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Ultrafine particles and black carbon concentrations and determinants in aircraft cabins of a French airline: Paris-aircraft study

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ABSTRACT

People are spending increasing amounts of time on airplanes. Nevertheless, few studies have characterized the concentrations of ultrafine particles (UFP) and black carbon (BC) in aircraft cabins, which are particulate pollutants known to have adverse health effects. This study aims to assess indoor air quality by measuring UFP and BC concentrations in aircraft cabins during different phases of flight and identifying the key determinants influencing their levels. This study reports pollutant concentrations measured from the beginning of boarding to the end of disembarkation across 16 European commercial flights conducted on three aircraft types (A220, A319, A321). A phase-by-phase multivariate regression analysis was performed to identify the factors associated to these concentration levels. Average concentrations of 9,122 particles/cm^3 for UFP and 207 ng/m^3 for BC were observed. Ground phases showed higher concentrations than in-flight phases, with levels decreasing after take-off and increasing again during descent (UFP) and after landing (UFP and BC). The analyses of determinants revealed: (1) a decrease in UFP levels with longer cruise duration; (2) an increase in both UFP and BC levels during extended taxiing; (3) higher BC levels with a greater number of passengers; (4) specific aircraft types elevated UFP levels during climb and descent; (5) a lack of association with altitude, turbulence events, or duration of meal service. Measured levels showed much lower concentrations of these pollutants compared to other modes of transport. Cabin concentrations of UFP and BC appeared to be primarily driven by outdoor sources, particularly those related to airport ambient air pollution.

1. Introduction

Air pollution is a major risk factor for respiratory, cardiovascular and neurological diseases. According to the World Health Organization (WHO), it was estimated that in 2020, indoor air pollution was responsible for 3.2 million premature deaths (WHO 2024). Over the past four decades, numerous studies have linked both short- and long-term exposure to ambient particulate matter (PM) with increased mortality and hospital admissions from cardiovascular (Bourdrel et al. 2017; de Bont et al. 2022; Zhao et al. 2017) and respiratory diseases (Su et al. 2024). In 1998, the United States National Research Council formally recognized ultrafine particles (UFP – diameter less than 100 nm; $PM_{0,1}$) as a key research priority in the field of air pollution (ANSES - Particulate matter in ambient air, 2014). A nationwide Dutch cohort study involving 10.8 million adults followed from 2013 to 2019 had identified a significant association between UFP concentrations and all-cause mortality, as well as mortality from respiratory cancer and other specific causes (Bouma et al. 2023). Epidemiological studies provided robust evidence linking cardiopulmonary morbidity and mortality to exposure to black carbon (BC – component of $PM_{2.5}$) (Song et al. 2022). Moreover, several studies have also highlighted the impact of fine and, more specifically, ultrafine particles on neurological development and the onset of certain neurodegenerative diseases, particularly Alzheimer's and Parkinson's diseases (Calderón-Garcidueñas et Ayala 2022; Schraufnagel 2020). To date, within the European Union, UFP and BC are monitored but are not subject to any regulatory standards

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As individuals are spending approximately 90 % of their time in indoor environments, attention has traditionally focused on air quality in residential, occupational, and educational settings (Cincinelli and Martellini, 2017). More recently, attention has expanded to include air quality in transportation environments, such as subways (Aarnio et al. 2005; Cheng et al. 2009; Grana et al. 2017; Mendes et al. 2018; Bista et al. 2022; Kumar et al. 2023) and taxis (Moreno et al. 2019; Bos et al. 2021; Hachem et al. 2021; 2022).

Grana et al. have reported mean UFP concentrations of approximately 14,134 particles/cm^3 in the Rome subway. Similarly, Cheng et al. have found average concentrations of 10,600 particles/cm^3 inside train cars in the Taipei metro. Regarding BC, Aarnio et al. have measured average concentrations of 6300 ng/m^3 in Helsinki subway stations, whereas Bista et al. have reported mean levels of 1820 ng/m^3 in the breathing zones of passengers in the Paris metro. Hachem et al. have observed higher UFP levels in Lebanese taxis (35,200 particles/cm^3) than in Parisian taxis (29,700 particles/cm^3). Similarly, Bos et al. have reported mean BC concentrations of 6800 ng/m^3 in London taxis.

Although approximately 5.2 billion passengers are expected to travel on commercial flights in 2025, representing a 6.7 % increase over 1 year and marking the first time that global air passenger numbers will exceed 5 billion (IATA, 2024), few studies have investigated air quality in commercial aircraft cabins (Le 2018; Hafsat et al., 2019; Guan et al., 2019; Rivera-Rios et al. 2021; Targino et al. 2017; Williams et al., 2021). With the increasing accessibility of air travel and the growing amount of time passengers spend in transit, assessing and understanding air quality in aircraft cabins has become a major concern. Aircraft cabins represent closed environments with numerous internal emission sources such as: solvents and disinfectants used for aircraft hygiene; flame retardants present in the various materials composing the aircraft; biocides applied for vector control (Hayes et al. 2021). Indeed, indoor air quality is influenced by various pollutants, including volatile organic compounds (VOC), ozone, nitrogen dioxide, gaseous pollutants, and particulate matter (PM). Both crew members and passengers could be exposed to various pollutants. For flight attendants, this exposure represents an occupational risk, requiring careful assessment to protect their long-term health. For passengers, particularly frequent flyers, exposure to cabin air pollutants raises public health concerns. Evaluating these exposures is essential to ensure overall well-being during air travel.

