

Jet fuel variability propagates to aircraft particle emissions at the airport scale

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Abstract

Aircraft emissions at airports are a major source of ultrafine particles (UFPs), affecting local air quality and human health. Although jet fuel composition varies among certified fuel batches and influences particle formation under controlled conditions, whether these effects remain detectable during routine airport operations remains unresolved, as aircraft-specific fuel properties and operating conditions are generally unavailable simultaneously.

Here, we combine in situ emission measurements with aircraft-level fuel characterization and detailed aircraft performance data during routine operations at Copenhagen Airport. Analysis of approximately 400 exhaust plumes, with selected events linked to fuel samples from individual aircraft, enables operational variability to be assessed independently of fuel properties. Non-volatile particle emissions increase with aromatic content and decrease with hydrogen content, while total particle emissions additionally increase with sulfur content. Detailed molecular characterization indicates that differences in cyclic species explain deviations from these relationships.

Our results demonstrate that variability among certified jet fuels propagates to measurable differences in aircraft particle emissions despite the complexity of routine airport operations. Fuel composition therefore represents a measurable and potentially actionable lever for reducing particle emissions and improving air quality at and around airports.

Keywords: Aircraft emissions, Ultrafine particles, Jet fuel, Air quality, Sustainable aviation

Introduction

Airports are central nodes in the aviation system and, at the same time, significant sources of emissions from routine operations, particularly during taxiing, take-off, and landing of aircraft [1, 2]. These emissions degrade local air quality [3–5], raising concerns about public health impacts in surrounding communities [6–10] and prompting increasingly strict regulation [11, 12]. With global air traffic projected to grow by 2.4–3.8% annually through 2050 [13], mitigating airport emissions is an urgent challenge [14]. To this end, understanding the key drivers of aircraft emissions, and how they manifest under real-world operational conditions, is essential for developing and deploying effective mitigation strategies.

Among aircraft emissions, ultrafine particles (UFPs, defined as particles smaller than 100 nm in diameter) are of particular concern and are commonly subdivided into non-volatile (soot) and volatile particles. Non-volatile particles form in localized regions of incomplete combustion and poor fuel–air mixing within the primary zone of the combustor [15], arising from a complex interplay between combustor technology, fuel chemistry, and combustion kinetics, and are subsequently modified by ageing processes in the ambient atmosphere after emission [16]. For aircraft operating under real-world conditions, the influence of these processes is expressed through factors such as engine technology, engine maintenance status, engine thrust setting defined by pilot behaviour, and fuel composition as key drivers of UFP formation intensity. Unlike engine technology or maintenance status, fuel composition varies from flight to flight while remaining largely unobservable under routine airport operations. In addition, aircraft gas turbine engines are often operated outside their optimal efficiency regimes during airport operations, including high-thrust conditions during take-off and low-power settings such as idle during taxiing, which are associated with elevated particle number concentrations [17].

Volatile ultrafine particles are generally understood to consist primarily of sulfuric acid and organic fuel components that nucleate in the young exhaust plume [18, 19], with recent studies indicating that engine lubrication oil can also act as an efficient nucleation agent [20, 21]. UFPs have been linked to significant degradation of local air quality in the vicinity of airports [22–24] and are therefore a key focus in efforts to reduce aircraft engine emissions. Consequently, UFP formation and emissions from aircraft engines have been investigated using test rigs [25–27], ground measurements [28–31], and airport-based measurements [32–34]. Collectively, these studies demonstrate that reducing soot-precursor compounds in fuels, in particular aromatic and other unsaturated species, leads to lower emissions of non-volatile particles, with higher hydrogen content generally

80 associated with reduced soot formation [29, 35]. However, whether these rela-
81 tionships persist under routine airport operations remains unresolved because
82 previous operational studies generally lacked simultaneous information on air-
83 craft operating conditions and aircraft-specific fuel properties, preventing fuel
84 effects from being distinguished from operational variability.

85 Among these factors, fuel composition represents a particularly challenging
86 source of variability under real-world operating conditions. Although jet fuel is
87 treated as a commodity on the global market, fuels certified under technical
88 specifications such as ASTM D1655 [36] or DefStan 91-091 [37] (Jet A/Jet A-1)
89 exhibit batch-to-batch variability in properties such as density, aromatic content,
90 and sulfur content. This variability arises because specifications define acceptable
91 property ranges rather than exact values or a fixed chemical composition, allow-
92 ing fuels derived from different crude oil feedstocks and refining processes [38]
93 to occupy distinct positions within the permitted property space, and hence also
94 within the composition space, while remaining operationally equivalent.

95 Because certified fuel batches can be mixed while remaining within specifica-
96 tion, fuels from different sources are routinely combined throughout the supply
97 chain. Although operationally efficient, this practice complicates the attribution
98 and tracing of fuel property variability.

99 This challenge is particularly pronounced at airports, where fuel is supplied
100 into shared storage and mixing systems and subsequently distributed via hydrant
101 networks or fuel bowzers to individual aircraft. As a result, variations in fuel prop-
102 erties and composition, including aromatic and sulfur content, cannot be directly
103 attributed to specific refuelling events or flight operations. Previous studies have
104 reported fuel property measurements at refineries [39, 40], selected airport fuel
105 farms [32], and experimental flights [41–43], but extending such measurements
106 to the level of individual aircraft under regular operations has so far remained
107 beyond the reach of routine operational studies. Consequently, whether variabil-
108 ity in fuel properties contributes measurably to aircraft UFP emissions during
109 routine airport operations remained an open question. Addressing this question
110 requires direct aircraft-level fuel characterization together with detailed opera-
111 tional information, capabilities that have largely been unavailable in previous
112 studies. Here, we show that variability in jet fuel properties produces measurable
113 differences in aircraft UFP emissions under fully operational airport conditions.

114 Measurement campaign

115 To investigate the influence of fuel variability under routine airport operations,
116 we conducted an integrated aircraft-emissions and fuel-characterization campaign
117 at a major European airport. By combining aircraft-level fuel sampling, detailed

aircraft performance data, and high-resolution emission measurements, the campaign enables fuel properties to be linked directly to emissions from individual aircraft. A high-fidelity mobile emissions laboratory was deployed on the apron of Copenhagen Airport (CPH) in close proximity to active taxiways, which enabled the capture and analysis of exhaust plumes generated during routine taxiing operations (see Figure 1). This configuration allowed quantification of both volatile and non-volatile particle emissions. For selected aircraft, a fuel sample was collected from the main fuel tank after arrival and after the corresponding emission measurements, enabling the linkage of observed emission characteristics with the associated fuel properties. To assess operational parameters relevant to engine performance, such as fuel flow rates and thrust settings, we incorporated detailed aircraft performance data into the analysis.

