In-Flight/Onboard Monitoring: ACER's Component for ASHRAE 1262, Part 2

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16. Abstract

Environmental monitoring was conducted in the passenger cabin of 83 commercial flights (3 additional flights as a part of the Onboard Pressure Study). Six aircraft models (2 Airbus and 4 Boeing), flying U.S. domestic and international routes, were monitored for environmental conditions and air quality, including carbon monoxide, carbon dioxide, particles, ozone, volatile organic compounds (VOCs), semi-VOCs, carbonyls, and tricresyl phosphate. Except for low pressure, occasionally high ozone, extremely dry air and perhaps slightly higher noise levels, the air quality and environmental conditions in the passenger cabin of commercial airplanes are comparable or better than conditions reported for offices, schools and residences, with a few exceptions. While most environmental conditions met minimum standards, some exceptions were noted, one being the presence of carbonyls (formed in ozone reactions). These and other aldehydes are recognized irritants, and together with dry air may contribute to dry eye symptoms and fatigue. Concentrations of these ozone-reaction by-products increased with increased ozone levels and with reduced ventilation rates. Ventilation rates on high-passenger load flights can be below the required 3.5 Liters/second/person, as indicated by higher carbon dioxide levels. Some passenger-related VOCs and aldehydes were higher for flights with decreased ventilation rates. Cabin pressure was in compliance with Federal Aviation Regulations (FARs), with all flights operating below 8,000 feet. Cabin noise levels could exceed the NIOSH-recommended level of 85 dB (8-hour time-weighted average) but only for a short period of time, but were below the Department of Transportation and OSHA (90 dB) workplace limits.

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IN-FLIGHT/ONBOARD MONITORING: ACER'S COMPONENT FOR ASHRAE 1261, PART 2

INTRODUCTION

Air quality standards for the aircraft cabin conditions were set decades ago and vary by country. In the United States, the airline industry is regulated by the Federal Aviation Agency (FAA). The FAA has established Federal Aviation Regulations (FARs) to govern the operational requirements for commercial aircraft. Currently the FARs address only a few cabin environmental parameters that might affect safety aspects of crew performance, and to a lesser extent, might protect passengers from adverse health effects and discomfort (pressure, ventilation, ozone, carbon dioxide, carbon monoxide). As noted in the 2002 National Research Council report (NRC 2002), established FARs may be inadequate to protect the health of some members of the flying public. There are design performance standards for environmental control systems in aircraft cabins but U.S. airline companies are not required to certify compliance through routine direct monitoring or audits. Further, ASHRAE has issued ANSI/ASHRAE Standard 161-2007 for air quality within commercial aircraft (ASHRAE 2007). The ASHRAE standards include the FAA Federal Aviation Regulations (FARs) (FAA 2011) and also address temperature and ventilation in different areas of the aircraft cabin, as well as bleed air contaminants.

This report examines environmental conditions and cabin air contaminants measured on 83 aircraft, across three different airlines, operating eight airplane models (B737-300, B737-700, B737-800, A340, A380, B747, B767 and B777), and compares these conditions and contaminants to existing standards as well as other indoor environments.

METHODS

The cabin air of 83 flights was monitored between February 2008 and August 2010 as a component of a FAA/ASHRAE study of onboard environmental conditions and passenger and crew responses. These flights were on three different airlines: airline A (20 flights), airline B (39 flights), and airline C (24 flights). The air contaminants measured included ozone (O_3), carbon dioxide (CO_2), carbon monoxide (CO), ultrafine particles (UFP), particle matter ≤ 2.5 µm ($PM_{2.5}$), volatile and semi-volatile organic compounds (VOCs and SVOCs), aldehydes, and tricresyl phosphate (TCP) isomers. Environmental parameters measured included relative humidity (RH), cabin pressure (P), temperature (T), and cabin sound levels (dB(A)); operative temperature ,which is derived from dry bulb, wet bulb and radiant temperatures, was not measured. Monitors were located either in an aisle seat or a middle seat and it was assumed that operative temperature equaled the air temperature.

Also collected from the airline during flight was information about flight characteristics, including flight duration, flight departure time, aircraft model, flight date and season, aircraft capacity and occupancy loads. For flights across the continental U. S., minute-by-minute latitude and longitude were obtained from http://flightaware.com/.

Exposure assessment was conducted by a project engineer onboard the aircraft. Measurements were recorded continuously, at one-minute intervals, from 10,000 feet ascent through 10,000 feet descent. In addition, TCP isomers, VOCs, SVOCs, and aldehydes were collected via integrated samplers. For each analysis batch, for all analytes except for the VOC canisters in airline A, at least five duplicates and five blanks were included to estimate the signal-to-noise ratios. Sensors and samplers were situated in the middle of the economy class. Instruments with pumps and batteries were positioned under the seat, and VOCs and aldehydes samplers were placed at the back of the seat with inlets at seat pocket height of 50 cm. All instruments used onboard were electro-magnetic interference (EMI) certified at Boeing (Everett, WA). The sensors were also tested for performance under pressure flight conditions at Battelle (Columbus, OH). In Appendix A, Table A-1 lists equipment used in this study and Appendix Table A-2 lists all the analytes/compounds measured.

The descriptive analysis was performed on the median values of the recorded continuous one-minute measurements. Also reported are the overall flight averages and the ranges of these median values. VOCs, SVOCs, TCPs and aldehydes were summed separately. A maximum hourly value was calculated for ozone for flights with a monitoring duration of 30 minutes or more, in order to compare these values with other recently proposed criteria and the hourly FAR ozone standard. Running 15-minute averages were calculated for UFPs, reported as particle number counts per cubic centimeter for particles ranging in size from 6 nm up to 0.3 μm. Latitude categorization was based on the flight path rather than the latitude of the departure and arrival cities. Each flight route was classified by the fraction of flight time north of 35°N (or south of 35°S). Flights that followed northern routes (higher latitudes) were those that had fractions higher than 0.5.

RESULTS

Flight Characteristics

Flight characteristics of the sample set are listed in Table 1. The length of the flights varied from 1 hour to more than 16 hours, with 37% of all flights classified as short-haul flights ($\leq$ 2 hours). Fifty-eight percent of all flights were at or above 75% load factor (passengers per capacity of plane). Of the total flights across all airlines, 20% operated entirely in the southern hemisphere, 19% crossed the equator, and 61% operated entirely in the northern hemisphere. About 28 flights were routes mostly north of 35°N. Only nine flights (10%) crossed more than five time zones. Table 2 lists the summary statistics for the continuous measurements of cabin contaminants (O_3, CO_2, CO and UFPs) and cabin environmental conditions (RH, P, T, and sound level).

Table 1. Flight characteristics of 83 flights with environmental measurements and surveys collected for passengers and crew.

Variables	Mean ± SD	Range	No. (%)
Model of Aircraft			**83**
• A340			2(2.41)
• A380			5(6.02)
• B737(800;300;700)			41(49.40)
• B747			10(12.05)
• B767			10(12.05)
• B777			15(18.07)
Airlines			**83**
• airline A			20(24.10)
• airline B			39(46.99)
• airline C			24(28.92)
Duration			**83**
• Short <3hrs			31 (37.35)
• Medium (3-6hrs)			35(42.17)
• Long(>6hrs)			17(20.48)
Ventilation Rate L/sec/person	**5.5 ±1.8**	**3.0-10.9**	**83***
• <5 L/sec/person			40(48%)
• >5 L/sec/person			43(52)
Season			**83**
• Winter			69(83.13)
• Summer			14(16.87)
Latitude			**83**
• Lower			50(60.24)
• Higher			33(39.76)
Time Zones Crossed			**83**
• 0-1			47(56.63)
• 2-5			27(32.53)
• >5			9(10.84)
Occupancy	**0.77±0.20**	**0.23-100**	**83**
• <75%			35(42.17)
• >75%			48 (57.83)
Flights on aircraft fitted with ozone converters			**83**
• Yes			20(24.10)
• No			63(75.90)

***Ventilation was calculated using a G(CO_2) value of 18.2 L/hr**

Table 2. Summary of continuous measurements of cabin contaminants (ozone, carbon dioxide, carbon monoxide and ultrafine particles) and cabin conditions (sound, temperature, relative humidity and pressure).

Variables	Flight Mean ±SD	Flight Min-Max	N	Standard Limits
Ozone (ppb)	16 ± 18	0-116	81	• FAA: 0.25 ppm (250 ppb) anytime above 9,800 ft; 0.1 ppm (100 ppb) TWA during any 3 h interval • ASHRAE: 0.05 ppm • OSHA PEL 0.1ppm • EPA NAAQS 0.12 ppm (1 h) and 0.08 ppm (8 hr) • ACGHIH TWA: 0.05; 0.08; 0.1 ppm (heavy, moderate and light work) • NIOSH: 0.10 ppm • WHO: 0.06 ppm for 8 h
Ozone 1 h max	27± 32	1.88-210	73	• See above listing
Carbon Dioxide (ppm)	1,404 ± 297	863-2,056	83	• FAA: 5,000 ppm • ASHRAE: 700 ppm above ambient air • OSHA PEL: 5,000 ppm • ACGHIH TWA: 500 ppm; 30,000 ppm (STEL)
Carbon Monoxide (ppm)	ND	ND	63	• FAA: 50 ppm (sea level equivalent) • ASHRAE: 9 ppm (8 h); 35 ppm (1 h) • OSHA PEL: 50 ppm • EPA NAAQS: 35 ppm (1 h); 9 ppm (8 h) • ACGHIH TWA: 25 ppm • Fuel fumes should not be present
Ultrafine Particles (p/cm^3)	616 ± 3,398	0- 24,600	56	• No Standard available*
UFP 15 min max (p/cm^3)	12,450 ± 43,605	1-312,000	55	• No Standard available*
Sound (dB(A))	74.86±1.91	68.10-76.94	82	• OSHA: 90dB (8 h) TWA; PEL (115) • NIOSH: 85 dB • DOT: 90 dB
Relative Humidity (%)	11±5	1.7- 41	83	• FAA ventilation design ~18%
Temperature (°C)	24±2.0	19 -31	83	• ASHRAE: operative temperature (18.3°C to 23.9°C) not to exceed • 26.7°C
Cabin Pressure (kPa)	80± 2.8	76-88.5	83	• FAA: 75 kPa (2,440 m)

*The *WHO Air Quality Guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide* (WHO 2006) state "Ultrafine particles (UF), i.e. particles smaller than 0.1 μm in diameter, have recently attracted significant scientific and medical attention. These are usually measured as a number concentration. While there is considerable toxicological evidence of potential detrimental effects of UF particles on human health, the existing body of epidemiological evidence is insufficient to reach a conclusion on the exposure–response relationship of UF particles. Therefore no recommendations can be provided as to guideline concentrations of UF particles at this point in time."

The Cabin Environment

Cabin Pressure

The FAA Federal Aviation Regulation (FAR) 14CFR25.841 (CFR 2010a) states that the minimum cabin pressure under normal operating conditions should not be less than the pressure found at an altitude of 8,000 ft (75.3 kPa). The mean cabin pressure across all flights was 79 kPa, reaching an average per flight maximum of 88 kPa. None of the 83 flights had pressures below 75.3 kPa (above 8,000 ft); 68 flights of the 83 had pressures between 82 kPa and 75.3 kPa (6,000-8,000 ft); 15 flights had pressures above 82 kPA (below 6,000 ft). Figure 1 shows cabin pressure by aircraft models. The B747 cabin pressure was significantly different from all five aircraft models with more than five flights. The B747 had an average cabin pressure of 83.9 kPa, which was 3.4 kPa higher than the next highest model. The B737-700 had the lowest average cabin pressure, 77.8. kPa. The B737-700 cabin pressure was significantly different from other aircraft models except the B737-300 (Table 3), with a mean pressure 2.5 kPa above the 75.3 kPa standard.

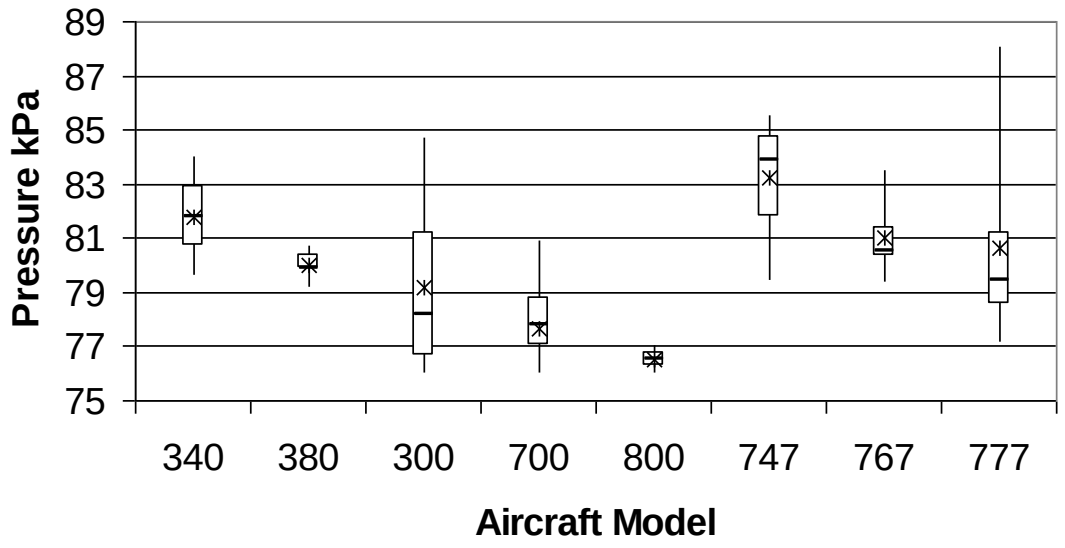

Figure 1. Box plot of cabin pressure (kPa) by aircraft model

Table 3. Mean values of cabin pressure (kPa) and t-test P values by aircraft model, for aircraft models with at least five flights. Bold denotes a t-test P value of less than 0.05.

Aircraft	B737-300	B737-700	A380	B747	B767	B777
mean	78.2	77.8	79.9	83.9	80.5	79.4
B737-300		0.169	0.434	**0.004**	0.118	0.268
B737-700	0.169		**0.000**	**0.000**	**0.000**	**0.003**
A380	0.434	**0.000**		**0.001**	0.051	0.470
B747	**0.004**	**0.000**	**0.001**		**0.009**	**0.023**
B767	0.118	**0.000**	0.051	**0.009**		0.715
B777	0.268	**0.003**	0.470	**0.023**	0.715	

Ventilation

FAR 14CFR25.831 (CFR 2010b) states that the ventilation system must provide a sufficient amount of uncontaminated air to enable the crew to perform duties without much discomfort or fatigue. It specifies that airflow for each occupant must be at least 0.55 pounds of fresh air per minute. The FAR related to ventilation has been amended several times since first being issued in 1964; the specific ventilation requirements that apply to commercial aircraft are dependent upon the date that the manufacturer requests FAA approval and the effective date of the amendment. Therefore, aircraft models in operation before issuance of the most recent FAR 14CFR25.831 may be in compliance even if calculated ventilation rates fall below current standards. ANSI/ASHRAE Standard 161-2007 (ASHRAE 2007) describes the ventilation requirement as 3.5 Liters/second/person (L/s/p) (7.5 CFM/person) divided by the ventilation efficiency, which is assumed to be 1.0 for the interior passenger section, which typically have more than six air changes per hour. This ANSI/ASHRAE standard further states that a total air supply of 7.1 L/s/p (15 CFM/person) is the minimum, with 9.4 L/s/p (20 CFM/Person) recommended. The total air supply can be a mixture of outside air and filtered recirculated air.

To estimate outside air ventilation rates in the 86 flights (three additional flights from the onboard pressure study were added to the 83 onboard flights in this study), we used indoor CO_2 using the constant concentration method (ASHRAE 2001) :

$$\text{Ventilation rate (L/s)} = \frac{G(CO_2)\,(\text{L/hr})}{(C_i - C_0) \times 3600\ (\text{s/hr})} \qquad (1)$$

where:

$G(CO_2)$ = resting rate of production of CO_2 (L/hr) by an average person;

C_i = concentration of CO_2 measured during flight;

C_0 = concentration of CO_2 in the outside air.

This method requires the measurements to be collected once the cabin air has equilibrated and the cabin CO_2 has reached a steady state concentration. CO_2 levels were relatively stable in–flight, suggesting this assumption is valid. The method also requires a value for the CO_2

generation rate per person. Our review of the literature yielded two slightly different values: 18 L/hr (ASHRAE 2011) and 13.2 L/hr (Lee and Siconolfi 1994).

The ASHRAE values for the rate of CO_2 generation, $G(CO_2)$, were calculated from the following equation (Persily1997; ASHRAE 2001; ASHRAE 2011):

$$G(CO_{2)} = RQ\ (0.00276A_DM)/(0.23RQ+77) \quad (2)$$

where:

RQ = respiratory quotient: 0.83 for an adult of average size and engaged in sedentary activities

A_D = DuBois surface area in m^2 (1.8 m^2 for an adult of average size)

and A_D is calculated as:

$$A_D = 0.203H^{0.725} W^{0.425} \quad (3)$$

H = height in meters,

W = weight in kilograms.

M = Metabolic rate per unit of surface area.

To obtain a $G(CO_{2)}$ value of 18 L/hr, ASHRAE (2001) used a Metabolic rate value (M) of 1.2, which corresponds to an adult engaged in light work representing typical office work (*The ASHRAE Handbook, HVAC applications* [2011] uses roughly the same value [0.0105 SCFM = 17.8 L/hr] in its aircraft calculations).

Lee and Siconolfi (1994) measured $G(CO_2)$ on 23 astronauts in a seated position and obtained a value of 13.2 L/hr +/- 1.2 L/hr. People in a seated position have an M value of 1 (Persily 1997). Apart from the difference in M value, the measured $G(CO_2)$ value (13.2 L/hr) is comparable to the ASHRAE $G(CO_2)$ assuming 1 M (15 L/hr).

To conduct a sensitivity analysis of the ventilation rate estimates initially calculated using point estimate values, we performed a two-part Monte Carlo simulation to obtain a distribution of outdoor air flow rate per person for comparison to ANSI/ASHRAE Standard 161-2007 (ASHRAE 2007). The first part of the Monte Carlo simulation involved determining the distribution of the CO_2 generation rate per person ($G[CO_2]$) by running simulations of 100-person flights with a varying mix of travelers. This distribution was then used in the second part of the Monte Carlo simulation to estimate a distribution of the ventilation rate (V) for each flight in our study. For the first part of the simulation, we ran 10,000 simulations of 100-person flights. The model first selected the gender of each occupant (binomial distribution) followed by selection of the age of the passenger (discrete distribution). Passenger age was divided into 5 age groups according to the *EPA Exposure Factors Handbook* (U.S. EPA 2011a): 20-29 years, 30-39 years, 40-49 years, 50-59 years, and 60-74 years. After gender and age were selected, the height and weight of the passenger were selected by the model based on gender- and age-specific distributions of height and weight as reported in the *Exposure Factors Handbook* (normal distribution).

For each passenger, the Dubois surface area (A_D) was calculated according to equation 3. The A_D was then used in equation 2 along with the metabolic rate and respiratory quotient to calculate the CO_2 generation rate per person ($G[CO_2]$). A constant respiratory quotient of 0.83 was used. Metabolic rate for each passenger was selected using a uniform distribution derived from the metabolic rates presented in Table 4, and based on the *2011 Compendium of Physical Activities* (Ainsworth et al. 2011).

Table 4. Metabolic rates (METS) by activity type*.

Activity Type	Metabolic Rate
Sleeping	0.9 METS
In Bed	0.9-1.37 METS
Sit/Watch TV	1.3 METS
Ride in a bus or train	1.3 METS

*Source: 2011 Compendium of Physical Activities (Ainsworth et al. 2011)

The computational steps from the first part of the simulation are presented in Figure 2. Mean $G(CO_2)$for the 10,000 simulations was 18.2 L/hr (standard deviation: 0.3), with a range of 17 – 19.3 L/hr (Figure 3).

