Source Apportionment of Volatile Organic Compounds at an International Airport

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ABSTRACT

Concentrations of 22 volatile organic hydrocarbons (VOCs) were measured at the airport apron of Taipei International Airport, Taiwan, for 48 d in July, September, October, and December of 2011. Forty-eight air samples were collected using stainless steel canisters and analyzed using gas chromatography with a flame ionization detector (GC/FID) and gas chromatography with a mass selective detector (GC/MSD). The five most abundant VOC species on all sampling days were toluene, m,p-xylene, o-xylene, i-pentane, and styrene. Total concentrations of VOCs (TVOC) were 85.38 ± 26.61, 89.70 ± 13.14, and 86.21 ± 14.51 μg/m³ in summer, autumn, and early winter, respectively. Aromatics (36.6–41.4%) represented the largest proportion of TVOCs, followed by i-alkanes (22.9–25.5%), n-alkanes (20.3–21.8%), alkenes (11.5–13.3%) and alkynes (3.0–4.4%). The benzene-to-toluene (B/T) ratio was used to differentiate between exhaust from aircraft ignition and that from ground vehicles at the airport apron. The absolute principal component score (APCS) receptor model was then applied to quantify the contributions of these sources of VOCs at the airport apron.

Keywords: Volatile organic hydrocarbons (VOCs); Airport; Receptor model; Absolute principal component score (APCS).

INTRODUCTION

Several empirical studies of jet-engine emissions have characterized particulate matter (PM), black carbon (BC), carbonyls, NO_x, CO, metals, hydrocarbons (HCs), and polycyclic aromatic hydrocarbons (PAHs) during the standard landing and takeoff (LTO) cycle (Chen *et al.*, 2006; Agrawal *et al.*, 2008; Yu *et al.*, 2010; Kinsey *et al.*, 2011; Mazaheri *et al.*, 2011). In recent years, airport-related emissions, particularly VOCs, have received considerable attention. Determination of VOC concentrations related to aircraft activities during various engine operations have been the focus of few studies (Spicer *et al.*, 1992, 1994). Zhu *et al.* (2011) focused on ultrafine particles, PAHs, and VOCs (i.e., acrolein, benzene, 1,3-butadiene, and formaldehyde) in a field study near the Los Angeles International Airport, USA, to determine the influence of airport operations on local air quality. In another study, 55 VOCs were measured in exhaust at aircraft parking lots and aircraft plumes at Zurich–Kloten airport, Switzerland, to assess the influence of airport operations on local air quality (Schürmann *et al.*,

2007); however, the receptor model did not quantify the source apportionment of atmospheric VOCs at the airport.

Airport ground personnel perform various tasks, such as filling aircraft fuel tanks, routine aircraft maintenance, airplane parking and towing, and baggage charge and discharge, each of which can expose workers to complex chemical mixtures, including several VOCs produced by jet-fuel vapors or combustion, and by diesel and gasoline engine combustion of runway shuttles and baggage trolleys operated near planes. Notably, data for the source apportionment of VOCs at airports are limited. Therefore, this study measures the concentrations of 22 VOC species at the Taipei International Airport (International Air Transport Association code: TSA), an international airport in Taiwan. Potential sources were identified using principal component analysis (PCA), and their contributions to atmospheric VOCs were quantified using the absolute principal component score (APCS).

METHODS

The Sampling Site

The TSA is a midsize commercial airport and military airbase located in Taipei City, Taiwan (N 25°04'10", E 120°33'06"). The airport covers 1.82 km², and has one runway, six taxiways, and eight air bridges. The runway is 2,065 m long and 60 m wide. Flights in and out of TSA

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generally proceed from west to east, flying into the prevailing winds. On average, 162–173 aircraft movements occur daily at TSA. The aircraft using the airport during sampling periods were the Airbus A302, A321, and A330, Boeing 738, 757, 763, and 767, and McDonnell Douglas MD83 and MD90. The ground-support vehicles consist of airport shuttle bus, baggage haulage trucks, potable water trucks, catering vehicles, belt loaders, pushback tugs and tractors, and fuel tracks. The diesel engines include large shuttle bus, belt loaders, pushback tugs and tractors, and fuel tracks.

