

Supplementary Materials for: Jet fuel variability propagates to aircraft particle emissions at the airport scale

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Error analysis for absolute uncertainties of the emission indices

To assess the total uncertainty to each measured emission event the Gaussian error propagation method was applied. For the applied approach of determining emission indices (eq. S1) this translates to eq. S2. Please refer to the main manuscript for an explanation on the formula symbols.

$$\text{EI}_{\text{nvPM},n} = \frac{\Delta \text{nvPM},n}{\Delta \text{CO}_2} \overbrace{\frac{V_m}{M_{\text{CO}_2}}}^{=:k} \text{EI}_{\text{CO}_2} \quad (\text{S1})$$

$$\begin{aligned} \Delta \text{EI}_{\text{nvPM},n} &= \sqrt{\left(\frac{\partial \text{EI}_{\text{nvPM},n}}{\partial \Delta \text{nvPM},n} \Delta \Delta \text{nvPM},n \right)^2 + \left(\frac{\partial \text{EI}_{\text{nvPM},n}}{\partial \Delta \text{CO}_2} \Delta \Delta \text{CO}_2 \right)^2 + \left(\frac{\partial \text{EI}_{\text{nvPM},n}}{\partial \text{EI}_{\text{CO}_2}} \Delta \text{EI}_{\text{CO}_2} \right)^2} \\ &= k \sqrt{\left(\frac{\text{EI}_{\text{CO}_2}}{\Delta \text{CO}_2} \Delta \Delta \text{nvPM},n \right)^2 + \left(\frac{\Delta \text{nvPM},n}{\Delta \text{CO}_2^2} \Delta \Delta \text{CO}_2 \right)^2 + \left(\frac{\Delta \text{nvPM},n}{\Delta \text{CO}_2} \Delta \text{EI}_{\text{CO}_2} \right)^2} \end{aligned} \quad (\text{S2})$$

For the sake of clarity the determination of $\Delta \Delta \text{nvPM},n$ and $\Delta \Delta \text{CO}_2$ is given individually below. The values for $\Delta \text{nvPM},n$ are obtained by a numerical integration of the values measured for each time step t subtracted by a background (BG) value. Since a constant background was subtracted, it is subtracted n times resulting in eq. S3.

$$\Delta \text{nvPM},n = \sum_{t=1}^n \text{nvPM},n(t) - n \cdot \text{nvPM},n(\text{BG}) \quad (\text{S3})$$

Applying Gaussian error propagation to this expression leads to eq. S4 with the corresponding uncertainties u for measured particle concentration and background concentration, respectively.

$$\Delta \Delta \text{nvPM},n = \sqrt{\left[\sum_{t=1}^n \frac{\partial \text{nvPM},n}{\partial \text{nvPM},n(t)} \cdot u(\text{nvPM},n(t)) \right]^2 + \left[\frac{\partial \text{nvPM},n}{\partial \text{nvPM},n(\text{BG})} \cdot u(\text{nvPM},n(\text{BG})) \right]^2} \quad (\text{S4})$$

This can be simplified under the assumption of a relative uncertainty x for particle number concentration measurements according to $x \Rightarrow u(\text{nvPM},n(t)) = x \cdot \text{nvPM},n(t)$ leading to the final eq. S5.

$$\begin{aligned}
\Delta\Delta_{\text{nvPM},n} &= \sqrt{\left(x \cdot \sum_{t=1}^n \text{nvPM}_{,n}(t)\right)^2 + (n \cdot x \cdot \text{nvPM}_{,n}(BG))^2} \\
&= x \cdot \sqrt{\left(\sum_{t=1}^n \text{nvPM}_{,n}(t)\right)^2 + (n \cdot \text{nvPM}_{,n}(BG))^2}
\end{aligned} \tag{S5}$$

In an analogous manner this can be derived for the error in ΔCO_2 , i.e. $\Delta\Delta\text{CO}_2$, and the corresponding uncertainty y of the CO_2 measurement device. For the error bars given in Fig. S1 $y = 1.5\%$ and $x = 15\%$ were used according to comparison measurements and manufacturer information.