Studies on cabin air quality have measured various gaseous pollutants such as ozone (Weisel et al., 2013; Bekö et al., 2015) and carbon monoxide (Zelnick et al., 2002; Hageman et al., 2024), as well as VOC (Nagda et al., 2003; Yin et al., 2022).

Only few teams studied particulate pollutants including fine particles (Cao et al., 2018), UFP (Guan et al., 2019), and BC (Targino et al. 2017). Levels of pollutants by phase of flight (at ground, climbing/descent, cruise) were poorly documented (Hafsat et al., 2019; Guan et al., 2019; Rivera-Rios et al. 2021) and have reported UFP concentrations ranging from 72 to 109pt/cm^3 during cruise, levels exceeding 38,000pt/cm^3 while parked at the gate averaged 2242pt/cm^3 during taxi-out and 1395pt/cm^3 during taxi-in, and reached mean levels of 539pt/cm^3 during climb and 264pt/cm^3 during descent. Average BC concentrations reached up to 250 ng/m^3 across all flights according to (Targino et al. 2017; Le 2018). Finally, UFP and BC remain understudied in the aircraft cabin environment.

Several determinants have been identified as potentially influencing pollutant levels in aircraft cabins. Stacey et al. have demonstrated that aircraft type and passenger load significantly affect UFP emissions at airports, suggesting a potential impact of these factors on the air quality inside aircraft cabins. Targino et al. and Guan et al. investigated BC and UFP concentrations, respectively, across different flight phases. Guan et al. also considered aircraft age and the duration of turbulence events. Other authors have examined the influence of meal service duration on both particulate and gaseous pollutant levels (Bekö et al. 2015; Hafsat et al., 2019; Rivera-Rios et al. 2021), as well as the effect of door-opening time during parking on variations in pollutant concentrations (Targino et al. 2017).

In this context, the current study (henceforth Paris-aircraft study) focuses on two particulate pollutants, UFP and BC. It aims to quantify their concentrations and to identify the factors influencing their levels by flight phase, based on measurements collected during 16 European commercial flights.

2. Materials and methods

2.1. Study design

This observational study was conducted from April 13 to May 23, 2022, on eight aircraft operated by a French airline. It consisted of measuring UFP and BC concentrations inside the aircraft cabin during 16 selected flights (corresponding to 8 rounds trips, i.e., 1 round trip per aircraft), from the beginning of boarding to the end of disembarkation. The flights departed from Charles de Gaulle Airport (CDG) in Paris to various European destinations, as well as their return flights from those European cities to CDG. The flight segments included 14 short-haul flights (0.5–3 h) and 2 medium-haul flights (3–6 h).

Flight selection was based on operational compatibility, ensuring that round trips were completed on the same day with the same crew, and that schedules aligned with runway controllers responsible for bringing the equipment. Aircraft type was not a criterion for flight selection. Additionally, the selection process accounted for the 8-hour battery life of the Miniature Diffusion Size Classifier (DiSCmini®) device, ensuring its functionality during both the outbound and return segments.

2.2. Instrumentation and measurement devices

The study employed three specialized instruments for air quality monitoring: the DiSCmini®, the microAeth®, and a Rotronic® USB-based data logger. Parameters were measured in the aircraft cabin from the time of boarding until passenger disembarkation at the end of the flight. The measurement devices were positioned according to the flight occupancy, either on an available passenger seat in the front rows or in the galley area at the front of the aircraft.

At the beginning of the measurement campaigns, these three measurement devices had been recently checked and calibrated by their respective manufacturers. Together, these instruments provided high-resolution, real-time data useful for the analysis of air quality and environmental conditions in the aircraft environment. They were also highly compatible with aeronautical constraints in a commercial environment (small size, no sound alarm, no user required).

2.2.1. Miniature diffusion size classifier (DiSCmini®)

The DiSCmini® (Testo, Switzerland) is a compact and portable device (12 × 8 × 4 cm, 0.7 kg) designed for the measurement of nanoparticle concentrations and size distributions in ambient air like UFP. It utilizes a diffusion charger to electrically charge aerosol particles, followed by two electrometer stages: the diffusion stage for smaller particles and a filter stage equipped with a high-efficiency particulate air (HEPA) filter for larger particles. This device allows simultaneous measurement of three parameters: particle number concentration (1E3 to 1E6 pt/cm^3), average particle diameter (10–300 nm), and lung-deposited surface area (μm^2/cm^3) with an accuracy of ± 30 % for size and number (Asbach et al. 2017).

