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In-flight particulate matter concentrations in commercial flights are likely lower than other indoor environments

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Abstract

Air quality in indoor environments can have significant impacts on people's health, comfort, and productivity. Particulate matter (PM; also referred to as aerosols) is an important type of air pollutant, and exposure to outdoor PM has been associated with a variety of diseases. In addition, there is increasing recognition and concern of airborne transmission of viruses, including severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), especially in indoor environments. Despite its importance, indoor PM data during the COVID-19 pandemic are scarce. In this work, we measured and compared particle number and mass concentrations in aircraft cabins during commercial flights with various indoor environments in Atlanta, GA, during July 2020, including retail stores, grocery stores, restaurants, offices, transportation, and homes. Restaurants had the highest particle number and mass concentrations, dominated by cooking emissions, while in-flight aircraft cabins had the lowest observed concentrations out of all surveyed spaces.

KEYWORDS
aircraft air quality, indoor particulate matter

1 | INTRODUCTION

Humans spend most of their time in indoor environments.[1] This makes the air quality indoors especially important for their comfort, health, and productivity. Due to the substantial amount of time spent indoors, air can be a dominant exposure route for environmental pollutants. Indoor Air Quality (IAQ) depends on many factors including environmental parameters such as temperature and relative humidity, ventilation, as well as concentrations of irritants including volatile organic compounds (VOCs), ozone, nitrogen dioxide, and particulate matter (PM).[2] Among these, the importance of PM in indoor environments has commonly been acknowledged in the context of vaping and cigarette smoke, with several studies measuring indoor particle mass concentrations before and after bans on smoking.[3–5]

Outdoors, the United States Environmental Protection Agency (US EPA) sets standards and actively regulates the mass concentrations (μg m^{-3}) of fine and coarse particles ($PM_{2.5}$ and PM_{10}, particles with diameters ≤2.5 μm and ≤10 μm, respectively). This is enforced via a PM monitoring network in outdoor locations throughout the United States.[6] The availability of PM data has enabled clear epidemiological links between outdoor PM mass concentration and human health.[7,8] While small particles account for a negligible fraction of PM mass concentration, they penetrate deeply into the lungs and can be further distributed throughout the body via circulation.[9] Thus, small particles are better quantified by number concentration

in the context of their health impacts.[10,11] Currently, PM number concentrations are not regulated; however, their importance has been recognized, particularly when considering the adverse health effects of ultrafine particles (particles with diameters ≤100 nm), which are abundant in ambient environments.[12] Indoor PM mass and number concentrations data are available, but due to the large variety and heterogeneity of indoor environments, it is often difficult to make broad assessments of IAQ outside of concerted efforts by government agencies.[13,14] Indoor sources of PM include particles emitted directly from activities such as cooking, smoking, cleaning, and/or from oxidation of VOCs followed by gas-particle partitioning.[15] Humans are also a source of particles indoors, through breathing, talking,[16] or singing,[17,18] and through shedding skin flakes.[19] In addition, incursion of ground-level ambient air can introduce PM and ozone from outdoor sources into the indoor environment, which is usually characterized in Inside/Outside (I/O) PM concentration measurements.[20,21] Ozone, either from outside or directly emitted[22] from office equipment, can initiate reactions that lead to the formation of PM indoors.[15] The use of particle filters in HVAC (heating, ventilation, and air conditioning) systems and ventilation rates also modulate indoor particle concentrations and can be a dominant removal pathway (sink) of PM.[23] Another PM sink is collision with surfaces which leads to deposition. The presence of furniture and other items in indoor environments leads to a larger surface area to volume ratio relative to outdoors, which increases the importance of deposition as a loss mechanism of PM indoors. Resuspension of dust from carpets or other surfaces can also contribute significantly to PM levels.[24,25]

Over the course of the COVID-19 pandemic, there is increasing recognition of the importance of airborne transmission of the disease.[26–31] Particles are emitted as infected individuals breathe and talk, and in larger concentrations during singing, coughing, or sneezing, where the particles can range from 0.1 to 1,000 μm in diameter.[32–35] The physical properties of particles depend on their size. Bigger particles (>100 μm; droplets) are quickly removed via deposition and have limited airtime. However, smaller particles (<100 μm; aerosols) can linger in the air for extended periods of time, allowing them to be transported away from their initial sources.[26,28,36,37] In environments below 100% relative humidity, liquid water in particles can quickly evaporate, reducing their sizes and extending the time they spend airborne.[38] These exhaled particles can accumulate in indoor environments, particularly if these spaces are densely occupied and poorly ventilated. Aircraft are well ventilated indoor environments, but are by design, densely occupied and require passengers to remain in them for a prolonged amount of time. Cases of airborne disease transmission in commercial aircraft are relatively rare but have been reported.[39–44]

