Committee on the Toxicity of Chemicals in Food, Consumer Products and the Environment.

Volatile organic compounds in aircraft cabin air: comparison with work environments

Introduction

1. In 2007, the Committee on Toxicity (COT) published a statement on aircraft cabin air, relating to organophosphate (OP) compounds, the cabin air environment, ill-health in aircraft crews and the possible relationship to smoke/fume events in aircraft (COT, 2007). Subsequently, the COT reviewed the results of Department for Transport (DfT)-funded aircraft cabin environment research commissioned in response to recommendations made by COT in 2007, after which the COT issued a position statement on cabin air (COT, 2013).

2. The COT has now been asked by DfT to investigate if any new data have been published and to re-evaluate their previous view in the original statement from 2007 (COT, 2007) and position statement from 2013 (COT, 2013). Following the May 2022 COT meeting, the request of COT has been further refined to: “Is there evidence of exposure to chemical contaminants in cabin air that could have long-term health impacts, either from acute exposures or due to long-term low level exposures including mixtures, e.g. of VOCs?”

Background

3. The COT reviewed an introductory paper on this topic on cabin air in May 2022 (TOX/2022/30), which provided a full background to the Committee’s previous conclusions. The scope of the work was expanded to

include volatile organic compounds (VOCs) and semi-volatile organic compounds (sVOCs), on which there has been more focus in recent years.

4. The current paper provides a narrative on the concentrations of VOCs reported in different work environments, including aircraft, to support consideration of whether exposures to VOCs in aircraft are different to exposures elsewhere. A paper has already been published that considered concentrations of VOCs in different modes of transport (TOX-2022-46).

5. The studies identified are summarised in paragraphs 11-81, and a comparison of the different office environments is provided in the summary from paragraph 90.

Literature search

6. A literature search was carried out to collate concentration data on VOCs in aircraft in comparison with other work environments such as offices, hospitals and schools. Search terms used were presented in TOX/2022/30.

7. Data published by the European Aviation Safety Authority (EASA) were also included, as well as studies cited in the EASA report.

8. Only literature that presented concentration data in tabular format were included in the analysis (i.e. not extracted from figures or graphs). Papers presenting data as figures were excluded. All data were included in analyses.

9. Thirty-two papers were initially identified based on their title from which fifteen papers were selected following screening of the abstract. Six papers/reports related to exposure to VOCs in aircraft, ten in offices, one in hospitals and four in schools.

Aircraft

10. The concentrations of VOCs in aircraft were presented in TOX-2022-46 and are presented in Annex 1.

Offices

Cacho et al. (2013)

11. Cacho et al. (2013) carried out a review of air pollutants in office environments and emissions from electronic equipment, with the aim to evaluate the existing knowledge on indoor air contaminants such as VOCs in office buildings. Data were presented on mean concentrations of VOCs in modern office buildings in both European and non-European countries (Table and **Error! Reference source not found.**).

12. Regarding emissions from office equipment, no data were presented in tabular format. Authors noted that ‘in general, the emission rates from photocopiers are much higher than those from printers and multi-functional devices but the variability among the studies is very high. Most commonly emitted compounds include BTEX (benzene, toluene, ethylbenzene and xylene), carbonyl compounds (i.e. formaldehyde, acetaldehyde, benzaldehyde) and linear alkanes with emissions as high as 30,000 µg/h per unit’.

13. Authors concluded average concentrations of benzene and toluene in European countries range from 2 to 11.2 and 4.3 to 43.1 µg/m^3, respectively, while in non-European countries, they range from 3.4 to 87.1 and from 52.8 to 287.3 µg/m^3, respectively. Differences between the countries were attributed to diverse ventilation rates, relative humidity values, ventilation systems and construction materials.

Table 1. Mean concentrations of VOCs measured in office buildings – European countries

VOC	Mean conc. ($\mu g/m^3$) Ireland	Mean conc. ($\mu g/m^3$) Netherlands	Mean conc. ($\mu g/m^3$) Greece	Mean conc. ($\mu g/m^3$) Finland	Mean conc. ($\mu g/m^3$) Germany	Mean conc. ($\mu g/m^3$) Cyprus	Mean conc. ($\mu g/m^3$) Belgium	Mean conc. ($\mu g/m^3$) Hungary
1,2,4-Trimethylbenzene	1.8	0.75	7.8	-	1.3	7.4	1.6	0.3
1,2-Propanediol	-	-	-	7.0	-	-	-	-
1-Butanol	-	1.8	1.2	5.7	12.2	4.2	1.6	-
2-Ethyl-1-hexanol	-	-	-	3.4	-	-	-	-
2-Phenoxyethanol	-	-	-	1.6	-	-	-	-
Acetaldehyde	4.7	6.4	9.3	-	11.1	7.2	7.3	7.3
Acetic acid	-	-	-	7.1	-	-	-	-
Acetone	12.3	-	11.3	-	-	29.6	21.9	19.3
Benzaldehyde	-	-	-	5.0	-	-	-	-
Benzene	2.0	2.7	11.2	3.9	2.0	8.0	1.9	2.7
Buthoxypropanol	-	-	1.3	-	0.5	-	-	-
Carene	-	-	-	1.7	-	-	-	-
Decane	5.3	-	-	13.9	-	-	-	-
Dichloromethane	-	-	-	50.2	-	-	-	-
Dodecane	13.7	-	-	-	-	-	-	-
Ethyl acetate	-	-	-	2.1	-	-	-	-
Ethylbenzene	1.9	1.1	7.7	16.1	0.9	3.7	0.8	0.5
Formaldehyde	16.9	9.0	17.9	11.0	24.3	26.9	12.2	16.2
Heptane	2.3	-	-	-	-	-	-	-

VOC	Mean conc. ($\mu g/m^3$) Ireland	Mean conc. ($\mu g/m^3$) Netherlands	Mean conc. ($\mu g/m^3$) Greece	Mean conc. ($\mu g/m^3$) Finland	Mean conc. ($\mu g/m^3$) Germany	Mean conc. ($\mu g/m^3$) Cyprus	Mean conc. ($\mu g/m^3$) Belgium	Mean conc. ($\mu g/m^3$) Hungary
Hexanal	6.6	8.6	5.1	5.0	21.2	13.3	12.7	18.5
Hexane	0.8	2.5	5.3	6.7	25.6	4.6	2.3	2.1
Hexanoic acid	-	-	-	5.5	-	-	-	-
Isoprene	-	-	-	-	-	-	-	-
Limonene	3.5	-	3.2	14.2	2.2	15.8	7.0	2.8
m- and p-Xylene	2.2	2.7	21.7	4.2	1.8	9.5	2.0	1.2
Methylcyclohexane	0.9	14.2	-	-	-	9.5	1.8	2.0
Nonanal	-	-	-	2.5	-	-	-	-
Nonane	-	-	-	7.6	-	-	-	-
Octanal	-	-	-	3.0	-	-	-	-
Octane	1.6	-	-	-	-	-	-	-
o-Xylene	1.2	1.5	7.7	16.3	0.7	3.9	1.0	0.4
Propanal	0.9	2.8	1.9	-	4.4	2.6	3.4	2.7
Propylbenzene	-	-	-	3.6	-	-	-	-
Toluene	4.3	5.2	43.1	32.3	3.7	19.4	7.7	2.2
Undecane	1.4	-	-	13.0	-	-	-	-
α-Pinene	1.4	0.25	2.6	5.5	0.8	2.6	1.3	2.1

Table 2. Mean concentrations of VOCs measured in office buildings – non-European countries

VOC	**Mean conc. (μg/m^3) Singapore**	**Mean conc. (μg/m^3) Hong Kong**	**Mean conc. (μg/m^3) Thailand**	**Mean conc. (μg/m^3) USA**
1,2,4-Trimethylbenzene	-	2.2		8.6
1,2-Propanediol	-	-	-	-
1-Butanol	4.4	-	-	3.3
2-Ethyl-1-hexanol	30.6	-	-	1.8
2-Phenoxyethanol	-	-	-	-
Acetaldehyde	-	-	17.1	7.8
Acetic acid	-	-	-	-
Acetone	16.5	-	-	42.0
Benzaldehyde	29.0	-	-	-
Benzene	87.1	8.1	8.8	4.2
Buthoxypropanol	-	-	-	-
Carene	-	-	-	-
Decane	24.8	-	-	15.6
Dichloromethane	-	-	-	21.0
Dodecane	29.8	-	-	9.6
Ethylacetate	-	-	-	3.7
Ethylbenzene	-	-	-	3.7

VOC	Mean conc. ($\mu g/m^3$) Singapore	Mean conc. ($\mu g/m^3$) Hong Kong	Mean conc. ($\mu g/m^3$) Thailand	Mean conc. ($\mu g/m^3$) USA
Formaldehyde	-	-	-	16.0
Heptane	14.7	-	-	9.8
Hexanal	-	-	-	5.4
Hexane	34.6	-	-	3.9
Hexanoic acid	-	-	-	-
Isoprene	10.5	-	-	-
Limonene	65.1	-	-	12.0
m- and p-Xylene	143.0	-	-	14.0
Methylcyclohexane	36.4	-	-	2.6
Nonanal	-	-	-	4.3
Nonane	-	-	-	9.4
Octanal	-	-	-	-
Octane	-	-	-	3.3
o-Xylene	43.4	5.5	9.6	4.1
Propanal	-	-	-	-
Propylbenzene	-	-	-	1.7
Toluene	287.3	52.8	110.0	16.0
Undecane	32.9	-	-	9.5
α-Pinene	-	-	-	3.9

Goodman et al. (2018)

14. Goodman et al. (2018) investigated VOCs at various locations within a large Austrian university, including campus services, restrooms, renovated offices, a green building, meeting areas and classrooms. Forty-one VOCs were measured across 20 locations.

15. Indoor air samples were collected and analysed in accordance with US Environment Protection Agency (USEPA) compendium methods TO–17 and TO–11A. all samples were collected during normal working hours, between 8.30 and 18.30, in February and March 2016. For VOCs (other than carbonyl compounds), two multi-adsorbent tubes in series were connected to a SKC Pocket Pump 210–1002 at a flow rate of approximately 35 mL per minute for 2.5 h (5 L).

A total of 47 VOC tubes were analysed, using an automated thermal desorber and a GC-MS/FID. The geometric mean, geometric standard deviation and range are presented in Table **3** and Table 4. Authors also presented the twelve most prevalent VOCs in each environment (Table 5-

16. Table 6).

17. In campus services, ethanol, d-limonene, n-butane, acetone, 2-methylbutane and formaldehyde were among the most prevalent compounds at the highest concentrations which have associated with consumer products and cleaning supplies.

18. In restrooms, ethanol, isobutane, d-limonene, acetone, and formaldehyde had some of the highest concentrations, which are frequently reported in studies of air freshener emissions and cleaning products.

19. In renovated offices, ethanol, n-butane, isobutane, formaldehyde, and toluene had the highest concentrations, which are found in building materials, furnishings and floorings and fragranced consumer products.

20. In the green building, the construction and finishing materials were selected based on performance and environmental parameters. However, the highest acetaldehyde, acetone, m-xylene, and p-xylene indoor/outdoor ratios, occurred in this green building. Many of these compounds are associated with compressed wood products, wood finishing compounds, adhesives, and occupant density.

21. In meeting areas and classrooms, ethanol, formaldehyde, toluene and acetone had the highest concentrations along with n-butane (meeting rooms) and α-Pinene (classrooms).

Table 3. Mean, standard deviation and range of VOCs in campus services, restrooms and offices in an Austrian university

VOC	Mean conc. ± SD (µg/m^3) Campus services	Range (µg/m^3) Campus services	Mean conc. ± SD (µg/m^3) Restroom	Range (µg/m^3) Restroom	Mean conc. ± SD (µg/m^3) Office	Range (µg/m^3) Office
Isobutane	4.8±2.0	1.7-11.6	40.4±7.7	5.2-312.0	33.6±3.5	95.0-118.0
n-Butane	8.2±1.8	3.4-17.0	27.5±6.2	4.4-170.0	61.7±3.9	15.9-239.0
Ethanol	61.3±5.4	9.8-462.0	1.1±6.2	16.3-62.8	127±2.3	56.2-287.0
2-Methylbutane	7.5±2.2	3.1-23.0	3.6±1.8	1.9-6.5	12.8±1.1	12-13.5
Benzene	0.5±1.8	0.2-1.0	0.4±1.0	0.4-0.5	2.2±1.1.0	2.2-2.3
Trichloroethylene	0.2±1.7	<LOD-0.4	0.2±1.2	0.1-0.3	1.4±1.1.0	1.3-1.4
Methyl methacrylate	-	<LOD	-	<LOD	-	<LOD
Toluene	2.8±2.0	1.4-7.3	5.4±1.0	5.1-5.7	13.9±1.1	13.3-14.5
Tetrachloroethylene	0.2±3.6	0.3-1.3	0.2±1.2	0.1-0.2	0.5±1.1.0	0.4-0.5
Ethyl benzene	0.6±1.6	0.6-2.4	0.6±1.1	0.5-0.7	2.2±1.1.0	1.9-2.5
p-Xylene	1.2±1.6	0.2-1.0	1.2±1.1	1.1-1.3	7.2±1.4	5.1-10.0
m-Xylene	0.5±1.8	0.1-1.6	0.4±1.1	0.3-0.5	2.2±1.2	1.8-3.6
Styrene	0.4±2.3	0.4-1.6	2.9±1.3	2.1-3.8	0.8±1.2	0.7-1.0
o-Xylene	0.8±1.6		0.7±1.1	0.5-0.8	3.1±1.2	2.7-3.4

VOC	Mean conc. ± SD (μg/m³) Campus services	Range (μg/m³) Campus services	Mean conc. ± SD (μg/m³) Restroom	Range (μg/m³) Restroom	Mean conc. ± SD (μg/m³) Office	Range (μg/m³) Office
R(-)3,7-Dimethyl-1,6-octadiene	0.61±3.3	0.1-2.3	0.9±28.7	<LOD	-	<LOD
α-Pinene	1.0±1.5	0.5-1.7	1.0±1.8	0.6-2.0	13.2±1.1	12.6-13.8
β-Pinene	0.5±1.8	0.2-1.3	0.9±1.8	0.5-1.7	10.9±1.1	10.2-11.6
d-Limonene	12.6±1.9	5.7-30.6	35.5±1.2	30.6-41.1	6.4±1.1	5.9-7.0
Eucalyptol	1.1±1.7	0.4-1.9	3.8±1.3	2.8-5.1	1.3±1.3	1-1.7.0
2-Methyl-6-methlene-2-octanol	0.2±7.5	<LOD -3.6	1.3±43.4	<LOD -56.5	0.3±1.1	0.2-0.4
Phenylethyl acetate	-	<LOD	0.7±24.3	<LOD -17.7	-	<LOD
Phenylmethyl acetate	0.2±2.2	<LOD -0.5	1.7±6.0	0.2-10.0	0.2±1.2	0.1-0.2
a-Methylbenzyl acetate	0.03±1.0	<LOD -0.1	5.5±2.9	1.8-15.8	-	<LOD
Naphthalene	0.2±1.2	0.1-0.3	0.2±1.3	0.1-0.3	0.4±1.1	0.3-0.4
Benzothiazole	0.3±1.7	0.1-0.6	0.7±1.2	0.5-0.8	0.4±1.2	0.3-0.5
4-tert-Butylcyclohexyl acetate	0.2±8.3	<LOD -3.2	-	<LOD	-	<LOD

VOC	Mean conc. ± SD (µg/m^3) Campus services	Range (µg/m^3) Campus services	Mean conc. ± SD (µg/m^3) Restroom	Range (µg/m^3) Restroom	Mean conc. ± SD (µg/m^3) Office	Range (µg/m^3) Office
Formaldehyde	7.2±1.9	3.9-18.9	6.2±1.6	3.8-9.9	14.2±1.1	13.5-15.0
Acetaldehyde	3.2±1.9	1.7-9.2	3.2±1.2	2.7-3.8	4.0±1.2	3.4-4.6
Acetone	8.1±1.2	6.1-10.7	8.5±1.3	6.7-10.8	12.5±1.1	11.4-13.6
Acrolein	-	<LOD	-	<LOD	-	<LOD
Propionaldehyde	0.1±8.9	<LOD -2.2	0.5±1.4	0.3-0.7	0.4±1.1	0.3-0.5
Crotonaldehyde	-	<LOD	-	<LOD	-	<LOD
Methyl ethyl ketone	0.5±1.6	0.3-0.9	0.8±1.4	0.5-1.1	2.3±1.1	2.1-2.4
Methacrolein	0.03±3.7	<LOD -0.4	-	<LOD	-	<LOD
Butyraldehyde	0.2±4.9	<LOD -1.5	0.3±1.1	0.2-0.4	0.6±1.1	0.5-0.7
Benzaldehyde	0.3±3.4	<LOD -1.0	0.5±1.3	0.4-0.7	0.3±1.1	0.2-0.3
Valeraldehyde	0.1±55.0	<LOD -1.3	0.2±1.3	0.1-0.3	0.7±1.1	0.7-0.8
Glyoxal	0.3±1.7	0.1-0.5	0.1±1.6	<LOD -0.2	0.2±1.1	0.1-0.3
m-Tolualdehyde	-	<LOD	-	<LOD	-	<LOD
Methyl glyoxal	2.4±1.5	1.8-4.8	0.4±1.3	0.3-0.6	1.9±1.1	1.7-2.1
Hexaldehyde	0.8±4.1	0.1-4.6	0.6±1.5	0.4-1.0	3.6±1.1	3.2-4.0

Table 4. Mean, standard deviation and range of VOCs in a green building, meeting area and classroom in an Austrian university

VOC	**Mean conc. ± SD (μg/m³) Green building**	**Range (μg/m³) Green building**	**Mean conc. ± SD (μg/m³) Meeting area**	**Range (μg/m³) Meeting area**	**Mean conc. ± SD (μg/m³) Classroom**	**Range (μg/m³) Classroom**	**Mean conc. ± SD (μg/m³) Outdoor**	**Range (μg/m³) Outdoor**
Isobutane	1.2±1.2	0.9-1.5	1.4±1.0	1.3-1.5	2.9±1.1	2.6-3.0	0.9±2.0	0.2-2.3
n-Butane	2.9±1.3	1.9-3.6	3.6±1.0	3.3-3.8	5.9±1.2	5-7.8	1.5±1.9	0.5-3.4
Ethanol	49.6±2.4	15-125.0	22.0±1.1	20.2-24.0	34.1±1.3	25.5-50.7	1.0±1.9	0.5-3.8
2-Methylbutane	2.8±1.5	1.7-4.8	0.9±1.0	0.8-0.9	5.2±1.1	4.7-6.1	1.1±2.3	0.3-2.9
Benzene	0.2±1.1	0.1-0.3	0.2±1.0	0.2-0.3	0.9±1.1	0.7-1.0	0.2±2.1	<LOD -0.5
Trichloroethylene	0.03±1.0	<LOD -0.1	-	<LOD	1.7±1.1	1.6-1.8	0.07±2.4	<LOD -0.3
Methyl methacrylate	0.2±10.7	<LOD -4.6	-	<LOD	-	<LOD	-	<LOD
Toluene	6.5±3.3	2.7-35.1	1.7±1.0	1.6-1.7	25.5±2.3	13.1-81.9	1.1±2.3	0.3-2.9
Tetrachloroethylene	0.07±1.2	<LOD -0.1	0.2±1.0	0.1-0.2	0.2±1.1	0.2-0.3	0.07±1.7	<LOD -0.2
Ethyl benzene	0.7±1.8	0.3-1.5	0.3±1.4	0.2-0.3	1.8±1.3	1.3-2.8	0.2±2.6	<LOD -0.7
p-Xylene	1.5±1.8	0.7-3.1	0.7±1.3	0.5-0.6	4.1±1.2	3.2-5.5	0.4±2.6	0.1-1.5
m-Xylene	0.5±1.8	0.2-1.1	0.3±1.3	0.2-0.3	1.3±1.2	1-1.9	0.2±2.7	<LOD -0.6

VOC	Mean conc. ± SD (µg/m³) Green building	Range (µg/m³) Green building	Mean conc. ± SD (µg/m³) Meeting area	Range (µg/m³) Meeting area	Mean conc. ± SD (µg/m³) Classroom	Range (µg/m³) Classroom	Mean conc. ± SD (µg/m³) Outdoor	Range (µg/m³) Outdoor
Styrene	1.5±6.7	0.3-21.8	0.3±2.4	0.1-0.6	5.9±1.5	4-9.9	0.04±1.8	<LOD -0.2
o-Xylene	0.7±1.6	0.3-1.2	0.7±1.1	0.6-0.7	2.9±1.1	2.3-3.5	0.4±2.5	<LOD -0.8
R(-)3,7-Dimethyl-1,6-octadiene	0.06±2.6	<LOD -0.3	-	<LOD	-	<LOD	-	<LOD
α-Pinene	2.8±1.5	1.7-4.3	0.3±1.5	0.2-0.5	17.3±1.7	10.4-35.8	0.08±1.8	<LOD -0.3
β-Pinene	1.4±1.8	0.5-2.2	0.2±1.0	0.1-0.2	7.8±1.2	6.8-9.5	0.04±1.9	<LOD -0.2
d-Limonene	1.0±1.4	0.6-1.6	1.1±1.1	1-1.1	7.4±1.6	4.8-14.9	0.07±2.2	<LOD -0.3
Eucalyptol	0.3±1.4	0.1-0.5	0.2±1.1	0.1-0.2	0.8±1.3	0.6-1.2	0.05±1.7	<LOD -0.2
2-Methyl-6-methlene-2-octanol	-	<LOD	-	<LOD	-	<LOD	-	<LOD
Phenylethyl acetate	-	<LOD	-	<LOD	-	<LOD	-	<LOD
Phenylmethyl acetate	0.04±1.4	<LOD - 0.06	-	<LOD	-	<LOD	-	<LOD

VOC	Mean conc. ± SD (μg/m³) Green building	Range (μg/m³) Green building	Mean conc. ± SD (μg/m³) Meeting area	Range (μg/m³) Meeting area	Mean conc. ± SD (μg/m³) Classroom	Range (μg/m³) Classroom	Mean conc. ± SD (μg/m³) Outdoor	Range (μg/m³) Outdoor
a-Methylbenzyl acetate	-	<LOD	-	<LOD	-	<LOD	-	<LOD
Naphthalene	0.2±1.6	<LOD-0.3	0.1±1.3	<LOD -0.2	1.3±1.2	1-1.5	0.03±1.1	<LOD - 0.04
Benzothiazole	0.2±2.5	0.04-0.3	0.1±1.2	<LOD -0.1	4.4±1.2	3.3-5.8	-	<LOD
4-tert-Butylcyclo-hexyl acetate	-	<LOD	-	<LOD	-	<LOD	-	<LOD
Formaldehyde	13.6±1.1	12.4-14.8	4.5±1.1	4.1-4.8	16.9±1.4	13.5-26.0	1.1±1.7	0.5-2.4
Acetaldehyde	6.1±1.5	3.4-10.0	1.3±1.2	1-1.6	9.4±1.6	6.5-18.9	0.4±1.9	0.1-0.8
Acetone	24.7±1.6	12.6-38.4	2.7±1.2	2.3-2.4	48.6±1.5	36.4-86.3	1.4±1.8	0.5-3.8
Acrolein	-	<LOD	-	<LOD	-	<LOD	-	<LOD
Propionaldehyde	0.9±2.2	0.3-2.4	-	<LOD	2.3±2.4	1.1-7.8	-	<LOD
Crotonaldehyde	-	<LOD	-	<LOD	-	<LOD	-	<LOD
Methyl ethyl ketone	0.9±1.7	0.4-1.8	-	<LOD	2.7±1.2	2.2-3.7	0.1±1.9	0.1-0.6

VOC	Mean conc. ± SD (μg/m^3) Green building	Range (μg/m^3) Green building	Mean conc. ± SD (μg/m^3) Meeting area	Range (μg/m^3) Meeting area	Mean conc. ± SD (μg/m^3) Classroom	Range (μg/m^3) Classroom	Mean conc. ± SD (μg/m^3) Outdoor	Range (μg/m^3) Outdoor
Methacrolein	0.1±3.3	<LOD -0.3	-	<LOD	0.1±3.9	<LOD -0.5	-	<LOD
Butyraldehyde	0.8±1.6	0.4-1.5	-	<LOD	1.4±1.5	1-2.6	0.02±1.5	<LOD - 0.06
Benzaldehyde	0.6±1.4	0.5-1.0	-	<LOD	1.9±1.2	1.6-2.6	0.04±1.4	<LOD - 0.04
Valeraldehyde	1.3±1.4	1-2.1	-	<LOD	3.4±1.7	2.2-7.5	-	<LOD
Glyoxal	0.3±1.3	0.2-0.4	0.1±1.3	0.1-0.2	0.2±1.1	0.1-0.3	0.09±3.6	<LOD -0.5
m-Tolualdehyde	0.04±2.1	<LOD -0.2	-	<LOD	-	<LOD	-	<LOD
Methyl glyoxal	1.5±1.2	1.1-1.8	0.9±1.1	0.8-0.9	1.1±1.2	0.8-1.4	0.45±2.5	0.1-1.7
Hexaldehyde	5.6±1.2	4.3-6.4	0.1±1.4	<LOD -0.1	13.2±1.7	8.9-27.6	0.05±1.6	<LOD -0.2

Table 5. Mean conc. of the top twelve VOCs in campus services, restrooms and offices in an Austrian university

VOC	**Mean conc. (µg/m^3) Campus services**	**VOC**	**Mean conc. (µg/m^3) Restrooms**	**VOC**	**Mean conc. (µg/m^3) Office**
Ethanol	61.3	Ethanol	101.0	Ethanol	127.0
d-Limonene	12.6	Isobutane	40.4	n-Butane	61.7
n-Butane	8.2	d-Limonene	35.5	Isobutane	33.6
Acetone	8.1	n-Butane	27.5	Formaldehyde	14.2
2-Methylbutane	7.5	Acetone	8.5	Toluene	13.9
Formaldehyde	7.2	Formaldehyde	6.2	α-Pinene	13.2
Isobutane	43.8	α-Methylbenzyl acetate	5.5	2-Methylbutane	12.8
Acetaldehyde	3.2	Toluene	5.4	Acetone	12.5
Toluene	2.8	Eucalyptol	3.8	β-Pinene	10.9
Methyl glyoxal	2.4	2-Methylbutane	3.6	p-Xylene	7.2
p-Xylene	1.2	Acetaldehyde	0.2	d-Limonene	6.4
Eucalyptol	1.1	Styrene	2.9	Acetaldehyde	4.0

Table 6. Mean conc. of the top twelve VOCs in a green building and meeting area in an Austrian university

VOC	Mean conc. (μg/m^3) green building	VOC	Mean conc. (μg/m^3) meeting area	VOC	Mean conc. (μg/m^3) Class-room	VOC	Mean conc. (μg/m^3) Ambient
Ethanol	49.6	Ethanol	22.0	Acetone	48.6	n-Butane	1.5
Acetone	24.7	Formaldehyde	4.5	Ethanol	34.1	Acetone	1.4
Formaldehyde	13.6	n-Butane	3.6	Toluene	25.5	Formaldehyde	1.1
Toluene	6.5	Acetone	2.7	α-Pinene	17.3	Toluene	1.1
Acetaldehyde	6.1	Toluene	1.7	Formaldehyde	16.9	2-Methylbutane	1.1
Hexaldehyde	5.6	Isobutane	1.4	Hexaldehyde	13.2	Ethanol	1.0
n-Butane	2.9	Acetaldehyde	1.3	Acetaldehyde	9.4	Isobutane	0.9
α-Pinene	2.8	d-Limonene	1.1	β-Pinene	7.8	Methyl glyoxal	0.45
2-Methylbutane	2.8	Methyl glyoxal	0.9	d-Limonene	7.4	Acetaldehyde	0.44
Styrene	1.5	2-Methylbutane	0.9	n-Butane	5.9	p-Xylene	0.43
p-Xylene	1.5	o-Xylene	0.7	Styrene	5.9	o-Xylene	0.24
Methyl glyoxal	1.5	p-Xylene	0.7	2-Methylbutane	5.2	Ethyl benzene	0.19

22. Kozielska and colleagues published two papers on the indoor air quality in offices, flats and residential buildings in Poland (Kozielska, Brągoszewska and Kaleta 2020) and in offices during different seasons of the year (Kozielska and Kaleta 2021).