The DiSCmini® features a time resolution of 1 s, with data logging set at 1-minute intervals for operational simplicity. It is declared to work effectively at pressures as low as 800 hPa. Data are stored on an SD card for subsequent analysis using a dedicated toot (DiSCmini® Data Conversion Tool version 2.0). To operate the device, users simply activate it by pressing the power button, allowing a 5-minute warm-up period, and then pressing the “REC” button to initiate data recording (Hachem et al.

2021b).

During 4 of the 16 flights, the DiSCmini® malfunctioned, resulting in a lack of UFP data for those flights.

2.2.2. MicroAeth®

The microAeth® AE-51 (Aethlabs, USA) is a pocket-sized aethalometer, real-time aerosol BC measurement device (11.7 × 6.6 × 3.8 cm, 0.25 kg). This aethalometer quantifies BC concentrations by measuring the rate of light absorption at 880 nm, resulting from continuous deposition of aerosols on a Teflon filter. The instrument offers a high temporal resolution, with the capability of 1-second measurements, and was set to record data at 1-minute intervals during the study.

One of the microAeth's key advantages lies in its low power consumption, enabling 24-hour operation on a single charge. It measures BC concentrations with a resolution of 0.001 μg BC/m3 and a precision of ± 0.1 μg BC/m3. The measurement range spans 0–1 mg BC/m3. Data are recorded onto the device and later transferred to a computer using dedicated software (microAethCOM version 2.2.4.0). To activate the device, the power button is pressed for 5 s, followed by a 1-minute warm-up, after which a flashing LED confirms the start of data recording (Hachem et al. 2021).

2.2.3. Data logger Rotronic® CP11

A USB-based data logger Rotronic® CP11 (Tekcoplus, Hong Kong) (90 g) equipped with integrated humidity and pressure sensors was employed for comfort parameters. The sensors log data at configurable intervals of 30 s or 5 min. For this study, a 30-second logging interval was chosen.

The data logger operates within a humidity range of 0.1–99 % (accuracy: ±3%), and a pressure range of 300–1100 hPa (accuracy: ±3%). It is powered by batteries and activated by pressing the start button for 5 s, after which a green LED blinking every 10 s indicates active data logging.

2.3. Determination of aircraft- and operation-related characteristics

For each flight leg, operational data, flight phase details, and aircraft characteristics were systematically collected through a standardized questionnaire. The cabin crew supervisor was tasked with documenting specific flight parameters, including start and end times of boarding and disembarkation, door closure and opening times, duration of in-flight meal service, duration of turbulence events, and location of the measurement devices and the aircraft registration number. Additional aircraft-specific information, such as the engine type of the aircraft, was retrieved from the Flight Aware database (FlightAware). The precise delineation of phase start and end times was supported by the questionnaire completed by the cabin crew supervisor. Flight records from the air traffic tracking website Flight Radar (Flightradar24) were used to define the in-flight phases. Exact take-off and landing times were cross validated with the recorded altitude data during the flight. An altitude above 29,800 feet was considered indicative of the cruise phase.

2.4. Outdoor air pollution

Ambient air pollution data at airports during relevant flight segments were collected from air quality monitoring databases located near to the respective airports. Due to the absence of specific regulations, UFP and BC were not routinely measured at standard ambient air quality monitoring stations. Given the availability of monitoring data, $PM_{2.5}$ concentrations (μg/m^3) were used as a proxy for ambient air pollution to evaluate particulate matter levels in the neighborhood of both the departure and arrival airports. For instance, for Paris-CDG Airport, the Airparif monitoring station in Tremblay-en-France was selected (Airparif, 2022). The closest monitoring stations to each airport were identified using the Aqicn.org platform. The hourly average concentration of $PM_{2.5}$ recorded by the monitoring station during the hour corresponding to the aircraft's parking at the stand was used for analysis.

