TOX/2022/46

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

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

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 modes of transport, including aircraft, to support consideration of whether exposures to VOCs in aircraft are different to exposures elsewhere. A further paper is planned to consider concentrations of VOCs.

5. The studies identified are summarised in paragraphs 10-123, and a comparison of the different modes of transport is provided in the summary from paragraph 124.

Literature search

6. A literature search was carried out to collate concentration data on VOCs in aircraft in comparison with other modes of transport such as cars, taxis, buses and metros. 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. Cases where VOC concentrations were measured in only one vehicle were noted.

9. Forty-one 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, seven in cars and taxis, four in buses and one in metros.

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 detected in the aircraft cabins as presented in more than two studies are shown in Table 1 and Table 2.

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	12	2.5	123
Limonene	24	31	1.4	276
m- and p-xylene	2.5	23	0.6	21
Benzene	5.9	5.5	0.1	57
Benzaldehyde	>2.5	2.0	0.0	14
Undecane	2.9	1.6	0.0	13
o- Xylene	2.5	2.8	0.3	14
Ethylbenzene	2.3	2.9	0.2	23
Styrene	1.0	0.9	0.0	6.1
Nonanal	7.8	5.6	1.9	24
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
Tetrachloroethylene	7.3	5.7	0.6	16
Decanal	14	5.0	2.7	36
Acetone	14	5.6	0.5	49
Dodecane	3.1	1.8	0.0	13
6- methyl-5-hepten-2-one/6-MHO	7.0	3.5	0.2	16
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
Ethyl acetate	6.5	4.4	3.9	16
p-dichlorobenzene/1,4-dichlorobenzene	2.4	2.9	0.1	6.9
Hexane	20	31	0.0	68
Octanal	4.2	1.8	1.3	10

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	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	3.4	3.5	13
Dichloromethane/methylene chloride	1.4	10.	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	899	81	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
a-Pinene	1.1	0.3	0.0	1.2
b-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	22.8
Tributyl phosphate (TiBP)	0.495	59	0.037	9.1
Tricresyl phosphates (TCP)	0.035	0.0077	0.0003	14.9
Naphthalene	1.241	0.166	0	49.1
Trichloroethylene TCE)	0.483	0.036	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	0.642
Diphenyl-2-ethylhexyl phosphate (DPEHP)	0.015	0.0002	0	0.282
Tris (ethylhexyl) phosphate (TEHP)	<LOD	-	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/m^3)	SD (µg/m^3)	Min conc. (µg/m^3)	Max conc. (µg/m^3)
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 3. 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 4). 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. (µg/m^3) Before take-off**	**SD (µg/m^3) Before take-off**	**Mean conc. (µg/m^3) Cruise**	**SD (µg/m^3) Cruise**	**Mean conc. (µg/m^3) After landing**	**SD (µg/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	14.34	17.1	52.8
2-methyl-1,3-butadiene	<LOD	1.4	<LOD	1.2	1.1	2.2

VOC	Mean conc. (µg/m^3) Before take-off	SD (µg/m^3) Before take-off	Mean conc. (µg/m^3) Cruise	SD (µg/m^3) Cruise	Mean conc. (µg/m^3) After landing	SD (µg/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 5). 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	-	3.3	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 6). 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. (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**
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) Recirculated air**	**SD (µg/m^3) Recirculated 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 7. 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	14.78	4.49	56.95
Toluene	29.84	6.73	123.08
Ethylbenzene	7.04	1.47	22.5
p-Xylene	4.83	1.16	20.92
o-Xylene	4.55	1.25	14.42
Decanal	25.78	14.16	32.77
Nonanal	18.65	14.62	24.55
Dodecane	6.43	4.19	13.42
Undecane	2.94	1.66	5.82
Octanal	6.30	3.03	10.23
1-Hexanol, 2-ethyl-	7.75	4.79	11.90
Tetrachloroethylene	2.94	0.60	6.68
Benzaldehyde	5.68	0.15	13.88
d-Limonene	80.13	5.47	276.32
Acetic acid	10.29	4.04	15.53
5-Hepten-2-one, 6-methyl-	8.86	0.21	16.38
Styrene	2.06	0.54	3.49
Menthol	4.32	1.04	7.03
Acetone	4.27	0.46	9.80
Total	254.96	131.84	606.41

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 8 and Table 9, 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/m^3)**	**Min conc. (µg/m^3)**	**Max conc. (µg/m^3)**
2-Hydroxybenzaldehyde	0.5	0.0	8.0
Ethanol	82.3	7.0	616
1-Propanol	80.7	0.6	1524
1,2-Propanediol	45.2	0.0	363
Isopropyl alcohol	12.6	0.1	248
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
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
1,1'-Dipropane-1,2-diol ether	1.7	9.2	124
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
Dimethylformamide	7.7	63.9	541
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
Cyclotrisiloxane	1.8	0.0	42.3
Cyclotetrasiloxane	1.8	0.0	35.4

VOC	**Mean conc. (μg/m^3)**	**Min conc. (μg/m^3)**	**Max conc. (μg/m^3)**
Cyclohexasiloxane	1.0	0.0	9.3
Cycloheptasiloxane	0.7	0.0	3.4
Limonene	12.3	0.0	216
Menthol	11.6	0.1	60.7
Eucalyptol	2.0	0.0	40.3
Menthone	1.5	0.0	13.5
a-Pinene	1.2	0.0	11.7
3-Carene	1.3	0.0	42.2
p-Cymene	0.8	0.0	33.4
b-Pinene	0.6	0.0	26.1

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

VOC	**Mean conc. (μg/m^3)**	**Min conc. (μg/m^3)**	**Max conc. (μg/m^3)**
Acetic acid	7.5	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/m^3)**	**Min conc. (µg/m^3)**	**Max conc. (µg/m^3)**
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
a-Pinene	0.5	0.0	1.9

VOC	Mean conc. (μg/m^3)	Min conc. (μg/m^3)	Max conc. (μg/m^3)
3-Carene	0.1	0.0	0.3
p-Cymene	0.2	0.0	1.0
b-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 10. The mean VOC and sVOC air concentration for each flight was also calculated from the measured concentration in each phase of flight (Table 11). 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	0.07	0.88	<LOD	22.8
Tri-butyl phosphate	1.0	1.96	<LOD	21.8
Toluene	13.93	21.23	<LOD	170.2
m- and p-Xylene	1.78	3.63	<LOD	52.3
Limonene	37.8	45.77	<LOD	540.3
Tetrachloroethylene	1.8	1.04	<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	0.08	0.38	<LOD	2.5
Tri-butyl phosphate	1.11	1.72	<LOD	8.2
Toluene	03.95	14.28	<LOD	70.1
m- and p-Xylene	1.75	2.55	<LOD	11.3
Limonene	11.68	42.88	<LOD	342.7
Tetrachloroethylene	0.43	0.67	<LOD	3.7

37. Data for each VOC/sVOC were also calculated per phase of flight (Table 12) and measured in different aircraft (Table 13).

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	0.11	0.09	0.08	0.03	0.24	0.03	0.08	0.03	0.08	0.03
Tri-butyl phosphate	1.26	2.06	1.06	1.01	0.8	0.79	0.65	0.86	1.08	1.21
Toluene	11.62	26	22.95	16.76	10.1	7.57	8	9.38	12.12	13.8
m- and p-Xylene	3.12	3.77	2.72	1.77	0.88	0.73	0.71	0.61	0.9	2.37
Limonene	13.77	16.46	16.94	11.88	12.25	9.97	12.16	7.64	8.8	10.31
Tetrachloroethylene	0.65	0.89	0.51	0.39	0.35	0.23	0.25	0.2	0.31	0.54
Undecane	4.02	4.49	3.71	3.13	1.92	1.39	1.46	1.21	1.61	4.33

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	0.24	<LOD-7.8	1.66	<LOD-22.8	<LOD	<LOD	0.002	<LOD-0.2	0.007	<LOD-0.7
Tri-butyl phosphate	3.18	<LOD-21.8	0.38	<LOD-1.9	0.65	<LOD-2.9	1.04	<LOD-9.1	0.47	<LOD-5.6
Toluene	6.21	<LOD-170.2	3.37	<LOD-18.4	12.33	<LOD-82.8	30.42	<LOD-159.0	20.19	<LOD-152.2
m- and p-Xylene	0.93	<LOD-9.2	1.60	<LOD-8.4	0.81	<LOD-3.4	0.77	<LOD-29.6	5.46	<LOD-52.3
Limonene	0.65	<LOD-20.5	10.77	<LOD-150.7	92.96	<LOD-540.3	4.99	<LOD-83.5	1.44	<LOD-22.0
Tetrachloroethylene	0.21	<LOD-4.7	0.86	<LOD-6.1	1.78	<LOD-21.3	0.49	<LOD-4.9	0.74	<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 14 and Table 15. 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/m^3) Airline A**	**Min conc. (μg/m^3) Airline A**	**Max conc. (μg/m^3) Airline A**	**Median conc. (μg/m^3) Airline B**	**Min conc. (μg/m^3) Airline B**	**Max conc. (μg/m^3) Airline B**	**Median conc. (μg/m^3) Airline C**	**Min conc. (μg/m^3) Airline C**	**Max conc. (μg/m^3) Airline C**
1,3-Butadiene	0	0	0.044	0.67	0	212.72	0.53	0	50.41
Methyl tert-butyl ether	0	0	0.086	0.034	0	16.16	0.02	0	3.66
Benzene	0.88	0	3.29	0.55	0	20.07	0.12	0	62.34
Toluene	2.78	1.01	30.03	2.85	0.46	115.38	10.11	0.119	132.93
Ethylbenzene	0.19	0	0.58	0.23	0.06	13.45	0.11	0	3.86
m- and p-Xylene	0.33	0.15	0.72	0.96	0.21	28.67	0.11	0	9.39
o-Xylene	0.16	0.07	0.42	0.29	0	14.17	0.41	0	3.44
Methylene chloride	45.64	0	661.82	2.84	0.19	46.53	0.09	0	1.96
Chloroform	0.035	0	0.54	0.14	0.02	2.09	0.03	0	0.56
1,1,1-Trichloroethane	0.010	0	0.03	0.06	0	1.85	0.64	0	2.80
Carbon tetrachloride	0.03	0	0.04	0.65	0	1.70	0.13	0	41.29
Trichloroethene	0.02	0	0.65	0.32	0	2.94	10.67	0	0.53
Cis-1,3-dichloropropene	0	0	0	0	0	2.10	0.3	0	123.03
Trans-1,3-dichloropropene	0	0	0	-	-	-	-	-	-
Tetrachloroethene	0.62	0.05	1.93	1.17	0.07	10.01	10.67	1.177	12.74
1,4-Dichlorobenzene	0.19	0.04	0.70	0.3	0.05	2.42	0.31	0	12.74
Acrolein	2.98	0	5.97	-	-	-	3.21	0	52.77
Acetone	23.56	13.70	53.16	-	-	-		-	-
2-Butanone	2.15	1.27	4.05	-	-	-	1.36	0	11.50