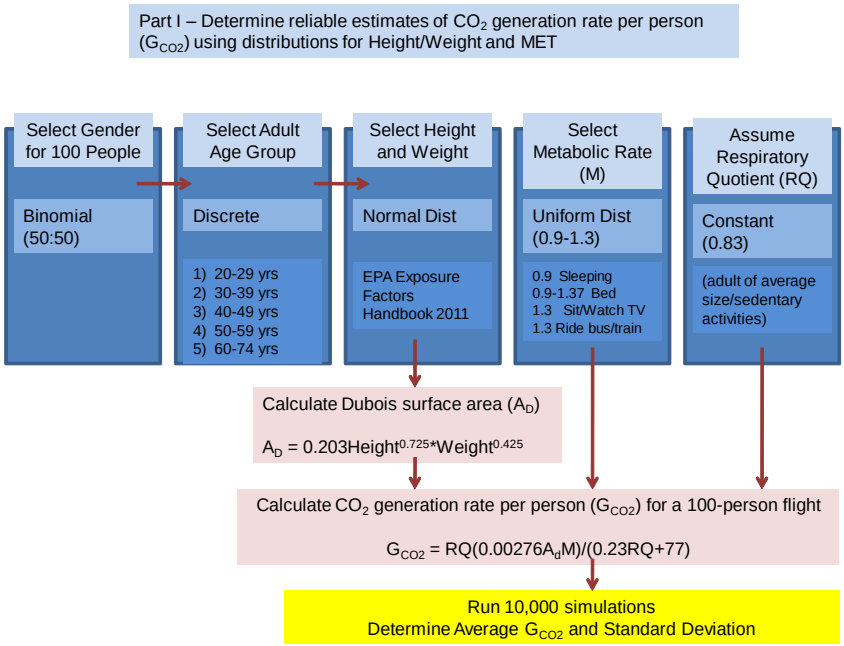

Figure 2. Steps in first part of the Monte Carlo simulation

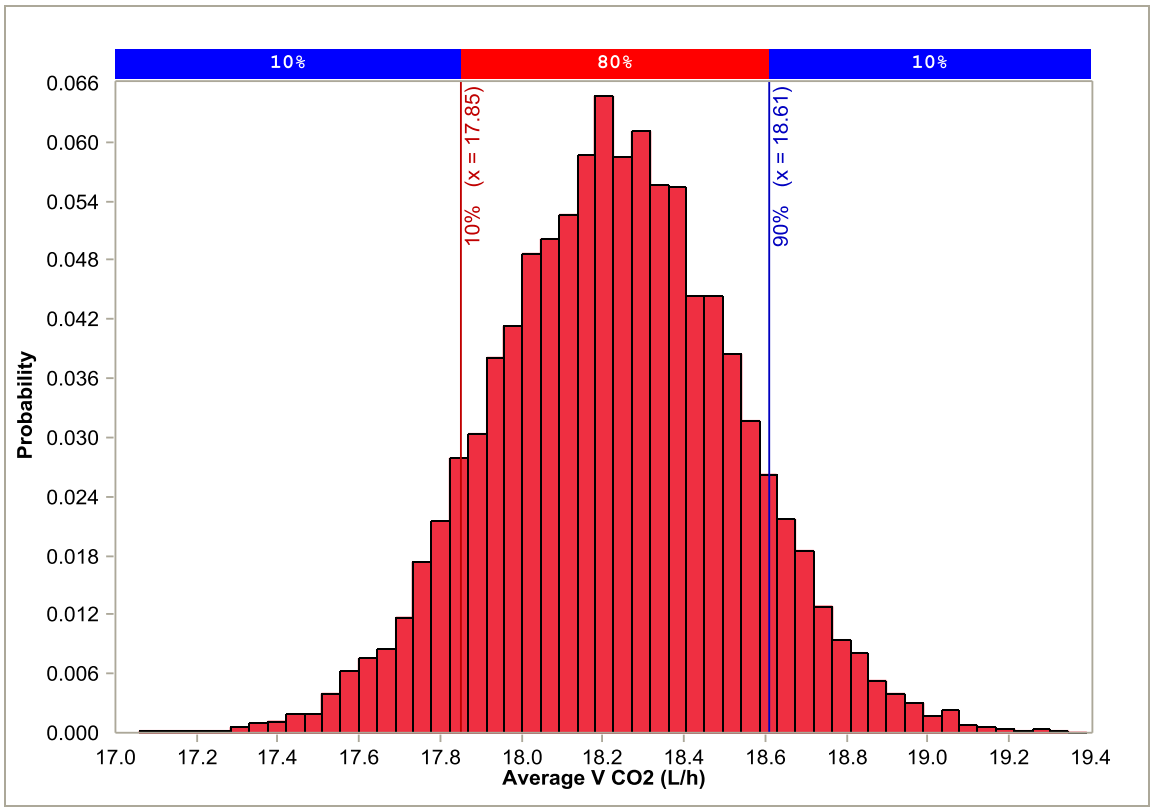

Figure 3. The mean generation of CO_2 for the 10,000 simulations was 18.2 L/hr (standard deviation: 0.3), with a range of 17 – 19.3 L/hr

The second part of the Monte Carlo simulation used the distribution of CO_2 generation rates (Figure 4) along with data collected on each of the 86 flights to calculate a distribution of potential ventilation rates for each flight (10,000 simulations for each flight). Ventilation rate (V) was determined by using equation 1, which included: the measured mean CO_2 concentration (ppm) on each flight (assuming the average represents steady-state); an assumed outdoor CO_2 concentration of 386 ppm, which represents the global monthly outdoor CO_2 concentration at sea-level as reported by NOAA (Table 5); and the distribution of CO_2 generation rates from the first part of the simulation. Figure 5 provides an example for six flights showing the central estimate of ventilations rate per passenger in liters per second (L/s/p) and the distributions derived from the Monte Carlo simulations. Of the 86 flights in our study, six were found to have central tendency estimates of ventilation rate below 3.5 L/s/p. In one case, the uncertainty around the central estimate had a 95% confident interval that included 3.5 L/s/p.

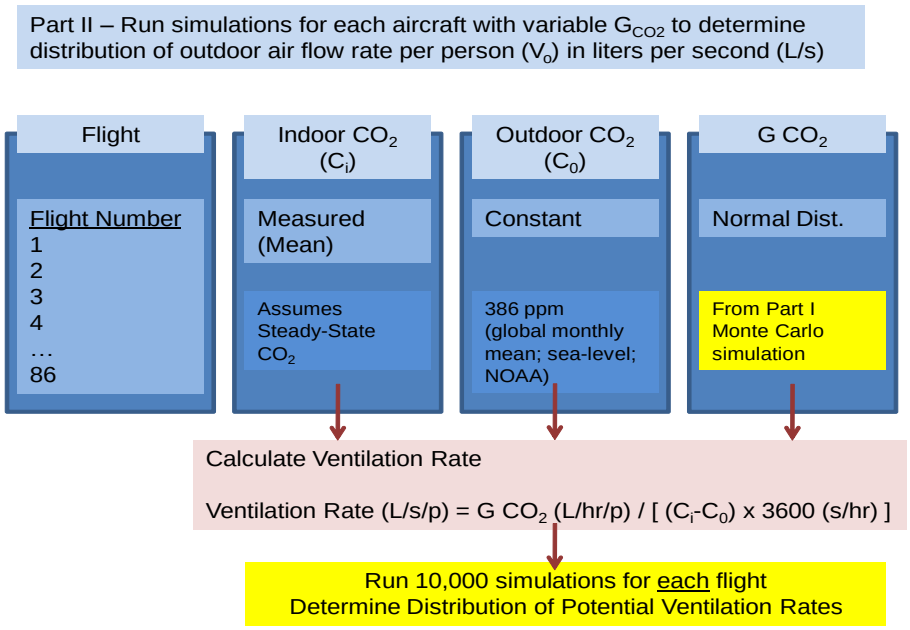

Figure 4. Computational steps of second phase of the Monte Carlo simulation used to estimate ventilation rates

Table 5. Monthly mean global CO_2 sea level from NOAA (ppm) for the six months in which onboard sampling was performed, ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_mm_gl.txt. The uncertainty in the global monthly mean is estimated using a Monte Carlo technique that computes 100 globally-averaged time series, each time using a slightly different set of measurement records from the NOAA ESRL cooperative air sampling network. The reported uncertainty, 0.13 ppm, is the mean of the standard deviations for each monthly mean using this technique. (Conway et al 1994).

Airline	Month	Year	CO_2 ppm
A	March	2008	386.0
A	July	2008	383.3
B	Jan	2009	386.7
B	Feb	2009	387.0
C	July	2010	388.8
C	August	2010	386.0

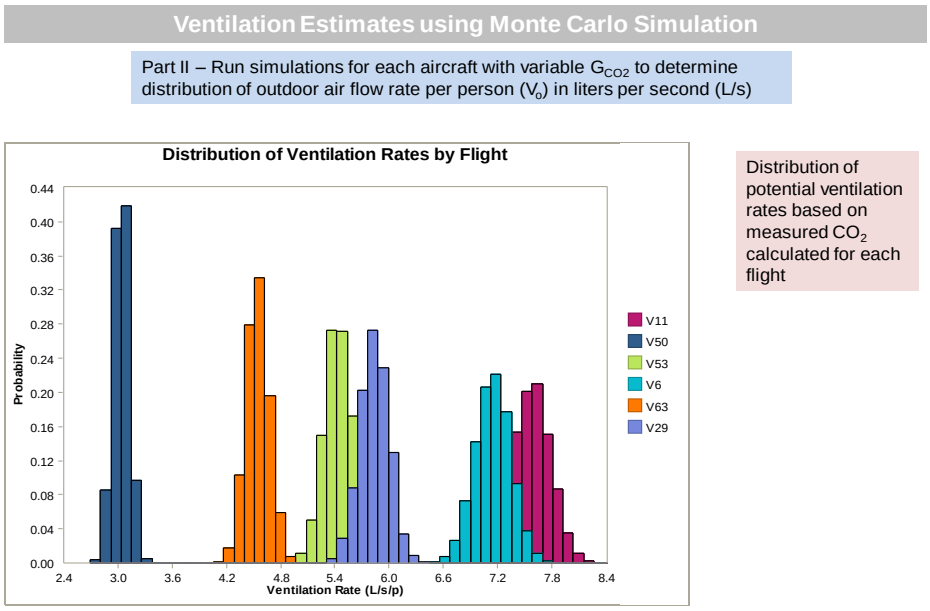

Figure 5. Ventilation (Liters/second/person) estimates using Monte Carlo simulation

Ozone

As addressed in FAR 14CFR25.832 (CFR 2010c), cabin ozone levels must not exceed 0.25 ppm when the aircraft is above 32,000 ft, and a time-weighted average ozone concentration should not exceed 0.1 ppm for any 3-hour period when the aircraft is above 27,000 ft. Ozone was detected in 73 out of 81 flights with complete records. The average ozone concentration across all flights was 15.9 ppb (parts per billion), and the highest average ozone concentration within a single flight was 115.6 ppb with minute readings as high as 256 ppb. The maximum 1-hour ozone value for each flight was calculated from the running hourly (60-min) ozone concentrations. Across all flights the mean of the highest hourly value per flight was 27 ppb, with the highest 1-hour reaching 210 ppb for a single flight. No flights exceeded the 3-hour standard of 0.1 ppm (100 ppb). Figure 6 is the rank ordering of flights by 1-hour ozone levels (ppb). It can be seen that aircraft equipped with ozone converters were more likely to be among those with lower maximum 1-hour ozone concentrations.

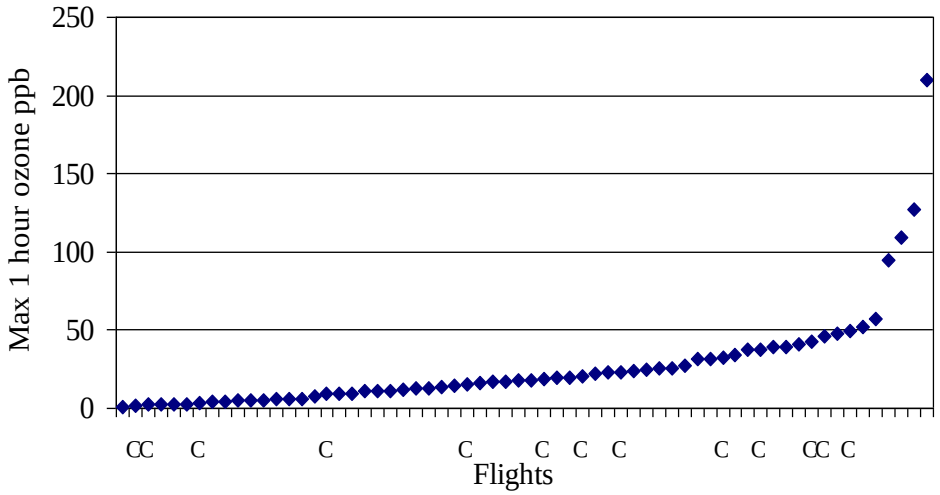

Figure 6. Rank ordering of flights by 1-hour ozone levels (ppb). C denotes flights with ozone converters.

Only airline A (20 of the total flights) used aircraft fitted with ozone converters. The *average* 1-hour maximum concentration of ozone in aircraft across flights with converters was 22.3 ppb, while the flights without converters had an average 1-hr maximum ozone of 28.2 (not significantly different). The *maximum* 1-hour ozone concentrations measured per flight was 47 ppb with converters versus 209 ppb without converters.

Ozone concentrations were significantly higher for flights that followed higher latitude routes (>35°N) (average 24 ppb and maximum concentration 115 ppb) versus flights that followed lower latitudes (average 10 ppb with a maximum of 39 ppb). Figure 7 displays the ozone concentrations by location of the aircraft in flights with a flight path over the U.S. The presence of ozone was episodic with the tendency to encounter more ozone at higher latitude routes.

To evaluate the potential for ozone concentrations on flights to exceed the current National Ambient Air Quality Standard (NAAQS) and proposed reduction to 60 ppb, we calculated ppb-hours for each standard and ppb-hours for each flight (Figure 8). The vast majority of flights had ozone exposure concentrations (ppb-hours) that fell well below the guidance values. Several flights had ozone exposure concentrations that were approximately half of the new proposed standard of 60 ppb (480 ppb-hours).

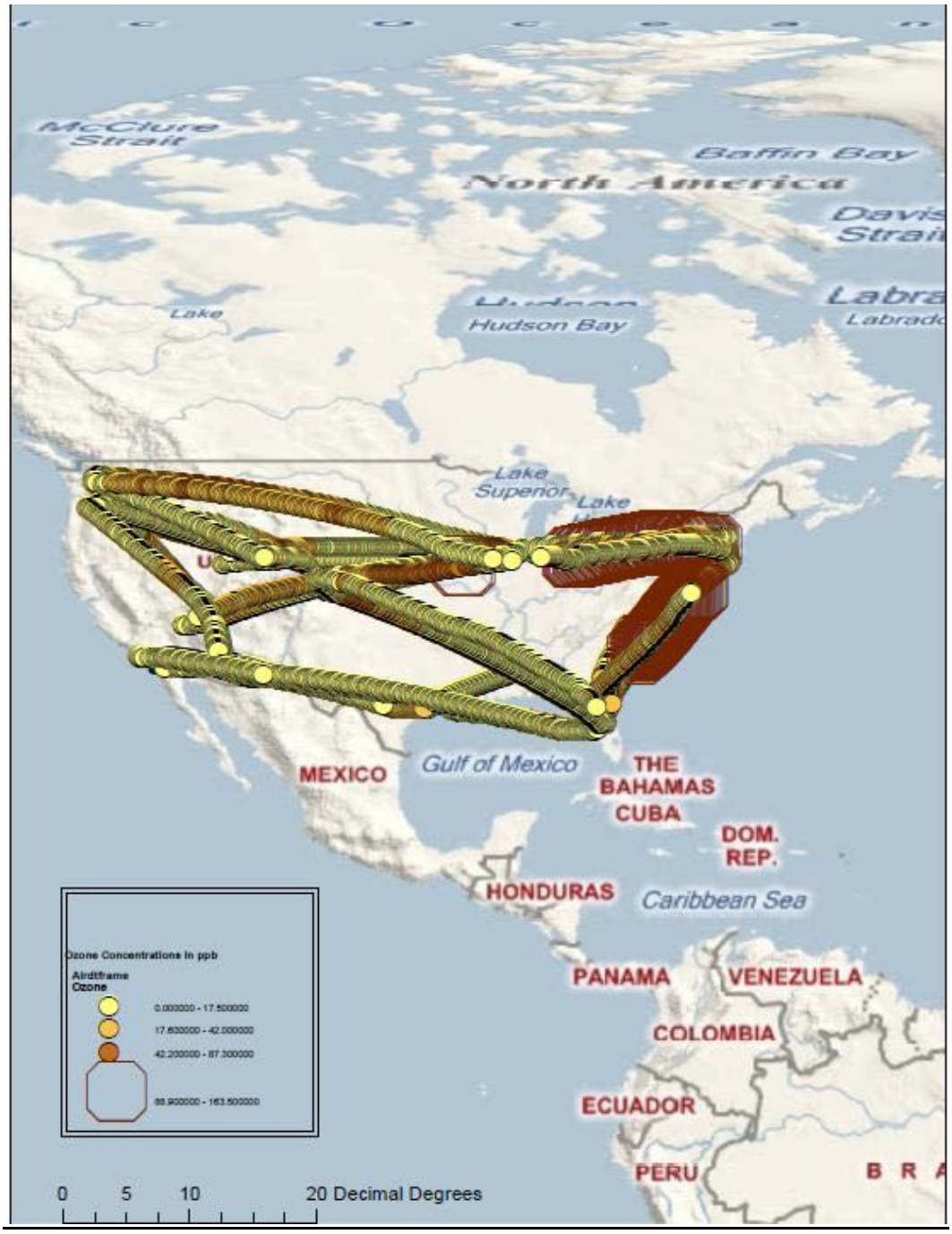

Figure 7. Map of ozone concentrations (ppb) and flight path

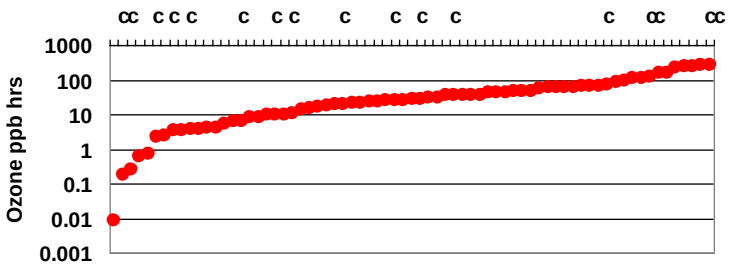

Figure 8. Total ozone exposure in ppb hours, rank ordered from low to high, for each of the 83 flights monitored. C indicates the flight aircraft was equipped with an ozone converter.

Temperature

ANSI/ASHRAE standard 161-2007 (ASHRAE 2007) defines the acceptable conditions for in-flight temperature, giving the target operative temperature range of 18.3ºC to 23.4ºC (65ºF to 75ºF), not to exceed 29.4ºC (85ºF). Temperatures reported in our study reflect seating areas away from side walls or galleys. In 72 flights (83% of all flights) the temperature did not exceed 25ºC. The average temperature across flights was 24.4°C. Among aircraft (Figure 9), the B737-700 had the highest average temperature 25ºC, with a mean temperature significantly different from all aircraft models except the B777 (Table 6). Long and medium duration flights had significantly cooler temperatures 23.9ºC than flights of short duration 24.8 (P value=0.048). Load factor and season were not significantly associated with temperature. Temperature fluctuations within flights were associated with the aircraft air warming or cooling after departure to a set point or were caused by manual adjustment of the temperature by the flight crew. Aside from these temperature changes from one stable set point to another stable set point, temperatures in-flight remained stable.

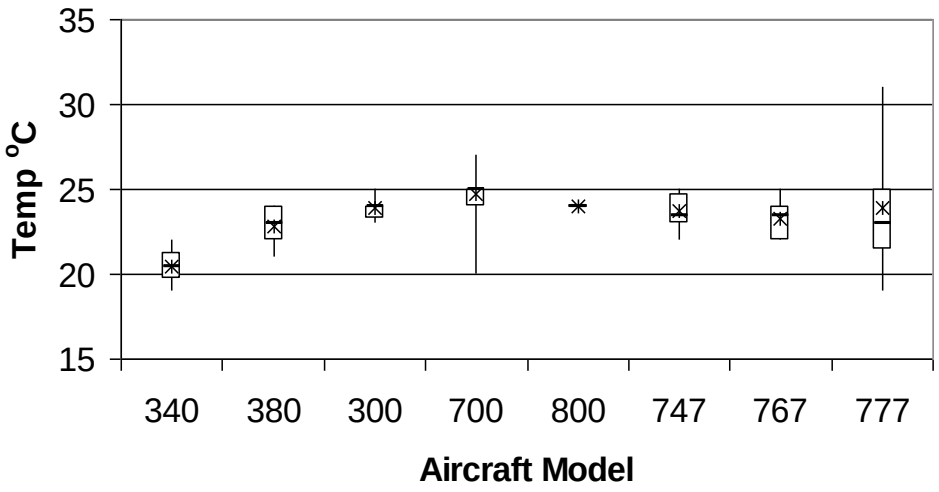

Figure 9. Box plot of temperature (°C) by aircraft model

Table 6. Mean values of cabin temperature (°C) and t-test P values by aircraft model, for aircraft models with at least five flights. Bold denotes a t-test P value of less than 0.05.