2.5. Statistical analysis

A database related to the 16 sampled flights was established comprising the mean concentrations of UFP and BC over the entire flights, as well as the average concentrations of both pollutants for each individual flight phase. Means were calculated based on 12 flights for UFP and 16 flights for BC. Potential predictive determinants (independent variables) of pollutant levels in aircraft cabins were identified, based on the literature review cited previously. These determinants included aircraft- and flight-specific characteristics which were collected for all 16 flights: aircraft type, age of aircraft (months), number of passengers, average cruising altitude (feet), duration of turbulence events (minutes), duration of in-flight meal service (minutes), duration of door opening at departure and arrival (minutes). Flight phases included: parking at departure, taxi-out, climb, cruise, descent, taxi-in, parking on arrival. The parking phases included passenger boarding at departure, disembarkation upon arrival, and the duration of door opening. These phases began with passenger boarding and ended with the completion of passenger disembarkation. Given the close similarity between the durations of boarding and door opening, only the door opening variable was retained in the statistical model for boarding and disembarkation phases. The refueling of the aircraft was carried out prior to passenger boarding, which marked the beginning of the parking phase. The distributions of the pollutants were first examined by flight, and then by flight phase. Concentrations of UFP and BC were log-transformed to give data a normal distribution. A one-way analysis of variance was performed to compare mean pollutant levels across the different flight phases. Bonferroni correction was applied to identify statistically significant differences in pairwise phase comparisons. Regression models were used to identify pollutant-specific determinants across flights and flight phases for each pollutant. A stepwise ascending regression model was applied to identify variables of interest. Results from multivariate regression were presented as adjusted beta coefficients with the corresponding p-values. In a model where the dependent variable is log-transformed, a positive coefficient indicates that an increase in the independent variable is associated with a multiplicative increase in the original scale of the dependent variable. Conversely, a negative coefficient suggests a multiplicative decrease. The percentage of change in pollutant concentrations relative to each predictor was calculated using (exp(Beta) − 1) × 100 %. All statistical analyses were conducted using STATA software (version 17; StataCorp, College Station, Texas, USA). A *p*-value of <0.05 was considered indicative of statistical significance.

3. Results

3.1. Fleet and flights characteristics

The analysis includes results for UFP obtained from 12 flights operated by 6 aircraft and for BC from 16 flights operated by 8 aircraft. The characteristics of the 16 flights are detailed in the Table A1, Appendix A.

Four of the flights were domestic, heading to French cities, four were to neighboring countries, and height were to other European countries. The average flight duration was 127 min with an average flight duration of 116 min for short-haul flights and 203 min for medium-haul flights. The layover time before returning to Paris-CDG Airport varied between 30 min and 1 h. The planes flew an average distance of 1114 km and carried an average of 133 passengers. Nine of the flights experienced turbulence, lasting on average 6 min. All flights provided a catering service for a snack, with an average service duration of 24 min. The average parking time at departure, measured from the beginning of passenger boarding, was 34.6 min, while parking time on arrival until the end of passenger disembarkation took an average of 8.6 min (see

Appendix A).

Eight of the flights were conducted on the Airbus A220, four on the Airbus A319, and four on the Airbus A321. All Airbus A220 aircraft were equipped with Pratt & Whitney PW1524G-3 engines and had a passenger capacity of 148. The Airbus A319 aircraft were fitted with CFM56-5B5/3 engines and had a capacity of 143 passengers, while the Airbus A321 aircraft were equipped with CFM56-5B1/3 engines and could accommodate 212 passengers. The load factor of the flights ranged from 57 % to 98 %. All aircraft were single-aisle models. During flight, all these aircraft receive conditioned air through an environmental control system (ECS) incorporating a bleed air subsystem, which extracts air from the engine intakes and mixes it with recirculated cabin air. For 2 of the 16 flights (1 round trip), the flight questionnaire could not be fully completed by the cabin crew due to operational constraints. As a result, the duration of food services and turbulence events were not recorded during these two flights.

3.2. Comfort parameters

The average relative humidity measured inside the aircraft was 22.6 %, with a minimum of 11.6 % and a maximum of 49.7 %. The average measured pressure was 921.7 hPa, with a minimum of 778 hPa and a maximum of 1013 hPa. The cabin temperature was set between 19 °C and 23 °C across all flights. Temperatures ranged from 10 °C to 24 °C in Paris (outdoor) during the sampling period. The various European cities observed temperatures ranging from 4 °C in mid-April to 32 °C at the end of May during the final flight.

3.3. UFP and BC levels in aircraft cabins

The distribution of UFP and BC mean levels is presented in Table 1. The arithmetic means of UFP and BC concentrations in the airplane cabins were 9,122pt/cm^3 and 207 ng/m^3, respectively. The interquartile range of the mean UFP levels was 8,973pt/cm^3, while the interquartile range of the mean BC levels was 233 ng/m^3.

The distributions of UFP and BC concentrations across flight phases are shown in Fig. 1 and detailed in the Table A2, Appendix A. Overall, both pollutants followed a similar pattern: levels were highest during the initial parking and taxi-out phases, then decreased substantially during climb and cruise, reaching their lowest levels during cruise for UFP and descent for BC. Concentrations began to rise again during descent for UFP and after landing for BC and were elevated during taxi-in and final parking at arrival.

Almost 36 % of the total flight time was spent in the cruise phase. The climb phase was on average shorter than the descent phase, accounting for 9.6 % and 15.1 % of the flight time, respectively. The parking time at departure was four times longer than the parking time on arrival, accounting for about 21.7 % and 5.3 % of the flight time, respectively.

3.4. Determinants of UFP and BC concentrations inside aircraft cabins

While the multiple regression analysis does not identify any statistically significant determinants of pollutant concentrations throughout the entire flight, it does reveal several associations between specific factors and concentration levels across flight phases. The results of these multivariable regression analyses are presented in Table 2.

