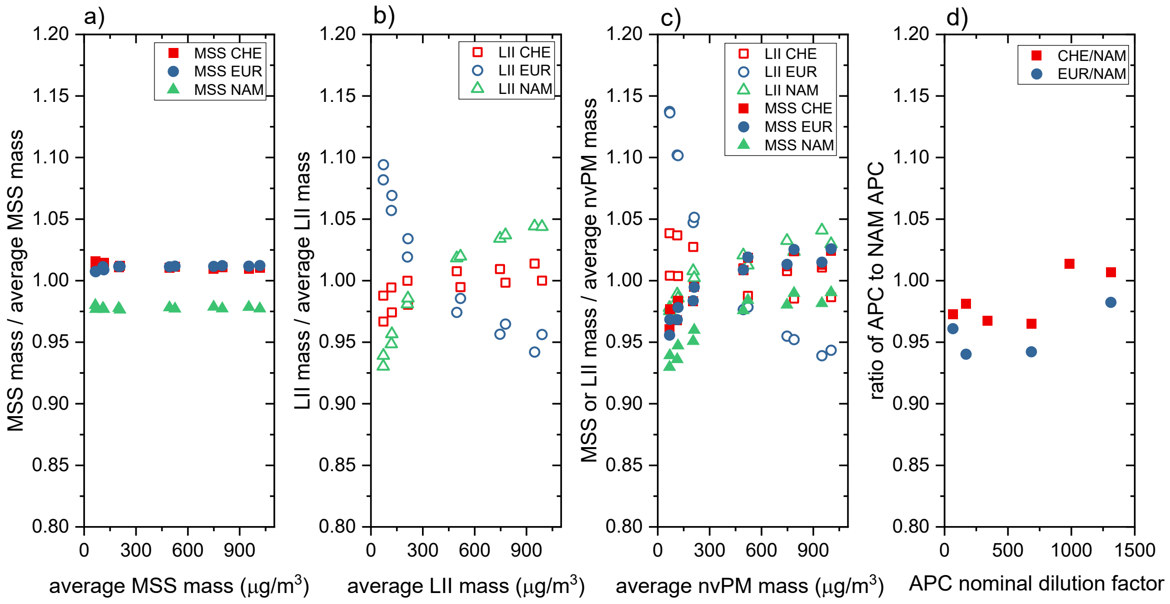

Figure 3: Comparison of nvPM mass (a, b, c) and number (d) instruments using the miniCAST 5201C soot generator

3.2 nvPM mass and number emission profiles for the CFM56-7B26/3 engine

The nvPM mass and number concentrations were converted to nvPM mass-based emission index (EI_m) and nvPM number-based emission index (EI_n), respectively, using the measured nvPM and gaseous emissons concentration and following the procedures specified in AIR6241 (SAE, 2013). The EIs are reported at a standard temperature of 273.15 K and standard pressure of 101.325 kPa. The nvPM mass and number emission indices were not corrected for either the thermophoretic loss in the sample extraction system or for size-dependent diffusional and inertial losses that occurred in the sampling and measurement systems, and CPC efficiencies for nvPM number. The nvPM mass and number emission indices for the CFM56-7B26/3 engine as a function of percent rated thrust are presented in Figure 4. For the nvPM mass emission index profile, the emissions for this engine were generally higher at idle conditions (3-7% rated thrust), decreased to a minimum at low engine thrust conditions (15-30% rated thrust), and increased linearly to maximum rated thrust. The nvPM number emission index also exhibited behavior similar to that of nvPM mass emissions at idle and low engine thrust conditions. However, the emissions increased up to a maximum at ~60% rated thrust and then slightly decreased up to the maximum rated thrust. The nvPM mass and number emissions profiles shown here are consistent with previously reported profiles for a CFM56-7B24/3 engine (which is the same engine model but rated at a lower take-off thrust) (Lobo et al., 2015a).

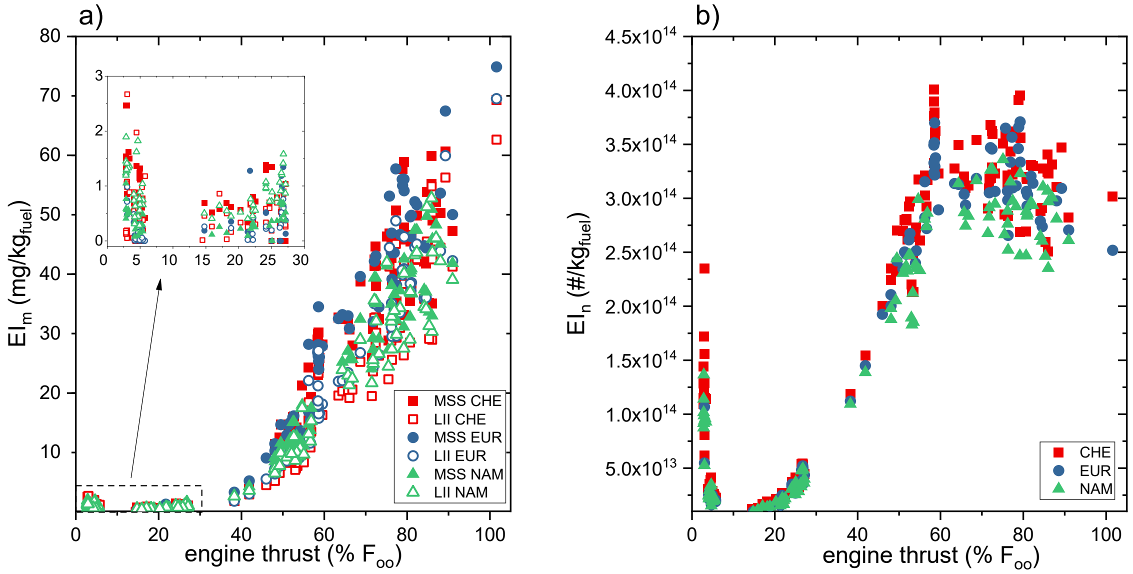

Figure 4: nvPM mass (a) and number (b) emission index profiles for the CFM56-7B26/3 engine

3.3 2-way reference system comparisons (CHE-EUR; CHE-NAM)

Comparison of nvPM mass and number emissions for pairs of reference systems, i.e., CHE-EUR and CHE-NAM was performed during the test campaign and is presented in Figure 5. The multi-point sampling probe was used for the CHE-EUR comparison, while the single-point probe was used for the CHE-NAM comparison. However, since the extracted exhaust samples were representative of the engine emissions, the use of a particular sampling probe did not influence the comparisons between the reference systems. The 2-way comparisons with reference systems in parallel were performed to assess system to system differences without the additional complexity of including a third system (also performed and described in the next section). The nvPM mass and number emission index for each instrument in the reference system pairs were averaged and compared against the ensemble average for a specific pair-wise comparison. The average nvPM mass and number emission indices for the CHE-EUR comparison were slightly higher than the CHE-NAM comparison because of the higher engine thrust conditions achieved during the respective tests.

The theoretical total uncertainties in the nvPM EIs presented are estimated to be ~22% for EI mass and ~25% for EI number. These estimates are based on typical uncertainty values for the nvPM mass and number instruments (including calibration uncertainty), CO_2 measurement, and the determination of the dilution factor in the nvPM number instrument (SAE, 2013). These estimates do not account for either the particle losses in the sampling and measurement systems or the increased uncertainty for nvPM mass measurements near the limit of detection (LOD).

All instruments in the three reference systems were generally ±22% of the average nvPM mass emission index and ± 25% of the average nvPM number emission index (grey shaded area in Fig. 5), except for the nvPM mass emission index which exhibited a >22% variation at low nvPM mass concentrations levels (corresponding to EIs of < 30 mg/kg), and significantly higher differences as the instruments approached the LOD (3 $\mu g/m^3$, corresponding to EIs of <2 mg/kg). The high variability in mass at low concentrations was exhibited for both types of nvPM mass instruments (MSS and LII 300). This trend for high variability in nvPM mass at low concentrations is consistent with results for emissions measurements of other engine types (Lobo et al., 2015a; Lobo et al., 2016). For nvPM number, the CHE reference system registered consistently higher values compared to the EUR and NAM reference systems. The overall magnitude of variation for each instrument from the average was consistent for the two pairs of reference system comparisons, i.e ± 15%. It should be noted that since only a single type of nvPM number instrument was compared, there is no information on the uncertainty associated with using different types of nvPM number instruments that meet the specifications.

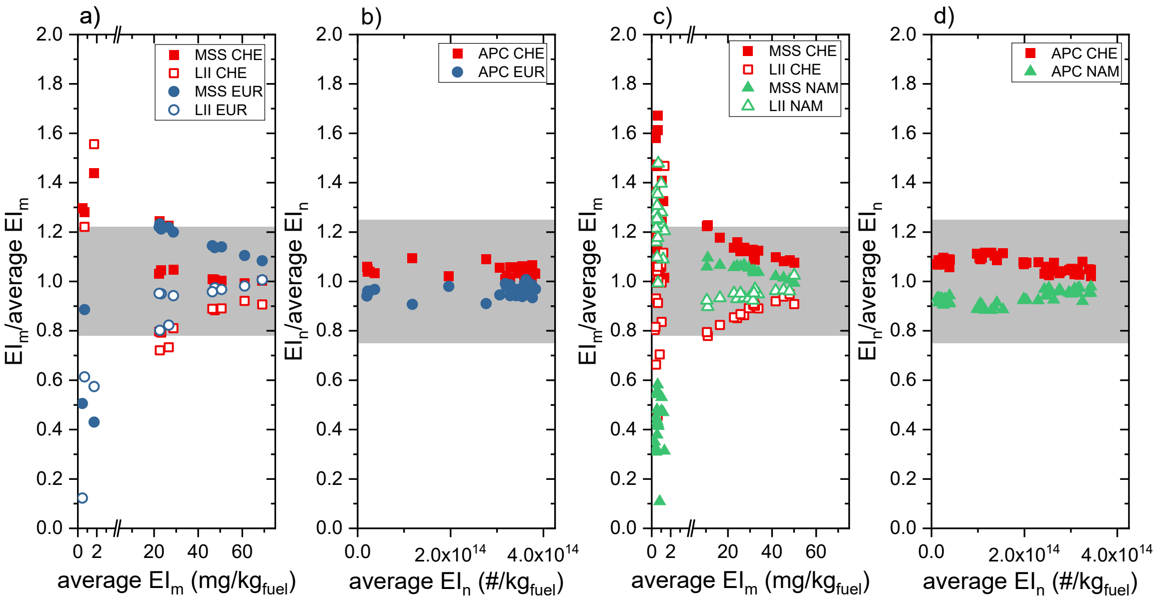

Figure 5: Comparison between CHE and EUR reference systems (a, b) and CHE and NAM reference systems (c, d) for nvPM mass and number emission indices

3.4 3-way reference system comparisons (CHE-EUR-NAM)

All three reference systems were compared simultaneously using the CFM56-7B26/3 engine. The comparisons between the reference systems in terms of the ratio of the nvPM mass and number emission index to the average emission index as a function of the average emission index are presented in Figure 6. Similar trends in nvPM mass and number EIs during the 2-way comparisons are also observed for the 3-way comparisons. The average nvPM mass and number EIs for the 3-way reference system comparisons are lower than those for the 2-way comparisons because the nvPM emissions produced by the engine for these tests were lower. Variability in nvPM mass emission index was higher than 20% for EIs up to 40 mg/kg fuel (corresponding to a mass concentration of ~ 95 µg/m^3 at the instrument), while the variability in nvPM number emission index was ±15% for all test conditions.

