AIMS Environmental Science, 3(3): 362-381.
DOI: 10.3934/environsci.2016.3.362
Received: 13 May 2016
Accepted: 16 June 2016
Published: 21 June 2016

http://www.aimspress.com/journal/environmental

Research article

Car indoor air pollution by volatile organic compounds and aldehydes in Japan

Masahiro Tokumura[1,*], Rurika Hatayama[2], Kouichi Tatsu[2,3], Toshiyuki Naito[3], Tetsuya Takeda[3], Mohammad Raknuzzaman[2,4], Md. Habibullah-Al-Mamun[2,4] and Shigeki Masunaga[1]

[1] Faculty of Environment and Information Sciences, Yokohama National University, Kanagawa 240-8501 Japan
[2] Graduate School of Environment and Information Sciences, Yokohama National University, Kanagawa 240-8501 Japan
[3] Isuzu Advanced Engineering Center, LTD., Kanagawa 252-8501 Japan
[4] Department of Fisheries, University of Dhaka, Dhaka 1000, Bangladesh

* **Correspondence:** Email: masahiro.tokumura@veritas-sys.jp; Tel/Fax: +81-45-339-4371.

Abstract: Fifty-five organic substances including volatile organic compounds (VOCs) and aldehydes present in indoor air were measured from 24 car cabins in Japan. A screening-level risk assessment was also performed. Acetaldehyde (3.81–36.0 μg/m^3), formaldehyde (3.26–26.7 μg/m^3), *n*-tetradecane (below the method quantification limit (<MQL) to 47.7 μg/m^3), toluene (4.23–78.3 μg/m^3), and *n*-undecane (<MQL to 6.24 μg/m^3) concentrations exceeded method detection limits in all the investigated car cabins. Ratios between indoor and outdoor concentrations revealed that most organic compounds originated from the car interior materials. Total volatile organic compound (TVOC) concentrations in 14 car cabins (58% of all car cabins) exceeded the advisable values established by the Ministry of Health, Labour and Welfare of Japan (400 μg/m^3). The highest TVOC concentration (1136 μg/m^3) was found in a new car (only one month since its purchase date). Nevertheless, TVOC concentrations exceeded the advisable value even for cars purchased over 10 years ago. Hazard quotients (*HQs*) for formaldehyde obtained using measured median and highest concentrations in both exposure scenarios for occupational use (residential time in a car cabin was assumed to be 8 h) were higher than that expected, a threshold indicative of potential adverse effects. Under the same exposure scenarios, *HQ* values for all other organic compounds remained below this threshold.

Keywords: Aldehydes; car; indoor environment; risk assessment; TVOC; VOC

1. Introduction

Most people in modern societies spend approximately 90% of their time indoors on a daily basis [1]. Thus, indoor air quality has become a major concern. In this regard, the car indoor environment has attracted considerable attention because cars have become the main means of transportation in our society [2-4]. Overall, people spend 5% of their time in cars on a daily basis, which proportionally follows the times spent in homes and offices [5].

The indoor air in a car cabin is polluted by organic compounds, especially volatile organic compounds (VOCs) and aldehydes [3,6]. Several studies have revealed that vehicle exhaust gases could be significant sources of VOCs such as benzene, toluene, and xylenes [7-10]. In addition to these gases, Rahman and Kim [11] found that exhaust gases diffusing back into a car cabin, or back diffusion gases, polluted the air in a car cabin and contained high concentrations of toluene, formaldehyde, acetaldehyde, propionaldehyde, and butylaldehyde. Moreover, organic compounds emission from car materials such as carpets, paints, leather, plastics, and foam in the seats are air pollutants in car cabins [12-14]. In addition to these various pollutants, the nature of car construction, such as high surface area and small volume, easily leads to elevated concentrations of organic compounds emitted from car interiors. Because most VOCs are toxic to humans when inhaled at sufficient concentrations, high concentrations of these pollutants may cause adverse health effects to passengers [2,15].

Compared with the indoor environment of dwellings, only limited studies have addressed the indoor environment of car cabins. Zhang et al. [4] reported that under static conditions, emissions from the interior materials of car cabins contribute significantly to air pollution in many compact car models sold in China. In their study, however, the number of air pollutants measured was limited to formaldehyde, benzene, toluene, and xylenes. Because many kinds of VOCs exist in car cabins, a more comprehensive quantification of the organic compounds is needed. Conversely, Yoshida and Matsunaga [16] measured 162 organic compounds including many aliphatic and aromatic hydrocarbons in a new privately used car. Interestingly, high concentrations of *n*-nonane (458 $\mu g/m^3$), *n*-decane (1301 $\mu g/m^3$), *n*-undecane (1616 $\mu g/m^3$), *n*-dodecane (716 $\mu g/m^3$), *n*-tridecane (320 $\mu g/m^3$), 1-hexadecene (768 $\mu g/m^3$), ethylbenzene (361 $\mu g/m^3$), xylene (4003 $\mu g/m^3$), and 2,2'-azobis (isobutyronitrile) (429 $\mu g/m^3$) were also detected. The total volatile organic compound (TVOC) concentration approximated 14,000 $\mu g/m^3$, which significantly exceeded the advisable value established by the Ministry of Health, Labour and Welfare of Japan (400 $\mu g/m^3$). Chen et al. [2] determined the concentrations of seven VOC species including benzene, toluene, ethylbenzene, xylenes, styrene, butyl acetate, and undecane and TVOC in 38 taxis in China. Benzene, toluene, ethylbenzene, xylene, styrene, butyl acetate, undecane, and TVOC concentrations in taxi cabins averaged 82.7, 212.3, 74.7, 182.3, 24.7, 33.5, 61.3, and 1441.7 $\mu g/m^3$, respectively. These findings indicated that in-car airborne VOC and TVOC pollution may induce health problems in passengers and drivers.

In this study, a comprehensive measurement of VOCs in car interiors was carefully conducted for 24 unoccupied cars. The number of target organic compounds amounted to 55. The effects of vehicle age on organic compound concentrations were also discussed. Finally, a screening-level risk assessment was also performed to evaluate organic compound concentrations in car cabins.

2. Materials and Method

2.1. Air sampling and analytical methods

Air samples were collected from 24 unoccupied cars (n = 24, Table 1). Sampling was conducted at several outdoor parking lots in Yokohama and Kawagoe, Japan from November 17 to 27, 2013. Outdoor temperatures during the sampling ranged from 14.3 to 23.0 °C while indoor temperatures spanned from 13.7 to 25.8 °C. During the sampling period, weather conditions were mostly cloudy. Only one driver of the investigated cars smoked regularly (Car 9). During sampling, an air freshener was found in Cars 2, 9, and 11.

Most drivers spend 5% of their day in their cars [5]. Taking into account round trips, this corresponds to about 30 min in a single private-use car on a usual day for routine activities, such as traveling from home to workplaces, shopping, and returning home. To reflect these driving habits, VOC and aldehyde emissions were measured for 30 min. Before air sampling, the engine was turned off and the car cabin was ventilated for 10 min by opening the doors. Next, all the doors and windows were closed. Sampling devices for VOCs, TVOC, and aldehydes were positioned near the driver's headrest to sample the air around the driver's breathing zone.

2.1.1. Aldehyde sampling and analysis

Aldehydes were sampled by collecting the interior air of the vehicles using a 2,4-dinitrophenylhydrazine (DNPH) cartridge (InertSep mini AERO DNPH, GL Sciences Inc., Tokyo, Japan) incorporating an ozone scrubber (InertSep mini Ozone Scrubber, GL Sciences Inc., Tokyo, Japan). A portable pump (MP-Σ300NII, Sibata Scientific Technology Ltd., Saitama, Japan) was turned on for 30 min at an air flow rate of 1 L/min. Subsequently, the samples were extracted from the cartridges using acetonitrile (5 mL) and analyzed by high-performance liquid chromatography (HPLC) using an Agilent 1100 apparatus (Agilent Technologies Inc., Santa Clara, CA, USA) equipped with a column (Atlantis T3, 100 mm × 4.5 mm i.d., film thickness: 3 μm, Waters Corporation, Milford, MA, USA) and a UV detector (360 nm). The HPLC analysis was performed using 1:1 acetonitrile/water (v/v) as an isocratic mobile phase at a flow rate of 0.8 mL/min, an injection volume of 20 μL, and a column temperature of 40 °C.