Aircraft	B737-300	B737-700	A380	B747	B767	B777
Mean	24	25	23	24	24	23
B737-300		**0.032**	0.137	0.631	0.212	0.973
B737-700	**0.032**		**0.023**	**0.028**	**0.008**	0.418
A380	0.137	**0.023**		0.224	0.499	0.319
B747	0.631	**0.028**	0.224		0.451	0.818
B767	0.212	**0.008**	0.499	0.451		0.542
B777	0.973	0.418	0.319	0.818	0.542	

Relative Humidity

FARs and ASHRAE do not provide a standard for humidity in aircraft cabin environments because it is recognized that the outside air at flight altitudes is very dry, making a humidification requirement impractical. However, ANSI/ASHRAE Standard 161-2007 (ASHRAE 2007) acknowledges that low humidity can be associated with adverse effects.

The median relative humidity per flight was below 10% for 41 flights and below 18% for 78 flights, while the average RH across all flights was 11%. Relative humidity was not significantly different by aircraft model (Table 7). On mid and long-haul flights, relative humidity decreased (13.3% to 9.3%) when compared to short flights (p value =0.007).

Table 7. Mean values of cabin relative humidity (%) and t-test P values by aircraft model, for aircraft models with at least five flights. Bold denotes a t-test P value of less than 0.05.

Aircraft	B737-300	B737-700	A380	B747	B767	B777
Mean	9.1	9.7	10.5	8.3	13.7	10.7
B737-300		0.721	0.469	0.680	0.198	0.219
B737-700	0.721		0.711	0.388	0.286	0.319
A380	0.469	0.711		0.163	0.350	0.391
B747	0.680	0.388	0.163		0.071	0.074
B767	0.198	0.286	0.350	0.071		0.912
B777	0.219	0.319	0.391	0.074	0.912	

Cabin Noise

Neither FARs 14CFR25 nor ANSI/ASHRAE Standard 161-2007 (ASHRAE 2007) address cabin noise. OSHA (29CFR1910.95 [CFR 2010d)]) sets noise limits for the workplace as an 8-hour time-weighted average of 90 dB (A) and requires hearing conservation programs be available for employees whose time-weighted average exceeds 85 dB (A). The B767 had an average sound level of 71.9 dB (A), which was significantly different from all other aircraft models except the A380. The A380 had an average sound level of 67.9 dB (A); however with the limited number of flights (five) it was not possible to differentiate the A380 from the other

models (Table 8). Sound levels will vary across a cabin, depending on aircraft model, engine, thrust mode, and seat location. Our measurements were made at the midpoint of the economy section, which varied between aircraft types and carriers. Sound level was not significantly different for load factor and flight duration.

Table 8. Mean values of cabin sound level (dB (A)) and t-test P values by aircraft model, for aircraft models with at least five flights. Bold denotes a t-test P value of less than 0.05.

Aircraft	B737-300	B737-700	A380	B747	B767	B777
Mean	75.7	75.8	67.9	74.2	71.9	75.5
B737-300		0.374	0.794	0.485	**0.000**	0.222
B737-700	0.374		0.909	0.310	**0.004**	0.126
A380	0.794	0.909		0.629	0.639	0.564
B747	0.485	0.310	0.629		**0.020**	0.831
B767	**0.000**	**0.004**	0.639	**0.020**		**0.001**
B777	0.222	0.126	0.564	0.831	**0.001**	

Carbon Dioxide and Carbon Monoxide (CO_2 and CO)

The FARs for ventilation states that the passenger cabin must be free from harmful concentrations of gases and vapors (CFR 2101b). It stipulates that CO_2 not exceed 5,000 ppm and CO not exceed 50 ppm. The average CO_2 level during cruise across all flights was 1,404 ppm, with a range of 863 ppm to 2,056 ppm. CO_2 was highly correlated with occupancy level (Spearman's r=0.7) and was also associated with relative humidity (Spearman's r=0.65). CO_2 levels were slightly higher for short-haul flights compared to mid and long-haul flights, but the difference was not significant. CO_2 levels were not significantly different by aircraft model except for the B777. The B777 aircraft had the highest mean CO_2 level, 1,499 ppm, which was significantly different from all other aircraft models except the B737-300 which had a mean CO_2 level of 1,457 ppm (Table 9). These levels are consistent with the ventilation rates previously discussed in this report.

Table 9. Mean values of cabin CO_2 (ppm) and t-test P values by aircraft model, for aircraft models with at least five flights. Bold denotes a t-test P value of less than 0.05.

Aircraft	B737-300	B737-700	A380	B747	B767	B777
Mean	1457	1383	1253	1131	1319	1499
B737-300		0.861	0.563	0.217	0.719	0.115
B737-700	0.861		0.161	0.067	0.473	**0.032**
A380	0.563	0.161		0.274	0.846	**0.002**
B747	0.217	0.067	0.274		0.304	**0.003**
B767	0.719	0.473	0.846	0.304		**0.025**
B777	0.115	**0.032**	**0.002**	**0.003**	**0.025**	

Figures 10 and 11 show the continuous measurement made during two flights. In the first case instruments were operating during the boarding process. Figure 10 shows continuous measurements for a B747-400 US continental flight. CO_2 levels during boarding reached 1,400 ppm while averaging about 1,000 ppm during the flight. Figure 11 shows the continuous measurements made during a long international flight on a B747. CO_2 levels varied by a few hundred ppm across the flight, showing a downward trend from mid-flight when many passengers were sleeping followed by an increase around and after the time meals were served.

Carbon monoxide was not detected above the instrument's level of detection of 1 ppm in any flight.

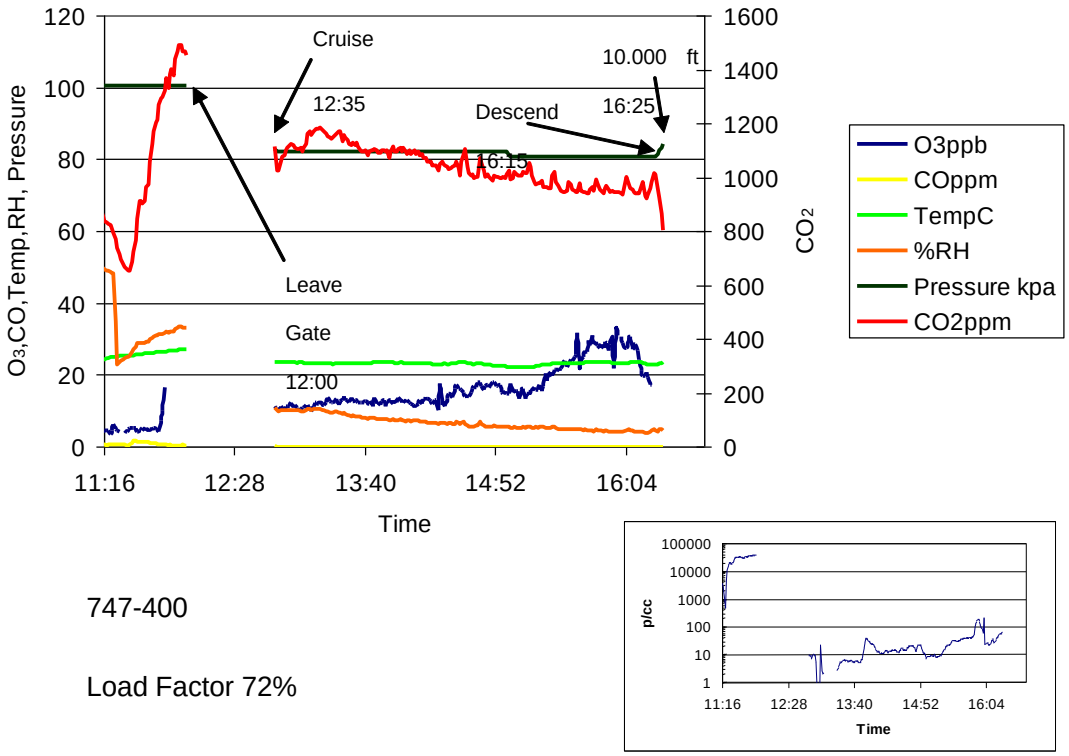

Figure 10. Continuous measurements for a B747-400 U.S. continental flight

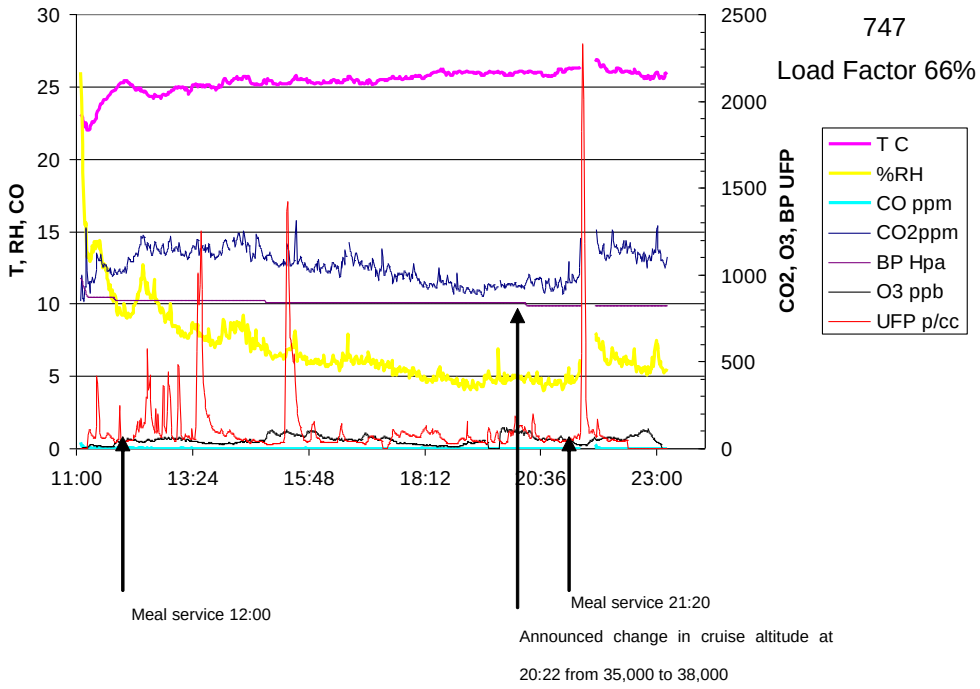

Figure 11. Continuous measurements made during a long international flight on a B747

Ultrafine Particles (UFPs)

Ultrafine particles were measured on 55 flights, with a maximum 15-minute concentration across flights ranging from 1 p/cc to 312,000 p/cc. UFP levels were quite low for most of the flights (< 1,000 p/cm^3), and fluctuated with latitude but were not significantly correlated with ozone concentrations which did fluctuate with latitude. The mean UFP for flights with lower latitude routes was 1,104 p/cc compared to a mean UFP of 55 p/cc for flights with higher latitude routes. UFP events were defined as major events having 15-minute averages >10,000 p/cc, and minor events having 15-minute averages between 500 and 10,000 p/cc. For flights which had no food preparation onboard (an activity expected to raise UFP), both minor and major UFP events were associated with elevated ozone (Table 10). Out of 39 flights with no food preparation on board only two had both major and minor UFP events, and four flights had only minor UFP events.

For flights with meal service, the association between UFP and ozone was not as evident, probably because meal preparation aboard these flights confounded any chance of observing a relationship. Eight of 22 flights had major and minor UFP events, one flight had only major UFP events, and four flights had only minor UFP events. All events were associated with meal preparation and were of moderate or long duration. Figure 11, which shows a long international flight with meal service, demonstrates periodic short duration spikes in UFP during typical meal times. Episodic variation in UFP might be associated with switchover in bleed air from pressure in the Environmental Control System or variations in engine power. However, it was not possible to discern these events during the course of air monitoring in the cabin.

Table 10. Major and minor UFP (p/cc) events and ozone concentration (ppb)

P/cc Event Type	N (minutes)	Mean ozone (ppb)	Median ozone(ppb)	Maximum ozone (ppb)	5th Percentile ozone (ppb)
No Food preparation					
Major >10,000 p/cc	130	74	63.7	126.7	30.3
Minor <10,000 p/cc >500 p/cc	97	45.4	35.0	118.2	20.6
>500 p/cc	3982	16.9	9.8	152	3.6
Meal Service					
Major >10,000 p/cc	194	4.4	47	16.6	1.0
Minor <10,000 p/cc >500 p/cc	609	10.9	5.5	92.3	2.1
>500 p/cc	6979	15.9	7.5	131.1	1.4

The relationship between particle generation in the presence of ozone is illustrated for a flight that originated in Colorado and flew through an upper level trough, descending from Canada over the upper mid-west on its way to the mid-west. Figure 12 shows the synoptic weather features (12a), the flight path (12b), the maximum and minimum temperatures for the day (12c), the 500 mb heights (12d), and the precipitation for 7:00 a.m. on the flight date (12e). Figure 13 plots ozone ppb and UFP p/cc at flight altitude in this cabin. Ozone starts off low with no detectable UFPs, and about 30 minutes into the flight ozone begins to rise, exceeding 60 ppb for 45 minutes, before decreasing on descent. The UFP levels increased sharply after ozone levels increased, reaching UFP of 25,000 p/cc through the remaining cruise time, then UFPs also decrease as ozone sharply decreases upon descent.

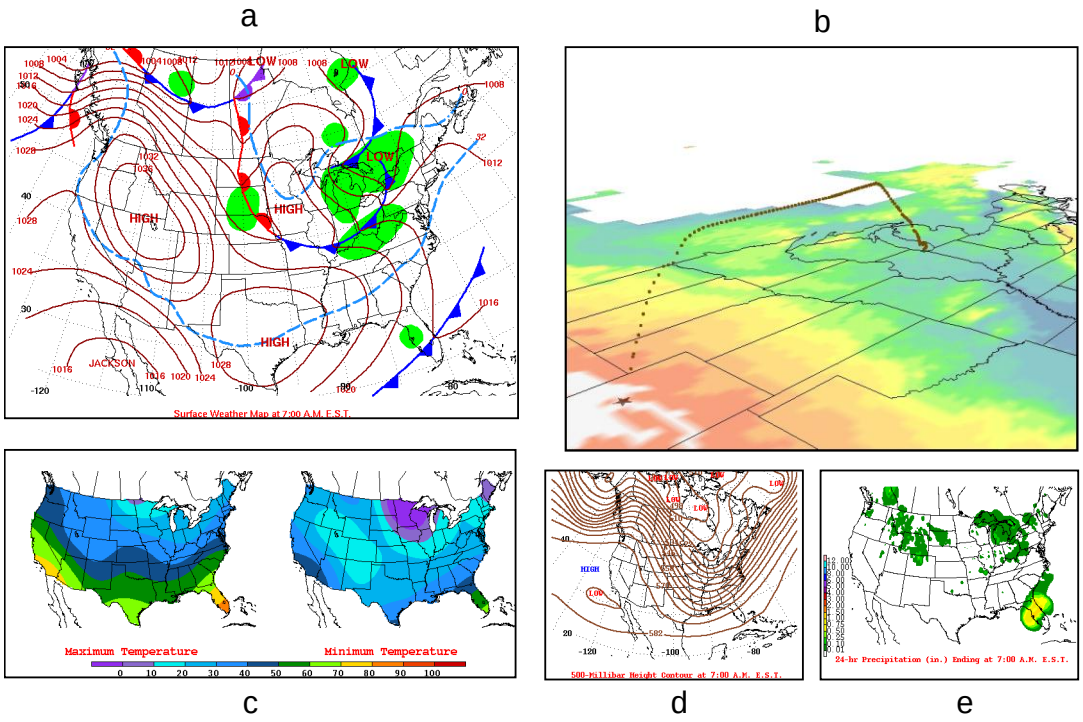

Figure 12. The association of particle generation with ozone is illustrated for a flight that originated in Colorado and flew through an upper level trough (descending from Canada over the upper mid-west) on its way to the mid west. This figure shows the synoptic weather features (12a), the flight path (12b), the max and min temperatures for the day (12c), and the 500 mb heights (12d) and precipitation for 7:00 a.m. on the flight date (12e).

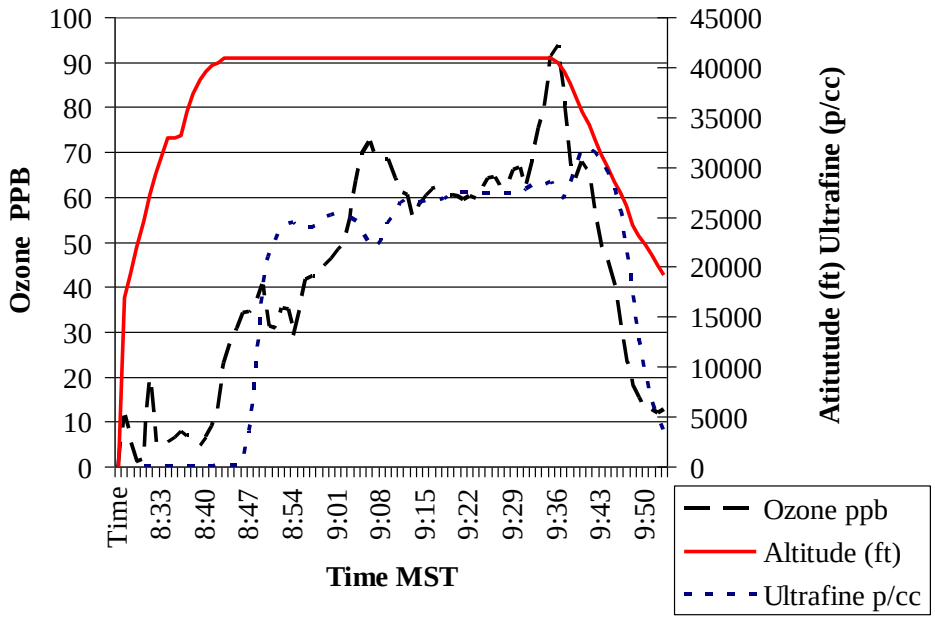

Figure 13. Ozone, ultrafine particle and altitude data for the flight between Colorado and the mid west in which ozone-initiated particle formation was observed

Carbonyls

A total of five carbonyls (acetaldehyde, acetone, acrolein, formaldehyde, propionaldehyde) were monitored but not all of them in each flight. Table 11 presents a summary for just three carbonyls (acetaldehyde, formaldehyde, propionaldehyde) which were sampled using the same method on airlines B and C. Acetaldehyde was detected in 81% of the samples (airlines B and C only); acetone was detected in 79% of the samples (all airlines); acrolein was detected in 71% of the samples (airlines A and C only); formaldehyde was detected in 49% of the samples (airlines B and C only); and propionaldehyde was detected in 17% of the samples. See Appendix B, Table B-1, for a summary of the percent of detection for all the carbonyls (as well as volatile organic compounds) sampled across all three airlines.

Table 11. Descriptive statistics of carbonyls sampled in airlines B and C only; all other carbonyls are presented in Appendix B, Table B-1.

	N	Percent detected	Q25	Minimum	Median	Maximum	Q75
Formaldehyde	70	35	1.90	0.00	2.71	11.72	4.18
Acetaldehyde	70	57	4.46	0.86	7.40	75.79	17.08
Propionaldehyde	70	29	1.25	0.00	2.18	8.87	3.34

There were no significant differences between aircraft models for acrolein, acetone and formaldehyde. Figure 14 shows plots of the carbonyl samples by aircraft model. Table 12 presents the results of statistical analysis of differences for acetyaldehyde among aircraft models. In the B737-700, the mean concentration of acetalaldehyde was 20.3 $\mu g/m^3$, which was significantly different from the mean concentrations in the A380 (8.0 $\mu g/m^3$), B747 (8.3 $\mu g/m^3$) and B767 (5.5 $\mu g/m^3$). The A380 aircraft cabin also had a significantly different mean acetaldehyde concentration from the B767. Similarly, Table 13 shows the differences between aircraft models for propionaldehyde. The B737-300 aircraft mean propionaldehyde concentration was 3.4 mg/m^3. This was significantly different from the mean concentrations for A380 (1.3 $\mu g/m^3$), the B747 (1.7 $\mu g/m^3$), and the B767 (1.9 $\mu g/m^3$) aircraft. The A380 mean propionaldehyde concentration (1.3 $\mu g/m^3$) was also significantly different from the B737-700 mean concentration (2.7 $\mu g/m^3$).