VOC	**Median conc. (µg/m^3) Airline A**	**Min conc. (µg/m^3) Airline A**	**Max conc. (µg/m^3) Airline A**	**Median conc. (µg/m^3) Airline B**	**Min conc. (µg/m^3) Airline B**	**Max conc. (µg/m^3) Airline B**	**Median conc. (µg/m^3) Airline C**	**Min conc. (µg/m^3) Airline C**	**Max conc. (µg/m^3) Airline C**
Ethanol	1433.77	221.100	4916.00	-	-	-	-	-	-
Ethyl acetate	1.75	0.360	7.14	-	-	-	16.13	0	-
Hexane	0.26	0	0.70	68.360	0.038	1123.078	0	0	-
Isoprene	2.23	1.056	5.64	-	-	-	14.32	0.705	49.93
Isopropyl alcohol	3.10	0	32.02	-	-	-	6.31	0	84.03
Styrene	0.16	0.040	0.50	0.369	0.112	3.391	0.42	0	12.08
2-Methylpentane	-	-	-	2.042	0.009	392.507	0.08	0	29.67
2-Methylhexane	-	-	-	0.174	0.008	16.467	0.13	0	1.30
2,3-Dimethylpentane	-	-	-	0.073	0.010	9.544	0.10	0	1.18
3-Methylhexane	-	-	-	0.118	0	19.670	0.18	0	62.33
2,2,4-Trimethylpentane	-	-	-	0.979	0.121	29.019	0.87	0	69.14
Methylcyclohexane	-	-	-	0.114	0.024	5.211	0.27	0	5.22
Propylene	1.15	0	71.96	-	-	-	-	-	-
Methyl bromide	0	0	3.24	-	-	-	-	-	-
Methyl methacrylate	0	0	1.99	-	-	-	-	-	-
1,2,4-Trimethylbenzene	0.21	0.055	1.40	-	-	-	-	-	-
Dichlorodifluoromethane	0.28	0.247	1.02	-	-	-	-	-	-
Tetrahydrofuran	0	0	1.48	-	-	-	-	-	-
Cyclohexane	0.11	0	0.94	-	-	-	-	-	-
Methyl chloride	0.63	0	0.76	-	-	-	-	-	-

VOC	**Median conc. ($\mu g/m^3$) Airline A**	**Min conc. ($\mu g/m^3$) Airline A**	**Max conc. ($\mu g/m^3$) Airline A**	**Median conc. ($\mu g/m^3$) Airline B**	**Min conc. ($\mu g/m^3$) Airline B**	**Max conc. ($\mu g/m^3$) Airline B**	**Median conc. ($\mu g/m^3$) Airline C**	**Min conc. ($\mu g/m^3$) Airline C**	**Max conc. ($\mu g/m^3$) Airline C**
Vinyl acetate	0.29	0	0.76	-	-	-	-	-	-
Carbon disulfide	0.57	0	0.80	-	-	-	-	-	-
Heptanes	0.06	0	0.58	-	-	-	-	-	-
Trichlorofluoromethane	0.12	0.114	124.40	-	-	-	-	-	-
1,3,5-Trimethylbenzene	0.06	0.019	303.30	-	-	-	-	-	-
2-Hexanone	0.08	0	347.35	-	-	-	-	-	-
Trans-1,2-dichloroethene	0	0	360.36	-	-	-	-	-	-
1,3-Dichlorobenzene	0	0	224.22	-	-	-	-	-	-
Methyl isobutyl ketone	0.17	0	619.62	-	-	-	-	-	-
4-Ethyl toluene	0.05	0.015	0.23	-	-	-	-	-	-
Chlorobenzene	0	0	0.22	-	-	-	-	-	-
Ethyl chloride	0	0	0.25	-	-	-	-	-	-
1,2,4-Trichlorobenzene	0.02	0	0.07	-	-	-	-	-	-
1,1,2-Trichlorethane	0	0	0.08	-	-	-	-	-	-
1,2-Dichlorobenzene	0	0	0.07	-	-	-	-	-	-
1,1,2,2-Tetrachloroethane	0	0	0.06	-	-	-	-	-	-
1,1,2-Trichloro-1,2,2-trifluoroethane	0.03	0.024	0.05	-	-	-	-	-	-
Bromoform	0	0	0.03	-	-	-	-	-	-
Benzyl chloride	0	0	0.07	-	-	-	-	-	-

VOC	**Median conc. (µg/m^3) Airline A**	**Min conc. (µg/m^3) Airline A**	**Max conc. (µg/m^3) Airline A**	**Median conc. (µg/m^3) Airline B**	**Min conc. (µg/m^3) Airline B**	**Max conc. (µg/m^3) Airline B**	**Median conc. (µg/m^3) Airline C**	**Min conc. (µg/m^3) Airline C**	**Max conc. (µg/m^3) Airline C**
Hexachlorobutadiene	0	0	0.02	-	-	-	-	-	-
1,2-Dichloroethane	0	0	0.05	-	-	-	-	-	-
1,2-Dichlorotetrafluoroethane	0.004	0	0.02	-	-	-	-	-	-
Dibromochloromethane	0	0	0.02	-	-	-	-	-	-
1,2-Dibromoethane	0	0	0.2	-	-	-	-	-	-
Bromodichloromethane	0	0	0.01	-	-	-	-	-	-
Vinyl chloride	0	0	0	-	-	-	-	-	-
1,1-Dichloroethene	0	0	0	-	-	-	-	-	-
1,1-Dichloroethane	0	0	0	-	-	-	-	-	-
Cis-1,2-dichloroethene	0	0	0	-	-	-	-	-	-
1,2-Dichloropropane	0	0	0	-	-	-	-	-	-
1,4-Dioxane	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	0.24	0.12
Benzene	1.03	0.72	0.90
Toluene	7.65	3.01	4.95
Ethylbenzene	0.40	0.23	0.14
m- and p- Xylene	0.71	0.62	0.49
Chloroform	0.20	0.06	0.07
Trichloroethene	0.12	0.46	0.66
1,4-dichlorobenzene	0.54	0.11	0.17
Hexane	0.49	50.00	1.02

Cars and taxis

Bakhtiari et al. (2018)

44. Bakhtiari et al. (2018) investigated VOCs in taxis focussing on benzene, toluene, ethylbenzene, xylene (BTEX), acetaldehyde and formaldehyde concentrations in indoor car compartments of different models and ages of cars, before and after the refuelling process, with different fuel types (compressed natural gas (CNG), gas, and liquefied petroleum gas (LPG)).

45. Measurements were made in taxis in Tehran, Iran in the summer of 2016. Sampling was performed in two moderate-traffic streets in the central area of the city.

46. Four commonly used taxi models were investigated in the study, namely Peugeot 405, Pride, Samand, and Peykan (Models 1 to 4, respectively). Only vehicles using gasoline, CNG or LPG fuel were included in the study. Three vehicles per model were investigated to assess inter-model

differences. Only taxis where the driver had no history of smoking were selected, and polish and gloss materials had not been used on the interior and exterior surfaces.

47. Three age groups were defined for each model of car: a) between 6 months and 1 year, b) between 1 and 5 years, and c) between 5 and 10 years. Since the manufacturing of the model 4 vehicle had been stopped several years ago, model 4 taxis were investigated only for ages of 5-10 years. All taxis had catalytic converters except for model 4, and models 1 and 2 were equipped with a vapour recovery system.

48. Benzene, toluene, ethylbenzene, xylene, formaldehyde, and acetaldehyde were sampled 30 min before and after refuelling for each of the 90 taxis. Sampling was performed when the taxis were moving at a constant speed (30 ± 5 km/h) and on a specified path. The sampling point was along the central axis of the cabin and between the two front seats at a location at approximately the same distance from the breathing zone of four possible passengers. The pump flow rate was calibrated before each sampling using a gas flow meter. During the sampling period the windows were closed, and the cooling/heating system was off. Interior air temperature, humidity and barometric pressure was measured during sampling.

49. BTEX was sampled actively with coconut shell charcoal tubes and a pump at a flow rate of 200 mL/min for 30 min. The charcoal was extracted for 0.5 h with sonication. Gas chromatography/flame ionization detector (GC-FID) was employed to determine the concentrations of the BTEX components.

50. Formaldehyde samples were collected using a cartridge containing silica gel coated with (2-hydroxymethyl) piperdine, and a pump with flow rate of 50 mL/min. It was desorbed from the cartridge with 10 mL of carbonyl-free acetonitrile and 30 min sonication. GC-FID was used to measure the formaldehyde concentrations.

51. Acetaldehyde was sampled by a solid sorbent tube and a pump with flow rate of 50 mL/min for 30 min. Collected samples were desorbed with 5mL

toluene and 60 min ultrasonic. GC-FID was used to measure the acetaldehyde concentrations.

52. Table 16 -Table 18 present the mean concentrations of BTEX, formaldehyde and acetaldehyde before and after refuelling with different types of fuels. No data for sVOCs were presented.

53. The age of the vehicle or model of vehicle did not impact the BTEX concentrations measured. However, for formaldehyde, <1 year old model 1 and 3 vehicles had lower concentrations than other age groups and 1-5-year-old model 2 taxis had higher levels compared to other age groups.

54. Comparison between different models of the same age showed that model 3 taxis generally had higher concentrations of formaldehyde. For acetaldehyde, >5-year-old model 1 and 3 taxis and 1-5-year-old model 2 taxis had higher levels compared with other age groups. <1- and 1-5-year-old model 2 taxi also had higher levels of acetaldehyde compared with other models of the same age group, but models 1 and 3 had higher levels in the oldest age group.

55. The use of gasoline significantly increased concentrations of BTEX in all models of taxi compared to other fuels as well as increased formaldehyde in model 2 taxis, and acetaldehyde in all models apart from model 1 with CNG.