Table 1. Characteristics of investigated cars.

Car No.	Age of the car [year]	Mileage [km]	Country of origin	Maker	Name	Type	Interior dimension [mm]	Use	Sampling Date	Interior Temperature [°C]	Load
1	>4*	40,000	Japan	Nissan	Bluebird sylphy	Sedan	2115×1395×1210	Private	NOV. 17	17.4	Cushion, Tissue box
2	9	68,000	Japan	Honda	Fit	Wagon	1835×1385×1280	Private	NOV. 17	17.8	Cushion ×4, Tissue box (with case), Plastic sheet
3	5	80,000	Japan	Toyota	Noah	Minivan	2970×1435×1350	Private	NOV. 17	16.7	Cardboard, Comforter, Umbrella ×3, Clothes
4	2.5	35,000	Japan	Subaru	Legacy	Wagon	2190×1545×1230	Private	NOV. 18	19.2	Scooter, Cushion ×3, Comforter, Mini table, Outdoor mat
5	>2*	143,018	Japan	Honda	Life	Wagon	2005×1295×1315	Private	NOV. 18	18.5	Boots, Plastic case, Cleaner of Car
6	8.08	66,500	Japan	Mitsubishi	Minica	Wagon	1655×1220×1220	Private	NOV. 19	13.8	Blanket, Cushion ×2, Umbrella, Tissue box
7	3	20,000	Japan	Toyota	Vitz	Wagon	1865×1390×1270	Private	NOV. 20	18.1	Umbrella ×2, Car sunshade
8	3	24,247	Japan	Daihatsu	Mira cocoa	Wagon	1930×1345×1240	Private	NOV. 20	18.2	Folding bicycle, Car sunshade, Cushion ×3, Blanket
9	3	70,000	Japan	Subaru	Legacy	Wagon	2190×1545×1230	Private	NOV. 20	24.0	Flashlight, Plastic case, Shoes ×2, Plastic plaything
10	10	50,000	Japan	Toyota	Fun cargo	Wagon	1905×1370×1290	Private	NOV. 20	22.0	Deodorant, Stuffed toy, Cushion
11	11	8000	Japan	Mazda	Premacy	Wagon	2370×1695×1250	Private	NOV. 20	15.7	Plastic case, Wagon (metal)
12	13	55,000	Japan	Honda	Odyssey	Minivan	2740×1530×1215	Private	NOV. 20	14.3	Tissue box, Cleaning tool, Dust cloth, CD, Air freshener, Deodorant
13	0.08	1000	Japan	Nissan	Serena	Minivan	3060×1480×1380	Private	NOV. 25	14.9	Plastic case, Eco bag, Emergency box, Cleaning tool, Plastic bag
14	4	39,612	Japan	Toyota	Passo	Wagon	1830×1400×1275	Private	NOV. 25	12.6	Umbrella ×2, Car sunshade, Boots, Plastic case
15	10	44,983	Japan	Nissan	X-trail	SUV	2045×1445×1265	Private	NOV. 25	14.3	Book ×3, Bat, Toolbox, Plastic bag
16	0.25	854	Japan	Suzuki	Wagon R	Wagon	2165×1295×1265	Official	NOV. 26	25.5	No loading
17	5	26,443	Japan	Toyota	Crow hybrid	Sedan	2060×1520×1205	Official	NOV. 26	25.2	No loading
18	6	37,967	Japan	Isuzu	Elf	Truck	2450×1540×1420	Official	NOV. 26	25.8	No loading
19	1	8371	Japan	Suzuki	Landy	Wagon	3060×1480×1380	Official	NOV. 26	21.2	No loading
20	3	28,478	Japan	Isuzu	Como	Wagon	2800×1545×1350	Official	NOV. 26	23.2	No loading
21	0.42	2320	Japan	Mazda	Atenza	Sedan	1930×1550×1170	Official	NOV. 26	23.3	No loading
22	3	20,345	Japan	Nissan	Serena	Minivan	2760×1470×1355**	Private	NOV. 27	13.7	Plastic case, Plastic bag, Golf bag, Cushion ×6
23	13	107,234	Japan	Toyota	Vitz	Wagon	1800×1380×1500**	Private	NOV. 27	14.1	Plastic sheet, Book, Deodorants
24	9	156,748	Japan	Subaru	Legacy	Wagon	1840×1445×1190**	Private	NOV. 27	16.7	Car sheet, Cushion, Toolbox

* ”>” means that the car owner bought an used car. ** Interior dimensions changed with model updates.

2.1.2. VOC sampling and analysis

The interior air of the vehicles was collected for 2 min in 10 L Flek polyester bags (Flek-Sampler, Omi Odor-Air Service Corporation, Shiga, Japan) using a hand-operated air pump (DC1-NA, Omi Odor-Air Service Corporation, Shiga, Japan) at an air flow rate of 1 L/min from 28 min after starting aldehyde sampling. Air samples were analyzed using two gas chromatographs equipped with a flame ionization detector (GC-FID) (HP5890A, Hewlett-Packard, San Fernando, CA, USA). Specifically, highly polar VOCs were characterized using a GC-FID equipped with an HP-1 column (15 m × 0.32 mm i.d., film thickness: 5 μm, Hewlett-Packard, San Fernando, CA, USA). Their low-polarity counterparts were analyzed using a GC-FID fitted with an HP-5 column (15 m × 0.32 mm i.d., film thickness: 1.05 μm, Hewlett-Packard, San Fernando, CA, USA). For all compounds, the GC-FID oven temperature was initially held at 35 °C for 5 min and increased to 180 °C at a rate of 20 °C/min, 200 °C at a rate of 2 °C/min, and finally 220 °C at a rate of 10 °C/min. The injector and detector temperatures were 250 °C. Helium (He) acted as a carrier gas. The air samples were injected to GC-FID by an auto injection system.

2.1.3. TVOC, temperature, and relative humidity measurements

The TVOC concentrations in the interior air of the vehicles were measured using a TVOC meter (FTVR-01, Figaro Engineering Inc., Osaka, Japan) for concentrations ranging from 0 to 9999 μg/m^3. The limit of detection (LOD) and resolution amounted to 1 μg/m^3. Temperatures were also determined using the TVOC meter.

Hori et al. [17] related values obtained using the same TVOC meter and data acquired by active sampling by measuring VOC concentrations in different rooms through these approaches. They found a good correlation between both sets of measurements regardless of differences in VOC compositions between individual samples. They also found that the detection of VOCs with ultralow or ultrahigh sensitivity using the TVOC meter provided values that may differ from actual TVOC concentrations. However, they concluded that the TVOC meter could be used to monitor TVOC concentrations without considering individual VOCs. Therefore, this instrument was chosen to measure TVOC concentrations in car cabins.

2.2. Quality assurance/quality control

The external calibration method and the linear regression model were used for the calibration for VOCs and acetaldehydes. The calibration ranges of acetaldehyde, benzaldehyde, and formaldehyde were 2–330, 33–330, and 2–330 μg/m^3, respectively. The values of R^2 for acetaldehyde, benzaldehyde, and formaldehyde were more than 0.999. The LOD for VOCs was calculated based on a signal-to-noise ratio (S/N) of 3:1, while the limit of quantification (LOQ) was determined to be 10 times the LOD. In the case of aldehydes, LOD and LOQ were defined as 3σ and 10σ of blank level samples (n = 5), respectively. The method detection limit (MDL) and method quantification limit (MQL) were calculated using LOD, LOQ, extract volumes, and air sampling volume. Obtained MDL and MQL for aldehydes and VOCs are listed in Table 2.