The sampling site was located roadside between the terminal building/office area and airport apron (Fig. 1). The sampling site was also 150 m from the taxiway area, and 500 m from the runway. The sampler was placed 1.5 m above the ground to acquire samples at a typical breathing level. Table 1 presents meteorological parameters, including atmospheric pressure, temperature, wind speed, wind direction, and relative humidity (RH), each of which was provided by the airport's meteorological station, located approximately 800 m north of the sampling site. Due to some special limitations of sampling for the airport, in this study, the sampling periods from Oct. 24 to Nov. 8 in 2011 are defined as early winter (Table 1). Mean atmospheric pressure was in the range of 1004.4 ± 2.9 to 1015.6 ± 3.1 (hPa), mean temperature was 24.9 ± 2.7 to 31.3 ± 1.9°C, and mean RH was 61.0 ± 8.9 to 74.2 ± 7.6% at TSA during the sampling periods. Prevailing wind directions were NNE/NE, NNE/ESE, and NNE/E during summer, autumn, and early winter, respectively. The highest wind speeds were from northeast monsoonal winds in autumn and early winter.

Samples and Analyses

Sampling was conducted over 48 days in July, September, October, and December of 2011. In total 48 air samples were collected during the three periods. The 10-h sampling period on each day was from 08:00–18:00. A sample of ambient air was drawn through a sampling train comprised of components that regulate the rate and duration of sampling into a pre-evacuated specially prepared passivated canister. Air sampling of C_2–C_{12} hydrocarbons was conducted using 6 L polished stainless steel canisters with a high vacuum of 10^{-4} Torr, certified according to the U.S. EPA Method TO-14. Sampling flow rate was controlled by a
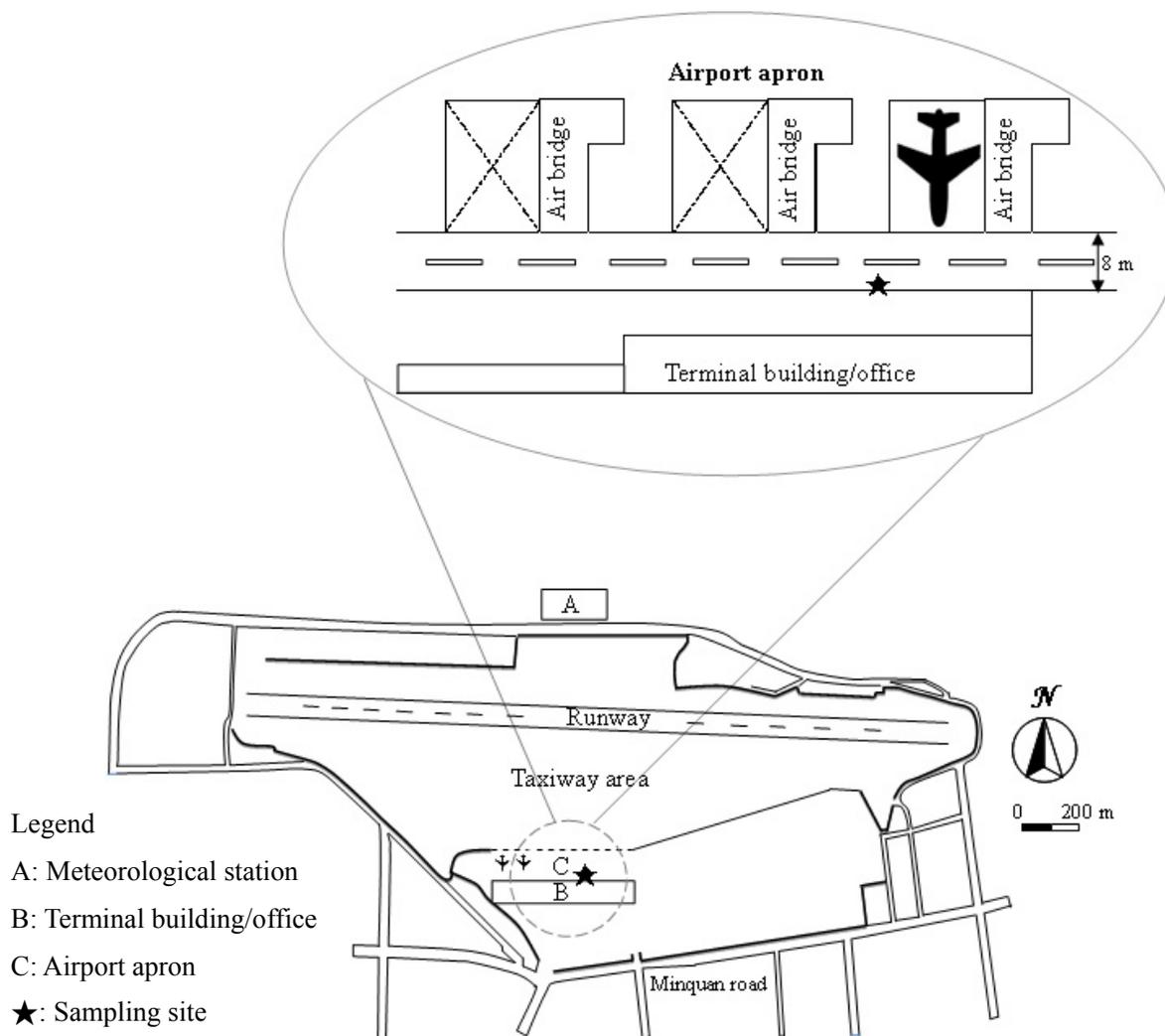

Fig. 1. Map of the measurement site at the airport apron of Taipei International Airport.