The factors that contribute to aircraft cabin PM concentrations are similar to those in other indoor environments. This includes humans, human activities, deposition and resuspension from surfaces, the presence of filters, intrusion of outside air during "cabin door open" periods, and air exchange rates. Air in the aircraft is typically exchanged 10–30 times per hour (every 2–6 minutes depending on aircraft type). There are two typical aircraft designs, those that recirculate air within the cabin and those that do not. In aircraft that do recirculate air, the air supplied to the passenger cabin while in flight is a combination of fresh ambient air and recirculated air. Recirculated air is passed through a HEPA filter before being reintroduced into the cabin.[45] Aircraft that do not recirculate air (ie, 100% fresh ambient air supply) are not equipped with HEPA filters. PM measurements in aircraft during commercial flights are extremely limited. Previous studies in aircraft have mostly focused on cabin air quality after smoking bans or on cabin conditions as related to passenger comfort.[46] Guan et al. measured ultrafine particle number concentrations and found that they decreased during cruising (mean: 72 # cm^{-3}).[47] The same group measured size distributions during flights, reporting an average of 10.4, 1.4, 0.37, 0.19, 0.018, and 0.013 # cm^{-3} for particle sizes of 0.3–0.5, 0.5–1, 1–2, 2–5, 5–10, and >10 μm in diameter, respectively.[48] A few other studies measured particle mass concentrations during flights, with PM_{10} mass concentrations typically below 15 μg m^{-3}.[5,49–51] To our knowledge, no co-located measurements of particle number and mass distributions (over a wide particle size range) during all stages of a commercial flight, terminal to terminal, have been reported in the literature.

In this work, we performed particle number and mass concentration measurements during 19 domestic (U.S.A.) commercial flights. On each flight, measurements were taken during the entire trip, from terminal (departure) to terminal (arrival). To place these data into context, similar measurements were taken in a variety of indoor environments where a person might find themselves spending a significant amount of time. These environments include retail stores, grocery stores, restaurants, offices, transport (cars, buses, and trains), and homes (living rooms). These measurements were carried out in the city of Atlanta, GA, during July 2020. The data were gathered using handheld instruments described in the Methods section. It is noted that these instruments measure all airborne particles; they do not discriminate between biological particles versus nonbiological particles. The measured parameters include the number concentrations of particles with diameters ≤1 μm (PM_1), size-resolved particle number distributions from 0.3 to 25 μm, and sized-resolved particle mass concentrations (PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{15}). The data were summarized as box plots to facilitate the comparison of their distributions. The results show that PM levels in aircraft

Practical Implications

- Particulate matter (PM) concentrations were measured in a variety of indoor spaces
- In-flight aircraft had the lowest PM concentrations of all observed locations, likely due to the fast circulation and clean fresh air
- Restaurants had the largest PM concentrations, dominated by cooking

cabins, particularly while in-flight, were substantially lower than all other surveyed indoor environments.

2 | METHODS

2.1 | Instrumentation

Three handheld instruments were deployed to each location to measure particle number and particle mass concentrations. A P-Trak (TSI 8525) measures particle number concentration from 0.02 to 1 μm in aerodynamic diameter (PM_1 number concentration). Number concentrations are expressed as # cm^{-3}. Prior studies have shown that data taken with the P-Trak correlated very well with those from research-grade condensation particle counters.[52] An AeroTrak (TSI 9306) measures size-resolved particle number concentrations from 0.3 to 25 μm in diameter with ±5% accuracy. The resolved size bins are 0.3–0.5 μm, 0.5–1 μm, 1–3 μm, 3–5 μm, 5–10 μm, and 10–25 μm. The third instrument is a DustTrak (TSI 8534), which measures size-resolved particle mass concentrations with PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{15} size bins with units of μg m^{-3}. The uncertainty in DustTrak measurements is ±0.1% of the reading or 1 μg m^{-3} whichever is greater. DustTrak mass concentrations can be biased high depending on the aerosol type which we do not correct for. The time resolution for all instruments was 1 minute. The instruments were calibrated by TSI prior to the study and zeroed regularly. Data were analyzed using IGOR Pro software. The whisker box plots represent the following statistics: lower-whisker: 10th percentile, box: lower quartile, median, and upper quartile, upper-whisker: 90th percentile, solid circle: mean value.

2.2 | Sampling schedule

Three sets of handheld instruments were deployed simultaneously in Atlanta, GA, from 7/13/2020 to 7/30/2020. A total of 6 different types of indoor spaces were investigated and categorized as follows: retail stores (6 different locations), grocery stores (6), restaurants (6), office spaces (6), transport (4 private cars, 2 buses, and 2 trains), and homes (living rooms) (6). The number of locations per category is similar to other studies looking at IAQ in a variety of buildings.[21] The dates and sampling times for each individual location are given in the Supplementary Information. Grocery stores, restaurants, retail stores, and offices were sampled in sets of three (by three different researchers; each sampled at one location) at the same time of day to avoid potential differences due to occupancy or ambient environmental conditions (that could affect building intake air). The individual indoor locations were chosen based on their accessibility to the researchers and the indoor environment category. The other three locations for the same category were sampled at the same time of day the next day. This sampling method was performed twice to have duplicate measurements in all 6 locations of each of these categories. All cars were sampled in the same hour window, on consecutive days, while driving the same route (each car had its own route). Further, sampling in cars was carried out with the same conditions: riders were wearing masks, windows were up, and air conditioning was on, with air recirculation off. Buses and trains were measured in the same hour window, but on different routes. The instruments were placed in backpacks or bags, using lines of conductive tubing to sample the air in each location. Researchers moved within the sampled indoor locations as any other visitor would. The instruments remained in the backpacks or bags, but these were sometimes placed in more convenient locations, such as across the table while inside the restaurants. We aimed for at least 30 minutes of sampling at each location. Sampling in offices and homes lasted for 3 hours; however, to be consistent with the other indoor spaces, only the first 30 minutes of office data and first hour of home data were reported in this study, the first 30 minutes may or may not include cooking events in homes. The sampling in buses and trains lasted as long as the ride allowed, ranging from 16 to 30 min.