Kozielska et al. (2020)

23. In the first study, VOC samples were collected from February to May 2017 in six offices at the University of Technology in Poland. The sampling position in the centre of the room was approximately 1.5 m above the floor away from the door. Samples were taken for 8 hours from 08.00 – 16.00 whilst employees were present. No windows were opened during sampling.

24. VOCs were actively sampled using Tenax GR tubes using a flow rate of 8 dm^3/hour. Samples were thermally desorbed and analysed using GC. Quantification was carried out using calibration curves for 14 VOCs (Table 7).

Table 7. Mean, SD and range of concentrations of VOCs in offices in Poland

VOC	**Mean conc. (µg/m^3) Offices**	**SD (µg/m^3)**	**Range**	**Mean conc. (µg/m^3) Outdoor**	**SD (µg/m^3)**	**Range**
Benzene	1.2	1.0	0.4-4.0	0.9	0.9	0.1-3.6
Toluene	10.8	8.2	1.0-33.1	8.4	8.0	0.3-23.8
Ethylbenzene	0.6	0.2	0.4-0.9	0.3	0.2	0.1-1.1
m- and p-Xylene	0.5	0.2	0.3-0.9	0.2	0.2	0.04-0.7
o-Xylene	1.2	0.5	0.6-2.6	0.1	0.1	0.03-0.3
Styrene	0.4	0.2	0.2-1.0	0.1	0.1	0.01-0.6

25. Authors noted that toluene emission sources include glues, paints, enamels, varnishes, floor coverings, Styrofoam and wallpaper. In addition, o-xylene originates from paint and varnish.

Kozielska and Kaleta (2021)

26. In their second study, samples were taken from six newly renovated offices in the University of Technology in Poland. The renovation was carried out between June and September 2018 and involved replacing all doors and painting walls and ceilings. Each room was equipped with new medium-density fibreboard (MDF) furniture. Office 4 and 5 floors were varnished whereas all other offices had tiled floors.

27. Samples were collected after renovation between 1 October 2018 and 31 October 2019. Sampling points were set in the centre of the room at 1.2 m above the floor and away from doors and windows. Offices had air conditioning and windows were partially opened during measurements.

28. VOC samples were collected for a year in one-month periods using passive samplers with Tenax GR tubes. Passive samplers were thermally desorbed and analysed using TD-GC/FID. Data were quantified using a calibration mix of 16 VOCs. VOC concentrations in individual offices in the cold and warm season are presented in Table 8 and

29. Table **9**, respectively. Overall mean concentrations and SD in the cold and warm seasons are presented in

30. Table **10** and Table 11, respectively.

31. Both papers published by this group (Kozielska et al. 2020, Kozielska and Kaleta 2021) presented data in offices from other available literature around the world (

32. Table **12**).

33. Authors concluded that all six VOCs were found in all offices, the concentrations of which had decreased at the end of the study compared to the beginning, immediately after renovation. Levels of benzene were higher in the cold season compared to the warm season whereas all other VOCs were higher in the summer.

Table 8. Mean and SD concentrations of VOCs in offices in the cold season (Oct-Mar)

VOC	**Mean conc. (µg/m³) Office 1**	**Mean conc. (µg/m³) Office 2**	**Mean conc. (µg/m³) Office 3**	**Mean conc. (µg/m³) Office 4**	**Mean conc. (µg/m³) Office 5**	**Mean conc. (µg/m³) Office 6**	**Mean conc. (µg/m³) Outdoor**
Benzene	1.1±0.6	1.1±0.7	1.2±0.8	1.3± 0.9	1.1±0.6	1.1± 0.7	1.3±0.7
Toluene	14.4±20.7	14.2±23.8	20.7±38.7	28.1±30.6	22.0±28.0	16.8±4.1	22.6±50.3
Ethylbenzene	2.5±3.1	1.7±0.5	2.2±0.7	2.8±0.2	2.2±0.7	2.5±1.3	0.5±0.3
m- and p-Xylene	3.2±4.8	2.3±0.9	3.4±1.1	4.8±1.2	3.9±1.6	3.8±2.4	0.5±0.1
o-Xylene	1.3±1.1	0.8±0.3	0.8±0.2	0.8±0.1	0.7±0.2	0.84±0.4	0.4±0.3
Styrene	2.7±4.1	2.0±0.9	3.2±1.0	4.7±1.3	3.5±1.2	3.40±1.45	0.3±0.1
1,3,5-Trimethylbenzene	1.3±0.4	1.2±0.3	1.0±0.4	1.0±0.2	1.2±0.3	1.24±0.32	1.3±1.0

Table 9. Mean and SD concentrations of VOCs in offices in the warm season (Apr-Sept)

VOC	**Mean conc. (µg/m³) Office 1**	**Mean conc. (µg/m³) Office 2**	**Mean conc. (µg/m³) Office 3**	**Mean conc. (µg/m³) Office 4**	**Mean conc. (µg/m³) Office 5**	**Mean conc. (µg/m³) Office 6**	**Mean conc. (µg/m³) Outdoor**
Benzene	0.5±0.5	0.6±0.7	0.4±0.6	0.3±0.1	0.4±0.3	0.4±0.3	0.6±0.6
Toluene	25.1±31.5	20.4±9.0	21.4± 2.8	17.8±0.7	27.1±32.3	24.4±39.6	22.4±30.3
Ethylbenzene	1.8±0.8	2.2±0.8	7.4±10.1	3.3±1.8	4.6±3.9	4.3±3.7	0.5±0.4
m- and p-Xylene	1.7±0.9	2.3±1.8	6.1±3.4	4.2±2.6	4.6±2.4	7.0±8.3	0.5±0.4
o-Xylene	1.9±2.4	1.3± 0.5	1.1±0.8	1.5± 0.7	1.4±0.5	1.4±1.1	0.3±0.2
Styrene	1.2±0.5	1.9±1.1	4.8±3.2	3.6± 2.1	6.5±6.1	6.2±6.0	0.3±0.2
1,3,5-Trimethylbenzene	1.5±0.3	1.5±0.3	1.5±0.3	1.8± 0.4	2.1±0.5	1.8±0.7	1.0±0.3

Table 10. Mean, SD, minimum and maximum concentrations of VOCs in offices in the cold season (Oct-Mar)

VOC	Mean conc. ($\mu g/m^3$) Cold season	SD ($\mu g/m^3$) Cold season	Min conc. ($\mu g/m^3$) Cold season	Max conc. ($\mu g/m^3$) Cold season	Mean conc. ($\mu g/m^3$) Outdoor	SD ($\mu g/m^3$) Outdoor	Min conc. ($\mu g/m^3$) Outdoor	Max conc. ($\mu g/m^3$) Outdoor
Benzene	1.1	0.7	0.2	2.6	1.3	0.7	0.3	2.4
Toluene	19.4	26.6	2.5	99.5	22.6	50.3	1.4	125.3
Ethylbenzene	2.3	1.4	0.7	8.6	0.5	0.3	0.3	1.0
m- and p-Xylene	3.6	2.4	0.7	12.9	0.5	0.1	0.3	0.6
o-Xylene	0.9	0.5	0.3	3.4	0.4	0.3	0.1	0.7
Styrene	3.2	2.0	0.4	11.0	0.3	0.1	0.2	0.4
1,3,5-Trimethylbenzene	1.2	0.3	0.3	1.9	1.3	1.0	0.5	3.2

Table 11. Mean, SD, minimum and maximum concentrations of VOCs in offices in the warm season (Apr-Sept)

VOC	**Mean conc. (µg/m³) Warm season**	**SD (µg/m³) Warm season**	**Min conc. (µg/m³) Warm season**	**Max conc. (µg/m³) Warm season**	**Mean conc. (µg/m³) Outdoor**	**SD (µg/m³) Outdoor**	**Min conc. (µg/m³) Outdoor**	**Max conc. (µg/m³) Outdoor**
Benzene	0.5	0.4	0.1	2.0	0.6	0.6	0.3	2.0
Toluene	25.2	27.8	1.8	113.8	20.4	30.3	1.9	90.0
Ethylbenzene	4.0	4.9	0.7	30.0	0.5	0.4	0.3	1.5
m- and p-Xylene	4.2	4.3	0.8	25.7	0.5	0.4	0.2	1.2
o-Xylene	1.4	1.2	0.3	7.2	0.3	0.2	0.1	0.7
Styrene	4.0	4.2	0.7	19.5	0.3	0.2	0.1	0.7
1,3,5-Trimethylbenzene	1.7	0.5	1.0	2.9	1.0	0.3	0.6	1.4

Table 12. Mean concentrations of VOCs in offices around the world

VOC	**Mean conc. (µg/m³) Korea**	**Mean conc. (µg/m³) UK**	**Mean conc. (µg/m³) India**	**Mean conc. (µg/m³) Thailand**	**Mean conc. (µg/m³) Kuwait**	**Mean conc. (µg/m³) Hong Kong**	**Mean conc. (µg/m³) Singapore**	**Mean conc. (µg/m³) Europe**	**Mean conc. (µg/m³) Hungary**	**Mean conc. (µg/m³) Finland**	**Mean conc. (µg/m³) Poland**	**Mean conc. (µg/m³) Poland**
Benzene	12.6	5.9	44.9	8.8	1.5	8.1	87.1	14.6	2.7	1.2	1.2	0.8
Toluene	80.4	22.0	0.83	110.0	11.8	52.8	287.3	35.1	2.2	10.8	10.8	22.1
Ethyl-benzene	7.6	2.4	0.06	12.1	1.4	7.3	-	-	0.5	0.6	0.6	3.3
m- and p-Xylene	23.4	7.7	-	12.2	4.0	18.9	143.0	22.2	1.2	0.3	0.5	4.0
o-Xylene	14.5	1.8	-	9.6	1.5	5.5	43.4	10.2	0.4	0.5	1.2	1.2
Styrene	5.0	0.6	-	3.2	1.2	5.1	-	-	-	1.2	0.3	3.7
1,3,5-Trimethyl benzene	6.4	0.3	0.1	-		8.8	-	-	-	6.7	6.7	2.0
References – as cited in Kozielska and Kaleta, 2021	Baek (1997)	Kim (2001)	Srivastava and Devotta (2007)	Ongwandee et al. (2011)	Al-Mudhaf et al. (2012)	Geiss (2001)	Zuraimi (2006)	Ongwandee, (2011)	Srivastava, (2007)	Edwards, (2001)	Other study	This study

Licina and Langer (2021)

34. Licina and Langer (2021) compared indoor air quality before and after relocation to two WELL-building standard-certified office buildings, using the same cohort of occupants. The WELL concept ‘aims to ensure high levels of indoor air quality across a building’s lifetime through diverse strategies that include source elimination or reduction, active and passive building design and operation strategies and human behaviour interventions. The WELL Building Standard™ is a vehicle for buildings and organizations to deliver more thoughtful and intentional spaces that enhance human health and well-being’.

35. Two office building pairs located in a large city in the Netherlands were selected on the basis that they were planning to relocate to a WELL-certified building in 2019 and had a minimum of 50 employees. Company A already has BREEAM certification before the relocation, whereas company B was a conventional non-certified building. BREEAM is ‘a science-based suite of validation and certification systems for sustainable built environments’.

36. The study consisted of three 4-week measurement periods per company within 3 months before relocation, within 3 months after relocation and after 7-8 months from the second measurement period. All measurement periods fell into winter and summer seasons.

37. In each measurement period, at least four measurements and sampling locations were included, namely open office space, meeting room, and private office. Samplers were positioned within 1-1.2 m from the floor and at least 1.5 m away from doors, windows, walls and ventilation diffusers.

38. Samples were collected using Tenax tubes, which were thermally desorbed and analysed using GC-MS. Ten individual VOCs were quantified.

39. Mean VOC concentrations from open spaces, private office and meeting room are presented for the two companies before and after their relocation into WELL buildings (Table 13).

40. Authors concluded that some VOCs were detected in WELL buildings, but for the majority of VOCs in WELL buildings, concentrations decreased within 7-8 months after relocation, suggesting a contribution from off-gassing from indoor materials, particularly from solvents in paints, used as part of the relocation.

Table 13. Mean and SD of VOCs in two companies before and after relocation

VOC	Mean ± SD conc. (µg/m^3) Company A BREEAM Winter 2019	Mean ± SD conc. (µg/m^3) Company A WELL Summer 2019	Mean ± SD conc. (µg/m^3) Company A WELL Winter 2020	Mean ± SD conc. (µg/m^3) Company B Conventional Summer 2019	Mean ± SD conc. (µg/m^3) Company B WELL Winter 2020	Mean ± SD conc. (µg/m^3) Company B WELL Summer 2020
Benzene	1.5±0.3	<0.5	2.7±0.4	<0.5	2.4±0.2	<0.5
Toluene	6.3±2.2	5.4±1.1	7.0±0.7	1.6±0.04	5.5±1.2	4.1±0.5
Ethylbenzene	0.9±0.1	2.1±0.2	22±0.1	0.5±0.03	13±4.0	5.1±2.1
Xylene	6.3±1.1	10.2±1.9	10.5±0.2	2.0±0.1	106.0±36.0	44.0±19.0
α-Pinene	0.8±0.4	5.2±0.4	36.9±0.2	<0.5	4.6±1.9	3.0±2.0
3-Carene	<0.5	1.4±0.3	0.8±0.1	<0.5	0.8±0.2	<0.5
Limonene	3.2±0.1	5.1±1.3	13.0±2.0	1.6±0.04	16.0±5.0	4.0±2.0
Hexanal	<0.5	9.4±1.2	4.4±1.0	0.9±0.03	3.5±0.7	3.0±1.3
Nonanal	3.0±2.0	6.0±1.0	6.0±3.0	2.4±0.1	8.0±2.0	15.0±1.0
Decanal	4.0±3.0	3.6±0.3	8.0±0.1	2.5±0.2	<0.5	3.4±0.8
Cyclotetrasiloxane, octamethyl-	12.0±3.0	13.0±7.0	11.0±2.0	0.9±0.1	14.0±8.0	12.0±2.0

VOC	Mean ± SD conc. (μg/m³) Company A BREEAM Winter 2019	Mean ± SD conc. (μg/m³) Company A WELL Summer 2019	Mean ± SD conc. (μg/m³) Company A WELL Winter 2020	Mean ± SD conc. (μg/m³) Company B Conventional Summer 2019	Mean ± SD conc. (μg/m³) Company B WELL Winter 2020	Mean ± SD conc. (μg/m³) Company B WELL Summer 2020
Cyclopentasiloxane, decamethyl-	<0.5	<0.5	5.5±0.7	0.7±0.5	13.0±7.0	4.9±0.6
Ethanol, 2-butoxy-	<0.5	2.4±1.4	2.9±0.8	<0.5	<0.5	2.0±0.7
Ethanol, 1-(2-butoxyethoxy)-	<0.5	16.0±10.0	14.0±2.0	<0.5	<0.5	<0.5
Ethanol, 2-(2-butoxyethoxy)-, acetate	<0.5	98.0±74.0	30.0±8.0	0.6±0.5	<0.5	<0.5
2-Butanone, oxime	<0.5	<0.5	<0.5	<0.5	322.0±223.0	<0.5
1-Butanol	1.3±0.5	4.8±1.0	1.5±0.6	1.2±0.1	5.0±2.0	3.0±1.0
2-Ethylhexanol	5.0±2.0	4.7±1.4	6.5±0.3	2.1±0.3	14.0±1.0	14.0±2.0
Formaldehyde	7.5±0.2	17.0±3.0	15.0±0.9	15.0±5.0	3.9±2.0	15.0±4.0
Acetaldehyde	3.2±0.5	7.9±0.7	6.9±0.3	3.8±0.5	2.3±0.7	5.0±2.0

Stamp et al. (2020)

41. Stamp et al. (2020) carried out air quality monitoring in an office building, hospital (para 63) and school (para 73).

42. All buildings were modern and had been occupied for at least 3 years at the start of the study. The office was based in Keynsham, the school in south London and a hospital in Bristol.

43. The office building was made up of three interconnecting blocks, was naturally ventilated and there was no mechanical cooling in open plan office spaces. Exposed thermal mass was combined with natural ventilation (openable window louvers) to help regulate internal temperatures in summer. Three open plan offices were monitored continuously, across each of the three blocks at different floor heights. The building sits at the end of a busy high-street and a short distance from a major bypass.

44. Continuous indoor measurements were made in each building for 6-10 months. In addition, key VOCs were measured using passive sampling techniques across periods of 5-14 months in both the heating and non-heating seasons (Table 14).

Table 14. Mean, minimum and maximum concentrations of VOCs in offices in UK

VOC	**Mean conc. (µg/m^3)**	**Min conc. (µg/m^3)**	**Max. conc. (µg/m^3)**
Formaldehyde	16.4	10.3	27.1
Benzene	1.18	0.95	2.3
Toluene	2.52	0.80	4.4
Trichloroethylene	0.46	0.45	0.50
Tetrachloroethylene	0.56	0.55	0.60
Styrene	1.50	0.50	2.60
Naphthalene	0.40	0.40	0.40
d-Limonene	44.8	2.9	87.8
α-Pinene	136.3	9.5	286.4

Al-Mudhaf et al. (2013)

45. Al-Mudhaf et al. (2013) collated indoor air samples from eight large office buildings in Kuwait. The offices were located in various urban areas. All offices had central heating, ventilation and air-conditioning systems, with several air handling units on each floor. Smoking was not permitted, and windows were kept closed at all times. During the sampling period no renovation or refurbishment was carried out.

46. All test areas were served by a heating, ventilation and air conditioning (HVAC) unit and by no more than two air handling units and did not share a common ventilation with mechanical or storage rooms or cafeterias. Air samples were collected passively using cleaned and evacuated 6 L cannisters. Flow rates of approximately 12.5 and 4.2 cc/min were used to obtain 8- and 24-hour integrated air samples, respectively. All sampling was conducted from August 2010 and December 2011, starting at 07.00 am.

47. Samples were analysed within one week, using GC/MS for 78 VOCs (Table 15).

48. Authors noted that there was considerable variation in the composition of the VOC mixtures between the different offices, with alcohols representing the greatest proportion of VOCs for all offices, specifically ethanol, followed by carbonyl compounds (acetone and acetaldehyde), aliphatic hydrocarbons (Propene and pentane) and aromatic compounds (toluene).

49. Some offices had higher levels of some VOCs, which was attributed to vehicle and industrial emissions from nearby sites.

Table 15. Mean, SD, minimum and maximum concentrations of VOCs in offices in Kuwait

VOC	Mean conc. ($\mu g/m^3$) Office	SD ($\mu g/m^3$) Office	Min conc. ($\mu g/m^3$) Office	Max. conc. ($\mu g/m^3$) Office	Mean conc. ($\mu g/m^3$) Outdoor	SD ($\mu g/m^3$) Outdoor	Min conc. ($\mu g/m^3$) Outdoor	Max. conc. ($\mu g/m^3$) Outdoor
Pentane	5.5	9.7	0.4	151.1	3.8	5.4	0.4	45.5
Hexane	1.7	1.7	0.4	17.5	1.5	1.0	0.4	15.3
Propene	12.4	32.7	0.7	627.0	5.5	3.8	0.4	51.3
Isoprene	2.0	1.8	0.2	17.6	0.9	0.6	0.2	8.7
Isobutene	5.4	18.6	0.4	186.0	1.7	0.6	0.4	37.2
1,3-Butadiene	1.0	1.2	0.2	16.1	0.5	0.4	0.2	11.4
Chlorodifluoromethane	32.9	162.0	1.6	1340.0	10.3	1.9	1.4	928.0
Dichlorodifluoromethane	2.3	2.9	0.2	20.8	0.8	0.6	0.2	10.3
Chloromethane	1.1	2.5	0.3	48.5	0.8	0.7	0.3	7.0
Trichlorofluoromethane	0.8	2.9	0.1	51.8	1.0	0.3	0.1	80.7
Methylene chloride	1.6	6.4	0.2	96.8	0.9	0.5	0.2	18.1
Acetaldehyde	7.7	5.3	0.5	38.5	4.6	3.9	0.5	51.1
Acrolein	1.0	1.8	0.4	24.1	0.7	0.4	0.3	8.3
Acetone	14.8	29.1	0.4	520.0	10.8	5.9	0.5	270.0

VOC	Mean conc. (µg/m³) Office	SD (µg/m³) Office	Min conc. (µg/m³) Office	Max. conc. (µg/m³) Office	Mean conc. (µg/m³) Outdoor	SD (µg/m³) Outdoor	Min conc. (µg/m³) Outdoor	Max. conc. (µg/m³) Outdoor
Propanal	6.1	5.5	0.3	70.8	3.7	2.9	0.3	62.4
Methacrolein	0.8	1.1	0.2	7.3	1.2	0.7	0.2	14.6
Butanal	1.4	3.9	0.3	33.9	1.0	0.5	0.3	24.2
Methyl ethyl ketone	2.8	8.6	0.2	115.0	1.1	0.6	0.2	8.2
Pentanal	1.5	0.4	0.2	3.4	0.4	0.3	0.2	2.3
Hexanal	1.0	2.1	0.1	34.0	0.6	0.5	0.1	4.4
Methanol	35.1	42.1	1.6	289.0	23.0	10.6	1.2	965.0
Ethanol	112.0	253.0	0.5	4380.0	7.6	3.3	0.4	212.0
1-Propanol	16.8	40.5	0.3	240.0	80.8	5.6	0.3	486.0
2-Propanol	12.3	17.3	0.4	207.0	5.3	3.5	0.5	55.4
1-Butanol	27.0	2.1	0.4	15.3	2.0	1.4	0.4	6.4
Benzene	1.5	1.3	0.2	11.1	1.3	0.8	0.2	74.0
Toluene	11.8	22.0	0.5	185.0	5.1	2.8	0.5	72.7
Ethyl benzene	1.4	4.2	0.2	71.8	0.7	0.5	0.2	11.0
m-Xylene	2.7	8.4	0.3	145.1	1.6	0.8	0.3	27.9

VOC	Mean conc. (µg/m^3) Office	SD (µg/m^3) Office	Min conc. (µg/m^3) Office	Max. conc. (µg/m^3) Office	Mean conc. (µg/m^3) Outdoor	SD (µg/m^3) Outdoor	Min conc. (µg/m^3) Outdoor	Max. conc. (µg/m^3) Outdoor
p-Xylene	1.3	4.0	0.3	67.4	0.8	0.4	0.3	10.6
Styrene	1.2	3.5	0.3	22.7	1.4	0.3	0.3	32.3
o-Xylene	1.5	3.8	0.3	61.7	0.8	0.5	0.3	16.3
1,2,4-Trimethylbenzene	1.1	2.4	0.2	32.4	0.6	0.4	0.2	14.4
p-Dichlorobenzene	2.5	5.1	0.2	24.4	2.3	0.4	0.2	10.0
Cyclopentane	1.8	2.2	0.2	17.7	1.4	0.9	0.2	23.5
Cyclohexane	1.1	6.1	0.3	99.8	0.6	0.4	0.3	14.6
Acetonitrile	4.1	6.0	0.5	56.8	3.3	1.6	0.4	60.2
Vinyl acetate	0.5	0.4	0.3	3.1	0.5	0.3	0.3	5.0
Methyl tertiary butyl ether	0.9	1.2	0.3	16.6	0.7	0.5	0.3	13.0

50. A number of authors reported data from the European Indoor Air Monitoring and Exposure assessment (AIRMEX) study, which measured VOCs in working environments (offices, classrooms, waiting halls), public buildings, schools, kindergartens and homes in eleven cites over north, central and south Europe. Samples were taken during different seasons between 2003 and 2008 (Geiss et al. 2011, Kotzias et al. 2009).