Over a two-week period in early May 2025, we analyzed approximately 400 exhaust plumes and obtained fuel samples from 55 arriving aircraft. The dataset includes aircraft from the Airbus A320, A320neo, A350, A319, and A330 families, providing a representative range of short-haul and long-haul operations. Because fuel sampling is not feasible during regular turnaround procedures, samples were primarily taken from aircraft arriving late in the evening and scheduled to remain overnight at Copenhagen Airport. For each sampled aircraft, 5 liters of fuel were collected to enable subsequent laboratory analysis and linkage to the corresponding emission measurements. This analysis included the standard properties defined in ASTM D1655 for Jet A-1, as well as measurements of hydrogen content and two-dimensional gas chromatography [44, 45], which provided insight into the detailed chemical composition of the fuels.

[Fig. 1 about here.]

Results and discussion

Figure 2 provides a daily overview of the fuel samples and emission plumes collected during the measurement campaign, together with the predominant wind direction at the mobile emissions laboratory. Because Copenhagen Airport is located directly at the coast, variable wind conditions, including deviations from the predominant wind direction, limited the collection of emission plumes suitable for analysis during the first week of the campaign. In addition, the operational and technical effort associated with fuel sampling restricted the number of samples to approximately five per night on average, resulting in a reduced subset of measurements for which emissions, fuel properties, and aircraft performance data are available simultaneously. The annotated fuel numbers indicate samples for which valid emission plume measurements and corresponding aircraft

155 performance data were obtained. The following analysis focuses on these data
156 points.

157 [Fig. 2 about here.]

158 Table 1 summarizes key fuel properties relevant to the emission analysis for the
159 six fuel sample, together with the airport at which fuel was last uplifted prior to
160 the flight to Copenhagen, where fuel sampling was performed. As the sampled
161 fuel represents a mixture of newly uplifted fuel and residual fuel remaining on
162 board from previous flight operations, the reported airport indicates the loca-
163 tion of the most recent fuel uplift rather than the exclusive origin of the sampled
164 fuel. A clear variation in the properties is observed across the samples, reflect-
165 ing differences in fuel uplift airports and the associated fuel supply chains and
166 sourcing. In addition, median values and minimum and maximum ranges from
167 a representative worldwide Jet A-1 fuel survey [39] are included for comparison.
168 All six samples fall within the range reported in this survey and can therefore
169 be considered representative of current fuel uplift, without evidence of extreme
170 outliers in fuel properties.

171 [Table 1 about here.]

172 The fuel samples were obtained from four aircraft within the SAS fleet, as
173 detailed in Table 2. These aircraft belong to the Airbus A320-200neo, A319-100,
174 and A350-900 families. During the two-week measurement campaign, these air-
175 craft types accounted for approximately 20%, 5.8%, and 1.4% of total traffic at
176 Copenhagen Airport, respectively. In particular, the A320-200neo equipped with
177 CFM LEAP-1A26 engines represents a highly relevant aircraft-engine combina-
178 tion for current operations at airports with route networks comparable to that
179 of Copenhagen Airport.

180 [Table 2 about here.]

181 Aircraft performance data

182 All measurements were conducted during a ten days measurement campaign.
183 Over this relatively short period, no engine maintenance was performed on the
184 sampled aircraft that could have altered their emission characteristics.

185 To assess the influence of engine operating conditions and pilot behaviour,
186 aircraft engine performance parameters during taxiing are shown in Fig. 3 for
187 Fuels 1–3, which were collected at different days from the same aircraft. Owing to
188 the distance between the taxiway and the mobile laboratory (see Fig. 1 (right)),

as well as the complexity of wind conditions and exhaust plume dynamics, the exact timing between emission from the source aircraft and received signal at the location of the instruments cannot be determined precisely. Therefore, the grey shaded areas indicate the time intervals during which the emission signals were recorded, with the corresponding emission events occurring slightly earlier. An estimate of the emission arrival time at the measurement location, based on transport by the prevailing wind, is also indicated. Fuel mass flow and exhaust gas temperature characterize the operating state of the left (solid lines) and right (dashed lines) engines in terms of energy input and thermal loading, respectively, both of which are closely linked to emission formation. The thrust lever angle indicates pilot interaction with the engines during taxiing. To preserve confidentiality, all quantities are normalized with respect to the minimum and maximum values across the three measurements.

[Fig. 3 about here.]

Notably, during all three taxi operations, the right engine was shut down approximately 200 s after touchdown, resulting in single-engine taxiing, a common fuel-saving operational procedure for narrow-body aircraft. This does not affect the calculation of emission indices, which are reported per unit mass of fuel burned. The thrust lever angle and fuel flow profiles are largely consistent across all three taxi events, with minor transient increases observed for Fuel 1, likely associated with short stops at taxiway intersections. It should be noted that engine thrust during taxiing is substantially lower than during take-off or cruise, and the observed transients represent only minor adjustments compared with the variations typically encountered during flight operations. For reference, the ICAO Aircraft Engine Emissions Databank defines the standard taxi/idle operating point as 7% of rated engine thrust [46, 47], illustrating the comparatively low-power regime in which the present measurements were conducted. Overall, the data confirm stable low-thrust operating conditions throughout the three measurements, without significant variations in engine operation that could influence particle emissions. Corresponding engine performance data for Fuels 4–6, together with representative take-off profiles for comparison, are provided in the Supplementary Materials.

Taken together, these observations support the assumption that, for the dataset considered here, variations in fuel properties are the dominant driver of the observed differences in particle emissions, which forms the central hypothesis tested in the following analysis.

Fuel impact on emission indices

To assess particle emissions from these aircraft and link them to fuel properties and composition, we use the particle number emission index (EI_x), which quantifies the number of non-volatile or total particles emitted per kilogram of burned fuel, assuming complete conversion of fuel carbon to CO_2 (see Methods for details). Fig. 4 presents the non-volatile ((a), (b)) and total ((c), (d)) particle number emission indices for the four aircraft as a function of total aromatic content (left column), hydrogen content ((b)) and sulfur content ((d)) of the six fuel samples.