2.3 | Data acquired during flights

Delta employees deployed a set of the instruments described above in a total of 23 trips from 7/21/2020 to 7/31/2020. The Georgia Institute of Technology team trained Delta employees by providing step-by-step sampling instructions, as well as virtual meetings and in-person guidance, on how to properly operate, troubleshoot, and extract data from the instruments. Flights were chosen to cover a range of flight durations/destinations and aircraft models. Due to instrument issues on some of the trips, only the data from 19 flights were analyzed in this work. Instrument issues included batteries running out of power, tilted instrument / low alcohol warning (P-Trak), which resulted in loss of data (data not being logged). Table 1 contains relevant information for the 19 analyzed flights.

3 | RESULTS AND DISCUSSION

3.1 | Sampling in aircraft cabins during commercial flights

A total of 19 flights were analyzed for our comparison (Table 1). A detailed description of the sampling and instrumentation is provided in the Methods section. All 9 stages of travel were measured: Terminal (departure), Boarding, Taxiing (out), Climbing, Cruising, Descending, Taxiing (in), Deplaning, and Terminal (arrival). Figure 1 shows the PM_1 number concentrations, $PM_{0.3–25}$ number concentrations, and PM_{15} mass concentrations during all travel stages. The data shown in Figure 1 were averaged data from all 19 flights. Figure S1 A-F shows the same data for all individual flights. The particle number and mass concentrations varied widely across the different stages of travel. In general, they all exhibited a V-shape pattern, with the lowest concentrations observed while cruising, having a mean PM_1 number concentration of 104 # cm^{-3}, $PM_{0.3–25}$ number concentration of

TABLE 1 Commercial flights where measurements were conducted.

Tail number	Date	Leg	Aircraft type	Age of aircraft (y)	Air supply[†]	Aircraft capacity	Aircraft load
696	7/24/2020	ATL-SLC	757–200	21.5	F + R	199	106
3702	7/24/2020	SLC-PDX	737–800	22	F + R	160	79
276	7/25/2020	PDX-SEA	ERJ 175–100	-	F + R	70	28
3841	7/26/2020	SEA-ATL	737–900	5	F + R	180	93
8970	7/30/2020	ATL-AEX	CRJ-200	-	F	50	20
		AEX-ATL		-		50	25
9513	7/30/2020	ATL-CHS	717–100	20	F	110	52
	7/31/2020	CHS-ATL				110	45
8110	7/24/2020	ATL-ORD	A220-100	1.4	F + R	109	63
		ORD-LGA				109	50
3084	7/30/2020	ATL-JFK	A321-200	4	F + R	191	43
		JFK-ATL				185	109
9573	7/23/2020	ATL-MKE	717–100	19.9	F	110	47
3017	7/22/2020	ATL-LGA	A321-200	3.5	F + R	191	59
8242	7/23/2020	LGA-CLT	ERJ 175–200	-	-	76	22
9547	7/23/2020	CLT-ATL	717–100	18	F	110	59
9337	7/21/2020	ATL-XNA	CRJ-900	-	F + R	76	39
		XNA-ATL		-		76	29
3608	7/30/2020	ATL-EYW	737–700	11	F + R	124	57

[†]F + R corresponds to Fresh ambient air + Recirculated air (HEPA filtered); F corresponds to 100% Fresh ambient air.

0.44 # cm^{-3}, and PM_{15} mass concentration of 13 μg m^{-3}. As seen in Figure 1A and B, the number concentration of PM_1 is two to three orders higher than $PM_{0.3–25}$ for every travel stage. Since the PM_1 number concentration measurement includes particles smaller than 0.3 μm in diameter, this indicates that most of the particles have diameters below 0.3 μm. For most of our PM measurements, the observed medians tend to be lower than the means. This is due to short spikes in PM concentrations, outliers, or different behaviors between locations within the same type of indoor spaces.

Terminals are complex environments which can feature retail stores, restaurants, and large numbers of passengers. As such, particle concentrations will depend on what part of the terminal is being measured. For example, a large spike in PM number concentration (up to PM_1: 130,566 # cm^{-3}, $PM_{0.3-25}$: 810 # cm^{-3}) and mass concentration (PM_{15}: 342 μg m^{-3}) was observed near a restaurant in the Atlanta terminal prior to boarding the ATL-ORD (Atlanta-Chicago O'Hare) flight (Figure S2A). Typically, both number and mass concentrations were elevated during the boarding process. Particle concentrations began decreasing after the cabin door was closed and the plane took off, owing to aircraft Environmental Control Systems (ECS) packs and Auxiliary Power Unit (APU) operation. PM concentrations continued decreasing and reached a stable minimum concentration during cruising. Slight increases in particle mass concentration during food service with corresponding increases in number concentration (Figure S2B) were occasionally observed. When the plane began descending, particle concentrations started increasing and an abrupt increase was typically observed once the cabin door was opened and the deplaning process began. This V-shape pattern has been shown previously for ultrafine particles during flights.[47,53] The increase of particle concentrations during boarding and deplaning can be due to incursions from outside the aircraft[47] and resuspension of particles from the floor as passengers find their seats or prepare to leave.[54] Air exchange rates in the cabin are rapid during flight, reducing the number of particles in the cabin significantly. In addition, ambient air at altitude contains fewer particles than air at the surface, contributing to low cruising particle number and mass concentrations and which also explains the decrease and increase observed during climbing and descending, respectively.[45]