51. The duration of the measuring campaigns was fixed to one week, including weekends. Radial type diffusion passive samplers were positioned at different places within the buildings at a height of 2-2.5 m from the floor, covering areas of main access for occupants i.e. entrance halls and offices. In schools and kindergartens, samplers were mounted in classrooms or areas where children predominantly reside. Samples were analysed using GC-FID or TD-GC/MS.

Kotzias et al. (2009)

52. Kotzias et al. (2009) reported data on benzene and formaldehyde in public buildings, such as offices and waiting halls (Table 16).

Table 16. Mean, minimum and maximum concentrations of VOCs in public buildings

VOC	Min conc. (µg/m^3) Public buildings	Max. conc. (µg/m^3) Public buildings	Min conc. (µg/m^3) Outdoor	Max. conc. (µg/m^3) Outdoor
Benzene	0.9	10.9	0.6	10.5
Formaldehyde	8.3	27.3	1.2	5.4

Mandin et al. 2017; Sakellaris et al. 2021

53. Several papers reported data obtained from the framework of the European OFFICEAIR project, which consisted of monitoring office buildings in eight countries. The project focussed on modern office buildings, in

Portugal (5 buildings), Spain (3 buildings), Italy (4 buildings), Greece (5 buildings), France (9 buildings), Hungary (5 buildings), the Netherlands (3 buildings) and Finland (3 buildings) (Mandin et al. 2017, Sakellaris et al. 2021).

54. In the study, 148 offices from 37 buildings (4 offices per building) were monitored during different seasons. The summer campaign occurred between June 18, 2012 and October 19, 2012. Four buildings were investigated between May 13, 2013 and June 14, 2013. The winter campaign occurred between November 5, 2012 and April 19, 2013. Two buildings were investigated between November 15 and November 22, 2013 (Mandin et al. 2017, Sakellaris et al. 2021).

55. Twelve VOCs were selected for investigation based on a literature review of indoor air pollutants in office environments and their potential to be associated with irritation symptoms (Mandin et al. 2017).

56. Sampling for VOCs was carried out over 5 days, from approximately 09.00 on Monday to approximately 17.00 on Friday at four diverse locations in each building, preferentially on different floors of the building at different orientations i.e. north, south, east or west. Diversity of rooms was considered, namely open spaces and cellular offices if the building had both types of workspaces.

57. Samplers were placed in the centre of the room not closer than 1 m to the wall, and approximately 1.1 m from the floor (the breathing zone of seated occupants). Analysis was carried out within one month using TD-GC/MS.

58. Mandin et al. (2017) reported data during summer and winter seasons (Table 17). Sakellaris et al. (2021) reported the difference in VOCs between sick building syndrome and non-sick building syndrome. Sick building syndrome was determined based on the WHO definition namely ‘work-related non-specific symptoms complexes for which the cause is not always known whilst most of the occupants report relief soon after leaving the building’ (Table 18).

Table 17. Mean concentrations of VOCs in offices

VOC	Mean conc. (µg/m³) Summer	SD. (µg/m³) Summer	Min conc. (µg/m³) Summer	Max. conc. (µg/m³) Summer	Mean conc. (µg/m³) Winter	SD. (µg/m³) Winter	Min conc. (µg/m³) Winter	Max. conc. (µg/m³) Winter
Benzene	1.4	1.3	<LOD	10.0	2.1	1.7	<LOQ	8.9
Toluene	8.1	8.5	<LOD	63.0	6.1	8.8	<LOD	62.0
Xylenes	3.8	5.1	<LOD	40.0	3.3	3.7	<LOD	20.0
Ethyl benzene	1.8	2.0	<LOD	14.0	1.3	1.2	<LOD	6.7
n-Hexane	1.9	1.6	<LOD	9.1	1.5	1.4	<LOD	8.6
Trichloroethylene	<LOD	-	<LOD	0.8	-	-	<LOD	1.8
Tetrachloroethylene	<LOQ	-	<LOD	1.0	8.2	45.0	<LOD	290.0
α-Pinene	4.2	6.3	<LOD	66.0	6.3	8.3	<LOD	68.0
d-Limonene	4.7	4.0	<LOD	34.0	19.0	18.0	<LOQ	81.0
2-Butoxyethanol	5.7	10.0	<LOD	80.0	2.7	6.8	<LOD	43.0
2-Ethylhexanol	4.7	4.5	<LOD	31.0	3.9	14.4	<LOD	34.0
Styrene	1.0	1.1	<LOD	12.0	0.8	0.7	<LOQ	5.6
Formaldehyde	16.0	7.6	4.7	49.0	8.1	4.1	1.7	23.0
Acetaldehyde	6.4	2.2	<LOQ	16.0	4.9	2.0	<LOD	12.0

VOC	Mean conc. (µg/m^3) Summer	SD. (µg/m^3) Summer	Min conc. (µg/m^3) Summer	Max. conc. (µg/m^3) Summer	Mean conc. (µg/m^3) Winter	SD. (µg/m^3) Winter	Min conc. (µg/m^3) Winter	Max. conc. (µg/m^3) Winter
Acrolein	2.5	1.1	<LOD	5.5	1.3	1.0	<LOD	7.7
Propionaldehyde	2.8	1.5	<LOD	11.0	1.4	0.9	<LOQ	5.7
Benzaldehyde	1.0	0.5	<LOQ	4.9	<LOQ	-	<LOD	4.9
Glutaraldehyde	1.3	0.8	<LOQ	3.9	<LOQ	-	<LOQ	4.3
Hexanal	11.0	5.0	4.6	35.0	5.0	2.4	1.5	14.0

Table 18. Comparison of concentrations of VOCs between sick building syndrome and non-sick building syndrome

VOC	Mean conc. (µg/m^3) Sick building syndrome	Mean conc. (µg/m^3) Non-sick building syndrome
Benzene	2.2	1.9
Toluene	9.5	7.3
Xylenes	4.2	3.0
Ethyl benzene	1.7	1.3
n-Hexane	1.8	1.4
Trichloroethylene	0.1	0.2
Tetrachloroethylene	4.3	8.5
α-Pinene	1.9	4.3
d-Limonene	17.2	17.9
2-Butoxyethanol	9.5	8.4
2-Ethylhexanol	4.4	3.4
Styrene	0.8	0.7
Formaldehyde	11.2	10.8
Acetaldehyde	5.6	5.3
Acrolein	1.7	1.4
Propionaldehyde	2.2	1.8
Benzaldehyde	1.0	0.7
Glutaraldehyde	1.2	1.0
Hexanal	8.3	7.0

Zuraimi et al. (2006)

59. Zuraimi et al. (2006) compared the emission of VOCs in office buildings in Europe and Singapore. The European offices were located in downtown, suburban, rural or industrial areas of Switzerland, Germany, Denmark, UK, Greece, France, Finland and Norway. They used mixing and natural ventilation systems. The ceilings, walls and floors were made from various materials including acoustic tiles and concrete, plaster board and painted

walls, and carpet, PVC and linoleum, respectively. The offices in Singapore were located in downtown and suburban areas. They had mixing ventilation systems. The ceilings, walls and floors were made from acoustic tiles, wallpaper and painted walls, and carpet and linoleum, respectively.

60. There were some main differences between the offices. European offices had heating systems, were in temperate or cold climates, had an air re-circulation rate of 0-90%, had a large outdoor airflow rate per occupant or square meter, had 31±5% smokers and had a mean building age of 17.9 years. Singapore offices had air conditioning, were in a tropical climate, had a high re-circulation rate from 90%, had reduced outdoor air flow per occupant or square meter, no smoking was allowed and had a mean building age of 3.2 years.

61. In Europe, VOCs were collected on conditioned Tenax TA tubes by active sampling and in Singapore, using on conditioned multi-sorbent tubes by active sampling. Ten tubes were used per building. The VOCs were analysed using TD-GC/MS. Twenty-three VOCs were found in both European and Singapore offices (Table 19).

62. Authors noted that concentrations of 2-methylpentane and n-heptane were significantly higher in European buildings compared with those in Singapore, while n-tetradecane, 2-ethyl 1-hexanol, benzene, toluene, m- and p-xylene, benzaldehyde and naphthalene were significantly higher in Singapore buildings. There were no differences in VOCs (1,1,1-trichloroethane and 2-propanone) related to occupants, suggesting similar use of consumer products and occupant densities.

Table 19. Mean concentrations, SD, range of means* and maximum concentrations of VOCs in offices in Europe and Singapore

VOC	Mean conc. (µg/m³) Singapore building	SD. (µg/m³) Singapore building	Range of means* (µg/m³) Singapore building	Max. conc. (µg/m³) Singapore building	Mean conc. (µg/m³) European building	SD. (µg/m³) European building	Range of means* (µg/m³) European building	Max. conc. (µg/m³) European building
2-Methylpentane	6.4	5.0	1.5-17.0	31.3	17.8	35.3	1.0-192.0	933.1
3-Methylpentane	5.7	5.6	1.1-15.7	28.8	30.8	59.6	2.4-242.0	1176.0
n-Hexane	34.6	43.1	4.4-114.5	210.2	52.5	137.4	1.0-708.0	3441.0
n-Heptane	14.8	22.3	2.4-69.0	150.6	31.7	62.6	1.9-314.0	1526.0
n-Decane	24.8	258.6	1.3-57.7	294.0	8.6	6.4	3.4-21.2	80.4
n-Undecane	32.9	41.7	2.7-114.8	278.5	13.8	20.2	2.0-65.2	261.8
n-Dodecane	29.8	44.1	1.9-134.8	160.2	10.9	8.4	2.0-19.0	139.1
n-Tetradecane	38.6	31.9	3.9-97.9	97.9	3.1	2.0	1.0-5.4	63.4
Isoprene	10.5	5.6	3.6-21.6	60.9	9.0	7.5	1.6-26.6	223.9
Benzene	87.1	44.3	32.4-167.5	444.1	14.6	10.9	1.0-109.0	590.3
Toluene	287.3	518.3	112.9-1641.8	3209.0	35.1	40.6	2.0-158.0	1435.0
o-Xylene	43.4	30.2	15.4-103.5	255.8	10.2	9.3	1.0-29.5	281.5
m- and p-Xylene	143.0	141.3	53.7-404.6	499.9	22.2	39.8	1.0-243.2	914.3

VOC	Mean conc. (μg/m^3) Singapore building	SD. (μg/m^3) Singapore building	Range of means* (μg/m^3) Singapore building	Max. conc. (μg/m^3) Singapore building	Mean conc. (μg/m^3) European building	SD. (μg/m^3) European building	Range of means* (μg/m^3) European building	Max. conc. (μg/m^3) European building
Naphthalene	143.9	93.0	42.9-310.0	744.8	6.5	4.33	3.1-11.3	685.0
Ethanol	173.2	15.1	6.5-27.8	61.6	20.8	30.5	1.7-109.6	340.2
1-Butanol	4.4	2.6	1.4-6.3	18.7	15.8	26.5	1.4-83.7	541.3
2-Ethyl 1-hexanol	30.6	10.0	1.0-244.4	244.4	1.5	0.7	1.0-2.0	18.1
Methylcyclopentane	8.1	14.5	0.1-33.9	75.0	57.5	105.4	9.0-337.0	1638.0
Methylcyclohexane	664.0	34.7	2.9-98.8	181.5	26.4	51.0	1.0-235.0	1142.0
1,1,1-Trichloroethane	36.1	35.6	0.6-112.2	306.1	17.3	18.4	2.0-67.6	46.5
2-Propanone	16.5	26.3	0.1-63.1	216.5	17.4	17.2	1.0-83.5	787.2
Benzaldehyde	29.0	26.8	2.1-83.5	184.9	4.1	2.4	1.5-10.9	60.1
Limonene	65.1	52.9	14.7-144.7	278.9	34.6	76.7	1.0-365.0	1242.0

* this is reported in the paper as the range, but is assumed to be the range of means

Hospitals

Stamp et al. (2020)

63. As described above, Stamp et al. (2020) carried out air quality monitoring in an office building (para 41), hospital and school (para 73).

64. All buildings were modern and had been occupied for at least 3 years at the start of the study. The office was based in Keynsham, the school in south London and the hospital in Bristol.

65. Three wards within the hospital were monitored in this study. The ventilation system was based on mechanical ventilation with high air exchange rates in most areas, with a carbon dioxide-based demand control system. The building was fully sealed with no openable windows. Mechanical ventilation inlets are based next to air handling units, facing the relatively quieter north façade. To control the risk of infection, wards were intensively and frequently cleaned.

66. Continuous indoor measurements were made in each building for 6-10 months. In addition, key VOCs were measured using passive sampling techniques across periods of 5-14 months in both the heating and non-heating seasons (Table 20).

Table 20. Mean, minimum and maximum concentrations of VOCs in a hospital in UK

VOC	Mean conc. (µg/m^3)	Min conc. (µg/m^3)	Max. conc. (µg/m^3)
Formaldehyde	4.0	2.7	6.3
Benzene	0.8	0.65	0.95
Toluene	1.73	0.45	2.50
Trichloroethylene	0.35	0.25	0.45
Tetrachloroethylene	0.43	0.30	0.50
Styrene	0.40	0.30	0.50
Naphthalene	0.38	0.25	0.60
d-Limonene	14.3	2.9	23.7

VOC	Mean conc. ($\mu g/m^3$)	Min conc. ($\mu g/m^3$)	Max. conc. ($\mu g/m^3$)
α-Pinene	3.8	0.7	7.8

Schools

Godwin and Batterman (2007)

67. Godwin and Batterman (2007) investigated indoor air quality parameters, including VOCs, in 64 elementary and middle school classrooms in Michigan, USA.

68. Four elementary schools and five middle schools in a suburban school district in Michigan were selected. Within each school, at least one art room, one miscellaneous use room (e.g., music, library), two general classrooms, two science rooms (in middle schools), and two office/clerical rooms were selected at random. Three portable classrooms that were self-contained, prefabricated and free-standing were also included. The age of the schools ranged from 31 to 81 years of age. Classrooms had various levels of ventilation, with some having unopenable windows and some having air conditioning. All schools had mechanical ventilation.

69. Five to eight randomly selected classrooms in each school were simultaneously studied for a period of 1 week in spring and early summer (March 31 to June 7, 2003).

70. Sampling was carried out in occupied rooms over a 4.5-day period in most schools (3.5 days in schools 3 and 8 due to holidays). Samplers were placed at least 0.6 m above the floor away from doors and windows. VOC samples were collected passively onto thermally desorbed Tenax GR tubes and analysed for over 80 compounds using an automated short-path thermal desorption/cryofocusing system and GC-MS.

71. The mean and maximum concentrations of VOCs measured in all schools are presented in Table 21 and in elementary and middle schools are presented in Table 22.

Table 21. Mean and maximum concentrations of VOCs in schools

VOC	Mean conc. (µg/m^3) Schools	Max conc. (µg/m^3) Schools	Mean conc. (µg/m^3) Outdoor	Max conc. (µg/m^3) Outdoor
Benzene	0.09	1.6	0.06	0.1
Ethyl benzene	0.24	2.8	-	0.0
Toluene	2.81	74.6	0.52	1.0
m- and p-Xylene	2.3	63.0	0.0	10.0
o-Xylene	0.24	3.8	-	0.0
Styrene	0.04	1.4	-	0.0
1,3,5-Trimethylbenzene	0.02	0.2	-	0.0
1,2,4-Trimethylbenzene	0.14	1.5	0.01	0.0
p-Isopropyltoluene	0.02	0.6	-	0.0
1,3-Dichlorobenzene	0.02	0.4	-	0.0
1.2.3-Trichlorobenzene	0.01	0.3	-	0.0
1.2.4-Trichlorobenzene	0.07	3.9	-	0.0
Chloroform	0.09	2.5	-	0.0
Trichloroethylene	0.02	0.3	0.01	0.1
Tetrachloroethylene	0.02	0.3	-	0.0
1,2,3-Trichloropropane	0.01	0.1	-	0.0
2-Butanone	0.24	3.0	-	0.0
Tetrahydrofuran	0.16	3.8	-	0.0
Methyl isobutyl ketone	0.46	8.2	0.02	0.1
Phenol	0.61	12.1	0.13	1.2
α-Pinene	1.35	35.2	0.11	0.6
Limonene	4.41	45.1	0.29	1.6
Naphthalene	0.82	10.3	0.10	0.9

Table 22. Mean concentrations of VOCs in elementary and middle schools

VOC	Mean conc. ($\mu g/m^3$) Elementary school	Mean conc. ($\mu g/m^3$) Middle school
Benzene	0.03	0.15
Toluene	2.05	1.20
m- and p-Xylene	1.64	0.15
α-Pinene	0.86	1.84
Limonene	5.45	2.65
Naphthalene	0.11	0.97

72. Authors noted that the room-to-room variability and the low outdoor levels (not presented in this report|) suggest local (classroom) sources rather than building or outdoor sources, as art and science rooms had some of the highest levels of VOCs.

Stamp et al. (2020)

73. As described above, Stamp et al. (2020) carried out air quality monitoring in an office building (para 41), hospital (para 63) and school.

74. All buildings were modern and had been occupied for at least 3 years at the start of the study. The office was based in Keynsham, the school in south London and the hospital in Bristol.

75. A typical classroom, lab-based classroom and library space across three different blocks were monitored in the study. The school was constructed from precast concrete façade panels in six new buildings in central London. It was occupied weekdays from 8.30 to 15.50 as well as out of hours and weekend use. Mechanical ventilation with heat recovery was provided by centralised roof mounted air handling systems using wall mounted diffusers to distribute the supply air and controlled based on carbon dioxide sensors in each room. Small openable windows provided additional

ventilation. Furnishings were typical of UK schools and not specified in terms of off-gassing of VOCs.

76. Continuous indoor measurements were made in each building for 6-10 months. In addition, key VOCs were measured using passive sampling techniques across periods of 5-14 months in both the heating and non-heating seasons (Table 23).

Table 23. Mean, minimum and maximum concentrations of VOCs in a school in UK

VOC	**Mean conc. (μg/m^3)**	**Min conc. (μg/m^3)**	**Max. conc. (μg/m^3)**
Formaldehyde	3.5	0.6	12.9
Benzene	1.40	0.95	2.50
Toluene	1.62	0.80	3.50
Trichloroethylene	0.45	0.45	0.45
Tetrachloroethylene	0.55	0.55	0.55
Styrene	1.75	0.50	4.20
Naphthalene	0.50	0.40	1.00
d-Limonene	3.6	2.9	3.6
α-Pinene	5.6	0.7	9.9

77. A number of authors reported data from the European Indoor Air Monitoring and Exposure assessment (AIRMEX) study, which measured VOCs in working environments (offices, classrooms, waiting halls), public buildings, schools, kindergartens and homes in eleven cites over north, central and south Europe. Samples were taken during different seasons between 2003 and 2008 (Geiss et al. 2011, Kotzias et al. 2009).

78. The duration of the measuring campaigns was fixed to one week, including weekends. Radial type diffusion passive samplers were positioned at different places within the buildings at a height of 2-2.5 m from the floor, covering areas of main access for occupants i.e. entrance halls and offices. In

schools and kindergartens, samplers were mounted in classrooms or areas where children predominantly reside. Samples were analysed using GC-FID or TD-GC/MS.

Pegas et al. (2010)

79. Pegas et al. (2010) carried out a preliminary study to investigate indoor air quality in primary schools in Lisbon.

80. Samples were collected from three elementary schools (183, SJB and SJ) located in the city centre in December 2008. Two classrooms per school were collected. One classroom in 183 and SJB schools always had electric heating connected and the windows closed. In the 183 school activities with paints and glue took place in the classroom. All other classrooms had windows and doors open frequently. In the SJ school, the windows of both classrooms were always shut. All classrooms depended on natural ventilation through doors and windows.

81. VOCs were passively sampled over a two-week period. Samplers were positioned 1.5 m above the floor, and at a position that was not more than 1 m from a door or window. Analysis was carried out using FID-GC. Formaldehyde was collected in DNPH cartridges and analysed by HPLC.

82. The concentrations of VOCs are presented in Table 24. Authors noted that SJ School, which has the oldest building among all institutions, registered both the highest concentrations of limonene, β-pinene, sabinene, n-butyl acetate, methyl acetate and formaldehyde, and also the most diverse set of VOC compounds. It was suggested that this was due to the inadequate ventilation which favours accumulation of pollutants. The 183 School registered the lowest concentrations of VOCs, probably because this institution had better ventilation than the other schools, higher classroom volumes and lesser number of pupils.

83. Authors also offered explanations about the source of some VOCs and stated ‘n-Hexane, n-heptane and n-decane could have indoor sources in some architectural finishes, floor adhesives, PVC flooring, consumer products (e.g. floor waxes and aerosol air fresheners). Limonene could be derived from

cleaning products, air fresheners and many other consumer products. Benzene, toluene, xylenes and styrene could be originated from engine vehicle exhaust, gasoline/fuel, tobacco smoke, solvent-based paints, floor adhesives, PVC flooring, carpeting, printed material and solvent-based consumer products'.

Table 24. Mean concentration of VOCs in three schools in Lisbon

VOC	**Mean conc. (µg/m^3) SJB**	**Mean conc. (µg/m^3) Outdoor**	**Mean conc. (µg/m^3) 183**	**Mean conc. (µg/m^3) Outdoor**	**Mean conc. (µg/m^3) SJ**	**Mean conc. (µg/m^3) Outdoor**
Pentane	3.6	0.7	1.0	1.1	1.4	1.1
Methyl acetate	52.0	-	34.0	-	83.0	-
Ethyl acetate	2.1	-	1.3	-	3.6	-
n-Hexane	3.0	0.5	1.2	0.6	1.7	0.8
Benzene	2.9	<LOD	3.1	3.1	2.5	2.5
Cyclohexane	0.9	0.2	0.2	0.1	1.6	0.2
Isooctane	1.2	0.2	0.2	0.2	0.4	0.2
n-Heptane	3.2	0.4	3.3	0.5	1.0	0.5
Toluene	10.3	2.0	2.5	2.6	4.6	2.9
n-Butyl acetate	4.2	0.6	1.4	0.9	6.7	1.4
m- and p-Xylene	8.8	1.2	1.4	1.3	2.8	1.8
Styrene	ND	-	ND	-	0.3	-
o-Xylene	3.1	0.4	1.1	0.5	5.5	0.6
α-Pinene	0.5	-	0.2	-	4.3	0.2
Sabinene	0.8	-	ND	0.1	12.2	0.2
β-Pinene	ND	-	ND	-	29.0	-
n-Decane	1.00	0.40	0.60	0.3	1.7	0.7
(+)-3-Carene	ND	-	ND	-	0.2	-
g-Terpinene	0.65	-	ND	0.2	0.8	0.2
Limonene	3.17	-	0.39	-	86.0	-

Kotzias et al. (2009)

84. Kotzias et al. (2009) reported data on benzene and formaldehyde in schools (Table 25).

Table 25. Minimum and maximum concentrations of VOCs in schools

VOC	**Min conc. (µg/m³) Schools**	**Max. conc. (µg/m³) Schools**	**Min conc. (µg/m³) Outdoor**	**Max. conc. (µg/m³) Outdoor**
Benzene	0.7	7.4	0.5	5.9
Formaldehyde	8.8	31.9	0.9	3.7

UK outdoor monitoring network data

85. The Environment Agency manages the UK's national monitoring sites on behalf of Defra and the Devolved Administrations. There are two major types of monitoring networks in the UK - automatic and non-automatic networks.

Non-automatic hydrocarbon networks

86. The non-automatic hydrogen network measures ambient benzene concentrations at 35 sites around the United Kingdom to assess compliance with UK Objectives (between 3.25 and 16.25 µg m^3 depending on area and compliance date, expressed as a running annual mean), as well as with the corresponding EC Air Quality Directive Limit Value (5 µg m^3 annual average).

87. Non-automatic networks measure daily, weekly or monthly, and samples are collected by some physical means (such as diffusion tube or filter). These samples are then subjected to analysis, and concentrations of the chemical are calculated.

88. Data for benzene from two representative sites (Nottingham centre and Oxford centre roadside) over the last three years are presented for illustrative purposes in Figure 1.