Table 2. Organic compound concentrations obtained in the 24 car cabins and their corresponding literature values [μg/m^3].

Compounds	This study (*n* = 24) Concentration					References New car (*n* = 1) (Yoshida and Matsunaga 2006)	New car (*n* = 1) (You et al. 2007)	One year old Car (*n* = 1) (You et al. 2007)	Five years old car (*n* = 1) (You et al. 2007)
	Median	Min	Max	MDL	MQL				
Acetaldehyde	13.4	3.81	36.0	0.50	1.66	-	-	-	-
Benzaldehyde	N.D.	N.D.	N.D.	8.56	28.5	-	-	-	-
Benzene	0.60	N.D.	11.3	0.03	0.32	6.3	48	10	2.4
n-Butanol	3.82	N.D.	9.62	0.03	0.30	150.5	-	-	-
Butylacetate	N.D.	N.D.	3.70	0.05	0.47	27	225	0	2.3
Cyclohexane	3.24	N.D.	85.7	0.03	0.34	14.2	70	-	-
n-Decanal	N.D.	N.D.	2.39	0.06	0.64	-	-	-	-
n-Decane	N.D.	N.D.	22.7	0.06	0.58	1300.6	345	89.3	8.1
Dichloromethane	6.45	N.D.	69.4	0.03	0.35	-	-	-	-
Diethylether	0.33	N.D.	25.2	0.03	0.30	-	-	-	-
n-Dodecane	1.30	N.D.	8.45	0.07	0.70	715.7	-	-	6.4
Ethylacetate	2.69	N.D.	20.5	0.04	0.36	17.3	-	-	-
Ethylbenzene	3.85	N.D.	8.10	0.04	0.43	360.9	-	-	3.5
2-Ethylhexanal	2.13	N.D.	6.85	0.05	0.52	-	-	-	-
Formaldehyde	9.41	3.26	26.7	0.16	0.55	46.4	-	-	-
n-Heptane	1.53	N.D.	7.65	0.04	0.41	195.2	188	-	-
n-Hexanal	N.D.	N.D.	7.57	0.04	0.41	-	-	15.7	-
n-Hexane	11.5	N.D.	22.7	0.04	0.35	107	-	-	-
Isopropylbenzene	N.D.	N.D.	3.29	0.05	0.49	13.1	-	-	-
Limonene	N.D.	N.D.	3.93	0.06	0.56	5.8	-	-	14.4
Methylcyclohexane	1.50	N.D.	7.87	0.04	0.40	19.7	122	-	-
Methylcyclopentane	2.73	N.D.	13.5	0.03	0.34	24.6	-	-	-
1-Methyl-2-ethylbenzene	1.84	N.D.	31.7	0.05	0.49	58.4	-	-	-
1-Methyl-3-ethylbenzene	1.61	N.D.	20.6	0.05	0.49	102.8	-	-	-
1-Methyl-4-ethylbenzene	1.38	N.D.	83.9	0.05	0.49	34.2	-	-	-
MethylEthylketone	4.13	N.D.	13.2	0.03	0.29	5.2	-	-	-

2-Methyloctane	N.D.	N.D.	5.92	0.05	0.52	64	-	-	-
2-Methylpentane	0.83	N.D.	7.24	0.04	0.35	80.6	-	-	-
2-Methylpropane	N.D.	N.D.	310	0.02	0.24	-	-	-	-
3-Methylpentane	1.97	N.D.	342	0.04	0.35	9.9	-	-	-
Naphthalene	N.D.	N.D.	5.94	0.05	0.52	3.8	-	49.3	-
n-Nonanal	N.D.	N.D.	2.17	0.06	0.58	2.4	-	-	-
n-Nonane	0.98	N.D.	12.2	0.05	0.52	457.6	341	18.3	2.0
n-Octanal	2.20	N.D.	29.9	0.05	0.52	-	-	-	-
n-Octane	1.74	N.D.	21.4	0.05	0.47	33.9	127	-	-
1-Propanol	5.16	N.D.	15.1	0.02	0.25	-	-	-	-
2-Propanol	N.D.	N.D.	0.46	0.02	0.25	-	-	-	-
p-Dichlorobenzene	1.15	N.D.	209	0.06	0.60	7.3	-	-	-
n-Pentane	N.D.	N.D.	34.7	0.03	0.29	-	-	-	-
n-Propylbenzene	N.D.	N.D.	4.59	0.05	0.49	33.6	-	-	-
α-Pinene	N.D.	N.D.	3.12	0.06	0.56	3.1	200	-	-
Styrene	N.D.	N.D.	3.18	0.04	0.43	73.6	155	9.8	2.3
1,2,3-Trimethylbenzene	<MQL	N.D.	163	0.05	0.49	84.3	-	-	-
1,2,4-Trimethylbenzene	N.D.	N.D.	1.38	0.05	0.49	212.2	-	-	-
1,3,5-Trimethylbenzene	<MQL	N.D.	4.59	0.05	0.49	67.8	-	-	3.1
Tetrachloroethylene	N.D.	N.D.	4.43	0.07	0.68	1.0	242	-	-
n-Tetradecane	2.27	<MQL	47.7	0.08	0.81	109.6	-	77.8	-
Tetrahydrofuran	N.D.	N.D.	9.63	0.03	0.29	-	-	-	-
Toluene	23.5	4.23	78.3	0.04	0.38	225.8	82	50	32.2
1,1,1-Trichloroethane	3.42	N.D.	48.3	0.05	0.55	0.7	-	-	-
n-Tridecane	<MQL	N.D.	113	0.08	0.75	319.8	-	-	-
n-Undecanal	<MQL	N.D.	78.0	0.07	0.70	-	-	-	-
n-Undecane	1.30	<MQL	6.24	0.06	0.64	1615.8	40	130	9.3
m,*p*-Xylene	3.65	N.D.	17.4	0.04	0.43	3104	346	20	10.2
o-Xylene	1.62	N.D.	5.27	0.04	0.43	898.9	95	9.9	3.3
TVOC	464	8	1136			14081.4	4940	1240	132

MDL = Method detection limit, MQL = Method quantification limit, **-** = No Data, N.D. = Not detected (lower than MDL), < MQL = lower than MQL.

Before each VOC sampling round, sampling bags were flushed twice with ultrapure nitrogen. In the preliminary accuracy tests, the coefficients of variation for VOCs, the ratio of the standard deviation to the mean, were observed to be well below 5%. Slightly higher coefficients of variation (5.5–6.0%) were observed for 1,2,4-trimethyl benzene and 1,3,5-trimethyl benzene. These coefficients of variation amounted to 1.3% and 2.6% for formaldehyde and acetaldehyde, respectively. Recovery efficiencies reached 101% and 93% for spiked formaldehyde (3.8 μg) and acetaldehyde (7.6 μg), respectively. In blank DNPH cartridges, all aldehyde concentrations measured in this study were below MDL. A breakthrough test ensured that no breakthrough would occur from DNPH cartridges during the experimental procedure. The air flow rates of pumps used for air sampling were calibrated before sampling and measured after sampling to ensure that they were unchanged during the sampling. The TVOC meter was calibrated daily using the air passing through the activated carbon filter as a zero gas.

2.3. Statistical analysis

All statistical analyses were performed using Excel (Microsoft Office 2013). To include all data, values that were non-detected (N.D.) or below MQL were replaced by half MDL and half MQL in statistical calculations, respectively [5,18-20]. Non-parametric tests were used because of limited sample numbers. The Spearman rank order correlation coefficient was calculated to correlate VOC, aldehyde, and TVOC concentrations; car age; and interior temperature. The criterion for significance was $p < 0.01$ or $p < 0.05$.