Table 1. Meteorological conditions at the Taipei International Airport during sampling periods.

Date	Pressure (hPa)	Temperature (°C)	Wind speed (m/s)	Relative humidity (%)	Wind direction
(a) *Summer*					
07/11–07/26	1004.4 ± 2.9	31.3 ± 1.9	4.1 ± 1.6	61.0 ± 8.9	NNE[a]/NE[b]
(b) *Autumn*					
09/15–09/30	1010.1 ± 2.8	28.1 ± 2.9	5.1 ± 2.1	61.3 ± 5.8	NNE/ESE[c]
(c) *Early winter*					
10/24–10/31	1018.4	23.1	5.4	70.4	NNE
11/01–11/08	1012.8	26.8	4.3	78.0	E[d]
Mean ± SD	1015.6 ± 3.1	25.0 ± 2.7	4.9 ± 1.6	74.2 ± 7.6	

[a] NNE: north-northeast; [b] NE: northeast; [c] ESE: east-southeast; [d] E: east.

flow controller at a constant flow rate of 10 mL/min for the 10-h sampling period. To prevent accumulation of water and other contaminants, the sampler was operated prior to sampling without attaching the can to purge all lines in the sampler with clean particle-free dry air.

Canisters were cleaned in the laboratory, pressurized with humidified zero air at approximately 100°C prior to sampling, and air sampler was pre-concentrated in a purge-and-trap system (Entech 7100 instrument). Samplers were subsequently analyzed using a GC/FID (HP-6890) and a GC/MSD (HP-5973 N Mass Spectrometer). The GC/FID was utilized to quantify concentrations of C_2 hydrocarbons. Separation was achieved using a capillary column (60m long, 0.32 mm I.D., 3.0 μm film thickness RTX-1 column). A GC/MS was used to identify and quantify C_3–C_{12} hydrocarbons. These hydrocarbons were separated in a 60-m-long, DB-1 fused silica column (J&W Scientific, USA) with an I.D. of 0.32 mm, coated with a 1.0-μm-thick polydimethylsiloxane film. Quality control and assurance required the establishment of GC retention times, R^2 calibration, the method detection limit, and the reproducibility of all compound analyses. The relative standard deviation (SD) was 5–15%, within the acceptable range of ± 20%. Precision, determined from five replicate analyses of standards and samples, was within ± 15% for compounds at concentrations exceeding 5 ppb.

Source Identification Using PCA and the APCS

Receptor-oriented source apportionment models have been used frequently to identify sources of ambient air pollutants and to estimate source contributions to air pollutant concentrations. The most commonly used models are the chemical mass balance (CMB), principal component analysis (PCA)/absolute principal component scores (APCS), positive matrix factorization (PMF), and graphical ratio analysis for composition estimates (GRACE)/source apportionment by factors with explicit restriction (SAFER), incorporated into the UNMIX model. The PCA/APCS, PMF, and UNMIX are all multivariate receptor models, that analyze a series of observations simultaneously in an attempt to determine the number of sources, their chemical composition and their contributions to each observation (Miller *et al.*, 2002). Multivariate models do not require extensive knowledge about the number and nature of sources. Nice feature of these analyses is the ability to summarize a multivariate data set using a few components.

This study conducted multivariate factor analysis using PCA to identify potential sources of atmospheric VOCs. The PCA transformed a large set of original variables into a smaller set of new variables. These new variables (i.e., factors) are linear combinations of the original variables and hopefully explain most (typically 80–90%) total variance in observed data (Derwent *et al.*, 1995; Johnson and Wichern, 2002). In this study, factors were extracted using PCA, which involves varimax orthogonal rotation, to determine the eigenvalues of the variance matrix of original variables; factors with eigenvalues > 1 were typically chosen. Once a factor is determined by PCA, it consists of patterns of variation of factor loadings of input parameters. The correlation between a specific pollutant and a factor increases as factor loading increase. The characteristics of a factor can then be inferred from dominant pollutants, such as VOCs and semi-VOCs (Ho *et al.*, 2002; Lai *et al.*, 2009; Wang *et al.*, 2010a, b).