$$\Delta\Delta\text{CO}_2 = y \cdot \sqrt{\left(\sum_{t=1}^n \text{CO}_2(t)\right)^2 + (n \cdot \text{CO}_2(BG))^2} \tag{S6}$$

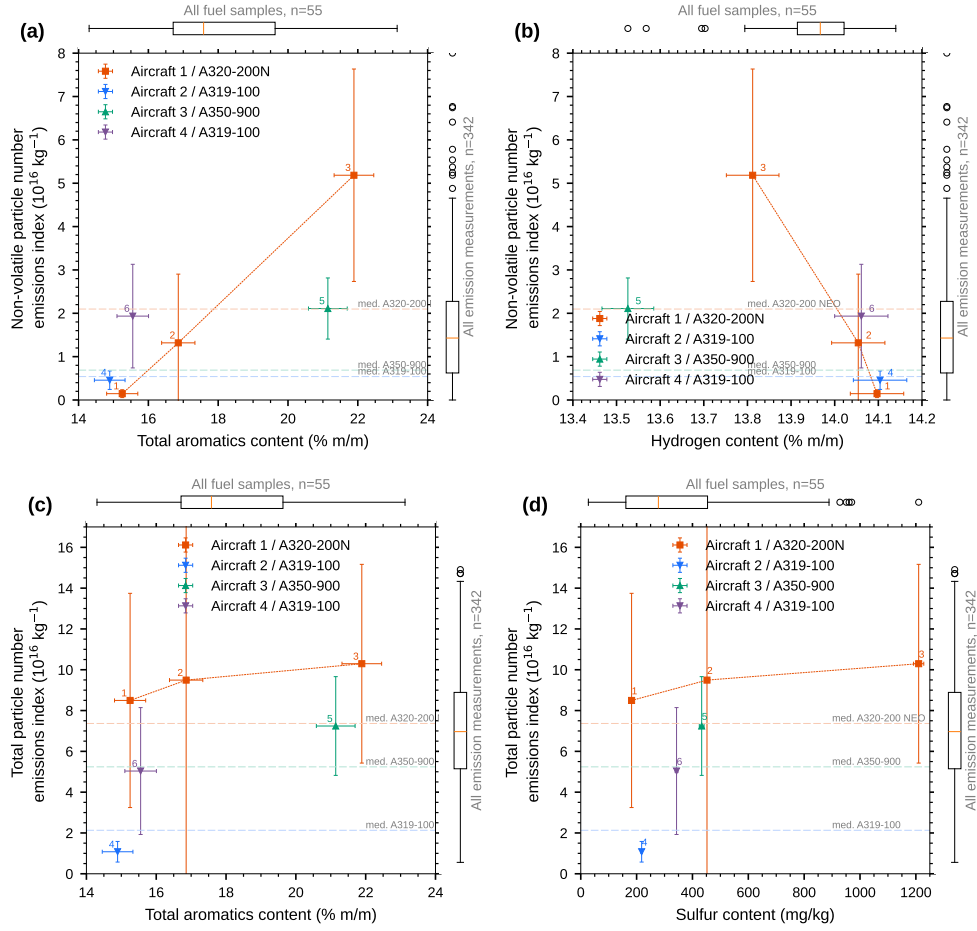


Fig. S1: Dependence of particle emission indices on fuel composition across the six selected fuel samples - absolute uncertainty. (a,b) $EI_{nvPM,n}$ as a function of total aromatics and hydrogen content, respectively. (c,d) $EI_{tPM,n}$ as a function of total aromatics and sulfur content, respectively. Dashed horizontal lines indicate median values for the respective aircraft type derived from the full dataset; dotted lines are shown for visual guidance only. Boxplots represent the distribution of the respective variable across the full dataset. Numbers denote fuel samples as defined in Table 1 in the main manuscript. Horizontal error bars indicate 95% confidence intervals for repeatability according to the respective ASTM standards; vertical error bars indicate 95% confidence intervals with respect to the absolute uncertainty of the measured emission indices.