More insights on the characteristics of particles can be obtained by examining the number and mass distributions over wide particle size ranges across all travel stages. Overall, the observed V-shape pattern is more prominent for the smaller particle size ranges (bins), which was reflected in the strong variation in particle number concentrations but relatively modest changes in mass concentrations. Figure 2A shows the measured $PM_{0.3–25}$ number distributions during all stages of travel. The number concentration in each stage is dominated by particles with 0.3–0.5 μm in diameter. Interestingly, while the number concentration of particles of all sizes varies across each travel stage, the extent of change is highly dependent on the particle size. Specifically, the size bins from 0.3 to 3 μm show a one to two orders of magnitude decrease in numbers from Terminal to Cruising stages. The size bins from 3 to 25 μm also have the same V-shape pattern, but it is attenuated significantly. This difference in behavior between small and large particles could arise from differences in

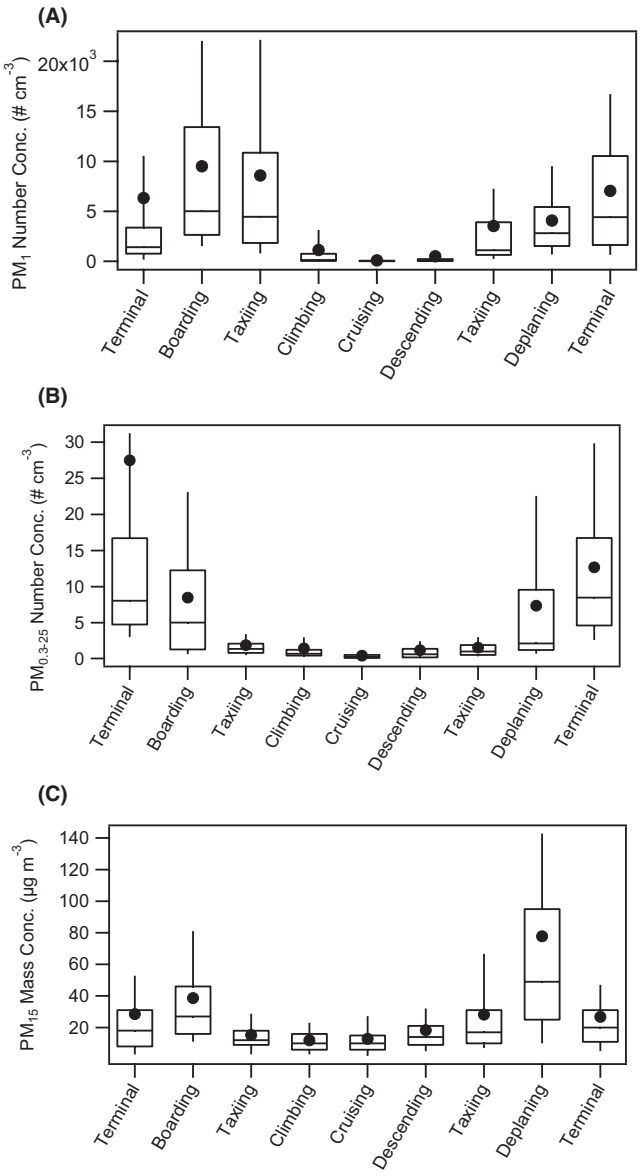

FIGURE 1 PM number and mass concentrations across flight stages (A) PM_1 number concentrations, (B) $PM_{0.3–25}$ number concentrations, and (C) PM_{15} mass concentrations during each travel stage

their sources. Small particles are likely from ambient air entering the aircraft (hence, more sensitive to altitude) while the sources of larger particles are likely from human activities within the aircraft. In terms of particle mass, large particles ($PM_{10–15}$) dominate the PM mass concentration at most travel stages, with higher contributions from small particles at the departure terminals. This is shown in Figure 2B where PM mass concentrations for different size bins within a travel stage tend to stay at the same level but show a substantial increase in the final size bin (10–15 µm). The slight variation in the number concentrations of larger particles across all stages (Figure 2A) is mirrored by the PM mass concentrations shown in Figure 2B, with the exception of the largest size bin ($PM_{10–15}$) which varied significantly. Human activities being the source of larger particles explains why the highest increase in PM mass concentration was observed during boarding/deplaning as the passengers manage their luggage and enter/exit the aircraft.

3.2 | Sampling in various indoor environments in Atlanta, GA

Six types of indoor environments were sampled: retail stores, grocery stores, restaurants, offices, transport (cars, buses, and trains), and homes (living rooms). Only a few previous studies have looked at PM in several different types of indoor environments, and most studies focused on one particular type of indoor environment.[20,21] Six different locations for each indoor environment type were studied. Transport was an exception where 4 cars, 2 trains, and 2 buses were sampled. Each location sampled is referred to by Category (eg, Restaurant, Retail, Office, etc) and a letter (A-F), such as Restaurant A, Restaurant B, etc. For the purpose of our discussion, we grouped data from all locations in each sampled indoor environment category and compared them with one another. Additional details of the sampled locations in each indoor category are provided in the Supporting Information. Indoor spaces showed large variabilities in their particle levels. Figure 3 shows (A) PM_1 number concentrations, (B) mean number distributions of particles larger than 0.3 µm, colored by size bin, and (C) mean particle mass distributions, also colored by size bins, for indoor locations grouped by category. To facilitate a comparison of the PM concentrations in aircraft to other indoor locations, all travel stages where the plane had its door closed were grouped into an "In-Flight" category. This category includes Taxiing (out), Climbing, Cruising, Descending, and Taxiing (in), and it is also shown in Figure 3.