3. Results and discussion

3.1. Detection frequency of organic compounds in car cabins

Figure 1 shows the detection frequencies of organic compounds in the 24 investigated car cabins. Acetaldehyde (3.81–36.0 μg/m^3), formaldehyde (3.26–26.7 μg/m^3), *n*-tetradecane (< MQL to 47.7 μg/m^3), toluene (4.23–78.3 μg/m^3), and *n*-undecane (< MQL to 6.24 μg/m^3) were detected in all car cabins. In addition, dichrolomethane (N.D. to 69.4 μg/m^3), *n*-dodecane (N.D. to 8.45 μg/m^3), ethylbenzene (N.D. to 8.10 μg/m^3), 2-ethylhexanal (N.D. to 6.85 μg/m^3), *n*-hexane (N.D. to 22.7 μg/m^3), methylcyclohexane (N.D. to 7.87 μg/m^3), methylcyclopentane (N.D. to 13.5 μg/m^3), 1-methyl-2-ethylbenzene (N.D. to 31.7 μg/m^3), 1-methyl-3-ethylbenzene (N.D. to 20.6 μg/m^3), 1-methyl-4-ethylbenzene (N.D. to 83.9 μg/m^3), methylethylketone (N.D. to 13.2 μg/m^3), *n*-octanal (N.D. to 29.9 μg/m^3), *n*-octane (N.D. to 21.4 μg/m^3), 1-propanol (N.D. to 15.1 μg/m^3), *m,p*-xylene (N.D. to 17.4 μg/m^3), and *o*-xylene (N.D. to 5.27 μg/m^3) were observed in more than 80% of the cars. These high detection frequencies implied that the measured organic compounds mainly originated from car structural materials. In contrast, benzaldehyde (MDL = 8.56 μg/m^3) was not detected in any car cabin.

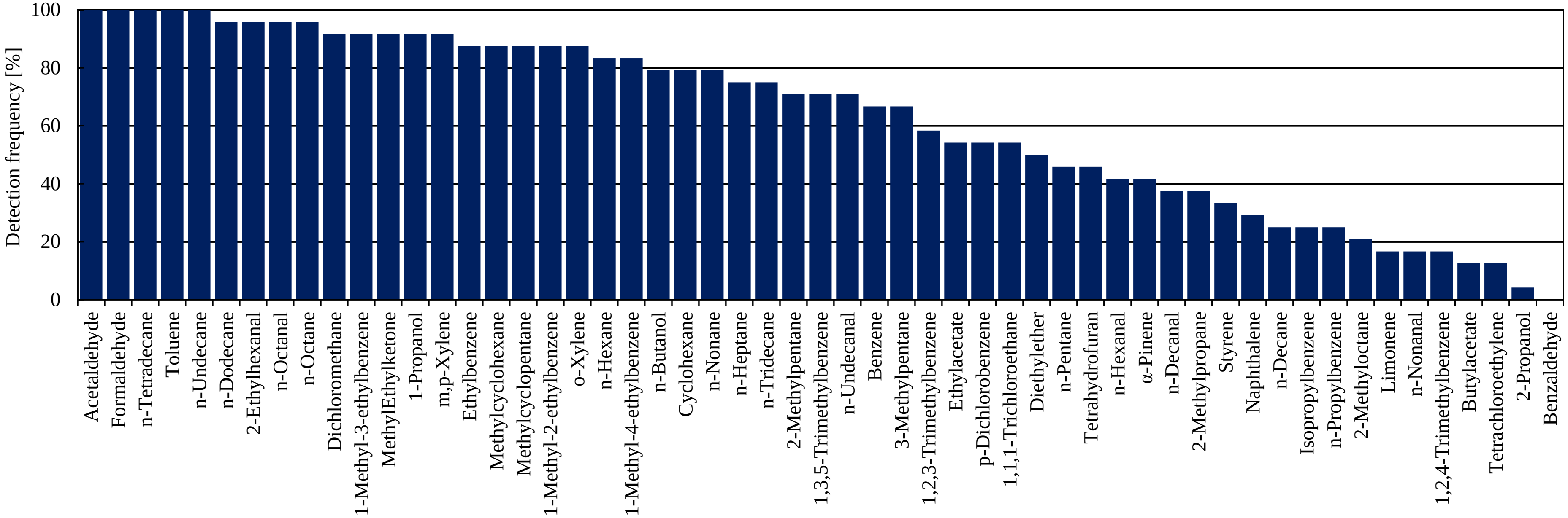

Figure 1. Detection frequencies of 55 organic compounds in 24 car cabins.

3.2. Organic compound concentrations in car cabins

Organic compound and TVOC concentrations in the 24 car cabins are listed in Table 2 (see individual data in Table S1, Supporting Information). An unidentifiable broad peak was detected near 22 min corresponding to the retention time of benzene for Car 18, preventing the quantification of benzene in this vehicle.

Organic compound concentrations ranged from N.D. to 342 μg/m^3. 3-methylpentane observed in Car 8 exhibited the highest concentration (342 μg/m^3). However, its median concentration amounted to 1.97 μg/m^3, making it the 18th most abundant organic compound. According to Zuraimi et al. [21], this compound may mainly originate from adhesives and solvents. Also, its emission rates highly depend on the country producing these materials. For example, materials fabricated in Europe (EU) and Singapore presented emission rates of 166.4 and 137 μg/m^2/h, respectively. Tsai et al. [22] reported that motorcycle exhaust contained high concentrations of 3-methylpentane (1900–274,100 μg/m^3). In addition to 3-methylpentane, 2-methylpropane (310 μg/m^3), *p*-dichlorobenzene (209 μg/m^3), 1,2,3-trimethylbenzene (163 μg/m^3), and *n*-tridecane (113 μg/m^3) were also detected in high concentrations. 2-methylpropane and 1,2,3-trimethylbenzene are also present in exhaust gas [23]. *p*-dichlorobenzene is typically used as a moth repellent and a deodorizer [24,25]. *n*-tridecane may result from vinyl-based materials [26]. Toluene displayed the highest median concentration (23.5 μg/m^3). This compound may originate from many kinds of emission sources, such as tobacco smoke, solvent-based paints, and consumer products [24]. As mentioned above, it is also the main component of car exhaust gas. Acetaldehyde (13.4 μg/m^3), *n*-hexane (11.5 μg/m^3), and formaldehyde (9.41 μg/m^3) exhibited the next-highest median concentrations. In addition to their wide use as adhesives for wood products, formaldehyde and acetaldehyde are also utilized as surface coatings for furniture and floors. They are present in composite wood, products containing urea–formaldehyde resin, and tobacco smoke [24,27]. *n*-hexane, which exists in car exhaust gas, is also used as an adhesive and solvent [22,28].

Most median concentrations obtained in this study were lower than data reported for new cars by Yoshida and Matsunaga [16] and You et al. [29], with the exception of 1,1,1-trichloroethane. In general, most chemicals detected in car cabins were considered to originate from the original structural materials. New cars tend to display higher organic compound concentrations than their old counterparts. Here, the car age averaged 5.56 years, except used Cars 1 and 5, which did not have any clear information on their ages. This may largely explain the low organic compound concentrations obtained compared with literature values for new cars. On the other hand, except for ethylbenzene, most organic compounds measured in this study presented comparable median concentrations to values for two old cars reported by You et al. [29]. The influence of car age on these concentrations will be discussed below. Moreover, temperature differences during air sampling may impact results. Temperatures during sampling in this study ranged from 14.3 to 23.0 °C instead of remaining at 25 °C [29]. High temperatures enhance organic compound emission rates from materials, which is expected to increase high organic compound concentrations. This may explain why most median concentrations in this study were lower than those reported by You et al. [29]. The relationship between temperature and organic compound concentration will be discussed later.