Notably, factor loadings in PCA only provide the relative influences of individual pollution sources on specific pollutants. The contributions of individual sources to specific pollutants can be determined using the APCS (Guo *et al.*, 2004a; Chen *et al.*, 2008; Lai *et al.*, 2009; Wang *et al.*, 2010b). With the APCS, the concentration of each pollutant at each sampling site was normalized with respect to its mean and standard deviation. For PCA, the new standardized variables with zero means and unit variances are expressed as a linear combination of pollution sources and pollutants in source profiles, which can then be solved by varimax orthogonal rotation to identify the coefficients and therefore the absolute scores (or contributions) of the pollution sources. Like all other multivariate receptor models, the PCA and APCS models require adequate source profiles and degrees of freedom to perform regressions. Furthermore, these receptor models may not be able to differentiate between similar sources. The collinear problem can be overcome by combining similar sources into one category (Ho *et al.*, 2002; Guo *et al.*, 2004b; Karar *et al.*, 2007), or by using other methods, such as EPA library profiles (SPECIATE Version 4.3) (EPA, 2011) to help identify probable sources.

RESULTS AND DISCUSSION

Characterization of VOCs at the Airport Apron

Only 22 VOC species of the 55 US EPA-Photochemical

Assessment Monitoring Stations (PAMS) pollutants were identified at the airport apron. Table 2 lists the mean and SD of the 22 VOCs obtained at the airport apron during sampling periods. Total VOCs (TVOC) were 85.38 ± 26.61, 89.70 ± 13.14, and 86.21 ± 14.51 μg/m³ in summer, autumn, and early winter, respectively. The TVOC concentration in autumn was 1.1 and 1.0 times higher than that in summer and early winter, respectively. The VOC levels were possible affected from airport outside road emissions when prevailing wind direction was ESE in autumn (Table 1). TVOC levels were slightly elevated between autumn and other sampling seasons (Table 2). In addition, Table 1 also indicates that the highest temperature occurs in summer, this finding agrees with that higher solar radiation usually accompanies with higher temperature. Therefore, high temperature is associated with high losses of TVOC by photochemical degradation. Notably, differences in TVOC levels among the three seasons were not statistically significant by non-parametric one-way analysis of variance (Kruskal-Wallis test) (χ^2 = 0.096, *p*-value = 0.953). The

average VOC compositions were very similar in the three seasons (Fig. 2). The weight percentage of the 22 VOCs that are marked with an asterisk (Fig. 2) were statistically significant ($p < 0.05$), by Kruskal-Wallis test. Only eight VOCs differed significantly among seasons. These species reflect the residual VOC mixture of aircraft and vehicle exhausts (i.e., ethylene, acetylene, and propene) and fuel constituents (i.e., n-propane, n-butane, and i-pentane) (Schürmann *et al.*, 2007).

In the other hand, these ground vehicle operations are close to sampling site when aircraft arrival or departure. The relatively high error bar of toluene should be attributed to vehicle exhaust from light-duty gasoline engines and diesel engines at the airport. It may also because of the mass fraction of toluene are relatively higher than other species (Table 3). Although variations in VOC levels are also influenced by photochemical reaction, photochemical reaction rate of toluene is relatively lower than other VOCs (Atkinson, 1990). However, VOC concentrations are affected by individual emission rates rather than just chemical

Table 2. Concentrations (mean ± SD) of 22 VOCs at the TSA airport apron (unit: μg/m³).