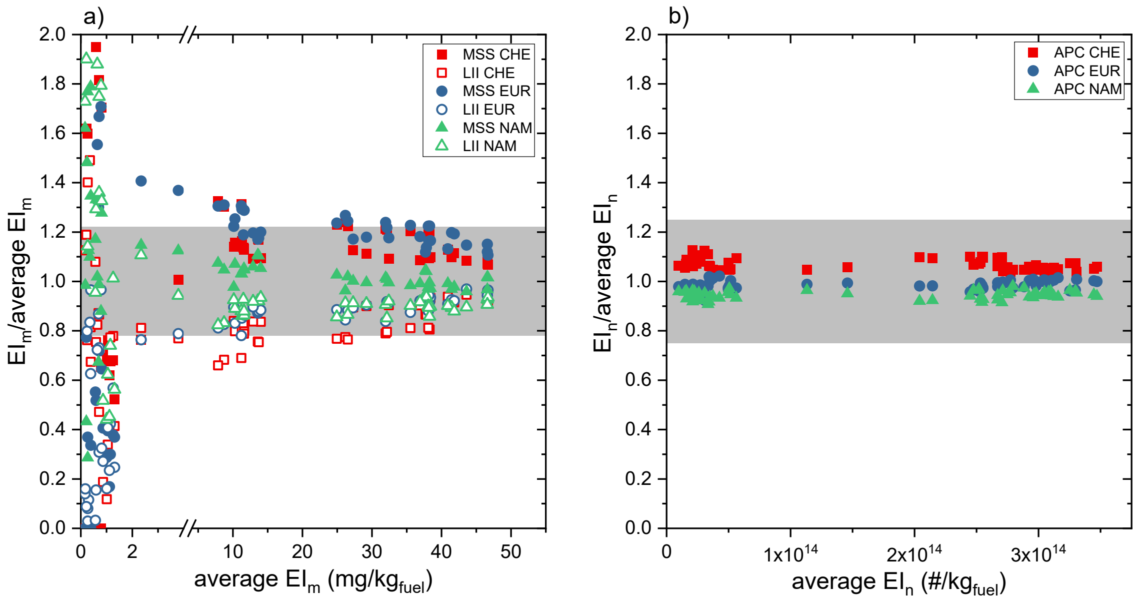

Figure 6: Comparison between CHE, EUR, and NAM reference systems for nvPM mass (a) and number emission index (b).

It is also informative to view the nvPM mass and number emission indices for the instruments used in the three reference systems using parity plots as shown in Figure 7. The EI data reported for each instrument are plotted against the average EI. While these plots are not suitable to illustrate differences at low concentration levels, they provide an overall magnitude of variability between the instruments. As can be seen in Figure 7, the nvPM EI$_m$ and EI$_n$ for each instrument were well correlated with the average. The nvPM EI$_n$ for all three systems was within ± 6% of the average. For the nvPM EI$_m$, the magnitude of the differences was ~10% for the LII 300 and ~15% for the MSS. Ideally, quartz filters would have been collected in parallel with the real-time instruments to determine EC content using TOA, and then used as the reference to compare the nvPM mass instruments. The filter collection for TOA was not performed during the campaign due to limitations on sampling time at each test condition preventing adequate sample to be collected for analysis.

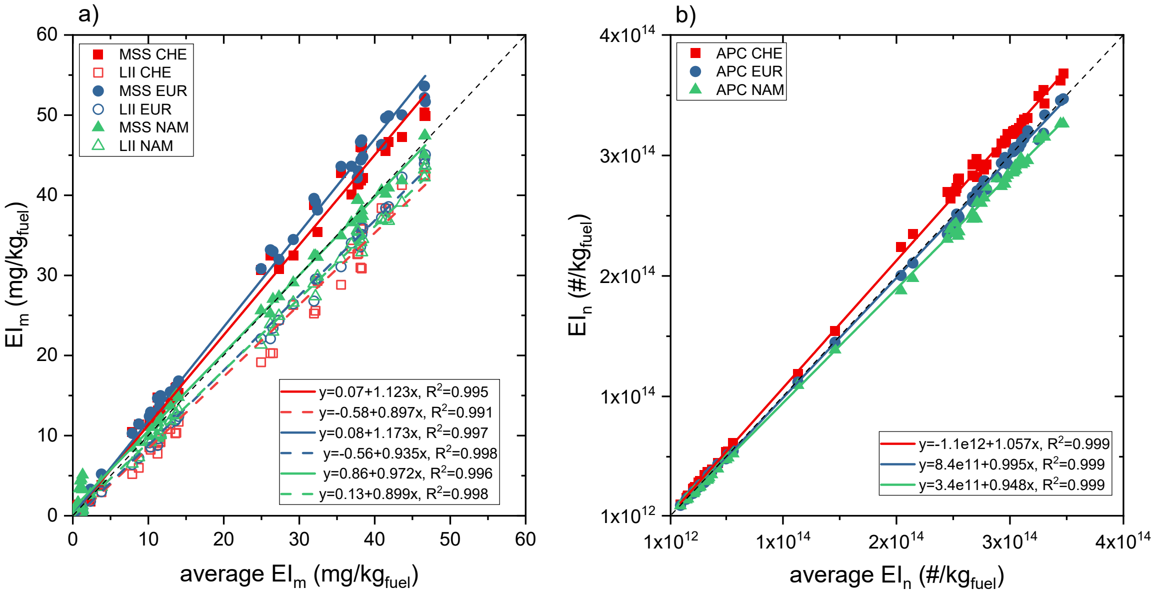

Figure 7: Parity plot comparisons of CHE, EUR, and NAM reference systems for nvPM mass (a) and number emission index (b).

3.5 Reference system comparisons for nvPM mass and number concentration

The comparison between the reference systems in terms of nvPM mass and number concentrations for each type of measurement instrument is presented in Figure 8 to assess performance on a concentration basis (the primary output of the instrument). The concentration data at the measurement location (Figure 8) have been corrected for dilution since each system had slightly different dilution factors. All data recorded during the campaign when at least 2 systems were operating in parallel are included in this analysis. The comparison between the three reference systems is presented as a function of the ensemble averages for the different types of measurement instruments, i.e. MSS and LII 300 for nvPM mass, and APC for nvPM number.

As was previously reported, the largest differences between the three reference systems for nvPM mass were observed for dilution corrected nvPM mass concentrations < 50 $\mu g/m^3$ at the measurement location (~ 5 $\mu g/m^3$ at the instrument). Beyond this threshold, the particular nvPM mass instrument type, i.e. MSS or LII 300, in the reference systems were within 20% of the instrument-specific average mass concentrations. For a given nvPM mass instrument type, the variability in the measured nvPM mass emissions is constrained in a narrow range, which is not the case when both nvPM mass instrument types are included in the analysis (see Figures 5 and

6). Unlike the instrument comparisons with the miniCAST (Figures 3 a and b), both types of nvPM mass instruments each demonstrate similar variability, exceeding 20% only below 50 μg/m^3 (Figures 8 a and b) on engine exhaust. For nvPM number, all three reference systems were well within 20% of the dilution corrected average concentration over the entire range of values recorded.

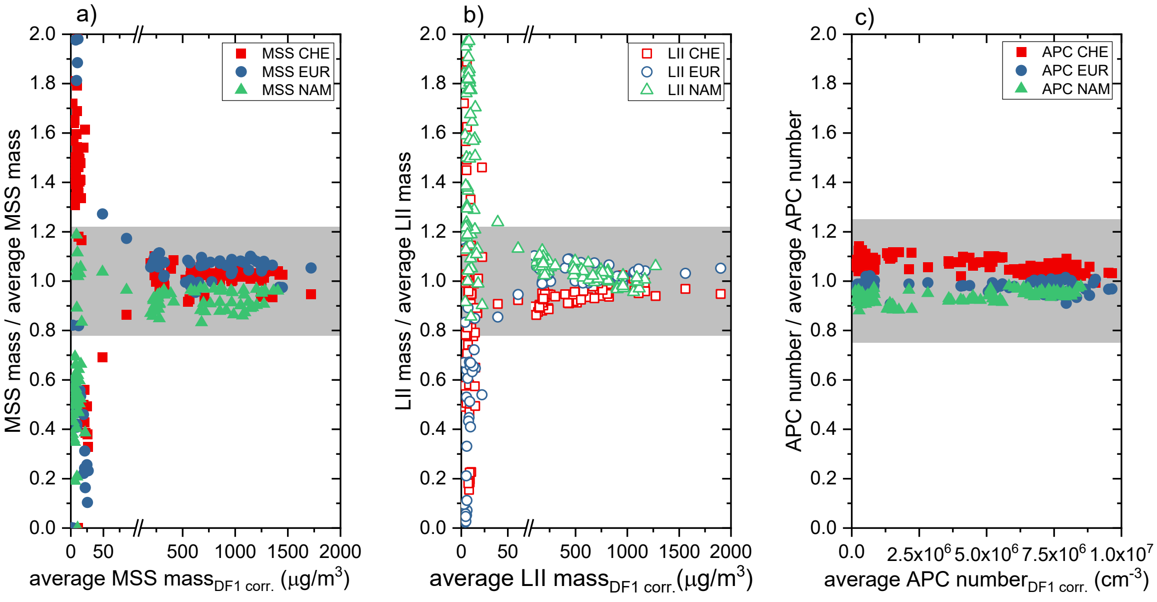

Figure 8: Comparison between CHE, EUR, and NAM reference systems for nvPM mass (a,b) and number concentrations (c). The concentrations are reported at the measurement location and corrected for dilution.

3.6 Variability

The variability in nvPM mass and nvPM number emissions was computed by calculating the RSD of the ratio of the respective EI to the average EI (data from Figures 5 and 6). This method for determining variability was adopted to focus on the relative response of the instruments (as a function of concentration), and to decouple the thrust dependency of the EIs and variability in ambient temperature. The measurement campaign was conducted over the course of a month, and the wide range of ambient conditions affected the nvPM emissions produced by the engine.

Previous studies have also reported on the impact of ambient conditions such as temperature on nvPM emissions variability (Lobo et al., 2015a).

The three reference systems were inter-compared to establish repeatability and intermediate precision of the sampling and measurement systems. Repeatability is defined as the variability of many measurements where the same equipment and operator are used to make repeated measurements over a short time period, while intermediate precision refers to the variability of measurements when only some of the four precision conditions (time, calibration, equipment, operator) are different (JCGM, 2012). The variability in nvPM mass emissions for repeatability (intra-system) and intermediate precision (inter-system) comparisons are presented in Table 3 as a function of average nvPM concentrations, with lowest concentrations of nvPM mass and number grouped in the case of the CFM56-7B26/3 engine at low engine thrust ranges(3-30%), with increasing concentrations averaged at medium engine thrust (38-60%), and high engine thrust (63-101%). A similar analysis for nvPM number emissions for intermediate precision comparisons is presented in Table 4. Intra-system (repeatability) variability for nvPM number emissions is not considered since each reference system used the same instrument type (APC) for the measurement.

The variability for nvPM mass was highest in the lowest mass concentrations (low engine thrust) range, where the average instrument concentration was below the LOD for both types of nvPM mass instruments at 0.7 μg/m^3. The resolution of the MSS instruments used during the campaign was 1 μg/m^3, whereas the LII 300 had a resolution of 0.01 μg/m^3. The higher variability of the MSS compared to LII 300 at the LOD is likely introduced through the resolution of the instrument. For medium and high concentrations (successively higher engine thrust ranges), the variability within a system and between the reference systems was <13%. For nvPM number, the variability was <3% across the engine thrust ranges. The sensitivity of nvPM number to the limit of detection was not a factor since the measured concentration was significantly above the LOD.

Table 3: Variability in nvPM mass emissions

Comparison	Average instrument mass concentration	0.7 µg/m^3						28 µg/m^3						87.8 µg/m^3					
	Thrust range	Low (3-30%)						Medium (38-60%)						High (63-101%)					
	Reference System	CHE MSS	EUR MSS	NAM MSS	CHE LII	EUR LII	NAM LII	CHE MSS	EUR MSS	NAM MSS	CHE LII	EUR LII	NAM LII	CHE MSS	EUR MSS	NAM MSS	CHE LII	EUR LII	NAM LII
Repeatability (Intra-system)	CHE	62%			48%			6.9%			10%			5.5%			7.1 %		
	EUR		65%			71%			3.8%			5.7%			3.7%			4.8%	
	NAM			60%			33%			3.1%			3.7%			2.4%			2.6%
Intermediate precision (Inter-system)	CHE-EUR and CHE-NAM	16%	40%	36%	32%	62%	30%	8.7%	1.2%	1.8%	4.6%	8%	2%	5.8%	4.1%	2.2%	5.1%	6.9%	2.7%
	CHE-EUR-NAM	126%	109%	68%	71%	75%	56%	12.8%	5.2%	5.5%	8%	5.3%	7.9%	5.2%	3.2%	5.6%	8%	3.7%	2.4%

Table 4: Variability in nvPM number emissions

Comparison	Average instrument number concentration (corrected for 2-stage dilution in the APC)	4.9×10^4 /cm^3			5.4×10^5 /cm^3			7.6×10^5 /cm^3		
	Thrust range	Low (3-30%)			Medium (38-60%)			High (63-101%)		
	Reference System	CHE	EUR	NAM	CHE	EUR	NAM	CHE	EUR	NAM
Intermediate precision (Inter-system)	CHE-EUR and CHE-NAM	2.1%	2.3%	1.8%	2.2%	2.2%	1.7%	1.8%	3.1%	1.0%
	CHE-EUR-NAM	2.4%	2.7%	1.7%	2.0%	1.1%	2.4%	1.0%	1.3%	0.9%

The other significant contributor to the variability in nvPM EI_m and nvPM EI_n is the CO_2 concentration. The diluted CO_2 measurements were used to calculate the EIs from mass and number concentrations measured by each reference system. It was not possible to evaluate the variability of the diluted CO_2 measurements. Each reference system had slightly different dimensions for the ejector-diluter vent, which resulted in subtle differences in overall dilution factors. A comparison of the CO_2 analyzers measuring the same exhaust sample on the diluted nvPM line during the engine tests was not performed. However, the variability in undiluted CO_2 concentrations measured by the CHE and the EUR reference systems was evaluated. The slope of a linear interpolation comparing the undiluted CO_2 concentrations in the EUR system to those from the CHE system was 0.993 (R^2=0.997).