[Fig. 4 about here.]

Consistent with the previously defined hypothesis, Fig. 4 (a) illustrates for Aircraft 1 a clear increase in $EI_{nvPM,number}$ with increasing aromatics content. This trend is in line with previous experimental findings [26] and, to our knowledge, represents a first observation of this relationship under fully operational airport conditions. Aircraft 4 and 6, which are equipped with the same engine type, exhibit a similar tendency, although these observations are based on different, albeit comparable, aircraft. Notably, Aircraft 3 shows significantly lower $EI_{nvPM,number}$ at high aromatic content compared with Aircraft 1. However, as indicated by the dashed horizontal lines, median emissions across all A350-type aircraft in the dataset are generally lower than those across A320-type aircraft, suggesting that differences between aircraft and engine types contribute to the observed deviation.

Consistent with the trends observed for aromatic content, Fig. 4 (b) shows that hydrogen content exhibits an inverse relationship with $EI_{tPM,number}$ in agreement with previous experimental findings [29]. This further supports the interpretation that hydrogen content serves as a more robust indicator of particle emission tendencies than aromatic content [35].

Total particle numbers

Total particle number emission indices are presented in Fig. 4 (c), where $EI_{tPM,number}$ increases with increasing aromatic content, although this dependence is somewhat less pronounced for Aircraft 1. Total particle number emissions include both non-volatile and volatile particles. While the formation of non-volatile particles is linked to soot precursor compounds in the fuel, such as mono- and di-aromatics, volatile particle formation can result from sulfur oxidation during combustion [48], as well as from volatile organic compounds and lubrication oil vapours [21]. To assess the contribution of fuel sulfur, Fig. 4 (d)

relates $EI_{tPM,number}$ to the sulfur content of the respective fuel samples. A general increase in total particle emissions with increasing sulfur content is observed, although this tendency is less pronounced for Aircraft 1.

Particle size distributions

Emission indices provide an aggregated mean value to characterize the emission plume, which in reality consists of a mixture of volatile and non-volatile particles spanning a range of diameters. Additional insight into individual emission events is provided by particle size distributions (PSD), as shown in Fig. 5 for three fuel and emission samples from Aircraft 1. A shift in the modal diameter of the PSD towards larger particle sizes is observed for both non-volatile and total particle number distributions with increasing aromatic content. Notably, the non-volatile PSD for Fuel 3 exhibits a weakly bimodal distribution. This feature may reflect enhanced particle ageing during transport from the aircraft to the measurement location, resulting in a partial shift towards larger particle diameters [16]. Consistent with this interpretation, Fuel 3 exhibits the longest delay between the inferred engine emission event and the onset of the measured plume signal among Fuels 1–3 (Fig. 3), corresponding to the longest estimated transport and particle ageing time.

[Fig. 5 about here.]

Fuel composition

Boxplots in Fig. 6 provide an overview of all emission measurements in the dataset. Individual measurements for Aircraft 1–4 are shown as scatter points, with annotations corresponding to the six fuel samples. Notably, $EI_{nvPM,number}$ and $EI_{tPM,number}$ for Fuel 5 measured on Aircraft 3 are both at the upper end of the range observed for A350 aircraft. A closer examination of the aromatic and hydrogen content for this fuel sample in Fig. 7 indicates a deviation from the trend defined by the other fuels, with a comparatively low hydrogen content relative to its aromatic content.

To this end, we analyse the detailed chemical composition of the six fuels using comprehensive two-dimensional gas chromatography (GC×GC), to shed light on the origin of this deviation. Figure 8 (a) presents the mass fractions of key fuel chemical families, as commonly used for the rapid assessment of aviation fuels [49], derived from the GC×GC analysis for the six fuel samples. For reference, data from a worldwide fuel survey [39] are included as boxplots. While Fuels 1–3 and 6 fall within the typical compositional ranges indicated by the survey, Fuel 4 exhibits an elevated fraction of iso-alkanes and a slightly reduced fraction

of mono-aromatics. Together with the predominance of C16–C18 iso-alkanes in Fig. 8 (e), this composition is consistent with the possible presence of a HEFA-derived SAF blend [50]. Such a blend would remain fully compliant with Jet A-1 specifications and would not necessarily be distinguishable from conventional fuel based on fuel certification alone. No information on the composition or blending history of the fuel uplifted at Amsterdam was available beyond compliance with the ReFuelEU Aviation blending requirement applicable at the time of fuel uplift. This observation illustrates that compositional variability associated with emerging SAF deployment may already be detectable within the range of fuels encountered during routine airport operations, although the present data do not permit definitive attribution of the observed composition to a specific blending history.

In contrast, Fuel 5 is characterized by a substantially higher fraction of saturated cyclic components, including both cycloalkanes and aromatics, accompanied by a reduced fraction of n- and iso-alkanes, consistent with its lower hydrogen content, as ring formation lowers hydrogen-to-carbon ratio and hence hydrogen content in hydrocarbon jet fuels [51]. This compositional shift may explain the comparatively high $EI_{nvPM,number}$ and $EI_{tPM,number}$ observed for Fuel 5 among the A350 aircraft in Fig. 6. More generally, the results highlight that fuels complying with the same Jet A-1 specification can nevertheless differ substantially in their detailed chemical composition, with corresponding implications for particle emission characteristics.

[Fig. 6 about here.]

[Fig. 7 about here.]

[Fig. 8 about here.]

Implications for fuel specifications and future fuels

Our combined fuel, aircraft performance, and emission measurements demonstrate that the influence of fuel properties on particle emission intensity can be resolved under routine airport operations, despite concurrent operational variability. This finding indicates that fuel composition should be considered in the design of emission monitoring and air quality assessment strategies at airports, and highlights the need for improved understanding and documentation of fuel uplift and associated fuel properties.

Fuel specifications for Jet A-1 permit up to 25% aromatics (by volume) and 3000 ppm sulfur, with mean values for Europe around 16.7% and 400 ppm,

respectively [52]. Our results suggest that the upper bounds of these specifications may warrant reassessment to unlock potentials for emission reductions. Reductions in aromatic and sulfur content can be achieved through established refining processes [5, 53], albeit at additional cost [54, 55], and may also provide co-benefits for climate impacts, including reduced contrail formation [41, 42]. In addition to optimizing conventional jet fuel, the increasing use of sustainable aviation fuels [56] offers further potential for emission reduction, as these fuels typically contain very low aromatic fractions [57]. Moreover, because they are not derived from crude oil, sustainable aviation fuels provide additional flexibility to tailor fuel composition towards minimizing emission formation during production [58]. As the aviation fuel pool becomes increasingly compositionally diverse, understanding how these differences translate into emissions under real-world operating conditions will become increasingly important.