Restaurants had the highest particle number and mass concentrations among all indoor spaces, the mean PM_1 number and PM_{15} mass concentrations were 29,400 # cm^{-3} and 50 µg m^{-3} (Figure 3A and C), respectively. A large spread in PM levels was observed across all restaurants (Figures S3 and S4). A major reason for the spread were restaurants that had separate cooking and eating areas and those that did not. Cooking aerosols are a well-known source of indoor PM which has been previously shown to lead to elevated PM concentrations, sometimes well above outdoor regulatory standards for $PM_{2.5}$ mass concentration (ie, 35 µg m^{-3} for 24-hour standard).[55,56] Cooking in the same space as the seating area (Restaurants C and D) allows cooking aerosols to mix freely within the restaurant, leading to enhanced particle concentrations in the seating area.[57] Notably, the mean PM_1 number and mass concentrations were as high as 91,392 # cm^{-3} and 109 µg m^{-3} in these restaurants, respectively. On the other hand, restaurants that had separate kitchen areas (Restaurants A and B) exhibited low mean PM_1 levels (16 and 17 μm^{-3}). Interestingly, although all the major enhancements in PM mass that are due to cooking appear to be in the PM_1 size bin, the cooking method and type of food also influence the size distributions of cooking aerosols in larger size bins. PM_1 is almost always enhanced during cooking but PM_{10} can also be affected.[58,59] For instance, PM mass in

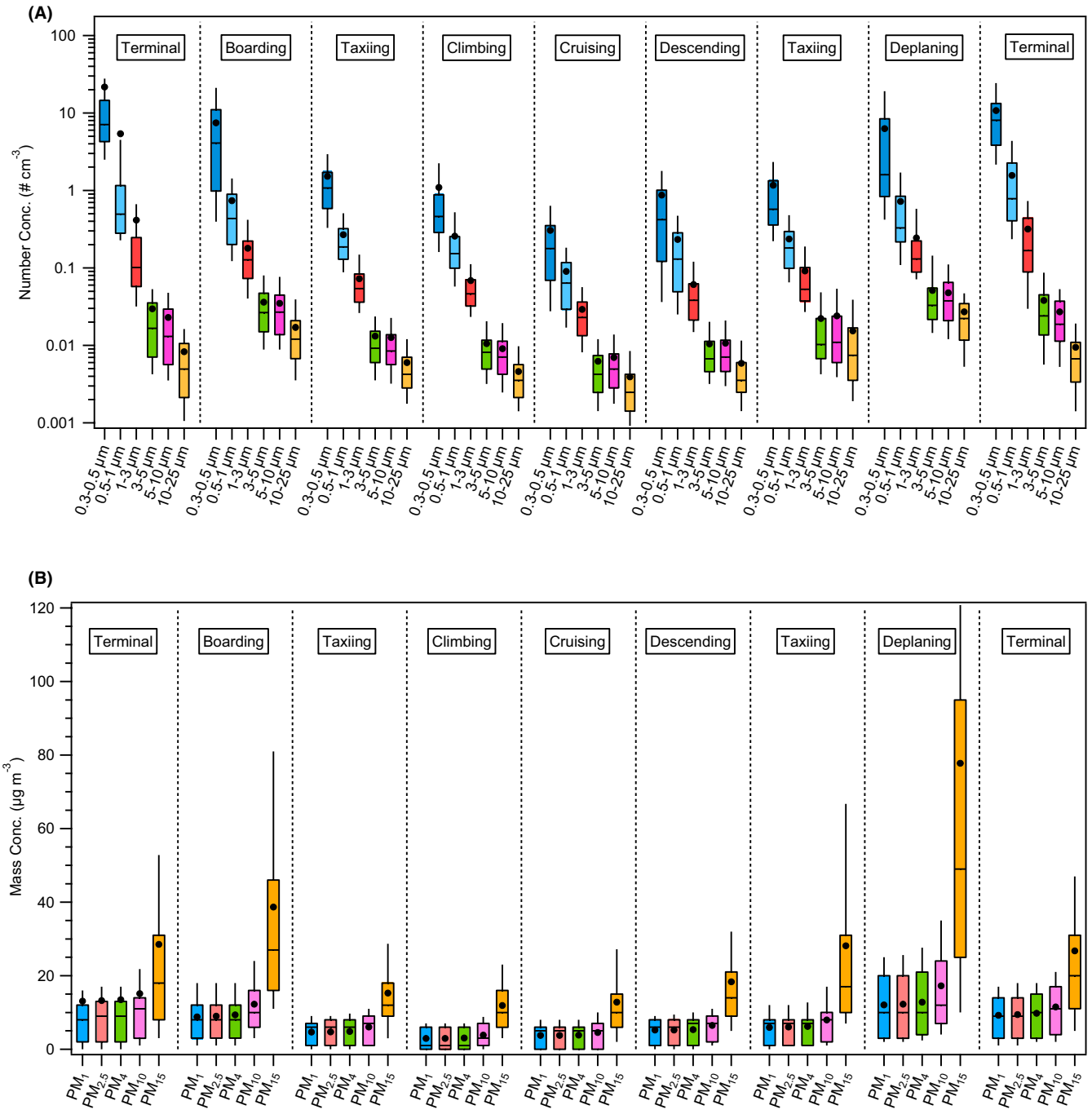

FIGURE 2 Size-resolved particle number and mass concentrations during each travel stage. (A) Number distribution of particles with diameters from 0.3 to 25 µm and (B) Mass distribution of particles with diameters ≤15 µm. Note that the mass concentration data shown in (B) are cumulative, where PM_x corresponds to mass concentration of particles with diameters ≤x µm

Restaurant D is dominated by PM_1 but has modest enhancements in PM mass in every size bin which could also be due to cooking (Figure S4). Restaurants E and F have minimal cooking (ie, salad bar or sushi) and lower particle concentrations were observed (mean PM_1 number and mass concentrations of 8,685 # cm^{-3} and 10 µg m^{-3} for Restaurant E). Taken together, the differences in kitchen/seating area configuration, cooking method, and food type are key contributors to the large spread of particle number and mass concentrations across all restaurants.