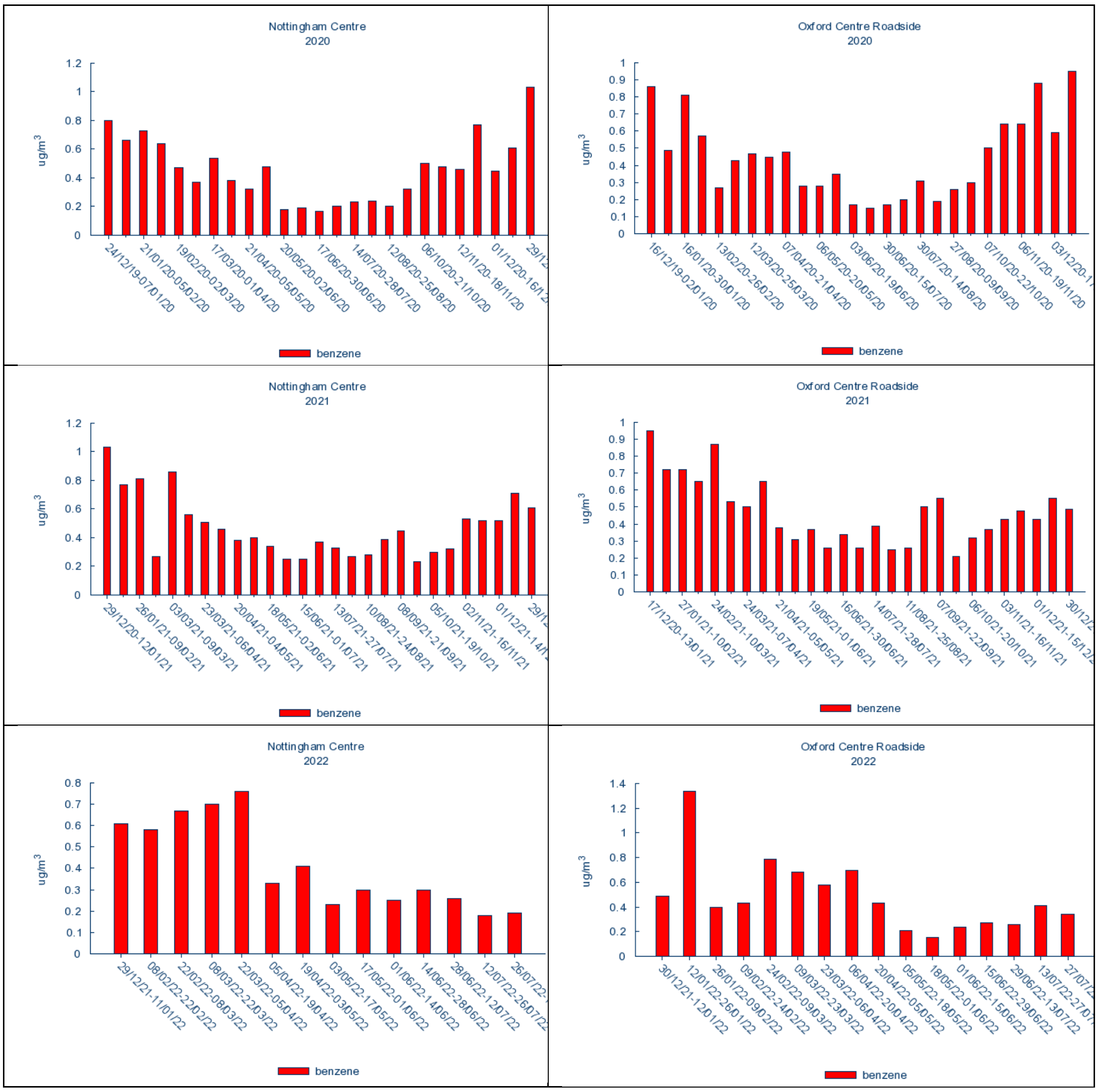
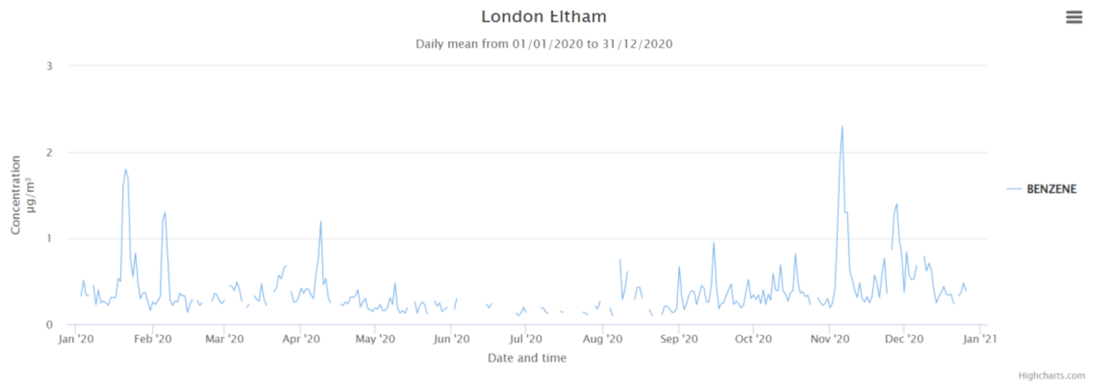


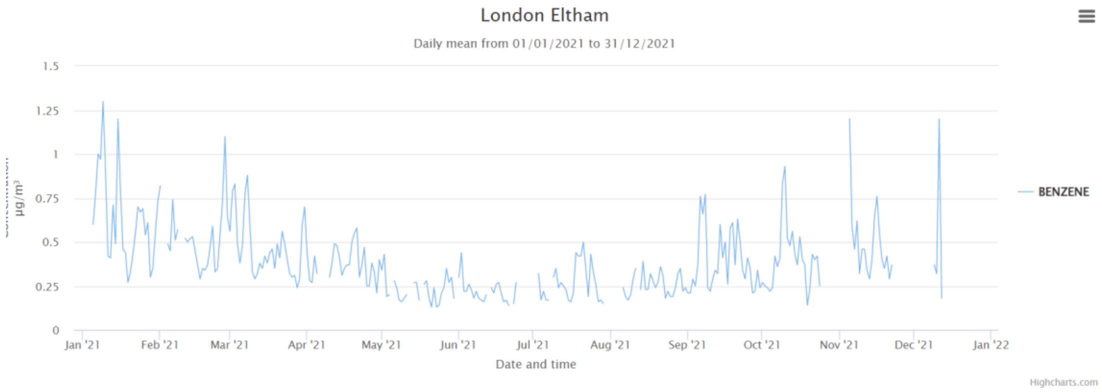
Figure 1. Concentrations of benzene measured during 2020-2022 in Nottingham centre (left) and Oxford centre roadside (right)

Automatic hydrocarbon networks

89. The automatic hydrocarbon networks measure more frequently compared to non-automatic networks, and produce hourly pollutant concentrations, with data being collected from four individual sites for 29 chemicals, some of which are reported in aircraft cabin air, including benzene, hexane, heptane, toluene, ethyl benzene, m+p-xylene, octane, o-xylene and trimethylbenzenes.

90. Data for benzene from two representative sites (London Eltham and Chilbolton Observatory) obtained over the last three years are presented in Figure 2 and Figure 3 and data for VOCs are presented in Figure 4 and Figure 5 for illustrative purposes.





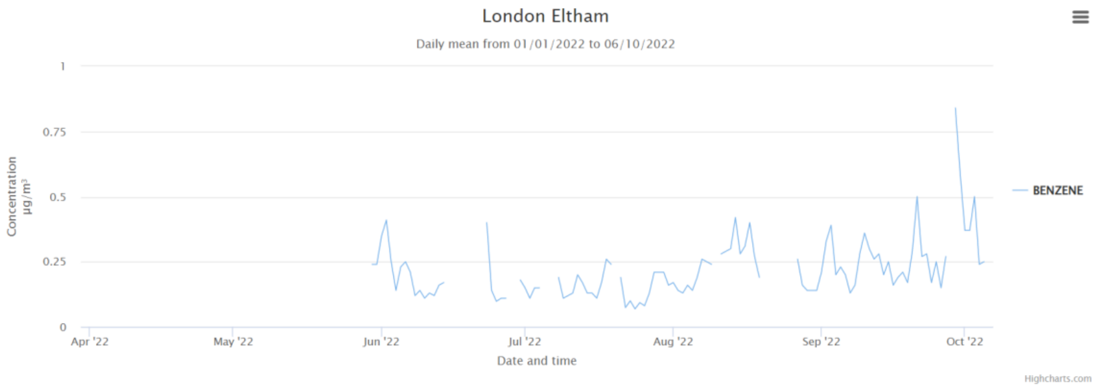


Figure 2. Concentrations of benzene measured during 2020-2022 in London Eltham

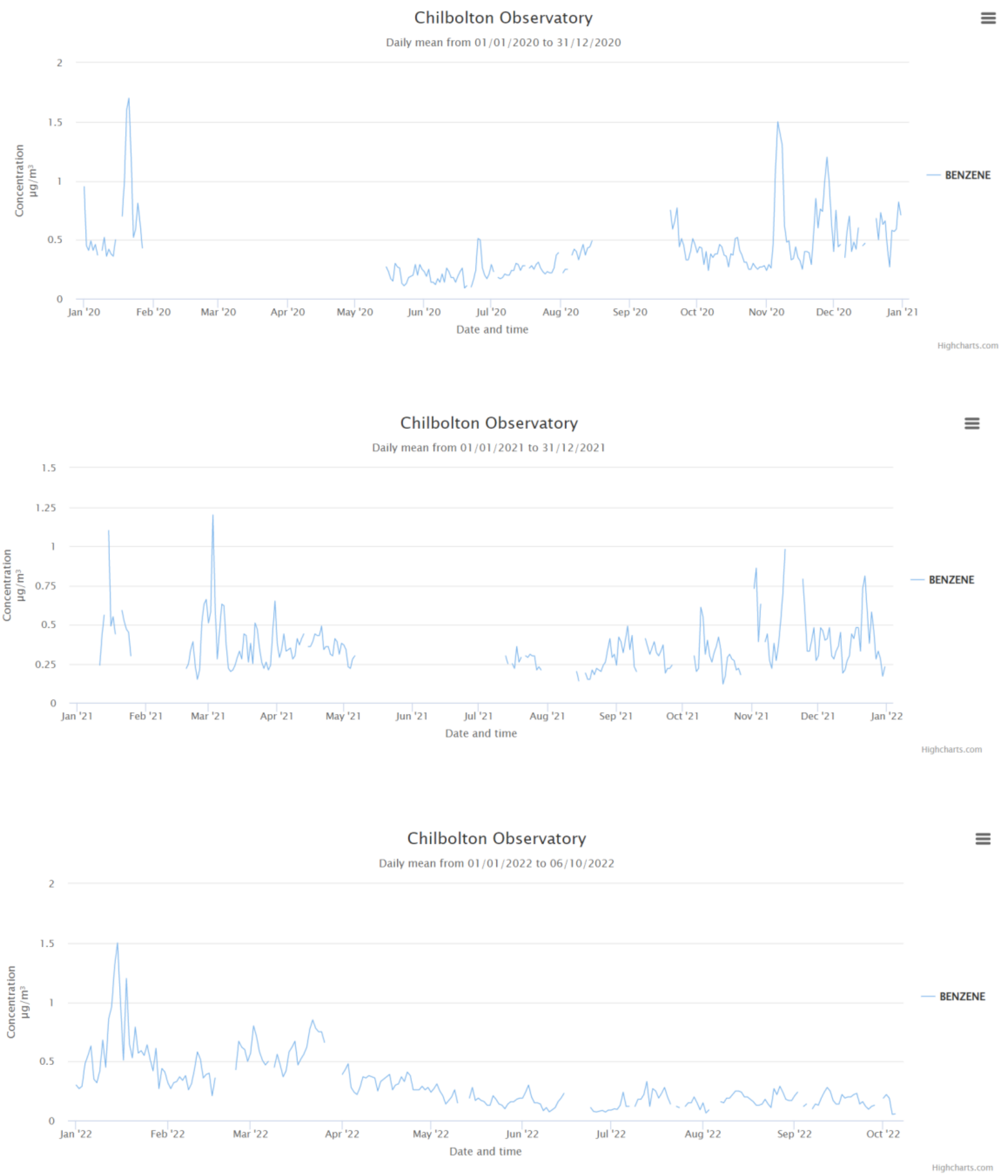


Figure 3. Concentrations of benzene measured during 2020-2022 in Chilbolton Observatory

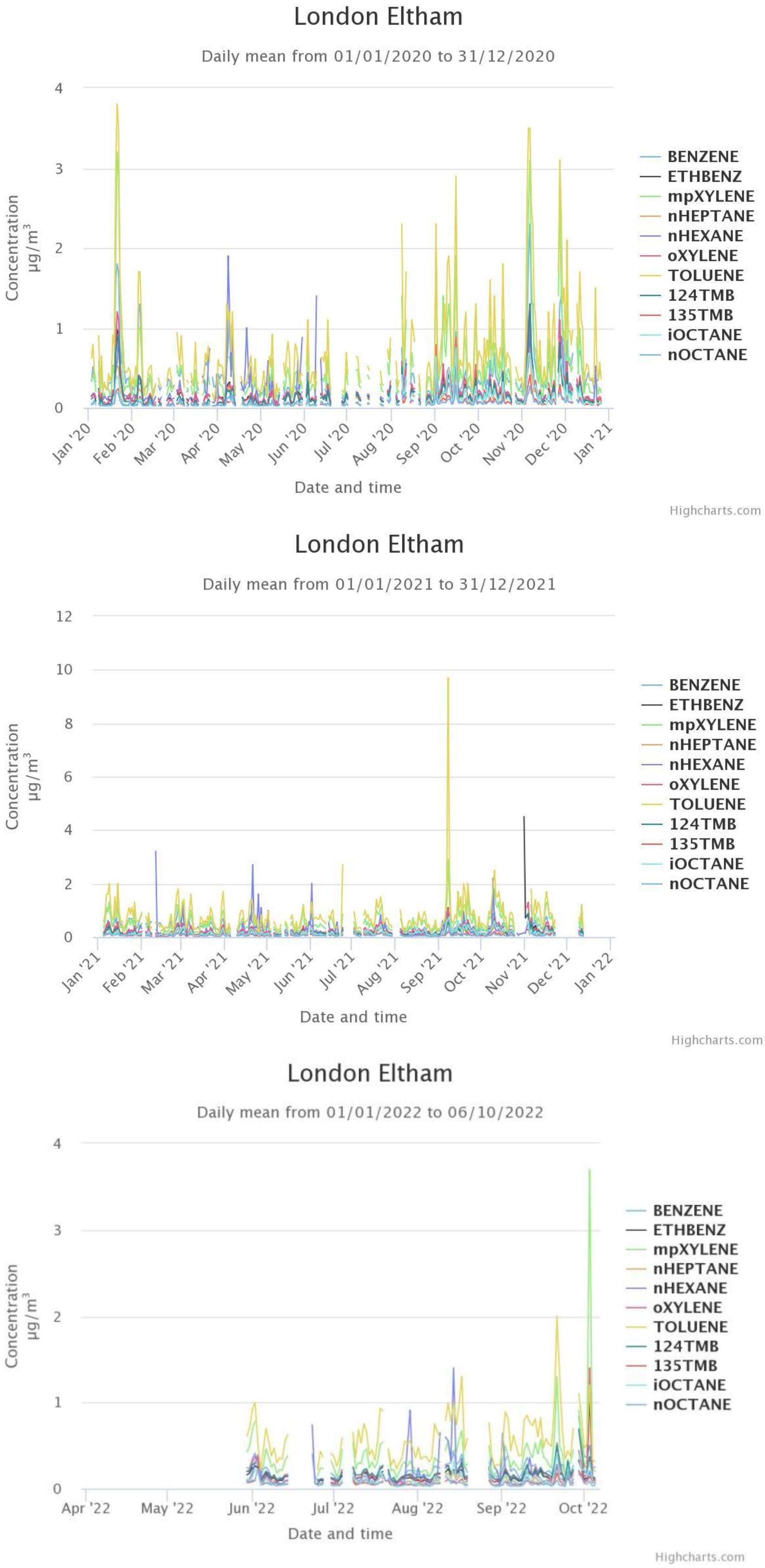


Figure 4. Concentrations of VOCs measured during 2020-2022 in London Eltham

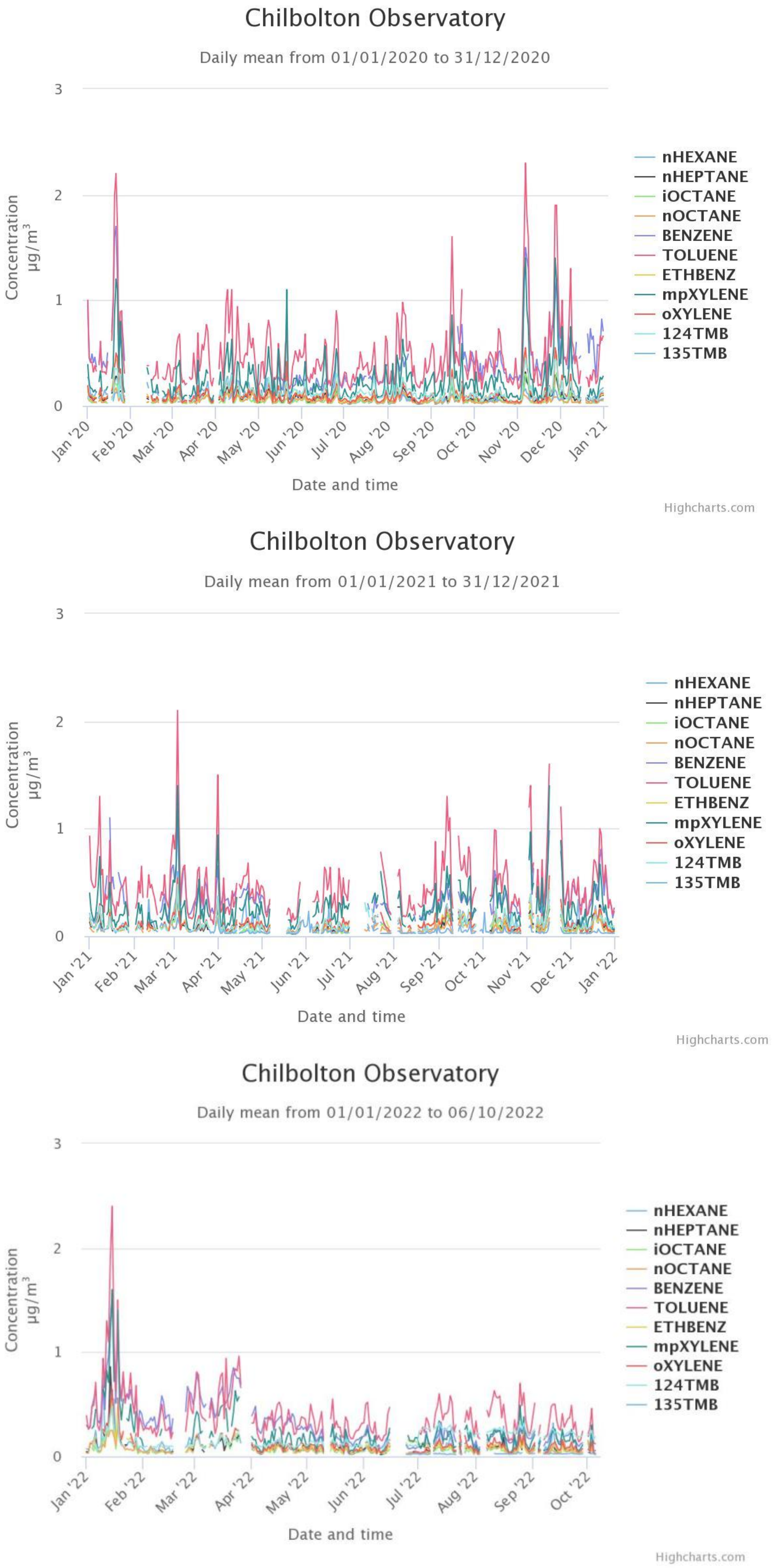


Figure 5. Concentrations of VOCs measured during 2020-2022 in Chilbolton Observatory

91. From the sites assessed, the maximum concentration of benzene measured in the non-automatic network was 1.3 µg m^3. The maximum concentrations of VOCs measured in the automatic network are shown in Table 26.

Table 26. Maximum concentrations of VOCs reported in the automated network

VOC	Highest mean (µg/m^3) London Eltham	Highest mean (µg/m^3) Chilbolton Observatory	Highest mean (µg/m^3) Non automated	Highest mean (µg/m^3) Aircraft
n-Hexane	0.7	0.7	-	20.0
n-Heptane	0.7	0.9	-	1.8
n-Octane	0.2	0.2	-	1.9
Benzene	0.6	1.5	1.3	16.1
Toluene	1.0	2.4	-	29.8
Ethyl benzene	0.5	0.4	-	8.1
m and p-Xylene	1.3	1.6	-	8.8
o-Xylene	0.5	0.6	-	9.4
1,2,4-Trimethylbenzene	0.7	0.48	-	0.21
1,3,5-Trimethylbenzene	0.2	0.03	-	0.06

Summary

92. This summary brings information on VOCs reported in work environments with that from modes of transport together. VOCs that were reported in different modes of transport were considered in a previous paper (TOX/2022/46), which is also provided in Annex 1. Transcription errors in the previous paper have been amended.

Work environments

93. In total, 50 VOCs were reported in aircraft and work environments. Thirty-one VOCs were reported in aircraft and one work environment, ten VOCs in aircraft and two work environments and 9 VOCs in aircraft and all three work environments.

94. α-Pinene, benzene, formaldehyde, limonene, naphthalene, styrene, tetrachloroethylene, toluene and trichloroethylene were reported in aircraft and all three work environments (Table 27).

95. When comparing the highest mean values, limonene, naphthalene, tetrachloroethylene and trichloroethylene were higher in aircraft compared with other work environments (Table 27). However, when comparing maximum values, only trichloroethylene was higher in aircraft compared with concentrations measured in offices, which showed the highest concentrations of all work environments (Table 29).

96. 3-Carene, decane, ethyl acetate, ethylbenzene, heptane, hexane, m- and p-xylene, nonane, o-xylene and pentane were measured in aircraft and two work environments, namely offices and schools (Table 27).

97. When comparing the highest mean values, only ethyl acetate was higher in aircraft compared with other work environments (Table 27). However, when comparing maximum values, 3-carene, ethyl acetate and nonane were higher in aircraft compared with concentrations measured in offices, which had the highest concentrations of all work environments (Table 29).

98. The remaining VOCs presented in Table 27 were reported in aircraft and offices. None were reported in hospitals or schools.

99. When comparing the highest mean values, 1,2-propanediol, 2-phenoxyethanol, acetic acid, decanal, ethanol, hexanoic acid, nonanal and octanal were higher in aircraft compared with offices (Table 27). However, when comparing maximum values, 1,2-propanediol, 1-butanol, 2-phenoxyethanol, acetic acid, β-pinene, benzothiazole, decanal, dodecane,

ethanol, eucalyptol, hexanoic acid, isopropyl alcohol, methylcyclohexane, nonanal, octanal and octane were higher in aircraft compared with offices (Table 29).

100. Overall, when comparing highest mean values, VOCs that are higher in aircraft compared to other work environments are (those shown in italics are common to both groups (highest mean values and maximum values)):

- limonene, naphthalene, tetrachloroethylene, *trichloroethylene*, *ethyl acetate*, 1,2-propanediol, 2-phenoxyethanol, acetic acid, *decanal, ethanol, hexanoic acid, nonanal, octanal*

101. When comparing maximum values, VOCs that are higher in aircraft compared to other work environments are:

- *trichloroethylene*, 3-carene, *ethyl acetate*, nonane, 1,2-propanediol, 1-butanol, 2-phenoxyethanol, acetic acid, β-pinene, benzothiazole, *decanal*, dodecane, *ethanol, eucalyptol*, *hexanoic acid*, isopropyl alcohol, methylcyclohexane, *nonanal, octanal,* octane

102. The concentration of all VOCs in aircraft and other work environments were higher than those measured outdoors.

103. A number of other VOCs have been reported in aircraft but similar determinations have not been reported for any work environment; this however, does not mean they are unique to aircraft (Table 31).

Modes of transport

104. Benzene, toluene, ethylbenzene, m- and p-xylene and styrene were reported in all four modes of transport. When considering the highest mean concentrations, only styrene was higher in aircraft compared to other modes of transport, namely buses and metros. When considering the maximum values reported, benzene, toluene, ethylbenzene, m- and p-xylene and styrene concentrations were all lower in aircraft compared with cars/taxis,

which reported the highest values of all modes of transport investigated (Table 28).

105. Acetaldehyde, formaldehyde, heptane, nonane, octane and tetrachloroethylene were reported in three modes of transport. When considering the highest mean values, all six VOCs were lower in aircraft compared to other modes of transport. Similarly, the maximum concentrations reported in aircraft were also lower than other modes of transport (Table 28).

106. For the VOCs reported in two modes of transport, when considering the highest mean concentrations, only 1,4-dichlorobenzene and limonene were higher in aircraft compared to buses and cars/taxis, respectively (Table 28).

107. When considering the maximum concentrations, 1,4-dichlorobenzene, acetic acid, β-pinene, ethyl acetate, hexane, limonene and pentane were all higher in aircraft compared to cars/taxis or buses (Table 30).

108. Overall, when comparing highest mean values, VOCs that are higher in aircraft compared to other modes of transport are (those shown in italics are common to both groups (highest mean values and maximum values)):

- styrene, *1,4-dichlorobenzene*, *limonene*

109. When comparing maximum values, VOCs that are higher in aircraft compared to other modes of transport are:

- *1,4-dichlorobenzene*, acetic acid, β-pinene, ethyl acetate, hexane, *limonene*, pentane

Conclusion

110. Overall, if based on mean data, results indicate that passengers and aircrew could be exposed to higher concentrations of limonene, naphthalene, tetrachloroethylene, trichloroethylene, ethyl acetate, 1,2-propanediol, 2-phenoxyethanol, acetic acid, decanal, ethanol, hexanoic acid, nonanal and octanal for part of their journey when travelling in aircraft as compared with

working in offices, and exposed to higher concentrations of styrene, 1,4-dichlorobenzene and limonene as compared to other modes of transport.