Future work should quantify how systematic changes in fuel properties and composition translate into emission reductions across entire airport operations. In particular, assessing the air-quality benefits of reduced aromatic and sulfur content across an airport will require coordinated, system-level measurements linking fuel composition, aircraft operation, emissions, and atmospheric transport. Such assessments should encompass both departing and arriving aircraft, as the latter carry fuel uplifted at their respective departure airports.

Overall, our findings demonstrate that fuel-property effects remain observable despite the complexity of routine airport operations. Fuel composition therefore represents a measurable and potentially actionable lever for reducing aircraft particle emissions, complementing advances in engine technology and operational measures for improving air quality at and around airports.

Supplementary information. Additional data on aircraft performance and emission measurements are provided in the supplementary materials.

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Declarations

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- 372 • **Data availability:** The datasets generated and/or analysed during this study will
373 be deposited in a publicly accessible repository prior to publication. The accession
374 number or DOI will be included in the published article. Due to confidentiality obli-
375 gations with the industrial partner SAS Scandinavian Airlines, aircraft performance
376 data will be provided in normalized form, as described in the manuscript.
- 377 • **Author contribution:** B.E., S.S., N.G., T.G., M.R., P.H. and P.L.C. planned and
378 coordinated the measurement campaign. S.S., T.G., N.R., N.G., M.K. and Z.Y.
379 performed the emission measurements and analyzed the data. B.E., G.E., P.O. and
380 U.B. analyzed the fuel samples. H.L. and K.F. performed the GCxGC measurements
381 and analyzed the data. M.R. collected and analyzed the aircraft performance data.
382 B.E. wrote the initial draft of the paper. All authors contributed to the paper and
383 commented before submission.

Methods

Mobile emissions measurement laboratory.

Emission measurements were conducted using the DLR mobile laboratory, a van-based platform equipped with state-of-the-art instrumentation. As the system has been described in detail previously [34, 59], only a brief overview is provided here. Owing to its modular design and compact footprint, the DLR mobile laboratory is well suited for measurements at critical infrastructures such as airports. Table 3 summarizes the instrumentation deployed during the measurement campaign.

[Table 3 about here.]

Sampling was performed continuously through an inlet probe equipped with a PM₁₀ impactor (Derenda) positioned at a height of 3.5 m (see left panel of Fig. 1). Aerosol samples were transferred through a temperature-controlled sampling line (313 K, Hillesheim, inner diameter 8 mm, length 3 m) into a 4 L manifold for distribution to the respective measurement instruments. All instruments were operated at a measurement frequency of 1 Hz to provide sufficient temporal resolution for capturing transient aircraft exhaust plumes.

Gas analysers (LI850 for CO₂/H₂O and CLD64 for NO_x) were calibrated every few days using zero and span gases. To ensure stable signal intensity throughout the campaign, the DMS500 was reset daily under zero-air conditions.

Emission measurement data analysis.

Emission indices for total particle number (tPN), non-volatile particle number (nvPN), and NO_x were calculated following the well-established approach of Moore et al. [32], while detailed data processing followed the methodology described by Schmitt et al. [34].

Non-volatile particle size distributions were corrected for losses introduced by the catalytic stripper using the manufacturer-provided correction algorithm (Catalytic Instruments). Particle losses in the sampling line were estimated to be below 5%. Given the similar particle size distributions observed across all measurement events, these losses were not expected to affect the comparative analysis that forms the focus of this study and were therefore neglected. Non-volatile particle number concentrations were adjusted by a calibration factor of 0.74 to match the reference scanning mobility particle sizer (SMPS) of the World Calibration Centre for Aerosol Physics (WCCAP). This factor was applied

uniformly because the deviation was found to be independent of particle size (see [34] for details).

The corrected data were subsequently temporally aligned and screened for relevant emission events, defined as distinct peaks in particle and gas concentrations attributable to a single aircraft and not influenced by other sources, such as nearby aircraft or ground vehicles. Emission events were assigned to individual aircraft based on the prevailing wind conditions and aircraft positions during the corresponding time window. Aircraft position data were obtained from an internal Copenhagen Airport database containing detailed records of aircraft ground movements.

Emission indices for nvPN, tPN, and NO_x were then calculated according to the following equations:

$$\text{EI}_{\text{nvPM,number}} = \frac{\Delta \text{nvPM,number}}{\Delta \text{CO}_2} \cdot \frac{V_m}{M_{\text{CO}_2}} \cdot \text{EI}_{\text{CO}_2} \quad (1)$$

$$\text{EI}_{\text{tPM,number}} = \frac{\Delta \text{tPM,number}}{\Delta \text{CO}_2} \cdot \frac{V_m}{M_{\text{CO}_2}} \cdot \text{EI}_{\text{CO}_2} \quad (2)$$

$$\text{EI}_{\text{NO}_x} = \frac{\Delta \text{NO}_x}{\Delta \text{CO}_2} \cdot \frac{M_{\text{NO}_2}}{M_{\text{CO}_2}} \cdot \text{EI}_{\text{CO}_2} \quad (3)$$

Here, $\Delta \text{nvPM,number}$, $\Delta \text{tPM,number}$, ΔNO_x , and ΔCO_2 denote the background-corrected integrals of the corresponding concentration peaks. V_m is the molar volume at standard conditions (22.41 L mol^{-1}), and M_X denotes the molar mass of species X . EI_{CO_2} represents the mass of CO_2 emitted per kilogram of burned Jet A-1 fuel and depends on the carbon content of the fuel. A constant value of 3160 g kg^{-1} is commonly assumed in the literature [32]. For events with an associated fuel sample, however, EI_{CO_2} was derived from the measured fuel properties. The average value across all fuel samples analysed in this study was 3155 g kg^{-1} (see the Supplementary Materials).

The absolute uncertainty associated with the emission index calculation can be estimated by Gaussian error propagation of the individual measurement uncertainties (see the Supplementary Materials). The resulting uncertainties may be substantial, particularly for highly diluted exhaust plumes. However, this approach includes uncertainty contributions that are largely systematic and therefore of limited relevance when comparing emission events measured with the same instrumentation at the same location under similar atmospheric conditions.