Homes were also influenced by cooking and follow restaurants in terms of PM number and mass concentrations (Figure 3 and Figures S5 and S6). All measurements were conducted in living rooms, but if living rooms and kitchens are connected, cooking activities can enhance PM concentrations in both areas.[60] Some sampled homes in this study had cooking activities (Homes B, D, and E; all living rooms in this study shared the same open space as the kitchens) and some did not (Homes A, C, and F). The spread in PM levels measured in homes was related to cooking activities within the houses.

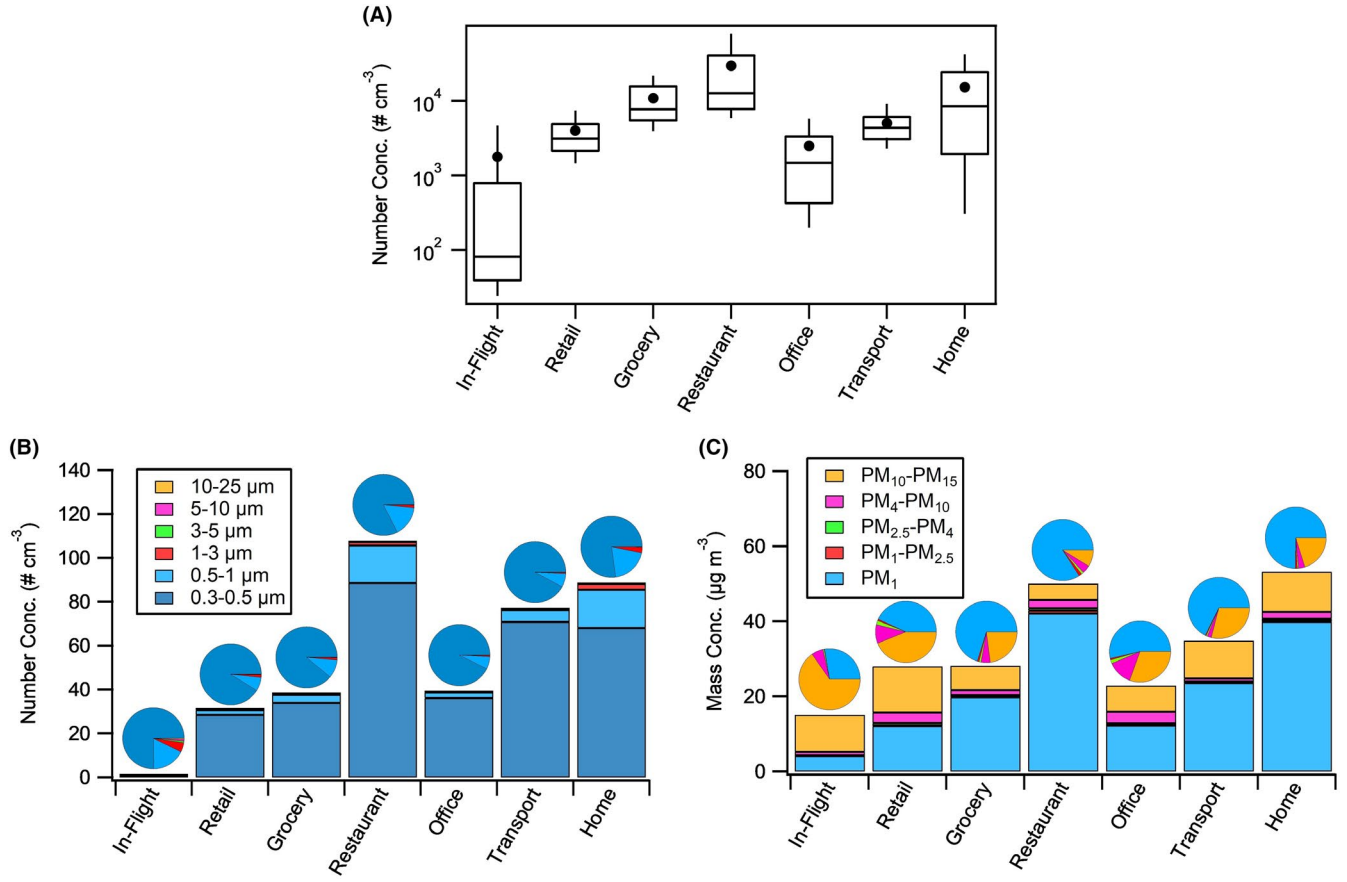

FIGURE 3 Comparison between in-flight aircraft data and other indoor spaces around Atlanta, GA. (A) PM_1 number concentration measurements (mean values). (B) $PM_{0.3\text{-}25}$ number distributions (mean values), colored by the contribution per size bin. (C) PM_{15} mass distributions (mean values), colored by the contribution per size bin. The pie charts above the bar show the fractional contribution of each size bin to the total measured particle number and mass concentrations. Data for particles with similar size ranges in (B) and (C) are shaded in similar colors