Table 16. Mean concentrations of BTEX in four different model of taxis, before and after refuelling with different fuels

Vehicle model	**Age**	**Mean ± SD conc. (μg/m^3) LPG before fuelling**	**Mean ± SD conc. (μg/m^3) LPG after fuelling**	**Mean ± SD conc. (μg/m^3) CNG before fuelling**	**Mean ± SD conc. (μg/m^3) CNG after fuelling**	**Mean ± SD conc. (μg/m^3) Gasoline before fuelling**	**Mean ± SD conc. (μg/m^3) Gasoline after fuelling**
Model 1	<1	20.8±2.8	35.2±5	23.1±3.0	46.3±5.3	47.8±5.4	66.9±7.2
Model 1	1-5	32.8±4.7	53.1±7.5	37.9±3.8	60.1±7.9	49.3±4.2	69.4±9.3
Model 1	>5	38.8±3.9	50.1±5	40.1±5.6	59.5±7.4	64.3±9.6	88.8±8.3
Model 2	<1	30.9±2.9	36.4±3.6	31.1±4.5	42.8±4.3	36.8±4.8	58.9±4.8
Model 2	1-5	31.5±4.0	36.4±4.8	34.1±4.8	42.8±4.7	41.5±5.0	87.0±12.0
Model 2	>5	32.1±3.3	49.3±7.2	35.2±3.4	52.2±6.4	61.3±8.4	88.2±11.4
Model 3	<1	29.5±4.0	41.5±4.8	43.8±6.6	24.9±4.7	55.1±8.2	78.4±10.2
Model 3	1-5	27.3±3.5	41.2±5.2	34.4±4.9	51.2±7.2	51.7±5.6	73.5±9.5
Model 3	>5	34.1±4.8	52.0±7.2	38.2±4.7	58.2±6.4	48.0±6.0	76.0±10.6
Model 4	>5	42.6±4.6	65.8±8.9	47.8±7.0	74.2±10.4	72.4±8.1	126.0±15.2

n=3 per model of taxi

Table 17. Mean concentrations of formaldehyde in four different model of taxis, before and after refuelling with different fuels

Vehicle model	**Age**	**Mean ± SD conc. (µg/m^3) LPG before fuelling**	**Mean ± SD conc. (µg/m^3) LPG after fuelling**	**Mean ± SD conc. (µg/m^3) CNG before fuelling**	**Mean ± SD conc. (µg/m^3) CNG after fuelling**	**Mean ± SD conc. (µg/m^3) Gasoline before fuelling**	**Mean ± SD conc. (µg/m^3) Gasoline after fuelling**
Model 1	<1	344±44	621±64	500±54	762±68	457±55	481±53
Model 1	1-5	612±89	1173±111	732±79	1193±143	1011±147	1231±158
Model 1	>5	790±92	861±74	1150±130	1272±119	1272±119	1541±231
Model 2	<1	548±66	626±50	562±78	705±105	661±88	986.8±97
Model 2	1-5	828±11	929±106	887±79	954±140	1174±95	1378±138
Model 2	>5	205±31	651.8±55	295±28	711±96	1134±158	1280±173
Model 3	<1	616±83	1158±118	682±78	1164±166	1006±90	1209±189
Model 3	1-5	1190±159	1145±164	1220±106	1228±180	1017±103	1368±144
Model 3	>5	1085±131	1313±145	1155±156	1393±180	1215±142	1435±141
Model 4	>5	746±65	891±121	852±112	927±126	1006±89	1184±117

n=3 per model of taxi

Table 18. Mean concentrations of acetaldehyde in four different model of taxis, before and after refuelling with different fuels

Vehicle model	**Age**	**Mean ± SD conc. (µg/m^3) LPG before fuelling**	**Mean ± SD conc. (µg/m^3) LPG after fuelling**	**Mean ± SD conc. (µg/m^3) CNG before fuelling**	**Mean ± SD conc. (µg/m^3) CNG after fuelling**	**Mean ± SD conc. (µg/m^3) Gasoline before fuelling**	**Mean ± SD conc. (µg/m^3) Gasoline after fuelling**
Model 1	<1	217±26	288±42	220±28	310±33	250±33	234±35
Model 1	1-5	188±18	253±29	228±28	363±53	567±77	700.6±79
Model 1	>5	269±26	354±29	628±56	728±77	728±76	851±08
Model 2	<1	301±37	416±42	329±38	430±45	367±48	450±55
Model 2	1-5	562±47	740±94	573±48	752±112	662±70	762±69
Model 2	>5	45±5	125±13	49±5.9	139±16	545±77	689±84
Model 3	<1	175±21	248±32	216±26	284±24	567±62	701±103
Model 3	1-5	236±24	318±42	246±29	325±43	294±43	35±31
Model 3	>5	545±59	662±53	615±53	698±62	695±87	790±105
Model 4	>5	361±37	507±72	425±54	525±43	477±60	596±82

n=3 per model of taxi

56. Overall, authors concluded that model of taxi and age of the vehicle can impact on the concentrations of formaldehyde and acetaldehyde but not BTEX measured in the cabin. Refuelling with CNG and LPG can increase all VOCs measured, which is attributed to the outdoor air pollution impacting the in-vehicle air concentrations. In-cabin concentrations of BTEX are also influenced by vehicle characteristics such as age, maintenance, fuel, air intake location and ventilation.

Kim et al. (2016)

57. Kim et al. (2016) measured 24 VOCs in a closed-cabin environment in three cars (compact, mid- and large sized of the same brand) under multiple ventilation and engine scenarios in 2016. Three different idling modes were used (engine and ventilation, exterior air ventilation with engine idling and internal air recirculation with engine idling).

58. All vehicles were parked in an open-air carpark surrounded by buildings, small trees and a hill. All cars were parked for 3 hours with the engine off before sampling was carried out. Sampling was carried out with all windows closed and the air conditioning off. Twelve samples were collected by pulling air samples through a DNPH cartridge for 6 minutes using a vacuum pump. VOCs were collected using a 3-bed sorbent tube, which, after sampling was analysed within 6 hours. Quantitative analysis was carried out using High performance liquid chromatography-ultraviolet (HPLC/UV) and gas chromatography/mass spectrometry (GC/MS).

59. Of the 24 VOCs measured, 17 were detected in most cabin air samples (6 aromatic hydrocarbons, 2 ketones, 4 volatile fatty acids, 1 alcohol, and 1 ester) while 7 compounds were below the detection limit (e.g., propionic acid, n-butyric acid, i-valeric acid) in all samples (Table 19). No data for sVOCs were presented.

60. Authors noted some trends in the data. Benzene levels in large sedan cars with the engine on were higher and increased more abruptly during engine idling compared with compact and midsized cars. In contrast, most other aromatic VOCs (toluene, styrene, m-xylene, p-xylene, and o-xylene)

increased smoothly above ambient exterior air. In the case of carbonyl compounds, acetaldehyde showed the highest concentration in the compact car and butyraldehyde and formaldehyde in the mid-size sedan.

61. Methyl ethyl ketone, acetone and butyl acetate, were highest in the mid-size sedan, while methyl isobutyl ketone was the highest in the large sedan. All the compounds (except toluene and methyl ethyl ketone) showed an increase in concentration with engine on with either exterior or interior ventilation (scenario 2 and 3, respectively) suggesting an influence of the engine activity.

62. Authors concluded that except for toluene, the exterior air VOC concentrations were temporally stable. In contrast, the cabin concentrations of three VOCs (acetaldehyde, acetone, and formaldehyde) were significantly higher in the vehicles compared with ambient exterior air irrespective of engine and ventilation settings. In general, cabin VOC concentrations (particularly for acetaldehyde, acetone, and formaldehyde) increased as the temperature difference between the car interior and exterior ambient air became larger, irrespective of car size.

Table 19. Concentrations of VOCs in compact, mid and large cars

VOC	**Conc. (µg/m^3) Compact Scenario 0**	**Conc. (µg/m^3) Compact Scenario 1**	**Conc. (µg/m^3) Compact Scenario 2**	**Conc. (µg/m^3) Compact Scenario 3**	**Conc. (µg/m^3) Mid Scenario 0**	**Conc. (µg/m^3) Mid Scenario 1**	**Conc. (µg/m^3) Mid Scenario 2**	**Conc. (µg/m^3) Mid Scenario 3**	**Conc. (µg/m^3) Large Scenario 0**	**Conc. (µg/m^3) Large Scenario 1**	**Conc. (µg/m^3) Large Scenario 2**	**Conc. (µg/m^3) Large Scenario 3**
Benzene	1.06	1.43	2.42	2.17	1.21	1.70	2.19	2.89	0.75	1.30	6.03	5.58
Toluene	4.77	7.00	7.46	7.59	13.3	15.0	14.1	13.6	17.1	14.8	11.7	14.2
m-Xylene	1.23	3.59	3.95	4.93	1.54	3.64	4.29	6.89	1.65	3.48	3.92	5.52
P-Xylene	0.42	2.29	2.66	4.56	0.58	2.44	2.83	4.88	0.582	1.41	1.42	2.46
o-Xylene	0.37	1.41	1.72	2.72	0.51	1.61	1.95	2.63	0.47	1.31	1.43	2.16
Styrene	0.05	0.20	0.15	0.24	0.10	0.37	0.40	0.44	0.0069	0.36	0.3	0.48
Acetaldehyde	3.41	11.0	11.6	14.0	2.11	4.41	6.56	7.70	2.39	7.91	7.91	8.26
Propionaldeyde	0.81	1.29	1.51	2.38	0.07	1.53	2.61	4.00	0.07	1.58	2.09	2.94
Butyraldehyde	0.07	0.07	0.07	0.07	1.82	2.32	2.73	3.17	0.94	174	1.66	1.6
n-Valeraldehyde	0.1	0.10	0.10	0.01	0.10	0.10	0.10	4.86	0.10	0.10	0.10	0.10
Formaldehyde	10.6	19.7	21.3	27.2	9.25	17.1	20.8	38.2	7.03	20.5	18.7	18.7
Crotonaldehyde	3.66	10.6	10.3	10.5	4.83	10.3	11.0	15.9	3.54	6.45	5.31	5.31

VOC	**Conc. (µg/m^3) Compact Scenario 0**	**Conc. (µg/m^3) Compact Scenario 1**	**Conc. (µg/m^3) Compact Scenario 2**	**Conc. (µg/m^3) Compact Scenario 3**	**Conc. (µg/m^3) Mid Scenario 0**	**Conc. (µg/m^3) Mid Scenario 1**	**Conc. (µg/m^3) Mid Scenario 2**	**Conc. (µg/m^3) Mid Scenario 3**	**Conc. (µg/m^3) Large Scenario 0**	**Conc. (µg/m^3) Large Scenario 1**	**Conc. (µg/m^3) Large Scenario 2**	**Conc. (µg/m^3) Large Scenario 3**
Methyl ethyl ketone	0.29	0.057	0.49	0.51	0.51	0.74	13.35	2.09	0.34	0.41	0.18	0.18
Methyl isobutyl ketone	0.06	1.09	1.52	1.4	0.25	0.44	0.36	0.41	0.13	2.17	2.27	2.27
n-Valeric acid	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.09	0.11	0.04	0.04
Isobutyl alcohol	0.004	0.004	0.004	0.004	0.004	0.004	0.32	0.57	0.005	0.005	0.04	0.04
Butyl acetate	0.10	0.34	0.28	0.54	0.15	0.64	0.55	0.78	0.28	0.36	0.33	0.33

Scenario 0. Background air (outside the vehicle)
Scenario 1. cold engine off and cabin ventilation off for 20 min.
Scenario 2. warm engine idling with exterior air cabin ventilation for 20 min
Scenario 3. warm engine idling with internal in-cabin air circulation for 20 min
n=1 per model of car

Chen et al. (2014a)

63. Chen et al. (2014a) measured VOCs in 38 taxis used in Changsha City, China. All taxis had non-leather interior, used air conditioning and gasoline fuel. Taxis were classified according to sampling site (university campus, train station, bus station, near prosecuting building), interior volume (small (<10 m^3) or large (10-20 m^3) cabin) or purchase price and exhaust volume (low-grade or mid-grade).