To estimate the relative uncertainty relevant for the present analysis, data from the sustainable aviation fuel (SAF) test period of a previous measurement campaign at Copenhagen Airport were evaluated [34]. During this campaign, emissions from the same aircraft operating on a single fuel batch were monitored

over a two-week period. Based on the observed variability across 84 aircraft movements, a relative uncertainty of approximately $\pm 50\%$ was derived for the emission indices used in this study.

Fuel analysis.

Fuel samples were analysed for compliance with ASTM D1655 (Jet A-1) by a certified external laboratory using the referee test methods specified in the standard. Specifically, specific energy was determined using ASTM D4809 (heat of combustion by bomb calorimetry), total sulfur using ASTM D5453 (ultraviolet fluorescence), and aromatic and naphthalene content using ASTM D6379 (high-performance liquid chromatography with refractive index detection).

Hydrogen content was determined at DLR using proton nuclear magnetic resonance (^1H NMR), with three replicate measurements per sample, in accordance with ASTM D7171 (low-resolution pulsed NMR spectroscopy).

Measurement uncertainties for all fuel properties were derived from the 95% confidence intervals associated with repeatability, as defined in the respective ASTM standards.

GCxGC FID/qMS.

The fuels considered in this study were analysed using a comprehensive two-dimensional gas chromatography (GCxGC) system with a split-detector configuration described previously [45]. Fuel composition was quantified using a flame ionization detector (FID), while compound identification was supported by quadrupole mass spectrometry (qMS). The analysis employed a reversed-phase column configuration. Detailed instrument parameters are given in Table 4.

[Table 4 about here.]

Aircraft performance data.

Flight performance data were obtained using standard onboard sensors and avionics systems available on commercial aircraft, without additional instrumentation. Recorded parameters included fuel flow, engine temperatures, exhaust gas temperature (EGT) and thrust per engine, as well as aircraft mass, meteorological conditions, and GPS position.

Flight data were acquired through a combination of onboard recording and communication systems. Core flight parameters were logged by the Flight Data Recorder (FDR), while higher-resolution operational data were captured by the Quick Access Recorder (QAR) for post-flight analysis. Selected data

streams were transmitted in near real time via the Aircraft Communications Addressing and Reporting System (ACARS). Aircraft system and engine performance metrics were aggregated by the Aircraft Condition Monitoring System (ACMS), with data integration and processing supported by Integrated Modular Avionics (IMA) architecture. Dedicated data management software was used to preprocess, store, and prepare datasets for transmission and subsequent analysis.

Due to confidentiality obligations associated with the industrial partner, the original operational data cannot be disclosed. All reported values were therefore normalized by a constant scaling transformation before analysis. This transformation preserves all relative relationships, trends, and statistical properties relevant to the analyses presented in this study.

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Fig. 1: Measurement setup on the apron at Copenhagen Airport. Photograph (left) showing the mobile laboratory positioned at aircraft stand C39, with the sampling inlet visible on top of the van, and an A320-200neo aircraft taxiing on the adjacent taxiway. Map (right) showing the location of the mobile laboratory on the apron, the taxi routes of aircraft associated with the six selected fuel samples, and terminal buildings (black outlines).

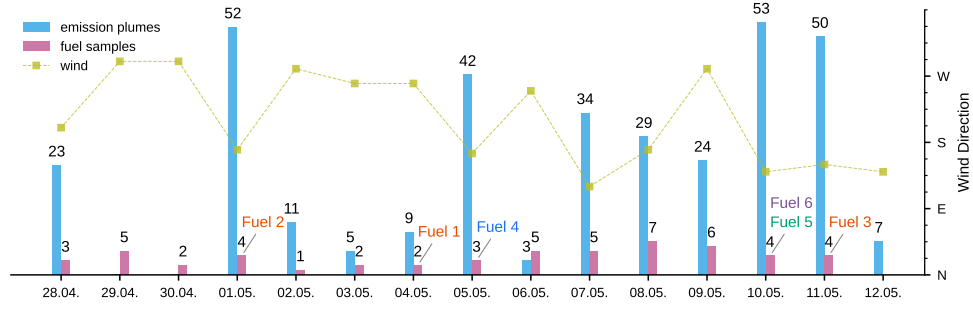


Fig. 2: Overview of fuel samples and valid emission plumes collected during the measurement campaign. Bars show the daily number of emission plumes and fuel samples; numbers above the bars indicate the corresponding counts. Median wind direction at the mobile laboratory is indicated for each day. Annotations on the fuel sample bars mark the collection days of the six selected fuel samples (see Table 1) and their corresponding emission plumes.