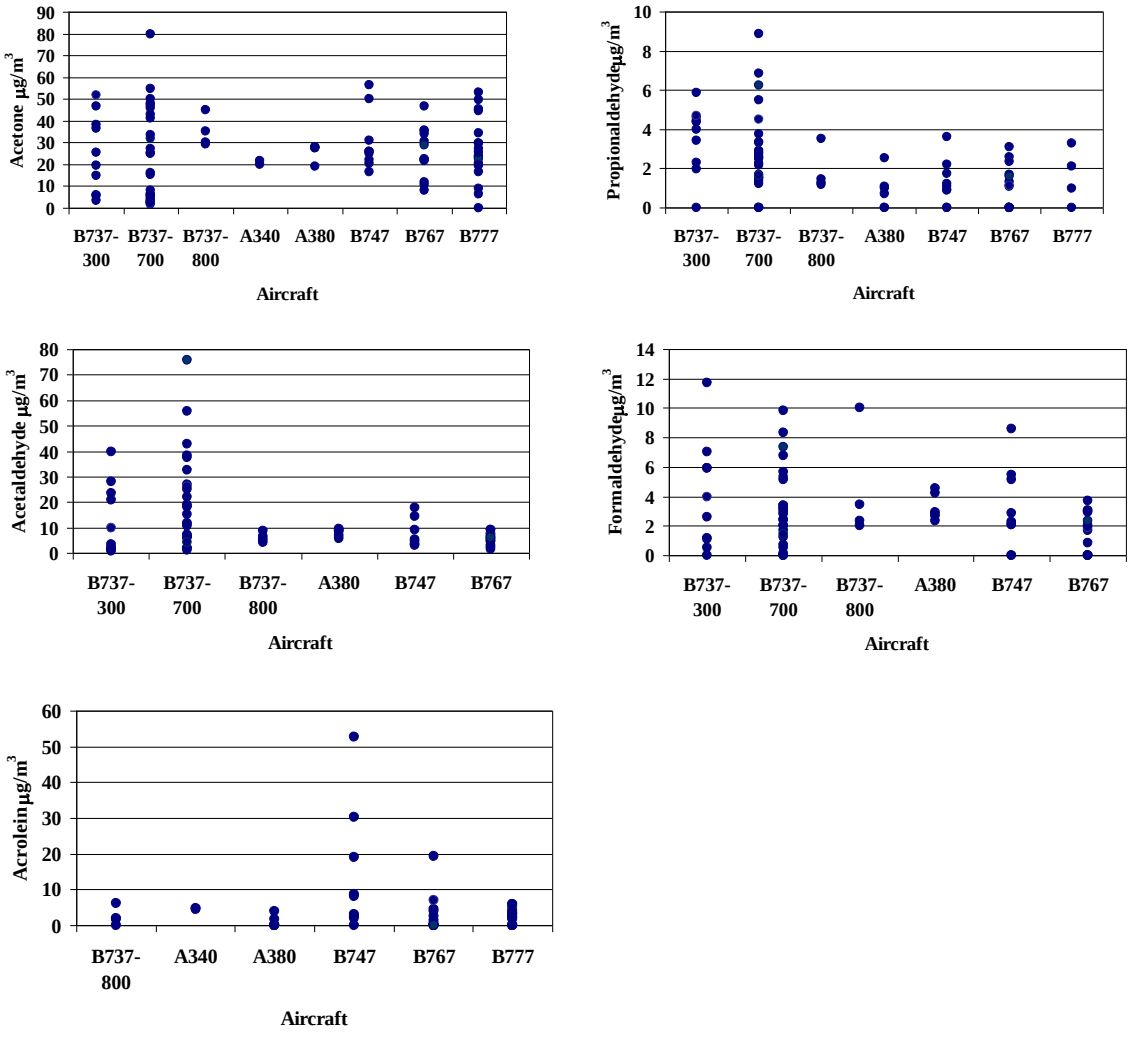

Figure14. Plots of carbonyl concentrations (µg/m^3) by aircraft

Table 12. Mean acetaldehyde concentration (µg/m^3) and t-test P values by aircraft model, for aircraft models with at least five flights. Bold denotes a t-test P value of less than 0.05

Aircraft	B737-300	B737-700	A380	B747	B767
Mean	13.2	20.3	8.0	8.3	5.5
B737-300		0.222	0.273	0.342	0.121
B737-700	0.222		**0.002**	**0.007**	**0.000**
A380	0.273	**0.002**		0.886	**0.017**
B747	0.342	**0.007**	0.886		0.266
B767	0.121	**0.000**	**0.017**	0.266	

Table 13. Mean values of cabin propionaldehyde concentration (µg/m^3) and t-test P values by aircraft model, for aircraft models with at least five flights. Bold denotes a t-test P value of less than 0.05.

Aircraft	B737-300	B737-700	A380	B747	B767	B777
Mean	3.4	2.7	1.3	1.7	1.9	2.1
B737-300		0.368	**0.019**	**0.035**	**0.048**	0.212
B737-700	0.368		**0.042**	0.098	0.135	0.527
A380	**0.019**	**0.042**		0.571	0.321	0.377
B747	**0.035**	0.098	0.571		0.662	0.584
B767	**0.048**	0.135	0.321	0.662		0.746
B777	0.212	0.527	0.377	0.584	0.746	

Flight characteristics affected some of the concentrations. Some compound concentrations varied by flight duration and ventilation but not by seasonality. Short flights were significantly different for propionaldehyde (p=0.002) only, with an average of 3.6 µg/m^3 for short flights and 1.7 µg/m^3 for long flights. Acetone levels were significantly different (p=0.025) for flights with greater than 90% occupancy (30.4 µg/m^3) compared to flights with less than 90% occupancy (23.3 µg/m^3). Formaldehyde and acetone levels were significantly different for flights with ventilation rates less than 6.0 L/s/p compared to flights with ventilation rates greater than 6.0 L/s/p: 3.7 µg/m^3 compared to 2.4 µg/m^3 for formaldehyde (p value = 0.042); and 27.8 µg/m^3 compared to 20.2 µg/m^3 for acetone (p value = 0.026).

Volatile Organic Compounds (VOCs)

VOCs were sampled using evacuated canisters for airline A and thermal desorption tubes for airlines B and C. The target analytes and the number and percent of samples above the detection limit for each airline can be found in Appendix B, Table B-1. Overall for compounds measured on all three airlines, toluene was detected in 91% of the samples, followed by carbon tetrachloride and tetrachloroethene in 90% of the samples. M&p-xylene was detected in 75% of the samples. Benzene, ethylbenzene, o-xylene, methylene chloride, hexane, and styrene were detected in 50% to 75% of the samples. Table 14 lists the descriptive statistics of VOCs sampled on all three airlines. Table 15 lists the mean values of VOCs measured on all three airlines and the t-test p-values from comparisons among airlines.

Table 14. Descriptive statistics of volatile organic compounds by airline (ng/m^3).

	airline A					airline B					airline C				
	25th	Min	Median	Max	75th	25th	Min	Median	Max	75th	25th	Min	Median	Max	75th
Non-chlorinated															
1,3-butadiene	0	0	0	44	0	126	0	618	212715	6173	8	0	534	50408	1760
methyl tert-butyl ether	0	0	0	86	6	14	0	35	16163	196	0	0	19	3662	493
benzene	537	0	876	3286	1176	259	0	548	20073	1471	0	0	116	62341	3012
toluene	1886	1007	2783	30028	4388	1926	463	2846	115378	6426	6077	119	10105	132926	15745
ethylbenzene	123	0	187	575	277	134	60	230	13452	501	272	0	418	3855	652
m&p-xylene	224	152	333	715	519	487	206	956	28674	1896	762	0	1120	9387	2381
o-xylene	103	73	163	419	236	129	0	291	14174	484	273	0	409	3441	758
Chlorinated															
methylene chloride	168	0	45641	661819	196325	761	19	2842	46533	5925					
chloroform	0	0	35	535	95	80	21	138	2089	275	0	0	95	1955	458
1,1,1-trichloroethane	0	0	10	26	15	53	0	63	1852	119	0	0	31	560	111
carbon tetrachloride	23	0	28	38	31	561	0	649	1704	877	430	0	639	2796	855
trichloroethene	14	0	21	653	31	68	0	324	29448	1399	0	0	132	41286	2329
cis-1,3-dichloropropene	0	0	0	0	0	0	0	0	2104	0	0	0	0	527	0
trans-1,3-dichloropropene	0	0	0	0	0										
tetrachloroethene	274	54	619	1928	915	810	68	1166	10007	2600	3443	1177	10670	123025	13318
1,4-dichlorobenzene	122	42	187	701	283	170	51	322	2420	593	44	0	307	12738	769
Other															
acrolein	1978	0	2976	5969	4086						1681	0	3207	52773	8775
acetone	19643	13702	23563	53157	29667										
2-butanone	1888	1273	2154	4051	2588						823	0	1356	11500	2421
ethanol	807338	221100	1433770	4916004	2213250										
ethyl acetate	1026	360	1751	7140	2567						5131	0	16132		29969
hexane	198	0	262	700	444	2962	38	68360	1123078	153401	0	0	0		1517
Isoprene	1818	1056	2225	5637	3337						8500	705	14316	49932	18574
isopropyl alcohol	2147	0	3095	32021	4495						2896	0	6312	84029	23898
styrene	83	40	161	503	228	275	112	369	3391	620	149	0	416	12083	900
airlines B and C only															
2-Methylpentane						409	9	2042	392507	3800	0	0	76	49673	2074

	airline A					airline B					airline C				
	25th	Min	Median	Max	75th	25th	Min	Median	Max	75th	25th	Min	Median	Max	75th
2-Methylhexane						107	8	174	16467	395	47	0	128	1304	691
2,3-Dimethylpentane						31	10	73	9544	184	48	0	101	1179	271
3-Methylhexane						53	0	118	19670	325	67	0	175	62330	634
2,2,4-Trimethylpentane						375	121	979	29019	1514	376	0	867	69137	1506
Methylcyclohexane						58	24	114	5211	280	104	0	274	5223	537
airline A only															
propylene	898	0	1148	71959	1382										
methyl bromide	0	0	0	3241	37										
Methyl methacrylate	0	0	0	1999	0										
1,2,4-trimethylbenzene	157	55	208	1397	298										
dichlorodifluoromethane	267	247	282	1018	295										
tetrahydrofuran	0	0	0	1484	93										
cyclohexane	93	0	110	939	202										
methyl chloride	567	0	629	757	694										
vinyl acetate	188	0	290	759	425										
carbon disulfide	425	0	571	800	672										
Heptanes	40	0	61	577	98										
trichlorofluoromethane	117	114	124	400	138										
1,3,5-trimethylbenzene	36	19	56	303	75										
2-hexanone	0	0	81	347	188										
trans-1,2-dichloroethene	0	0	0	360	80										
1,3-dichlorobenzene	0	0	0	224	11										
methyl isobutyl ketone	0	0	169	619	320										
4-ethyl toluene	34	15	51	229	70										
chlorobenzene	0	0	0	217	20										
ethyl chloride	0	0	0	250	0										
1,2,4-trichlorobenzene	0	0	16	69	30										
1,1,2-trichlorethane	0	0	0	76	0										
1,2-dichlorobenzene	0	0	0	72	12										
1,1,2,2-tetrachloroethane	0	0	0	59	0										
1,1,2-trichloro-1,2,2-trifluoroethane	26	24	31	46	33										
bromoform	0	0	0	34	0										

	airline A					airline B					airline C				
	25th	Min	Median	Max	75th	25th	Min	Median	Max	75th	25th	Min	Median	Max	75th
benzyl chloride	0	0	0	69	0										
hexachlorobutadiene	0	0	0	21	2										
1,2-dichloroethane	0	0	0	50	0										
1,2-dichlorotetrafluoroethane	0	0	4	22	7										
dibromochloromethane	0	0	0	18	0										
1,2-dibromoethane	0	0	0	20	0										
bromodichloromethane	0	0	0	11	0										
vinyl chloride	0	0	0	0	0										
1,1-dichloroethene	0	0	0	0	0										
1,1-dichloroethane	0	0	0	0	0										
cis-1,2-dichloroethene	0	0	0	0	0										
1,2-dichloropropane	0	0	0	0	0										
1,4-dioxane	0	0	0	0	0										

Table 15. Mean values (µg/m^3) and t-test P values for VOC comparisons between airlines (for VOCs measured in all three airlines). P values in bold are less than 0.05.

	Mean A	Mean B	Mean C	Airlines A-B	Airlines A-C	Airlines B-C
	Mean Concentrations (µm/m^3)			**P-Values**		
VOCp (MTBE, benzene, toluene, ethylebenzene, m/p xylene, and o-xylene)	10.16	5.07	6.75	0.05	0.12	0.25
chlorinated compounds	3.01	1.17	3.45	**0.00**	0.32	**0.01**
MTBE	0.02	0.24	0.12	0.07	**0.02**	0.23
Benzene	1.03	0.72	0.90	0.15	0.42	0.40
Toluene	7.65	3.01	4.95	**0.04**	0.16	0.13
ethylbenzene	0.40	0.23	0.14	0.08	**0.00**	0.20
m/p xylene	0.71	0.62	0.49	0.36	**0.05**	0.29
chloroform	0.20	0.06	0.07	**0.03**	**0.03**	0.42
trichloroethene	0.12	0.46	0.66	0.05	0.06	0.31
1,4-dichlorobenzene	0.54	0.11	0.17	**0.00**	**0.00**	0.28
Hexane	0.49	50.00	1.02	**0.00**	0.30	**0.00**

A variable representing the sum of hydrocarbons that may originate from petroleum combustion was created. There were no significant differences among the sum of the petroleum hydrocarbons, summarized as "VOCp" (MTBE, benzene, ethylbenzene, toluene, m&p-xylene, and o-xylene). Hexane was not included in this sum since the values for hexane were much greater than the values of the other compounds. Airline B had a significantly higher mean hexane value than airlines A and C. For the sum of the chlorinated compounds (chloroform, carbon tetrachloride, trichloroethene and 1,4-dichlorobenzene), airline B had a significantly lower mean concentration than both airlines A and C. For toluene, airline A was significantly higher than airline B. For ethyl benzene, airline A was significantly higher than airline C. Dichlorobenzene and chloroform were significantly higher in airline A than in airline B and C. Airline C had a significantly higher mean MTBE concentration than airline A. The mean MTBE concentration of airline B was higher than Airline C, but because of the higher variance in the MTBE values in airline B, the p-value comparing airline A to C was 0.07. As would be expected, flights with ventilation rates lower than 6.0 L/s/p had a mean VOCp of 8.0 µg/m^3 which was significantly different (p-value = 0.004) to flights with ventilation rates higher than 6.0 L/s/p with a mean VOCp concentration of 3.3 µg/m^3.

Three large surveys of VOCs collected in other indoor settings were used to compare the VOCs measured in the cabin air. In the Building Assessment Survey Evaluation (BASE) study, the EPA conducted a large exposure and health survey of 100 U.S. office buildings. In the Toxic Exposure Assessment Columbia-Harvard (TEACH) study, researchers measured VOCs in residences in New York City and Los Angeles; the Los Angeles data was readily available for

comparison to the cabin air data. In the Boston Exposure Assessment in Microenvironments (BEAM) study, researchers investigated VOC levels in homes and other indoor environments in the Boston area. Specific comparisons are graphically displayed in this report while summary tables are available in Appendix B. Table B-2 (Appendix B) compares the median values in the EPA BASE Large Building Study (Brightman et al. 2008) to the median values measured in each airline. The BASE building values were higher for most compounds except for methylene chloride in airline A, hexane in airline B and ethyl acetate, toluene and tetrachloroethene in airline C. Table B-3 (Appendix B) compares cabin VOC measurements to outdoor data collected and analyzed with similar methods in the TEACH Los Angeles Study (Sax et al. 2004), as well as the BEAM study conducted in the greater Boston metropolitan area (Dodson et al. 2007). Median values and 75 percentile values were generally either comparable or lower in the cabin air than in the two sets of outdoor data, while the cabin air maximum values were generally higher than the outdoor maximum values. VOC concentrations by aircraft type were compared to the median and 95^{th} percentile values from TEACH and BASE data. The comparisons for select VOCs are presented in Figure 15 through 17 (Note: boxplots depict the median, 25^{th}/75^{th} percentiles, 5^{th}/95^{th} percentiles, and outliers).

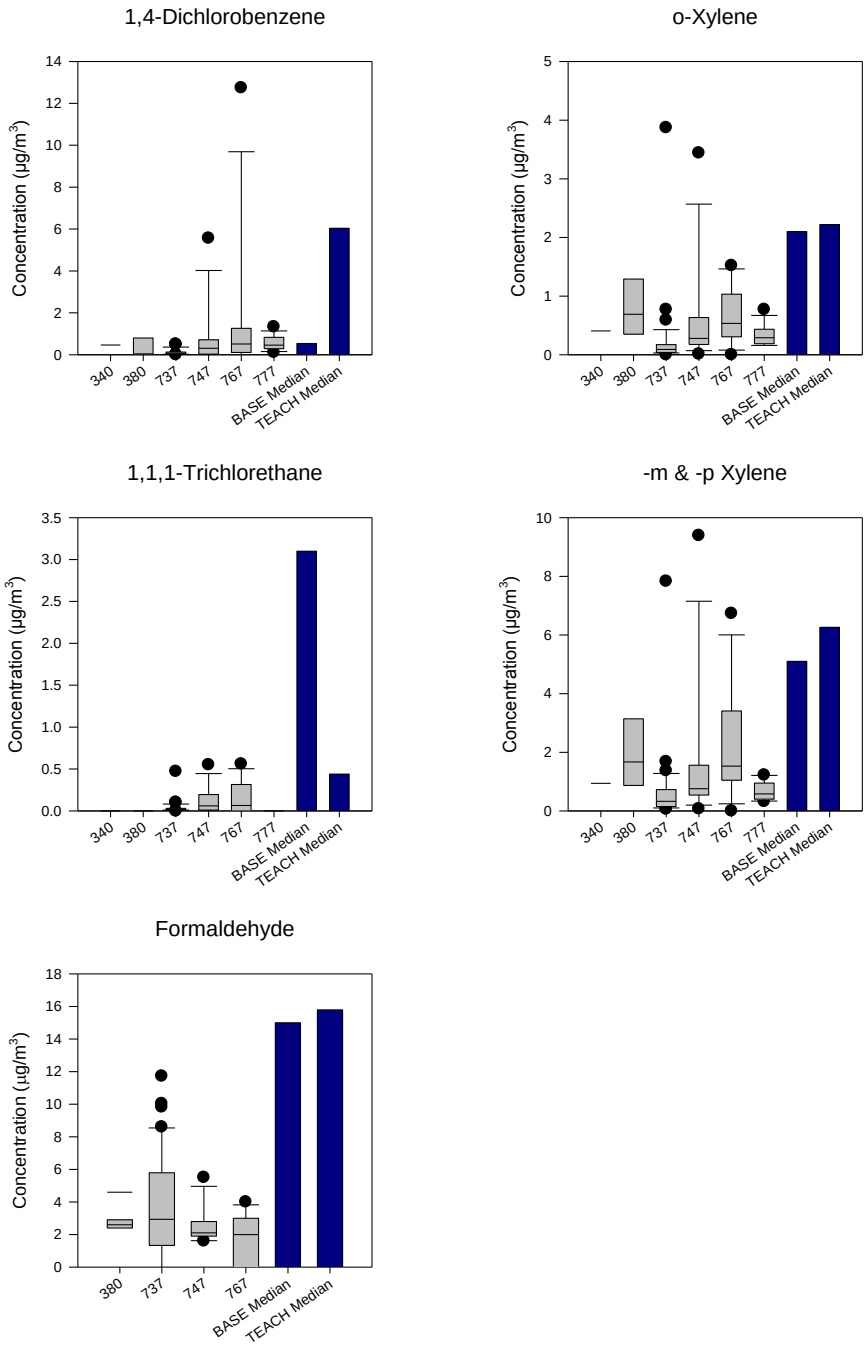

Figure 15. Box-plot distributions of VOC concentrations by aircraft type in comparison to the Building Assessment Survey and Evaluation (BASE) and the Toxic Exposure Assessment: Columbia-Harvard (TEACH) normative data for homes/offices. The BASE and TEACH bar represents the median BASE/TEACH value. VOCs shown did not exceed the BASE and TEACH 95th percentile values (not included in the figure).