64. Taxis were sampled under static and closed conditions i.e. engine was off, and all windows and door were closed. Samples of interior and outdoor air of taxi were collected in the centre of the taxi, 0.6 m above the floor in Tenax tubes for 40 minutes using flow rate of 0.5-L/min. VOCs were quantified using GC-FID. Sampling was carried out from May to June 2009. No smoking was allowed in any taxi.

65. Under static and closed conditions, the airborne VOCs pollution concentrations in tested taxis are summarized in Table 20. No data for sVOCs were presented.

Table 20. Mean, minumum and maximum concentrations of VOCs commonly measured in taxis

VOC	**Mean conc. (µg/m^3)**	**SD (µg/m^3)**	**Min conc. (µg/m^3)**	**Max conc. (µg/m^3)**
Benzene	82.7	22.9	33.5	128.7
Toluene	212.3	58.3	84.7	320.2
Ethylbenzene	74.7	209	31.2	115.9
Xylenes	182.3	21.2	73.6	283.9
m- and p-xylene	116.0	32.4	46.9	180.3
o- Xylene	66.3	188	26.7	103.6
Styrene	24.7	7.4	9.7	39.5
Butyl acetate	33.5	9.5	12.4	52.3
Undecane	1.3	11.8	35.3	3.6
Total	1441.7	413.7	570.9	2253.5

n=38 taxis

66. Authors noted that the mean mass concentrations of in-car benzene, toluene, ethylbenzene, xylenes, p/m-xylenes, o-xylenes, styrene, and TVOC were 4.8, 6.3, 13.6, 8.6, 7.1, 13.5, 10.7, and 5.5 times more than those in outdoor air, respectively. Differences in concentrations of VOCs may be due to differences in the vehicle tested, sampling sites, location or period, exhaust leakage, indoor material emissions, photochemical formation, atmospheric environment, transportation modes, vehicle fuel composition, and catalysers of exhaust air (Ongwandee and Chavalparit 2010 and Pang and Mu 2007 cited in Chen et al. (2014a)).

67. Authors concluded that in-car VOCs and TVOC pollution concentrations are influenced by factors including vehicular age, interior temperature, relative humidity, grade of vehicle, sampling sites, interior volume and total mileage, with car age followed by in-cabin temperature and total mileage being the most important factors influencing airborne VOC concentration.

68. Toluene was the highest VOC measured, thought to be due to its use in solvents in paints and surface coatings in vehicle trims (Zhang et al. 2008 and Yuan et al. 2010 cited in Chen et al. (2014a)), interior trims (Hsu and Huang 2009 cited in Chen et al. (2014a)), and air freshener (Wang et al. 2009a cited in Chen et al. (2014a)) and from vehicle exhaust (Okada et al. 2012 cited in Chen et al. (2014a)).

69. Temperature impacted the levels of VOCs measured, with concentrations increasing with increasing in-car temperatures as high temperatures can enhance the evaporation of VOCs from interior materials, although authors noted other studies reported a decrease in VOC concentrations in buses in Spain with elevated temperature due to photochemical degradation of VOCs through increased solar radiation(Parra et al., 2008 cited in Chen et al. (2014a)). An increase in humidity also caused an increase in VOC concentrations.

70. The location of the sampling site i.e. the external environment of the vehicle also influenced the concentration of VOCs. Lower VOCs were

detected in rural locations with less traffic compared to more urban environments.

71. Grade and age of vehicle also contributed to the concentration of VOCs measured, with concentrations in mid-grade taxis generally being lower than low-grade vehicles due to types and differences of interior materials with older vehicles generally having lower VOCs compared to newer ones. In addition, decreasing trends of VOCs and TVOC concentrations were noted with an increase in total mileage, which correlated with the influence of vehicle age.

72. An increase in the interior bulk of vehicles led to a decreasing trend of in-car VOCs and TVOC although only minimally.

73. Authors concluded that in-car VOCS and TVOC pollution concentrations are affected by vehicular age, interior temperature, relative humidity, vehicular quality, sampling sites, interior bulk, and total mileage, with the greatest influencing factor of in-car VOCs and TVOC concentrations being vehicular age, followed by interior temperature and total mileage.

Faber and Brodzik (2017)

74. Faber and Brodzik (2017) investigated the vehicle interior air quality, focussing on VOCs, by compiling published data from new and older cars in various conditions and locations.

75. Air samples were collected under static conditions i.e. the engine was not running and all doors and windows were closed and in most cases, the cars were conditioned at specific temperatures before sampling to ensure homogeneous distribution of organic compounds in the vehicle compartment.

76. Vehicles of less than three years of age were considered to be new and those more than three years were considered to be older. VOCs detected are presented in Table 21. No data for sVOCs were presented.

77. Differences in concentrations are a result of differences in vehicle model, cabin height and volume, temperature, smoking, being stationary or

driving, driving speed, driving length, meteorological parameters, seasons, type of fuel and external air pollution.

Table 21. Minimum and maximum concentrations of VOCs in newer and used cars

VOC	**Min conc. (μg/m^3) Newer cars**	**Max conc. (μg/m^3) Newer cars**	**Min conc. (μg/m^3) Used cars**	**Max conc. (μg/m^3) Used cars**
1,2,4-TMB	8.3	170	15.6	47
1-Butanol	23	58	-	-
1-Hexadecene	767.8	-	-	-
1-Nonanal	5.9	-	-	-
2,2,4,6,6-Pentamethyl-heptane	218	-	-	-
2,4-Dimethylheptane	20	-	-	-
2,4-Dimethylheptane	97	-	-	-
2-Ethylhexane acid	83	-	-	-
2-Methyldecane	375	-	-	-
2-Methylnonane	227	-	-	-
2-Methylpentane	15	36	-	-
3-Ethyltoluene	5.5	-	-	-
3-Methylnonane	68	-	-	-
5-Methyldecane	271	-	-	-
a-Pinene	200	-	-	-
Acetaldehyde	-	-	12.47	73.8
Acetone	-	-	250	-
Acrolein	-	-	20.65	-
Benzene	48	270	1.14	250
Butyl acetate	225	-	-	-
Butane	-	-	54.3	-
Butyraldehyde	-	-	24.13	-
Cyclohexanone	301	-	-	-

VOC	**Min conc. (µg/m^3) Newer cars**	**Max conc. (µg/m^3) Newer cars**	**Min conc. (µg/m^3) Used cars**	**Max conc. (µg/m^3) Used cars**
Decane	16	1300.6	-	-
Dodecane	44.5	928.9	-	-
e-caprolaktam	96	-	-	-
Ethyl acetate	5.7	-	-	-
Ethylbenzene	72	85	0.9	69.4
Ethylhexanol	-	-	56.2	-
Ethyltoluene	-	-	0.4	-
Formaldehyde	80	-	16.43	49
Heptane	28	150	13.6	-
Hexane	23	65	-	-
Isopentane	-	-	68.7	-
Limonene	35.4	38.8	-	-
m- and p-Xylene	9.7	3104.4	4.5	127.2
Methylcyclohexane	-	-	91.7	-
Methylcyclopentane	7.9	-	-	-
Methylisobutyl ketone	34	-	-	-
Methylpyrrolidinone	425.1	-	93	-
Naphthalene	-	-	5	-
Nonane	341	-	-	-
o-Xylene	21	1400	4.5	54.6
Pentane	-	-	-	-
Phenol	194	-	30.8	-
Propionaldehyde	-	-	13.5	-
Styrene	94	1500	1.15	6.78
Tetrachloroethylene	242	-	-	-
tetradecane	26	-	-	-
Toluene	5.5	2000	10.4	770

VOC	**Min conc. (µg/m^3) Newer cars**	**Max conc. (µg/m^3) Newer cars**	**Min conc. (µg/m^3) Used cars**	**Max conc. (µg/m^3) Used cars**
Tridecane	29	687.1	-	-
Undecane	18.4	1615	-	-

n=various

78. Emission of VOCs into the vehicle cabin air is largely due to plastics such as polystyrene, polyethylene, polypropylene, polyamide, polyester, polyacetal, and acrylonitrile-butadiene-styrene, followed by rubber, natural or artificial leather, textiles, fibres, polyurethane foams, coatings and adhesives. The concentration of VOCs emitted from materials depends on several factors including air temperature and relative humidity inside the vehicle, air exchange rate, type of material and age of vehicle. Levels of VOCs are also higher in static vehicles compared with those under normal operating conditions.

79. Authors noted that in many studies, the concentrations of VOCs varied significantly in newer vehicles and suggested that such differences were probably due to differences in the vehicles age and differences in materials used. In older vehicles, studies focussed on VOCs from vehicle exhaust gases such as BTEX, which are emitted during fuel combustion in engines or during refuelling and can penetrate the interior of the cabin due to natural circulation of air or suction through the ventilation system. This increase is counterbalanced by a decrease in emissions from interior materials.

80. The authors concluded that the use of synthetic materials in vehicle interiors lead to higher concentrations of VOCs being detected in new vehicles, which decrease with time due to decreased emission from materials. The concentrations of VOCs in new vehicles varied significantly, depending mainly on vehicle age and the type and materials used in a vehicle interior. The vehicle cabin may also contain VOCs originating from fuel combustion.

Brodzik et al. (2014)

81. VOCs were measured in nine unconditioned, newly produced cars of the same brand and model (Brodzik et al. 2014). Four vehicles had identical interiors whereas five differed in terms of upholstery, presence of a sunroof or being convertible.

82. The sampling event took place outside of the car assembly plant and the cars tested left the assembly line no later than 24 hr before the sampling took place. Sampling systems were placed inside the car's cabin with sorbent tubes placed approximately 15 cm from the steering wheel and approximately 50 cm above the driver seat, at dashboard level. Sampling lasted for 20 minutes; total sampling volumes were 2000 mL for both kinds of sorbents. The VOCs composition of in-vehicle air was analysed by active sampling on Carbograph 1TD and Tenax TA sorbents, followed by thermal desorption- gas chromatography and simultaneous analysis on flame ionization and mass spectrometry (TD-GC/FID-MS) within one week. The VOCs detected are presented in Table 22. No data for sVOCs were presented.