3.3. Ratios between indoor and outdoor organic compound concentrations

Table 3 shows the ratios between indoor and outdoor concentrations (I/O ratios) for the 55 organic compounds. Outdoor concentrations are shown in Table S2. An I/O ratio higher than 1.0 shows that the pollutant is likely inside the car cabin whereas an I/O ratio less than or equal to 1.0 indicates that the pollution source is outside the car cabin. Maximum I/O values were extremely high for most organic compounds, except for benzaldehyde. Acetaldehyde (median = 3.0), benzene (median = 3.3), 2-ethylhexanal (median = 5.1), 1,2,3-trimethylbenzene (median = 5.0), 1,3,5-trimethylbenzene (median = 10.0), and n-undecanal (median = 10.0) exhibit median I/O ratios exceeding 1.0. This implies that these compounds originated from interior sources such as back diffusion gases and adsorbed vehicle exhaust gases.

Table 3. I/O ratios of organic compounds [-].

Compounds	I/O ratio		
	Median	Min	Max
Acetaldehyde	3.0	1.2	9.0
Benzaldehyde	1.0	1.0	1.0
Benzene	3.3	0.01	336
n-Butanol	1.5	0.01	392
Butyl acetate	1.0	1.0	155
Cyclohexane	2.7	0.01	1057
n-Decanal	1.0	0.03	74
n-Decane	1.0	1.0	780
Dichloromethane	2.4	0.6	598
Diethylether	1.0	0.01	30
n-Dodecane	2.1	0.3	93
Ethylacetate	1.0	0.4	168
Ethylbenzene	1.6	0.004	6.3
2-Ethylhexanal	5.1	0.1	168
Formaldehyde	2.7	1.3	5.7
n-Heptane	1.0	0.01	243
n-Hexanal	1.0	1.0	370
n-Hexane	1.2	0.002	4.6
Isopropylbenzene	1.0	1.0	134
Limonene	1.0	1.0	141
Methylcyclohexane	1.6	0.01	10
Methylcyclopentane	1.4	0.01	262
1-Methyl-2-ethylbenzene	1.6	0.1	1289
1-Methyl-3-ethylbenzene	1.8	0.02	112
1-Methyl-4-ethylbenzene	2.4	0.01	3416
MethylEthylketone	1.7	0.004	579
2-Methyloctane	1.0	0.1	226
2-Methylpentane	1.2	0.05	10
2-Methylpropane	1.0	0.01	26130

3-Methylpentane	1.3	0.03	243
Naphthalene	1.0	1.0	227
n-Nonanal	1.0	0.03	75
n-Nonane	2.0	0.1	467
n-Octanal	2.0	0.2	150
n-Octane	2.8	0.03	75
1-Propanol	1.4	0.01	617
2-Propanol	1.0	1.0	37
p-Dichlorobenzene	1.0	0.02	6966
n-Pentane	1.0	0.01	2354
n-Propylbenzene	1.0	1.0	187
a-Pinene	1.0	1.0	112
Styrene	1.0	0.01	150
1,2,3-Trimethylbenzene	5.0	0.5	6637
1,2,4-Trimethylbenzene	1.0	1.0	56
1,3,5-Trimethylbenzene	10	0.1	187
Tetrachloroethylene	1.0	1.0	131
n-Tetradecane	1.7	0.3	63
Tetrahydrofuran	1.0	0.02	262
Toluene	1.7	0.8	5.0
1,1,1-Trichlhoroethane	1.4	0.9	1772
n-Tridecane	1.0	0.01	2989
n-Undecanal	10	0.02	150
n-Undecane	1.8	0.2	195
m,*p*-Xylene	2.4	0.01	14
o-Xylene	2.0	0.01	243

3.4. Correlation between organic compound concentrations

Correlation coefficients (r) between organic compounds are shown in Table S3. Two groups of compounds presented high correlation coefficients. The first group consisted of *n*-decane, butylacetate, and naphthalene (*n*-decane and butylacetate: $r = 0.81$, $p < 0.01$; naphthalene and butylacetate: $r = 0.72$, $p < 0.01$; naphthalene and n-decane: $r = 0.87$, $p < 0.01$). The other group included dichloromethane, n-nonane, and toluene (dichloromethane and n-nonane: $r = 0.70$, $p < 0.01$; dichloromethane and toluene: $r = 0.84$, $p < 0.01$; *n*-nonane and toluene: $r = 0.78$, $p < 0.01$). The high correlation coefficients within each group imply that their components may have common emission sources. Additionally, good correlation pairs, such as diethylether–1,3,5-trimethylbenzene ($r = 0.72$, $p < 0.01$), *n*-pentane–ethylacetate ($r = 0.77$, $p < 0.01$), *n*-nonane–isopropylbenzene ($r = 0.71$, $p < 0.01$), *n*-propylbenzene–isopropylbenzene ($r = 0.73$, $p < 0.01$), *n*-tridecane–1-methyl-3-ethylbenzene ($r = 0.71$, $p < 0.01$), *n*-nonane–*n*-propylbenzene ($r = 0.71$, $p < 0.01$), *m*,*p*-xylene–n-nonane ($r = 0.70$, $p < 0.01$), and *m*,*p*-xylene–*n*-propylbenzene: $r = 0.71$, $p < 0.01$, were also found.

3.4.1. Correlation between temperature and concentrations of organic compounds

In general, a higher interior temperature leads to higher concentrations of VOCs and aldehydes. The higher interior temperature can enhance the emission rate of organic compounds from the interior materials in car cabin. However, in this study, not only significant positive correlations (formaldehyde: $r = 0.58$, $p < 0.01$; methylcyclohexane: $r = 0.52$, $p < 0.05$) but also significant negative correlations (1,2,3-trimethylbenzene: $r = −0.57$, $p < 0.01$; tetrahydrofuran: $r = −0.43$, $p < 0.05$) were found. Parra et al. [30] also found the negative correlation between interior temperature and organic compounds (benzene, toluene, ethyl benzene, xylenes) in buses. The higher interior temperature may increase not only the emission rate of organic compounds but also the photochemical degradation rate, which plays an important role in reducing the concentrations of organic compounds [30].

3.4.2. Correlation between car age and organic compound concentrations

Organic compound concentrations tend to decrease with increasing car age because of long-term ventilation or emission [2,5]. However, no significant negative correlations were observed between car age and organic compound concentrations in this study. Li et al. [31] found that toluene, ethylbenzene, xylene, and trimethylbenzene concentrations decreased quickly with time and dropped by 23%, 32%, 10%, and 50% in one year, respectively. Chen et al. [2] also demonstrated that, in the case of benzene, toluene, ethylbenzene, xylenes, styrene, butyl acetate, and undecane, VOC and TVOC concentrations decreased rapidly when the car age increased from 1.5 to 23.9 months. However, these concentrations did not decrease significantly when the car age rose from 23.9 to 39.4 months. As a result, a significant decrease in organic compound concentrations is likely to occur for one to two-year-old cars. In this study, the average car age approximated 5.6 years. Therefore, the large number of older cars masked any important negative correlation between car age and organic compound concentrations. In fact, TVOC concentrations in Cars 13, 16, and 21, which were 0.08, 0.25, and 0.42 years old, respectively, surpassed those of the other cars.

3.5. TVOC concentrations in car cabins

Figure 2 shows the TVOC concentrations in the 24 car cabins along with the advisable value established by the Ministry of Health, Labour and Welfare of Japan (400 $\mu g/m^3$, red line). Fourteen cars (58%) exceeded the provisional guideline value. Car 13, which had been purchased one month before testing, displayed the highest TVOC concentration (1136 $\mu g/m^3$). Purchased over 10 years before sampling, Cars 11 and 15 presented TVOC concentrations that exceeded the provisional guideline value. Cars 2, 9, and 11, in which an air freshener existed during sampling, exhibited relatively high TVOC concentrations. The correlation between car age and TVOC concentration was not significant ($r = −0.12$, $p = 0.61$). However, new cars (cars younger than one year old, Car 13) showed significantly higher TVOC concentrations, consistent with the extremely high values obtained by Yoshida and Matsunaga (14,081 $\mu g/m^3$) [16] and You et al. (4940 $\mu g/m^3$) [29]. For new cars, these concentrations may stem mainly from the emission of organic compounds from the original car materials. On the other hand, they likely depend on the way drivers use their cars for vehicles older than one year. In other words, the driver's habits strongly impact the car indoor environment in these older cars.