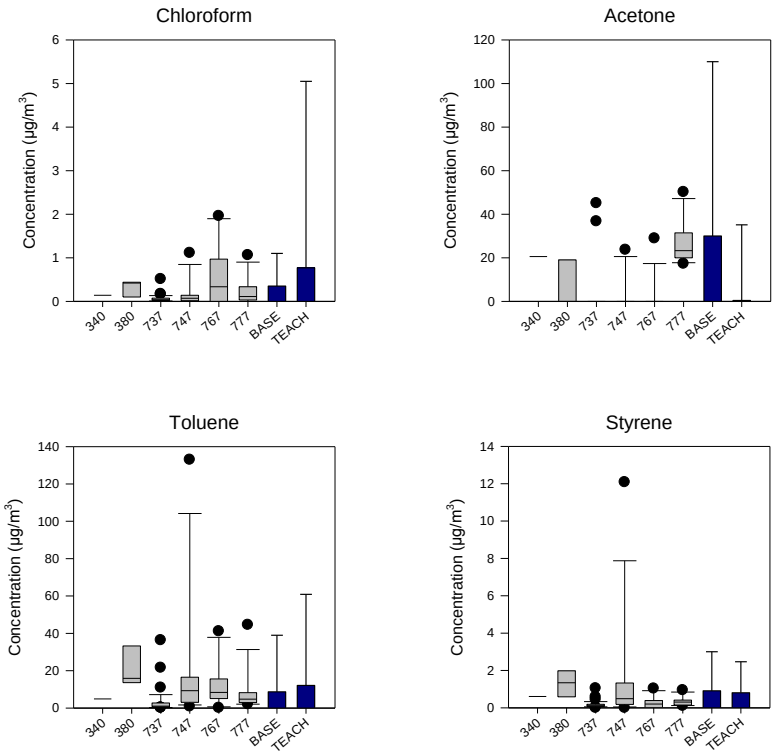

Figure 16. Box-plot distributions of VOC concentrations by aircraft type in comparison to the BASE and the TEACH normative data for homes/offices. The BASE and TEACH bar represents the median BASE/TEACH value. VOCs shown did not exceed the BASE and TEACH 95th percentile values (not included in the figure).

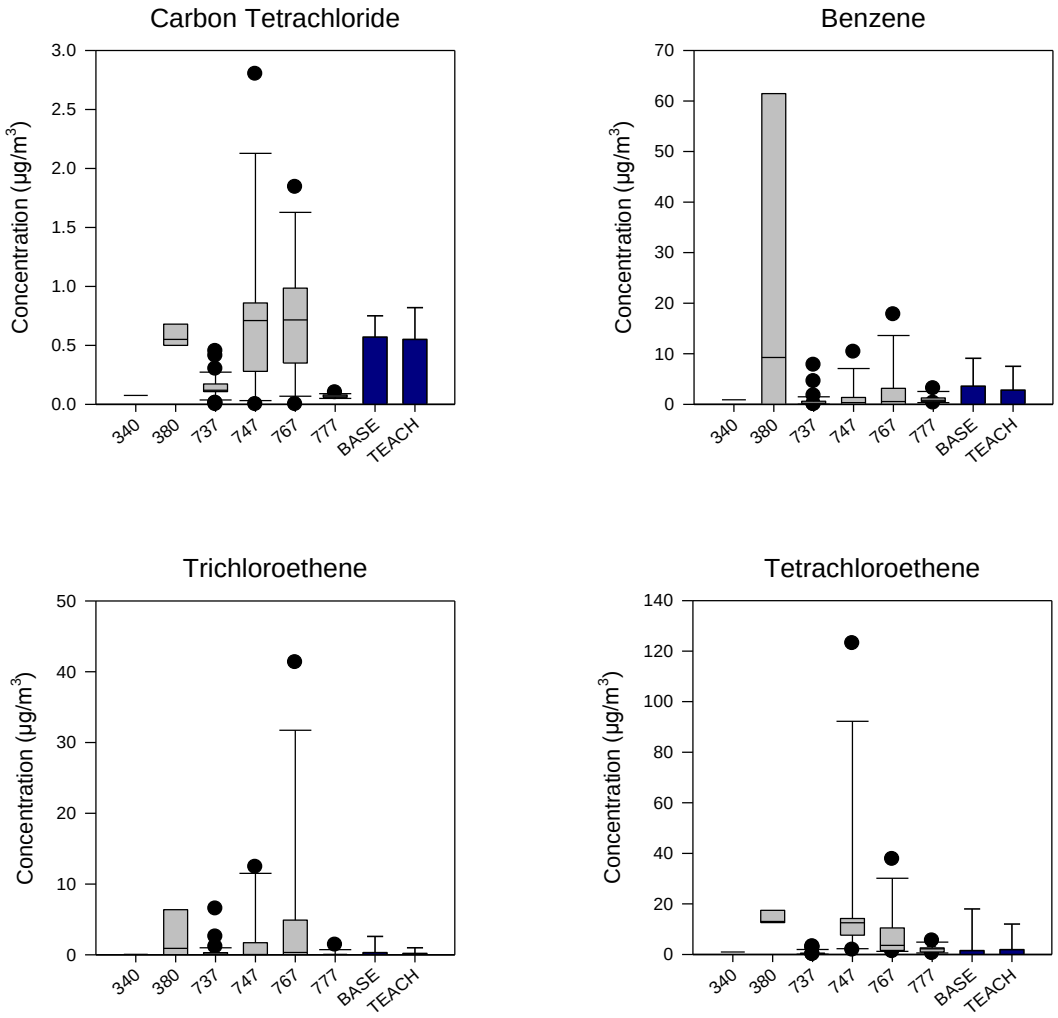

Figure 17. Box-plot distributions of VOC concentrations by aircraft type in comparison to the BASE and TEACH normative data for homes/offices. The BASE and TEACH bar represents the median BASE/TEACH value. VOCs shown did not exceed the BASE and TEACH 95th percentile values (not included in the figure).

Tricresyl Phosphate (TCP)

TCP samples were collected only for airlines B and C, and TCP was detected in only one airline B sample, 0.1 ppt (T[m]CP). Detection limits were calculated as the higher value of either three times the standard deviation of the field blanks or the method detection limit for each target compound. A summary of the results is shown in Table 16. For airline C TCP analysis, two additional isomers identified by De Nola et al. (2008) as constituents of jet engine oil were added to the target analyte list.

Table 16. Limits of detection and percentage of samples above the LOD for TCP analysis (total N=71 samples).

Target Compound	Batch 1 LOD (ng)	Batch 2 LOD (ng)	N > LOD	% Samples > LOD
airline B	N=16	N=19		
T(o)CP	0.9	0.4	0	0
T(m)CP	0.64	0.4	1*	2.8
T(p)CP	0.74	0.4	0	0
airline C	N=19	N=17		
T(o)CP	0.4	0.4	0	0
T(m)CP	0.4	0.4	0	0
T(p)CP	0.4	0.4	0	0
T(m,m,p)CP	0.4	0.4	0	0
T(m,p,p)CP	0.4	0.4	0	0

***** The one sample detected of T(m)CP in airline B was at 0.1 ppt.

Semi-Volatile Organic Compounds (SVOCs)

SVOCs were sampled on 63 flights of airlines B and C, but final results are available for only 21 flights of airline B, as of this report date. The remaining SVOCs samples from airline B were analyzed only for flame retardants under a separate project. Over-recovery of analytes from matrix spike QA samples from airline C are still under investigation. Table 17 lists the target analytes and the number of samples above the limit of detection (LOD), and Figure 18 presents box plots of the SVOC samples. Fragrance-related SVOC ($SVOC_f$) detected in the flight samples were: hexyl cinnemal, AHTN, HHCB and benzyl acetate. The concentrations of these four $SVOC_f$'s exhibited an inverse relationship with ventilation (Figure 18), but due to the limited number of samples and detection limits no significant association can be inferred.

Table 17. Number and percentage of samples above the LOD for SVOCs measured in 21 flights in airline B. $SVOC_f$ are underlined.

	N > LOD	% >LOD		N > LOD	% >LOD
Diethyl Phthalate	19	86	AHTN	17	77
Dibutyl Phthalate	5	23	PCB 52	7	32
Butyl Benzyl Phthalate	5	23	Fluoranthene	4	18
Di-2-Ethyl Hexyl Phthalate	5	23	Pyrene	5	23
Limonene	19	86	Tris(dichloro)phosphate	4	18
Phenethyl Alcohol	0	0	Benzo(a)anthracene	6	27
Benzyl Acetate	16	73	Chrysene	3	14
Naphthalene	15	68	4,4'methylene bis(o-chloroaniline)	0	0
Biphenyl	16	73	Sumithrin	1	5
Acenaphthene	14	64	cis-Permethrin	3	14
Fluorene	17	77	trans-Permethrin	3	14
Hexyl cinnemal	17	77	Benzo(b)fluoranthene	3	14
Tris(2-chloroethyl)phosphate	6	27	Benzo(k)fluoranthene	2	9
PCB 11	3	14	Benzo(e)pyrene	1	5
Phenanthrene	17	77	Benzo(a)pyrene	5	23
Anthracene	7	32	Dibenzo (a,h)anthracene	2	9
HHCB	17	77	Indeno(1,2,3-cd)pyrene	2	9
			Benzo(ghi)perylene	3	14

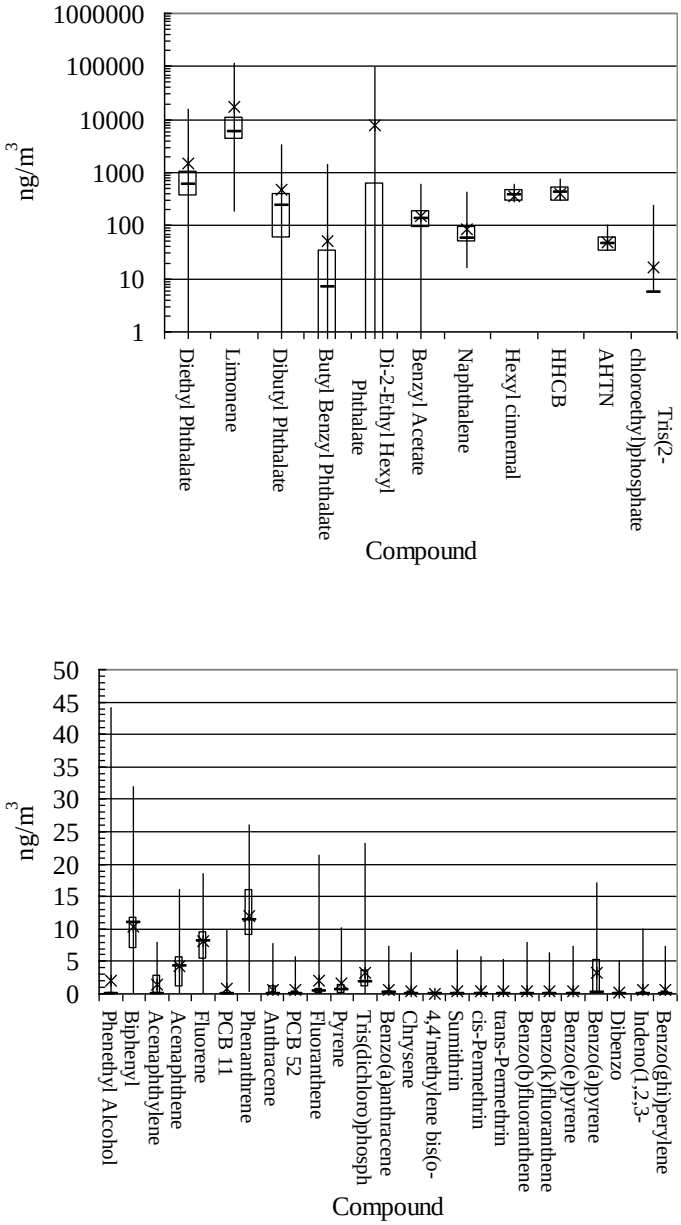

Figure 18. Box plots of SVOCs (ng/m^3) measured on 21 flights on airline B

DISCUSSION

Cabin environmental conditions were monitored on 83 commercial flights which varied by aircraft model, passenger load factor and several other flight-specific characteristics. Except for low pressure, and occasionally high ozone, extremely dry air and perhaps slightly higher noise levels, the air quality and environmental conditions in the passenger cabin of commercial airplanes are comparable or better than conditions reported for offices, schools and residences, with a few exceptions. While most environmental conditions met minimum standards, some exceptions were noted. Further, reported for the first time are carbonyls formed in ozone reactions. These and other aldehydes are recognized irritants, and together with dry air may contribute to dry eye symptoms and fatigue.

Pressure levels did not exceed the lowest limit of 75.3 kpa (cabin equivalent altitude of 8,000 ft) required by the FAR 14 CFR 25.841 (CFR 2010a), and overall were similar to cabin pressures reported previously, ranging between 72 kpa and 100 kpa (Spengler et al. 1997; Cottrell et al.1995). Cabin pressure did vary among the different aircraft models. Even though cabin pressures complied with FAA FAR regulation, more recent evidence on healthy subjects associated prolonged durations at reduced pressure (even below the threshold of 8,000 feet equivalent, i.e. 7,000 feet altitude) with moderate oxygen desaturation. Muhm et al. (2007) reported a decrease of approximately 4.3% between 7,000 and 8,000 feet that contributed to increased discomfort in unacclimated participants after 3 to 9 hours.

The aging population of air travelers underscores the importance of understanding the effects of mild hypoxia in older healthy and health-compromised passengers. Related ACER research studied the blood oxygen saturation response of such individuals during a 5-hour simulated flight in a hypobaric chamber with pressurization equivalent to a commercial flight at 7,000 feet altitude (McNeely et al. 2011). These typical cabin pressures resulted in moderate desaturation in vulnerable seniors. Importantly, current medical guidelines for determining passenger fitness to fly and the need for in-flight supplemental oxygen underestimated the prevalence of desaturation during flight found in this study. While current medical guidelines consider baseline health conditions, health status (i.e., healthy senior or cardiac patient) did not predict the degree of desaturation during flight. However, health status *was* associated with the level of compensatory response and significantly different compensatory responses were seen in cardiac patients, suggestive of greater physiological loads. Furthermore, passengers with cardiac disease experienced greater frequency of arrhythmias at cabin altitudes. These results suggest that longer flight durations (i.e., greater than the 5-hour duration evaluated in these studies) may be even more stressful for healthy and unhealthy seniors, especially when flying to high altitude destinations. In all, the pressure studies have identified the potential need for added protections for senior flyers either in terms of revised rule-making for cabin altitudes, recommended guidelines for use of supplemental in-flight oxygen, or accepted use of personal monitors that measure oxygen saturation in order to prevent moderate hypoxia in vulnerable passengers.

The Aerospace Medical Association, Aviation Safety Committee released a position paper recommending further research about the effects of mild hypoxia for passengers and for these worker groups in particular (Aerospace Medical Association 2008). A number of research studies have shown performance decrements between 5,000 and 10,000 feet, notably at altitudes

below the current requirement for supplemental oxygen. In addition, the aging workforce of crew and pilots may be vulnerable because of the reduced oxygen capacity related to aging and because of the increased metabolic demands for oxygen in crew as they push utility carts down the aisles of jumbo planes at 34,000 feet.

In sum, the current FAA regulations for limiting cabin pressures to 8,000 feet equivalent altitudes allow for mildly hypoxic conditions. These environments are expected to have little effect on healthy passengers, pilots or crew, however, older individuals and persons with compromised cardiopulmonary status may be at risk. More than thirty years has passed since the thresholds for pressure were set. In the meantime, new composite materials in the fuselage that withstand greater pressure differential between the cabin and outside air provide a potential for reducing the maximum cabin altitude to less than 8,000 feet. Newer aircraft are able to fly higher and for longer periods, extending the exposure to hypoxia. The need for closing these gaps in information has never been more important given the rise in older and health compromised passengers.

The ventilation system must be designed to provide each occupant with an airflow containing at least 0.55 pounds of fresh air per minute according to the FAR14 CFR 25.831 (CFR 2010b) and 3.5 L/s/p according to ANSI/ASHRAE 161-2007. Using measured CO_2 to calculate ventilation rates, the majority of the flights were in compliance with the 3.5 L/s/p standard set by ASHRAE (2007). In six cases the central estimate for ventilation rates were below 3.5 L/s/p. However, CO_2 is not a perfect proxy for ventilation since it is contingent upon the occupancy density, assumed exhaled CO_2 rate, and mixing efficiency. Measurements were made in the mid-section of economy class seating and for these calculations of ventilation rates the air mixing effectiveness within the cabin was assumed to be unity. While the turnover rate of cabin air is quite high (every 6 to 12 minutes) mixing of the air within the cabin may not be uniform, resulting in a mixing efficiency less that one. To the extent that internal mixing efficiencies are not equal to 1.0 the ventilation calculated here may be underestimated/overestimated.

Estimated ventilation rates presented here did not account for the presence of young children with lower CO_2 generation rates. We do not have information about the age and gender composition of the monitored flights. However, including children in these estimates would bias ventilation rate estimates downward in proportion to age adjusted CO_2 generation rates. CO_2 generation rates are known to be a function of metabolic oxygen demand. If a significant number of passengers slept during flight, then the CO_2 generation rates would be lower than those used in this report and the estimated ventilation rates would need to be adjusted downward. The FAR requirements set a design criterion for the ECS based on 0.55 lbs of air per minute per passenger at full load. While some flights had estimated ventilation rates below the equivalent 3.5 L/s/p, it does not imply that the FAR was being violated for those flights since the FAR that applies to a specific aircraft depends on which FAR amendment was in effect when that model was in design. Also, the presence of CO_2 in the cabin from dry ice, if not accounted for, would result in a downward bias in estimates of ventilation rates.

Flights with higher passenger load factors had higher CO_2 levels and hence lower ventilation rates. Across the aircraft models in this study, estimated ventilation rates varied from

about 3 L/s/p to > 10 L/s/p. The study did not include commuter fleets or some models reputed to have lower ventilation rates (i.e., B757), so generalizing to the current fleet of commercial aircraft is limited. Additional factors that influence internal mixing within the cabin are CO_2 generation rates for different metabolic activities for a more age and gender diverse passenger composition; accounting for these factors will further refine estimates of ventilation rates.

Even with these limitations, the concentrations of several contaminants appeared to be inversely proportional to estimated ventilation rates. These include the sum of a subset of SVOCs identified as related to fragrances, carbonyls produced by ozone reactions, as well as some VOCs. The first interpretation that has merit is that these compounds have sources related to humans since they also demonstrate proportionality to passenger load factor. Ventilation rates were not associated with ozone and ultrafine particle concentrations, which were more episodic and independent of passenger loads.

While recognizing the limitations of this particular study it is important to consider the role of ventilation and transmission of infectious agents. Recently, an expert panel convened by ASHRAE critically reviewed the literature and concluded that there were associations between low ventilation rates and an increased risk of allergies, sick building syndrome (SBS) symptoms and respiratory infections (Sundell et al. 2011). It is not clear at this time whether the cabin environment's high air exchange rates and HEPA filtration mitigates against airborne disease transmission.

While ambient atmospheric levels of ozone at cruising altitudes of commercial aircraft can exceed 0.5 ppm at times these high levels are not seen in the passenger cabin (Spengler et al. 2004). Ozone is unstable and is removed in the bleed air system and by deposition to surfaces (ASHRAE 2007; Coleman et al. 2008). However, removal rates may not always be sufficient to remove all ozone so elevated ozone in cabin air can occur. Ozone levels are sufficient to react with unsaturated hydrocarbons that may also be present in the cabin air (Weschler et al. 2007).

The majority of the time ozone levels were in accordance with FAR, 14CFR25.832 (CFR 2010c): only one flight approached the maximum ozone instantaneous FAR ozone level of 0.25 ppm (250 ppb); and three flights exceeded the maximum allowable 1-hour level (100 ppb). The ozone-related FARs were established in 1980. Since then there have been substantial advancements in the scientific evidence on the health effects of ozone (U.S. EPA 2011b).