Table 22. Minimum and maximum concentrations of VOCs commonly measured in newly manufactured cars

VOC	**Min conc. (µg/m^3)**	**Max conc. (µg/m^3)**
2-Methylpentane	3.2	3.6
3-Methylpentane	2.2	14.9
Hexane	1.7	13.9
2,2-Dimethylpentane	18.7*	-
3,3-Dimethylpentane	1.3	16.0
2-Methylhexane	1.8	283.7
2,3-Dimethylpentane	1.5	96.4
3-Methylhexane	5.0	421.8
3-Ethylpentane	2.1	35.5
Heptane	9.1	670.1
2,4-Dimethylhexane	1.3	35.6

VOC	**Min conc. (µg/m^3)**	**Max conc. (µg/m^3)**
2,3-Dimethylhexane	1.2	7.4
2-Methylheptane	1.0	167.3
4-Methylheptane	57.0*	-
3-Methylheptane	141.7*	-
Octane	2.0	109.0
2,5-Dimethylheptane	2.7	6.4
2,3-Dimethylheptane	1.6	5.2
3,4-Dimethylheptane	1.2	1.9
2-Methyloctane	1.9	11.9
3-Methyloctane	1.2	15.8
2,2-Dimethyloctane	1.1*	-
3,3-Dimethyloctane	1.5	5.1
2,3-Dimethyloctane	1.6	5.2
2-Methylnonane	2.9	19.4
Decane	16.8	84.9
Undecane	60.6	272.3
Dodecane	40.0	76.2
Tridecane	6.3	12.6
Tetradecane	1.4	10.3
Pentadecane	1.9	3.2
Methylcyclopentane	3.1	14.1
Cyclohexane	2.7	53.6
1,1-Dimethylcyclopentane	3.2	6.6
cis-1,3-Dimethylcyclopentane	1.4	80.9
trans-1,3-Dimethylcyclopentane	2.1	69.5
trans-1,2-Dimethylcyclopentane	3.6	116.6
Methylcyclohexane	4.0	686.5
Ethylcyclopentane	12.3	171.7
ctc-1,2,4-Trimethylcyclopentane	1.2	43.3
ctc-1,2,3-Trimethylcyclopentane	1.5	52.7

VOC	**Min conc. (µg/m^3)**	**Max conc. (µg/m^3)**
ctt-1,2,4-Trimethylcyclopentane	13.6*	
trans-1,4-Dimethylcyclohexane	2.1	40.9
trans-1,2-Dimethylcyclohexane	2.2	20.8
Propylcyclopentane	0.7	2.2
cis-1,2-Dimethylcyclohexane	1.1	6.4
ccc-1,3,5-Trimethylcyclohexane	1.4	4.7
ctc-1,2,4-Trimethylcyclohexane	1.5	12.6
ctt-1,2,4-Trimethylcyclohexane	0.9	6.3
1,1,2-Trimethylcyclohexane	1.1	13.4
Butylcyclopentane	3.3	26.9
Isobutylcyclohexane	4.3	19.1
1-Methyl-2-propylcyclohexane	3.1	16.8
Benzene	6.3	12.8
Toluene	19.4	315.1
Ethylbenzene	7.5	72.4
m-Xylene	18.9	218.7
p-Xylene	7.4	78.4
o-Xylene	12.9	130.5
Isopropylbenzene	1.0	10.1
1-Propylbenzene	2.9	16.5
1-Ethyl-3-methylbenzene	4.5	27.1
1-Ethyl-4-methylbenzene	12.4	37.4
1,3,5-Trimethylbenzene	1.4	9.6
1-Ethyl-2-methylbenzene	2.2	11.4
1,2,4-Trimethylbenzene	4.6	17.3
1,2,3-Trimethylbenzene	2.9	59.6
2-Ethyl-1,4-dimethylbenzene	1.8	8.4
2-Methyl-1-phenylbutane	4.1	14.4
Naphthalene	6.0	10.6
2-Butanone	2.4	10.6

VOC	**Min conc. ($\mu g/m^3$)**	**Max conc. ($\mu g/m^3$)**
Ethyl acetate	1.8	28
1-Butanol	2.5	18.4
2-Ethoxy ethanol	1.1	2.5
1,2-Propanediol	2.3	13.5
Butyl acetate	2.5	19.6
Cyclohexanone	1.3	6.2
α-Pinene	1.6	4.2
Phenol	3.5	10.0
2-Ethyl-1-hexanol	13.6	58.4
Acetophenone	5.0	36.2
Other alcohols	10.3	51.8

n=9; *only measured in one vehicle

83. Authors noted some differences between vehicles, largely due to differences in interior equipment and presence of a sunroof which caused an increase in VOCs due to off-gassing, especially as the presence of a sunroof necessitates additional sealing materials and adhesives which contribute to off-gassing.

84. It was concluded that in all cases aliphatic hydrocarbons, both alkanes and cycloalkanes, were the dominant group of VOCs in collected air samples.

Moreno et al. (2019).

85. Vehicle interior air quality was investigated inside 14 diesel/non-diesel taxis operating simultaneously and under normal working conditions over six weekday hours (10.00–16.00) in Barcelona, Spain (Moreno et al. 2019). On each day, two taxis, one diesel and one non-diesel (gasoline-hybrid, LPG, CNG or electric) carried the same monitoring equipment. Both taxis started their journeys at the same place, drove for six hours and returned to the same location. Mileage was noted as well as use of air fresheners or air conditioning or whether windows were open or closed. The number of passengers was not

recorded. Data were collected over four weeks and were de-seasonalised to remove temporal fluctuations to allow comparison between taxis.

86. VOCs were collected using stainless steel cartridges custom packed with three successive sections of activated graphitised adsorbents. For active sampling, the cartridges were coupled to a low-flow pump with constant flow at 20 ml/min for 6 hours. The VOCs were analysed using GC/MS coupled with thermal desorption.

87. Out of a total of 99 VOCs investigated, 47 were detected and quantified (Table 23). No data for sVOCs were presented in the paper.

Table 23. Mean, minimum and maximum concentrations of VOCs commonly measured in cars using different fuels

VOC	**Mean conc. (µg/m^3) LPG**	**Mean conc. (µg/m^3) Diesel**	**Mean conc. (µg/m^3) Hybrid**	**Mean conc. (µg/m^3) Electric**	**Mean conc. (µg/m^3) CNG**
n-Pentane	21	20	18	17	28
n-Heptane	5.9	4.9	2.9	6.	7.5
n-Hexane	5.0	4.8	3.8	5.6	5.4
n-Octane	3.1	2.6	2.1	2.3	3.4
n-Decane	5.1	0.8	0.6	1.0	1.7
2-Methylbutane	53	50	47	43	60
2,3-Dimethylpentane	2.2	2.0	1.6	2.3	2.4
Isooctane	0.3	0.7	0.5	2.2	1.3
Cyclohexane	2.2	2.1	1.6	2.6	3.2
Isoprene	11	4.1	2.0	31	5.7
1-Pentene	1.2	1.1	0.8	1.0	1.5
cis-Pentene	1.2	1.0	0.9	1.0	1.7
trans− 2-Pentene	3.5	2.9	2.2	2.9	5.1
Benzene	8.6	6.8	6.8	5.3	10
Toluene	51	39	37	40	56
Ethylbenzene	10	8.0	6.5	7.1	11

VOC	**Mean conc. (µg/m^3) LPG**	**Mean conc. (µg/m^3) Diesel**	**Mean conc. (µg/m^3) Hybrid**	**Mean conc. (µg/m^3) Electric**	**Mean conc. (µg/m^3) CNG**
m-Xylene	26	20	17	18	26
p-Xylene	9.9	7.8	6.5	6.8	11
o-Xylene	13	10	8.5	8.6	13
1,2,4-Trimethylbenzene	11	8.7	6.4	7.7	10
1,3,5-Trimethylbenzene	2.3	1.8	1.4	1.7	2.2
n-Propylbenzene	1.1	0.9	0.7	0.9	102
Styrene	1.0	0.7	0.8	0.5	1.0
Isopropylbenzene	0.4	0.3	0.3	0.3	0.4
n-Butylbenzene	0.3	0.2	0.2	<0.1	0.3
sec-Butylbenzene	0.1	0.1	0.1	<0.1	0.1
d-Limonene	4.5	0.8	0.9	30	4.4
Camphene	0.6	<0.1	<0.1	0.1	0.1
α-Pinene	0.4	0.2	0.3	1.8	0.6
(-)-β-Pinene/β-Myrcene	0.5	0.1	0.1	1.8	0.2
p-Cymene	0.6	0.2	0.2	0.6	0.4
δ-Terpinene	0.3	<0.1	<0.1	0.4	0.1
β-Ocimene	0.4	0.1	0.1	1.2	0.1
α-Ocimene	0.2	<0.1	0.1	0.6	<0.1
γ-Terpinene	0.1	<0.1	<0.1	1.3	0.1
δ3-Carene	0.1	0.1	0.1	0.2	0.1
Tetrachloroethylene	0.8	0.8	0.9	0.5	2.3
1,2,2-Trichlorotrifluoroethane	0.7	0.7	0.7	0.6	0.8
Carbon Tetrachloride	0.6	0.69	0.6	0.6	0.6
Chloroform	0.4	0.2	0.4	0.1	0.3
1,2-Dichloroethane	0.2	0.2	0.2	0.5	0.2

VOC	**Mean conc. (µg/m^3) LPG**	**Mean conc. (µg/m^3) Diesel**	**Mean conc. (µg/m^3) Hybrid**	**Mean conc. (µg/m^3) Electric**	**Mean conc. (µg/m^3) CNG**
Trichloroethylene	0.1	<0.1	0.1	0.1	0.2
1,4-Dichlorbenzene	<0.1	0.06	<0.1	<0.1	0.1
Methyl methacrylate	0.2	0.2	0.3	0.5	0.5
Tetrahydrofuran	0.2	0.2	0.2	0.3	0.5
Diethyl ether	0.1	0.1	0.1	3.9	0.1

N=14

88. The most abundant VOC was toluene as well as 2-methylbutane, pentane, m-xylene, o-xylene, 1,2,4-trimethylbenzene, ethylbenzene, p-xylene, benzene, and 1,3,5-trimethylbenzene, all of which are products of hydrocarbon fuel emissions. As four out of five taxis were driven with the windows open, this would account for such levels. The electric car was driven with the windows closed and showed very low concentrations of pentane and 2-methylbutane associated with hydrocarbon fuel emissions.

89. Authors concluded that the presence of 2-methylbutane and pentane comprised over half of the VOCs measured, thereby implicating the strong presence of light-hydrocarbon fuel emissions (gasoline, natural gas), and that such VOCs infiltrate the taxi from outside, from diesel vehicles. VOCs originating from the vehicle interior were also present, and the use of air freshers also contributed to the VOCs detected.

You et al. (2007)

90. You et al. (2007) measured VOCs in one new vehicle (vehicle A) and two old vehicles (vehicle B and C) under static conditions.

91. Vehicle A and B were same model, but vehicle A was a new car and vehicle B had been used for no more than one year. Vehicle C was another model, which had been used for approximately five years. All vehicles were well maintained and in good operating condition.

92. Prior to sampling the vehicle was moved to the environment test chamber and the chamber door was closed. The same chamber parameters were used for all vehicles throughout the testing period, including temperature, humidity, airflow velocity etc. The vehicle doors and windows were left open for 8 hours and the chamber left closed for 16 hours so the car could reach a steady state. In vehicle air samples were collected from the middle of the two headrests, 20 cm away from the roof. Samples were taken via active sampling, using controlled flow pumps at a rate of 100 ml/min for 30 minutes. Air was drawn through stainless steel Tenax TA tubes. TD-CG/MS was used for analysis of the VOCs.