No.	VOC species	Summer (*n* = 16)		Autumn (*n* = 16)		Early winter (*n* = 16)	
		Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
	n-Alkanes						
1	Ethane	2.36 ± 0.36	2.03–3.11	2.96 ± 1.39	1.94–5.93	3.17 ± 0.76	2.22–4.07
2	n-Propane	2.55 ± 1.01	1.40–4.03	2.51 ± 1.24	1.42–4.79	2.29 ± 0.76	1.63–3.80
3	n-Butane	4.46 ± 0.53	3.70–5.31	4.24 ± 0.68	3.51–5.61	3.41 ± 2.15	1.91–8.12
4	n-Pentane	2.47 ± 0.22	2.24–2.87	2.43 ± 0.38	1.89–2.90	2.76 ± 0.37	2.07–3.26
5	n-Hexane	3.27 ± 0.23	3.08–3.77	3.55 ± 0.29	3.12–3.88	3.39 ± 0.57	2.87–4.60
6	n-Heptane	2.74 ± 0.10	2.59–2.87	2.56 ± 0.23	2.14–2.82	3.77 ± 0.28	3.29–4.12
	i-Alkanes						
7	i-Butane	3.33 ± 0.96	2.31–4.85	3.91 ± 1.08	2.34–5.38	2.86 ± 1.48	2.15–6.21
8	i-Pentane	6.15 ± 1.19	4.88–8.03	4.43 ± 2.26	2.93–9.00	4.25 ± 1.79	2.96–8.00
9	2,3-Dimethylbutane	2.97 ± 0.18	2.71–3.12	2.74 ± 0.31	2.25–3.09	3.31 ± 0.36	2.83–3.89
10	2-Methylpentane	3.01 ± 0.25	2.64–3.43	3.05 ± 0.23	2.77–3.47	3.14 ± 0.25	2.83–3.54
11	3-Methylpentane	3.15 ± 0.21	2.78–3.39	3.07 ± 0.20	2.84–3.47	3.10 ± 0.31	2.76–3.54
12	2,2,4-Trimethyl pentane	3.16 ± 0.12	2.95–3.32	3.37 ± 0.38	2.76–3.72	3.94 ± 0.46	3.28–4.69
	Alkenes						
13	Ethylene	3.73 ± 0.36	3.46–4.46	4.35 ± 0.50	3.95–5.42	5.02 ± 0.46	4.38–5.53
14	Propene	1.36 ± 0.12	1.17–1.54	1.38 ± 0.14	1.19–1.52	1.88 ± 0.21	1.69–2.25
15	1-Butene	1.84 ± 0.19	1.56–2.07	1.78 ± 0.26	1.35–2.03	2.15 ± 0.16	1.84–2.30
16	Isoprene	2.88 ± 0.32	2.41–3.25	3.11 ± 0.26	2.74–3.56	2.41 ± 0.26	1.96–2.80
	Alkynes						
17	Acetylene	2.57 ± 0.31	2.28–3.21	3.10 ± 0.58	2.52–4.19	3.76 ± 1.16	2.67–6.21
	Aromatics						
18	Benzene	0.70 ± 0.08	0.64–0.86	0.69 ± 0.02	0.65–0.73	0.71 ± 0.03	0.66–0.74
19	Toluene	16.60 ± 14.33	4.76–41.42	17.17 ± 26.38	4.08–75.68	14.50 ± 12.57	4.92–40.13
20	Styrene	4.28 ± 0.47	3.73–4.97	4.73 ± 0.31	4.19–5.03	4.35 ± 0.51	3.85–5.14
21	m,p-Xylene	7.21 ± 0.21	6.97–7.60	7.48 ± 0.36	7.05–8.12	7.97 ± 0.69	6.54–8.72
22	o-Xylene	4.59 ± 0.61	3.89–5.49	7.08 ± 0.42	6.41–7.69	4.06 ± 0.36	3.49–4.36
	TVOC ± TSD[a]	85.38 ± 26.61		89.70 ± 13.14		86.21 ± 14.51	
	n-Alkanes	20.9%		20.3%		21.8%	
	i-Alkanes	25.5%		22.9%		23.9%	
	Alkenes	11.5%		11.8%		13.3%	
	Alkynes	3.0%		3.5%		4.4%	
	Aromatics	39.1%		41.4%		36.6%	

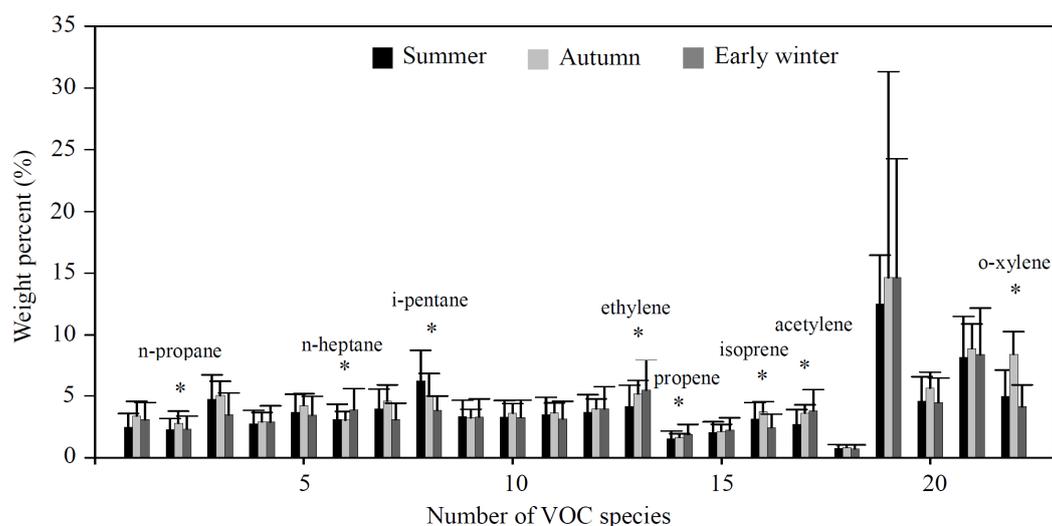[a] TSD = $(\Sigma SD_i^2)^{1/2}$, where SD_i is the standard deviation of the compound *i*.