For example, a house with (Home B) and without cooking (Home A) had mean PM_1 mass concentrations of 166 and 6.53 µg m^{-3}, respectively. Figure S7 clearly shows that the particle number and mass concentrations in Home E were low before cooking but rose significantly during and after cooking. Elevated levels of PM from home cooking have been measured in previous studies, with the amount of aerosols and their chemical composition depending on the type of food and method of cooking.[55,57,58,60–62]

There were elevated levels of PM in grocery stores with cooking activities (Figures S8 and S9). Cooking in grocery stores was carried out in deli areas (Stores A, C, D, and E), leading to elevated particle concentrations compared to others. The amount of cooking in these grocery stores depends on the customer demand for the items at the deli which can explain why Store D displayed the highest levels observed, with mean PM_1 number and mass concentrations of 21,805 # cm^{-3} and 40.3 µg m^{-3}, respectively. However, since grocery stores were typically much larger than restaurants and homes, cooking aerosols were more diluted and PM concentrations did not reach the same levels that were observed in homes and restaurants. In addition to cooking sources, contributions from outside the location cannot be disregarded. Grocery stores in Midtown, Atlanta (Stores A and D), had the highest PM_1 number concentrations (17,165 and 21,805 # cm^{-3}). These PM_1 number concentrations are likely due to cooking, but since these two stores are located relatively close to each other, incursion of aerosols from nearby traffic, construction work, or secondary organic aerosols in the Midtown area cannot be ruled out.[63,64] Measurements of particle composition would be needed to separate the contributions from these sources.

Transport, including cars, buses, and trains, featured higher PM_1 number concentrations than offices and retail stores, but lower than locations that had cooking activities (Figure 3A). Cars showed substantial variability between each other, which could be due to the presence and condition of air filters, the age of the vehicle, or the route taken during sampling (Figures S10 and S11). Two of the highest particle measurements in cars (Cars C and D, mean PM_1 number concentration 5,979 and 7,214 # cm^{-3}) were in relatively old vehicles, 2010 and 2002 models with the second having a significant amount of PM_{15} (mean: 68 µg m^{-3}). Trains and buses had similar and relatively constant concentrations over the course of the measurements. This could be due to their doors opening/closing constantly and quick air circulation. For these reasons, the PM concentrations in trains and buses were likely more representative of a mixture of the air inside and outside the vehicles. Traffic conditions, ambient PM levels, and localized PM sources can all affect the concentrations

measured in a vehicle.[65] PM concentrations near roads are usually enhanced relative to other nearby locations in the urban area.[66] A study in Atlanta showed an urban background $PM_{2.5}$ concentration of 8 μg m^{-3} but roadside concentrations of 21 μg m^{-3}, an enhancement of a factor of ~3.[67] Overall, our Transport $PM_{2.5}$ concentrations (mean: 24 μg m^{-3}) are in line with previous roadside measurements and the $PM_{2.5}$ concentrations in vehicles (16 and 25 μg m^{-3} in the warm and cold seasons) reported by Brown et al. in Atlanta.[65]

Finally, offices and retail stores (with some exceptions) were some of the cleanest indoor environments measured excluding in-flight aircraft (Figures 3A, S12–S15). Offices did show variability, with some being enhanced in small particles (Office C, mean PM_1: 32 μg m^{-3}) and others in large particles (Office E, mean PM_{15}: 48 μg m^{-3}). All offices were in different buildings in the Georgia Institute of Technology campus. It is possible that the low PM levels observed in these offices are due to their low occupancy from limited campus access forced by the COVID-19 pandemic. The reason for the elevated PM_1 concentrations in Office C could be due to reactions between VOCs released from the building materials (mostly wood) and ozone incursions, which are well-established sources of secondary organic aerosols.[36] The retail category was the second cleanest, following offices, but had some outliers. One of the outliers was Retail F, a home improvement store, which featured high mean PM_{15} concentrations (70.8 μg m^{-3}). This could be due to woodcutting and other mechanical/abrasive activities that release dust particles in this store type. The other outlier was Retail E, a pharmacy that also had a high mean PM_{15} concentrations of 38.6 μg m^{-3}. Retail E is a carpeted location, and resuspension of dust from the floor could lead to the observed PM_{15} concentrations.[24] Dust particles are larger than cooking or secondary organic aerosols, so they are observed as an enhancement in the $PM_{10\text{-}15}$ size bin. The high $PM_{10–15}$ contributions from Retails E and F enhance the mean PM mass shown in Figure 3C for the retail category.