111. As a worst-case scenario and considering maximum concentrations reported, trichloroethylene, 3-carene, ethyl acetate, nonane, 1,2-propanediol, 1-butanol, 2-phenoxyethanol, acetic acid, β-pinene, benzothiazole, decanal, dodecane, ethanol, eucalyptol, hexanoic acid, isopropyl alcohol, methylcyclohexane, nonanal, octanal and octane in aircraft all exceeded mean values reported in other work environments. In addition, maximum concentrations of 1,4-dichlorobenzene, acetic acid, β-pinene ethyl acetate, hexane, limonene and pentane all exceeded mean values reported in other modes of transport.

112. Concentrations of all other VOCs reported in aircraft are generally lower when compared with other work environments and other modes of transport and all VOCs, with the exception of the trimethylbenzenes, were higher than those measured outdoors.

Table 27. Lowest and highest mean concentrations VOC in aircraft and different work environments

VOC	Lowest mean/ median (µg/m³) Aircraft	Highest mean/ median (µg/m³) Aircraft	Lowest mean/ median (µg/m³) Office	Highest mean/ median (µg/m³) Office	Lowest mean/ median (µg/m³) Hospital	Highest mean/ median (µg/m³) Hospital	Lowest mean/ median (µg/m³) School	Lowest mean/ median (µg/m³) School	Highest mean/ median (µg/m³) Outdoor
Reported in aircraft and all work environments									
α-Pinene	0.5	1.2	0.1	136.3	-	3.8	0.11	5.6	0.08
Benzene	0.9	16.1	0.2	87.1	-	0.8	0.03	3.1	1.3
Formaldehyde	-	5.4	1.1	26.9	-	4.0	0.9	8.8	1.1
Limonene	1.44	93.0	0.07	65.1	-	14.3	0.3	86.0	0.07
Naphthalene	0.8	14.0	0.03	1.3	-	0.4	0.1	0.97	0.03
Styrene	0.2	6.4	0.04	6.5	-	0.4	0.3	1.75	1.4
Tetrachloroethylene	2.6	38.0	0.07	8.5	-	0.4	0.02	0.55	0.07
Toluene	2.8	29.8	0.8	287.3	-	1.7	0.03	10.3	22.6
Trichloroethylene	0.4	16.2	0.03	1.7	-	0.35	0.01	2.1	2.9
Reported in aircraft and two work environments									
3-Carene	0.1	1.3	0.8	4.6	-	-	-	0.2	-
Decane	1.0	13.0	5.27	24.8	-	-	0.3	1.7	-
Ethyl acetate	1.1	9.1	2.1	3.7	-	-	1.3	3.6	-
Heptane	0.7	1.8	2.3	31.7	-	-	0.37	3.3	-
Hexane	0.5	20.0	0.8	52.5	-	-	0.53	3.0	1.5
m- and p-Xylene	0.9	8.8	0.2	143.0	-	-	0.0	8.8	0.5

VOC	Lowest mean/ median (µg/m³) Aircraft	Highest mean/ median (µg/m³) Aircraft	Lowest mean/ median (µg/m³) Office	Highest mean/ median (µg/m³) Office	Lowest mean/ median (µg/m³) Hospital	Highest mean/ median (µg/m³) Hospital	Lowest mean/ median (µg/m³) School	Lowest mean/ median (µg/m³) School	Highest mean/ median (µg/m³) Outdoor
Nonane	1.4	2.1	7.6	9.4	-	-	0.39	5.5	-
o- Xylene	0.6	9.4	0.09	43.4	-	-	0.24	5.5	0.8
Ethylbenzene	0.3	8.1	0.06	22.0	-	-		0.2	0.7
Pentane	1.0	1.4	3.8	5.5	-	-	0.71	3.6	3.8
Reported in aircraft and one work environment									
1,2,4-Trimethylbenzene	0.2	0.21	0.6	8.6	-	-	-	-	0.6
1,2-Propanediol	10.9	45.2	7.0	7.0	-	-	-	-	-
1,3,5-Trimethylbenzene	-	0.06	0.1	8.8	-	-	-	-	1.31
1-Butanol	0.9	2.4	1.2	5.0	-	-	-	-	-
2-Ethyl-1-hexanol	2.3	7.75	1.8	30.6	-	-	-	-	-
2-Ethylhexanol	2.9	4.0	3.4	4.7	-	-	-	-	-
2-Methylpentane	76.0	2.04	6.4	17.8	-	-	-	-	-
2-Phenoxyethanol	1.0	4.6	1.6	1.6	-	-	-	-	-
Acetaldehyde		6.4	0.4	17.1	-	-	-	-	4.6
Acetic acid	7.5	11.8	7.1	7.1	-	-	-	-	-
Acetone	6.0	17.1	1.4	48.6	-	-	-	-	10.8
β-Pinene	0.3	0.6	0.04	10.9	-	-	-	-	0.04
Benzaldehyde	1.7	9.9	0.04	29.0	-	-	-	-	0.16
Benzothiazole	<LOD	0.9	0.1	4.4	-	-	-	-	-
Decanal	2.7	145.7	2.5	8.0	-	-	-	-	-
Dichloromethane	0.8	1.1	0.9	50.2	-	-	-	-	0.9
Dodecane	2.6	6.7	9.6	29.8	-	-	-	-	-

VOC	Lowest mean/ median (μg/m^3) Aircraft	Highest mean/ median (μg/m^3) Aircraft	Lowest mean/ median (μg/m^3) Office	Highest mean/ median (μg/m^3) Office	Lowest mean/ median (μg/m^3) Hospital	Highest mean/ median (μg/m^3) Hospital	Lowest mean/ median (μg/m^3) School	Lowest mean/ median (μg/m^3) School	Highest mean/ median (μg/m^3) Outdoor
Ethanol	80.7	386.0	1.0	173.2	-	-	-	-	7.3
Eucalyptol	0.5	2.0	0.05	3.8	-	-	-	-	0.05
Hexanoic acid	3.8	6.2	5.5	5.5	-	-	-	-	-
Isoprene	5.0	9.0	9.0	10.5	-	-	-	-	-
Isopropyl alcohol	3.5	12.6	4.7	65.1	-	-	-	-	-
Methacrolein	-	<LOD	0.8	1.2	-	-	-	-	1.2
Methylcyclohexane	0.7	0.9	0.9	36.4	-	-	-	-	-
n-butyraldehyde/butanal		1.0	6.5	143.9	-	-	-	-	-
Nonanal	1.9	18.65	2.4	15	-	-	-	-	0.1
Octanal	1.3	6.3	3.0	3.0	-	-	-	-	0.57
Octane	>0.5	1.9	1.6	3.3	-	-	-	-	-
p-Xylene	-	4.83	0.4	7.2	-	-	-	-	0.8
Tetradecane	2.1	2.6	3.1	38.6	-	-	-	-	-
Undecane	1.5	4.9	1.4	32.9	-	-	-	-	-

Table 28. Lowest and highest mean concentrations VOC in different modes of transport

VOC	Lowest mean (µg/m^3) Aircraft	Highest mean (µg/m^3) Aircraft	Lowest mean (µg/m^3) Car/taxi	Highest mean (µg/m^3) Car/taxi	Lowest mean (µg/m^3) Bus	Highest mean (µg/m^3) Bus	Lowest mean (µg/m^3) Metro	Highest mean (µg/m^3) Metro
Reported in all modes of transport								
Benzene	0.9	16.1	2.4	270.0	0.02	63.2	4.67	33.48
Ethylbenzene	0.3	8.1	0.9	85	0.2	95.9	1.16	10.5
m- and p-xylene	0.9	8.8	10.2	1570.7	0.18	234.8	0.94	10.29
Styrene	0.2	6.4	0.5	1500.0	1.88	2.05	0.44	6.8
Toluene	2.8	29.84	5.5	2000.0	0.44	503.0	5.22	63.4
Reported in three modes of transport								
Acetaldehyde		6.4	12.47	790.0	-	-	0.39	10.6
Formaldehyde		5.4	16.43	1541.0	-	-	2.4	26.9
Heptane	0.7	1.8	2.9	670.1	0.59	0.81	-	-
Nonane	1.4	2.1	2.0	341	0.17	150.0	-	-
Octane	>0.5	1.9	2.0	127	3.2	3.55	-	-
Tetrachloroethylene	2.6	38.0	0.5	320.2	0.02	3.45	-	-

VOC	Lowest mean (µg/m³) Aircraft	Highest mean (µg/m³) Aircraft	Lowest mean (µg/m³) Car/taxi	Highest mean (µg/m³) Car/taxi	Lowest mean (µg/m³) Bus	Highest mean (µg/m³) Bus	Lowest mean (µg/m³) Metro	Highest mean (µg/m³) Metro
Reported in two modes of transport								
1,3-dichlorobenzene	0.0	-	-	-	0.08	47.09	-	-
1,4-dichlorobenzene	0.11	22.9	-	-	0.01	5.41	-	-
Acetic acid	7.5	11.8	3.41	14.0	-	-	-	-
Acetone	6.0	17.1	9.3	250 .0	-	-	-	-
Acrolein		<0.8	20.65		-	-	-	-
α-Pinene	0.5	1.2	0.2	4.2	-	-	-	-
β-Pinene	0.3	0.6	0.2	1.8	-	-	-	-
Decane	1.0	13.0	0.6	1300.6	-	-	-	-
Dodecane	2.6	6.7	44.5	928.6	-	-	-	-
Ethyl acetate	1.1	9.1	1.8	28.0	-	-	-	-
Hexane	0.5	20.0	1.7	65.0	-	-	-	-
Isoprene	5.0	9.0	-	-	-	-	-	-
Limonene	1.44	92.96	0.8	38.8	-	-	-	-
Methanol	4.32	9.6	122.0	-	-	-	-	-
Naphthalene	0.8	14.0	6.0	49.3	-	-	-	-
o- Xylene	0.6	9.4	3.3	1400	-	-	-	-

VOC	Lowest mean (µg/m³) Aircraft	Highest mean (µg/m³) Aircraft	Lowest mean (µg/m³) Car/taxi	Highest mean (µg/m³) Car/taxi	Lowest mean (µg/m³) Bus	Highest mean (µg/m³) Bus	Lowest mean (µg/m³) Metro	Highest mean (µg/m³) Metro
Pentane	1.0	1.4	0.07	30.8	-	-	-	-
p-Xylene	?	6.8	78.4	78.4	-	-	-	-
Tridecane	1.2	1.7	1.3	687.1	-	-	-	-
Undecane	1.5	4.9	9.3	1615.0	-	-	-	-

Table 29. Maximum concentrations reported in aircraft and maximum or highest mean in other work environments. Highest values are indicated in bold.

VOC	Maximum conc. ($\mu g/m^3$) Aircraft	Reference	Maximum conc. / Highest mean ($\mu g/m^3$) Work environments	Reference	Highest mean ($\mu g/m^3$) Outdoor	Reference
Reported in all modes of transport						
α-Pinene	11.7	EASA (2014)	**286.4** (Office)	Stamp et al. (2020)	0.1	Goodman et al. (2018)
Benzene	77.9	Guan et al. (2014b)	**590.3** (Office)	Zuraimi et al. (2006)	1.3	Al-Mudhaf et al. (2013)
Formaldehyde	7.1	Chen et al. (2021)	**49.0** (Office)	Mandin et al. (2017)	1.1	Goodman et al. (2018)
Limonene	1048.0	Guan et al. (2014b)	**1242.0** (Office)	Zuraimi et al. (2006)	0.1	Goodman et al. (2018)
Naphthalene	49.1	EASA (2014)	**744.8** (Office)	Zuraimi et al. (2006)	0.03	Goodman et al. (2018)
Styrene	12.1	Spengler et al. (2012). Airline C	**32.3** (Office)	Al-Mudhaf et al. (2013)	1.4	Kozielska et al. (2020)
Tetrachloroethylene	73.9	EASA (2014)	**290.0** (Office)	Mandin et al. (2017)	0.1	Goodman et al. (2018)
Toluene	303.9	Guan et al. (2014b)	**3209.0** (Office)	Zuraimi et al. (2006)	22.6	Kozielska and Kaleta (2021)
Trichloroethylene	**209.3**	Guan et al. (2014b)	1.8 (Office)	Mandin et al. (2017)	2.9	Pegas et al. (2010)
Reported in three modes of transport						
3-Carene	**42.2**	EASA (2014)	4.6 (Office)	Licina and Langer (2021)	-	-

VOC	**Maximum conc. (μg/m³) Aircraft**	**Reference**	**Maximum conc. / Highest mean (μg/m³) Work environments**	**Reference**	**Highest mean (μg/m³) Outdoor**	**Reference**
Decane	43.7	Guan et al. (2014b)	**294.0** (Office)	Zuraimi et al. (2006)	-	-
Ethyl acetate	**68.1**	Guan et al. (2014b)	3.7 (Office)	Cacho et al. (2013)	-	-
Ethylbenzene	45.0	Guan et al. (2014b)	**71.8** (Office)	Al-Mudhaf et al. (2013)	-	-
Heptane	24.8	EASA (2014)	**1526.0** (Office)	Zuraimi et al. (2006)	-	-
Hexane	1123.1	Spengler et al. (2012)	**3441.0** (Office)	Zuraimi et al. (2006)	1.5	Al-Mudhaf et al. (2013)
m- and p-xylene	70.7	Guan et al. (2014b)	**914.3** (Office)	Zuraimi et al. (2006)	0.5	Kozielska and Kaleta (2021)
Nonane	**12.9**	EASA (2014)	9.4 (Office)	Cacho et al. (2013)	-	-
o- Xylene	163.0	Guan et al. (2014b)	**281.5** (Office)	Zuraimi et al. (2006)	0.8	Al-Mudhaf et al. (2013)
Pentane	63.7	EASA (2014)	**151.1** (Office)	Al-Mudhaf et al. (2013)	3.8	Al-Mudhaf et al. (2013)
Reported in two modes of transport						
1,2,4-Trimethylbenzene	1.4	Spengler et al. (2012)	**32.4** (Office)	Al-Mudhaf et al. (2013)	0.6	Al-Mudhaf et al. (2013)
1,2-Propanediol	**363.0**	EASA (2014)	7.0 (Office)	Cacho et al. (2013)	-	-
1,3,5-Trimethylbenzene	0.3	Spengler et al. (2012)	**8.8** (Office)	Kozielska and Kaleta (2021)	1.3	Kozielska and Kaleta (2021)
1-Butanol	**31.5**	EASA (2014)	5.0 (Office)	Licina and Langer (2021)	-	-
2-Ethyl-1-hexanol	30.3	Guan et al. (2014b)	**244.4** (Office)	Zuraimi et al. (2006)	-	-
2-Ethylhexanol	15.1	EASA (2014)	**34.0** (Office)	Mandin et al. (2017)	-	-

VOC	Maximum conc. (µg/m^3) Aircraft	Reference	Maximum conc. / Highest mean (µg/m^3) Work environments	Reference	Highest mean (µg/m^3) Outdoor	Reference
2-Methylpentane	392.5	EASA (2014)	**933.1** (Office)	Zuraimi et al. (2006)	-	-
2-Phenoxyethanol	**29.4**	EASA (2014)	1.6 (Office)	Cacho et al. (2013)	-	-
Acetaldehyde	7.7	Chen et al. (2021)	**38.5** (Office)	Al-Mudhaf et al. (2013)	4.6	Al-Mudhaf et al. (2013)
Acetic acid	**59.4**	EASA (2014)	7.1 (Office)	Al-Mudhaf et al. (2013)	-	-
Acetone	384.4	Guan et al. (2014b), Spengler et al. (2012)	**520.0 (**Office)	Al-Mudhaf et al. (2013)	10.8	Al-Mudhaf et al. (2013)
β-Pinene	**26.1**	EASA (2014)	11.6 (Office)	Goodman et al. (2018)	0.04	Goodman et al. (2018)
Benzaldehyde	106.2	Guan et al. (2014b)	**184.9** (Office)	Zuraimi et al. (2006)	0.16	Pegas et al. (2010)
Benzothiazole	**18.7**	Guan et al. (2014b)	5.8 (Office)	Goodman et al. (2018)	-	-
Decanal	**145.7**	Guan et al. (2014b)	8.0 (Office)	Licina and Langer (2021)	-	-
Dichloromethane	71.9	EASA (2014)	**96.8** (Office)	Al-Mudhaf et al. (2013)	0.9	Al-Mudhaf et al. (2013)
Dodecane	**30.0**	EASA (2014)	29.8 (Office)	Cacho et al. (2013)	-	-
Ethanol	**4916.0**	Spengler et al. (2012)	4380.0 (Office)	Al-Mudhaf et al. (2013)	7.3	Al-Mudhaf et al. (2013)
Eucalyptol	**40.3**	EASA (2014)	5.1 (Office)	(Goodman et al. Goodman et al. (2018)	0.05	
Hexanoic acid	**34.8**	EASA (2014)	5.5 (Office)	Cacho et al. (2013)	-	-
Isoprene	46.8	EASA (2014)	**590.3** (Office)	Zuraimi et al. (2006)	-	-
Isopropyl alcohol	**248.0**	EASA (2014)	65.1 (Office)	Zuraimi et al. (2006)	-	-
Methacrolein	3.9	Guan et al. (2014b)	**14.6** (Office)	Al-Mudhaf et al. (2013)	1.2	Goodman et al. (2018)
Methylcyclohexane	**73.8**	EASA (2014)	36.4 (Office)	Cacho et al. (2013)	-	-
n-butyraldehyde/butanal	1.3	Chen et al. (2021)	**143.9** (Office)	Zuraimi et al. (2006)	-	-
Nonanal	**70.9**	Guan et al. (2014b)	15.0 (Office)	Licina and Langer (2021)	0.1	Godwin and Batterman (2007)

VOC	**Maximum conc. (µg/m^3) Aircraft**	**Reference**	**Maximum conc. / Highest mean (µg/m^3) Work environments**	**Reference**	**Highest mean (µg/m^3) Outdoor**	**Reference**
Octanal	**31.4**	EASA (2014)	3.0 (Office)	Cacho et al. (2013)	0.6	
Octane	**8.2**	Guan et al. (2014b)	3.3 (Office)	Cacho et al. (2013)	-	-
p-Xylene	20.9	Wang et al. (2014a)	**67.4** (Office)	Al-Mudhaf et al. (2013)	0.8	Pegas et al. (2010)
Tetradecane	13.3	EASA (2014)	**97.9** (Office)	Zuraimi et al. (2006)	-	-
Undecane	60.3	Guan et al. (2014b)	**278.5** (Office)	Al-Mudhaf et al. (2013)	-	-

Table 30. Maximum concentrations reported in aircraft and highest mean of the next highest mode of transport. Highest value is indicated in bold.

VOC	**Maximum conc. (µg/m^3) Aircraft**	**Reference**	**Highest mean (µg/m^3) Other mode of transport**	**Reference**
Benzene	77.9	Guan et al. (2014b)	**270.0** (Car/Taxi)	Faber and Brodzik (2017)
Ethylbenzene	45.0	Guan et al. (2014b)	**115.9** (Car/Taxi)	Chen et al. (2014b)
m- and p-Xylene	70.7	Guan et al. (2014b)	**1570.7** (Car/Taxi)	Faber and Brodzik (2017)
Styrene	12.08	Spengler et al. (2012). Airline C	**1500.0** (Car/Taxi)	Faber and Brodzik (2017)
Toluene	303.0	Guan et al. (2014b)	**2000.0** (Car/Taxi)	Faber and Brodzik (2017)
Acetaldehyde	7.7	Chen et al. (2021)	**790.0** (Car/Taxi)	Bakhtiari et al. (2018)
Formaldehyde	7.1	Chen et al. (2021)	**1541.0** (Car/Taxi)	Bakhtiari et al. (2018)
Heptane	24.8	EASA (2014)	**670** .0(Car/Taxi)	Faber and Brodzik (2017)
Nonane	12.9	EASA (2014)	**341.0** (Car/Taxi)	You et al. (2007)
Octane	8.2	Guan et al. (2014b)	**127.0** (Car/Taxi)	You et al. (2007)
Tetrachloroethylene	42.4	EASA (2014)	**320.2** (Car/Taxi)	Chen et al. (2014b)
1,3-Dichlorobenzene	0.22	Spengler et al. (2012). Airline A	**47.09** (Bus)	Parra et al. (2008)
1,4-Dichlorobenzene	**228.3**	Guan et al. (2014b)	5.41 (Bus)	Parra et al. (2008)

Acetic acid	**27.1**	EASA (2014)	14.0 (Car/Taxi)	Kim, Park and Lee (2019)
Acetone	53.16	Spengler et al. (2012). Airline A	**250**.0 (Car/Taxi)	Faber and Brodzik (2017)
α-Pinene	11.7	EASA (2014)	**200.0** (Car/Taxi)	You et al. (2007)
β-Pinene	**26.1**	EASA (2014)	1.8 (Car/Taxi)	Moreno et al. (2019)
Decane	43.7	Guan et al. (2014b)	**1300.6** (Car/Taxi)	Faber and Brodzik (2017)
Dodecane	17.6	EASA (2014)	**928.9** (Car/Taxi)	Faber and Brodzik (2017)
Ethyl acetate	**44.0**	Guan et al. (2014b)	28.1 (Car/Taxi)	Brodzik et al. (2014)
Hexane	**1123.08**	Spengler et al. (2012). Airline B	65.0 (Car/Taxi)	Faber and Brodzik (2017)
Limonene	**1048.0**	Guan et al. (2014b)	38.8 (Car/Taxi)	Faber and Brodzik (2017)
Naphthalene	49.1	EASA (2014)	**49.3** (Car/Taxi)	You et al. (2007)
o-Xylene	62.9	Guan et al. (2014b)	**1400.0** (Car/Taxi)	Faber and Brodzik (2017)
Pentane	**63.7**	EASA (2014)	30.8 (Car/Taxi)	Faber and Brodzik (2017)
p-Xylene	20.9	Wang et al. (2014a)	**784.0** (Car/Taxi)	Brodzik et al. (2014)
Tridecane	12.2	EASA (2014)	**687.1** (Car/Taxi)	Faber and Brodzik (2017)
Undecane	60.3	Guan et al. (2014b)	**1615.8** (Car/Taxi)	Faber and Brodzik (2017)

Table 31. Minimum and maximum mean concentrations VOC only reported in aircraft compared to work environments

VOC	Lowest mean / median (µg/m^3) Aircraft	Highest mean / median (µg/m^3) Aircraft
1,1,2,2-Tetrachloroethane	0.0	ND
1,1,2-Trichloro-1,2,2-trifluoroethane	**31.0**	ND
1,1'-Dipropane-1,2-diol ether	0.0	1.7
1,2,4-Trichlorobenzene	ND	16.0
1,2-dichloroethane	0.0	1.2
1,2-Dichlorotetrafluoroethane	ND	4.0
1,2'-Dipropane-1,2-diol ether	0.0	1.6
1,3-Butanediol	0.4	5.2
1,4-dichlorobenzene	0.11	22.9
1-Methoxy-2-propylacetate	0.2	1.0
1-Propanol	0.6	80.7
2,2,2-Trimethylpentane dioldiisobutyrate	ND	1.1
2,2,4,4,6,8,8-Heptamethyl nonane	0.6	2.4
2,2,4,6,6-Pentamethyl heptane	1.6	10.5
2,2,4-Trimethyl pentane	0.1	0.1
2,2,4-Trimethylpentanedioldiisobutyrate	0.2	1.3
2,3-Dimethylpentane	73.0	101.0
2-Butanone	ND	2154.0
2-Ethylhexyl salicylate	0.3	2.3
2-Hexanone	ND	81.0
2-Hydroxybenzaldehyde	0.2	0.5
2-methyl-1,3-butadiene	1.0	1.2
2-Methylhexane	128.0	174.0
3-Methylbutanol	0.6	0.8
3-Methylhexane	118.0	175.0
3-Methylpentane	0.2	0.3
4-Cy-pentadien-1,3-dion4phenyl	0.0	0.1
4-Ethyl toluene	ND	51.0
5,9-Undecandien-2-one-6,10-dimethyl	0.1	3.9
6- methyl-5-hepten-2-one/6-MHO	7.0	8.86
6-methyl-5-hepten-2-one (6-MHO)	1.7	6.2
Acetonitrile	19.4	27.0
Acetophenone	0.7	1.6
Acrolein	ND	<0.8
Benzoic acid	3.3	5.3
Benzothiazole	<LOD	0.9

VOC	Lowest mean / median ($\mu g/m^3$) Aircraft	Highest mean / median ($\mu g/m^3$) Aircraft
Benzyl alcohol	0.8	1.4
Butanal	0.5	0.7
Butanone/2-butanone	1.2	2.9
Butyl acetate	0.7	2.2
Butylated hydroxytoluene (BHT)	0.2	0.6
Capronaldehyde/hexaldehyde/hexanal	ND	5.2
Carbon disulfide	ND	571.0
Carbon tetrachloride	28.0	649.0
Chloroform	35.0	138.0
Cycloheptasiloxane	0.7	1.1
Cyclohexane	0.3	0.8
Cyclohexasiloxane	0.5	1.0
Cyclopentasiloxane	9.8	18
Cyclotetrasiloxane	0.6	1.8
Cyclotrisiloxane	0.6	1.8
Dibutyl phthalate	0.3	0.3
Dichloromethane/methylene chloride	ND	1.4
Diethyl phthalate	0.1	0.7
Diethyltoluamide	0.1	0.9
Diisobutyl phthalate	0.2	0.5
Dimethylformamide	0.0	7.7
Dioctyl ether	0.4	6.4
Formic acid	0.0	0.7
Glycerine	0.0	0.4
Heptadecane	0.6	1.1
Hexadecane	0.7	1.2
Hexanal	2.4	4.4
Homosalate	0.2	0.7
Hydroxyacetone	0.3	3.3
Isopropyl myristate	0.5	1.7
Isopropyl palmitate	0.3	1.0
Menthol	3.3	11.6
Menthone	0.6	1.5
Methanol	4.3	9.6
Methoxy-bis-1,2'-dipropane-1,2-diol ether	0.0	2.4
Methyl chloride	ND	629.0
Methyl isobutyl ketone	ND	169.0
Methyl tert-butyl ether	0.0	35.0
Methylene chloride	2842.0	45641.0
MTBE	0.02	0.24