All three reference systems were built to and compliant with the specifications for the standardized system detailed in AIR6241, and in this case used nominally identical nvPM instruments. Hence, the differences in particle losses in these three sampling and measurement systems are expected to be negligible compared to the variability in other factors described previously.

Building on the knowledge gained from this campaign, several changes to the instrument performance and calibration protocols were implemented. The resolution of the MSS instruments was updated to 0.01 $\mu g/m^3$. The procedure to demonstrate conformity of the nvPM mass instruments to performance specifications was updated to include an additional applicability criterion for validation of the calibration to EC on aircraft turbine engine exhaust. The limit of detection of the nvPM mass instruments was also lowered from 3 $\mu g/m^3$ to 1 $\mu g/m^3$ (ICAO, 2017).

3.7 Size distributions

The standardized protocol for aircraft engine nvPM mass and number emissions does not specify a measurement of particle size distribution. However, a size distribution measurement is being considered for future standardized methodologies for particle loss correction. Since particle loss mechanisms such as diffusion and inertial losses are size-dependent, measurement of size distributions along with nvPM number and mass concentration provides information to estimate particle loss factors. These loss factors can then be used to calculate nvPM emissions at the engine exit plane. Engine exit plane emissions would be more relevant for aircraft engine nvPM emissions inventory and impact assessments. The size distributions for the CFM56-7B26/3 engine along with characteristic parameters – geometric mean diameter (GMD) and geometric standard deviation (GSD) are presented in Figure 9 as a function of engine thrust setting. These size distributions were obtained with the DMS500 installed on the ancillary line of the EUR reference system and corrected for primary dilution (DF1) in the ejector diluter. The size distributions could be approximated to lognormal distributions (R^2 >0.97) with GMD ranging from 15nm at idle to 38nm at 90% rated thrust, and GSD varying between 1.53 and 1.92. The magnitude and general increasing trend of GMD and GSD with engine thrust setting are consistent with previously reported values for this engine type (Lobo et al., 2011; Lobo et al., 2015a; Durdina et al., 2017; Elser et al., 2019).

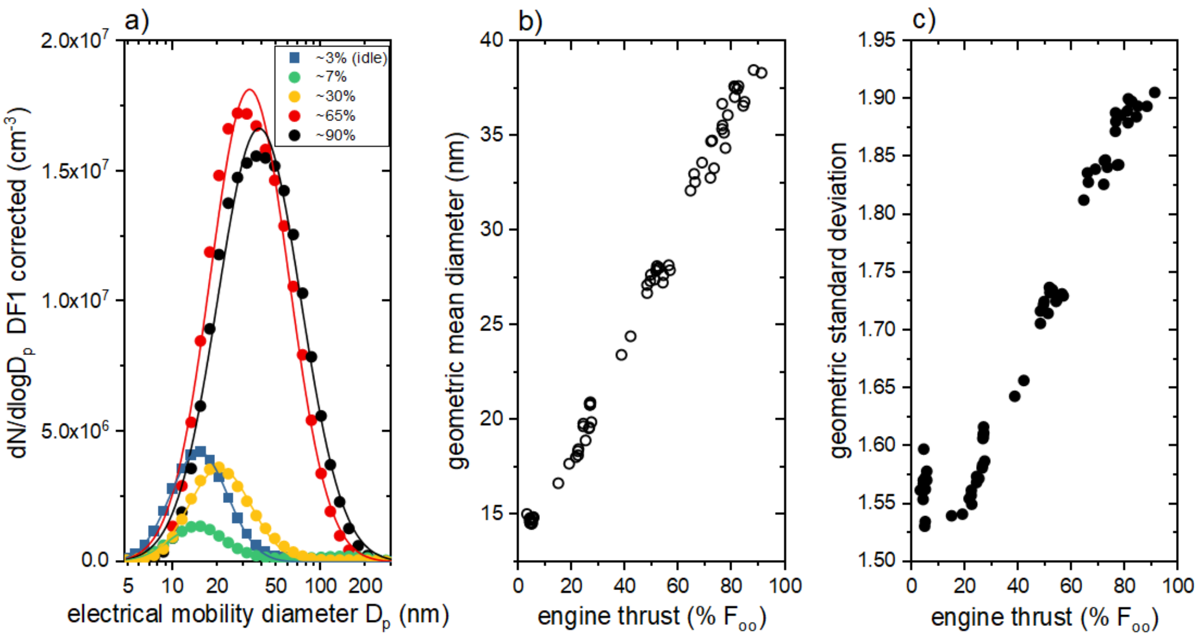

Figure 9: Particle size distributions (a) and characteristic parameters – GMD (b) and GSD (c) for the CFM56-7B26/3 engine

4 Conclusions

Three reference systems for aircraft engine nvPM emissions measurement – the Swiss (CHE) system, the European (EUR) system, and the North American (NAM) system – were developed in compliance with the specifications for the standardized sampling and measurement methodology. The first and only inter-comparison to date of these three reference systems was performed at the SR Technics engine test facility in Zürich, Switzerland using a commercial CFM56-7B26/3 aircraft engine as the emissions source to establish repeatability and intermediate precision of the sampling and measurement systems. All three reference systems measured nvPM number concentration using an APC, and nvPM mass concentration was measured using both an LII 300 and an MSS. The nvPM mass and number concentrations were converted to their respective emission indices for comparison. The specifications for the standardized sampling and measurement system implemented in the three reference systems were robust, as demonstrated by the variability observed between the systems. During the dedicated engine tests with the CFM56-7B26/3 engine, all instruments in the three reference systems were generally within 30% of the average nvPM mass emission index (determined with different nvPM mass instrument types and manufacturers) and 15% of the average nvPM number emission index (determined with the same nvPM number instrument type and manufacturer) (see Fig. 6). The only exception was for the mass instruments, which exhibited a higher variation as the concentration levels approached the LOD of 3 $\mu g/m^3$. A comparison between the three reference systems as a function of the measurement instrument type revealed that similar measurement methodologies had a better agreement and lower variability. As more fuel efficient aircraft engines with low emission combustors continue to be developed, instruments for measuring nvPM mass should have the capability of higher resolution and sensitivity for low concentration levels. Future studies should consider the variability associated with other instruments that meet the performance specifications in AIR6241 but were not evaluated in this study.

It should be noted that the emission index values reported for nvPM mass and number have not been corrected for size-dependent particles losses in the sampling and measurement systems, and hence do not represent the actual emissions at the engine exit plane. Including a traceable size measurement in the standardized measurement system would enable a more accurate estimation of engine exit plane nvPM emissions to improve airport emissions inventory development and environmental impact assessment of aircraft engine nvPM emissions. Size distribution measurements, not currently specified in the standard method, were found to be approximated to lognormal distributions with GMD ranging 15nm - 38nm, and GSD varying 1.53 - 1.92.

The wide range of ambient conditions encountered during the campaign affected the nvPM emissions produced by the engine. A correction for changes in ambient conditions will need to be developed to decouple the variability in the ambient temperature from the measured nvPM mass and number emissions. Although the CFM56-7B26/3 engine used in this study is the most widely used engine in commercial aviation, other engine types could have different emissions profiles. It is essential that the reference systems be compared using an aircraft engine source with a different emissions profile to validate the repeatability and intermediate precision of the sampling and measurement systems established in this study. Also, long term comparison of the reference systems should be undertaken since these systems will continue to be used to varying extents over time.

As a direct consequence of the results from this campaign, several changes to the instrument performance were implemented such as updating the resolution of the MSS instruments to 0.01 μg/m^3, and lowering the limit of detection of the nvPM mass instruments from 3 μg/m^3 to 1 μg/m^3. The procedure to demonstrate the conformity of the nvPM mass instruments to performance specifications was updated to include an additional applicability criterion for validating the nvPM mass instrument calibration on aircraft turbine engine exhaust.

The results from this study are a benchmark for the variability in standardized sampling and measurement systems for measuring aircraft engine emissions. The three reference systems evaluated were subsequently used for comparisons with aircraft engine manufacturer sampling and measurement systems. The aircraft engine manufacturers contributed nvPM emissions datasets for 24 aircraft engine types that were representative of the current commercial fleet for inclusion in a database (Agarwal et al., 2019). With the database and knowledge of the uncertainty as characterized by the intermediate precision, the new ICAO nvPM mass and number emissions regulatory standard for in production and new engines (CAEP/11) was developed. This new ICAO regulatory standard will be used to certify all aviation engines with rated thrust > 26.7 kN for nvPM mass and number emissions performance.

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Comparison of Standardized Sampling and Measurement Reference Systems for Aircraft Engine Non-volatile Particulate Matter Emissions

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Abstract

The International Civil Aviation Organization has established new regulatory standards for emissions certification of non-volatile particulate matter (nvPM) from aircraft turbine engines. The adoption of the nvPM emissions regulatory standards required development of a standardized sampling and measurement methodology, and rigorous testing. Three reference systems for aircraft engine nvPM emissions measurement, compliant with the specifications for the standardized methodology, were independently developed. This paper reports the results of the first inter-comparison of these three reference systems using a CFM56-7B26/3 aircraft engine to establish repeatability and intermediate precision of the sampling and measurement systems as part of the multi-agency international collaborative projects: Aviation-Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE) 5/ Studying, sAmpling and Measuring of aircraft ParticuLate Emissions (SAMPLE) III - SC03. The instruments used in the three reference systems recorded nvPM mass and number concentration, which were converted to their respective emission indices for comparison. The reference systems generally agreed to within 15% of the average nvPM number emission index and 30% of the average nvPM mass emission index. The only exception was for the nvPM mass instruments, which exhibited a higher variation as the concentration levels approached the limit of detection. The additional measured particle size distributions could be approximated to lognormal distributions with the geometric mean diameter ranging from 15 nm to 38 nm, and the geometric standard deviation varying between 1.53 and 1.92. The results from this study are a benchmark for the variability in standardized sampling and measurement systems for measuring aircraft engine nvPM emissions.

Highlights

- Comparison of three reference systems for measuring aircraft engine nvPM emissions
- The nvPM number emission index was generally within 15% of the average value
- The nvPM mass emission index was generally within 30% of the average value
- Mass-based emissions exhibited high variability towards the instrument limit of detection

Keywords

Aircraft engines, non-volatile particulate matter, aviation emissions, black carbon, particle number, size distributions

1 Introduction

Aircraft engine gaseous and particulate matter (PM) emissions are a unique source of pollution compared to other sources in the urban environment. The public awareness about aviation emissions has grown since the rapid increase in demand for commercial air travel in the 1960s, which led to the introduction of emission standards by the International Civil Aviation Organization (ICAO). Prior to 2010, the ICAO Committee on Aviation Environmental Protection (CAEP) developed emission standards and recommended practices (SARPs) limited to the emissions of gaseous pollutants such as oxides of nitrogen (NO_x), carbon monoxide (CO), and unburnt hydrocarbons (UHC), and emissions of smoke (reported in terms of smoke number, SN). The SARPs are applicable to turbojet and turbofan engines with maximum sea-level static rated thrust >26.7 kN for gaseous emissions and to all engine sizes for smoke emissions. The SARPs, intended to mitigate the impact of aircraft engine emissions on local air quality, have been established for the type certification of aircraft engines and are documented with approved test and measurement procedures in ICAO Annex 16 to the Convention on International Civil Aviation, Volume II (ICAO, 2017). The type certification process involves operating one or multiple representative engines of a specific model on a test stand at combustor inlet temperatures corresponding to the four thrust settings of the standardized Landing and Take-off (LTO) cycle – 7% (taxi), 30% (approach), 85% (climb), and 100% (take-off) – corrected to International Standard Atmosphere (ISA) conditions (ICAO, 1993). The engine manufacturers submit emissions data, acquired during these engine type certification tests to the certificating authority for approval and subsequently for inclusion in the ICAO Aircraft Engine Emissions Databank (EEDB) maintained by the European Union Aviation Safety Agency (EASA) (EASA, 2019a).