Fig. 2. Comparison of VOC chemical compositions in the three seasons. Numbers correspond to the number per compound, as in Table 2.

Table 3. Mass fractions of 11 source profiles from SPECIATE 4.3 library files (unit: weight %).

VOC species	Aircraft exhaust			Vehicle exhaust							
	All power engines burning	Idle power engines burning	Aircraft Land/ takeoff	Heavy-duty gasoline engines	light-duty gasoline engines				Diesel engines		
	#1216	#1217	#1098	#1186	#1203	#1204	#1101	#2521	#2520	#2526
Ethane	1.6	1.73	0.88	0.69	1.79	0.03	1.41	1.65	1.08	0.42
n-Butane	–	–	–	22.42	3.81	28.34	9.48	1.97	0.59	2.5
n-Propane	0.18	0.18	0.18	–	–	1.54	0.56	0.11	2.03	0.83
n-Pentane	0.46	0.49	0.21	4.86	1.6	4.67	2.88	2.94	1.39	2.44
n-Hexane	0.64	0.67		1.53	0.67	0.72	0.87	1.43	0.88	1.62
n-Heptane	1.58	1.77	0.06	0.73	0.53	0.52	0.65	0.74	0.52	0.81
i-Butane	–	–	–	3.43	0.62	6.56	1.7	0.23	0.25	0.8
i-Pentane	–	–	–	11.04	3.51	13.6	6.54	9.72	1.2	8.1
2,3-Dimethylbutane	–	–	–	0.98	0.53	1.04	0.69	1.17	0.29	0.84
2-Methylpentane	0.91	0.97	0.39	2.81	1.27	2.28	1.76	3.14	1.81	2.63
3-Methylpentane	0.6	0.65	–	1.54	0.86	1.17	1.09	1.76	0.83	1.62
2,2,4-Trimethyl pentane	–	–	–	1.5	1.95	0.59	1.97	3.51	1.36	1.74
1-Butene	3.35	3.38	1.97	1.11	–	–	0.85	1.69	2.7	3.08
Propene	9.5	9.61	5.15	1.57	2.88	–	1.06	2.54	3.66	4.27
Ethylene	25.73	24.71	17.45	4.35	8.41	0.03	3.92	6.67	9.05	9.3
Isoprene	–	–	–	0.1	0.17	–	0.07	0.33	–	0.46
Acetylene	11.11	10.69	4.17	2.66	2.25	0.01	0.75	2.28	2.34	1.68
Benzene	1.61	1.58	1.94	1.75	1.62	0.66	1.39	4.5	2.92	3.66
Toluene	1.83	1.94	0.52	2.98	5.72	8.51	5.14	8.68	4.12	5.87
Styrene	0.59	0.65	0.39	–	–	–	–	0.96	1.7	1.22
m,p-Xylene	1.86	2.04	0.29	–	–	–	–	7.27	10.07	4.59
o-Xylene	0.62	0.68	0.19	0.91	1.76	0.87	1.56	2.67	3.42	1.82

"–": No data.

reactions (Lai *et al.*, 2004). Thus, the seasonal effects of VOC concentrations may have been minor during sampling periods. Variations in VOC concentrations may be affected directly by airport emissions.

The most abundant species in the three seasons was toluene (14.50–17.17 μg/m³), followed by m,p-xylene, o-xylene, i-pentane, and styrene, with concentrations in the range of 4.06–7.97 μg/m³ (Table 2). Aromatics (36.6–41.4%) represent the largest proportion of TVOC, followed by i-alkanes (22.9–25.5%), n-alkanes (20.3–21.8%), alkenes (11.5–13.3%), and alkynes (3.0–4.4%). Although the fuel compositions may affect the exhaust characteristics of ground vehicles and aircraft, only limited information is available about the VOC compositions of fuel in Taiwan.

However, gasoline compositions in recent literature that have reported similar target species, including n-butane, n-pentane, 2-methyl butane, toluene, and m,p-xylene (Harley and Kean, 2004; Na *et al.*, 2004; Chin and Batterman, 2012). In a 2006 study of diesel fuel in Taiwan, the top five VOCs were C_{13}–C_{16} and C_{18} straght-chain alkanes, accounting for 46% of target compounds (Peng *et al.*, 2006). Chin and Batterman (2012) indicated that C_9–C_{16} straght-chain alkanes of diesel fuel were dominant and account for 90% of TVOCs. Branched paraffines (29.94%) represent the largest proportion of C_5–C_9 VOC composition of jet fuels, follow by monocyclic paraffines (20.34%), n-paraffines (19.69%), alkyl benzenes (14.05%), and others (15.98%) (van der Westhuizen *et al.*, 2011).