EPA's Clean Air Scientific Advisory Committee (CASAC) recommended that the NAAQS for ozone be set within a range of 60 to 70 ppb over 8 hours. In a March 30, 2011 letter to EPA Administrator, Lisa Jackson, CASAC Chair Jonathan Samet asserted that their review of the ozone health literature shows "no threshold" or level below which there is no risk of decrement in lung function (Samet 2011). CASAC points out that even in healthy individuals clinically relevant responses have been shown at 60 ppb exposure. Large segments of the population include asthmatics, children, and elderly individuals with chronic lung and heart disease who are more vulnerable to increased exposure. None of these conditions would exclude individuals from flying, thus it is reasonable to begin a review the now three-decade old ozone FAR.

The World Health Organization for European States issues ambient air quality guidelines (WHO 2010). Table 18 summarizes their more serious findings on ozone exposure (note that 100 $\mu g/m^3$ is equivalent to 50 ppb ozone concentration). The WHO findings on adverse effects for exacerbation of symptoms for asthmatics and increased hospital admissions for respiratory conditions occur at concentrations reported for that aircraft cabin environment.

Table 18. Health outcomes associated with changes in ozone concentrations in epidemiological studies.

Health Outcome	**Change in O_3 concentration $\mu g/m^3$**	
	1-hour averaging time	8-hour averaging time
Increase in symptom exacerbation among adults or asthmatics (normal activity)		
25%	200	100
50%	400	200
100%	800	300
Increase in hospital admissions for respiratory conditions[a]		
5%	30	25
10%	60	50
20%	120	100

[a] Given the high degree of correlation between the 1-hour and 8-hour ozone concentrations in the field studies, the reduction in health risk associated with decreasing 1-hour and 8-hour ozone levels should be identical (WHO 2010).

Since commercial aircraft fly at altitudes where ozone concentrations might be greater than those typically found at ground level, some planes are equipped with ozone (catalyst) converters. A new converter dissociates approximately 95% of the ozone in the bleed air and has a useful life of 12,000 flight hours (ASHRAE 2007). In this study, one airline equipped its aircraft with ozone converters and these passenger cabins had a mean maximum 1-hour ozone value of 16.9 ppb compared to 26.5 ppb for flights without converters. While ozone was higher in flights without converters, most flights remained in compliance with FAR14CFR25.832 (CFR 2010c). Aircraft encounters with high ambient ozone air masses are episodic so cabin ozone levels exceeding WHO-recommended values may occur. This study, while confirming observations on cabin ozone reported elsewhere, cannot be used to infer the frequency at which elevated ozone occurs in commercial flights.

The passenger cabin air temperature average for all flights (24.6ºC) was higher than the passenger cabin temperature (22ºC) reported in previous studies (Lee et al. 1999; Lindgren and Norback 2002). Cabin temperatures are typically higher than the temperature set points for offices to compensate for the lower relative humidity.

The relative humidity average for all flights (11%) was lower than values listed in the literature, which range from 15% to 19% (NRC 2002; Lee et al. 1999; Lindgren and Norback 2002; Boschi and Haghighat 2005; Lee et al. 1999). Nordstrom et al. (1994) found that in

hospital settings increases in relative humidities from ranges of 25% to 35% to 40% to 45% significantly reduced airway symptoms. In a double-blind study, Lindgren, Norbäck and Wieslander (2007) increased the relative humidity in a B767 by 10% in the forward part of an airplane, and by 3% in the aft section and cockpit. Seventy-one crew members participated in a randomized trial of outbound and returning international flights. When the humidification device was operating, the cabin was perceived as being less dry (P=0.008), and fresher (P=0.002). The authors comment that their findings were consistent with workplace studies where a modest 10% increase in relative humidity (to 30-40%) in the winter decreased the sensation of dryness.

Fang and co-workers (1998) demonstrated that subjects had a more favourable perception of air with lower enthalpy (cooler and drier) than air that was warmer with more moisture. While the range of temperatures tested in their experiments were typical of those experienced on an airplane, the lowest humidity levels were only 30%. By extrapolation passengers would experience cabin air with lower enthalpy than Fang and co-investigators created in their test. Fang et al. (1998) started with "clean air" in the absence of typical indoor sources that emit chemical compounds/odors. They found that in the presence of these indoor sources study participants could readily detect the presence of irritating odors when the air was cooler and drier. Furthermore, sources acted additively, degrading the perception more in air with lower enthalpy. Perception of cabin air quality should be quite favorable for "clear air" conditions. The introduction of sources such as body metabolites, "dirty" seats and carpets, personal care products, cleaning compounds, jet exhaust, and bleed air contaminates would be more readily recognized and considered objectionable when present in the conditioned air of the cabin environment.

Importantly, some viruses have been shown to thrive in low humidity environments at similar levels to the mean levels found in this study. Past research on the influenza virus has focused on airborne viruses and generally suggests that survival and/or transmission is facilitated by low relative humidity (Weber and Stilianakis, 2008). The influenza virus has been found to persist in the environment for hours to days, allowing for secondary transmission of influenza via inanimate objects known as fomites**.** How long viruses survive on fomites is important to transmission potential when an uninfected person contacts that surface. The survival of viruses on surfaces is influenced by temperature and humidity. In a recent publication, Shaman and Kohn (2009) concluded that absolute humidity is the controlling factor in both the inactivation of influenza virus and the transmission of influenza. Further study about virus transmission in the cabin environment is warranted.

The sound level measured inside the aircraft was within the recommended level of 85dB (A), however this threshold considers 8-hour exposures only and offers little guidance for extended flights. A few studies have investigated sound levels inside the aircraft cabin. Spengler et al. (1997) found that sound levels ranged between 80 and 85dB. Küpper et al. (2010) reported that noise levels were below 85 dB(A) inside an ambulance version of a Learjet 35A while the levels of the noise produced by the engines outside the cabin were significantly above 85 dB(A). Sound levels in the B767 were lower than sound levels measured in other aircraft models, both wide and narrow body aircraft, with the exception of the A380. Too few A380 flights were monitored to draw statistical inference but sound measurements in the economy section appeared

to be systematically lower than similarly recorded measurements in other aircraft models. Aircraft noise is becoming a well-recognized issue and more modern aircraft have been redesigned to dampen noise levels by 4 dB (Holzman 1997). Considering the technological advances that now permit ultra-long flights, such as 22 hours, the attention to noise exposures is increasingly important, especially when considering concomitant exposure to turbulence and vibration. These exposures excite the central nervous system and have been shown to increase blood pressure, heart rate, and cause sleep disturbances, with effects that last after the exposure (Babisch 2006). Notably, noise regulations are generally set to address problems with hearing loss only.

Carbon dioxide levels were above the recommended levels set by ASHRAE (2007) but below the 5,000 ppm limit mandated by the CO_2 FAR, 14CFR 25.831 (CFR 2010b). However, the maximum values were slightly higher than values reported in the literature, which were 1,100 ppm - 1,700 ppm (NRC 2002; Lee et al. 1999; Lindgren and Norback 2002). Carbon dioxide levels in excess of 1,000 ppm, once thought benign, have recently been investigated (Satish et al. 2011). Twenty-two subjects were exposed in a double-blind chamber study to three levels of carbon dioxide: ambient room conditions with 600 ppm CO_2; 1,000 ppm ultrapure CO_2; and 2,500 ppm ultrapure CO_2. After a period of acclimatization, subjects took the Measurement of Decision Making Performance: Strategic Management Simulation (SMS) to evaluate executive decision making. This computer simulation has various possible scenarios with tasks that are potentially complex and volatile, have ambiguity, and have delayed feedback. The SMS has been used widely in professional settings, including health care, as it provides results on parameters for "decision making" (e.g., responsiveness, initiative, emergency responses, planning, strategy, etc.). The Satish et al. (2011) study is the first to examine the effects of moderate levels of CO_2 on executive decision making as measured by SMS. Figure 19 shows the overall performance across several functional groups of human decision making. The findings, if substantiated, have particular relevance to the airplane environment where CO_2 levels are typically between 1,000 ppm and 1,500 ppm (or higher) for extended periods. Satish and collaborators (2011) found statistically significant decrements in decision making performance at 1,000 ppm CO_2 that were of a magnitude to be important at the societal level. Larger decrements in decision making performance were observed at 2,500 ppm CO_2. These results are broadly consistent with the prior findings of Kajtar et al. (2006).

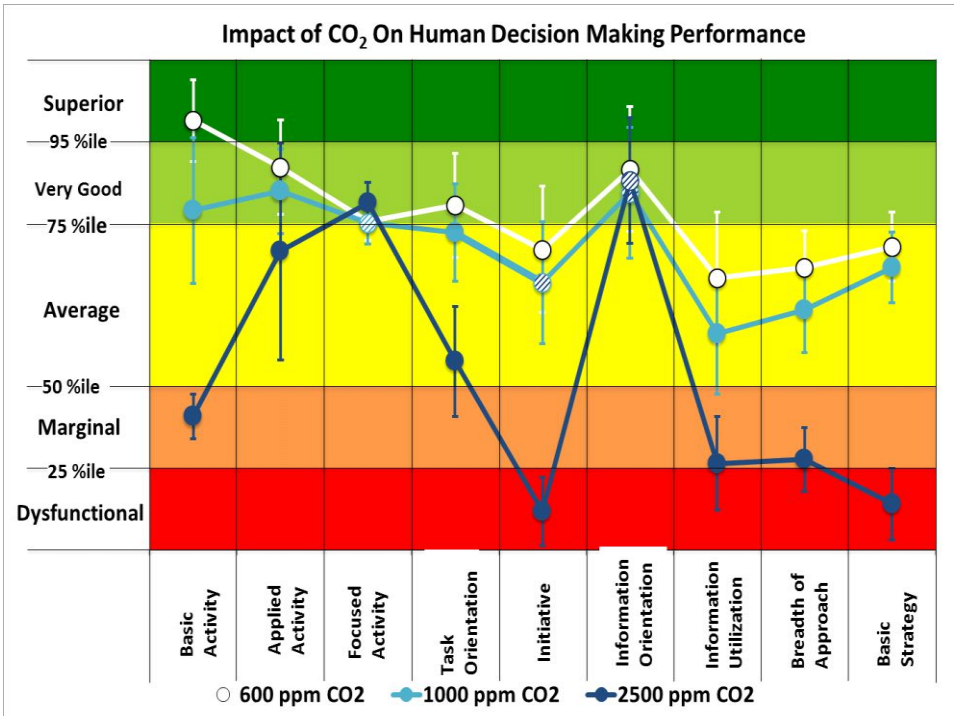

Figure 19. Results of decreased performance with exposure to CO_2 (after Satish et al. 2011)

Recent evidence has shown that ozone might react with unsaturated hydrogen compounds, such as those compounds found in furniture cleaning products, to form ultrafine particles, aldehydes and other compounds (Weschler et al. 2007; Wisthaler et al. 2005). In our study, ultrafine particles showed a positive trend with ozone, and in the absence of meal preparation, ozone was strongly associated with UFPs. Meal preparation has been noted by the flight scientists as a source of UFP generation, and Lindgren et al. (2007) noticed a regular but moderate increase in UFP counts (100 to 200 p/cm^3) when flights attendants heated bread and foods in the microwaves. These researchers also found that the concentration of UFPs varied within and across flights, reaching up to 300,000 particles/cm^3.[†] Evidence that ozone reactions are occurring is seen in the samples for ozone by-products: 6-methyl-5-heptene-2-one, octonal, nonanal and decanal, as measured on airline B. Figure 20 plots the concentration of 6-methyl-5-heptene-2-one versus ventilation for flights with total ozone exposures less than 35 ppb-hrs and flights greater than 35 ppb-hrs. Figure 21 plots the concentration of 6-methyl-5-heptene-2-one, octanal, nonanal, and decanal against ventilation for flights with total ozone exposures less than

[†]The *WHO Air Quality Guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide* (WHO 2006) state "Ultrafine particles (UF), i.e. particles smaller than 0.1 µm in diameter, have recently attracted significant scientific and medical attention. These are usually measured as a number concentration. While there is considerable toxicological evidence of potential detrimental effects of UF particles on human health, the existing body of epidemiological evidence is insufficient to reach a conclusion on the exposure–response relationship of UF particles. Therefore no recommendations can be provided as to guideline concentrations of UF particles at this point in time."

35 ppb-hrs and flights greater than 35 ppb-hrs. Thirty-five ppb-hrs is the median ozone total exposure over all 32 flights with ozone byproduct samples. Both plots show the concentrations of these compounds are affected by the presence of ozone as well as the ventilation. The flights with more than 35 ppb-hrs ozone have 6-methyl-5-heptene-2-one have on average concentrations four times higher than those with less than 35 ppb ozone. The three other ozone by-products measured: octanal, nonanal and decanal show similar relationships though not as strong (Figure 22). The eye and airway irritation of these reactive species need to be evaluated in the context of co-occurring ozone and these compounds.

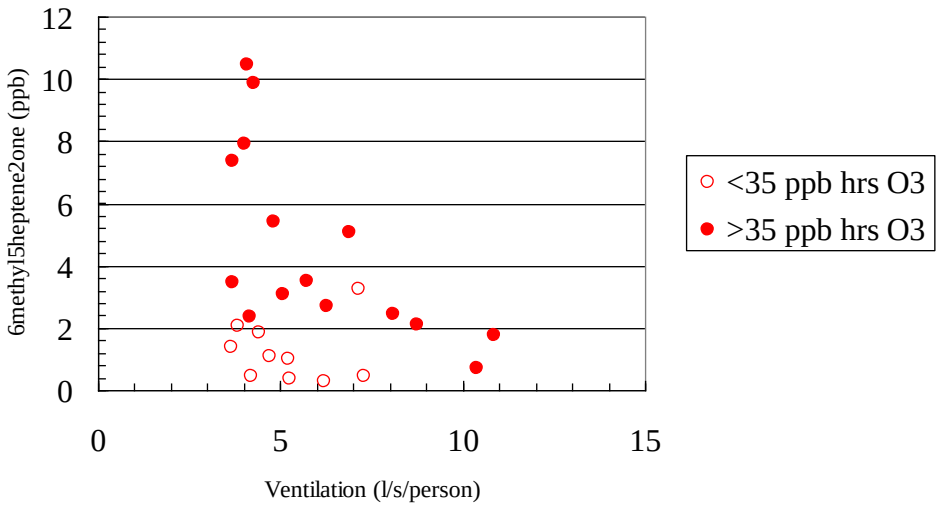

Figure 20. Cabin ventilation (Liters/second/person) plotted against cabin concentration 6-methyl-5-heptene-2-one (6-MHO), in ppb, for flights with a total ozone exposure less than 35 ppb hrs and flights with a total ozone exposure greater than 35 ppb hrs for 26 of the 32 airline B flights with detectable levels of 6-MHO. 35 ppb hrs was the median total ozone exposure for the 32 flights. Ventilation was of calculated using a G(CO2) value of 18.2 L/hr.

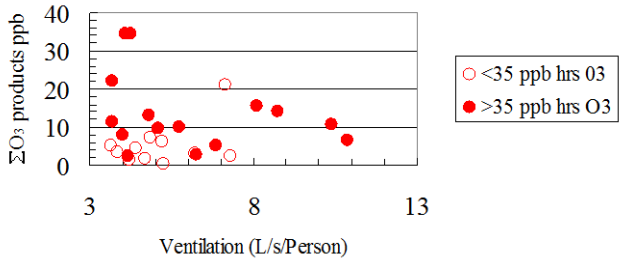

Figure 21. Cabin ventilation (L/s/p) plotted against the sum of the cabin concentrations of 6-methyl-5-heptene-2-one, octanal, nonanal and decanal (in ppb) for flights with a total ozone exposure less than 35 ppb hrs and flights with a total ozone exposure greater than 35 ppb hrs for 26 of 32 airline B flights with detectable levels of the sum of the four compounds. 35 ppb hrs was the median total ozone exposure for the 32 flights. Ventilation was calculated using a G(CO2) value of 18.2 L/hr.

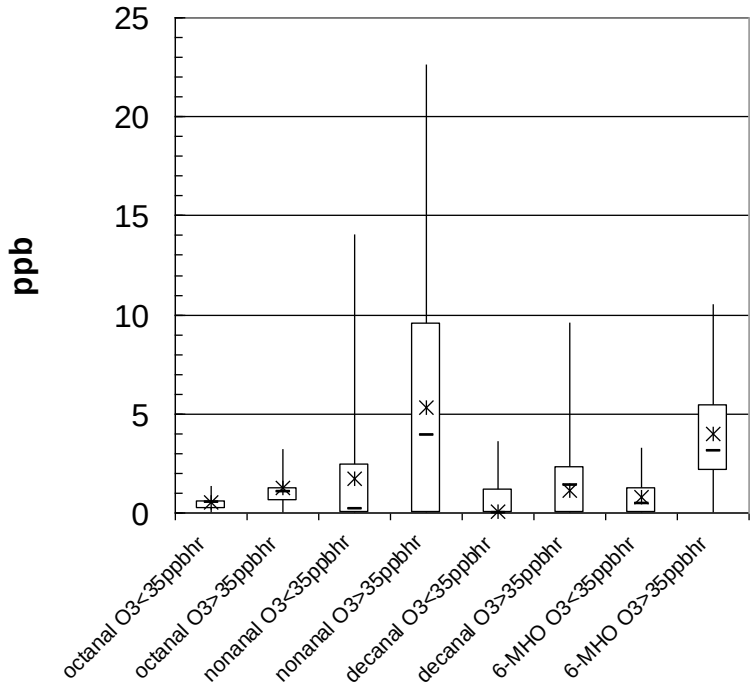

Figure 22. Box plot of ozone by-product concentrations with flights less than (n=16) and greater (n=16) than 35 ppb hr ozone exposure

Many of the VOC compounds concentrations were lower in the passenger cabin than what is typically reported of offices and residences (Brightman et al. 2008). The maximum levels of formaldehyde, m&p-xylene and o-xylene and acetone, averaged across flights, were higher than values previously reported inside aircraft cabins (Nagda and Rector 2003). Acetone and formaldehyde levels were correlated with ozone concentrations, suggesting that VOCs may undergo a chemical reaction in the presence of ozone. Elevated ethanol concentrations were consistent with previous studies that have attributed these levels to a large number of people inside a smaller cabin space and the service of alcoholic beverages during flight (Nagda and Rector 2003). The maximum range of acetaldehyde reported in the literature was between 26.4 $\mu g/m^3$ and 30.7 $\mu g/m^3$ in bleed air, and between 20.8 $\mu g/m^3$ and 70.2 $\mu g/m^3$ in the cabin air (NRC 2002). Acetone, tetrahydrofuran and isopropyl alcohol levels were lower than previously reported by Spengler et al. (1997).

There were some unexpected findings where the concentrations of several chlorinated compounds were higher for some models then found in indoor air. For example carbon tetrachloride and tetrachloroethene were elevated in the A380, B747 and B767 samples compared to the BASE (Brightman et al. 2008) and TEACH studies (Sax et al. 2004). Trichoroethene appeared higher in the A380 and B767 samples. The presence of chlorinated VOCs in the cabin environment needs to be explored further. It is unclear whether these compounds are associated with aircraft materials, cleaning practices (routine or during C-Check), or personal care products and clothing brought on board by passengers. Benzene was higher for the A380 in comparison to concentrations reported for offices and homes. There were a few

higher benzene concentrations found in the B767 samples as well. Toluene, another aromatic hydrocarbon, also showed higher levels in the A380, B747 and B767 samples. On occasion measurements taken on B737s showed elevated of aromatic compounds including 1,3-butadiene and MTBE. The reason for these aberrantly high values is unknown.

The 2004 Institute of Medicine report stated that there was insufficient data to establish the relationship between exposures to VOCs and the development of exacerbation of asthma (IOM 2004). Papers published after the IOM (2004) report was published offer some evidence linking VOCs to asthma and allergenic disease. A study of Australian children by Rumchev and co-workers (2004) linked an increase in VOC exposures to asthma symptoms. Dales and Raizenne (2004) in a literature review reported consistent findings of a relationship between VOCs and indicators for asthma. Additionally, Hulin and colleagues (2010) suggested that VOCs indoors are associated with increased asthma risk. Formaldehyde exposure has been associated with acute effects on eyes, nose and throat irritation. Vulnerable populations to formaldehyde exposures include children with allergic conditions (Hagerhed-Engman et al. 2006; Kulle 1993). Other links with VOC's and asthma have been reported by Dodson et al. (2012), Choi et al. (2010), and Bornehag et al. (2004).