Since aircraft engine emissions regulatory standards were first adopted in 1981, ICAO/CAEP has developed increasingly stringent standards for NO_x emissions. This, along with the introduction of newer, more fuel-efficient engine technologies, has resulted in lower aircraft engine emissions over time (Wey & Lee, 2018). However, with the growth of commercial and cargo air traffic at a rate of ~4.5% per year (Airbus, 2018; Boeing, 2018; IATA, 2019) the absolute emissions from the aviation sector have increased, including PM emissions which are forecast to increase over the next twenty years if current engine technology continues to be used (EASA, 2019b). This in turn has led to several studies to measure, model, and ultimately develop solutions to mitigate aviation-related emissions (Masiol and Harrison, 2014).

The smoke standard was introduced at a time when the visibility of exhaust plumes from aircraft engines was of significant concern for airport safety. Smoke number is determined by measuring the reduction in reflectance of a Whatman #4 filter used to sample a prescribed mass of exhaust per unit area of the filter, i.e. 16.2 kg of exhaust gas/m^2. The precision of the SN measurement method is reported as ±3 SN (SAE, 2011), which in some cases is higher than the recorded SN for modern turbofan engines. Also, the SN does not provide any information about the number, size, and composition of the PM emissions that are required for environmental impact assessments. In the absence of fleet-wide aircraft engine PM emissions data, the First Order Approximation (FOA) methodology was developed based on correlations between SN reported in the ICAO EEDB and available data for non-volatile particulate matter (nvPM) mass emissions (Wayson, Fleming, & Iovinelli, 2009). FOA and subsequent updates (current version FOA 4.0) have been used to estimate PM emissions from certified commercial aircraft engines during the LTO cycle at airports (Rissman et al., 2013; Winther et al., 2015; Woody et al., 2016).

The eighth meeting of CAEP (ICAO, 2010) recognized the need for PM emissions regulation in addition to the existing set of regulated pollutants. The first new regulatory standard for aircraft engine nvPM emissions was adopted by CAEP in 2016 (CAEP/10). It included reporting requirements and a nvPM mass emissions standard for in-production aircraft engines with rated thrust >26.7 kN on or after 1 January 2020. The CAEP/10 standard was set at a regulatory level that matched the existing smoke number visibility standard. The regulatory level for the CAEP/10 maximum nvPM mass concentration was developed based on a statistical relationship between nvPM mass concentration and smoke number (Agarwal et al., 2019). This ensured that any aircraft engine that would have met the certification requirements for smoke number would also meet the nvPM mass emissions level (all-pass standard). From 1 January 2023, regulatory limits for mass and number-based nvPM emissions will become applicable for in-production and new commercial aircraft engine types with a maximum rated thrust > 26.7 kN (CAEP/11 standard) (ICAO, 2019). Along with this new standard and since the CAEP/10 standard includes control of exhaust plumes visibility, CAEP agreed that the smoke number standard will no longer be applicable for these engines from 1 January 2023.

Before regulatory standards for nvPM mass and number emissions could be defined, a standardized sampling and measurement methodology was required for aircraft engine emissions certification tests. The Society of Automotive Engineers (SAE) Aircraft Engine Gas and Particulate Emissions Measurement Committee (E-31) was tasked with recommending a standardized protocol for aircraft engine nvPM mass- and number-based emissions. The development of this standardized protocol for aircraft engine nvPM emissions was the culmination of several years of effort to investigate sampling methods, evaluate measurement technologies, and assess engine type and fuel composition differences on nvPM emissions during the PARTEMIS (Petzold et al., 2003), APEX (Lobo et al., 2007; Timko et al., 2010; Kinsey et al., 2010), AAFEX (Kinsey et al., 2012), SAMPLE (Petzold et al., 2011; Crayford et al., 2012; Crayford et al., 2013; Boies et al., 2015), A-PRIDE (Durdina et al., 2014; Lobo et al., 2015a; Brem et al., 2015), and MERMOSE (Delhaye et al., 2017) projects, in addition to other studies (Lobo et al., 2015b). The results informed the development and publication of Aerospace Information Report (AIR) 6241 (SAE, 2013) and Aerospace Recommended Practice (ARP) 6320 (SAE, 2018). The standardized protocol is limited to only nvPM emissions, defined as particles that exist at the aircraft engine exhaust nozzle exit plane that do not volatilize at temperatures greater than 350°C (ICAO, 2017). Controlling aircraft engine nvPM emissions at the source will lead to lower emissions on local, regional, and global scales. Total PM emissions downstream of aircraft engines are not currently considered since they have been shown to vary in space and time as the exhaust plume cools and expands (Lobo et al., 2012; Timko et al., 2013; Beyersdorf et al., 2014), making it complicated to develop a standardized sampling and measurement protocol that reports repeatable concentrations, and to enforce through a certification requirement. The approach to limit the sampling and measurement system to nvPM was similar to that adopted by the Particle Measurement Programme (PMP) for the regulation of the number concentration of solid (non-volatile) particles with a diameter >23 nm emitted from automotive engines (Giechaskiel et al., 2012).

Analogous to the reference “golden” particle number measurement system used in PMP (Martini, Giechaskiel, & Dilara, 2009), three reference systems for aircraft engine nvPM emissions measurement were independently developed - the Swiss (CHE) fixed (later mobile) system by

Empa, the European (EUR) mobile system by Cardiff University, and the North American (NAM) mobile system by Missouri University of Science and Technology. All three reference systems were compliant with the specifications for the standardized system detailed in AIR6241, but not identical since AIR6241 permits tolerances for different components and specification ranges. It was essential to inter-compare the three reference systems using a common aircraft engine source to establish repeatability and intermediate precision of the sampling and measurement systems, and to estimate some of the uncertainties associated with the measurements of aircraft engine nvPM emissions.

In this paper, we present results of the Aviation-Particle Regulatory Instrumentation Demonstration Experiment (A-PRIDE) 5/ Studying, sAmpling and Measuring of aircraft ParticuLate Emissions (SAMPLE) III - SC03 campaign, the first multi-agency international collaborative project to inter-compare and evaluate the robustness of the Swiss, European, and North American standardized reference systems for the sampling and measurement of aircraft engine nvPM emissions. The measurements were performed from 28 July to 25 August 2013, on a leased CFM56-7B26/3 engine used during dedicated engine testing at the SR Technics engine test facility in Zürich, Switzerland.

2 Methods

2.1 ***CFM56-7B26/3 engine***

The engine used for the dedicated tests was a CFM56-7B26/3, which was leased for the duration of the campaign. The CFM56-7B engine is the sole powerplant for the Boeing 737NG family, and it is the most widely used engine in commercial aviation. The "/3" configuration (improved durability and emissions) was emissions-certified for gaseous pollutants and smoke in 2006. The specific engine used during this campaign had accumulated 5009 flight hours during 2000 flight cycles. The engine had representative operating and performance characteristics with minimal degradation and negligible oil consumption in the range of a brand-new engine. This engine was declared to be a representative reference engine to be used as a source of nvPM to inter-compare the standardized reference systems. Aircraft engine emissions certification-like tests for nvPM emissions were also performed with a single system (Durdina et al., 2017).

2.2 Fuel

The Jet A-1 fuel used for the emissions tests was provided by SR Technics. Seven fuel samples were collected during the measurement campaign, and the results of the fuel analysis performed by Intertek AG (Schlieren, Switzerland) for selected properties are presented in Table 1. The properties of the Jet A-1 fuel were all within the allowable range specified by ASTM D1655 (ASTM, 2019). The fuel also met all the specifications for emissions certification tests (ICAO, 2008) except that for naphthalenes content, which was below the lower limit requirement at the time (1%). This was also the case for a previous campaign conducted at SR Technics (Lobo et al., 2015a). The lower limit for naphthalenes specification was subsequently changed to 0% (ICAO, 2017). Overall, the different batches of Jet A-1 fuel used for the emissions tests had similar properties, thus eliminating fuel composition as a variable in the calculation of emission indices (EIs) and inter-comparison of the reference systems. An average hydrogen to carbon (H/C) ratio of 1.95 was used for the calculation of the number and mass emission indices for all three reference systems.

Table 1: Properties of Jet A-1 fuel used during the A-PRIDE 5/SAMPLE III-SC03 campaign

Property	Units	Method	Allowable Range	Test Fuel Samples[†]						
				29 Jul 2013	2 Aug 2013	5 Aug 2013	12 Aug 2013	17 Aug 2013	18 Aug 2013	25 Aug 2013
Density at 15°C	kg/m^3	ASTM D4052	780-820	797.6	797.6	797.8	797.8	797.8	797.8	797.2
Kinematic viscosity at -20°C	mm^2/s	ASTM D445	2.5-6.5	3.591	3.618	3.598	3.596	3.599	3.599	3.618
Distillation temperature 10% boiling point	°C	ASTM D86	155-201	169	168	168	168	167	168	169
Final boiling point			235-285	265	265	265	261	263	264	264
Net heat of combustion	MJ/kg	ASTM D3338	42.86-43.50	43.3	43.3	43.3	43.3	43.3	43.3	43.3
Aromatics	volume %	ASTM D1319	15-23	17.7	17.7	17.4	18.0	17.7	17.7	17.5
Naphthalenes	volume %	ASTM D1840	0-3%[‡]	0.68	0.72	0.71	0.71	0.74	0.75	0.70

[†] All fuel samples were collected from the fuel line in the test cell except the on 5 Aug 13, which was collected directly from the fuel tanker

[‡] Original allowable range 1.0-3.5%, subsequently updated to 0-3%

Smoke point	mm	ASTM D1322	20-28	21	21	21	21	22	21	22
Hydrogen content	mass %	ASTM D5291	13.4-14.3	14.18	14.18	14.28	14.04	13.96	14.00	13.76
Sulphur content	mass %	ASTM D5453	< 0.3%	0.053	0.033	0.039	0.039	0.042	0.042	0.042
H/C ratio (calculated)			1.84-1.99	1.97	1.97	1.99	1.95	1.93	1.94	1.90

2.4 Experimental Setup

A schematic of the experimental setup is shown in Fig. 1. Details of the various sections of the sampling and measurement systems are provided in the following sections.

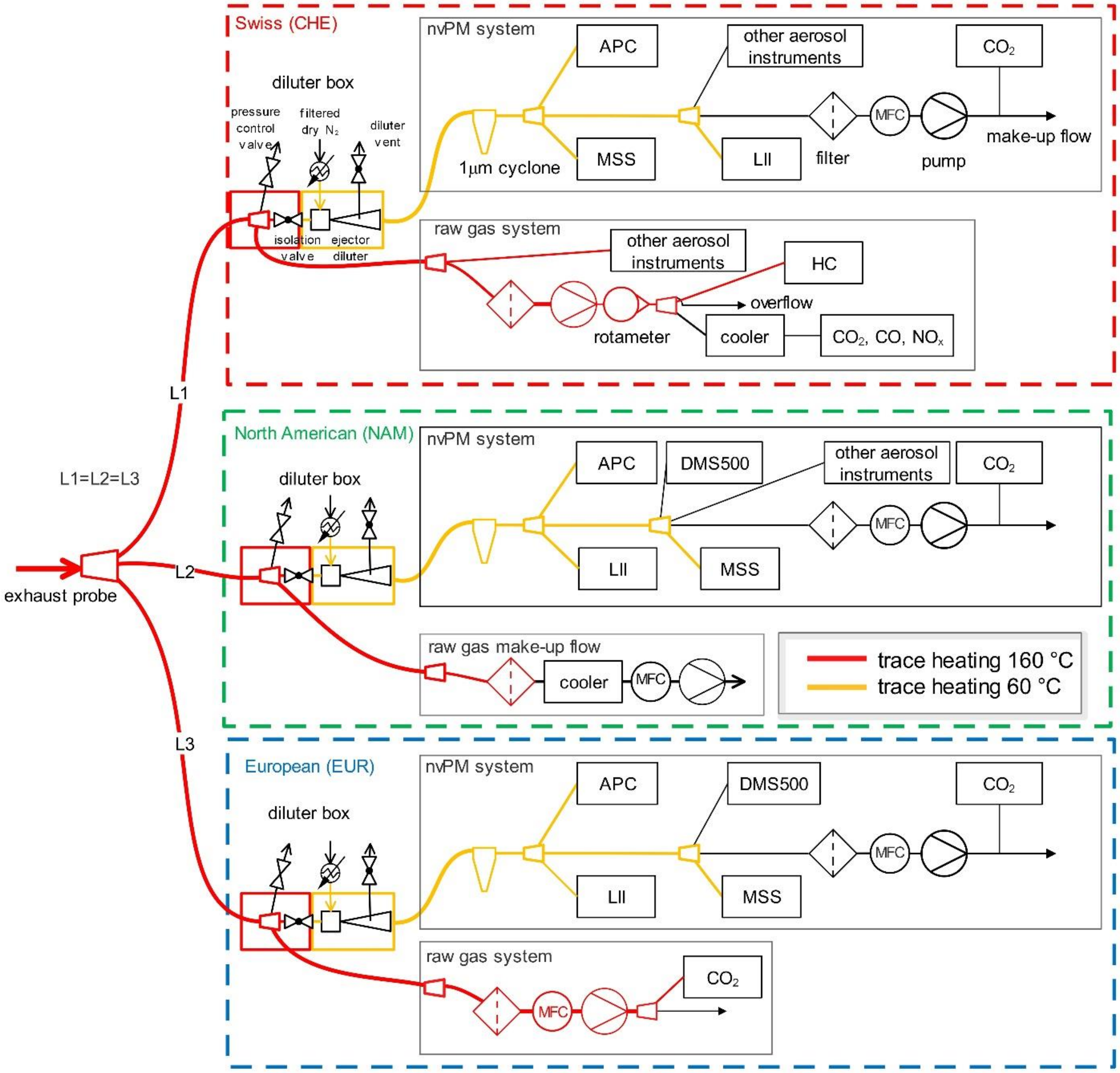

Figure 1: Experimental setup for CFM56-7B26/3 engine tests (not to scale)