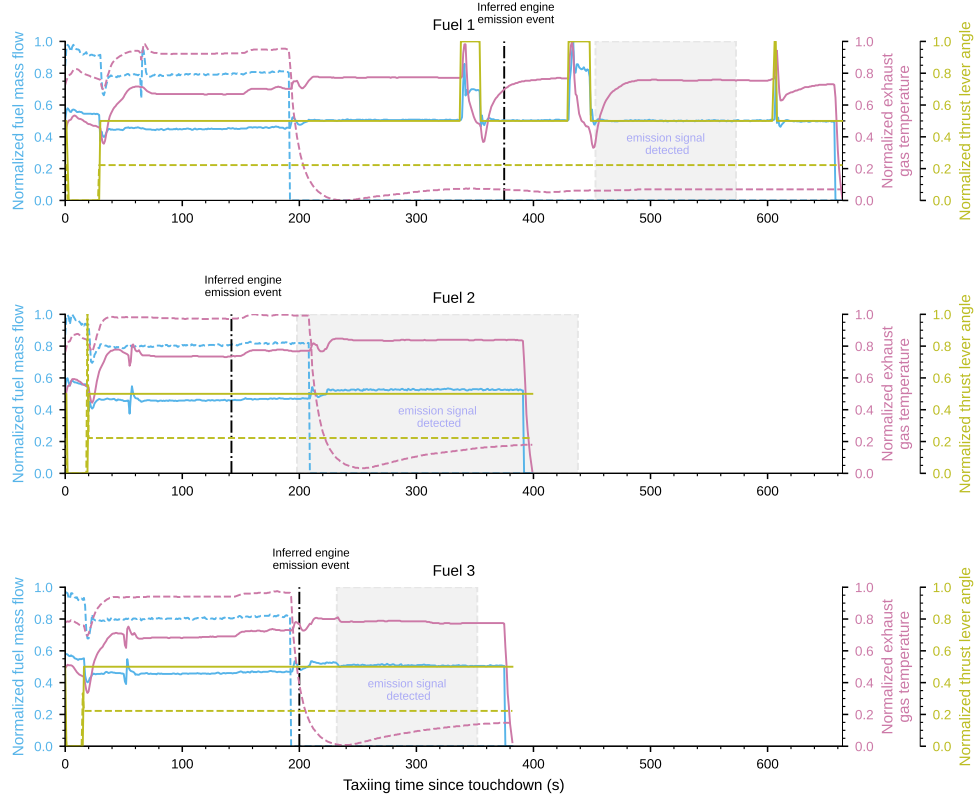


Fig. 3: Engine performance data during taxiing for emission measurements associated with Fuel 1–3 (top to bottom). Data were recorded from the flight data recorder of Aircraft 1 (see Table 2). Fuel mass flow, exhaust gas temperature, and thrust lever angle are shown for the left (solid lines) and right (dashed lines) engines; taxiing time is given relative to aircraft landing (touchdown); all quantities are normalized with respect to the minimum and maximum values across the three measurements. 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.

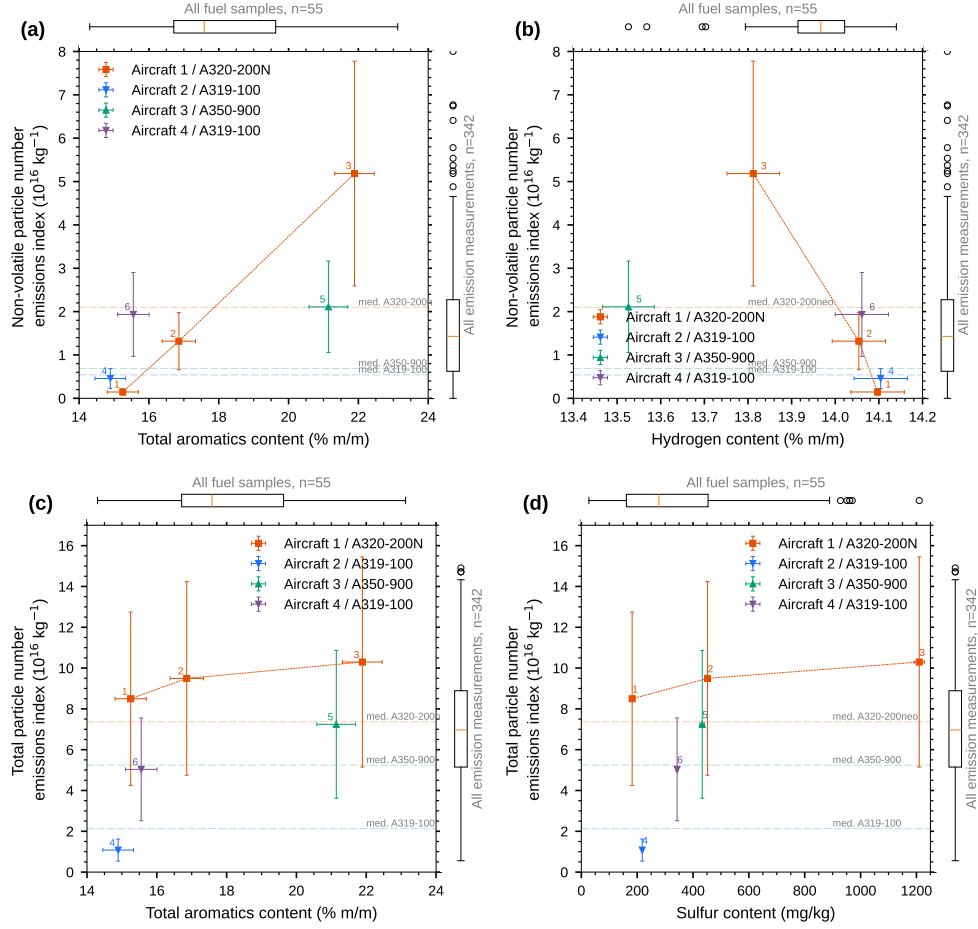


Fig. 4: Dependence of particle emission indices on fuel composition across the six selected fuel samples. (a,b) $EI_{\text{nvPM,number}}$ as a function of total aromatics and hydrogen content, respectively. (c,d) $EI_{\text{tPM,number}}$ as a function of total aromatics and sulfur content, respectively. 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. 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 relative uncertainty of the measured emission indices.

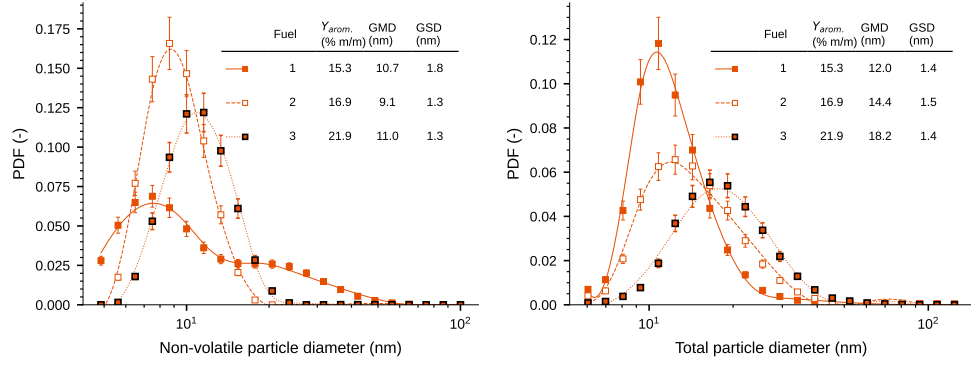


Fig. 5: Particle size distributions for three fuel samples spanning increasing aromatic content. Non-volatile (left) and total (right) particle size distributions are shown as probability density functions (PDFs), normalized to unit area, for three fuel samples measured on the same aircraft (Aircraft 1). Error bars indicate 95% confidence intervals for each size bin. Lines show spline interpolations for visual guidance. Insets summarize the geometric mean diameter (GMD) and geometric standard deviation (GSD) for each distribution.