VOC	Lowest mean / median (µg/m³) Aircraft	Highest mean / median (µg/m³) Aircraft
N,N- N-dimethylformamide	ND	<6.8
Nonanoic acid	1.2	1.9
Octanoic acid	1.4	2.1
p-Cymene	0.2	0.8
p-Dichlorbenzene	0.1	1.0
Pentadecane	0.9	1.5
Phenol	0.9	1.2
Phenylmaleic anhydride	0.1	0.3
Phthalic anhydride	0.0	0.9
tert.-Butanol	0.1	0.2
Tributyl phosphate	0.0	1.1
Tridecane	1.2	1.7
Triethyl phosphate	0.0	0.5
Tri-ortho cresyl phosphate	0.002	1.7
Undecanal	1.0	1.4

Table 32. Minimum and maximum mean concentrations VOC only detected in aircraft compared to other modes of transport

VOC	**Lowest mean / median (µg/m³) Aircraft**	**Highest mean / median (µg/m³) Aircraft**
1,1,1-Trichloroethane	10*	0
1,1,2,2-Tetrachloroethane	0	
1,1,2-Trichlorethane	0	
1,1,2-Trichloro-1,2,2-trifluoroethane	31*	
1,1-Dichloroethane	0	
1,1-Dichloroethene	0	
1,1'-Dipropane-1,2-diol ether	0	1.7
1,2,4-Trichlorobenzene	16*	
1,2-Dibromoethane	0	
1,2-Dichlorobenzene	0	
1,2-dichloroethane	0	1.2

VOC	Lowest mean / median (µg/m^3) Aircraft	Highest mean / median (µg/m^3) Aircraft
1,2-Dichloropropane	0	
1,2-Dichlorotetrafluoroethane	4	
1,2'-Dipropane-1,2-diol ether	0	1.6
1,2-Propanediol	10.9	45.2
1,3,5-Trimethylbenzene	56*	
1,3-Butadiene	0	
1,3-Butanediol	0.4	5.2
1,4-Dioxane	0	
1-Butanol	0.9	2.4
1-Methoxy-2-propylacetate	0.2	1
1-Propanol	0.6	80.7
2,2,2-Trimethylpentane dioldiisobutyrate	0.2	1.3
2,2,4,4,6,8,8-Heptamethyl nonane	0.6	2.4
2,2,4,6,6-Pentamethyl heptane	1.6	10.5
2,2,4-Trimethyl pentane	0.1	0.1
2,2,4-Trimethylpentanedioldiisobutyrate	0.2	1.3
2,3-Dimethylpentane	73	101
2-Butanone	2154	
2-ethyl-1-hexanol	0	7.75
2-Ethylhexanol	2.9	4
2-Ethylhexyl salicylate	0.3	2.3
2-Hexanone	81*	
2-Hydroxybenzaldehyde	0.2	0.5
2-methyl-1,3-butadiene	1	1.2
2-Methylhexane	118*	175*
2-Methylpentane	76*	2042*
2-Phenoxyethanol	1	4.6
3-Carene	0.1	1.3

VOC	Lowest mean / median (µg/m^3) Aircraft	Highest mean / median (µg/m^3) Aircraft
3-Methylbutanol	0.6	0.8
3-Methylhexane	118*	175*
3-Methylpentane	0.2	0.3
4-Cy-pentadien-1,3-dion4phenyl	0	0.1
4-Ethyl toluene	51*	
5,9-Undecandien-2-one-6,10-dimethyl	0.1	3.9
6-methyl-5-hepten-2-one (6-MHO)	0	6.2
Acetonitrile	19.4	27
Acetophenone	0.7	1.6
Acrolein	<0.8	
Benzaldehyde	1.7	9.9
Benzoic acid	3.3	5.3
Benzothiazole	<LOD	0.9
Benzyl alcohol	0.8	1.4
Butanal	0.5	0.7
Butanone/2-butanone	1.2	2.9
Butyl acetate	0.7	2.2
Butylated hydroxytoluene (BHT)	0.2	0.6
Capronaldehyde/hexaldehyde/hexanal		5.2
Carbon disulfide	571*	
Carbon tetrachloride	28*	649*
Chlorobenzene	0*	
Chloroform	35*	138*
Cis-1,2-dichloroethene	0*	
Cis-1,3-dichloropropene	0*	0*
Cycloheptasiloxane	0.7	1.1
Cyclohexane	0.3	0.8
Cyclohexasiloxane	0.5	1

VOC	Lowest mean / median (µg/m³) Aircraft	Highest mean / median (µg/m³) Aircraft
Cyclopentasiloxane	9.8	18
Cyclotetrasiloxane	0.6	1.8
Cyclotrisiloxane	0.6	1.8
Decanal	2.7	145.7
Dibutyl phthalate	0.3	0.3
Dichlormethane	0.8	1.1
Dichlorodifluoromethane	282	
Dichloromethane		1.4
Diethyl phthalate	0.1	0.7
Diethyltoluamide	0.1	0.9
Diisobutyl phthalate	0.2	0.5
Dimethylformamide	0	7.7
Dioctyl ether	0.4	6.4
Ethanol	80.7	386
Eucalyptol	0.5	2
Glycerine	0	0.4
Heptanal	0.7	3.2
Hexachlorobutadiene	0	
Hexadecane	0.7	1.2
Hexanal	2.4	4.4
Hexanoic acid	3.8	6.2
Homosalate	0.2	0.7
Hydroxyacetone	0.3	3.3
Isoprene	2	31
Isopropyl alcohol	3.5	12.6
Isopropyl myristate	0.5	1.7
Isopropyl palmitate	0.3	1
Menthol	3.3	11.6

VOC	**Lowest mean / median (µg/m³) Aircraft**	**Highest mean / median (µg/m³) Aircraft**
Menthone	0.6	1.5
Methacrolein		3.9
Methanol	4.32	9.6
Methoxy-bis-1,2'-dipropane-1,2-diol ether	0	2.4
Methyl bromide	0	
Methyl chloride	629*	
Methyl isobutyl ketone	169*	
Methyl methacrylate	0	
Methyl tert-butyl ether	0	35
Methylene chloride	2842*	45641*
MTBE	0.02	0.24
N,N- N-dimethylformamide/Dimethylformamide	<6.8	
n-butyraldehyde/butanal		1
Nonanal	1.9	18.65
Nonanoic acid	1.2	1.9
Octanal	1.3	6.3
Octanoic acid	1.4	2.1
p-Cymene	0.2	0.8
p-Dichlorbenzene	0.1	1
Pentadecane	0.9	1.5
Phenol	0.9	1.2
Phenylmaleic anhydride	0.1	0.3
Phthalic anhydride	0	0.9
tert.-Butanol	0.1	0.2
Tetradecane	2.1	2.6
Tributyl phosphate	0	1.1

VOC	Lowest mean / median ($\mu g/m^3$) Aircraft	Highest mean / median ($\mu g/m^3$) Aircraft
Trichloroethylene	0.4	16.2
Triethyl phosphate	0	0.5
Tri-*ortho* cresyl phosphate	0.002	1.66
Undecanal	1	1.4

*median

Questions on which the views of the Committee are sought

113. Members are invited to consider this paper and in particular the following questions:

i. Based on information in this paper, do Members want additional information on any specific VOC or further details on any of the papers on any specific VOC?

ii. Are there any candidate VOCs, for which a risk assessment should be considered in the context of aircraft cabin air in a future paper?

IEH Consulting under contract supporting the UKHSA COT Secretariat
October 2022

List of Abbreviations and Technical terms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineer
BTEX	Benzene, toluene, ethylbenzene, xylene
CNG	Compressed natural gas
COT	Committee on Toxicity
DfT	Department for Transport
EASA	European Aviation Safety Authority
FAA/	Federal Aviation Agency
FID	Flame ionization detection
GC/MS	Gas chromatography/mass spectrometry
GC-FID	Gas chromatography/flame ionization detector
HPLC/UV	High performance liquid chromatography-ultraviolet
HVAC	Heating, ventilation and air conditioning
LPG	Liquefied petroleum gas
LOD	Limit of detection
LOQ	Limit of quantification
MDF	Medium-density fibreboard
ND	Not detected
OP	Organophosphate
PID	Photoionization detection
SD	Standard deviation
sVOCs	Semi-volatile organic compounds
TD-GC/FID-MS	Thermal desorption-gas chromatography and flame ionization and mass spectrometry
TD-GC/MS	Thermodesorption and gas chromatography/mass spectrometry
TVOC	Total concentration of VOCs
USEPA	US Environment Protection Agency
VOC	Volatile organic compounds

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COMMITTEE ON TOXICITY OF CHEMICALS IN FOOD, CONSUMER PRODUCTS AND THE ENVIRONMENT (COT)

Volatile organic compounds in aircraft cabin air: comparison with other modes of transport

Extract of paragraphs 10 – 43 of discussion paper TOX/2022/46, containing information on VOCs in aircraft.

The full discussion paper is available here:
https://cot.food.gov.uk/sites/default/files/2022-09/TOX-2022-46 VOCs in aircraft and modes of transport_FINALv3.pdf

IEH Consulting under contract supporting the UKHSA COT Secretariat
October 2022

Aircraft

Chen et al. (2021)

10. Chen et al. (2021) carried out a review of 47 documents from 1967 to 2019 that reported VOC measurements in commercial aircraft. Measurements reported were performed on 2251 flights in approximately forty different aircraft, including those used for regional and intercontinental flights. Flights were categorised into four groups, namely very short-haul, short-haul, medium-haul to long-haul, according to flight times; although the categories for flight duration used in the original studies were adopted due to differences in the methods used to categorize flight duration between various studies. Authors considered that accurate determination of flight duration was irrelevant for the purpose of the review.

11. The paper considered the US ban on in-flight smoking on domestic flights of two hours or less in 1988, six hours or less in 1990 and on all domestic and international flights in 2000 was noted. Authors therefore considered studies published after 2000 to be from smoke-free aircraft unless otherwise stated. For studies pre-2000, authors looked for information on whether measurements were made on aircraft on which smoking did not occur.

12. Different methods were used to detect and analyse VOCs. In the paper, results were grouped according to method used. The total concentration of VOCs (TVOCs) was measured using flame ionization detection (FID) and photoionization detection (PID). Three sampling methods were used to sample VOCs, namely active, passive and canister sampling. Active sampling was the most commonly used, resulting in 140 VOCs being detected. Passive sampling resulted in 48 VOCs being detected and canister sampling resulted in 96 VOCs being detected.

13. Concentrations of VOCs and sVOCs reported in the aircraft cabins as presented in more than two studies are shown in Table and Table .

Table 1. Mean, minimum and maximum concentrations of VOCs commonly measured in more than two studies in aircraft

VOC	Mean conc. (μg/m^3)	SD (μg/m^3)	Min conc. (μg/m^3)	Max conc. (μg/m^3)
Toluene	15.0	12.0	2.5	123.0
Limonene	24.0	31	1.4	276.0
m- and p-xylene	2.5	23	0.6	21.0
Benzene	5.9	5.5	0.1	57.0
Benzaldehyde	>2.5	2.0	0.0	14.0
Undecane	2.9	1.6	0.0	13.0
o- Xylene	2.5	2.8	0.3	14.0
Ethylbenzene	2.3	2.9	0.2	23.0
Styrene	1.0	0.9	0.0	6.1
Nonanal	7.8	5.6	1.9	24.0
Acrolein	<0.8	1.0	<LOD	3.2
Formaldehyde	5.4	1.5	2.7	7.1
Capronaldehyde/hexaldehyde/hexanal	5.2	4.8	1.7	14.0
Tetrachloroethylene	7.3	5.7	0.6	16.0
Decanal	14.0	5.0	2.7	36.0
Acetone	14.0	5.6	0.5	49.0
Dodecane	3.1	1.8	0.0	13.0
6- methyl-5-hepten-2-one/6-MHO	7.0	3.5	0.2	16.0
Trichloroethylene	0.4	0.2	0.1	0.7
Acetaldehyde	6.4	1.2	5.2	7.7
Isoprene	6.8	4.9	0.8	14.0
Ethyl acetate	6.5	4.4	3.9	16.0
p-dichlorobenzene/1,4-dichlorobenzene	2.4	2.9	0.1	6.9
Hexane	20.0	31	0.0	68.0
Octanal	4.2	1.8	1.3	10.0

VOC	Mean conc. (µg/m^3)	SD (µg/m^3)	Min conc. (µg/m^3)	Max conc. (µg/m^3)
Nonane	>1.4	0.7	0.0	2.0
Heptane	>0.7	0.3	0.0	0.9
Decane	1.1	0.6	0.0	1.7
Acetic acid	11.0	2.7	1.1	16
n-butyraldehyde/butanal	1.0	0.2	0.8	1.3
Butanone/2-butanone	2.4	0.8	0	32
2,2,2-Trimethylpentane dioldiisobutyrate	1.1	0.3	0.2	1.3
Isopropyl alcohol	10.0	3.4	3.5	13
Dichloromethane/methylene chloride	1.4	10.0	0.0	2.8
Methylcyclohexane	0.6	0.5	0.1	1.1
Heptanal	3.2	1.3	0.7	4.6
N,N- N-dimethylformamide/ Dimethylformamide	<6.8	3.9	0.0	7.7
Methanol	9.6	3.6	1.0	12
Ethanol	386.0	899.0	81.0	3009
Tridecane	1.5	0.4	0.0	1.7
Pentane	1.4	0.4	0.4	4.7
3-Carene	1.1	0.5	0.0	1.3
α-Pinene	1.1	0.3	0.0	1.2
β-Pinene	0.5	0.2	0.0	0.6
Octane	>0.5	0.1	0.0	0.6

Table 2. Mean, minimum and maximum concentrations of sVOCs

VOC	**Mean conc. (µg/m^3)**	**SD (µg/m^3)**	**Min conc. (µg/m^3)**	**Max conc. (µg/m^3)**
Tri-ortho-cresyl phosphate/Tri-o-cresyl Phosphate (ToCP)	0.05	0.014	0.0	22.8
Tributyl phosphate (TiBP)	0.495	59.0	0.037	9.1
Tricresyl phosphates (TCP)	0.035	0.0077	0.0003	14.9
Naphthalene	1.241	0.166	0.0	49.1
Trichloroethylene TCE)	0.483	0.036	0.0	20.1
Triisobutyl phosphate (TBP)	0.092	0.0093	0.003	1.61
Tris (chloroethyl) phosphate (TCEP)	0.015	0.001	0.001	0.324
Tris (chloro-isopropyl) phosphate (TCPP)	0.506	0.0004	0.023	9.977
Tris(1,3-dichloro-isopropyl)phosphate (TDCPP)	0.0077	0.0003	0.001	0.049
Triphenyl phosphate (TPP)	0.0087	0.0003	0.001	0.119
Tris (butoxy-ethyl) Phosphate (TBEP)	0.071	0.0044	0.0	0.642
Diphenyl-2-ethylhexyl phosphate (DPEHP)	0.015	0.0002	0.0	0.282
Tris (ethylhexyl) phosphate (TEHP)	<LOD	-	0.0	0.088
Tri-m-cresyl phosphate (T-m-CP)	0.004.4	0.0003	0.001	0.428
Tri-mmp-cresyl phosphate (T-mmp-P)	0.0065	0.0004	0.001	0.691
Tri-mpp-cresyl phosphate (T-mpp-CP)	0.0042	0.0002	0.001	0.039
Tri-p-cresyl phosphate (T-p-CP)	0.0021	0.0001	0.001	0.057
Trixylyl phosphate (TXP)	<LOD	-	<LOD	<LOD
Acenaphthylene	0.0008	0.0006	0.0026	0.0033
Acenaphthene	0.0057	0.0047	0.017	0.024

VOC	Mean conc. (μg/m³)	SD (μg/m³)	Min conc. (μg/m³)	Max conc. (μg/m³)
Fluorene	0.003	0.0022	0.0088	0.012
Hexachlorobenzene	0.0002	0.0002	0.0004	0.0023
Phenanthrene	0.0049	0.0037	0.013	0.021
Anthracene	0.0003	0.0002	0.0008	0.0011
Trimethylolpropane phosphate (TMPP)	0	-	-	-
Fluoranthene	0.0005	0.0004	0	0.0019
Pyrene	0.0026	0.0019	0.0036	0.015
Tri-n-butyl phosphate (TnBP)	0.330	0.421	0.020	4.1
Retene	0.0014	-	0.0008	0.0002
cis-Permethrin	0.0009	-	ND	0.000.9
trans-Permethrin	0.0015	-	0.0011	0.002
Seven other PAH compounds	0.0009-0.0105	-	-	-
2,5-Diphenylbenzoquinone	<2.100	-	NR	NR
Dioctyl phthalate	1.300	-	NR	NR
Tertiary butylphenol	<2.100	-	NR	NR
Trimethylpentylphenol	<2.100	-	NR	NR

14. Overall, authors concluded that the data showed that the majority of VOCs detected were alcohols followed by aldehydes, alkanes, terpenes, aromatics, and ketones. Among the most prevalent compounds reported were toluene, ethylbenzene, benzene, formaldehyde, acetaldehyde, limonene, nonanal, hexanal, decanal, octanal, acetic acid, acetone, ethanol, butanal, acrolein, isoprene and menthol. Authors suggested that formaldehyde and acetaldehyde are likely to have been products of ozone chemistry that occurs in aircraft and associated with lubricant, hydraulic oils and fuel. They also noted that many sources can emit limonene, such as fragrances in aircraft cabins, fragrances in wet napkins, cleaning agents, and deodorizers, as well as from soft drinks and (earl gray) tea and citrus fruits.

15. Nonanal, capronaldehyde/hexaldehyde/hexanal, decanal, and octanal were detected frequently in aircraft cabins at high concentrations. These pollutants are associated with the presence of humans but are the results of heterogeneous reactions between ozone and human skin oils. Skin oils are present on human skin but can also be present on clothing and on all surfaces that have been touched by human skin, such as seats, armrests, and headrests.

Guan et al. 2014a / Guan et al. 2014b

16. Guan and colleagues published a number of papers relating to measurements of VOCs in aircraft cabins. Part I of the study covered the methodology used to detect VOCs in commercial flights and the detection rates of VOCs (Guan et al. 2014a) whereas part II presented data on the levels of detected VOCs (Guan et al. 2014b).

17. One hundred and seven flights were studied between August 2010 and August 2012 and included large commercial aircraft in operation in China and worldwide. Domestic flights of less than four hours (n=76) were included in the study as were international or transoceanic flights (n=31) of more than four hours duration. Such flights included single-aisle (n=66) and double-aisle planes (n=41). Private aircraft and short-haul flights of less than 30 minutes were excluded from the study (Guan et al. 2014a).

18. In part II of the series of papers, 51 of the 107 flights were randomly selected on which quantitative measurements were conducted. Domestic flights (n=36) that were less than four hours duration, and international or transoceanic flights (n=15) that were more than four hours duration were selected, and single-aisle (n=30) and double-aisle (n=21) planes were assessed (Guan et al. 2014b).

19. During the whole flight, measurements of VOCs were taken before take-off, during cruising and after landing, each of which represent a typical operating phase of the aircraft, resulting in a total of 639 air samples being taken. Samples were taken 0.5 m in front of the person taking the samples using a 50 ml syringe and Tenax-TA tube. The Tenax-TA tubes were

analysed in a laboratory by thermodesorption and gas chromatography/mass spectrometry (TD-GC/MS).

20. The concentration of VOCs detected in cabin air are shown in Table . No data for sVOCs were presented in the paper.

Table 3. Median, minimum and maximum concentrations of VOCs in aircraft cabin air in China and worldwide

VOC	**Median conc. (μg/m^3)**	**Min conc. (μg/m^3)**	**Max conc. (μg/m^3)**
Benzene	5.0	<LOD	77.9
Toluene	16.2	<LOD	209.3
Ethylbenzene	3.5	<LOD	45.1
m-/p-Xylene	3.0	<LOD	70.7
o-Xylene	5.0	<LOD	62.9
Naphthalene	1.1	<LOD	23.9
Tetrachloroethylene	2.8	<LOD	303.9
2-ethyl-1-hexanol	4.7	<LOD	30.3
N,N-dimethylformamide	<LOD	<LOD	7.3
1,4-dichlorobenzene	<LOD	<LOD	228.3
1,3-dichlorobenzene	<LOD	<LOD	12.8
1,2-dichloroethane	<LOD	<LOD	10.0
Nonanal	12.1	<LOD	70.9
Acetone	8.2	<LOD	384.4
2-methyl-1,3-butadiene	<LOD	<LOD	9.8
Limonene	15.1	<LOD	1048.2
Decanal	14.8	<LOD	62.2
6-methyl-5-hepten-2-one (6-MHO)	<LOD	<LOD	23.2
Methacrolein	<LOD	<LOD	3.9
Dodecane	3.2	<LOD	30.0
Octane	<LOD	<LOD	8.2
Undecane	2.4	<LOD	60.3

VOC	Median conc. ($\mu g/m^3$)	Min conc. ($\mu g/m^3$)	Max conc. ($\mu g/m^3$)
Nonane	<LOD	<LOD	11.7
Heptane	<LOD	<LOD	7.5
Decane	<LOD	<LOD	43.7
Benzaldehyde	6.1	<LOD	106.2
Styrene	<LOD	<LOD	42.4
Benzothiazole	<LOD	<LOD	18.7
Ethyl acetate	1.1	<LOD	44.0

n=51 flights

21. Authors reported that for most VOCs, there were significant differences in concentrations before take-off and during ascent and cruising (Table). During take-off, remaining VOCs from air outside the aircraft may still exist when the cabin air is supplied by air-conditioning or auxiliary power unit. Therefore, some VOCs may have a higher detection rate during take-off due to locally produced contaminants (e.g., exhaust from other aircraft and ground-support equipment), as well as pollution from other sources in the region that could enter the cabin through the environmental control system.

22. During ascent, the effect of on-ground air declines. Cabin temperature, relative humidity and pressure vary during this phase, which could exert a complex combined effect on VOC generation.

23. During cruising, there is generally a steady air supply and air recirculation, as well as steady cabin environmental parameters. However, passengers and crew activities are more mobile, and refreshments are provided, both of which may result in a higher VOC detection rate. Indeed, previous studies have shown that the highest VOC concentrations were generally encountered in cabin air during cruise conditions (Nagda et al., 2001 cited in Guan et al., 2014a, b).

24. During decent and landing, limited passenger activities/movement and variations of the supply of air are allowed hence variations in VOC detection rate are reduced (Guan et al., 2014a, b).

Table 4. Mean concentrations of VOCs in aircraft cabin air during different flight phases

VOC	Mean conc. ($\mu g/m^3$) Before take-off	SD ($\mu g/m^3$) Before take-off	Mean conc. ($\mu g/m^3$) Cruise	SD ($\mu g/m^3$) Cruise	Mean conc. ($\mu g/m^3$) After landing	SD ($\mu g/m^3$) After landing
Benzene	9.5	9.8	7.0	10.4	8.0	11.5
Toluene	32.8	42.3	18.3	16.6	25.7	33.0
Ethylbenzene	8.1	9.3	3.3	3.4	2.2	6.6
m-/p-Xylene	8.8	11.4	4.2	5.8	4.2	4.9
o-Xylene	9.4	8.7	5.8	5.6	5.3	4.8
Naphthalene	3.9	4.3	2.5	2.8	2.3	2.8
Tetrachloroethylene	16.9	45.3	13.4	3.6	16.9	41.8
2-ethyl-1-hexanol	7.0	5.8	5.3	4.3	2.3	3.8
N,N-dimethylformamide	<LOD	1.5	<LOD	0.6	<LOD	0.9
1,4-dichlorobenzene	7.7	5.8	10.2	4.3	22.9	3.8
1,3-dichlorobenzene	<LOD	2.1	<LOD	1.1	<LOD	1.2
1,2-dichloroethane	1.2	2.3	<LOD	0.8	<LOD	1.5
Nonanal	14.1	10.3	14.2	6.9	13.2	6.7
Acetone	12.7	19.7	10.3	14.3	17.1	52.8
2-methyl-1,3-butadiene	<LOD	1.4	<LOD	1.2	1.1	2.2

VOC	Mean conc. ($\mu g/m^3$) Before take-off	SD ($\mu g/m^3$) Before take-off	Mean conc. ($\mu g/m^3$) Cruise	SD ($\mu g/m^3$) Cruise	Mean conc. ($\mu g/m^3$) After landing	SD ($\mu g/m^3$) After landing
Limonene	39.5	89.2	52.4	148.3	19.3	19.5
Decanal	14.7	9.4	16.9	9.8	16.3	10.8
6-methyl-5-hepten-2-one (6-MHO)	1.7	3.8	3.6	5.1	4.9	6.6
Methacrolein	<LOD	0.7	<LOD	0.4	<LOD	0.5
Dodecane	6.7	6.4	4.1	1.8	6.4	5.0
Octane	1.5	1.9	<LOD	<LOD	1.9	1.0
Undecane	4.9	2.8	2.9	1.9	2.8	.4
Nonane	2.1	2.0	<LOD	<LOD	2.0	0.9
Heptane	1.1	1.8	<LOD	<LOD	1.8	0.7
Decane	1.7	4.1	<LOD	<LOD	4.1	2.0
Benzaldehyde	<LOD	1.7	9.9	7.4	1.7	8.1
Styrene	3.0	6.4	1.7	1.8	6.4	1.9
Benzothiazole	<LOD	0.9	<LOD	<LOD	0.9	1.0
Ethyl acetate	5.9	9.1	3.0	3.6	9.1	6.6

n=51 flights

25. Authors also compared selected VOCs before, during and after meal services (Table). VOCs such as limonene and some aromatics and alcohols are emitted during meal services. However, authors suggested that their contribution to the overall cabin VOC is limited due to short-term duration of the meal service and large dilution capability of the cabin ventilation system (Guan et al. 2014a, Guan et al. 2014b).