2.4.1 Extractive sampling probes

Two exhaust sampling probe assemblies were used to extract emission samples within 1 m of the engine exit plane. A fixed multi-point probe made of Inconel 625 alloy compliant with the requirements for nvPM sampling and measurements for emissions certification (ICAO, 2017) was used during a subset of the dedicated engine tests. It consisted of a cruciform with six sampling orifices located on each of the four arms, from which three orifices per arm were used to comply with the carbon balance check (air/fuel ratio estimated from the exhaust sample total carbon concentration agrees with the estimate based on engine air/fuel ratio). The sampling orifices were symmetrically located on circular radii from the center of the cruciform. Various configurations of the number and position of sampling orifices on the multi-point probe were evaluated during the campaign. The primary goal of this assessment was to ensure that the three reference systems operating in parallel were adequately supplied with sample flow, while still providing an exhaust representative sample and complying with the carbon balance check.

A traversable single-point probe used during previous campaigns at SR Technics (Lobo et al., 2015a) was used during piggy-back measurements and a subset of dedicated engine tests. The probe with an 8 mm ID orifice was made of Inconel 600 alloy. The probe's vertical traverse capability afforded representative sampling at the exit plane of different engine types operated in the test cell (for the CFM56-7B26/3 engine, the distance from the probe to the exit plane was 0.8 m). The specific vertical sampling location was optimized during testing, ensuring the carbon balance of the single-point probe maintained satisfactory agreement (< 10%) with the multi-point probe at all similar test conditions.

2.4.2 Sampling and measurement systems

The probe was connected to a three-way splitter using a 5.2 m long, 8 mm ID thin-walled stainless steel tubing, electrically trace heated and insulated to maintain a temperature of 160°C ± 15°C. The exhaust samples were distributed to the three reference systems. Each reference system, while compliant with the specifications detailed in AIR6241, was independently assembled from non-identical components and evaluated prior to deployment in the campaign. Briefly, each system had a three-way splitter to distribute the exhaust sample to the line for raw gaseous emission measurements, the pressure control line to regulate the sample inlet pressure, and the nvPM line for nvPM mass- and number-based emission measurements (Fig. 1). Of the three reference systems, only the NAM system did not have measurements of raw gaseous emissions on the raw exhaust line. Instead, a pump was used to draw flow down the gaseous emissions line in order to achieve a prescribed flow velocity in each leg of the splitter, and to be consistent with the CHE and EUR system flowrates. The undiluted CO_2 concentration data from the CHE reference system were used to calculate dilution factors for all three systems. The variability in undiluted CO_2 concentrations measured by the CHE and the EUR reference systems was evaluated. The slope of a linear interpolation comparing the undiluted CO_2 concentrations in the EUR system to those from the CHE system was 0.993 (R^2=0.997). This variability is within the uncertainty of the CO_2 measurements, estimated to be less than 4% across all test points.

The exhaust sample for the nvPM line was diluted with particle-free synthetic air (purity 99.999%) using a Dekati DI-1000 ejector diluter. The dilution factors achieved using the DI-1000 ejector diluter are highly dependent on the sample inlet pressure and diluent air pressure (Giechaskiel, Ntziachristos, & Samaras, 2004). The dilution factor at nominal sample and diluent inlet pressures was 8-14 (as specified in the SARPs); however, the range extended from 7 to 20 for some of the dilution factor sensitivity tests performed during the campaign. The diluted sample was transferred to the real-time diagnostic instruments by a 24 - 25 m long, carbon-loaded, electrically grounded polytetrafluoroethylene (cPTFE) line maintained at a temperature of 60°C ± 15°C followed by a sharp cut cyclone with a 1 µm cut size. The sample lines for each reference system had slightly different internal diameters, but well within the range 7.59 - 8.15 mm as specified by AIR6241. The diluted exhaust sample flow rate in the cPTFE line was maintained at 25 slpm ± 2 slpm. Another three-way splitter distributed the particle-laden flow to the nvPM number instrument, the nvPM mass instruments, and the excess flow line for CO_2 concentration, and other ancillary measurements that were not a requirement of the standardized system.

All three reference systems measured nvPM number emissions using an AVL Particle Counter (APC) Advanced (Giechaskiel et al., 2010), which consists of a primary dilution stage with a rotating disk diluter, a catalytic stripper with a sulphur trap (volatile particle remover, VPR) maintained at 350°C, a secondary dilution stage with a porous tube diluter, and an n-butanol-based condensation particle counter (CPC; TSI 3790E), with a 50% cut-off diameter ≈10 nm and 90% count efficiency at ≈15 nm (Lobo et al., 2015a). All CPC's were operated in single count mode by increasing the APC dilution factor when CPC concentrations approached 10,000 particles/cm^3. The diluent used for the APC was synthetic air. The nvPM mass emissions were measured using both an Artium Laser Induced Incandescence LII 300 (LII) (Snelling et al., 2005) and an AVL Micro Soot Sensor (MSS) (Schindler et al., 2004) on all three reference systems. Additionally, two Cambustion DMS500 fast mobility spectrometers (Reavell et al. 2002) were installed on the excess flow/ancillary line, one each on the EUR and NAM reference systems to measure PM size distributions. A compact time of flight aerosol mass spectrometer (CToF-AMS) (Drewnick et al. 2005) to obtain chemical composition information, and a Cavity Attenuated Phase Shift (CAPS) PM extinction monitor (Yu et al., 2011) to measure nvPM mass were installed on the ancillary line on the NAM reference system. Further aerosol instrumentation was also deployed in the CHE reference system to measure particle effective density (Durdina et al., 2014) and chemical composition (Abegglen et al., 2016).

2.4.3 Instrument calibrations

The LII 300 and MSS instruments were calibrated to the NIOSH 5040 protocol (NIOSH, 2003) for EC using thermal optical analysis (TOA) in accordance with AIR6241 in two batches at NRC-Metrology, Ottawa, Canada one month prior to the start of the campaign. The NRC inverted-flame burner (Coderre et al., 2011) was used as the source of black carbon (BC) particles. The BC particles generated by the inverted-flame burner were diluted using filtered air, and the diluted sample was divided using a splitter and then directed to two 1µm cyclones – one was upstream of the dual-stage filter collection system, and the other upstream of the nvPM mass instruments to be calibrated. Equal length (2 m) heated cPTFE 3/8” OD tubing was used from splitters to all measurement devices. The entire sampling system was heated to 60°C. The MSSs from all three reference systems and the LII 300 from the NAM reference system were calibrated in the first batch with 6 or more repeats at target mass concentrations of 0, 50, 100, 500, and 1000 $\mu g/m^3$. The remaining two LII 300s were calibrated in the second batch with 3 or more repeats at target mass concentrations of 0, 100, 250, and 500 $\mu g/m^3$. The correlation of mass concentration measured by the instruments to NIOSH 5040 EC was >0.995 in all cases.

The APC for all three reference systems had its annual calibration and maintenance performed by the manufacturer within nine months of the campaign. Combustion soot from a miniature combustion aerosol standard (miniCAST) generator was used as the source to establish penetration through the VPR. CO_2 calibration gas was used to verify dilution factors for the two-stage dilution of the APC. As part of the calibration procedure, VPR performance was evaluated in terms of volatile particle removal efficiency. The CPC linearity and counting efficiency were also determined and adjusted (counting efficiency at 10 nm > 50%). All three reference systems had similar particle penetration profiles for the VPR, and volatile particle removal efficiencies of 99.99%. The CHE and NAM reference systems had similar CPC counting efficiencies of 76% and 92% at 10 nm and 15 nm, respectively, while the EUR reference system had a much lower CPC counting efficiency of 53% at 10nm and slightly higher CPC counting efficiency of 98% at 15 nm.

2.5 ***Test Matrix***

The dedicated engine tests with the CFM56-7B26/3 engine started with a warm-up sequence used for conditioning the probe and the sampling systems. The warm-up sequence consisted of running the engine at five test points from ground idle to 85% sea-level static thrust for durations of 5 minutes each. The parameter used for setting the engine thrust was the combustor inlet temperature, T3. The T3 values were based on a correlation of sea-level static thrust with T3 corrected to ISA conditions (15°C, 1 atm). The full test matrix following the warm-up sequence consisted of 12 points on a descending power curve, starting at maximum continuous thrust (which was limited by the ambient conditions during the test) and ending at idle. These test points included the four thrust settings corresponding to the LTO cycle as well as an additional point at 65%. The duration of each test point was 10 minutes. A subset of the full test matrix was run during most dedicated engine tests. Table 2 lists the inter-comparison experiments performed during the measurement campaign, along with the range of ambient conditions recorded during each test.

Table 2: Overview of experiments performed for Reference Systems inter-comparison

Date	Ambient Condition Ranges			Engine/Source	Description	Sampling Probe	Reference System		
	T (° C)	P (kPa)	RH (%)				Swiss (CHE)	European (EUR)	North American (NAM)
28 Jul 2013	28.5-34.0	96.0-96.2	24-42	CFM56-7B26/3	AFR check (probe tips 1, 4, 6)	Multi-point	✓	✓	✗
29 Jul 2013	17.3-17.8	96.6-96.8	87-95	CFM56-7B26/3	AFR check (all 24 probe tips)	Multi-point	✓	✓	✗
2 Aug 2013				miniCAST 5201C	Instrument comparison	-	✓	✓	✓
3 Aug 2013	27.4-30.8	96.9-97.0	28-39	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✓	✓
4 Aug 2013	18.0-26.3	97.1-97.5	45-82	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✓	✓
5 Aug 2013	24.2-25.6	96.7-96.8	54-57	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✓	✓
10 Aug 2013	21.1-22.5	97.1-97.2	44-53	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✗	✓
11 Aug 2013	18.4-24.2	96.9-97.1	39-56	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✗	✓
12 Aug 2013	20.4-26.1	96.6-96.8	34-50	CFM56-7B26/3	Reference Systems comparison	Single-point	✓	✗	✓
24 Aug 2013	17.0-20.2	96.3-96.5	68-92	CFM56-7B26/3	Reference Systems comparison	Multi-point	✓	✓	✗

2.6 miniCAST

A miniCAST soot generator 5201C (Jing Ltd) was used as a surrogate emissions source to compare the nvPM mass and number diagnostic instruments used in the three reference systems prior to the dedicated engine tests. The miniCAST was operated at the following flowrates - propane: 0.06 lpm, N_2 mixing gas: 0 lpm, oxidation air: 1.55 lpm, N_2 quench air: 7 lpm, dilution air: 20 lpm, such that a high elemental carbon (EC) fraction (>80%), determined from TOA, was produced in the exhaust stream (Durdina et al., 2016). The mean size of particles at the miniCAST setting selected was ~130 nm. This test was performed to verify that the operation and performance of the instruments were optimal after transport to the SR Technics engine test facility. The configurations for the nvPM mass and number instrument comparisons using the miniCAST are presented in Figure 2.