Moreover, Schürmann *et al.* (2007) demonstrated that aircraft engine ignition emits some highly volatile alkanes, such as n-propane, n-butane, i-pentane, and n-pentane, and high aromatics (*i.e.*, toluene, xylene, and styrene). During initial aircraft taxiing, high amounts of C_2–C_3 alkenes are existed, increasing the values of highly volatile alkanes and high aromatics during the intermediate stage of aircraft taxiing. Isoprene (2.41–3.11 µg/m^3) was also emitted in significant amounts at the airport apron. Although isoprene is generally emitted by biological sources, it has been identified in traffic exhaust (Borbon *et al.*, 2001; Lai *et al.*, 2011; Lai and Peng, 2012). Isoprene is formed during aircraft combustion of kerosene (Schürmann *et al.*, 2007). Therefore, the VOC compositions in fuel were different to those from engine exhausts. Determining whether this VOC is from aircraft and vehicle exhaust is difficult. This study used the benzene-to-toluene (B/T) ratio to determine whether collected VOC levels were from aircraft exhaust or vehicle exhaust (this is discussed later).

Comparison of the Benzene-to-toluene Ratio with Those in Other Studies

Table 4 shows the B/T ratios at the TSA's airport apron of approximately 0.11–0.73, 0.05–0.85, and 0.09–0.73 in summer, autumn, and early winter, respectively. Because benzene and toluene levels were not statistically significant (Fig. 2), differences in B/T ratios during the three seasons were small. However, B/T ratios may differ due to airport operating characteristics, sampling sites, meteorological conditions, aircraft types, aircraft handling frequency, and emissions from nearby areas. Analytical results for B/T ratio are similar to, and different from, those obtained by other studies. During aircraft ignition, engines have not yet reached their final temperature; thus, high aromatic compounds are still relatively stable, as characterized by a B/T ratio well below 1 (Schürmann *et al.*, 2007). The B/T ratios during the intermediate stage of aircraft taxiing were similar to those during ignition. For example, B/T ratios were approximately 0.24–1.47 and 0.29–1.08 at Pier A (aircraft parking and handling), and Pier B (long-term parking and no handling) at Switzerland's Zurich Airport. Spicer *et al.* (1985) demonstrated that an approximate B/T ratio of 1.6 is typical for aircraft kerosene exhaust during aircraft taxiing.

The B/T ratio (0.05–0.85) at TSA is similar to that in the parking lot (aircraft handling) (0.54–0.59) at the Zurich Airport, to that in the exhaust plume during aircraft ignition (0.18–0.66) and that in vehicle exhaust (0.24–0.62). Although a low B/T ratio may suggest nearby sources are the dominant contributors, long-range transport was minor, and a B/T ratio exceeding 0.5 does not necessarily imply that this contribution is from vehicle emissions (Lai *et al.*, 2005). However, this study suggests that exhaust from aircraft ignition and ground vehicles may directly affect VOCs at the airport apron.

Source Identification Using PCA and APCS

This study applied PCA to identify potential emission

Table 4. Benzene/toluene (B/T) ratio in airport exhaust measured in this and other studies.

Exhaust source	Benzene/Toluene (B/T)	Reference
Airport apron[a]		
TSA apron (handling)		this study
Summer	0.11–0.73	
Autumn	0.05–0.85	
Early winter	0.09–0.73	
Zurich airport in Switzerland		
Pier A (aircraft parking and handling)	0.24–1.47	Schürmann *et al.* (2007)
Pier B (long-term parking and no handling)	0.29–1.08	Schürmann *et al.* (2007)
parking lot (handling)	0.54–0.59	Schürmann *et al.* (2007)
Exhaust plume of aircraft[a]		
ignition	0.18–0.66	Schürmann *et al.* (2007)
idle	1.51–1.72	Schürmann *et al.* (2007)
taxiing	1.44–1.63	Schürmann *et al.* (2007)
Vehicle exhaust		
Traffic tunnel[a]	0.39–0.62	Lai *et al.* (2011)
Light-duty vehicle[b]	0.24	Kawashima *et al.* (2006)
Heavy-duty vehicle[c]	0.6	Kawashima *et al.* (2006)

[a] Unit: ppbv; [b] light-duty passenger vehicles and light-duty trucks (under approximately 2 ton gross weight); [c] diesel trucks (above approximately 2 ton gross weight).

sources of VOCs. However, substantial overlap exists in source profiles, particularly when two or more emission sources are similar. Under such a scenario, PCA often fails to distinguish between similar sources because of collinearity problems; notably, Miller *et al.* (2002) evaluated the performance of four receptor models. One method of overcoming collinearity is to combine similar sources into one category. Because atmospheric VOCs at the airport apron are emitted from many sources, similar source profiles in chemical composition were combined. The abundant species of source profiles in SPECIATE 4.3 (EPA, 2011) would be helpful in identifying probable sources. Table 3 shows the 10 source profiles associated with airport pollution sources from SPECIATE 4.3 library files. Because different VOC species exist in individual source profiles in the SPECIATE 4.3 library, Table 3 lists only the related 22 VOCs.