An analysis of the correlation between TVOC and individual VOC concentrations revealed moderate correlations (*p* values lower than 0.05) for 2-ethylhexanal ($r = 0.46$, $p < 0.05$), *n*-nonanal ($r = 0.57$, $p < 0.01$), *n*-tetradecane ($r = 0.54$, $p < 0.01$), toluene ($r = 0.51$, $p < 0.05$), *n*-tridecane ($r = 0.46$, $p < 0.05$), and *n*-undecane ($r = 0.44$, $p < 0.05$) (Table S3, Supplementary materials).

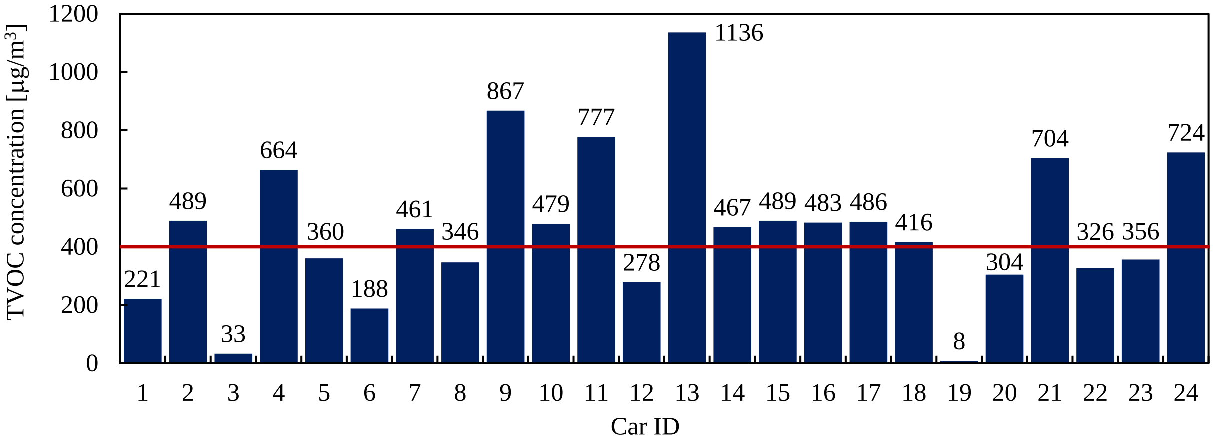

Figure 2. TVOC concentrations in the 24 car cabins.

3.6. Risk assessment for organic compounds in car cabins

A screening-level risk assessment was conducted to evaluate the health risk of drivers and passengers associated with exposure to organic compounds in cars. Exposure to organic compounds via inhalation of car indoor air was determined using:

$$I_{inh} = \frac{R_{inh} \cdot C_{air} \cdot t_{car}}{W} \quad (1)$$

where I_{inh} is the daily intake rate of organic compounds via inhalation in a car cabin [µg/kg-body weight/day], W is the body weight [kg], C_{air} is the concentrations of organic compounds in cabin air [µg/m^3], R_{inh} is the daily inhalation rate [m^3/day], and t_{car} is the exposure time in a car cabin [day].

Human exposure to organic compounds via inhalation in car cabins was assessed using two scenarios. (1) Typical exposure considered median concentrations between measured cars. (2) The worst case scenario accounted for the highest concentration. Both scenarios used the average body weight (50 kg) and inhalation rate for a Japanese person (15 m^3/day) [32,33]. The average residence time in a car cabin was estimated as (1) typical (0.05 day; 5% of 24 h) or (2) occupational (0.33 day; 8 h).

Azuma et al. [32] determined the estimated human no observed adverse effect level (NOAEL) via inhalation exposure, $NOAEL_{\mathrm{inh}}$ [mg/m^3] using a reference human body weight of 50 kg and respiration rate of 15 m^3/day for Japanese people. They accounted for three uncertainty factors. (1) Uncertainty factor 1 (UF1) was applied to lowest observed adverse effect level (LOAEL) when a NOAEL was unavailable. (2) Uncertainty factor 2 (UF2) was applied to extrapolation across durations. (3) Uncertainty factor 3 (UF3) was applied to extrapolation from animal studies to a human situation. Here, reference doses (*RfD*s) [μg/kg-body weight/day] were calculated using $NOAEL_{inh}$ as

$$RfD = \frac{NOAEL_{inh} \times 1000 \times 15\,\mathrm{m}^3/\mathrm{day}}{50\,\mathrm{kg} \times UF} \tag{2}$$

where *UF* is an uncertainty factor for individual uncertainty components [-]. In this study, a default factor of 10 was used for *UF*.

The hazard quotient (*HQ*) [-] was evaluated as

$$HQ = \frac{I_{inh}}{RfD} \tag{3}$$

Table 4 summarizes results of the screening-level risk assessment for driver and passenger exposure to organic compounds in cars. Figure 3 shows *HQ* values for the organic compounds. The *HQ* values for formaldehyde in both exposure scenarios exceeded one for occupational use (1.3 and 3.4 for typical and worst case scenarios, respectively). For exposure scenarios involving typical use, no organic compounds showed *HQ* values above one. However, passengers may be exposed to these organic compounds outdoors as well as indoors. Therefore, a more accurate risk assessment requires a more comprehensive exposure assessment, such as a personal exposure assessment.

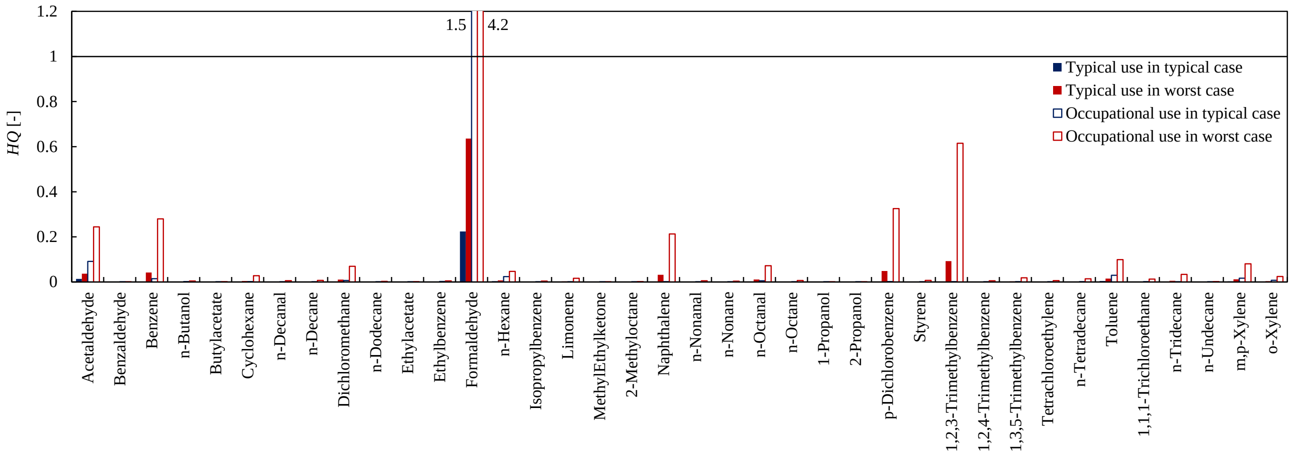

Figure 3. *HQ* values of organic compounds detected in car cabins.