Additional figures

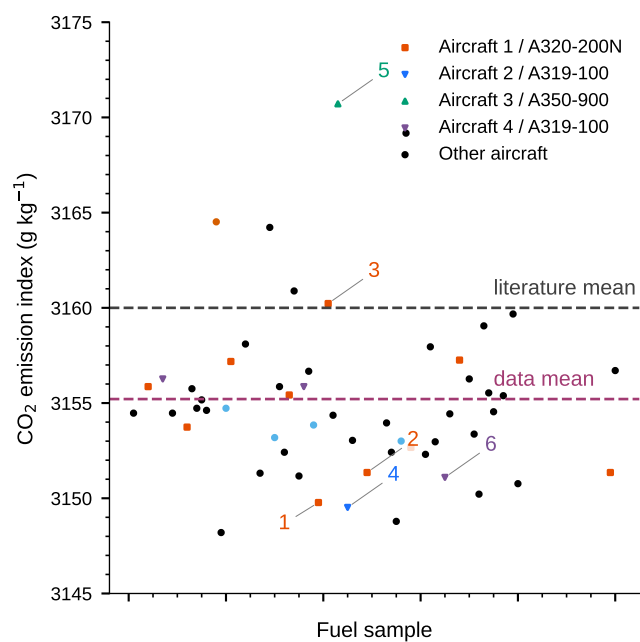


Fig. S2: Calculated CO₂ emission indices for the six selected fuel samples based on measured fuel carbon content. The dashed green line indicates the mean across all fuel samples, while the dashed blue line denotes the literature reference value derived from stoichiometric analysis. Coloured points highlight measurements from the four aircraft associated with the six selected fuel samples; numbers denote fuel samples as defined in Table 1 of the main manuscript.