LIMITATIONS

While continuous measurements were conducted for all the environmental conditions and most of the air contaminants, measurements on aldehydes and VOCs were performed only once, using integrated samplers. Notably, the sensors and samplers were positioned only in one location inside the cabin. Ventilation rates were estimated based on 100% ventilation efficiency rate and assumed that occupants are the only source for CO_2 inside the cabin. Also, we assumed that cabin air temperature was to equal to the operative temperature, in order to be able to compare it to the ASHRAE operative temperature standard.

Spatial variations in environmental conditions within the cabin could not be assessed in this study. If there were uneven distribution of sources, this might be an issue limiting generalization of our results. While some sources, like those associated with galleys, might lead to concentration differences in various sections of the cabin, the high overall air exchange rates of aircraft through a mechanical distribution system designed to supply air throughout the cabin certainly promotes a well-mixed environment. Thus, sampling location in the middle of economy class was not a limitation for the U.S. domestic flights.

CONCLUSIONS

Despite the challenging task of recruiting airlines to participate in the FAA/ASHRAE onboard study of cabin environments, three forward-looking carriers did permit assessments of cabin environmental conditions and passenger/crew perceptions during regularly scheduled commercial flights. Environmental monitoring was conducted on 83 flights and 4,306 passenger surveys. All flights maintained cabin altitudes below 8,000 feet.

Carbon dioxide values ranged from 863 to 2,056 ppm during cruise and were highly correlated (r^2=0.7) with load factors. While still very much below the 5,000 ppm limit set by FARs (FAA 2011), recent studies show impaired cognitive function at CO_2 exposures in the range of 1,000 ppm to 2,500 ppm, raising concerns about possible diminutions of flight crew performance that needs further evaluation.

Ventilation rates were calculated from the mean CO_2 levels measured during cruise. Estimating ventilation rates in this way has some inherent uncertainties, as has been discussed in this report. Nevertheless, calculations suggest that 7% of the flights monitored had estimated ventilation rates lower than ASHRAE 161-2007 recommended levels. Compliance with FAR 14CFR25.831 (CFR 2010b) could not be determined. The relationship among airplane ventilation rates, air pollutant concentrations, passenger perceptions of cabin air quality and airborne disease transmission need further study.

This study offers further evidence that cabin ozone levels can exceed the FARs and that ozone converters will substantially reduce the chance for high excursions. For the first time, direct evidence of ozone chemical reactions forming irritating carbonyls and ultrafine particles in aircraft cabins is presented. The role that these compounds and ultrafine particles play in passengers' perception of air quality or contribute to irritation related symptoms remain to be investigated.

Organophosphates, in the form of tricrysel phosphate (TCP) isomers, in cabin air were assessed in this study. No flight in this study experienced an incident of smoke or fumes in the cabin. Thus, the TCP samples taken on 63 flights, with analytical methods able to detect the o-, m- and p-TCP isomers at sub ppb levels, are only able to document background levels on commercial flights. Only one sample had a detectable level (0.1 ppt [parts per trillion]) of one of three isomers. For this single case T(m)CP was detected at sub ppb concentration. No conclusions can be made about the magnitude or frequency of exposures to TCP isomers that might occur as a consequence of a smoke-in-cabin incident. Background levels of three TCP isomers in cabin air of commercial flights, based on this study, are in the subparts per billion concentration range.

This onboard study of environmental conditions in the passenger cabin of commercial flights, along with evidence on health, irritation and discomfort of exposures to some of the environmental conditions that have emerged since many of the FARs related to cabin air quality were established, suggests that FAA ought to rigorously review the adequacy of current FARs. In fact, the first recommendation in the National Research Council (2002) report *The Airliner Cabin Environment and the Health of Passengers and Crew* called upon the FAA to provide "quantitative evidence and rationales to support sections of the FARs that establish air-quality-related design and operational standards for aircraft (standards for CO, CO_2, O_3, ventilation, and cabin pressure)". Results presented in this study may be interpreted as showing that for these selected set of flights there was general compliance with the FARs. However, the understanding of health effects and irritation has progressed substantially since most of the current FARs were established. The change in crew and passenger demographics over the years, reflecting the aging of U.S. populations, has implications for vulnerability to cabin conditions. Contaminants not

previously recognized or measured in the cabin environment have now been documented and will need to be considered in a review of some FARs.

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APPENDIX A

In-Flight/Onboard Monitoring: ACER's Component for ASHRAE 1262, Part 2

Air Sampling Instruments and Analytical Methods

Table A-1 List of Equipment							
Instrument	**Variable**	**Measurement Mode**	**Manufacturer**	**Model Number**	**Operating Range**	**Precision**	**Accuracy**
1	Ozone	Continuous	2B Technologies	205	1.5 ppb -100 ppm	± 1. ppb	± 1. ppb
2	Relative humidity/Temp	Continuous	TSI	7565 Qtrak	0–95% 32 140 F^o	± 3% 1 F^o	± 3% 1 F^o
2	Carbon monoxide	Continuous	TSI	7565 Qtrak	0 - 500 ppm	± 3 ppm	± 3%
2	Carbon dioxide	Continuous	TSI	7565 Qtrak	0 5,000 ppm	≤ ± 500 ppm at low end of scale	± 3%
2	Pressure	Continuous	TSI	7565 Qtrak	688-1238 mb	2% of reading	2% of reading
3	Pressure	Continuous	Setra	278-500	500 – 1500 mb	± 0.04mbar	± 0.6mbar
4 (	Noise	Continuous	Quest	1100	30-140 dB	1 dB	± 0.5 dB
5	Motion	Continuous	Crossbow Technology	CXTLA02	± 20°	0.03°	± 5% (est)
6	Respirable particles	Continuous	TSI	SidePak AM510	1 mg/m^3– 20 mg/m3	± 1 mg/m^3	
7	Volatile organic compounds (VOCs)	Integrated samples	BGI Omni pump	Omni	cc/min orifice (20 min sampling)	± 5%	± 5%
7	Semi-volatile organic compounds (SVOCs)	Integrated samples	BGI Omni pump	Omni	8 L/min	± 5%	± 5%
8 and 9	Data Acquisition	Continuous	Onset	HOBO U12-006	4 channels 0-2.5 Volts	2 mv or 2 % of reading	2 mv or 2 % of reading

Table A-2 List of target analytes

1,1,1-trichloroethane
1,1,2,2-tetrachloroethane
1,1,2-trichloro-1,2,2-trifluoroethane (Freon-113)
1,1,2-trichloroethane
1,1-dichloroethane
1,1-dichloroethene
1,2,4-trichlorobenzene
1,2,4-trimethylbenzene
1,2-dibromoethane
1,2-dichlorobenzene
1,2-dichloroethane
1,2-dichloropropane
1,2-dichlorotetrafluoroethane (Freon-114)
1,3,5-trimethylbenzene
1,3-butadiene
1,3-dichlorobenzene
1,4-dichlorobenzene
1,4-dioxane
2,2,4-trimethylpentane
2,3-dimethylpentane
2-butanone (methyl ethyl ketone)
2-hexanone (methyl butyl ketone)
3-Methylhexane
4,4'methylene bis(o-chloroaniline)
4-ethyl toluene
6methyl5heptene2one
acenaphthene
acetaldehyde
acetone
acrolein
AHTN
anthracene
benzene
benzo(a)anthracene
benzo(a)pyrene
benzo(b)fluoranthene
benzo(e)pyrene
benzo(ghi)perylene
benzo(k)fluoranthene
benzyl acetate
benzyl chloride
biphenyl
bromodichloromethane
bromoform (tribromomethane)
butyl benzyl phthalate
carbon disulfide
carbon tetrachloride (tetrachloromethane)
chlorobenzene
chloroform (trichloromethane)
chrysene
cis-1,2-dichloroethene
cis-1,3-dichloropropene
cis-permethrin
cyclohexane
decanal
di-2-ethyl hexyl phthalate
dibenzo (a,h)anthracene
dibromochloromethane
dibutyl phthalate
dichlorodifluoromethane (Freon-12)
diethyl phthalate
ethanol
ethyl acetate
ethyl chloride (chloroethane)
ethylbenzene
fluoranthene
fluorene
formaldehyde
heptane
hexachloro-1,3-butadiene
hexane
hexyl cinnemal
HHCB
Indeno(1,2,3-cd)pyrene
isoprene (2-methyl-1,3-butadiene)
isopropyl alcohol
limonene
m&p-xylene
methyl bromide (bromomethane)
methyl chloride (chloromethane)
methyl isobutyl ketone (4-methyl-2-pentanone)
methyl methacrylate
methyl tert-butyl ether
methylcyclohexane
methylene chloride (dichloromethane)
naphthalene
nonanal
octanal
o-xylene
PCB 11
PCB 52
phenanthrene
phenethyl alcohol
propene
propionaldehyde
Pyrene
styrene
Sumithrin
tetrachloroethene
tetrahydrofuran
toluene
trans-1,2-dichloroethene
trans-1,3-dichloropropene
trans-Permethrin
trichloroethene
trichlorofluoromethane (Freon 11)
tri-m,m,p-cresyl phosphate
tri-m,p,p-cresyl phosphate
tri-m-cresyl phosphate
tri-o-cresyl phosphate
tri-p-cresyl phosphate
tris(2-chloroethyl)phosphate
tris(dichloro)phosphate
vinyl acetate
vinyl chloride (chloroethene)

Continuous Instruments

Ozone

The Model 205 Ozone Monitor (2B Technologies, Boulder Colorado) was used to measure ozone. It is measures ozone ranging from low ppb (precision of ~1 ppb) up to 250,000 ppb (0-250 ppm) based on the technique of absorption of UV light at 254 nm. It uses two detection cells to improve precision, baseline stability and response time. UV light intensity measurements Io (ozone-scrubbed air) and I (unscrubbed air) are made simultaneously, which makes it possible to reduce the time between ozone measurements to 2 seconds. Fast measurements are especially desirable for aircraft measurements where high spatial resolution is desired. The manufacturer provided several customizations to the monitor including removing all exterior switches and ports and placing them on the instrument's mother board, mountain the instrument in a Pelican 1510 case. (Pelican Inc, Torrance, CA) The 1510 Pelican case is designed to fit under passenger airline seats. All interior surfaces of the pelican case were treated with anti-static paint. In flight the ozone monitor was powered by a Bescor NMH54, (Bescor Video Accessories Ltd, Farmingdale, NY) 4.5 AmpHr Nickel Metal Hydride rechargeable battery. Each battery provided 7 hours of continuous operation. The ozone monitor battery also powered the Setra pressure transducer and the Crossbow Tilt sensor.

Specifications of Model 205 Ozone Monitor, 2B Technologies, Boulder Colorado

Measurement Principle	UV Absorption at 254 nm; Dual Beam
Linear Dynamic Range	1.0 ppb to 250 ppm
Resolution	0.1 ppb
Precision (1σ; rms noise)	Greater of 1.0 ppb or 2% of reading
Accuracy	Greater of 1.0 ppb or 2% of reading
Limit of Detection (2σ)	2.0 ppb
NIST-Traceable Calibration	Yes
Measurement Interval	2 s (Data averaging options: 2 s; 10 s, 1 min, 5 min, 1 hr)
Flow Rate (nominal)	~1.8 Liter/min
Flow Rate Requirement	>1.2 L/min
Baseline Drift	<1 ppb/day, <3 ppb/year
Sensitivity Drift	<1%/day, <3%/year
Measurement Time, Frequency	2 s, 0.5 Hz
Response Time, 100% of Step Change	4 s, 2 points
Corrections	Temperature and Pressure
Operating Temperature Range	0 to 50 °C; -20 to 50 °C with low temperature modifications (rotary vane pump and lamp heater)
Operating Altitude Range	~0-30 km (~30-1000 mbar)

CO_2, CO, Temperature, RH and Pressure

CO_2, CO, Temperature, RH and Pressure were measured using a Q-Trak Model 7565 Indoor Air Quality Meter with a Model 982 probe (TSI Incorporated, Shoreview, Mn). This unit was selected because of its compact design and its small power requirement 4 AA alkaline batteries per nine hours of continuous operation. The specifications of each

individual sensors were comparable to the specifications of stand alone units for each parameter. The Probe was mounted on the top of the 1510 pelican case and the Q-trak unit was mounted on the inside cover. The Q-track unit was separated from the ozone monitor with 1 inch thick antistatic foam.

Q-TRAK Model 7565 (Model 982 Probe) Specifications

Carbon Monoxide (Probe Model 982)	Sensor Type Electro-chemical
Range	0 to 500 ppm
Accuracy	1 ±3% of reading or 3 ppm, whichever is greater
Resolution	0.1 ppm
Response Time	<60 seconds to 90% step change
Carbon Dioxide (Probe Model 982)	
Sensor Type	Dual-wavelength NDIR (non-dispersive infrared)
Range	0 to 5,000 ppm
Accuracy	2 ±3.0% of reading or ±50 ppm, whichever is greater
Resolution	1 ppm
Response Time	20 seconds
Temperature (Probe Model 982)	
Sensor Type	Thermistor
Range	32 to 140°F (0 to 60°C)
Accuracy	±1.0°F (0.6°C)
Resolution	0.1°F (0.1°C)
Response Time	30 seconds (90% of final value, air velocity at 400 ft/min [2 m/s])
Relative Humidity (Probe Model 982)	
Sensor Type	Thin-film capacitive
Range	0 to 95% RH
Accuracy	3 ±3% RH
Resolution	0.1% RH
Response Time	20 seconds (for 63% of final value)
Barometric Pressure	
Range	20.36 to 36.648 in. Hg
(517.15 to 930.87 mm Hg)	±2% of reading
Accuracy	
Operating Temperature	40 to 113°F (5 to 45°C)
Storage Temperature	-4 to 146°F (-20 to 60°C)

Ultrafine Particles

The Model 3781 Water-based Condensation Particle Counter (WCPC) (TSI Incorporated, Shoreview, MN) detects airborne particles down to 6 nm in diameter. Using single particle detection with live-time coincidence correction, the 3781 covers a wide particle concentration range up to $5x10^5$ particles/cm^3 . The WCPC uses water vapor* to enlarge particles for easy detection by an optical detector. It provides fast response to rapid changes in aerosol concentration. CPCs operate on the principle of enlarging small particles using a condensation technique to a size that is large enough to be detected optically. The Model 3781 brings the convenience of using water to measure submicrometer aerosol particles. Using a patented technique,(Technology from Aerosol Dynamics, Inc., United States Patent Number 6,712,881), an aerosol sample is drawn continuously through a cooled saturator and then into a heated condenser where water

vapor diffuses into the sample stream. Water diffuses to the centerline of the condenser faster than heat is transferred from the warm walls, producing super saturated conditions. Particles that are present in the sample stream (and larger than the minimum activation size) serve as condensation sites for the water vapor. Once condensation begins, particles grow quickly into larger water droplets and pass through an optical detector, where they are counted easily. The single-path sample flow design allows for precise, pressure-corrected flow control. An additional 0.48 L/min transport flow reduces particle diffusion losses at the sample inlet. A transport bypass lever allows measurement of aerosol flow rate directly at the sample inlet. The CPC was powered by a 10 Amp Hr Powerizer (AA Portable Power Corp, Redmond, CA). Each battery provided for 5 hours of continuous operation.

3781 Condensation Particle Counter Specifications

Min. Detectable Particle (D50)	6 nm, verified with DMA-classified sucrose particles
Max. Detectable Particle	>3 μm
Particle Concentration Range	0 to 5×105 particles/cm3, single particle counting with continuous live-time coincidence correction
Particle Concentration Accuracy	±10% at 5 × 105 particles/cm3
Response Time	<2 sec to 95% in response to concentration step change
Aerosol Flow Rate	0.12 ±0.012 L/min
Inlet Flow Rate	0.6 ± 0.12 L/min
False Background Counts	<0.01 particle/cm3, 1-hour average
Aerosol Medium	Air only, 10 to 35°C (50 to 95°F)
Ambient Temperature Range	10 to 35°C (50 to 95°F)
Ambient Humidity Range	0 to 90% RH, noncondensing
Inlet Pressure Operation (Absolute)	50 to 110 kPa (0.5 to 1.1 atm)
Inlet Pressure (Gauge)	0 to -2.5 kPa (0 to -10 in. water)
Condensing Liquid	Water (distilled water recommended)
Water System	Internal reservoir for up to 2-hour operation, external 250 ml bottle for up to 1 Week operation
Filling Method	Reservoir fed by gravity from external bottle via fill valve, controlled by float switch
Water Consumption	250 ml/week

$PM_{2.5}$

The SIDEPAK AM510 Personal Aerosol (TSI Incorporated, Shoreview, MN) is a laser photometer. It is compact and quiet which is ideal for the limited space aboard aircraft. The flow rate was set to 800 cc/min and a Harvard Mini-PEM was used as $PM_{2.5}$ a size selective inlet. The sidepak is powered by 6 AA Alkaline batteries, which provided 10 hours of continuous operation.

SIDEPAK AM510 Personal Aerosol Monitor Specifications

Sensor Type	90° light scattering, 670 nm laser diode
Aerosol Concentration Range `	0.001 to 20 mg/m^3 (calibrated to respirable fraction of ISO 12103-1, A1 test dust)
Particle Size Range	0.1 to 10 micrometer (μm)
Minimum Resolution	0.001 mg/m^3
Zero stability	±0.001 mg/m3 over 24 hours using 10-second time-constant
Temperature Coefficient	Approximately +0.0005 mg/m^3 per °C (for variations from temperature at which instrument was last zeroed)

Flow Rate Range	User-adjustable, 0.7 to 1.8 liters/min (L/min)
Operating Range	0 to 50°C (32 to 120°F)
Storage Range	-20 to 60°C (-4 to 140°F)

Inclinometer/Tilt Sensor

To measure pitch and roll we used the CXTA02 (Crossbow Technologies, Milpitas, CA) dual axis analog inclinometer design centers on a highly stable silicon micromachined capacitive inclination sensor element. The CXTA series is fully signal conditioned with a high level analog output(s), and optional analog temperature output. One reading was collected every two seconds. The damping constant of the inclinometer was chosen to respond adequately to movements of aircraft associated with turbulence, but not to higher frequency noise. The two-axis, solid state CXTLA02 by Crossbow Technology is compact (1" x 2" x 1"), lightweight (~0.1 lb), and will measure pitch and roll angles as large as ± 20°.

CXTA02 Inclinometer Specifications

Parameter		Units
Linear Angular Range	± 20°	
Full Angular Range	±75°	
Angular Resolution	0.05°	rms
Sensitivity	35	mV/°
Scale Factor Drift	0.01	%/°C
Zero Angle Voltage	2.5±0.15	Volts
Zero Angle Drift	1	mV/°C
Zero Angle Drift	0.2	°/°C
Non-Linearity	0.4°	
Bandwidth	125	Hz
Settling Time	0.2	Sec.
Alignment	± 1°	
Crossaxis Sensitivity	5	%
Storage Temperature	-55 to 85	°C
Operating Temperature	-40 to 85	°C
Vibration	10	Grms
Shock	2000	G
Supply Voltage	"8-30"	VDC
Current	8	mA

Sound Level

The Quest Model is a precision Class/Type 1 sound level meter. It is RFI-shielded. . Its dynamic range is large (30-140 dB), covers the levels expected in typical aircraft environment. The instrument is lightweight (~0.7 lbs), runs off a 9V battery (10 hours of continuous operation), and has excellent precision (1 dB) and accuracy (±0.5 dB).

Quest Model 1100 Sound Level Meter Specifications

Measurement Range	30 to 140 dBA
	40 to 140 dBC
Microphone	
Size	13.5 mm
Type	Electret
Preamp	Optional
Internal Filters	A,C
Response Time Constants	F, S
Exchange Rates	N/A
Outputs	AC/DC
Temperature Range	
Operating	-10°C to 50°C
Storage	-20°C to 60°C
Standards	
Class/Type	1
ANSI S1.4	Yes
ANSI S1.43	N/A
IEC 60651	Yes
IEC 60804	N/A
IEC 61672-1	Yes
CE Mark	Yes
ETL Intrinsic Safety Approval	Yes
CSA Intrinsic Safety Approval	Yes

Pressure (Secondary Sensor)

A Setra Model 278 pressure transducer (Setra Systems Inc, Boxborough, MA) served as a secondary pressure sensor.