Table 4. Screening-level risk assessment for driver and passenger exposure to organic compounds in cars.

Compounds	Concentration [µg/m³]		Intake rate [µg/kg-bw/day]				*RfD**	*HQ* [-]			
			Typical use		Occupational use		[µg/kg-bw/day]	Typical use		Occupational use	
	Median	Max	Typical case	Worst case	Typical case	Worst case		Typical case	Worst case	Typical case	Worst case
Acetaldehyde	13.4	36.0	0.20	0.54	1.34	3.60	15	1.4E-02	3.7E-02	9.1E-02	2.4E-01
Benzaldehyde	0.02	0.02	0.00	0.00	0.00	0.00	476	6.8E-07	6.8E-07	4.6E-06	4.6E-06
Benzene	0.60	11.3	0.01	0.17	0.06	1.13	4	2.2E-03	4.2E-02	1.5E-02	2.8E-01
n-Butanol	3.82	9.62	0.06	0.14	0.38	0.96	219	2.6E-04	6.6E-04	1.7E-03	4.4E-03
Butylacetate	0.02	3.70	0.00	0.06	0.00	0.37	429	8.3E-07	1.3E-04	5.5E-06	8.6E-04
Cyclohexane	3.24	85.7	0.05	1.29	0.32	8.57	307	1.6E-04	4.2E-03	1.1E-03	2.8E-02
n-Decanal	0.03	2.39	0.00	0.04	0.00	0.24	41	1.2E-05	8.7E-04	7.7E-05	5.8E-03
n-Decane	0.03	22.7	0.00	0.34	0.00	2.27	333	1.3E-06	1.0E-03	8.7E-06	6.8E-03
Dichloromethane	6.45	69.4	0.10	1.04	0.65	6.94	100	9.7E-04	1.0E-02	6.5E-03	6.9E-02
Diethylether	0.33	25.2	0.00	0.38	0.03	2.52	-	-	-	-	-
n-Dodecane	1.30	8.45	0.02	0.13	0.13	0.85	333	5.9E-05	3.8E-04	3.9E-04	2.5E-03
Ethylacetate	2.69	20.5	0.04	0.31	0.27	2.05	3000	1.3E-05	1.0E-04	9.0E-05	6.8E-04
Ethylbenzene	3.85	8.10	0.06	0.12	0.38	0.81	175	3.3E-04	6.9E-04	2.2E-03	4.6E-03
2-Ethylhexanal	2.13	6.85	0.03	0.10	0.21	0.69	-	-	-	-	-
Formaldehyde	9.41	26.7	0.14	0.40	0.94	2.67	1	2.2E-01	6.4E-01	1.5E+00	4.2E+00
n-Heptane	1.53	7.65	0.02	0.11	0.15	0.77	-	-	-	-	-
n-Hexanal	0.02	7.57	0.00	0.11	0.00	0.76	-	-	-	-	-
n-Hexane	11.5	22.7	0.17	0.34	1.15	2.27	49	3.6E-03	7.0E-03	2.4E-02	4.7E-02
Isopropylbenzene	0.02	3.29	0.00	0.05	0.00	0.33	88	4.2E-06	5.6E-04	2.8E-05	3.8E-03
Limonene	0.03	3.93	0.00	0.06	0.00	0.39	24	1.8E-05	2.5E-03	1.2E-04	1.6E-02
Methylcyclohexane	1.50	7.87	0.02	0.12	0.15	0.79	-	-	-	-	-
Methylcyclopentane	2.73	13.5	0.04	0.20	0.27	1.35	-	-	-	-	-
1-Methyl-2-ethylbenzene	1.84	31.7	0.03	0.47	0.18	3.17	-	-	-	-	-
1-Methyl-3-ethylbenzene	1.61	20.6	0.02	0.31	0.16	2.06	-	-	-	-	-
1-Methyl-4-ethylbenzene	1.38	83.9	0.02	1.26	0.14	8.39	-	-	-	-	-
MethylEthylketone	4.13	13.2	0.06	0.20	0.41	1.32	2606	2.4E-05	7.6E-05	1.6E-04	5.1E-04

2-Methyloctane	0.03	5.92	0.00	0.09	0.00	0.59	333	1.2E-06	2.7E-04	7.9E-06	1.8E-03
2-Methylpentane	0.83	7.24	0.01	0.11	0.08	0.72	-	-	-	-	-
2-Methylpropane	0.01	310	0.00	4.65	0.00	31.0	-	-	-	-	-
3-Methylpentane	1.97	342	0.03	5.14	0.20	34.2	-	-	-	-	-
Naphthalene	0.03	5.94	0.00	0.09	0.00	0.59	3	1.4E-04	3.2E-02	9.4E-04	2.1E-01
n-Nonanal	0.03	2.17	0.00	0.03	0.00	0.22	41	1.1E-05	7.9E-04	7.0E-05	5.3E-03
n-Nonane	0.98	12.2	0.01	0.18	0.10	1.22	333	4.4E-05	5.5E-04	2.9E-04	3.7E-03
n-Octanal	2.20	29.9	0.03	0.45	0.22	2.99	41	8.0E-04	1.1E-02	5.3E-03	7.2E-02
n-Octane	1.74	21.4	0.03	0.32	0.17	2.14	333	7.8E-05	9.6E-04	5.2E-04	6.4E-03
1-Propanol	5.16	15.1	0.08	0.23	0.52	1.51	27000	2.9E-06	8.4E-06	1.9E-05	5.6E-05
2-Propanol	0.01	0.46	0.00	0.01	0.00	0.05	667	2.8E-07	1.0E-05	1.8E-06	6.9E-05
p-Dichlorobenzene	1.15	209	0.02	3.14	0.11	20.9	64	2.7E-04	4.9E-02	1.8E-03	3.3E-01
n-Pentane	0.01	34.7	0.00	0.52	0.00	3.47	-	-	-	-	-
n-Propylbenzene	0.02	4.59	0.00	0.07	0.00	0.46	-	-	-	-	-
a-Pinene	0.03	3.12	0.00	0.05	0.00	0.31	-	-	-	-	-
Styrene	0.02	3.18	0.00	0.05	0.00	0.32	46	7.0E-06	1.0E-03	4.6E-05	6.9E-03
1,2,3-Trimethylbenzene	0.25	163.0	0.00	2.44	0.02	16.30	26	1.4E-04	9.2E-02	9.3E-04	6.2E-01
1,2,4-Trimethylbenzene	0.02	1.38	0.00	0.02	0.00	0.14	26	1.4E-05	7.8E-04	9.3E-05	5.2E-03
1,3,5-Trimethylbenzene	0.25	4.59	0.00	0.07	0.02	0.46	25	1.5E-04	2.8E-03	9.8E-04	1.8E-02
Tetrachloroethylene	0.03	4.43	0.00	0.07	0.00	0.44	73	7.0E-06	9.2E-04	4.7E-05	6.1E-03
n-Tetradecane	2.27	47.7	0.03	0.72	0.23	4.77	333	1.0E-04	2.1E-03	6.8E-04	1.4E-02
Tetrahydrofuran	0.01	9.63	0.00	0.14	0.00	0.96	-	-	-	-	-
Toluene	23.5	78.3	0.35	1.17	2.35	7.83	79	4.5E-03	1.5E-02	3.0E-02	9.9E-02
1,1,1-Trichloroethane	3.42	48.3	0.05	0.72	0.34	4.83	384	1.3E-04	1.9E-03	8.9E-04	1.3E-02
n-Tridecane	0.38	113	0.01	1.69	0.04	11.26	333	1.7E-05	5.1E-03	1.1E-04	3.4E-02
n-Undecanal	0.35	78.0	0.01	1.17	0.03	7.80	-	-	-	-	-
n-Undecane	1.30	6.24	0.02	0.09	0.13	0.62	333	5.9E-05	2.8E-04	3.9E-04	1.9E-03
m,p-Xylene	3.65	17.4	0.05	0.26	0.36	1.74	22	2.5E-03	1.2E-02	1.7E-02	8.0E-02
o-Xylene	1.62	5.27	0.02	0.08	0.16	0.53	22	1.1E-03	3.6E-03	7.5E-03	2.4E-02

* Reference doses (*RfD*s) [μg/kg-body weight/day] were calculated from the estimated human no observed adverse effect level (NOAEL) for organic compounds, $NOAEL_{inh}$ [μg/m^3], reported by Azuma, Uchiyama, and Ikeda [32]. N.A. = Data not available, **-** = No Data.