93. The VOCs measured inside each of the three cars are presented in Table 24 and the top 20 VOCs measured in each vehicle presented in Table 25. No data for sVOCs were presented in the paper.

Table 24. Concentrations of VOCs measured in a new, 1-year old and 5-year old car

VOC	**Conc. (µg/m^3) Car A (new)**	**Conc. (µg/m^3) Car B (1 yr)**	**Conc. (µg/m^3) Car C (5 yr)**
Benzene	48	10	2.4
Toluene	82	50	32.2
Ethyl benzene	85	909	3.5
m- and p-Xylene	346	20	10.2
o-Xylene	95	9.9	3.3
Styrene	155	9.8	2.3
Undecane	40	130	9.3
Butyl acetate	225	0	2.3

n=1 per model of car

Table 25. Concentrations of top 20 VOCs measured in a new, 1-year old and 5-year old car

VOC in car A	**Mean conc. (µg/m^3) Car A**	**VOC in car B**	**Mean conc. (µg/m^3) Car B**	**VOC in car C**	**Mean conc. (µg/m^3) Car C**
Decane	345	Dodecane	163.4	Toluene	32.2
Nonane	341	Undecane	130.0	d-Limonene	14.4
5-Isopropyl-2-methyl-bicyclo[3.1.0]hexan-2-ol	314	Decane	89.3	Butylated hydroxytoluene	14.1
Cyclohexanone	301	1-Chloro-2-dodecyl-oxyethane	81.8	m- and p-Xylene	10.2
Tetrachloroethylene	242	Tetradecane	77.8	Undecane	9.3
α-Pinene	200	5-Ethyl-2-methyloctane	52.6	Decane	8.1
3-Methylhexane	199	2,4-Dimethyl-1-decene	52.1	Dodecane	6.4
Heptane	188	Toluene	50.0	Bicyclo[3.1.1]hept-2-ene	4.2
3-Methylheptane	170	Naphthalene	49.3	5-Propyldodecane	4.1
2-Methylheptane	134	Tetramethyl succinonitrile	40.1	2-Methyltridecane	4.0
Octane	127	trans-Bicyclo[4.4.0]Decane	35.5	Ethylbenzene	3.5
Methylcyclohexane	122	1-Chloroundecane	22.7	o-Xylene	3.3

VOC in car A	**Mean conc. (μg/m^3) Car A**	**VOC in car B**	**Mean conc. (μg/m^3) Car B**	**VOC in car C**	**Mean conc. (μg/m^3) Car C**
2,7-Dimethyloctane	112	2,6-di-tert-butyl-p-Cresol	20.5	1,3,5-Trimethylbenzene	3.1
3-Methylnonane	107	m- and p-Xylene	20.0	Benzene	2.4
2-Methylhexane	105	Nonane	18.3	Butyl acetate	2.3
4-Methyloctane	96	Hexanal	15.7	Styrene	2.3
2,5-Dimethyl-2-undecene	90	2,6-dimethyl-2-Octene	15.1	2,4-Dimethylpentane	2.1
2,5-Dimethyloctane	86	2.2-dimethyl-Propanal	13.2	Nonane	2.0
Toluene	82	1,2-Dichloro-ethane	11.8	2-Bromooctane	1.9
Cyclohexane	70	Benzene	10.0	2-Methylhexane	1.2
TVOC	4940	TVOC	1240.0	TVOC	132.0

n=1 per model of car

94. Vehicle age affected VOCs concentrations, with concentrations decreasing with age as vehicle B had less VOCs compared with vehicle A, a car of the same make but a newer model, and both had higher VOCs compared to the five-year old car C. Authors noted the decrease is due to ventilation following delivery of the vehicle. The vehicle model also influences VOC concentrations as does temperature.

Buses

Gastelum-Arellanez et al. (2021)

95. Gastelum-Arellanez et al. (2021) measured VOCs inside public buses used on the three major bus lines in Leon Guanajuato, Mexico. Sampling was performed in the centre of each bus at approximately 1.5 m using personal equipment with an air pump which passed air into a stainless steel Tenax TA tubes, using a constant flow rate of 200 ml/min. All monitoring was carried out in winter.

96. All three routes (L1, L2 and L8) were sampled simultaneously for 13 non-consecutive days from January 16 to February 2019. Two simultaneous samples were taken per trip as well as a blank. Samples were analysed using TD-GC/MS.

97. Thirteen VOCs were detected in both samples on at least 75% of sampling days in the three bus routes (Table 26).

Table 26. Mean concentrations of VOCs in buses on three bus routes

VOC	**Mean conc. (µg/m^3) Route L1**	**SD (µg/m^3) Route L1**	**Mean conc. (µg/m^3) Route L2**	**SD (µg/m^3) Route L2**	**Mean conc. (µg/m^3) Route L3**	**SD (µg/m^3) Route L3**
Benzene	4.81	0.38	4.58	0.29	5.61	0.36
Toluene	39.46	4.36	44.36	3.03	83.18	40.07
Octane	3.55	0.37	3.28	0.11	3.20	0.26
Tetrachloroethene	0.72	0.22	1.17	0.11	1.43	0.41
Ethylbenzene	5.29	0.6	5.52	0.29	5.47	0.28
Xylene	28.00	2.89	18.07	1.73	28.09	1.52
Styrene	1.88	0.20	1.99	0.12	2.05	0.11
Hexane	13.71	1.75	16.21	1.02	23.45	4.45
Dichlorobenzene	11.33	1.53	8.29	1.25	6.81	1.01
Trimethylbenzene	4.86	0.71	5.49	0.31	3.70	0.44
Heptane	0.59	0.13	0.81	0.08	0.74	0.10
Butyl acetate	0.45	0.17	0.93	0.16	0.39	0.18
Chlorobenzene	0.28	0.09	0.53	0.07	0.26	0.09

n=13 days per route

98. Authors noted that there were no differences in VOCs measured in buses taking different routes except for dichloromethane and trimethylbenzene, which showed differences between L1 and L2, and L2 and L8, respectively. The main source of VOCs was the combustion of gasoline.

Chen et al. (2011)

99. Chen et al. (2011) measured the concentrations of BTEX in 22 public buses in Changsha, China. Six buses had leather interior and 16 had non-leather (fabric, plastic, wood, polyurethane) interior. Twelve of the 22 had air conditioning. Buses were categorised as high-grade (>7L), middle grade (6-7L) or low-grade (<6L), depending on their exhaust volume. The vehicle age, in-cabin temperature and humidity and travel distance were all noted.

100. The interior air was collected between May and June 2009. Prior to sampling buses were running a normal bus service. Two sampling points in the buses were equally distributed in the middle axes of the bus and samples were collected in the centre at 0.8 m from the floor using activated charcoal adsorption tubes and gas sampling equipment at 0.5 L/min flow for 40 minutes, during which the engine was stopped, and the windows, doors and vents were closed. The BTEX compounds were thermally desorbed and analysed using with GC-FID.

101. The concentration of BTEX measured in the 22 buses are presented in Table 27. No data for sVOCs were presented in the paper.

Table 27. Minumum and maximum concentrations of BTEX in buses

VOC	**Min conc. (µg/m^3)**	**Max conc. (µg/m^3)**
Benzene	21.3	106.4
Toluene	53.5	266.0
Ethyl benzene	19.6	95.9
Xylene	46.9	234.8

n=22 buses

102. Similar to other authors, Chen et al. (2011) noted the effect of temperature and humidity on BTEX concentrations as well as interior materials, age of vehicle and distance travelled. The presence of air conditioning also increased BTEX levels, due to better obturation, less natural ventilation and more air-conditioning pollution although authors noted that results differed to other studies that showed the use of air-conditioning generally decreased in-cabin VOC levels due to decreasing the temperature and emission potential or dilution.

103. The grade of vehicle also affected BTEX concentrations, with concentrations being lowest in low-grade vehicles and highest in the high-grade ones. Authors noted that exhaust volumes of high-grade buses were greater than those of low-grade buses, leading to the accumulation of interior BTEX, as vehicle exhaust was the major source of BTEX.

104. Overall, authors concluded that in-bus airborne BTEX concentrations changed with differences in car age, in-car temperature, relative humidity, interior decoration, air-conditioning, travel distance and car grade (exhaust volume). The change was explained partially by a combined effect of these factors. Among these factors, car age and in-car temperature were the two most important factors influencing BTEX concentrations in the interior air of buses.

Ongwandee and Chavalparit (2010)

105. Ongwandee and Chavalparit (2010) measured BTEX concentrations in public modes of transport in Bangkok, Thailand, including an air-conditioned bus and a non-air-conditioned bus. Both buses were manufactured in 1990 and used diesel fuel. The buses followed route A, B or C, all of which were between 8.3 and 9.4 km long and ran through major business and commercial areas. Air samples on all study routes were conducted during May, July, August 2007, and February 2008 to cover both seasonal monsoons. Routes were not simultaneously monitored due to limitation of equipment. However, each vehicle cruising on the same route was monitored in both morning and evening rush hours. In-bus sampling during these two rush-hour periods were conducted for both inbound and outbound routes.

106. In-vehicle air samples were collected using charcoal sorbent tubes placed 1 m from the floor within the breathing zone of commuters, placed in the middle front of the vehicle cabins to reduce the effect of bus doors. A personal sampling pump drew approximately 8-12L air at a flow rate of 0.2 L/min (duration not stated). Analysis was carried out using GC/MS.

107. Concentrations of BTEX detected in air-conditioned and non-air-conditioned buses are shown in Table 28 and Table 29. No data for sVOCs were presented in the paper.

Table 28. Mean concentrations of BTEX measured in air-conditioned buses in Thailand

VOC	**Mean conc. (µg/m^3) Bus route A**	**SD (µg/m^3) Bus route A**	**Mean conc. (µg/m^3) Bus route B**	**SD (µg/m^3) Bus route B**	**Mean conc. (µg/m^3) Bus route C**	**SD (µg/m^3) Bus route C**
Benzene	10.9	14.3	55.7	59.4	10.7	39.1
Toluene	84.6	13.6	503	690	139	71.5
Ethyl benzene	4.7	5.1	24.1	14.4	16.2	17.2
Xylene	28	14.1	7.0	27.2	45.2	39.8

n=1 bus per route. Multiple samples taken over time

Table 29. Mean concentrations of BTEX measured in non-air-conditioned buses inThailand

VOC	**Mean conc. (μg/m^3) Bus route A**	**SD (μg/m^3) Bus route A**	**Mean conc. (μg/m^3) Bus route B**	**SD (μg/m^3) Bus route B**	**Mean conc. (μg/m^3) Bus route C**	**SD (μg/m^3) Bus route C**
Benzene	24.7	24.2	82.9	64.6	63.2	75.9
Toluene	88.5	32.9	216	126	212	142
Ethyl benzene	9.9	9.2	24.6	18.9	22.2	10.3
Xylene	36.4	12.1	97.1	52.9	86	45.9

n=1 bus per route. Multiple samples taken over time

108. Authors noted that there was little difference in BTEX between routes apart from ethyl benzene, which was lower in route A, due to a lower traffic density compared with other routes. In addition, levels of benzene, ethyl benzene and xylene were generally higher in non-air-conditioned buses, but toluene was generally higher in air-conditioned vehicles.