Table 5. Mean concentrations of VOCs before/after and during meal services in aircraft cabin air

VOC	Mean conc. (μg/m^3) Before/after meals	SD (μg/m^3) Before/after meals	Mean conc. (μg/m^3) During meals	SD (μg/m^3) During meals
Benzene	5.3	10.7	3.4	4.6
Toluene	16.6	17.3	19.2	19.6
Ethylbenzene	3.2	4.2	2.4	2.7
m-/p-Xylene	2.8	4.0	2.8	3.
o-Xylene	4.8	4.9	4.1	3.6
Naphthalene	2.2	2.5	3.2	3.6
Tetrachloroethylene	24.0	50.4	23.7	48.2
2-ethyl-1-hexanol	5.7	5.0	6.7	4.7
N,N-dimethylformamide	<LOD	0.7	<LOD	0.3
1,4-dichlorobenzene	1.5	2.7	8.9	39.1
1,3-dichlorobenzene	<LOD	2.0	<LOD	1.7
1,2-dichlorobthane	<LOD	0.8	<LOD	1.0
Nonanal	12.6	7.6	13.1	5.4
Acetone	6.0	4.6	8.3	8.0
2-methyl-1,3-butadiene	<LOD	1.7	1.0	1.6
Limonene	63.2	220.7	80.7	217.0
Decanal	145.7	11.0	15.	9.5

VOC	Mean conc. (µg/m^3) Before/after meals	SD (µg/m^3) Before/after meals	Mean conc. (µg/m^3) During meals	SD (µg/m^3) During meals
6-methyl-5-hepten-2-one (6-MHO)	3.3	5.9	3.1	5.3
Methacrolein	<LOD	0.5	<LOD	0.6
Dodecane	2.6	3.7	2.9	3.5
Octane	<LOD	1.1	<LOD	1.3
Undecane	2.4	3.3	2.2	3.0
Nonane	<LOD	1.1	<LOD	0.7
Heptane	<LOD	0.8	<LOD	1.0
Decane	13	3.2	1.2	3.7
Benzaldehyde	8.7	7.7	9.0	7.8
Styrene	1.4	2.1	1.7	2.0
Benzothiazole	<LOD	0.1	<LOD	0.6
Ethyl acetate	1.8	3.8	3.3	3.5

n=22 flights

26. The effect of ventilation and sources of air supply was investigated in 13 flights, from which air was sampled from both the supply air (mix of approximately 50% bleed air and 50% recirculated air from the cabin) and recirculated air (Table). Results show that nine VOCs (including toluene, m- and p-xylene and tetrachloroethylene) were significantly lower in supply air than in recirculated air whilst others showed no differences. This may be due to the influence of VOC sources in bleed air and environmental control system.

Table 6. Mean concentrations of VOCs in aircraft cabin air due to supply air and recirculated air

VOC	Mean conc. ($\mu g/m^3$) Supply air	SD ($\mu g/m^3$) Supply air	Mean conc. ($\mu g/m^3$) Recircu-lated air	SD ($\mu g/m^3$) Recircu-lated air
Benzene	12.4	15.3	16.1	16.2
Toluene	22.5	23.	28.5	31.4
Ethylbenzene	4.9	5.2	7.2	8.3
m-/p-Xylene	2.7	2.1	4.6	3.3
o-Xylene	4.6	3.0	6.1	3.6
Naphthalene	2.7	3.3	2.5	2.7
Tetrachloroethylene	2.6	2.0	3.7	2.7
2-ethyl-1-hexanol	4.3	2.9	5.5	4.3
N,N-dimethylformamide	<LOD	0.1	<LOD	0.3
1,4-dichlorobenzene	1.1	3.2	2.2	6.1
1,3-dichlorobenzene	<LOD	0.1	<LOD	0.4
1,2-dichlorobthane	<LOD	0.8	<LOD	1.1
Nonanal	11.3	6.2	15.6	5.8
Acetone	7.2	7.9	13.0	12.0
2-methyl-1,3-butadiene	<LOD	1.2	1.2	2.2
Limonene	30.6	39.3	41.9	52.2
Decanal	13.9	11.4	18.4	14.5
6-methyl-5-hepten-2-one (6-MHO)	2.9	3.8	6.2	7.1
Methacrolein	<LOD	0.3	<LOD	0.6
Dodecane	3.3	3.4	4.5	4.2
Octane	<LOD	1.0	<LOD	0.9
Undecane	2.1	1.9	3.1	2.2
Nonane	<LOD	0.9	<LOD	0.8

VOC	Mean conc. (µg/m^3) Supply air	SD (µg/m^3) Supply air	Mean conc. (µg/m^3) Recircu-lated air	SD (µg/m^3) Recircu-lated air
Heptane	<LOD	1.0	<LOD	1.0
Decane	<LOD	0.9	<LOD	1.3
Benzaldehyde	7.1	4.7	9.2.	7.1
Styrene	1.2	1.4	2.9	3.5
Benzothiazole	<LOD	0.0	<LOD	1.7
Ethyl acetate	<LOD	0.9	1.4	2.4

n=13 flights

27. Overall, authors concluded that most VOCs had significant differences in concentrations between the different phases of the flight, with the highest levels typically found in the take-off and cruising and that the concentration of some VOCs was significantly lower in supply air than that in recirculated air, indicating a dilution effect of bleed air on cabin VOCs.

Wang et al. 2014a / Wang et al. 2014b

28. Wang and colleagues also measured VOCs in aircraft cabins (Wang et al. 2014a) and investigated the source apportionment of VOCs (Wang et al. 2014b). VOC sampling was conducted on board 14 flights in China from 17 to 26 September 2012. The flight duration ranged from 80 to 170 minutes. All measurements were carried out on a single-aisle Boeing 737. Samples were collected in Tenax TA tubes, in the cabin 1.2 m above the floor in the breathing zone and directly in front of the chest of the sampling personnel. VOCs were analysed by TD-GC/MS.

29. The mean concentrations of VOCs are shown in Table . No data for sVOCs were presented in the paper.

Table 7. Mean, minimum and maximum concentration of VOCs from flights in China

VOC	**Mean conc. (μg/m^3)**	**Min conc. (μg/m^3)**	**Max conc. (μg/m^3)**
Benzene	14.8	4.5	57.0
Toluene	29.8	6.7	123.01
Ethylbenzene	7.0	1.5	22.5
p-Xylene	4.8	1.2	20.9
o-Xylene	4.6	1.3	14.4
Decanal	25.8	14.2	32.8
Nonanal	18.7	14.6	24.6
Dodecane	6.4	4.2	13.4
Undecane	2.9	1.7	5.8
Octanal	6.3	3.0	10.2
1-Hexanol, 2-ethyl-	7.8	4.8	11.9
Tetrachloroethylene	2.9	0.6	6.7
Benzaldehyde	5.7	0.2	13.9
d-Limonene	80.1	5.5	276.3
Acetic acid	10.3	4.0	15.5
5-Hepten-2-one, 6-methyl-	8.9	0.2	16.4
Styrene	2.1	0.5	3.5
Menthol	4.3	1.0	7.0
Acetone	4.3	0.45	9.8
Total	255.0	131.8	606.4

n=14 flights

30. Authors concluded that the contributions of VOC groups to the total VOC concentrations were different between flights, as alkanes and alkenes, aromatics, and aldehydes were the most abundant compounds for 9 flights, 4 flights, and 1 flight, respectively. In addition, in-cabin services, chemical reactions, fuels, materials, combustion, non-fuel oil, cosmetics and perfumes, and cleaning agents were the main sources of VOCs. Nearly 30% of VOC concentrations in aircraft cabins were attributed to on-board services and

human passengers, followed by chemical reactions (15%), fuels (13%), materials (12%), combustion (12%), non-fuel oil (9%), cosmetics and perfumes (6%) and cleaning agents (4%).

EASA. 2014

31. The European Aviation Safety Authority (EASA) carried out monitoring on aircraft equipped with traditional engine bleed systems (main study) as well as in a Boeing 787 aircraft, which are equipped with electrical air compressors instead of engine bleed air systems (EASA 2014).

32. In total, measurements were carried out on 69 flights between July 2015 and June 2016, using eight types of aircraft/engine configurations. In the main study only bleed air supplied aircraft (61 flights) were investigated, while the B787 part covered 8 flights with the alternative no-bleed air supply system of the Boeing 787 (B787, Dreamliner). Two sets of measurement equipment were installed in the flight deck and the cabin respectively during regular passenger in-flight operations. Overall, samples were taken at defined flight phases (taxi-out, take off and climb, descent and landing, complete flight).

33. Samples were collected in Tenax TA tubes and VOCs analysed by MS-FID. Concentrations of VOCs detected in the main study and in the Boeing 787 are presented in Table and Table , respectively. No data for sVOCs were presented in the paper.

Table 8. Mean, minimum and maximum concentrations of VOCs in aircraft (main study)

VOC	Mean conc. (μg/m^3)	Min conc. (μg/m^3)	Max conc. (μg/m^3)
Acetic acid	11.8	0.1	59.4
Benzoic acid	5.3	0.1	72.8
Hexanoic acid	3.8	0.0	16.6
Octanoic acid	2.1	0.1	8.1
Nonanoic acid	1.9	0.1	6.1

VOC	Mean conc. (µg/m^3)	Min conc. (µg/m^3)	Max conc. (µg/m^3)
Decanoic acid	0.8	0.0	5.4
Formic acid	0.7	0.0	33.9
Phenylmaleic anhydride	0.3	0.0	6.1
Tetradecane	2.6	0.0	13.3
2,2,4,6,6-Pentamethyl heptane	1.6	0.0	61.4
2,2,4,4,6,8,8-Heptamethyl nonane	2.4	0.0	49.3
Undecane	2.2	0.0	22.3
Nonane	2.0	0.1	12.9
Dodecane	1.9	0.0	17.6
Tridecane	1.7	0.0	12.2
Decane	1.7	0.1	16.9
Pentadecane	1.5	0.0	6.1
Pentane	1.4	0.0	63.7
Hexadecane	1.2	0.0	3.2
Heptadecane	1.1	0.0	3.1
Heptane	0.9	0.1	24.8
Methylcyclohexane	0.9	0.0	73.8
Cyclohexane	0.8	0.0	48.1
Hexane	0.5	0.0	4.8
3-Methylpentane	0.3	0.0	18.9
2,2,4-Trimethyl pentane	0.1	0.0	2.3
Decanal	10.5	0.0	54.0
Nonanal	5.4	0.1	31.2
Hexanal	4.4	0.0	14.4
Octanal	2.9	0.0	31.4
Heptanal	2.3	0.1	13.6
Benzaldehyde	2.0	0.0	15.0
Undecanal	1.4	0.1	5.2
Butanal	0.7	0.1	4.5

VOC	Mean conc. (µg/m³)	Min conc. (µg/m³)	Max conc. (µg/m³)
2-Hydroxybenzaldehyde	0.5	0.0	8.0
Ethanol	82.3	7.0	616.0
1-Propanol	80.7	0.6	1524.0
1,2-Propanediol	45.2	0.0	363.0
Isopropyl alcohol	12.6	0.1	248.0
1,3-Butanediol	5.2	0.0	70.2
2-Phenoxyethanol	4.6	0.1	29.4
2-Ethylhexanol	4.0	0.1	14.3
1-Butanol	2.4	0.1	31.5
Benzyl alcohol	1.4	0.0	7.3
3-Methylbutanol	0.8	0.0	10.2
Butylated hydroxytoluene (BHT)	0.6	0.0	12.2
Glycerine	0.4	0.5	127.0
tert.-Butanol	0.2	0.0	13.6
Isoprene	9.0	0.1	46.8
4-Cy-pentadien-1,3-dion-4-phenyl	0.1	0.0	3.6
Toluene	11.5	0.0	62.0
Benzene	8.2	0.0	53.4
p+m-Xylene	1.6	0.2	11.7
Naphthalene	14	0.0	49.1
Phenol	1.2	0.0	5.0
o-Xylene	1.0	0.1	5.8
Ethylbenzene	0.7	0.0	10.8
Styrene	0.7	0.0	3.8
Tetrachloroethene	38	0.0	73.9
Dichlormethane	1.1	0.0	71.9
p-Dichlorbenzene	1.0	0.0	34.1
Ethyl acetate	4.9	0.4	68.1
2-Ethylhexyl salicylate	2.3	0.0	19.1

VOC	Mean conc. (µg/m^3)	Min conc. (µg/m^3)	Max conc. (µg/m^3)
Butyl acetate	2.2	0.0	44.8
Isopropyl myristate	1.7	0.0	8.6
2,2,4-Trimethylpentanedioldiiso-butyrate	1.3	0.0	6.7
1-Methoxy-2-propylacetate	1.0	0.0	9.7
Isopropyl palmitate	1.0	0.0	19.3
Homosalate	0.7	0.0	4.1
Dioctyl ether	6.4	0.0	42.8
Methoxy-bis-1,2'-dipropane-1,2-diol ether	2.4	18.5	142.0
1,1'-Dipropane-1,2-diol ether	1.7	9.2	124.0
1,2'-Dipropane-1,2-diol ether	1.6	8.9	114.8
Acetone	15.7	0.8	87.2
5,9-Undecandien-2-one-6,10-dimethyl	3.9	0.1	26.4
Hydroxyacetone	3.3	0.0	161.0
Butanone	2.9	0.1	31.8
Acetophenone	1.6	0.0	49.5
Acetonitrile	19.4	0.2	269.0
Dimethylformamide	7.7	63.9	541.0
Diethyltoluamide	0.9	0.0	19.2
Tributyl phosphate	1.1	0.0	6.4
Triethyl phosphate	0.5	0.0	18.4
Phthalic anhydride	0.9	0.0	48.9
Diethyl phthalate	0.7	0.0	4.1
Diisobutyl phthalate	0.5	0.0	7.1
Dibutyl phthalate	0.3	0.0	5.3
Cyclopentasiloxane	18.0	0.1	277.0
Cyclotrisiloxane	1.8	0.0	42.3
Cyclotetrasiloxane	1.8	0.0	35.4

VOC	**Mean conc. (μg/m³)**	**Min conc. (μg/m³)**	**Max conc. (μg/m³)**
Cyclohexasiloxane	1.0	0.0	9.3
Cycloheptasiloxane	0.7	0.0	3.4
Limonene	12.3	0.0	216.0
Menthol	11.6	0.1	60.7
Eucalyptol	2.0	0.0	40.3
Menthone	1.5	0.0	13.5
α-Pinene	1.2	0.0	11.7
3-Carene	1.3	0.0	42.2
p-Cymene	0.8	0.0	33.4
β-Pinene	0.6	0.0	26.1

Table 9. Mean, minimum and maximum concentrations of VOCs in B787 Dreamliner aircraft

VOC	**Mean conc. (μg/m³)**	**Min conc. (μg/m³)**	**Max conc. (μg/m³)**
Acetic acid	7.5	0. .0	27.1
Benzoic acid	3.3	0.3	9.1
Hexanoic acid	6.2	0.4	34.8
Octanoic acid	1.4	0.3	4.9
Nonanoic acid	1.2	0.2	4.0
Decanoic acid	0.1	0.0	0.4
Formic acid	0.0	0.0	0.0.
Phenylmaleic anhydride	0.1	0.0	0.3
Tetradecane	2.1	0.2	10.3
2,2,4,6,6-Pentamethyl heptane	10.5	0.2	49.1
2,2,4,4,6,8,8-Heptamethyl nonane	0.6	0.0	3.8
Undecane	1.5	0.2	8.5
Nonane	1.8	0.2	9.2

VOC	Mean conc. (μg/m^3)	Min conc. (μg/m^3)	Max conc. (μg/m^3)
Dodecane	1.3	0.2	10.8
Tridecane	1.2	0.1	9.8
Decane	1.0	0.1	6.0
Pentadecane	0.9	0.1	5.4
Pentane	1.0	0.0	4.0
Hexadecane	0.7	0.0	3.3
Heptadecane	0.6	0.1	2.6
Heptane	0.9	0.1	5.0
Methylcyclohexane	0.7	0.0	2.9
Cyclohexane	0.3	0.0	1.5
Hexane	0.7	0.1	2.6
3-Methylpentane	0.2	0.0	1.3
2,2,4-Trimethyl pentane	0.1	0.0	0.8
Decanal	2.7	0.1	7.9
Nonanal	1.9	0.0	5.4
Hexanal	2.4	0.1	10.3
Octanal	1.3	0.1	6.6
Heptanal	0.7	0.0	4.3
Benzaldehyde	1.7	0.4	5.2
Undecanal	1.0	0.2	3.0
Butanal	0.5	0.1	1.4
2-Hydroxybenzaldehyde	0.2	0.0	0.9
Ethanol	80.7	6.1	270.0
1-Propanol	0.6	0.0	2.8
1,2-Propanediol	10.9	0.3	33.3
Isopropyl alcohol	3.5	0.2	26.7
1,3-Butanediol	0.4	0.0	2.0
2-Phenoxyethanol	1.0	0.0	8.2
2-Ethylhexanol	2.9	0.2	15.1

VOC	Mean conc. (µg/m³)	Min conc. (µg/m³)	Max conc. (µg/m³)
1-Butanol	0.9	0.1	5.3
Benzyl alcohol	0.8	0.0	3.5
3-Methylbutanol	0.6	0.0	1.9
Butylated hydroxytoluene (BHT)	0.2	0.0	0.9
Glycerine	0.0	0.0	0.0
tert.-Butanol	0.1	0.0	0.3
Isoprene	5.0	0.4	12.5
4-Cy-pentadien-1,3-dion4phenyl	0.0	0.0	0.3
Toluene	3.5	0.1	17.0
Benzene	3.4	0.3	11.2
p+m-Xylene	0.9	0.0	4.5
Naphthalene	0.8	0.0	4.5
Phenol	0.9	0.2	2.6
o-Xylene	0.6	0.0	3.3
Ethylbenzene	0.3	0.0	1.5
Styrene	0.3	0.0	1.0
Tetrachloroethene	8.5	0.2	42.4
Dichlormethane	0.8	0.0	18.8
p-Dichlorbenzene	0.1	0.0	0.5
Ethyl acetate	3.9	0.1	18.6
2-Ethylhexyl salicylate	0.3	0.1	1.2
Butyl acetate	0.7	0.1	4.3
Isopropyl myristate	0.5	0.1	1.8
2,2,4-Trimethylpentanedioldiisobutyrate	0.2	0.0	1.0
1-Methoxy-2-propylacetate	0.2	0.0	2.0
Isopropyl palmitate	0.3	0.0	1.9
Homosalate	0.2	0.0	0.6
Dioctyl ether	0.4	0.0	2.1

VOC	Mean conc. (µg/m^3)	Min conc. (µg/m^3)	Max conc. (µg/m^3)
Methoxy-bis-1,2'-dipropane-1,2-diol ether	0.0	0.0	0.0
1,1'-Dipropane-1,2-diol ether	0.0	0.0	0.0
1,2'-Dipropane-1,2-diol ether	0.0	0.0	0.0
Acetone	10.1	0.8	36.2
5,9-Undecandien-2-one-6,10-dimethyl	0.1	0.0	0.9
Hydroxyacetone	0.3	0.0	0.9
Butanone	1.2	0.1	4.3
Acetophenone	0.7	0.1	1.9
Acetonitrile	27.0	0.2	207.0
Dimethylformamide	0.0	0.0	0.0
Diethyltoluamide	0.1	0.0	0.2
Tributyl phosphate	0.0	0.0	0.2
Triethyl phosphate	0.0	0.0	0.2
Phthalic anhydride	0.0	0.0	0.2
Diethyl phthalate	0.1	0.0	0.7
Diisobutyl phthalate	0.2	0.0	1.8
Dibutyl phthalate	0.3	0.0	3.1
Cyclopentasiloxane	9.8	0.4	52.2
Cyclotrisiloxane	0.6	0.0	2.8
Cyclotetrasiloxane	0.6	0.1	1.9
Cyclohexasiloxane	0.5	0.0	2.1
Cycloheptasiloxane	1.1	0.1	4.6
Limonene	5.1	0.2	26.0
Menthol	3.3	0.1	9.5
Eucalyptol	0.5	0.0	2.4
Menthone	0.6	0.0	2.0
α-Pinene	0.5	0.0	1.9

VOC	Mean conc. (µg/m³)	Min conc. (µg/m³)	Max conc. (µg/m³)
3-Carene	0.1	0.0	0.3
p-Cymene	0.2	0.0	1.0
β-Pinene	0.3	0.0	1.0

Crump, Harrison and Walton (2011)

34. Crump, Harrison and Walton (2011) carried out project to analyse for VOCs and sVOCs in normal operations during all phases of flight e.g. climb, cruise and descent. A total of 100 flights in five different aircraft types were monitored including a Boeing 757 cargo aircraft, Boeing 757, Airbus A320/1, BAe 146 and Airbus A319 passenger aircraft.

35. Samples were also collected onto sorbent tubes using a portable pump for subsequent laboratory analysis by TD-GC/MS to determine specific VOC/sVOC.

36. Mean values for VOC/sVOC in air for all data (all samples for all 100 flights and all flight phases) are presented in Table . The mean VOC and sVOC air concentration for each flight was also calculated from the measured concentration in each phase of flight (Table). As the sampling strategy involved more intense sampling during the early and late stages of flight than during cruise, authors stated that ‘this calculated mean may not be a true representation of the mean concentration particularly for a flight involving an extended cruise phase. It does, however, give an indication of the longer term mean concentration and therefore the exposure of crew through the duration of the flight’. No data for sVOCs were presented in the paper.

Table 10. Mean, minimum and maximum concentrations of VOC/sVOC in all flight phases

VOC	Mean conc. (µg/m^3)	SD (µg/m^3)	Min conc. (µg/m^3)	Max conc. (µg/m^3)
Tri-*ortho* cresyl phosphate	0.1	0.9	<LOD	22.8
Tri-butyl phosphate	1.0	2.0	<LOD	21.8
Toluene	13.9	21.2	<LOD	170.2
m- and p-Xylene	1.8	3.6	<LOD	52.3
Limonene	37.8	45.8	<LOD	540.3
Tetrachloroethylene	1.8	1.0	<LOD	20.1

Table 11. Mean, minimum and maximum concentrations of VOC/sVOC based on mean concentrations during each flight

VOC	Mean conc. (µg/m^3)	SD (µg/m^3)	Min conc. (µg/m^3)	Max conc. (µg/m^3)
Tri-*ortho* cresyl phosphate	0.1	0.4	<LOD	2.5
Tri-butyl phosphate	1.1	1.7	<LOD	8.2
Toluene	4.0	14.3	<LOD	70.1
m- and p-Xylene	1.8	2.6	<LOD	11.3
Limonene	11.7	42.9	<LOD	342.7
Tetrachloroethylene	0.4	0.7	<LOD	3.7

37. Data for each VOC/sVOC were also calculated per phase of flight (Table) and measured in different aircraft (Table).

38. Overall, authors concluded that the most abundant VOC/sVOC was generally limonene and toluene. Highest concentrations of TBP, limonene, m- and p-xylene and undecane occurred during engine first start, which TCE concentrations were highest during the 'immediate' sampling period. Highest levels of TOCP and toluene occurred during climb and take off, respectively.

39. The mean concentrations of most VOCs measured during the different phases of flight did show a trend, with minimum values occurring during the main phases of flight (climb to descent) and higher values when on the ground and during take-off. This trend was not found for limonene or TOCP.