4. Conclusion

Fifty-five organic compounds, such as VOCs and aldehydes, were measured in 24 car cabins in November 2013 in Yokohama and Kawagoe, Japan to assess car indoor environment. Acetaldehyde, formaldehyde, *n*-tetradecane, toluene, and *n*-undecane were detected in all car cabins. TVOC concentrations observed in 14 car cabins exceeded the advisable value established by the Ministry of Health, Labour and Welfare of Japan (400 $\mu g/m^3$). The highest TVOC concentration (1136 $\mu g/m^3$) was obtained in a new car (1 month after purchase). However, TVOC concentrations surpassed the advisable value in cars purchased over 10 years ago. For formaldehyde, *HQ* values in both exposure scenarios for occupational use were higher than one, indicating the need for a more comprehensive exposure assessment for this compound. The current study is limited in terms of number of vehicles and kinds of organic compounds possibly existing in car cabins. Nonetheless, its results provide useful information on actual car indoor environments.

Acknowledgement

This work was supported by the Japan Society for the Promotion of Science KAKENHI (Grant Number 25241023). We thank Ms. Kanako Naito for technical support.

Conflict of interest

All authors declare no conflicts of interest.

References

1. Klepeis NE, Nelson WC, Ott WR, et al. (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Anal Environ Epid* 11: 231-252.
2. Chen X, Feng L, Luo H, et al. (2014) Analyses on influencing factors of airborne VOCS pollution in taxi cabins. *Environ Sci Pollut Res* 21: 12868-12882.
3. Kim KW, Lee BH, Kim S, et al. (2011) Reduction of VOC emission from natural flours filled biodegradable bio-composites for automobile interior. *J Hazard Mater* 187: 37-43.
4. Zhang GS, Li TT, Luo M, et al. (2008) Air pollution in the microenvironment of parked new cars. *Build Environ* 43: 315-319.
5. Mandalakis M, Stephanou EG, Horii Y, et al. (2008) Emerging contaminants in car interiors: evaluating the impact of airborne PBDEs and PBDD/Fs. *Environ Sci Technol* 42: 6431-6436.
6. Jo WK, Lee JW (2002) In-vehicle exposure to aldehydes while commuting on real commuter routes in a Korean urban area. *Environ Res* 88: 44-51.
7. Baldasano JM, Delgado R, Calbó J (1998) Applying receptor models to analyze urban/suburban VOCs air quality in martorell (Spain). *Environ Sci Technol* 32: 405-412.
8. Mukund R, Kelly TJ, Spicer CW (1996) Source attribution of ambient air toxic and other VOCs in Columbus, Ohio. *Atmos Environ* 30: 3457-3470.

9. Sweet CW, Vermette SJ (1992) Toxic volatile organic compounds in urban air in Illinois. *Environ Sci Technol* 26: 165-173.
10. Chan C-C, Spengler JD, Özkaynak H, et al. (1991) Commuter Exposures to VOCs in Boston, Massachusetts. *J Air Waste Manage Assoc* 41: 1594-1600.
11. Rahman MM, Kim KH (2012) Exposure to hazardous volatile pollutants back diffusing from automobile exhaust systems. *J Hazard Mater* 241-242: 267-278.
12. Brodzik K, Faber J, Łomankiewicz D, et al. (2014) In-vehicle VOCs composition of unconditioned, newly produced cars. *J Environ Sci* 26: 1052-1061.
13. Chien YC (2007) Variations in amounts and potential sources of volatile organic chemicals in new cars. *Sci Total Environ* 382: 228-239.
14. Fedoruk MJ, Kerger BD (2003) Measurement of volatile organic compounds inside automobiles[dagger]. *J Expo Anal Environ Epid* 13: 31-41.
15. Faber J, Brodzik K, Gołda-Kopek A, et al. (2013) Air pollution in new vehicles as a result of VOC emissions from interior materials. *Pol J Environ Stud* 22: 1701-1709.
16. Yoshida T, Matsunaga I (2006) A case study on identification of airborne organic compounds and time courses of their concentrations in the cabin of a new car for private use. *Environ Int* 32: 58-79.
17. Hori H, Ishimatsu S, Fueta Y, et al. (2013) Evaluation of a real-time method for monitoring volatile organic compounds in indoor air in a Japanese university. *Environ Health Preventive Med* 18: 285-292.
18. Brommer S, Harrad S, Van den Eede N, et al. (2012) Concentrations of organophosphate esters and brominated flame retardants in German indoor dust samples. *J Environ Monit* 14: 2482-2487.
19. Chin JY, Godwin C, Jia C, et al. (2013) Concentrations and risks of *p*-dichlorobenzene in indoor and outdoor air. *Indoor air* 23: 40-49.
20. Van den Eede N, Dirtu AC, Neels H, et al. (2011) Analytical developments and preliminary assessment of human exposure to organophosphate flame retardants from indoor dust. *Environ Int* 37: 454-461.
21. Zuraimi MS, Roulet CA, Tham KW, et al. (2006) A comparative study of VOCs in Singapore and European office buildings. *Build Environ* 41: 316-329.
22. Tsai JH, Hsu YC, Weng HC, et al. (2000) Air pollutant emission factors from new and in-use motorcycles. *Atmos Environ* 34: 4747-4754.
23. Watson JG, Chow JC, Fujita EM (2001) Review of volatile organic compound source apportionment by chemical mass balance. *Atmos Environ* 35: 1567-1584.
24. Mendell MJ (2007) Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: a review. *Indoor air* 17: 259-277.
25. Sakai K, Norbäck D, Mi Y, et al. (2004) A comparison of indoor air pollutants in Japan and Sweden: formaldehyde, nitrogen dioxide, and chlorinated volatile organic compounds. *Environ Res* 94: 75-85.
26. Lundgren B, Jonsson B, Ek-Olausson B (1999) Materials Emission of Chemicals – PVC Flooring Materials. *Indoor air* 9: 202-208.
27. Liu W, Zhang J, Zhang L, et al. (2006) Estimating contributions of indoor and outdoor sources to indoor carbonyl concentrations in three urban areas of the United States. *Atmos Environ* 40: 2202-2214.

28. Wolkoff P (1998) Impact of air velocity, temperature, humidity, and air on long-term voc emissions from building products. *Atmos Environ* 32: 2659-2668.
29. You KW, Ge YS, Hu B, et al. (2007) Measurement of in-vehicle volatile organic compounds under static conditions. *J Environ Sci* 19: 1208-1213.
30. Parra MA, Elustondo D, Bermejo R, et al. (2008) Exposure to volatile organic compounds (VOC) in public buses of Pamplona, Northern Spain. *Sci Total Environ* 404: 18-25.
31. Li S, Chen S, Zhu L, et al. (2009) Concentrations and risk assessment of selected monoaromatic hydrocarbons in buses and bus stations of Hangzhou, China. *Sci Total Environ* 407: 2004-2011.
32. Azuma K, Uchiyama I, Ikeda K (2007) The risk screening for Indoor air pollution chemicals in Japan. *Risk Anal* 27: 1623-1638.
33. Saito I, Onuki A, Seto H (2007) Indoor organophosphate and polybrominated flame retardants in Tokyo. *Indoor air* 17: 28-36.