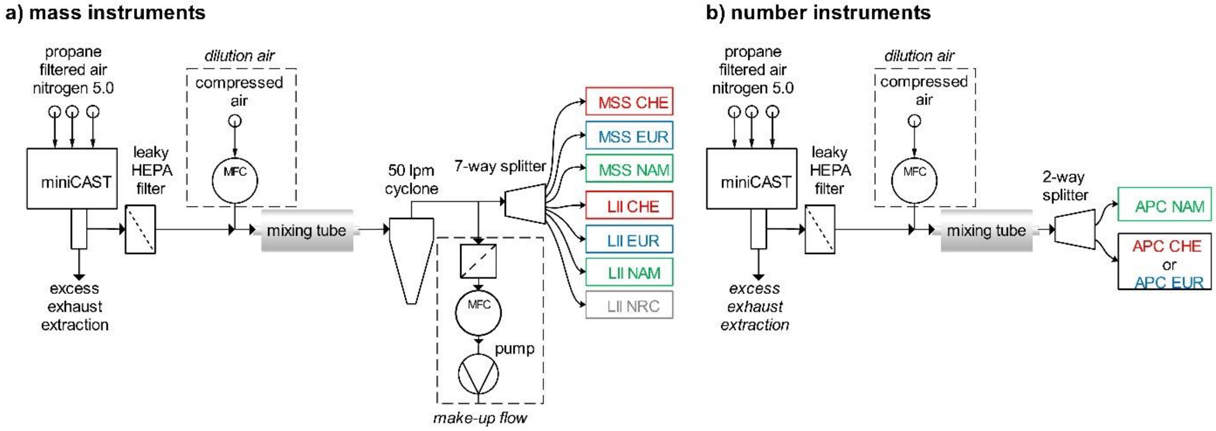

Figure 2: Configuration for the mass (a) and number (b) instrument comparisons using the miniCAST 5201C soot generator

For the nvPM mass instrument comparison, the miniCAST exhaust was passed through a HEPA filter dilution bridge and then diluted with compressed air to achieve target mass concentrations of 50, 100, 250, 500, 750, and 1000 µg/m^3. The diluted exhaust sample was then transferred through a mixing tube, a cyclone with a 1 µm cut-point at 50 lpm, and a 7-way splitter to the instruments under test – 6 instruments, (3 MSSs and 3 LII 300s) two from each reference system, and another LII 300 which was used to monitor source concentration levels during the course of the instrument comparisons. Only data from the instruments in the reference systems were used in the analysis. The calibration factors determined during the NRC-Metrology calibrations from the NIOSH 5040 EC protocol for all six nvPM mass instruments were applied prior to the comparison study. For the nvPM number instrument comparison, the miniCAST exhaust was diluted with compressed air and split into two legs – one providing a sample to the APC from the NAM reference system, and the other to the APC from either the CHE or EUR reference systems.

3 Results and Discussion

3.1 Instrument comparisons using the miniCAST

The results of the nvPM mass and number instrument comparisons conducted using the miniCAST as a source of nvPM are presented in Figure 3. The nvPM mass concentrations as measured by the MSS (Fig 3a) and LII 300 (Fig 3b) for each reference system were averaged for 60 seconds, and each instrument was then compared against the ensemble average. The data from the MSS and LII 300 instruments were tightly bound with a relative standard deviation (RSD) of 1.95% and 4.5%, respectively. A relatively higher degree of scatter (±10%) was observed with the LII 300 data for nvPM mass concentrations below 100 $\mu g/m^3$. Overall, the six nvPM mass instruments were within an RSD of 4.1% over the range of target nvPM mass concentrations explored. An RSD of 2.1% was observed between the 3 APCs used for the nvPM number measurements when the CHE and EUR reference system APCs were compared against the NAM reference system APC (Fig 3d). The repeatability of the miniCAST as reported by the manufacturer is ±5%. Larger differences have been observed from inter-day experiments (Moore et al. 2014), however, for the instrument comparison test the miniCAST settings were stable with RSDs in the mean nvPM mass and number concentrations <5%. Since the differences observed between the instruments were of a similar magnitude, the nvPM mass instruments and the nvPM number instruments were assessed as being in statistical agreement on the miniCAST source.

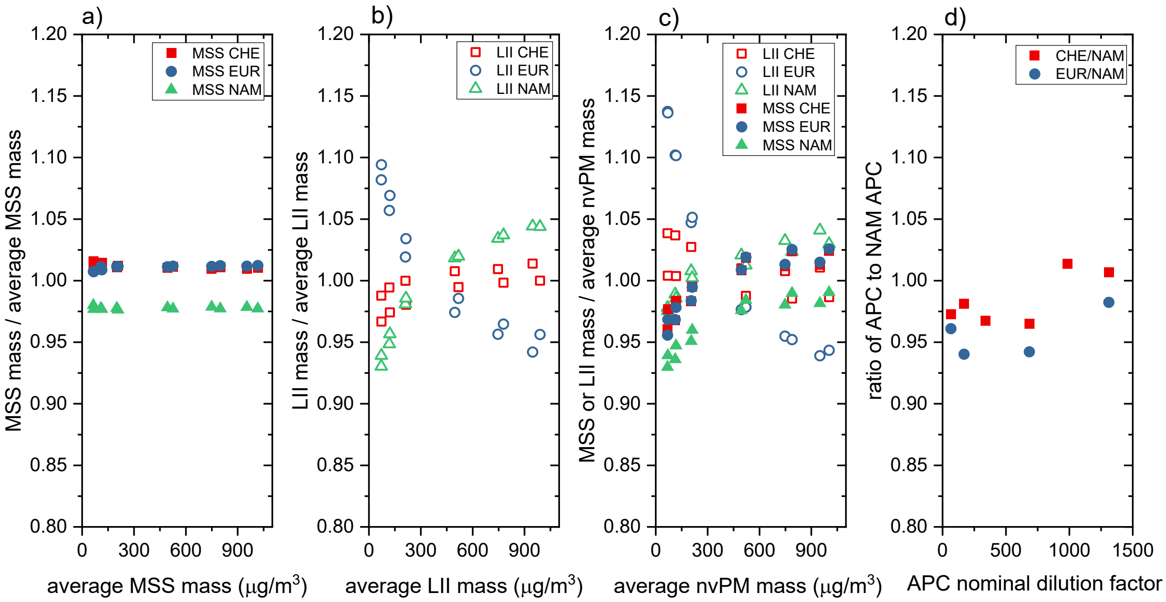

Figure 3: Comparison of nvPM mass (a, b, c) and number (d) instruments using the miniCAST 5201C soot generator

3.2 nvPM mass and number emission profiles for the CFM56-7B26/3 engine

The nvPM mass and number concentrations were converted to nvPM mass-based emission index (EI_m) and nvPM number-based emission index (EI_n), respectively, using the measured nvPM and gaseous emissons concentration and following the procedures specified in AIR6241 (SAE, 2013). The EIs are reported at a standard temperature of 273.15 K and standard pressure of 101.325 kPa. The nvPM mass and number emission indices were not corrected for either the thermophoretic loss in the sample extraction system or for size-dependent diffusional and inertial losses that occurred in the sampling and measurement systems, and CPC efficiencies for nvPM number. The nvPM mass and number emission indices for the CFM56-7B26/3 engine as a function of percent rated thrust are presented in Figure 4. For the nvPM mass emission index profile, the emissions for this engine were generally higher at idle conditions (3-7% rated thrust), decreased to a minimum at low engine thrust conditions (15-30% rated thrust), and increased linearly to maximum rated thrust. The nvPM number emission index also exhibited behavior similar to that of nvPM mass emissions at idle and low engine thrust conditions. However, the emissions increased up to a maximum at ~60% rated thrust and then slightly decreased up to the maximum rated thrust. The nvPM mass and number emissions profiles shown here are consistent with previously reported profiles for a CFM56-7B24/3 engine (which is the same engine model but rated at a lower take-off thrust) (Lobo et al., 2015a). ~~The theoretical total uncertainties in the nvPM EIs presented are estimated to be ~22% for EI mass and ~25% for EI number. These estimates are based on typical uncertainty values for the nvPM mass and number instruments (including calibration uncertainty), CO_2 measurement, and the determination of the dilution factor in the nvPM number instrument (SAE, 2013). These estimates do not account for either the particle losses in the sampling and measurement systems or the increased uncertainty for nvPM mass measurements near the limit of detection (LOD).~~

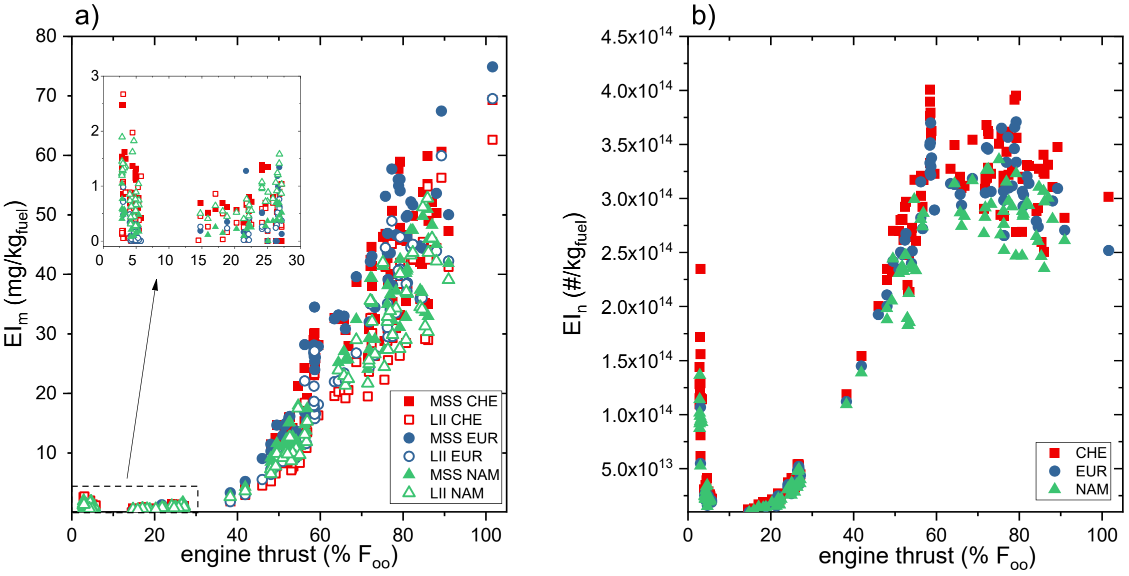

Figure 4: nvPM mass (a) and number (b) emission index profiles for the CFM56-7B26/3 engine

3.3 2-way reference system comparisons (CHE-EUR; CHE-NAM)

Comparison of nvPM mass and number emissions for pairs of reference systems, i.e., CHE-EUR and CHE-NAM was performed during the test campaign and is presented in Figure 5. The multi-point sampling probe was used for the CHE-EUR comparison, while the single-point probe was used for the CHE-NAM comparison. However, since the extracted exhaust samples were representative of the engine emissions, the use of a particular sampling probe did not influence the comparisons between the reference systems. The 2-way comparisons with reference systems in parallel were performed to assess system to system differences without the additional complexity of including a third system (also performed and described in the next section). The nvPM mass and number emission index for each instrument in the reference system pairs were averaged and compared against the ensemble average for a specific pair-wise comparison. The average nvPM mass and number emission indices for the CHE-EUR comparison were slightly higher than the CHE-NAM comparison because of the higher engine thrust conditions achieved during the respective tests.

The theoretical total uncertainties in the nvPM EIs presented are estimated to be ~22% for EI mass and ~25% for EI number. These estimates are based on typical uncertainty values for the nvPM mass and number instruments (including calibration uncertainty), CO_2 measurement, and the determination of the dilution factor in the nvPM number instrument (SAE, 2013). These estimates do not account for either the particle losses in the sampling and measurement systems or the increased uncertainty for nvPM mass measurements near the limit of detection (LOD).

All instruments in the three reference systems were generally ±22% of the average nvPM mass emission index and ± 25% of the average nvPM number emission index (grey shaded area in Fig. 5), except for the nvPM mass emission index which exhibited a >~~20~~22% variation at low nvPM mass concentrations levels (corresponding to EIs of < 30 mg/kg), and significantly higher differences as the instruments approached the LOD (3 µg/m^3, corresponding to EIs of <2 mg/kg). The high variability in mass at low concentrations was exhibited for both types of nvPM mass instruments (MSS and LII 300). This trend for high variability in nvPM mass at low concentrations is consistent with results for emissions measurements of other engine types (Lobo et al., 2015a; Lobo et al., 2016). For nvPM number, the CHE reference system registered consistently higher values compared to the EUR and NAM reference systems. The overall magnitude of variation for each instrument from the average was consistent for the two pairs of reference system comparisons, i.e ± 15%. It should be noted that since only a single type of nvPM number instrument was compared, there is no information on the uncertainty associated with using different types of nvPM number instruments that meet the specifications.