The duration of certain flight phases accounts for between 50 % and 70 % of the variation in pollutant levels measured during those phases. Some phase durations were associated with either an increase or a decrease in pollutant levels measured in the cabin. Levels of UFP significantly decreased ($p < 0.001$) with a longer cruise phase and increased ($p < 0.05$) with a longer descent and taxi-in phases. Regarding BC, an extended taxi-out phase was significantly associated with higher BC levels ($p < 0.01$). Each additional minute of taxi-in increased UFP levels by 22.2 %, and each additional minute of taxi-out increased BC levels by 28.3 %. Levels of UFP also increased by 14.3 % for every minute of descent.

Operating the flights on certain aircraft types was also significantly associated with variations in measured pollutant levels. Specifically, the use of Airbus A319 and A321 aircraft was associated with higher UFP levels compared to the reference Airbus A220 aircraft ($p < 0.001$).

Finally, a higher number of passengers on board was significantly associated with increased BC levels in the cabin during the cruise and descent phases ($p < 0.05$), with R^2 values of 0.40 and 0.49, respectively. During descent, each additional passenger was associated with a 1.5 % increase in BC concentrations.

The average $PM_{2.5}$ concentrations were 11.21 μg/m^3 at departure airports and 8.47 μg/m^3 in arrival airports, with values ranging from 2 μg/m^3 to 23 μg/m^3. $PM_{2.5}$ levels at both departure and arrival airports showed no significant association with UFP or BC concentrations during any flight phase.

Table 1
Distribution of mean levels of UFP in pt/cm^3 ($N = 12$) and BC in ng/m^3 ($N = 16$) by flight.

Statistical indicator	Levels of UFP (pt/cm^3)	Levels of BC (ng/m^3)
Mean	9,122	207
Median	10,239	177
Geometric mean	7,387	155
SD	5,391	158
Minimum	2,167	32
Maximum	17,704	640
25th percentile	3,681	86
75th percentile	12,654	319

SD: standard deviation

4. Discussion

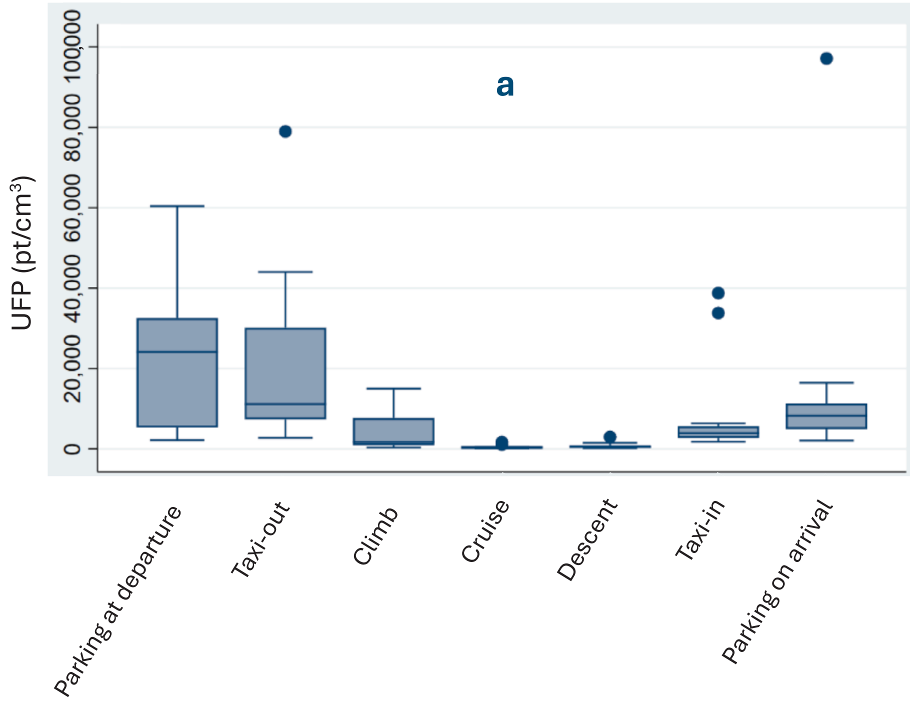
To the best of our knowledge, the current Paris-aircraft study is the first to investigate both UFP and BC using this design, which allows for the identification of level determinants. Our results showed that UFP and BC pollutant levels in commercial aircraft cabins strongly vary depending on the flight phase. They are influenced by different determinants: the number of passengers for BC, and the duration of specific flight phases and the type of aircraft operated for both pollutants.

4.1. UFP and BC concentrations

Several studies have separately investigated these pollutants in aircraft cabins. Their main findings are presented in Table 3.

In terms of concentration levels, two types of flight phases can be distinguished in our study: “ground phases” and “in-flight phases.” Higher UFP and BC levels are observed during ground phases, which tend to decrease during in-flight phases, likely due to the infiltration of more polluted outdoor air into the cabin through open doors or air conditioning systems.

