Supporting Information

Non-Volatile Particulate Matter Emissions of a Business Jet Measured at Ground Level and Estimated for Cruising Altitudes

Lukas Durdina[a,1,*], Benjamin T. Brem[a,2], David Schönenberger[b], Frithjof Siegerist[c], Julien Anet[d], Theo Rindlisbacher[e]

[a] Laboratory for Advanced Analytical Technologies, Empa, Dübendorf, CH-8600, Switzerland
[b] Laboratory for Air Pollution and Environmental Technology, Empa, Dübendorf, CH-8600, Switzerland

[c] SR Technics Switzerland AG, Zurich-Airport, CH-8058, Switzerland
[d] Centre for Aviation, School of Engineering, Zurich University of Applied Sciences, Winterthur, CH-8401, Switzerland

[e] Federal Office of Civil Aviation FOCA, Bern, CH-3003, Switzerland
[1] now at: Centre for Aviation, School of Engineering, Zurich University of Applied Sciences, Winterthur, CH-8401, Switzerland
[2] now at: Laboratory for Atmospheric Chemistry, Paul Scherrer Institute, Villigen, CH-5232 Switzerland

Number of pages: 6
Number of figures: 3
Number of tables: 2

Contents

Table S1 Fuel properties. Annex 16 LOW and HIGH are the lower and upper limits for the fuel used in emission testing.

Parameter	Unit	Annex 16 LOW	Annex 16 HIGH	Fuel sample 1	Fuel sample 2
Aromatics	% (V/V)	15	23	17.1	17.2
Sulfur, total	% (m/m)	0	0.3	0.109	0.097
10 Vol % recovered at	°C	155	201	173	169
End point	°C	235	285	271	266
Density at 15 °C	kg/m³	780	820	802.5	801.1
Viscosity at -20 °C	mm²/s	2.5	6.5	4.246	3.856
Specific energy, net	MJ/kg	42.86	43.5	43.2	43.2
Smoke point	mm	20	28	20	21.3
Naphthalenes	% (V/V)	0	3.5	1.48	1.41
Hydrogen	% (m/m)	13.4	14.3	13.6	13.4
H/C ratio (calculated)	NA	1.84	1.99	1.87	1.84

S1 Fuel properties

S2 Engine test matrix

Table S2 Engine test matrix.

Test point	% sea level thrust
Ground idle	~3
Warm-up 65%	65
Warm-up 85%	85
1	95 (100)*
2	85
3	75
4	65
5	50
6	35
7	30
8	25
9	12
10	7
11	~3

*limited by ambient conditions

S3 System loss correction factors

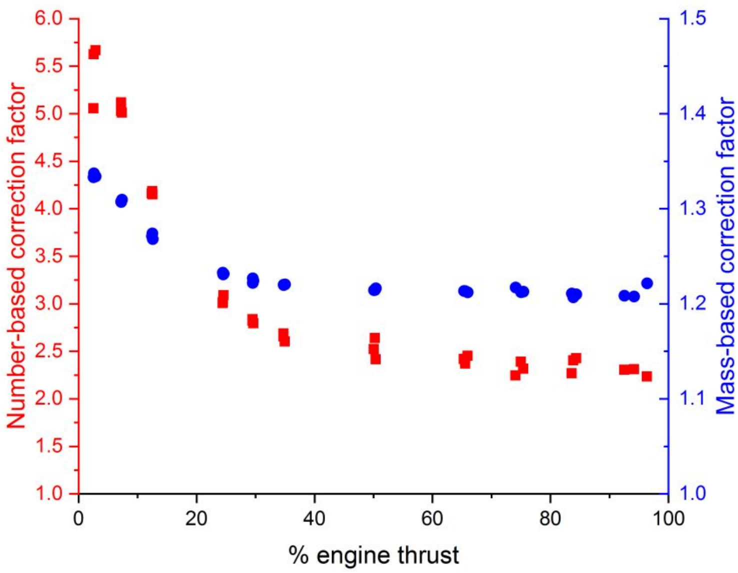

Figure S1 System loss correction factors for particle number (left, red) and particle mass (right, blue).