109. It was concluded that there were statistical differences in toluene, ethyl benzene and xylene concentrations among the bus routes in the non-air-conditioned buses although this was based on the limited number of samples and large vehicle-to-vehicle variation.

Parra et al. (2008)

110. Parra et al. (2008) investigated VOCs in public buses in a medium sized metropolitan area of Pamplona, Spain. Four commonly used bus routes were investigated which represented commercial, residential, peripheral or heavily trafficked roads. Routes were between 3.14 and 8.70 km long. Sampling was performed between January 13th and February 15th, 2007. Each day, one of the routes was sampled twice during peak (7:45–9:15 h) and again twice in non-peak (10:45–12:15 h) hours, to obtain a weekly profile for all the routes.

111. The typical ventilation condition in buses in Pamplona during this season was low, with the windows closed and the heater on although ventilation in the bus's interior increased when the doors were opened at the stops.

112. Samples were collected in the central area of the bus at 1.5 m above the floor level. The sampler consisted of a personal sampling pump drawing air through proportioning valves to split the flow through two adsorbent tubes. Samples were collected at a flow rate of 100 ml/min in each tube. The sampled volume was different among routes as the travel time varied. These times were from 20 to 40 minutes.

113. Air samples were collected in Tenax TA tubes and analysed using TD-GC/MS.

114. The concentration of VOCs measured in buses taking different routes are shown in Table 30. Concentrations of benzene were different between the routes, although VOCs in route A were generally higher than other routes. This was due to route A having many stops in the city centre, allowing for higher infiltration of pollutants from the outside. Route A also ran through narrow streets which favour the accumulation of VOCs. In comparison, route D had stops in residential areas and allowed for a higher driving speed, which would increase air turbulence and therefore dispersion of pollutants.

115. Concentrations of VOCs were also generally higher in peak hours, with the exception of route C, compared with non-peak hours due to traffic volume (Table 31). Authors suggested that this was due to the short commuting times during non-peak times; lower traffic density allowing faster driving speeds. No data for sVOCs were presented in the paper.

116. Overall, it was concluded that in-vehicle concentrations of benzene differed between routes, its highest value corresponding with the route that had the highest prevalence in the commercial area of the city, leading to higher density of traffic, higher frequency of stops and lower driving speed. Significant differences were also seen between peak and non-peak hours.

Table 30. Mean, minimum and maxomum concentrations of VOCs in buses in Spain

VOC	**Mean conc. (μg/m^3) Route A**	**SD (μg/m^3) Route A**	**Min-max (μg/m^3) Route A**	**Mean conc. (μg/m^3) Route B**	**SD (μg/m^3) Route B**	**Min-max (μg/m^3) Route B**	**Mean conc. (μg/m^3) Route C**	**SD (μg/m^3) Route C**	**Min-max (μg/m^3) Route C**	**Mean conc. (μg/m^3) Route D**	**SD (μg/m^3) Route D**	**Min-max (μg/m^3) Route D**
Benzene	3.08	2.46	0.74-10.25	2.09	1.02	0.57-4.43	1.79	1.09	0.47-4.04	1.75	1.9	0.02-5.41
Toluene	8.20	6.80	0.44-31.29	7.66	3.65	2.21-16.80	6.60	3.81	1.62-14.46	6.074	3.65	1.61-13.62
Tetrachloroethylene	0.3	0.28	0.04-1.49	0.32	0.67	0.02-3.45	0.24	0.36	0.01-1.57	0.13	0.11	0.02-0.43
Ethylbenzene	1.3	1.01	0.34-4.89	1.12	0.49	0.20-2.10	1.13	0.80	0.26-3.21	1.05	0.63	0.25-2.19
m- and p-xylene	2.3	1.91	0.34-9.40	1.75	0.88	0.40-3.20	1.63	1.05	0.37-3.76	1.66	1.06	0.18-3.59
o-xylene	1.59	1.36	0.31-6.48	1.31	0.59	0.33-2.32	1.19	0.74	0.29-3.10	1.07	0.61	0.17-2.41
1,3,5-trimethylbenzene	1.00	109	0.27-4.87	1.05	2.18	0.36-11.48	0.59	0.53	0.15-2.96	0.68	0.60	0.01-2.34
1,3-dichlorobenzene	0.83	1.01	0.08-47.09	0.75	0.51	0.14-2.08	0.59	0.57	0.16-2.25	0.69	0.67	0.01-2.98
1,4-dichlorobenzene	0.85	1.15	0.01-5.41	0.74	0.44	0.14-1.70	0.59	0.56	0.13-2.14	0.68	063	0.02-2.81

VOC	Mean conc. (μg/m^3) Route A	SD (μg/m^3) Route A	Min-max (μg/m^3) Route A	Mean conc. (μg/m^3) Route B	SD (μg/m^3) Route B	Min-max (μg/m^3) Route B	Mean conc. (μg/m^3) Route C	SD (μg/m^3) Route C	Min-max (μg/m^3) Route C	Mean conc. (μg/m^3) Route D	SD (μg/m^3) Route D	Min-max (μg/m^3) Route D
1,2-dichlorobenzene	0.88	1.19	0.02-5.36	0.76	0.48	0.14-2.08	0.59	0.58	0.17-2.26	0.71	0.68	0.01-2.99

n=1 bus per route. Multiple samples taken over time

Table 31. Mean concentrations of VOCs in different bus routes during peak and non-peak hours

VOC	Mean conc. (μg/m^3) Peak Route A	Mean conc. (μg/m^3) Non-peak Route A	Mean conc. (μg/m^3) Peak Route B	Mean conc. (μg/m^3) Non-peak Route B	Mean conc. (μg/m^3) Peak Route C	Mean conc. (μg/m^3) Non-peak Route C	Mean conc. (μg/m^3) Peak Route D	Mean conc. (μg/m^3) Non-peak Route D
Benzene	4.11	2.11	2.37	1.84	2.06	1.52	2.27	1.22
Toluene	10.47	6.09	7.43	7.87	7.00	6.19	6.85	5.22
Tetrachloroethene	0.37	0.24	0.3	0.49	0.096	0.38	0.14	0.13
Ethylbenzene	1.67	0.96	1.30	0.96	1.21	1.05	1.16	0.93
m- and p-xylene	3.04	1.60	1.90	1.58	1.71	1.55	1.86	1.45
o-xylene	2.15	1.08	150	1.14	1.40	0.99	1.26	0.87
1,3,5-trimethylbenzene	1.67	0.86	1.57	0.57	0.73	0.45	0.69	0.67
1,3-dichlorobenzene	0.41	1.19	0.75	0.76	0.74	0.45	0.90	0.48
1,4-dichlorobenzene	0.41	1.23	0.75	0.73	0.75	0.45	0.87	0.49
1,2-dichlorobenzene	0.43	1.27	0.74	0.77	0.75	0.46	0.93	0.50

n=1 bus per route. Multiple samples taken over time

Metro

Gong et al. (2017) / Gong et al. (2019)

117. Gong studied VOCs in metro carriages used in five routes in Shanghai, China (Gong et al. 2017, Gong et al. 2019). The selected lines were used to investigate the effects of five factors on the concentrations of nine VOCs in metro carriages, including (1) different train models, (2) service years of the train, (3) number of passengers, (4) ground or underground tracks, (5) urban or suburban areas. The train model on Line 8 (model A) was 19.5 m in length, 2.6 m in width and 2.1 m in height. The ventilation supply airflow rate is 8000 m^3/h with 20% of the total circulated air replaced by fresh air outside of the train compartments. All other lines used model B, which is 22.1 m in length, 3 m in width and 2.1 m in height. The ventilation supply airflow rate is 10000 m^3/h with 32% of the total circulated air replaced by fresh air outside of the train compartments.

118. Air conditioning was used in all carriages. VOCs were measured in the presence of different numbers of passengers. Samples were collected between 8-10 am on sunny days from 28th March to 20th October 2015 (Gong et al. 2017) and 28th March to 20th October 2016 (Gong et al. 2019) in the middle of the train carriage. VOC samples were collected using 6-L Teflon bags, portable pumps and stainless steel Tenax TA tubes. Flow rates of the pump were set at 0.2 L/min for aromatic VOCs and 0.4 l/min for carbonyl compounds. Analysis of VOCs was carried out by TD-GC/MS or HPLC. Total VOC, CO_2, temperature, relative humidity, barometric pressure, sampling time, travelling routes and number of passengers were recorded.

119. In the first paper, comparisons of VOCs were made between different old and new models, underground and overground tracks and urban and suburban environments in 2015 (Table 32) (Gong et al. 2017). The second paper also made comparisons between old and new metros, summer and autumn and overground vs underground tracks in 2016 (Table 33) (Gong et al. 2019). No data for sVOCs were presented in the paper.

120. Authors noted that VOCs in new metro carriages was generally lower than those in old carriages. Authors suggested this was due to water-based paints being used in new trains compared to solvent-based paints used in older trains which emit more VOCs.