Indeed, airport areas are known for their elevated pollution levels (Riley et al. 2021; Xu et al. 2020). A monitoring campaign conducted at Paris-CDG Airport in autumn 2022 by Airparif revealed that UFP levels in the airport area were comparable to those measured along the Paris ring road (Airparif, 2024). Although aircraft jet engine emissions are generally regarded as a major source of pollutants in airport environments (Xu et al. 2020; Riley et al. 2021; Owen et al. 2022), UFP and BC could also originate from the airport area itself, which is crossed by numerous combustion-engine vehicles in addition to aircraft (Targino et al. 2017). Indeed, airports rely on numerous ground support equipment (GSE) to ensure logistical operations. Airport GSE include diesel-powered passenger buses, baggage tractors, aircraft refueling trucks, catering vehicles, and ground power units (GPUs) that supply electricity to aircraft when the onboard auxiliary power units (APUs) are not operating (Schäfer et al. 2003). Emissions of UFP from these diesel-powered GSE have been reported to be up to four times higher than



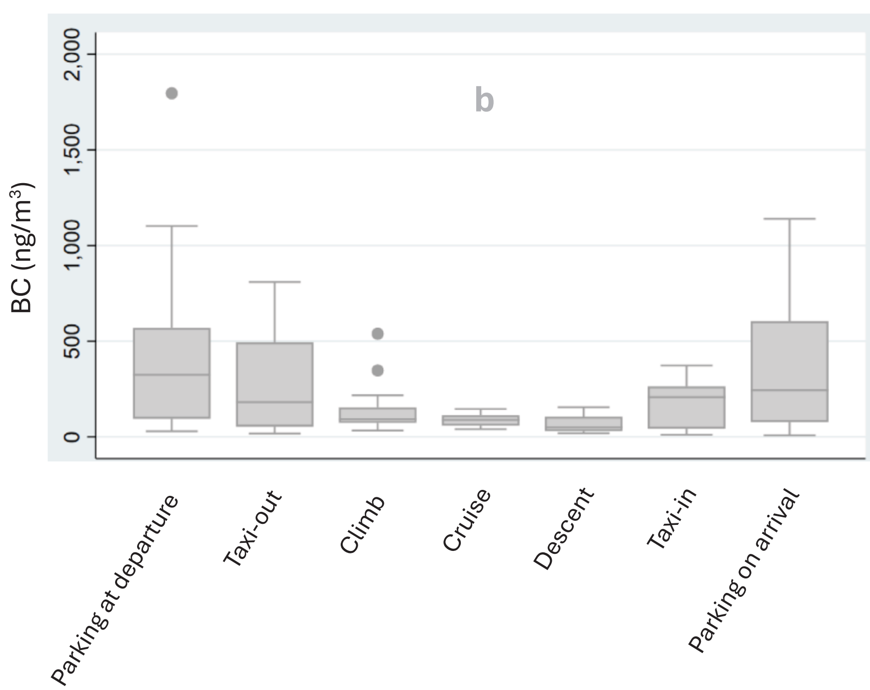


Fig. 1. Distribution of (a) ultrafine particles (UFP, in particles/cm^3; $N = 12$) and (b) black carbon (BC, in ng/m^3; $N = 16$) by flight phase, measured inside aircraft during the *UFP* Paris-aircraft study.

those from on-road trucks and buses (Targino et al. 2017). Non-combustion sources such as tire, brake, and asphalt wear, as well as resuspension due to airport operations, also increase local particulate burdens (Masiol and Harrison, 2014).

Ultrafine particles and BC are strongly associated with road traffic emissions, especially from diesel-powered vehicles (Argyropoulos 2016; Platt et al. 2017). Interestingly, UFP concentrations recorded at the end of the runway, where aircraft take off, were lower than in the central airport area, reinforcing the significance of non-engine aircraft related sources. Ultrafine particles concentrations are highly variable, influenced by wind direction and intensity as well as by the proximity of airport-related activities. Consequently, the highest levels are not

Table 2

Determinants of UFP ($N = 12$) and BC ($N = 16$) levels inside aircraft cabins from the Paris-aircraft study using multivariable linear regression analysis.

Flight phases *Determinants*	*Parking at departure*	*Taxi-out*	*Climb*	*Cruise*	*Descent*	*Taxi-in*	*Parking on arrival*	*Parking at departure*	*Taxi-out*	*Climb*	*Cruise*	*Descent*	*Taxi-in*	*Parking on arrival*
	Log UFP (pt/cm^3)							Log BC (ng/m^3)						
	Coefficient β													
$PM_{2.5}$ airport departure	x	x	x	–	–	–	–	x	x	x	–	–	–	–
Door opening duration at departure	x	x	x	–	–	–	–	x	x	x	–	–	–	–
Number of passengers	x	x	x	x	x	x	x	x	x	x	0.0076[a]	0.0145[a]	x	x
Aircraft type A220 (reference) Aircraft type A319/A321	x	x	1.7497[a]	x	1.5327[c]	x	x	x	x	x	x	x	x	−1.5899[a]
Phase duration	x	x	x	−0.0076[c]	0.1338[a]	0.2007[a]	x	x	0.2493[b]	x	x	x	x	x
Phase average altitude	–	–	x	x	x	–	–	–	–	x	x	x	–	–
Turbulence duration	–	–	x	x	x	–	–	–	–	x	x	x	–	–
Meal service duration	–	–	–	x	–	–	–	–	–	–	x	–	–	–
$PM_{2.5}$ airport arrival	–	–	–	–	x	x	x	–	–	–	–	x	x	x
Door opening duration on arrival	–	–	–	–	–	–	x	–	–	–	–	–	–	x
Coefficient of determination (R^2)			**0.45**	**0.71**	**0.71**	**0.41**			**0.50**		**0.40**	**0.49**		**0.33**