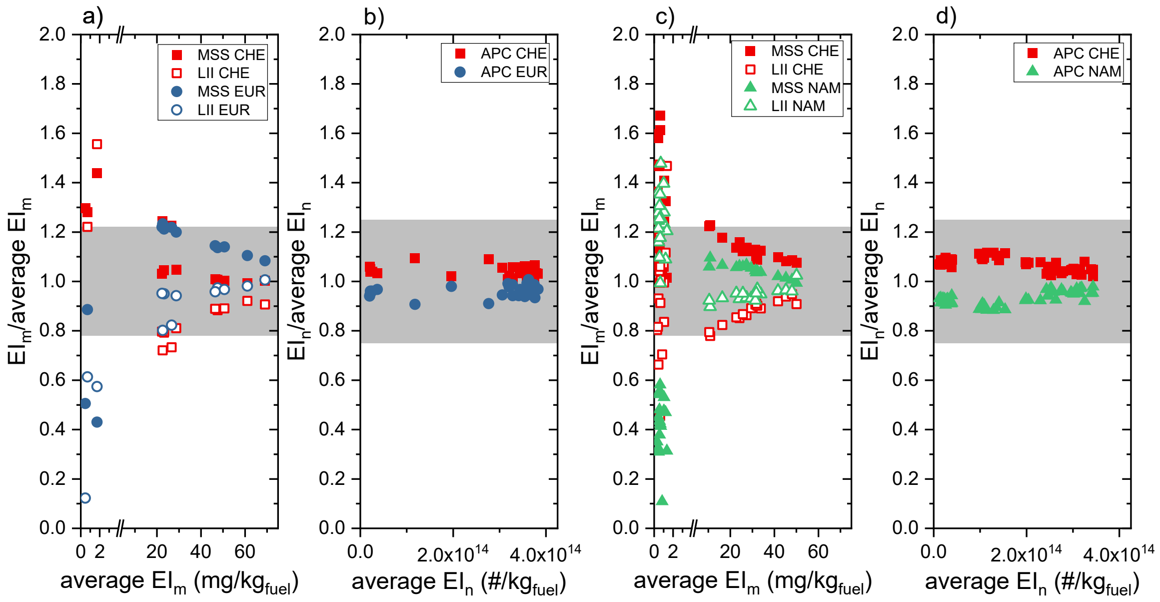

Figure 5: Comparison between CHE and EUR reference systems (a, b) and CHE and NAM reference systems (c, d) for nvPM mass and number emission indices

3.4 3-way reference system comparisons (CHE-EUR-NAM)

All three reference systems were compared simultaneously using the CFM56-7B26/3 engine. The comparisons between the reference systems in terms of the ratio of the nvPM mass and number emission index to the average emission index as a function of the average emission index are presented in Figure 6. Similar trends in nvPM mass and number EIs during the 2-way comparisons are also observed for the 3-way comparisons. The average nvPM mass and number EIs for the 3-way reference system comparisons are lower than those for the 2-way comparisons because the nvPM emissions produced by the engine for these tests were lower. Variability in nvPM mass emission index was higher than 20% for EIs up to 40 mg/kg fuel (corresponding to a mass concentration of ~ 95 $\mu g/m^3$ at the instrument), while the variability in nvPM number emission index was ±15% for all test conditions.

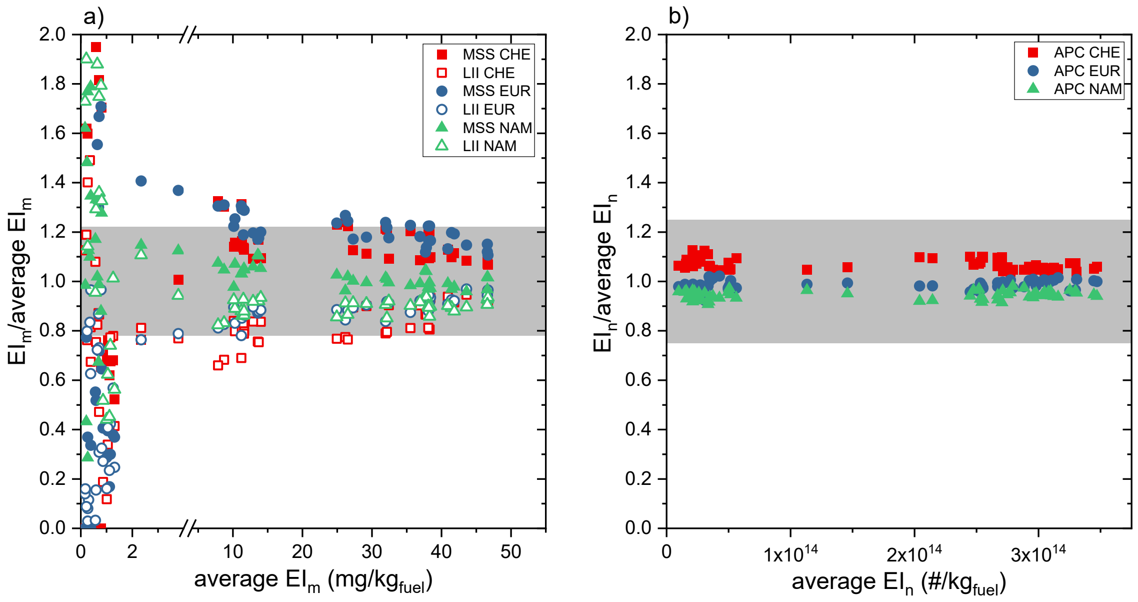

Figure 6: Comparison between CHE, EUR, and NAM reference systems for nvPM mass (a) and number emission index (b).

It is also informative to view the nvPM mass and number emission indices for the instruments used in the three reference systems using parity plots as shown in Figure 7. The EI data reported for each instrument are plotted against the average EI. While these plots are not suitable to illustrate differences at low concentration levels, they provide an overall magnitude of variability between the instruments. As can be seen in Figure 7, the nvPM EI_m and EI_n for each instrument ~~was~~ were well correlated with the average. The nvPM EI_n for all three systems was within ± 6% of the average. For the nvPM EI_m, the magnitude of the differences was ~10% for the LII 300 and ~15% for the MSS. Ideally, quartz filters would have been collected in parallel with the real-time instruments to determine EC content using TOA, and then used as the reference to compare the nvPM mass instruments. The filter collection for TOA was not performed during the campaign due to limitations on sampling time at each test condition preventing adequate sample to be collected for analysis.

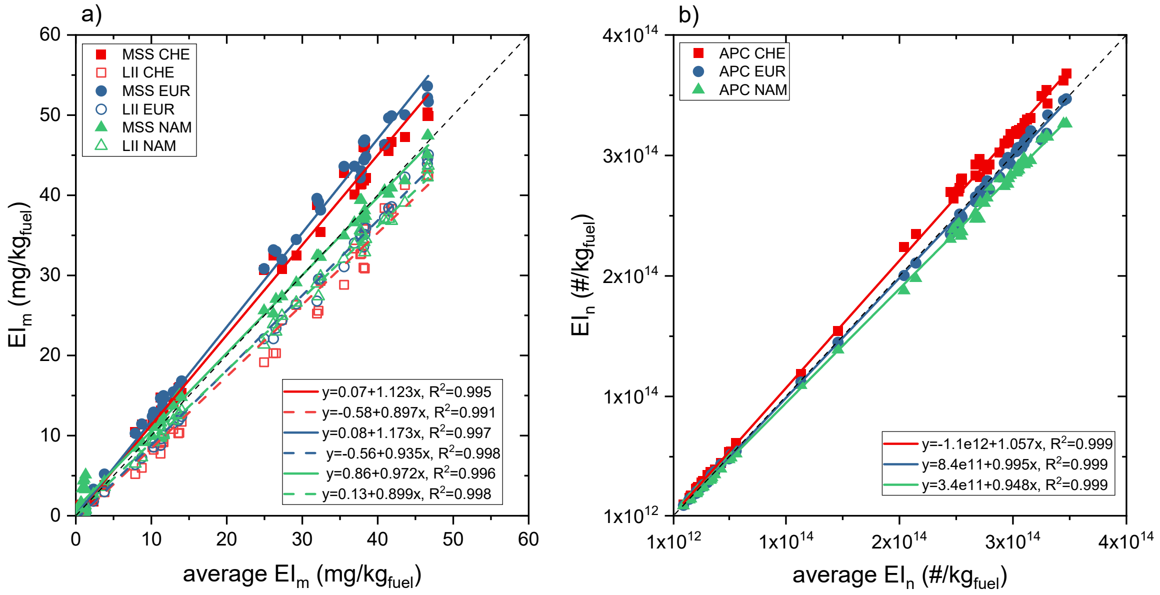

Figure 7: Parity plot comparisons of CHE, EUR, and NAM reference systems for nvPM mass (a) and number emission index (b).

3.5 Reference system comparisons for nvPM mass and number concentration

The comparison between the reference systems in terms of nvPM mass and number concentrations for each type of measurement instrument is presented in Figure 8 to assess performance on a concentration basis (the primary output of the instrument). The concentration data at the measurement location (Figure 8) have been corrected for dilution since each system had slightly different dilution factors. All data recorded during the campaign when at least 2 systems were operating in parallel are included in this analysis. The comparison between the three reference systems is presented as a function of the ensemble averages for the different types of measurement instruments, i.e. MSS and LII 300 for nvPM mass, and APC for nvPM number.

As was previously reported, the largest differences between the three reference systems for nvPM mass were observed for dilution corrected nvPM mass concentrations < 50 µg/m^3 at the measurement location (~ 5 µg/m^3 at the instrument). Beyond this threshold, the particular nvPM mass instrument type, i.e. MSS or LII 300, in the reference systems were within 20% of the instrument-specific average mass concentrations. For a given nvPM mass instrument type, the variability in the measured nvPM mass emissions is constrained in a narrow range, which is not the case when both nvPM mass instrument types are included in the analysis (see Figures 5 and

6). Unlike the instrument comparisons with the miniCAST (Figures 3 a and b), both types of nvPM mass instruments each demonstrate similar variability, exceeding 20% only below 50 µg/m^3 (Figures 8 a and b) on engine exhaust. For nvPM number, all three reference systems were well within 20% of the dilution corrected average concentration over the entire range of values recorded.

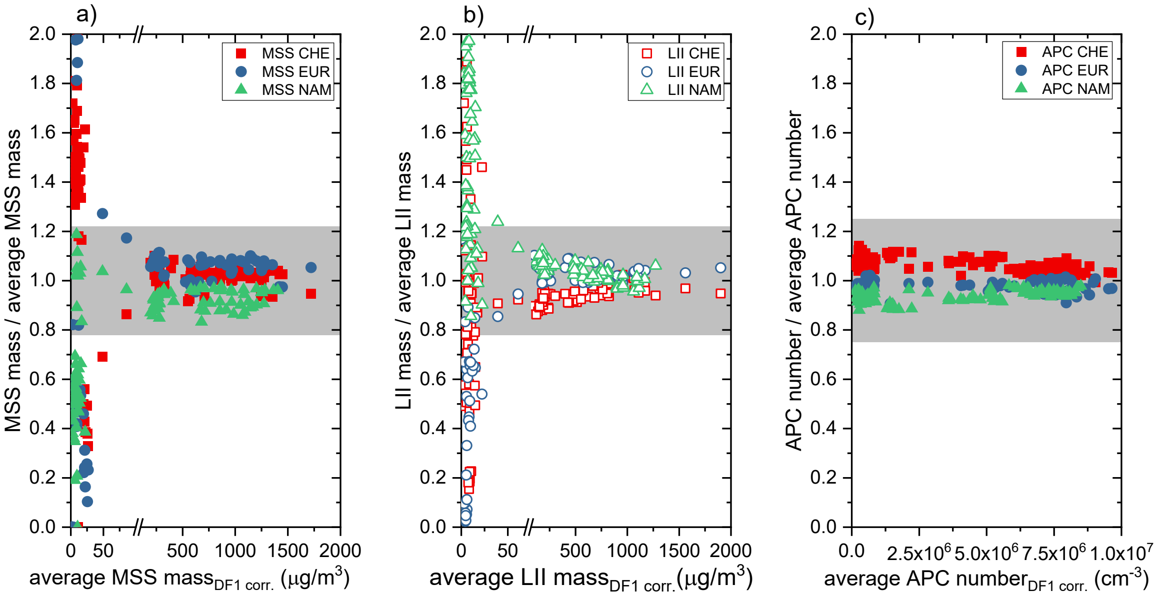

Figure 8: Comparison between CHE, EUR, and NAM reference systems for nvPM mass (a,b) and number concentrations (c). The concentrations are reported at the measurement location and corrected for dilution.

3.6 Variability

The variability in nvPM mass and nvPM number emissions was computed by calculating the RSD of the ratio of the respective EI to the average EI (data from Figures 5 and 6). This method for determining variability was adopted to focus on the relative response of the instruments (as a function of concentration), and to decouple the thrust dependency of the EIs and variability in ambient temperature. The measurement campaign was conducted over the course of a month, and the wide range of ambient conditions affected the nvPM emissions produced by the engine.

Previous studies have also reported on the impact of ambient conditions such as temperature on nvPM emissions variability (Lobo et al., 2015a).