Table 32. Mean concentrations of VOCs in metros on different lines in China

VOC	**Mean ± SD conc. (μg/m^3) Line 1 Model B Old metro urban underground**	**Mean ± SD conc. (μg/m^3) Line 4 Model B New metro urban underground**	**Mean ± SD conc. (μg/m^3) Line 4 Model B New metro urban overground**	**Mean ± SD conc. (μg/m^3) Line 8 Model A New metro urban underground**	**Mean ± SD conc. (μg/m^3) Line 9 Model B New metro urban underground**	**Mean ± SD conc. (μg/m^3) Line 9 Model B New metro suburban underground**	**Mean ± SD conc. (μg/m^3) Line 10 Model B New metro urban underground**
Benzene	15.44±2.96	27.50±0.64	33.48±1.96	15.25±0.21	5.44±0.13	5.30±0.12	4.67±0.53
Toluene	12.06±1.50	49.72±4.5	62.47±1.47	11.49±0.56	9.09±1.13	7.06±0.78	5.22±0.36
Ethylbenzene	3.56±0.47	8.65±0.05	10.16±0.47	4.21±0.26	2.41±0.09	1.84±0.10	1.16±0.27
Xylene	3.45±0.24	6.2±0.45	10.29±0.22	2.19±0.19	2.45±0.59	1.56±0.14	1.06±0.35
Styrene	0.94±0.06	3.79±0.39	3.19±0.15	1.44±0.34	1.06±0.57	0.83±0.54	0.44±0.15
Formaldehyde	19.85±0.33	10.19±1.74	11.11±1.99	23.30±1.32	4.47±0.49	12.02±2.11	18.47±2.39
Acetaldehyde	10.31±1.84	3.83±0.05	4.66±0.23	10.37±0.39	0.39±0.05	1.84±0.28	5.49±1.18
Acetone and acrolein	8.37±0.44	8.29±0.04	8.22±0.24	13.04±0.86	4.65±0.73	11.24±0.28	15.66±7.84
Total VOCs	89.90±8.45	118.27±4.5	143.89±2.98	99.21±3.6	29.97±2.33	41.70±3.91	68.10±9.55

n=1 metro per route. Multiple samples taken over time

Table 33. Concentrations of VOCs in old and new metros

VOC	**Mean ± SD ($\mu g/m^3$) New carriage 2015**	**Mean ± SD ($\mu g/m^3$) New carriage 2016**	**Mean ± SD ($\mu g/m^3$) Old carriage 2015**	**Mean ± SD ($\mu g/m^3$) Old carriage 2016**	**Mean ± SD ($\mu g/m^3$) Above-ground track 2015**	**Mean ± SD ($\mu g/m^3$) Above-ground track 2016**	**Mean ± SD ($\mu g/m^3$) Underground track 2015**	**Mean ± SD ($\mu g/m^3$) Underground track 2016**
Benzene	5.04±1.2	4.99±1.5	16.1±1.6	6.8±1.6	34.1±1.2	10.7±1.2	28.2±1.2	6.1±1.3
Toluene	6.43±1.3	4.46±1.4	13.3±1.3	13.2±1.3	63.4±1.3	20.3±1.2	50.9±1.3	12.7±1.3
Ethylbenzene	1.26±.1.5	1.73±1.6	3.9±1.5	5.8±1.5	10.5±1.5	8.0±1.6	9.1±1.4	5.3±1.3
Xylene	0.94±0.7	1.88±0.8	2.4±0.7	6.14±0.7	7.2±0.7	8.6±0.7	6.6±0.5	5.8±0.8
Styrene	0.61±0.7	0.44±0.3	1.1±0.7	0.9±0.7	3.6±0.7	6.8±0.8	3.9±0.7	3.5±0.7
Formaldehyde	26.9±0.5	4.46±0.6	27.0±0.5	6.2±0.5	18.4±0.5	4.6±0.8	17.4±0.3	2.4±0.5
Acetaldehyde	11.2±0.5	5.31±0.4	6.2±0.5	6.5±0.7	10.6±0.5	5.7±0.4	9.8±0.5	3.8±0.6
Acetone and acrolein	10.5±0.5	10.9±0.7	8.3±0.5	11.3±0.9	8.2±0.5	8.3±0.5	8.3±0.5	8.2±0.8

n=1 metro per route. Multiple samples taken over time

121. Authors also suggested that differences may also be due to different ventilation systems as the air filter used in the ventilation system of older metro trains is coarse stainless steel wire mesh or aluminium mesh that cannot effectively prevent VOCs from entering the carriage, while the newer metro trains are equipped with fibrous air filter with higher filtration efficiency.

122. VOC levels in the underground track were lower than those detected in the above-ground track in the same metro train due to the underground metro being less influenced by vehicle emissions and lower VOC levels were measured inside metro carriages in suburban areas than urban areas, again due to differences in vehicle emissions.

123. Seasons influence VOCs concentrations as levels were higher during summer compared with autumn, regardless of the age of the train. This may be due to the increased traffic during summer as well as an increase in VOC emissions from internal train fittings which can be enhanced by higher air temperatures. An increase in commuters also may contribute to the higher concentrations (Gong et al. 2019) of VOCs. In contrast, in the earlier paper, the number of passengers was shown not to significantly affect VOC concentrations (Gong et al. 2017).

Summary

124. 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.

125. 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 34).

126. 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).

127. 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.

128. 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.

129. 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 34).

130. Again, 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.

131. 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).

132. The remaining VOCs presented in Table 34 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.

133. The highest mean concentrations of 1,4-dichlorobenzene were higher in aircraft compared to buses.

134. The highest mean concentration of limonene was higher in aircraft compared to cars/taxis whereas all other VOCs were below concentrations reported in cars/taxis.

135. 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 taxi-ing. 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.

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

137. A comparison was made between the maximum concentration of VOCs detected in aircraft and the mean concentrations measured in any other mode of transport (Table 35). The mean concentrations were used for all other modes of transport as maximum concentrations were not consistently available.

138. For all VOCs, except 1,3- and 1,4-dichlorobenzene, highest mean concentrations were measured in cars/taxis out of all other modes of transport. The maximum concentration of benzene, ethylbenzene, m- and p-xylene, styrene, toluene, tetrachloroethylene, acetone, ethyl acetate, hexane, limonene, o-xylene and pentane in aircraft all exceeded the highest mean concentration reported in cars/taxis.

139. 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.

140. 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.

141. 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.

142. 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 36).

Conclusion

143. 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, b-pinene, ethyl acetate, hexane, limonene, pentane in aircraft all exceeded mean values reported for other modes of transport.

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

Table 34. 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	0.02	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	1.88	2.05	0.44	6.8
Toluene	2.8	29.84	5.5	2000	0.44	503	5.22	63.4
Reported in three modes of transport								
Acetaldehyde		6.4	12.47	790	-	-	0.39	10.6
Formaldehyde		5.4	16.43	1541	-	-	2.4	26.9
Heptane	0.7	1.8	2.9	670.1	0.59	0.81	-	-
Nonane	1.4	2.1	2	341	0.17	150	-	-
Octane	>0.5	1.9	2	127	3.2	3.55	-	-
Tetrachloroethylene	2.6	38	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	-	-	-	0.08	47.09	-	-
1,4-dichlorobenzene	0.11	22.9	-	-	0.01	5.41	-	-
Acetic acid	7.5	11.8	3.41	14	-	-	-	-
Acetone	6	17.1	9.3	250	-	-	-	-
Acrolein		<0.8	20.65		-	-	-	-
a-Pinene	0.5	1.2	0.2	4.2	-	-	-	-
b-Pinene	0.3	0.6	0.2	1.8	-	-	-	-
Decane	1	13	0.6	1300.6	-	-	-	-
Dodecane	2.6	6.7	44.5	928.6	-	-	-	-
Ethyl acetate	1.1	9.1	1.8	28	-	-	-	-
Hexane	0.5	20	1.7	65	-	-	-	-
Isoprene	5	9	-	-	-	-	-	-
Limonene	1.44	92.96	0.8	38.8	-	-	-	-
Methanol	4.32	9.6	122		-	-	-	-
Naphthalene	0.8	14	6	49.3	-	-	-	-
o- Xylene	0.6	9.4	3.3	1400	-	-	-	-
Pentane	1	1.4	0.07	30.8	-	-	-	-
p-Xylene		6.8	78.4	78.4	-	-	-	-

VOC	**Lowest mean ($\mu g/m^3$) Aircraft**	**Highest mean ($\mu g/m^3$) Aircraft**	**Lowest mean ($\mu g/m^3$) Car/taxi**	**Highest mean ($\mu g/m^3$) Car/taxi**	**Lowest mean ($\mu g/m^3$) Bus**	**Highest mean ($\mu g/m^3$) Bus**	**lowest mean ($\mu g/m^3$) Metro**	**Highest mean ($\mu g/m^3$) Metro**
Tridecane	1.2	1.7	1.3	687.1	-	-	-	-
Undecane	1.5	4.9	9.3	1615	-	-	-	-

Table 35. Maximum concentrations detected in aircraft and highest mean of the next highest mode of transport

VOC	**Maximum conc. ($\mu g/m^3$) Aircraft**	**Reference**	**Highest mean ($\mu g/m^3$) Other mode of transport**	**Reference**
Benzene	77.9	Guan et al. (2014b)	270 (Car/Taxi)	Faber and Brodzik (2017)
Ethylbenzene	45	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 (Car/Taxi)	Faber and Brodzik (2017)
Toluene	303	Guan et al. (2014b)	2000 (Car/Taxi)	Faber and Brodzik (2017)
Acetaldehyde	7.7	Chen et al. (2021)	790 (Car/Taxi)	Bakhtiari et al. (2018)
Formaldehyde	7.1	Chen et al. (2021)	1541 (Car/Taxi)	Bakhtiari et al. (2018)
Heptane	24.8	EASA (2014)	670 (Car/Taxi)	Faber and Brodzik (2017)
Nonane	12.9	EASA (2014)	341 (Car/Taxi)	You et al. (2007)
Octane	8.2	Guan et al. (2014b)	127 (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 (Car/Taxi)	Kim, Park and Lee (2019)
Acetone	34.4	Guan et al. (2014b) 12)	250 (Car/Taxi)	Faber and Brodzik (2017)
a-Pinene	11.7	EASA (2014)	200 (Car/Taxi)	You et al. (2007)
b-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	928.9 (Car/Taxi)	Faber and Brodzik (2017)
Ethyl acetate	44	Guan et al. (2014b)	28.1 (Car/Taxi)	Brodzik et al. (2014)
Hexane	1123.08	Spengler et al., 2012	65 (Car/Taxi)	Faber and Brodzik (2017)
Limonene	1048	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 (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 (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 36. Minimum and maximum mean concentrations VOC only detected in aircraft

VOC	**Lowest mean / median (µg/m^3) Aircraft**	**Highest mean / median (µg/m^3) 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
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

VOC	Lowest mean / median ($\mu g/m^3$) Aircraft	Highest mean / median ($\mu g/m^3$) Aircraft
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
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

VOC	**Lowest mean / median ($\mu g/m^3$) Aircraft**	**Highest mean / median ($\mu g/m^3$) Aircraft**
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
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

VOC	**Lowest mean / median (µg/m^3) Aircraft**	**Highest mean / median (µg/m^3) Aircraft**
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
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

VOC	**Lowest mean / median (µg/m^3) Aircraft**	**Highest mean / median (µg/m^3) Aircraft**
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
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

145. 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?

   - Are there any candidate VOCs, for which a risk assessment should be considered in the context of aircraft cabin air in a future paper, subject to the upcoming discussion paper on work environments?

ii. Would Members like a similar paper on VOCs/sVOCs in other similar environments to aircraft such as submarines?

IEH Consulting under contract supporting the PHE COT Secretariat
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List of Abbreviations and Technical terms

BTEX	Benzene, toluene, ethylbenzene, xylene
CNG	Compressed natural gas
COT	Committee on Toxicity
DfT	Department for Transport
EASA	European Aviation Safety Authority
FAA/ASHRAE	Federal Aviation Agency/ American Society of Heating, Refrigerating and Air-Conditioning Engineer
FID	Flame ionization detection
GC/MS	Gas chromatography/mass spectrometry
GC-FID	Gas chromatography/flame ionization detector
HPLC/UV	High performance liquid chromatography-ultraviolet
LPG	Liquefied petroleum gas
OP	Organophosphate
PID	Photoionization detection
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
VOC	Volatile organic compounds

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