Model 278 Specifications

Full Scale Pressure Output	2.5 VDC
Zero Pressure Output	0 VDC
Accuracy (RSS Method)	±0.25% Full Scale
Type of Pressure	Absolute
Pressure Range (hPa/mb)	500 to 1100
Temperature @	Accuracy (hPa/mb)
+20ºC (+68ºF)	±0.6
0 to +40ºC (+32º to +104ºF)	±1.2
-20º to +50ºC (-4º to +122ºF)	±2.0
-40º to +60ºC (-40º to +140ºF)	±2.5
Thermal Effects	Temperature
Operating °C (°F)	-40 to +60 (-40 to +140)
Storage °C (°F)	-60 to +120 (-76 to +248)
Media	Non-condensing air or gas

Integrated Samples

Volatile Organic Compounds (VOCs) Ozone Reaction By-products and Carbonyls

Methods

For airline A, VOC samples were collected using Entech Instruments, 400 ml silonite coated evacuated canisters. For airlines B and C, VOC samples were collected on stainless steel, multi-bed thermal desorption tubes (TDTs) from Supelco, triple sorbent tube multi-bed TDTs with 200 mg of Carbopack B, 230 mg of Carbopack X and 170 mg of Carboxen 1001 (Supelco/Perkin-Elmer), following USEPA Compendium Method TO-17: "Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes". Ozone reaction by products were collected on stainless steel, thermal desorption tubes (TDTs) from Supelco, packed with 500 mg Tenax A. The tubes were conditioned prior to their use, as described in TO-17, by heating the tubes at 350°C for 2 hours and passing 50 mL/min of pure helium gas through them. In addition, used tubes were re-conditioned for 15 minutes after analysis before returning to the field. Flows were collected at 27 cc/min (sd 6.2 cc/min) using a battery powered Omni Pump (BGI, Waltham, Ma). Final volumes were corrected to STP.

VOC samples were analyzed on Perkin-Elmer Automatic Thermal Desorber (ATD) interfaced to a Hewlett Packard GC/MSD using EPA method TO-17. The ATD transfer line connects directly to the J&W Scientific DB-1 column inside the GC oven. Dry purge and internal standard (IS) addition was accomplished in one step. Sample tubes were placed on a spiking device (tubing connected to an ultra high purity nitrogen tank with fitting for the tube) with carrier flow of 75 mL/min. A vapor phase IS was injected into the device and the tube was kept in place for 5-30 minutes. The vapor phase IS was made from liquid standards in solution (usually methanol) of a known concentration that are injected as a known volume into a 2 L static dilution bottle. A volume of vapor was drawn up with a gas-tight syringe and injected into the injector-port/spiking device with flow onto the sample tube. Initial calibration standards were prepared the same way. Drawing different volumes yields different masses and thus the different levels of calibration.

For airline B, Ozone reaction by product samples were analyzed on Perkin-Elmer Automatic Thermal Desorber (ATD) interfaced to a Hewlett Packard GC/MSD using EPA method TO-17. Flows were collected at 35.5 cc/min (sd 8.8 cc/min) using a battery powered Omni Pump (BGI, Waltham, Ma). Final volumes were corrected to STP. The ATD transfer line connects directly to the J&W Scientific DB-1 column inside the GC oven. Dry purge was accomplished in one step. Sample tubes were placed on a device (tubing connected to an ultra high purity nitrogen tank with fitting for the tube) with carrier flow of 75 mL/min. The tube was kept in place for 5-30 minutes. Calibration standards were made from liquid standards in solution (usually methanol) of a known concentration that are directly injected as a known volume onto clean TDTs. Injecting different volumes yields different masses and thus the different levels of calibration.

For airlines A, B and C, Formaldehyde, acetaldehyde, acetone and propionaldehyde were sampled actively using a commercially available sampler 2,4-dinitrophenylhydrazine (DPNH) coated silica cartridges (Waters Associates, Milford, MA). Samples were collected at 71.2 cc/min (sd 8.8 cc/min) and stored at –4°C. The samples were prepared by desorbing the DNPH derivative from the substrate with 5 mL of acetonitrile. This was done in a vacuum chamber with 12 sample positions, each fitted with a valve to control the extractant flow rate to approximately 1 mL per minute. The extracts were collected directly into 5 mL volumetric flasks or graduated test tubes. After removing the vacuum the samples were diluted to 5 mL with acetonitrile. Aliquots were pipetted into special 1 mL amber vials (Whatman mini-prep vials with 0.45 µm filter) for chemical analysis.

Formaldehyde, acetaldehyde, acetone and propionaldehyde samples were analyzed by High Performance Liquid Chromatography (HPLC) with ultraviolet detection using Agilent 1100 series HPLC equipped with a quaternary pumping system, a degassing unit, a 100-position autosampler, a thermostatted column compartment and a UV-visible variable wavelength detector (VWD) set at 360 nm. The mobile phase was a mixture of water, acetonitrile, and tetrahydrofuran at a flow rate of 1.5 mL/min. A 20 microliter sample was injected and the compounds including the DNPH derivatives were separated in less than 30 minutes with a gradient on a 150 mm x 3.9 mm ID Waters reverse-phase Nova-Pak C_{10} column. The data were processed automatically with the Agilent Chemstation© Software.

Detection limits were calculated by the higher value of either three times the standard deviation for each target compound of the field blanks or the method detection limit for each target compound of the instrument as determined by the Method TO-17, section 14.2. Method Detection Limit.

TCP

For airlines B and C, A sampling manifold split the flows from the pumps to obtain the target flow for each sample type. Flows for each sample were measured using a TSI model 4146 volumetric flow meter and recorded at sample set up and take down and periodically checked during the flight using a volumetric flow meter (Shoreview, Mn). Tricresyl Phosphate (TCP) samples were collected on Whatman QMA 37 mm quartz filters at flow rates of 1.8 to 4.5 liters per minute (Lpm). Filters were used as received.

Extraction

Extraction was accomplished by sonication. Each Whatman QMA 37mm quartz filters was placed inside a clean 8 mL vial and 5-6 mL dichloromethane (DCM) was added to each vial to ensure complete coverage of the filter. Vials were sealed with a Teflon-lined screw cap and sonicated for 30 minutes. Water in the sonication bath was kept chilled to approximately 4 °C with “blue-ice” packs. Each extract was transferred by Pasteur pipette to a clean 8 mL vial. The 5-6 mL extracts were placed under a gentle stream of nitrogen and reduced to dryness. A syringe was used to add 500 µL of Toluene to each vial, which was vortexed to ensure that Toluene rinsed the sides of the vial adequately. An aliquot was withdrawn and placed into an insert in the analytical vial to be placed on the GC/MS instrument.

Matrix Spiking
Two procedural blanks (PB) (unspiked clean filters) and six matrix spikes (spike of the target analyte) were analyzed The six matrix spikes were further divided into three each of low and high levels. The spike solution had a concentration of 100.0 ng/mL for each TCP isomer: tri-o-cresyl phosphate, tri-m-cresyl phosphate, and tri-p-cresyl phosphate (Accustandard, New Haven, CT). Spike volumes were 5.0 µl and 50.0µl for the low and high spikes, respectively. This yielded low spike amounts of 0.50 ng/filter and high spike amounts of 5.0 ng/filter.

Analysis
Samples are analyzed on an Agilent 6890N Gas Chromatograph with an attached 5975 Mass Spectrometer. The GC/MS is operated in Selective Ion Monitoring (SIM) mode with Electron Impact Ionization (EI). Separation is by capillary column, an HP-5MS from Agilent. Column dimensions are 30m x 250 um (id) x 0.25 um (film thickness). A four-point calibration curve was established using standards at 0, 2, 4, and 10 ng/mL.

Detection limits were calculated by using the higher value of either three times the standard deviation for each target compound of the field blanks or the method detection limit for each target compound of the instrument. The method of detection limit is calculated by analyzing nine replicate spiked samples (1 ng) and multiplying the standard deviation of the replicate samples by the appropriate Students' t-value at the 99% confidence level (2.90 for nine replicates).

SVOC

Flows for SVOCs averaged from 3.6 LPM (0.46) LPM (depending on flow requirements of other sample types collected concurrently). Flows for each sample were measured using a TSI model 4146 volumetric flow meter (Shoreview, Mn) and recorded at sample set up and take down and periodically checked during the flight. Samples were collected on either SKC model 226-143 glass sorbent tubes, 22 mm by 100 mm, packaged by SKC with 1.5 grams of XAD2 sandwiched between two 3.0 cm puf plugs or URG model URG-2000-30PUF-1 glass sorbet tubes, 28 mm by 137 mm, packed by Battelle Laboratory with 5 grams of XAD2 sandwiched between two 1.9 cm puf plugs. The sorbent tubes were shipped and maintained chilled after field spiking with deuterated surrogates until sample extraction.

Soxhlet extraction with dichloromethane (DCM), and concentration to 0.1 mL prior to analysis in the electron impact (El) GC/MS multiple ion detection mode for the majority of the analytes, followed by negative chemical ionization (NCI) GC/MS of the same extract for the selected brominated compounds.

APPENDIX B

In-Flight/Onboard Monitoring: ACER's Component for ASHRAE 1262, Part 2

Comparisons of Volatile Organic Compounds

Appendix B provides, for comparative purposes, indoor data on VOCs collected in three studies. The authors of this FAA technical report were involved with each of these studies.

First, Table B-1 summarizes the VOC compounds measured in cabin air and the percent of samples with concentrations above the limit of detection (LOD).

Table B-1. VOC compounds measured by airline and number of samples and percentage of samples above the LOD. Airline A had a total of 21 samples, airline B had a total of 35 samples, and airline C had a total of 31 samples.

	airline A		airline B		airline C	
	N >LOD	% >LOD	N >LOD	% >LOD	N >LOD	% >LOD
1,3-butadiene	1	5%	12	34%	8	24%
methyl tert-butyl ether	6	29%	7	20%	8	24%
Benzene	20	95%	26	74%	4	12%
Toluene	21	100%	33	94%	28	82%
Ethylbenzene	20	95%	15	43%	24	71%
m&p-xylene	21	100%	20	57%	27	79%
o-xylene	21	100%	11	31%	23	68%
methylene chloride	16	76%	25	71%	12	35%
Chloroform	15	71%	3	9%	14	41%
1,1,1-trichloroethane	12	57%	5	14%	11	32%
carbon tetrachloride	20	95%	32	91%	29	85%
Trichloroethene	17	81%	17	49%	7	21%
cis-1,3-dichloropropene	0	0%	0	0%	1	3%
trans-1,3-dichloropropene	0	0%				
Tetrachloroethene	21	100%	29	83%	31	91%
1,4-dichlorobenzene	21	100%	5	14%	13	38%
Acrolein	19	90%			19	56%
Acetone	21	100%				
2-butanone	21	100%			26	76%
Ethanol	21	100%			15	44%
ethyl acetate	21	100%			20	59%
Hexane	18	86%	27	77%	1	3%
Isoprene	21	100%			18	53%
isopropyl alcohol	20	95%			31	91%
Styrene	21	100%	14	40%	11	32%
2-Methylpentane			30	86%	2	6%
2-Methylhexane			10	29%	11	32%
2,3-Dimethylpentane			8	23%	14	41%
3-Methylhexane			9	26%	13	38%
2,2,4-Trimethylpentane			25	71%	28	82%
Methylcyclohexane			9	26%	22	65%
Propylene	20	95%				
methyl bromide	6	29%				
Methyl methacrylate	2	10%				
1,2,4-trimethylbenzene	21	100%				
Dichlorodifluoromethane	21	100%				
Tetrahydrofuran	6	29%				

	airline A		airline B		airline C	
	N >LOD	**% >LOD**	**N >LOD**	**% >LOD**	**N >LOD**	**% >LOD**
Cyclohexane	20	95%				
methyl chloride	20	95%				
vinyl acetate	17	81%				
carbon disulfide	19	90%				
Heptanes	16	76%				
Trichlorofluoromethane	21	100%				
1,3,5-trimethylbenzene	21	100%				
2-hexanone	11	52%				
trans-1,2-dichloroethene	10	48%				
1,3-dichlorobenzene	10	48%				
methyl isobutyl ketone	12	57%				
4-ethyl toluene	21	100%				
Chlorobenzene	9	43%				
ethyl chloride	2	10%				
1,2,4-trichlorobenzene	11	52%				
1,1,2-trichlorethane	1	5%				
1,2-dichlorobenzene	9	43%				
1,1,2,2-tetrachloroethane	2	10%				
1,1,2-trichloro-1,2,2-trifluoroethane	21	100%				
Bromoform	5	24%				
benzyl chloride	5	24%				
Hexachlorobutadiene	6	29%				
1,2-dichloroethane	4	19%				
1,2-dichlorotetrafluoroethane	15	71%				
Dibromochloromethane	2	10%				

The EPA Building Assessment Survey Evaluation (BASE) study was conducted to assess "background" conditions in non-complaint office buildings (buildings not reporting sick building syndrome) in the U.S. Using a sample selection scheme to represent probabilities for participation, owners of 100 buildings agreed to participate. All of the buildings were located in urban areas. The comprehensive evaluation of the HVAC systems along with extensive measurements of air quality parameters comprised the environmental component of BASE. In addition, over 5000 surveys were collected from building occupants reporting perceptions on environmental conditions as well as their health symptoms. We used the median VOC values from BASE to compare to the median values of compounds detected in each of the three airlines.

As shown in Table B-2, the majority of VOC compounds had median values in buildings similar to or higher than what has been found in the cabin. For more details on BASE see Brightman et al. (2008) *Indoor Air* 18:335-345.

Table B-2. Comparison of median EPA BASE VOC (ng/m^3) measurements with VOC measurements in all three airlines.

	BASE Median	airline A Median	airline B Median	airline C Median	Ratio BASE/A	Ratio BASE/B	Ratio BASE/C
Non-chlorinated							
1,3-butadiene	2100	0	618	534		3.4	3.9
methyl tert-butyl ether	1400	0	35	19		40.0	73.7
benzene	3500	876	548	116	4	6.4	30.2
toluene	9400	2783	2846	10105	3.4	3.3	0.9
ethylbenzene	1700	187	230	418	9.1	7.4	4.1
m&p-xylene	5700	333	956	1120	17.1	6.0	5.1
o-xylene	2200	163	291	409	13.5	7.6	5.4
Chlorinated							
methylene chloride	7700	45641	2842		0.2	2.7	
chloroform	440	35	138	95	12.6	3.2	4.6
1,1,1-trichloroethane	3600	10	63	31	360	57.1	116.1
carbon tetrachloride	900	28	649	639	32.1	1.4	1.4
trichloroethene	370	21	324	132	17.6	1.1	2.8
cis-1,3-dichloropropene	1500	0	0	0			
trans-1,3-dichloropropene	850	0					
tetrachloroethene	1800	619	1166	10670	2.9	1.5	0.2
1,4-dichlorobenzene	700	187	322	307	3.7	2.2	2.3
Other							
acetone	33000	23563			1.4		
2-butanone	2600	2154		1356	1.2		1.9
ethanol	43000	1433770			0		
ethyl acetate	2000	1751		16132	1.1		0.1
hexane	2400	262	68360	0	9.2	0.0	
isopropyl alcohol	22000	3095		6312	7.1		3.5
styrene	920	161	369	416	5.7	2.5	2.2

The cabin air VOCs were also compared to VOCs reported in residential studies conducted in Los Angeles, as part of the Toxic Exposure Assessment: Columbia-Harvard (TEACH), and in Boston, in the Boston Exposure Assessment in Microenvironments (BEAM) study. These studies collected VOCs with sorbent tubes and analyzed by thermal desorption with GC/MS. The lab and methods were the same as those used for samples from airlines B and C in this study.

In Table B-3, distributional information on VOCs from the TEACH and BEAM studies were compared to each of the airlines. The figures within the body of the report present graphically some of the data contained in this stable. Specific compounds have been found in higher concentrations in the cabin air. It should be noted that there are differences across airlines as well as within airline groupings. For example, while the median value for benzene in cabin air is comparable to BEAM data, a few flights had substantially higher values, one for airline B and one for airline C. Toluene, ethylbenzene, o-xylene, 1,3-budadiene, and styrene all showed a pattern where a few flights had values substantially higher than what might be expected in homes. A few chlorinated hydrocarbons also had this pattern. These concentrations are remarkable considering the high ventilation rates in airplanes compared to residences and the assumed low background levels in ambient air at cruise altitudes.

More details about the TEACH are reported by Sax et al. (2004) *Journal of Exposure Analysis and Enviornmental Epidemiology*, 14:S95-S109, and by Dodson et al. (2007) *Environmental Science & Technology*, 41(3):259-270 for the BEAM study.

Table B-3. Comparison of cabin VOC measurements (µg/m^3) with measurements made in the BEAM and Teach studies.

		min	25th	median	75th	max
Benzene	TEACH	0.36	1.47	2.13	3.28	8.35
	BEAM	0.02	0.41	0.75	1.16	3.59
	airline A	0.00	0.54	0.88	1.18	3.29
	airline B	0.00	0.26	0.55	1.47	20.07
	airline C	0.00	0.00	0.12	3.01	62.34
Toluene	TEACH	1.27	8.23	10.78	15.44	54.66
	BEAM	0.18	1.09	2.00	2.97	5.61
	airline A	1.01	1.89	2.78	4.39	30.03
	airline B	0.46	1.93	2.85	6.43	115.38
	airline C	0.12	6.08	10.10	15.74	132.93
Ethylbenzene	TEACH	0.02	1.60	2.35	2.97	18.68
	BEAM	0.05	0.23	0.36	0.53	1.87
	airline A	0.00	0.12	0.19	0.28	0.57
	airline B	0.06	0.13	0.23	0.50	13.45
	airline C	0.00	0.27	0.42	0.65	3.86
m/p Xylene	TEACH	0.16	5.73	8.46	10.99	26.00
	BEAM	0.13	0.65	1.12	1.61	6.63
	airline A	0.15	0.22	0.33	0.52	0.71
	airline B	0.21	0.49	0.96	1.90	28.67
	airline C	0.00	0.76	1.12	2.38	9.39
o Xylene	TEACH	0.14	2.19	3.05	4.12	32.05
	BEAM	0.06	0.25	0.40	0.56	2.34
	airline A	0.07	0.10	0.16	0.24	0.42
	airline B	0.00	0.13	0.29	0.48	14.17
	airline C	0.00	0.27	0.41	0.76	3.44

		min	25th	median	75th	max
1,3-butadiene	TEACH	0.03	0.03	0.03	0.03	1.70
	BEAM	0.03	0.15	0.18	0.28	2.81
	airline A	0.00	0.00	0.00	0.00	0.04
	airline B	0.00	0.13	0.62	6.17	212.71
	airline C	0.00	0.01	0.53	1.76	50.41
MTBE	TEACH	0.03	10.15	13.93	18.97	44.79
	BEAM	0.14	0.57	1.05	1.56	5.81
	airline A	0.00	0.00	0.00	0.01	0.09
	airline B	0.00	0.01	0.03	0.20	16.16
	airline C	0.00	0.00	0.02	0.49	3.66
Styrene	TEACH	0.14	0.38	0.61	0.80	4.31
	BEAM	0.00	0.06	0.09	0.13	0.33
	airline A	0.04	0.08	0.16	0.23	0.50
	airline B	0.11	0.27	0.37	0.62	3.39
	airline C	0.00	0.15	0.42	0.90	12.08
Chloroform	TEACH	0.03	0.06	0.07	0.14	0.98
	BEAM	0.02	0.03	0.04	0.06	1.13
	airline A	0.00	0.00	0.04	0.10	0.53
	airline B	0.02	0.08	0.14	0.27	2.09
	airline C	0.00	0.00	0.10	0.46	1.96
Trichloroethene	TEACH	0.03	0.07	0.10	0.15	0.76
	BEAM	0.02	0.02	0.02	0.09	4.06
	airline A	0.00	0.01	0.02	0.03	0.65
	airline B	0.00	0.07	0.32	1.40	29.45
	airline C	0.00	0.00	0.13	2.33	41.29
Tetrachloroethene	TEACH	0.08	1.03	1.59	1.94	4.28
	BEAM	0.03	0.15	0.24	0.37	7.56
	airline A	0.05	0.27	0.62	0.92	1.93
	airline B	0.07	0.81	1.17	2.60	10.01
	airline C	1.18	3.44	10.67	13.32	123.03
Dichlorobenzene_14	TEACH	0.32	0.91	1.55	3.16	197.04
	BEAM	0.02	0.07	0.13	0.29	3.28
	airline A	0.04	0.12	0.19	0.28	0.70
	airline B	0.05	0.17	0.32	0.59	2.42
	airline C	0.00	0.04	0.31	0.77	12.74