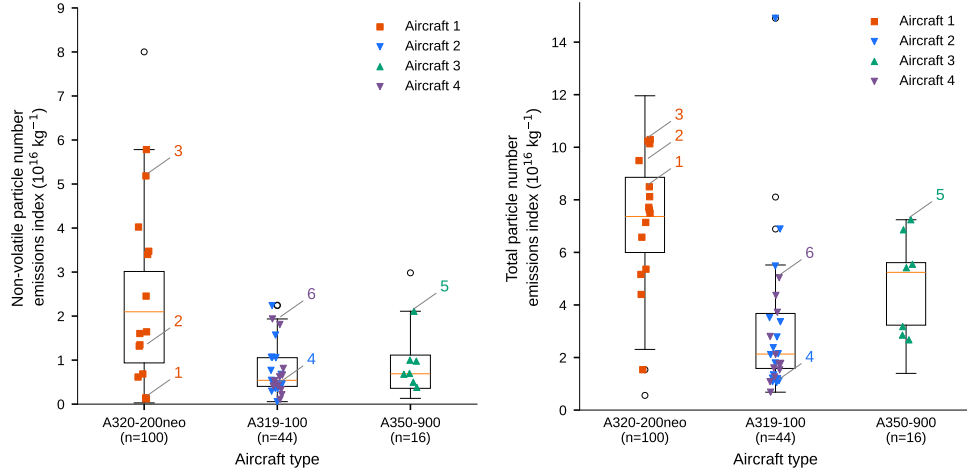


Fig. 6: Particle emission indices for three aircraft types across the full dataset. Non-volatile (left) and total (right) particle emission indices are shown for the three aircraft types (A320-200neo, A319-100, A350-900). Boxplots summarize distributions per aircraft type; boxes indicate the interquartile range (IQR), centre lines denote medians, and whiskers extend to $1.5 \times \text{IQR}$. Scatter points show measurements associated with the six selected fuel samples across the four aircraft; colours indicate individual aircraft, and numbers denote fuel samples as defined in Table 1. Boxplots include all available measurements per aircraft type (sample sizes are given in the x-axis labels).

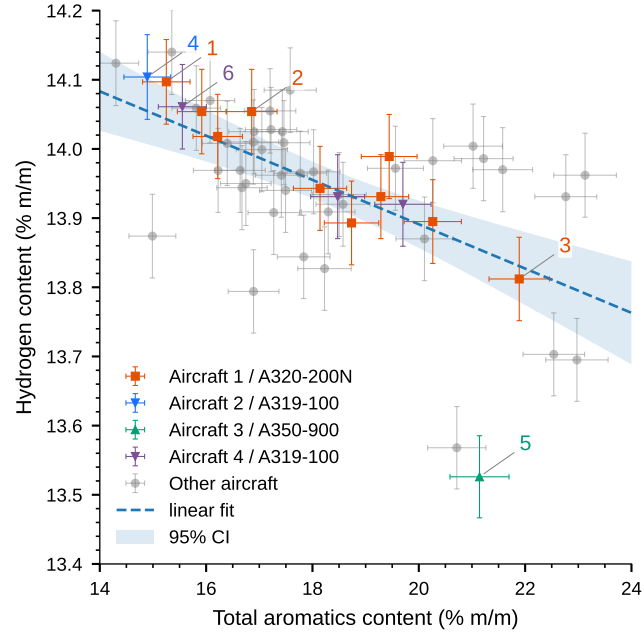


Fig. 7: Relationship between total aromatics and hydrogen content across all fuel samples. Error bars indicate 95% confidence intervals for repeatability according to the respective ASTM standards. The dashed line shows a linear fit to the data; the shaded region indicates its 95% confidence interval. The linear relationship is shown for orientation and is motivated by the ASTM D3343 [60] correlation. Coloured points highlight measurements from the four aircraft associated with the six selected fuel samples; numbers denote fuel samples as defined in Table 1 (see Table 2).