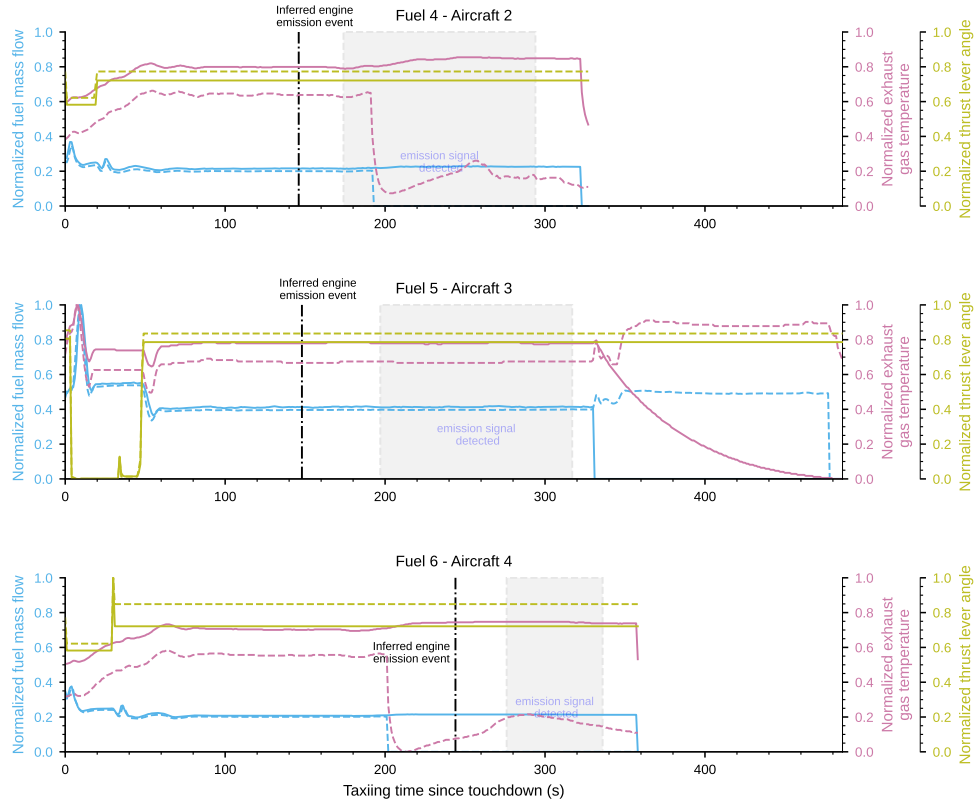


Fig. S3: Engine performance data during taxiing for emission measurements associated with Fuel 4–6 (top to bottom) from Aircraft 2–4, respectively. Data were recorded from the respective aircraft flight data recorders. Fuel mass flow, exhaust gas temperature, and thrust lever angle are shown for the left (solid lines) and right (dashed lines) engines; taxiing time is given relative to aircraft landing (touchdown); all quantities are normalized with respect to the minimum and maximum values of the respective time series. Grey shaded areas indicate the time spans during which emission signals were evaluated at the mobile laboratory. Dashed vertical lines indicate the inferred times of the corresponding engine emission events, derived from the estimated transport time based on local wind conditions.

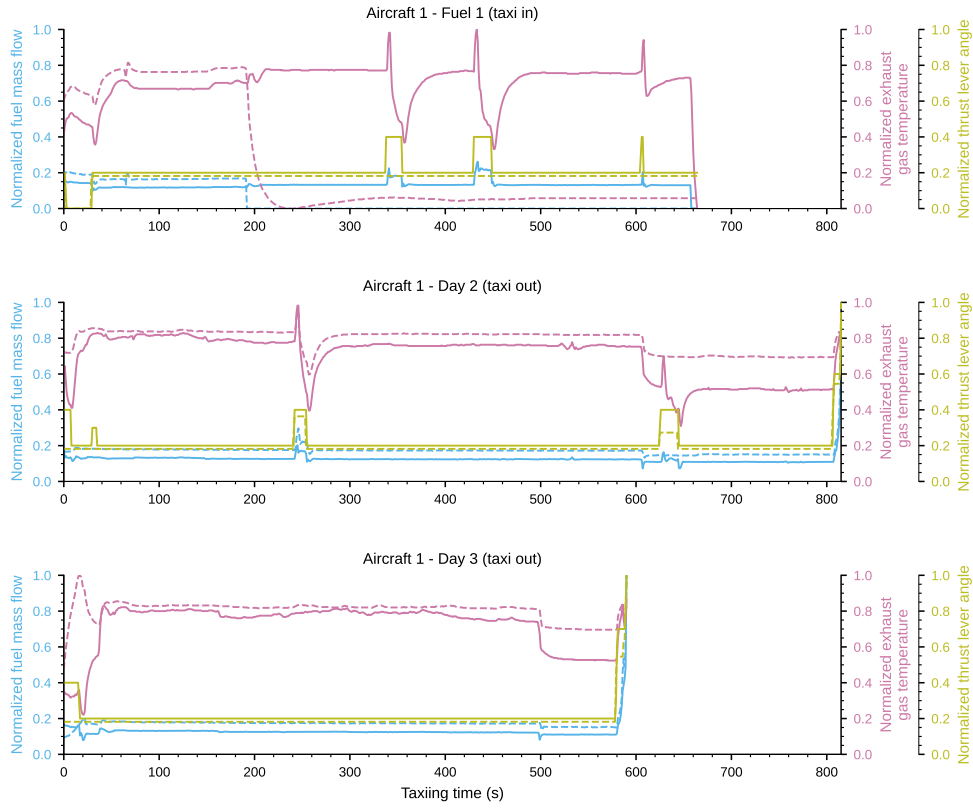


Fig. S4: Engine performance data during taxiing for emission measurements associated with Fuel 1 (top) and two additional taxi-out operations from Aircraft 1 (middle, bottom). Data were recorded from the aircraft flight data recorder. Fuel mass flow, exhaust gas temperature, and thrust lever angle are shown for the left (solid lines) and right (dashed lines) engines; all quantities are normalized with respect to the minimum and maximum values across the three measurements. For the two taxi-out time series, the recordings end before maximum take-off thrust is reached. Normalization with respect to the full time series, including the take-off roll, highlights that variations during taxiing are small compared with the increase in engine operating parameters during take-off.