3.3 | Comparison between in-flight and other indoor environments

Figure 3 shows the measured PM number concentrations and mass concentrations in various size bins while in-flight and in other indoor spaces. The PM_1 number concentrations in Figure 3A are 60–274 times higher than the $PM_{0.3–25}$ number concentrations in Figure 3B, highlighting that particles smaller than 0.3 μm dominate the number size distributions in all spaces, with particles between 0.3–0.5 μm being the next most abundant. When compared to other spaces, the in-flight particle number and mass concentrations are substantially lower. Specifically, the mean PM_1 number concentration during the in-flight period was 1,776 # cm^{-3}, 1.4 times lower than the next lowest mean value (2,473 # cm^{-3} for offices, Figure 3A). It is noted that the mean in-flight PM_1 number concentration is affected by some higher concentrations during taxiing periods. The corresponding median for the in-flight period is much lower at 81 # cm^{-3} which is 18 times lower than the median for offices (1,462 # cm^{-3}). The mean in-flight $PM_{0.3–25}$ number concentration was 0.54 # cm^{-3}, 49 times lower than offices (Figure 3B). The mean in-flight particle number concentrations were low across all size bins in general but comparable to other locations in the >3 μm size bins (0.3–0.5 μm: 0.8 # cm^{-3}, 0.5–1 μm: 0.19 # cm^{-3}, 1–3 μm: 0.05 # cm^{-3}, 3–5 μm: 0.01 # cm^{-3}, 5–10 μm: 0.01 # cm^{-3}, and 10–25 μm: 0.006 # cm^{-3}, Figure S16). The pie charts in Figure 3B also highlight that although small particles dominate particle numbers in all categories, larger particles (>1 μm) contribute about 7% of the total particles in the in-flight category, more than any other indoor environment. Interestingly, the in-flight particle number concentrations measured in this study were 2–10 times lower than the only other published in-flight size distribution found in the literature.[48] This could be due to the lower passenger loads (Table 1) and the use of masks by everyone on board as required by the airline, which filters out and reduces the number of exhaled particles released into the surrounding environment.

The particle mass concentrations in-flight are also lower than other indoor spaces, though the difference is not as drastic as for number concentrations. The mass concentration of $PM_{2.5}$ and PM_{10} in the cabin was below 10 μg m^{-3} (mean = 4.3 and 5.2 μg m^{-3}, respectively), about 3 times lower than offices. While EPA does not set PM standards for indoor air, these values are substantially lower than the EPA standards for outdoor air (24-hour standards for $PM_{2.5}$ and PM_{10} are 35 and 150 μg m^{-3}, respectively).[68] A few studies have reported PM_{10} mass concentration in flights, which ranged from 1 to 17 μg m^{-3} and is consistent with our results.[5,46,49,69] It is noted that while the in-flight category had the lowest measured mean PM_{10} mass concentration, the median PM_{15} in-flight (11 μg m^{-3}) was similar to retail stores and offices (both 15 μg m^{-3}) but lower than other indoor spaces (23–31 μg m^{-3}) (Figure S16). This is likely due to the high concentrations observed during the taxiing periods. $PM_{10–15}$ contributes 65% of the total PM mass for the in-flight category. This mass distribution is unique, as highlighted by the pie charts in Figure 3C where in-flight had the largest contribution from particles >10 μm in diameter to the overall particle mass, likely arising from human activities and the carpeted floor in the cabin acting as sources of dust particles. The only other indoor category with a large contribution of $PM_{10–15}$ are retail spaces, which are driven by Retails E (pharmacy; particle resuspension from carpeted floor) and F (home improvement store; dust particles). On the opposite end of the spectrum, restaurants and homes had the highest mean PM concentrations. PM_1 from cooking emissions dominated these categories, contributing over 75% of the total PM mass.

4 | CONCLUSION

In this work, we conducted the first simultaneous measurements of size-resolved particle number and mass concentrations in commercial flights, from terminal to terminal, and compared them to a variety of other indoor environments. Our main finding is that in-flight particle number and mass concentrations in aircraft were the lowest we measured in any of the surveyed indoor environments.

Particles with diameters smaller than 1 μm dominate the total particle number concentrations, which is consistent with the fact they are the most difficult to remove by physical filtration.[70] The low in-flight PM concentrations can be attributed to the frequent air exchange in cabins and low particle numbers outside the aircraft at altitude. Notably, the PM number concentrations measured in this work were up to an order of magnitude lower than results reported in the only other previously published study,[48] possibly due to lower passenger loads and the use of masks, which were required for all passengers by the airline during this period.

There are several limitations in this study. The instruments used, although useful due to their mobile nature, lack any information on particle composition or type. This is important when trying to differentiate between aerosol types, such as cooking aerosols, secondary organic aerosol, or direct emissions from the passengers in the aircraft. In addition, the instruments operate on broad size bins that enable us to broadly characterize the size distribution of the number and mass but cannot be quantitatively compared against each other. Finally, the particle composition could potentially influence the sensitivity of the instruments making comparisons between different environment types more challenging.

The measurements in this work alone cannot be used directly to assess the cabin air safety of commercial flights during the COVID-19 pandemic. However, it provides the particle number and mass concentration distributions needed to assess the PM levels in flights during this period. Results show that the air in aircraft cabins had substantially lower PM levels than other indoor environments, highlighting the role of frequent air exchange and clean air supply (clean outside air and/or HEPA-filtered recirculated air) in reducing particle concentration in indoor environments. Though these measurements are an important step in risk mitigation, further studies to assess the safety of air travel should include direct measurements of viral loads in aircraft cabins and tracing the movement of particles within the cabins.

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AUTHOR CONTRIBUTION

Jean C. Rivera-Rios involved in data curation, formal analysis, methodology, investigation, visualization, writing—original draft, writing—review, and editing. Taekyu Joo and Masayuki Takeuchi involved in data curation, formal analysis, methodology, investigation, and visualization. Thomas M. Orlando, John W. Mathis, Cliffton D. Pert, Brandon A. Tyson, Tyler M. Anderson-Lennert, and Joshua A. Smith performed investigation. Tracy Bevington involved in investigation, project administration, and resources. Nga Lee Ng performed conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, supervision, visualization, writing—original draft, writing—review, and editing.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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