β: coefficient beta; BC: black carbon; UFP: ultrafine particles.

x: tested but not retained in the multivariable model; –: not tested for this flight phase as it was not relevant.

[a] p-value < 0.05.

[b] p-value < 0.01.

[c] p-value < 0.001.

necessarily observed directly beneath departing aircraft, as take-offs generally occur facing the wind, which disperses emissions away from the monitoring sites (Airparif, 2024). The decrease in pollutant levels during in-flight phases suggests the effectiveness of aircraft's ventilation system (environmental control system, ECS), which replaces the entire cabin air volume over 20 times per hour using approximately 60 % recirculated air and 40 % outside air drawn through the bleed air system (Anses, 2024). Airport air laden with UFP and BC is gradually replaced by cleaner high-altitude air. However, during landing, pollutant levels rose again due to the reintroduction of polluted external air via the aircraft's engines and APU.

The limited number of studies investigating UFP and BC concentrations in aircraft cabins have documented patterns analogous to those observed in our study concerning pollutant levels both at ground level and during flight. In their study conducted on 100 flights, Hafsat et al. (2019) also observed the highest UFP concentrations during ground phases, especially the immediate phase (after boarding, before engine start), with mean values ranging from 26,846 to 57,951pt/cm^3 across five aircraft types. The lowest concentrations were reported during the cruise phase, with means as low as 55pt/cm^3. A similar pattern was found in a Chinese study on 14 domestic flights, with mean in-cabin UFP levels of 417pt/cm^3, and only 72pt/cm^3 during cruise (Guan et al., 2019). Targino et al. (2017), in a study of 12 airports and 41 commercial flights in British Columbia, reported BC levels of 3.78 μg/m^3 (3780 ng/m^3) during boarding/disembarkation and 2.78 μg/m^3 (2780 ng/m^3) during gate parking with doors open. Levels dropped to 0.20 μg/m^3 (200 ng/m^3) in-flight. Closed-door ground phases showed reduced concentrations (mean = 0.20 μg/m^3, 95th percentile = 0.52 μg/m^3). In his study, Le (2018) found that BC concentrations during flights between Hanoi and Singapore were the lowest among all travel-related micro-environments, averaging 250 ng/m^3. However, levels increased slightly during boarding.

Williams et al. (2021) conducted simultaneous in-cabin and outboard UFP measurements across 12 commercial flights. Peaks were observed mostly during low-altitude phases such as approach and landing. Some matched outdoor levels, indicating infiltration; others occurred independently, suggesting internal sources possibly linked to ventilation or engine activity. However, this study did not report phase-specific average concentrations.

The levels of UFP and BC observed in our study were lower than those reported for other modes of transportation. The PUF-Taxi study (Hachem et al., 2021) reported median concentrations of 27,900pt/cm^3 and 2.9 μg/m^3 (2,900 ng/m^3) during taxi rides in Paris traffic. In our study, the highest median concentrations were 24,125pt/cm^3 and 324 ng/m^3, respectively, during parking at departure. In the Paris public transport network, BC exposure was even higher: 4.83 μg/m^3 (4,830 ng/m^3) in the subway and 3.32 μg/m^3 (3,320 ng/m^3) in suburban trains (Bista et al., 2022). Guan et al. (2019) and Rivera-Rios et al. (2021) also confirmed that in-flight air quality is generally better than in other indoor environments, such as other modes of transportation or office spaces.

4.2. *Determinants of UFP and BC*

Beyond these general observations, multivariable regression analyses have identified specific determinants affecting pollutant levels. An extended duration spent in taxiing phases appears to be responsible for the introduction of polluted outside air into the cabin via the ECS and the APU. Conversely, a prolonged cruise phase contributes to the renewal of the polluted air previously introduced into the cabin, owing to the operation of the air conditioning system. An increase in BC concentration could potentially be attributed to higher fuel consumption resulting from increased aircraft weight and the associated combustion emissions.

Our results showed the impact of taxi-out and taxi-in phase durations on the concentration of pollutants measured in the cabin. Although taxi-

Table 3
Reported mean concentrations of UFP and BC in aircraft cabins by phase in the scientific literature.