S4 Engine performance model and cruise emission estimates

The GasTurb engine performance model was parametrized with the mechanical configuration of the engine to get accurate estimates of engine performance at cruising altitudes. From the GasTurb engine database we selected the engine type, which fitted the engine used – a mixed-flow geared turbofan engine with an axial low pressure- and a radial high pressure compressor. The design point for the engine performance was the take-off point at sea level. The model was calibrated to a limited amount of engine design- and performance data available:

- Cockpit data from the engine tests: N1, N2, inter-turbine temperature T45, fuel flow
- Manufacturer information: thrust-N1 correlation, bypass ratio – N1 correlation, overall pressure ratio, fan pressure ratio, gear ratio
- Calculated parameters: p3, T3 (equations from Stettler et al. 2013[1])
- Assumptions: compressor pressure ratios, component efficiencies

Overall, the final model matched well the engine performance data at ground level (Figure S2). Unfortunately, we could not compare the model with flight recorder data. We could compare the engine performance only with the manufacturer's information at the maximum cruise condition (Mach 0.8; 40,000 ft; ISA) in terms of thrust and specific fuel consumption (SFC; g/kN): 4.9 kN and SFC 19.2 g/s·kN. Our model (using the maximum T45 from the engine certification sheet as a limiter) agreed well with thrust 4.81 kN and SFC 22.8 g/s·kN. We note that the engine measured at ground had 20% higher fuel consumption than the data provided by the manufacturer (installation effects and possibly also engine deterioration effects). Previously, a GasTurb model of a CFM56-7B engine calibrated to ground performance data proved to agree well with flight recorder data.[2] Although the engine performance data used for the model development here were much more limited, it is the best possible approximation available.