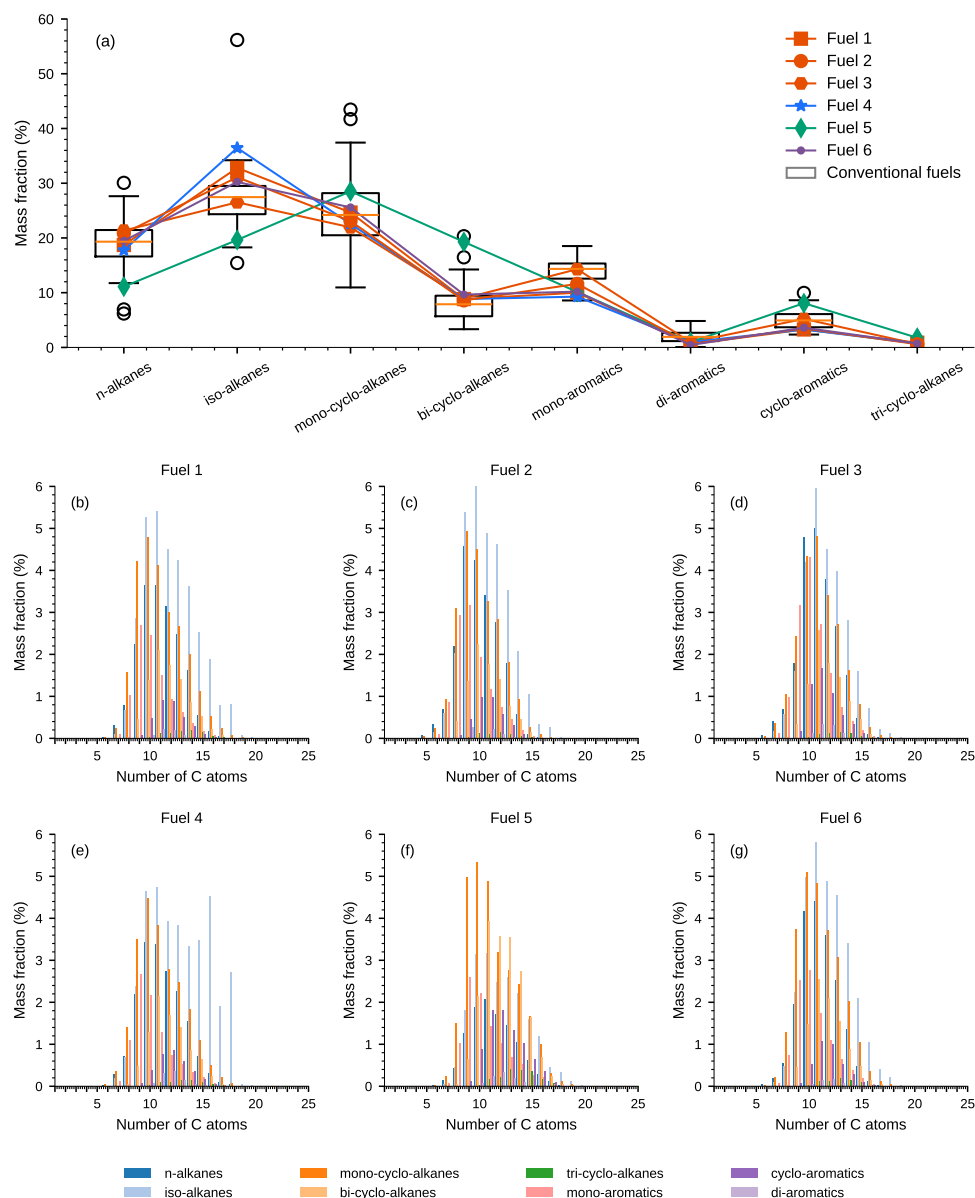


Fig. 8: Detailed chemical composition of six fuel samples from GC×GC FID/qMS analysis. (a) Mass fractions of key molecular families. Points show the six fuel samples (see Table 1); boxplots summarize data from a worldwide fuel survey (55 jet fuels) for comparison. Boxes indicate the interquartile range (IQR), centre lines denote medians, and whiskers extend to $1.5 \times$ IQR. Connecting lines are shown for visual guidance only. (b–g) Mass fractions for individual fuels as a function of carbon number. Bar colours indicate molecular families.

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Table 1: Properties of the six selected Jet A-1 fuel samples and world average Jet A-1 data.

Jet fuels	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	CRC fuel survey
Aromatics content (mass%) (ASTM D6379)	15.3 $\pm (0.9)$	16.9 $\pm (0.9)$	21.9 $\pm (1.1)$	14.9 $\pm (0.8)$	21.1 $\pm (1.1)$	15.6 $\pm (0.9)$	19.4 [12, 24]
Naphthalenes (mass%) (ASTM D6379)	0.73 $\pm (0.15)$	0.76 $\pm (0.15)$	1.08 $\pm (0.17)$	1.12 $\pm (0.18)$	1.14 $\pm (0.18)$	0.61 $\pm (0.14)$	1.2 [0.4, 2.7]
Hydrogen content (mass%) (ASTM D7171)	14.10 $\pm (0.06)$	14.05 $\pm (0.06)$	13.81 $\pm (0.06)$	14.10 $\pm (0.06)$	13.53 $\pm (0.06)$	14.06 $\pm (0.06)$	14.18 [13.88, 14.57]
Specific energy (MJ/kg) (ASTM D4809)	43.10 $\pm (0.05)$	43.38 $\pm (0.05)$	43.18 $\pm (0.05)$	43.37 $\pm (0.05)$	42.91 $\pm (0.05)$	43.45 $\pm (0.05)$	43.08 [42.92, 43.40]
Sulfur total (mg/kg) (ASTM D5453)	182.0 $\pm (2.6)$	452.0 $\pm (8.8)$	1210.0 $\pm (18.3)$	218.0 $\pm (3.2)$	433.0 $\pm (8.5)$	343.0 $\pm (5.0)$	260.0 [7.0, 2453.0]
Fuel uplift airport ^a	NCE	BCN	KEF	AMS	LAX	FLR	-

^a IATA airport codes: NCE, Nice Côte d’Azur Airport; BCN, Barcelona–El Prat Airport; KEF, Keflavik Airport; AMS, Amsterdam Airport Schiphol; LAX, Los Angeles International Airport; FLR, Florence Airport Peretola.

Table 2: Aircraft and engine types corresponding to the six selected fuel samples.

Name	Aircraft Type	Engine Type	Tailsign	Fuels
Aircraft 1	Airbus A320-200neo	CFM LEAP1A26	SE-ROB	1, 2, 3
Aircraft 2	Airbus A319-100	IAE V2522	OY-KBT	4
Aircraft 3	Airbus A350-900	RR Trent XWB-84	SE-RSC	5
Aircraft 4	Airbus A319-100	IAE V2524	OY-KBP	6

Table 3: Summary of instruments used in the DLR mobile lab during the emission measurement campaign at Copenhagen Airport.

Category	Measured quantity	Instrument
Particles	PSD ^a (6.04–523.3 nm)	TSI Engine Exhaust Particle Sizer (3090 EEPS)
Particles	Non-volatile PSD ^a (4.87–1000 nm)	Cambustion Differential Mobility Spectrometer DMS500 with Catalytic Stripper CS10
Gaseous species	CO ₂ , H ₂ O	LICOR LI-850
Gaseous species	NO, NO ₂ , NO _x	Ecophysics CLD64
Weather parameters	Wind direction/speed, humidity, temperature, dew point	Reinhardt weather station MWS55

^a PSD: particle size distribution.

Table 4: GCxGC FID/qMS operating parameters.

Parameter	Setting
Injection	0.3 μ L neat sample; split 100:1 at 300 $^{\circ}$ C
Oven Ramp 1	50–320 $^{\circ}$ C; 3.3 $^{\circ}$ C/min
Column 1	BPX50; 40 m $\times$ 0.25 mm; film: 0.25 μ m
Transfer Line Temperature	300 $^{\circ}$ C
Oven Ramp 2	40–330 $^{\circ}$ C; 3.3 $^{\circ}$ C/min
Column 2	BPX1; 3 m $\times$ 0.1 mm; film: 0.1 μ m
Carrier Gas Flow Rate	19 cm/s; constant velocity
Modulation Parameters	8 s; 0.5 s hot pulse (380 $^{\circ}$ C)
Guard Columns	MS: 0.35 m; ID: 0.15 mmFID: 0.47 m; ID: 0.2 mm
Auxiliary Pressure Splitter	40 kPa
MS Interface Temperature	300 $^{\circ}$ C
Ion Source Temperature	250 $^{\circ}$ C
Acquisition Frequency	FID (200 Hz); MS (50 Hz)

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