Author, year	Parking at departure	Taxi-out	Climb	Cruise	Descent	Taxi-in	Parking on arrival
	Levels of UFP (pt/cm^3)						
Paris-aircraft study	22,784	20,964	4,679	495	738	9,086	15,448
(Hafsat et al., 2019	38,666*	NA	NA	109	80	20,755	NA
(Guan et al., 2019)	NA	2,242	539	72	261	1,395	NA
(Rivera-Rios et al. 2021)				1,776			
	NA	NA	NA	104	NA	NA	NA
	Levels of BC (ng/m^3)						
Paris-aircraft study	439	267	143	89	69	171	373
				207			
(Targino et al. 2017)				200			
(Le 2018)				250			

* Parking before engine start. NA: not available.

out and taxi-in may appear to represent the same activity, as both involve aircraft taxiing, they also encompass distinct phases with different engine operations. Taxi-out includes the acceleration phase along the runway up to take-off, whereas taxi-in involves deceleration and braking after landing. Consequently, the engines are not used in the same manner during these phases (Agrawal et al. 2008). It can be hypothesized that the extreme acceleration during taxi-out may lead to increased BC emissions. Similarly, braking during taxi-in typically involves the use of thrust reversers, which redirect exhaust gases forward, further differentiating the configurations and emissions characteristics of these two phases.

Aircraft type showed inconsistent associations. Levels of UFP during climb and descent were higher in Airbus A319 and A321 aircraft compared to the newer Airbus A220. The older design and average manufacturing ages (20 and 14 years against 5 months) may contribute to this effect. However, BC levels were lower during final parking for these older models, suggesting confounding variables, such as passenger count or operational settings, may be influencing results. Moreover, additional work could be carried out to explain the influence of the number of passengers in aircraft on indoor air pollution levels. It is worth noting that BC, a product of incomplete combustion, has no known source inside the aircraft once it is airborne with the doors closed, especially on short-haul flights without onboard ovens. Nevertheless, the increase in BC following door closure supports the idea of pollutant ingress through the ventilation system, as previously reported by Targino et al. (2017).

4.3. Strengths and limitations

This study presents several strengths that enhance its scientific contribution. A key strength of the Paris-aircraft study is its rigorous standardized methodology, coupled with the extensive analysis of diverse determinants. From a methodological perspective, minute-by-minute measurements of pollutant levels allowed for a detailed analysis of pollution variation throughout the entire flight, from boarding to disembarkation. The precise recording of the different flight phases by the crew enabled an accurate association of pollutant level measurements with the corresponding flight phases. Furthermore, the limited number of studies published to date highlights the importance of this research in advancing the understanding of air quality in aircraft cabins. Despite the small sample size, which may limit the study's statistical power, some factors clearly stand out, with high coefficients of determination. These factors alone account for a substantial portion of the variation in pollutant levels.

Measurements were conducted exclusively on short- and medium-haul flights. This was due to the limited autonomy of the measuring devices, which did not allow for round trips on long-haul flights. Additionally, the exhaustive and precise collection of various data is more challenging to implement on long-haul flights. The timing of engine and APU activation for each flight could have helped identify whether the engines themselves were a significant source of cabin air contamination. Documenting the presence of jet bridges at departure and arrival could have refined the analysis of the impact of door opening duration. Unlike air stairs, jet bridges introduce terminal air, which may be cleaner than outdoor airport air. However, because the final parking phase constitutes only 5.3 % of total flight time, the available data may be insufficient to draw conclusions on this phase of the flight. The air quality monitoring stations selected for $PM_{2.5}$ data collection were chosen based on their geographical proximity to the airport. However, stations were not always located in the immediate area of airports. Some airport areas are close to downtown areas; urban road traffic may have influenced the $PM_{2.5}$ levels recorded.

Our results showed higher concentrations of particulate pollutants during ground phases compared to in-flight phases. This suggests that recommending continuous improvements in engine design to minimize emissions across all flight phases, particularly during high-thrust operations such as take-off, remains highly relevant. Likewise, enhancing bleed air systems to more effectively filter and remove cabin air pollutants could further reduce exposure for passengers and crew members during ground phases. Also, reducing particulate pollution in airport areas is recommended and involves lowering emissions from vehicles operating around aircraft in airside zones.

CRediT authorship contribution statement

Marine C. Laporte: Writing – review & editing, Writing – original draft, Formal analysis. **Jean-Ulrich Mullot:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Rita Hlal:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis. **Michel Klerlein:** Writing – review & editing, Methodology, Investigation. **Isabelle Momas:** Writing – review & editing, Validation, Supervision, Formal analysis. **Lynda Bensefa-Colas:** Writing – review & editing, Validation, Supervision, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michel KLERLEIN reports a relationship with Société Air France SA that includes: employment. Marine C. LAPORTE reports a relationship with Société Air France SA that includes: employment. Marine C. LAPORTE reports a relationship with National Association of Technical Research that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109905.

Data availability

The authors do not have permission to share data.

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