The three reference systems were inter-compared to establish repeatability and intermediate precision of the sampling and measurement systems. Repeatability is defined as the variability of many measurements where the same equipment and operator are used to make repeated measurements over a short time period, while intermediate precision refers to the variability of measurements when only some of the four precision conditions (time, calibration, equipment, operator) are different (JCGM, 2012). The variability in nvPM mass emissions for repeatability (intra-system) and intermediate precision (inter-system) comparisons are presented in Table 3 as a function of average nvPM concentrations, with lowest concentrations of nvPM mass and number grouped in the case of the CFM56-7B26/3 engine at low engine thrust ranges(3-30%), with increasing concentrations averaged at medium engine thrust (38-60%), and high engine thrust (63-101%). A similar analysis for nvPM number emissions for intermediate precision comparisons is presented in Table 4. Intra-system (repeatability) variability for nvPM number emissions is not considered since each reference system used the same instrument type (APC) for the measurement.

The variability for nvPM mass was highest in the lowest mass concentrations (low engine thrust) range, where the average instrument concentration was below the LOD for both types of nvPM mass instruments at 0.7 μg/m^3. The resolution of the MSS instruments used during the campaign was 1 μg/m^3, whereas the LII 300 had a resolution of 0.01 μg/m^3. The higher variability of the MSS compared to LII 300 at the LOD is likely introduced through the resolution of the instrument. For medium and high concentrations (successively higher engine thrust ranges), the variability within a system and between the reference systems was <13%. For nvPM number, the variability was <3% across the engine thrust ranges. The sensitivity of nvPM number to the limit of detection was not a factor since the measured concentration was significantly above the LOD.

Table 3: Variability in nvPM mass emissions

Comparison	Average instrument mass concentration	0.7 µg/m^3						28 µg/m^3						87.8 µg/m^3					
	Thrust range	Low (3-30%)						Medium (38-60%)						High (63-101%)					
	Reference System	CHE MSS	EUR MSS	NAM MSS	CHE LII	EUR LII	NAM LII	CHE MSS	EUR MSS	NAM MSS	CHE LII	EUR LII	NAM LII	CHE MSS	EUR MSS	NAM MSS	CHE LII	EUR LII	NAM LII
Repeatability (Intra-system)	CHE	62%			48%			6.9%			10%			5.5%			7.1 %		
	EUR		65%			71%			3.8%			5.7%			3.7%			4.8%	
	NAM			60%			33%			3.1%			3.7%			2.4%			2.6%
Intermediate precision (Inter-system)	CHE-EUR and CHE-NAM	16%	40%	36%	32%	62%	30%	8.7%	1.2%	1.8%	4.6%	8%	2%	5.8%	4.1%	2.2%	5.1%	6.9%	2.7%
	CHE-EUR-NAM	126%	109%	68%	71%	75%	56%	12.8%	5.2%	5.5%	8%	5.3%	7.9%	5.2%	3.2%	5.6%	8%	3.7%	2.4%

Table 4: Variability in nvPM number emissions

Comparison	Average instrument number concentration (corrected for 2-stage dilution in the APC)	4.9×10^4 /cm^3			5.4×10^5 /cm^3			7.6×10^5 /cm^3		
	Thrust range	Low (3-30%)			Medium (38-60%)			High (63-101%)		
	Reference System	CHE	EUR	NAM	CHE	EUR	NAM	CHE	EUR	NAM
Intermediate precision (Inter-system)	CHE-EUR and CHE-NAM	2.1%	2.3%	1.8%	2.2%	2.2%	1.7%	1.8%	3.1%	1.0%
	CHE-EUR-NAM	2.4%	2.7%	1.7%	2.0%	1.1%	2.4%	1.0%	1.3%	0.9%

The other significant contributor to the variability in nvPM EI_m and nvPM EI_n is the CO_2 concentration. The diluted CO_2 measurements were used to calculate the EIs from mass and number concentrations measured by each reference system. It was not possible to evaluate the variability of the diluted CO_2 measurements. Each reference system had slightly different dimensions for the ejector-diluter vent, which resulted in subtle differences in overall dilution factors. A comparison of the CO_2 analyzers measuring the same exhaust sample on the diluted nvPM line during the engine tests was not performed. However, the variability in undiluted CO_2 concentrations measured by the CHE and the EUR reference systems was evaluated. The slope of a linear interpolation comparing the undiluted CO_2 concentrations in the EUR system to those from the CHE system was 0.993 (R^2=0.997).

All three reference systems were built to and compliant with the specifications for the standardized system detailed in AIR6241, and in this case used nominally identical nvPM instruments. Hence, the differences in particle losses in these three sampling and measurement systems are expected to be negligible compared to the variability in other factors described previously.

Building on the knowledge gained from this campaign, several changes to the instrument performance and calibration protocols were implemented. The resolution of the MSS instruments was updated to 0.01 μg/m^3. The procedure to demonstrate conformity of the nvPM mass instruments to performance specifications was updated to include an additional applicability criterion for validation of the calibration to EC on aircraft turbine engine exhaust. The limit of detection of the nvPM mass instruments was also lowered from 3 μg/m^3 to 1 μg/m^3 (ICAO, 2017).

3.7 *Size distributions*

The standardized protocol for aircraft engine nvPM mass and number emissions does not specify a measurement of particle size distribution. However, a size distribution measurement is being considered for future standardized methodologies for particle loss correction. Since particle loss mechanisms such as diffusion and inertial losses are size-dependent, measurement of size distributions along with nvPM number and mass concentration provides information to estimate particle loss factors. These loss factors can then be used to calculate nvPM emissions at the engine exit plane. Engine exit plane emissions would be more relevant for aircraft engine nvPM emissions inventory and impact assessments. The size distributions for the CFM56-7B26/3 engine along with characteristic parameters – geometric mean diameter (GMD) and geometric standard deviation (GSD) are presented in Figure 9 as a function of engine thrust setting. These size distributions were obtained with the DMS500 installed on the ancillary line of the EUR reference system and corrected for primary dilution (DF1) in the ejector diluter. The size distributions could be approximated to lognormal distributions (R^2 >0.97) with GMD ranging from 15nm at idle to 38nm at 90% rated thrust, and GSD varying between 1.53 and 1.92. The magnitude and general increasing trend of GMD and GSD with engine thrust setting are consistent with previously reported values for this engine type (Lobo et al., 2011; Lobo et al., 2015a; Durdina et al., 2017; Elser et al., 2019).

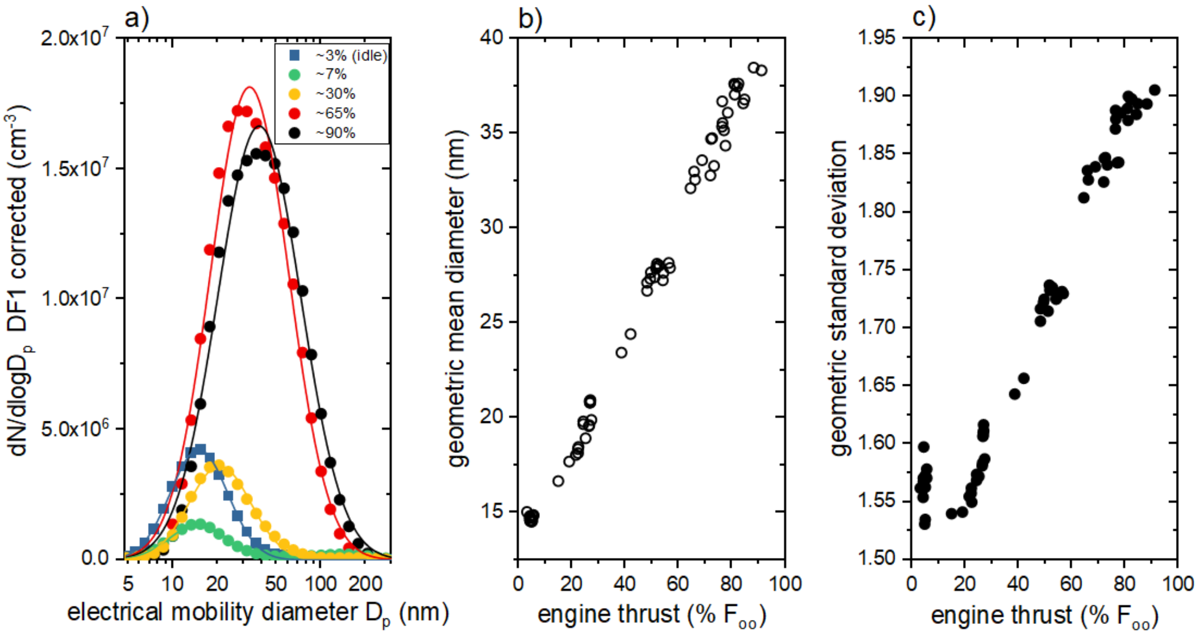

Figure 9: Particle size distributions (a) and characteristic parameters – GMD (b) and GSD (c) for the CFM56-7B26/3 engine

4 Conclusions

Three reference systems for aircraft engine nvPM emissions measurement – the Swiss (CHE) system, the European (EUR) system, and the North American (NAM) system – were developed in compliance with the specifications for the standardized sampling and measurement methodology. The first and only inter-comparison to date of these three reference systems was performed at the SR Technics engine test facility in Zürich, Switzerland using a commercial CFM56-7B26/3 aircraft engine as the emissions source to establish repeatability and intermediate precision of the sampling and measurement systems. All three reference systems measured nvPM number concentration using an APC, and nvPM mass concentration was measured using both an LII 300 and an MSS. The nvPM mass and number concentrations were converted to their respective emission indices for comparison. The specifications for the standardized sampling and measurement system implemented in the three reference systems were robust, as demonstrated by the variability observed between the systems. During the dedicated engine tests with the CFM56-7B26/3 engine, all instruments in the three reference systems were generally within 30% of the average nvPM mass emission index (determined with different nvPM mass instrument types and manufacturers) and 15% of the average nvPM number emission index (determined with the same nvPM number instrument type and manufacturer) (see Fig. 6). The only exception was for the mass instruments, which exhibited a higher variation as the concentration levels approached the LOD of 3 μg/m^3. A comparison between the three reference systems as a function of the measurement instrument type revealed that similar measurement methodologies had a better agreement and lower variability. As more fuel efficient aircraft engines with low emission combustors continue to be developed, instruments for measuring nvPM mass should have the capability of higher resolution and sensitivity for low concentration levels. Future studies should consider the variability associated with other instruments that meet the performance specifications in AIR6241 but were not evaluated in this study.

It should be noted that the emission index values reported for nvPM mass and number have not been corrected for size-dependent particles losses in the sampling and measurement systems, and hence do not represent the actual emissions at the engine exit plane. Including a traceable size measurement in the standardized measurement system would enable a more accurate estimation of engine exit plane nvPM emissions to improve airport emissions inventory development and environmental impact assessment of aircraft engine nvPM emissions. Size distribution measurements, not currently specified in the standard method, were found to be approximated to lognormal distributions with GMD ranging 15nm - 38nm, and GSD varying 1.53 - 1.92.

The wide range of ambient conditions encountered during the campaign affected the nvPM emissions produced by the engine. A correction for changes in ambient conditions will need to be developed to decouple the variability in the ambient temperature from the measured nvPM mass and number emissions. Although the CFM56-7B26/3 engine used in this study is the most widely used engine in commercial aviation, other engine types could have different emissions profiles. It is essential that the reference systems be compared using an aircraft engine source with a different emissions profile to validate the repeatability and intermediate precision of the sampling and measurement systems established in this study. Also, long term comparison of the reference systems should be undertaken since these systems will continue to be used to varying extents over time.

As a direct consequence of the results from this ~~project~~campaign, several changes to the instrument performance were implemented such as updating the resolution of the MSS instruments to 0.01 µg/m^3, and lowering the limit of detection of the nvPM mass instruments from 3 µg/m^3 to 1 µg/m^3. The procedure to demonstrate the conformity of the nvPM mass instruments to performance specifications was updated to include an additional applicability criterion for validating the nvPM mass instrument calibration on aircraft turbine engine exhaust.

The results from this study are a benchmark for the variability in standardized sampling and measurement systems for measuring aircraft engine emissions. The three reference systems evaluated were subsequently used for comparisons with aircraft engine manufacturer sampling and measurement systems. The aircraft engine manufacturers contributed nvPM emissions datasets for 24 aircraft engine types that were representative of the current commercial fleet for inclusion in a database (Agarwal et al., 2019). With the database and knowledge of the uncertainty as characterized by the intermediate precision, the new ICAO nvPM mass and number emissions regulatory standard for in production and new engines (CAEP/11) was developed. ~~Going forward, this~~ This new ICAO regulatory standard will be used to certify all aviation engines with rated thrust > 26.7 kN for nvPM mass and number emissions performance.

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