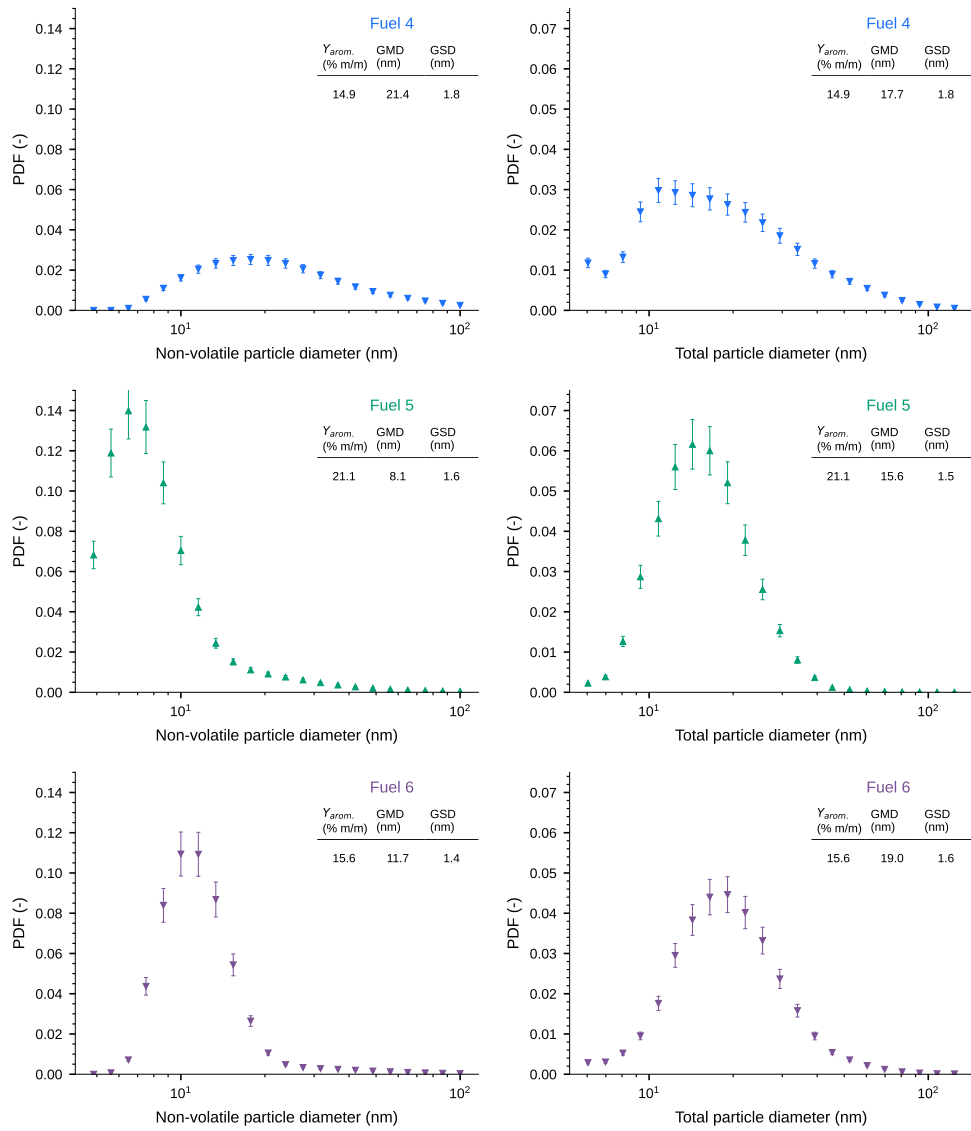


Fig. S5: Particle size distributions for fuel samples 4–6 from Aircraft 2–4, respectively. Non-volatile (left) and total (right) particle size distributions are shown as probability density functions (PDFs), normalized to unit area. Error bars indicate 95% confidence intervals for each size bin. Insets summarize the geometric mean diameter (GMD) and geometric standard deviation (GSD) for each distribution. As the distributions were measured on different aircraft, they should not be compared directly.