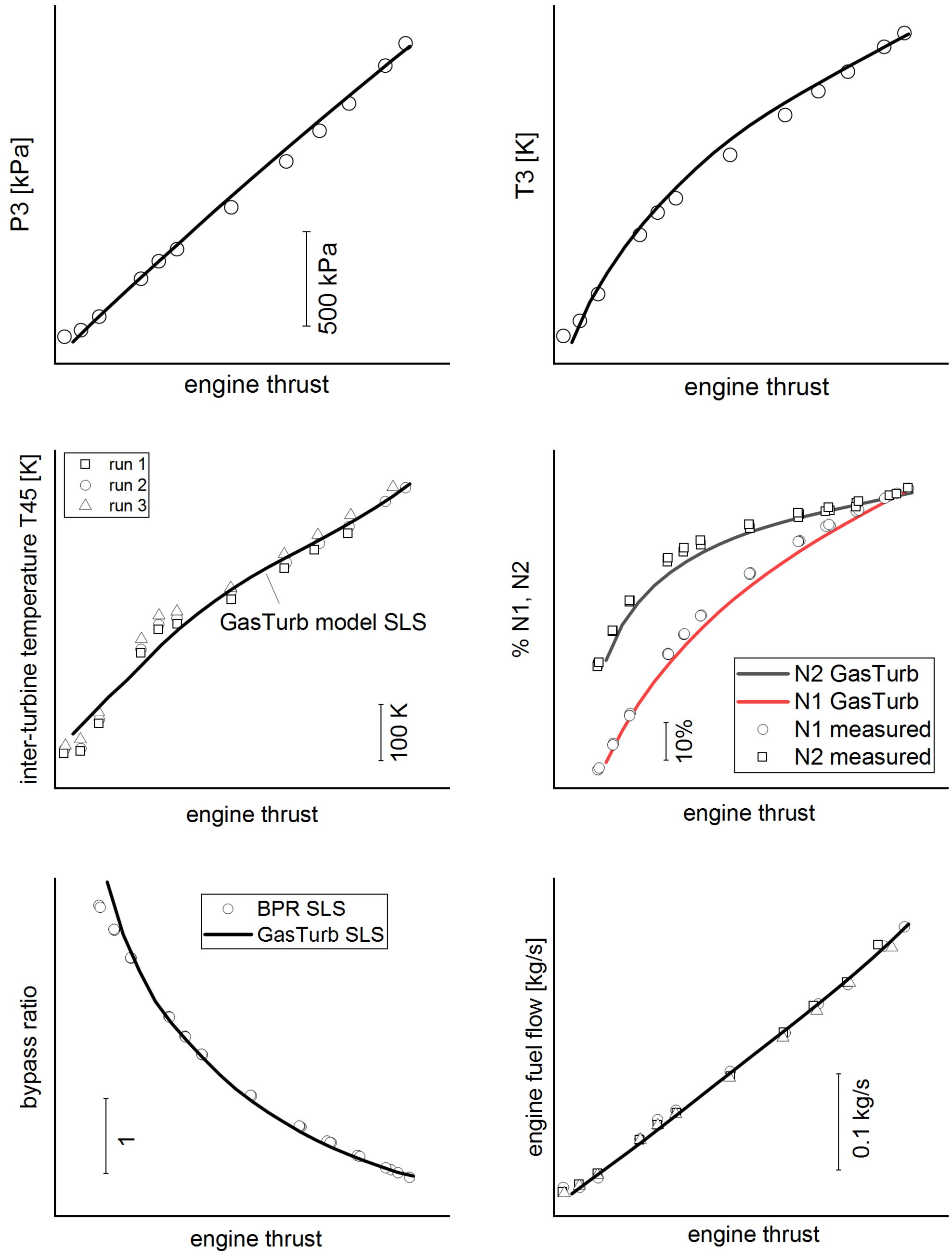

Figure S2 Comparison of the engine performance data and the GasTurb model.

The cruise nvPM emissions in the manuscript were calculated as in Durdina et al., 2017.[2] We corrected the nvPM mass-based emission indices at ground using the methodology of

Doepelheuer et al. 1999.[3] At first, the engine performance parameters at cruise are needed: combustor inlet temperature T3, combustor inlet pressure p3, and combustor exit AFR. The mass-based EI at ground at the T3 corresponding to a cruising altitude is then corrected using two correction factors, which are functions of p3 and AFR. The number-based EI is then calculated from the ratio of nvPM number to nvPM mass as a function of T3. This relationship is unique for each engine type and depends on particle size distribution characteristics. The critical assumption in this method is that the nvPM number/mass ratio and GMD are functions of T3 independent of ambient conditions (experimental data from the AEDC report of Howard et al., 1996[4]).

Alternatively, the nvPM EIs at cruise can be calculated from nvPM mass concentration, GMD, and engine performance, which we compared with the method above. The calculation requires much more information about the engine performance. The following steps were done:

- Calculate nvPM mass concentration in the engine core exhaust at ground as a function of T3 (needs bypass ratio information)
- Correct nvPM mass concentration at a T3 corresponding to cruise using the AFR and p3 correction equations from Doepelheuer et al.[3]
- Calculate exhaust volume per kg fuel at standard temperature and pressure in the core exit (GasTurb information on mass flow, static T, P, and fuel flow)
- Calculate mass-based emission index
- Calculate nvPM number from nvPM mass and GMD as a function of T3 (assuming a GSD of 1.8 and a constant particle density independent of particle size and engine conditions)
- Calculate number-based emission index