Table 12. Mean concentrations of VOCs and sVOCs in aircraft cabin air during different flight phases

VOC	**Mean conc. (µg/m³) Immediate**	**Mean conc. (µg/m³) First engine start**	**Mean conc. (µg/m³) Taxi**	**Mean conc. (µg/m³) Take off**	**Mean conc. (µg/m³) Climb**	**Mean conc. (µg/m³) Top of climb**	**Mean conc. (µg/m³) Cruise**	**Mean conc. (µg/m³) Start of descent**	**Mean conc. (µg/m³) Pre-landing**	**Mean conc. (µg/m³) Taxi back**
Tri-*ortho* cresyl phosphate	0.1	0.1	0.1	0.03	0.2	0.03	0.08	0.03	0.08	0.03
Tri-butyl phosphate	1.3	2.1	1.0	1.0	0.8	0.8	0.7	0.9	1.1	1.2
Toluene	11.6	26.0	23.0	16.8	10.1	7.6	8.0	9.4	12.1	13.8
m- and p-Xylene	3.1	3.8	2.7	1.8	0.9	0.7	0.7	0.6	0.9	2.4
Limonene	13.8	16.45	16.9	11.0	12.3	10.0	12.2	7.6	8.8	10.3
Tetrachloroethylene	0.7	0.9	0.5	0.4	0.4	0.2	0.3	0.2	0.3	0.5
Undecane	4.0	4.5	3.7	3.1	1.9	1.4	1.5	1.2	1.6	4.3

Table 13. Mean, minimum and maximum concentrations of VOCs in different aircraft

VOC	**Mean conc. (µg/m^3) Boeing 757 cargo**	**Min-max conc. (µg/m^3) Boeing 757 cargo**	**Mean conc. (µg/m^3) Boeing 757 passenger**	**Min-max conc. (µg/m^3) Boeing 757 passenger**	**Mean conc. (µg/m^3) Airbus A320/1**	**Min-max conc. (µg/m^3) Airbus A320/1**	**Mean conc. (µg/m^3) Bae 146 Passenger**	**Min-max conc. (µg/m^3) bae 146 Passenger**	**Mean conc. (µg/m^3) Airbus A319**	**Min-max conc. (µg/m^3) Airbus A319**
Tri-*ortho* cresyl phosphate	0.2	<LOD-7.8	1.7	<LOD-22.8	<LOD	<LOD	0.002	<LOD-0.2	0.007	<LOD-0.7
Tri-butyl phosphate	3.2	<LOD-21.8	0.4	<LOD-1.9	0.7	<LOD-2.9	1.0	<LOD-9.1	0.5	<LOD-5.6
Toluene	6.2	<LOD-170.2	3.4	<LOD-18.4	12.3	<LOD-82.8	30.4	<LOD-159.0	20.2	<LOD-152.2
m- and p-Xylene	0.9	<LOD-9.2	1.6	<LOD-8.4	0.8	<LOD-3.4	0.8	<LOD-29.6	5.5	<LOD-52.3
Limonene	0.7	<LOD-20.5	10.8	<LOD-150.7	93.0	<LOD-540.3	5.0	<LOD-83.5	1.4	<LOD-22.0
Tetrachloroethylene	0.2	<LOD-4.7	0.9	<LOD-6.1	1	<LOD-21.3	0.5	<LOD-4.9	0.7	<LOD-3.5

Spengler et al. (2012)

40. Spengler et al. (2012) monitored cabin air in 83 flights between February 2008 and August 2010 as part of a Federal Aviation Agency/ American Society of Heating, Refrigerating and Air-Conditioning Engineer (FAA/ASHRAE) study of onboard environmental conditions and passenger and crew responses. The flights measured were taken by three different airlines (airline A – 20 flights; airline B – 39 flights; airline C – 21 flights). Environmental parameters measured included relative humidity, cabin pressure, temperature, and cabin sound levels. Flight characteristics including flight duration, flight departure time, aircraft model, flight date and season, aircraft capacity and occupancy loads were also collected. Measurements were recorded continuously, at one-minute intervals, from 10,000 feet ascent through 10,000 feet descent. sVOCs were sampled on 63 flights of airlines B and C but data are only available for 21 flights of airline B.

41. VOCs and sVOCs were collected via integrated samplers, which were placed at the back of the seat with inlets at seat pocket height of 50 cm. VOCs were also sampled using evacuated canisters for airline A and thermal desorption tubes for airline B and C. sVOCS were sampled on 63 out of the 83 fights but data are only available for 21 flights of airline B.

42. Data on VOCs are presented in Table and Table . No data for sVOCs were presented in tabular format in the paper. Data on the number and percentage of sVOCs detected above the limit of detection were presented and concentration data were presented in figures.

43. Authors noted that the sum of VOCs was inversely proportional to estimated ventilation rates and 'the first interpretation that has merit is that these compounds have sources related to humans due to their proportionality to passenger load factor'. In addition, acetone and formaldehyde levels correlated with ozone concentrations suggested that VOCs may undergo a chemical reaction in the presence of ozone. Elevated ethanol concentrations were consistent with a large number of people in a small cabin space and the service of alcoholic beverages during the flight.

Table 14. Median, minimum and maximum concentrations of VOCs in three airlines

VOC	Median conc. (µg/m³) Airline A	Min conc. (µg/m³) Airline A	Max conc. (µg/m³) Airline A	Median conc. (µg/m³) Airline B	Min conc. (µg/m³) Airline B	Max conc. (µg/m³) Airline B	Median conc. (µg/m³) Airline C	Min conc. (µg/m³) Airline C	Max conc. (µg/m³) Airline C
1,3-Butadiene	0	0	0.04	0.7	0	212.7	0.5	0	50.4
Methyl tert-butyl ether	0	0	0.09	0.03	0	16.3	0.02	0	3.7
Benzene	0.9	0	3.3	0.6	0	20.1	0.1	0	62.3
Toluene	2.8	1.0	30.0	2.9	0.5	115.4	10.1	0.119	132.9
Ethylbenzene	0.2	0	0.6	0.2	0.1	13.5	0.1	0	3.9
m- and p-Xylene	0.3	0.2	0.7	1.0	0.2	28.7	0.1	0	9.4
o-Xylene	0.2	0.1	0.4	0.3	0	14.2	0.4	0	3.4
Methylene chloride	45.6	0	661.8	2.8	0.3	46.5	0.1	0	2.0
Chloroform	0.04	0	0.5	0.1	0.02	2.1	0.03	0	0.6
1,1,1-Trichloroethane	0.01	0	0.03	0.1	0	1.9	0.6	0	2.8
Carbon tetrachloride	0.03	0	0.04	0.7	0	1.7	0.1	0	41.3
Trichloroethene	0.02	0	0.7	0.3	0	2.9	10.7	0	0.5
Cis-1,3-dichloropropene	0	0	0	0	0	2.1	0.3	0	123.0
Trans-1,3-dichloropropene	0	0	0	-	-	-	-	-	-
Tetrachloroethene	0.6	0.05	1.9	1.2	0.1	10.0	10.7	1.1	12.7
1,4-Dichlorobenzene	0.2	0.04	0.7	0.3	0.1	2.4	0.3	0.0	12.7
Acrolein	3.0	0	6.0	-	-	-	3.2	0.0	52.8
Acetone	23.6	13.7	53.2	-	-	-	-	-	-

VOC	Median conc. (µg/m³) Airline A	Min conc. (µg/m³) Airline A	Max conc. (µg/m³) Airline A	Median conc. (µg/m³) Airline B	Min conc. (µg/m³) Airline B	Max conc. (µg/m³) Airline B	Median conc. (µg/m³) Airline C	Min conc. (µg/m³) Airline C	Max conc. (µg/m³) Airline C
2-Butanone	2.2	1.3	4.1	-	-	-	1.4	0.0	11.5
Ethanol	1433.78	221.1	4916.0	-	-	-	-	-	-
Ethyl acetate	1.8	0.4	7.1	-	-	-	16.1	0.0	-
Hexane	0.3	0.0	0.7	68.4	0.04	1123.1	0.0	0.0	-
Isoprene	2.2	1.1	5.6	-	-	-	14.3	0.7	49.9
Isopropyl alcohol	3.1	0.0	32.0	-	-	-	6.3	0.0	84.0
Styrene	0.2	0.04	0.5	0.4	0.1	3.4	0.4	0.0	12.1
2-Methylpentane	-	-	-	2.0	0.009	392.5	0.1	0.0	29.7
2-Methylhexane	-	-	-	0.2	0.008	16.5	0.1	0.0	1.3
2,3-Dimethylpentane	-	-	-	0.07	0.01	9.5	0.1	0.0	1.2
3-Methylhexane	-	-	-	0.1	0.0	19.7	0.2	0.0	62.3
2,2,4-Trimethylpentane	-	-	-	1.0	0.1	29.0	0.9	0.0	69.1
Methylcyclohexane	-	-	-	0.1	0.02	5.2	0.3	0.0	5.2
Propylene	1.2	0.0	72.0	-	-	-	-	-	-
Methyl bromide	0.0	0.0	3.2	-	-	-	-	-	-
Methyl methacrylate	0.0	0.0	2.0	-	-	-	-	-	-
1,2,4-Trimethylbenzene	0.2	0.06	1.4	-	-	-	-	-	-
Dichlorodifluoromethane	0.3	0.2	1.0	-	-	-	-	-	-
Tetrahydrofuran	0.0	0.0	1.5	-	-	-	-	-	-

VOC	Median conc. (µg/m³) Airline A	Min conc. (µg/m³) Airline A	Max conc. (µg/m³) Airline A	Median conc. (µg/m³) Airline B	Min conc. (µg/m³) Airline B	Max conc. (µg/m³) Airline B	Median conc. (µg/m³) Airline C	Min conc. (µg/m³) Airline C	Max conc. (µg/m³) Airline C
Cyclohexane	0.1	0.0	0.9	-	-	-	-	-	-
Methyl chloride	0.	0.0	0.8	-	-	-	-	-	-
Vinyl acetate	0.3	0.0	0.8	-	-	-	-	-	-
Carbon disulfide	0.6	0.0	0.8	-	-	-	-	-	-
Heptanes	0.06	0.0	0.6	-	-	-	-	-	-
Trichlorofluoromethane	0.1	0.114	124.4	-	-	-	-	-	-
1,3,5-Trimethylbenzene	0.06	0.019	303.3	-	-	-	-	-	-
2-Hexanone	0.08	0.0	347.4	-	-	-	-	-	-
Trans-1,2-dichloroethene	0.0	0.0	360.4	-	-	-	-	-	-
1,3-Dichlorobenzene	0.0	0.0	224.2	-	-	-	-	-	-
Methyl isobutyl ketone	0.2	0.0	619.6	-	-	-	-	-	-
4-Ethyl toluene	0.05	0.015	0.23	-	-	-	-	-	-
Chlorobenzene	0.0	0.0	0.22	-	-	-	-	-	-
Ethyl chloride	0.0	0.0	0.25	-	-	-	-	-	-
1,2,4-Trichlorobenzene	0.02	0.0	0.07	-	-	-	-	-	-
1,1,2-Trichlorethane	0.0	0.0	0.08	-	-	-	-	-	-
1,2-Dichlorobenzene	0.0	0.0	0.07	-	-	-	-	-	-
1,1,2,2-Tetrachloroethane	0.0	0.0	0.06	-	-	-	-	-	-

VOC	Median conc. (µg/m³) Airline A	Min conc. (µg/m³) Airline A	Max conc. (µg/m³) Airline A	Median conc. (µg/m³) Airline B	Min conc. (µg/m³) Airline B	Max conc. (µg/m³) Airline B	Median conc. (µg/m³) Airline C	Min conc. (µg/m³) Airline C	Max conc. (µg/m³) Airline C
1,1,2-Trichloro-1,2,2-trifluoroethane	0.03	0.02	0.05	-	-	-	-	-	-
Bromoform	0.0	0.0	0.03	-	-	-	-	-	-
Benzyl chloride	0.0	0.0	0.07	-	-	-	-	-	-
Hexachlorobutadiene	0.0	0.0	0.02	-	-	-	-	-	-
1,2-Dichloroethane	0.0	0.0	0.05	-	-	-	-	-	-
1,2-Dichlorotetrafluoroethane	0.004	0.0	0.02	-	-	-	-	-	-
Dibromochloromethane	0.0	0.0	0.02	-	-	-	-	-	-
1,2-Dibromoethane	0.0	0.0	0.2	-	-	-	-	-	-
Bromodichloromethane	0.0	0.0	0.01	-	-	-	-	-	-
Vinyl chloride	0.0	0.0	0.0	-	-	-	-	-	-
1,1-Dichloroethene	0.0	0.0	0.0	-	-	-	-	-	-
1,1-Dichloroethane	0.0	0.0	0.0	-	-	-	-	-	-
Cis-1,2-dichloroethene	0.0	0.0	0.0	-	-	-	-	-	-
1,2-Dichloropropane	0.0	0.0	0.0	-	-	-	-	-	-
1,4-Dioxane	0.0	0.0	0.0	-	-	-	-	-	-

Table 15. Mean, minimum and maximum concentrations of VOCs in three airlines

VOC	Mean conc. (µg/m^3) Airline A	Mean conc. (µg/m^3) Airline B	Mean conc. (µg/m^3) Airline C
MTBE	0.02	0.2	0.1
Benzene	1.0	0.7	0.9
Toluene	7.7	3.0	5.0
Ethylbenzene	0.4	0.2	0.1
m- and p- Xylene	0.7	0.6	0.5
Chloroform	0.2	0.06	0.07
Trichloroethene	0.1	0.5	0.7
1,4-dichlorobenzene	0.5	0.1	0.2
Hexane	0.5	50.0	1.0

Summary

44. In total, 31 VOCs were reported in more than one mode of transport. Twenty VOCs were reported in two modes of transport, six VOCs in three modes of transport and five VOCs in all four modes of transport.

45. Benzene, toluene, ethylbenzene, m- and p-xylene and styrene were reported in all four modes of transport. Overall, when comparing the highest mean values measured in all studies (worst-case scenario), benzene, ethylbenzene, m- and p-xylene and toluene were lower in aircraft compared to cars/taxis and buses. Styrene was also lower in aircraft compared with cars/taxis but higher compared to buses and metros (Table 27).

46. A comparison was also made between the maximum concentration of VOCs detected in aircraft and the mean concentrations measured in the highest of all other modes of transport (

Table 28. Lowest and highest mean concentrations VOC in different modes of transport

VOC	**Lowest mean (µg/m^3) Aircraft**	**Highest mean (µg/m^3) Aircraft**	**Lowest mean (µg/m^3) Car/taxi**	**Highest mean (µg/m^3) Car/taxi**	**Lowest mean (µg/m^3) Bus**	**Highest mean (µg/m^3) Bus**	**Lowest mean (µg/m^3) Metro**	**Highest mean (µg/m^3) Metro**
Reported in all modes of transport								
Benzene	0.9	16.1	2.4	270.0	0.02	63.2	4.67	33.48
Ethylbenzene	0.3	8.1	0.9	85	0.2	95.9	1.16	10.5
m- and p-xylene	0.9	8.8	10.2	1570.7	0.18	234.8	0.94	10.29
Styrene	0.2	6.4	0.5	1500.0	1.88	2.05	0.44	6.8
Toluene	2.8	29.84	5.5	2000.0	0.44	503.0	5.22	63.4
Reported in three modes of transport								
Acetaldehyde		6.4	12.47	790.0	-	-	0.39	10.6
Formaldehyde		5.4	16.43	1541.0	-	-	2.4	26.9
Heptane	0.7	1.8	2.9	670.1	0.59	0.81	-	-
Nonane	1.4	2.1	2.0	341	0.17	150.0	-	-
Octane	>0.5	1.9	2.0	127	3.2	3.55	-	-
Tetrachloroethylene	2.6	38.0	0.5	320.2	0.02	3.45	-	-

VOC	Lowest mean (µg/m^3) Aircraft	Highest mean (µg/m^3) Aircraft	Lowest mean (µg/m^3) Car/taxi	Highest mean (µg/m^3) Car/taxi	Lowest mean (µg/m^3) Bus	Highest mean (µg/m^3) Bus	Lowest mean (µg/m^3) Metro	Highest mean (µg/m^3) Metro
Reported in two modes of transport								
1,3-dichlorobenzene	0.0	-	-	-	0.08	47.09	-	-
1,4-dichlorobenzene	0.11	22.9	-	-	0.01	5.41	-	-
Acetic acid	7.5	11.8	3.41	14.0	-	-	-	-
Acetone	6.0	17.1	9.3	250 .0	-	-	-	-
Acrolein		<0.8	20.65		-	-	-	-
α-Pinene	0.5	1.2	0.2	4.2	-	-	-	-
β-Pinene	0.3	0.6	0.2	1.8	-	-	-	-
Decane	1.0	13.0	0.6	1300.6	-	-	-	-
Dodecane	2.6	6.7	44.5	928.6	-	-	-	-
Ethyl acetate	1.1	9.1	1.8	28.0	-	-	-	-
Hexane	0.5	20.0	1.7	65.0	-	-	-	-
Isoprene	5.0	9.0	-	-	-	-	-	-
Limonene	1.44	92.96	0.8	38.8	-	-	-	-
Methanol	4.32	9.6	122.0	-	-	-	-	-
Naphthalene	0.8	14.0	6.0	49.3	-	-	-	-
o- Xylene	0.6	9.4	3.3	1400	-	-	-	-

VOC	Lowest mean (µg/m^3) Aircraft	Highest mean (µg/m^3) Aircraft	Lowest mean (µg/m^3) Car/taxi	Highest mean (µg/m^3) Car/taxi	Lowest mean (µg/m^3) Bus	Highest mean (µg/m^3) Bus	Lowest mean (µg/m^3) Metro	Highest mean (µg/m^3) Metro
Pentane	1.0	1.4	0.07	30.8	-	-	-	-
p-Xylene	?	6.8	78.4	78.4	-	-	-	-
Tridecane	1.2	1.7	1.3	687.1	-	-	-	-
Undecane	1.5	4.9	9.3	1615.0	-	-	-	-

48. Table 29). The mean concentrations were used for all other modes of transport as maximum concentrations were not consistently available.

49. The highest concentrations of benzene, toluene, ethylbenzene, m- and p-xylene and styrene concentrations were all lower in aircraft compared with cars/taxis, which reported the highest values of all modes of transport investigated.

50. The highest concentration of all VOCs was reported in cars by Faber and Brodzik (2017) who compiled VOC data by different authors on new (less than three years old) and used cars in different scenarios. From the studies included in the paper, for some VOCs, data were collected from multiple cars whereas for other VOCs, data from a single car were presented. For example, for benzene, the highest concentration was the mean concentration from 803 new static cars in an underground carpark in Beijing, China, and styrene and toluene, which were both measured in five new vehicles in Taiwan. Conversely, the highest concentration of m- and p-xylene was measured in one static Nissan Serena in an outdoor carpark in the summer/autumn and the highest concentration of ethyl benzene was measured in one new static vehicle by both Faber and Brodzik (2017) and You et al. (2007).

51. For comparative purposes, the highest values reported in all modes of transport were used as a worst-case scenario as passengers may conceivably be exposed to such concentrations.

52. As mentioned by all authors, many factors affect the VOC concentrations including age of vehicle, temperature, fuel type, external surroundings, mileage, and driving speed amongst others.

53. Acetaldehyde, formaldehyde, heptane, nonane, octane and tetrachloroethylene were reported in three modes of transport. All six VOCs were reported in aircraft and cars/taxi, but only heptane, nonane, octane and tetrachloroethylene were reported in buses and only acetaldehyde and formaldehyde in metros (Table 27).

54. The maximum mean concentrations of all six VOCs were lower in aircraft compared to cars/taxis but unlike with BTEX, the highest concentrations were reported in different publications. Acetaldehyde and formaldehyde, and nonane and octane were also lower in aircraft compared to metros and buses, respectively. Heptane and tetrachloroethylene were higher in aircraft compared to buses.

55. The maximum concentrations measured in aircraft were also lower than those measured in cars/taxis.

56. The highest mean concentration of acetaldehyde was detected in one used car (< three years old) in an environmental chamber (Faber and Brodzik 2017); the highest concentration of formaldehyde was detected in a >5 year old gasoline taxi measured after refuelling (Bakhtiari et al. 2018); the highest concentration of heptane was detected in car with a black synthetic steering wheel, black and white synthetic fabric and a white dashboard (Brodzik et al. 2014), the highest concentration of nonane and octane were detected in a new car (You et al. 2007), and the highest concentration of tetrachloroethylene was measured in 38 gasoline fuelled taxis in China with non-leather decoration and air conditioner (Chen et al. 2014a).

57. The remaining VOCs presented in Table 27 were reported in only two modes of transport. With the exception of 1,3-dichlorobenzene and 1,4-dichlorobenzene, which were reported in aircraft and buses, all other VOCs were reported in aircraft and cars/taxis.

58. The highest concentration of limonene was detected in aircraft but varied during different flight phases, with an increase being during meal services, indicating that it could be largely released through meals and drinks (Guan et al. 2014b). Crump et al. (2011) also noted that limonene was one of the most abundant VOCs detected along with toluene, and showed the highest concentrations during first engine start, and taxing. Authors noted that it is present in natural products such as wood and citrus fruits and wildly applied as fragrances in a range of cosmetic and cleaning products.

59. In cars, the highest mean concentration of limonene was detected in 10 static cars of two different brands in Poland (Faber and Brodzik 2017).

60. The highest concentration of limonene was reported in aircraft by Guan et al. 2014b. Authors noted that limonene commonly arises from meal services or cleaning agents.

61. The highest concentration of pentane was reported by EASA, 2014, and was detected in the main study comprising analysis of 61 flights. The mean, minimum, maximum and median concentration of pentane detected was 1.4, 0.0, 63.7 and 0.2 µg/m^3, respectively. Authors did not make any comment regarding the source of pentane or the cause of the high maximum value.

62. The highest concentrations of all other VOCs were reported by Spengler et al. 2012. The highest concentrations of heptane, 1,3-dichlorobenzene and acetone were measured using evacuated canisters in airline A (20 flights); the highest concentrations of styrene and 1,4-dichlorobenzene were detected using thermal desorption tubes in Airline C (24 flights); and the highest concentration of all other VOCs were detected using thermal desorption tubes in Airline B (39 flights). Authors noted that toluene, ethylbenzene, o-xylene, 1,3-butadiene, and styrene all showed a pattern where a few flights had values substantially higher than what might be expected.

63. A number of other VOCs have been detected in aircraft but similar determinations have not been reported for any other mode of transport; this however does not mean they are unique to aircraft (Table 30. Maximum concentrations reported in aircraft and highest mean of the next highest mode of transport. Highest value is indicated in bold.

VOC	**Maximum conc. (µg/m^3) Aircraft**	**Reference**	**Highest mean (µg/m^3) Other mode of transport**	**Reference**
Benzene	77.9	Guan et al. (2014b)	**270.0** (Car/Taxi)	Faber and Brodzik (2017)
Ethylbenzene	45.0	Guan et al. (2014b)	**115.9** (Car/Taxi)	Chen et al. (2014b)
m- and p-Xylene	70.7	Guan et al. (2014b)	**1570.7** (Car/Taxi)	Faber and Brodzik (2017)
Styrene	12.08	Spengler et al. (2012). Airline C	**1500.0** (Car/Taxi)	Faber and Brodzik (2017)
Toluene	303.0	Guan et al. (2014b)	**2000.0** (Car/Taxi)	Faber and Brodzik (2017)
Acetaldehyde	7.7	Chen et al. (2021)	**790.0** (Car/Taxi)	Bakhtiari et al. (2018)
Formaldehyde	7.1	Chen et al. (2021)	**1541.0** (Car/Taxi)	Bakhtiari et al. (2018)
Heptane	24.8	EASA (2014)	**670** .0(Car/Taxi)	Faber and Brodzik (2017)
Nonane	12.9	EASA (2014)	**341.0** (Car/Taxi)	You et al. (2007)
Octane	8.2	Guan et al. (2014b)	**127.0** (Car/Taxi)	You et al. (2007)
Tetrachloroethylene	42.4	EASA (2014)	**320.2** (Car/Taxi)	Chen et al. (2014b)

1,3-Dichlorobenzene	0.22	Spengler et al. (2012). Airline A	**47.09** (Bus)	Parra et al. (2008)
1,4-Dichlorobenzene	**228.3**	Guan et al. (2014b)	5.41 (Bus)	Parra et al. (2008)
Acetic acid	**27.1**	EASA (2014)	14.0 (Car/Taxi)	Kim, Park and Lee (2019)
Acetone	53.16	Spengler et al. (2012). Airline A	**250**.0 (Car/Taxi)	Faber and Brodzik (2017)
α-Pinene	11.7	EASA (2014)	**200.0** (Car/Taxi)	You et al. (2007)
β-Pinene	**26.1**	EASA (2014)	1.8 (Car/Taxi)	Moreno et al. (2019)
Decane	43.7	Guan et al. (2014b)	**1300.6** (Car/Taxi)	Faber and Brodzik (2017)
Dodecane	17.6	EASA (2014)	**928.9** (Car/Taxi)	Faber and Brodzik (2017)
Ethyl acetate	**44.0**	Guan et al. (2014b)	28.1 (Car/Taxi)	Brodzik et al. (2014)
Hexane	**1123.08**	Spengler et al. (2012). Airline B	65.0 (Car/Taxi)	Faber and Brodzik (2017)
Limonene	**1048.0**	Guan et al. (2014b)	38.8 (Car/Taxi)	Faber and Brodzik (2017)
Naphthalene	49.1	EASA (2014)	**49.3** (Car/Taxi)	You et al. (2007)
o-Xylene	62.9	Guan et al. (2014b)	**1400.0** (Car/Taxi)	Faber and Brodzik (2017)
Pentane	**63.7**	EASA (2014)	30.8 (Car/Taxi)	Faber and Brodzik (2017)
p-Xylene	20.9	Wang et al. (2014a)	**784.0** (Car/Taxi)	Brodzik et al. (2014)
Tridecane	12.2	EASA (2014)	**687.1** (Car/Taxi)	Faber and Brodzik (2017)
Undecane	60.3	Guan et al. (2014b)	**1615.8** (Car/Taxi)	Faber and Brodzik (2017)

64. Table **31**).

Conclusion

65. Overall, if based on mean data, results indicate that passengers and aircrew could be exposed to higher concentrations of limonene for part of their journey when travelling in aircraft as compared with other modes of transport. As a worst-case scenario and considering maximum concentrations reported, 1,4-dichlorobenzene, acetic acid, β-pinene, ethyl acetate, hexane, limonene, pentane in aircraft all exceeded mean values reported for other modes of transport.

66. Concentrations of all other VOCs detected in aircraft are generally lower when compared with travelling by other modes of transport.

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