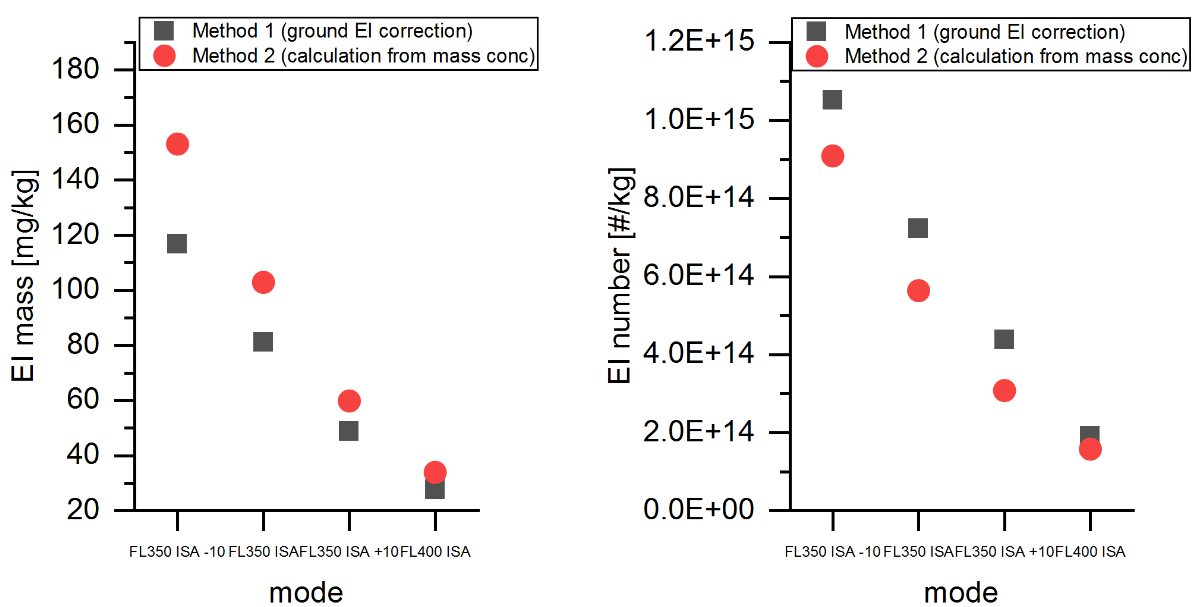

Figure S3 Comparison of the EIs of nvPM mass (left) and nvPM number (right) at cruise calculated using the direct correction of ground EIs and the calculation from nvPM mass concentration and engine performance.

The results obtained by the two methods agree within 30% (range 14–30%; Figure S3), which we consider excellent given the uncertainties. Unlike the more elaborate method (Method 2 in Figure S3), which derives number-based EI from GMD and a constant GSD and effective density, Method 1, using the number/mass ratio as a function of T3, considers changing particle morphology (effective density) and GSD as a function of T3. Effective density typically increases with increasing T3 and decreases with increasing particle size and GSD increases with increasing T3.[5] Thus, Method 1 provides a relatively simple approach to estimating nvPM EIs at cruise.

References

(1) Stettler, M. E. J.; Boies, A. M.; Petzold, A.; Barrett, S. R. H. Global civil aviation black carbon emissions. *Environ. Sci. Technol.* **2013**, 47, 10397–10404.

(2) Durdina, L.; Brem, B. T.; Setyan, A.; Siegerist, F.; Rindlisbacher, T.; Wang, J. Assessment of Particle Pollution from Jetliners: From Smoke Visibility to Nanoparticle Counting. *Environ. Sci. Technol.* **2017**, 51, 3534–3541.

(3) Döpelheuer, A.; Lecht, M. Influence of engine performance on emission characteristics. RTO Meeting Proceedings 14; RTO/NATO: Hull, Canada, 1999.

(4) *Experimental Characterization of Gas Turbine Emissions at Simulated Altitude Conditions*; AEDC-TR-96-3; Arnold Engineering Development Center, Tullahoma, TN, 1996.

(5) Durdina, L.; Brem, B. T.; Abegglen, M.; Lobo, P.; Rindlisbacher, T.; Thomson, K. A.; Smallwood, G. J.; Hagen, D. E.; Sierau, B.; Wang, J. Determination of PM mass emissions from an aircraft turbine engine using particle effective density. *Atmos. Environ.* **2014**, 99, 500–507.