Table 5 presents PCA factor loading results for the 22 VOCs at the airport apron during the three seasons. During summer, three primary factors (sources): vehicle exhaust from heavy-duty gasoline engines/aircraft exhaust (FC1: 65.47%), vehicle exhaust from diesel engines (FC2: 14.50%),

and vehicle exhaust from light-duty gasoline engines (FC3: 10.99%). These three sources accounted for approximately 90.96% of total variance at the airport apron.

The dominant FC1 species were n-butane, n-pentane, i-pentane, 2-methyl pentane, and 3-methyl pentane. These species are related to heavy-duty gasoline engines (Profile #1186–SPECIATE 4.3) (EPA, 2011). In addition to emissions from heavy-duty gasoline engines, n-heptane, isoprene, and acetylene exist in aircraft exhaust (Profile #1098, Profile #1217, Profile #1216) (Schürmann *et al.*, 2007; EPA, 2011).

The dominant FC2 species were 1-butene, propene, benzene, toluene, styrene, and m,p-xylene, which are associated with diesel engine emissions (Profile #2520, Profile #2526) (EPA, 2011).

Notably, i-butane, 2,2,4-trimethyl pentane, and ethylene were the dominant FC3 species emitted from light-duty gasoline engines (Profile #1101, Profile #1203, Profile #1204) (EPA, 2011).

Three factors at the airport apron accounted for approximately 94.42% of total variance in autumn (Table 5). Notably, FC1 explained 69.45% of total variance; the

Table 5. Factor loadings of PCA results for the TSA airport apron during the three seasons.

VOC species	Summer			Autumn			Early winter			
	FC1	FC2	FC3	FC1	FC2	FC3	FC1	FC2	FC3	FC4
Ethane	0.34	**0.80**	0.42	**0.99**			0.32	0.47	0.13	**0.77**
n-Butane	**0.83**	0.41	0.19	**0.89**	0.36	–0.22	**0.94**	–0.21		–0.25
n-Propane	**0.72**	0.67		**0.89**	0.17	0.33	**0.95**	–0.30		0.12
n-Pentane	**0.70**	0.17	0.68	**0.95**	0.23	0.12	–0.54	**0.82**		0.15
n-Hexane	0.56	0.32	**0.72**		**0.91**	0.34	**0.93**	–0.11		–0.32
n-Heptane	**0.93**		0.32	0.16	**0.98**		0.41	–0.41	**0.77**	–0.23
i-Butane		0.36	**0.84**	0.63	**0.73**		**0.87**	–0.36		–0.33
i-Pentane	**0.89**	0.37	0.14	**0.95**	0.23	0.12	0.24	0.64	0.49	0.12
2,3-Dimethylbutane	**0.95**			0.42	**0.80**	0.30	**0.91**		0.39	
2-Methylpentane	**0.79**	0.44	0.29	**0.81**	0.54	0.20	–0.21	**0.96**	0.12	
3-Methylpentane	**0.89**	0.20		**0.85**	0.42	0.23		0.55	0.54	0.59
2,2,4-Trimethyl pentane			**0.96**	0.34	**0.84**	0.40	–0.22	0.45	0.53	0.65
1-Butene	0.31	**0.70**	0.27	0.47	**0.80**	–0.36	–0.49	**0.81**		0.29
Propene		**0.96**	0.12	0.51	0.62	0.55	–0.16	0.24	**0.73**	0.28
Ethylene	0.43	0.38	**0.81**	**0.96**	0.25		–0.56	–0.26	0.12	**0.72**
Isoprene	**0.86**	0.27	0.20	**0.81**	0.53	–0.15	**0.91**		0.19	0.22
Acetylene	0.64	0.65	0.31	**0.79**	0.42	0.32	**0.93**	–0.34		
Benzene	0.55	**0.70**	0.45	**0.70**	0.67		0.53		**0.82**	–0.19
Toluene	0.31	**0.92**			0.12	**0.88**	**0.91**	–0.37	0.16	
Styrene	0.63	**0.75**		0.54		**0.72**			**0.85**	0.33
m,p-Xylene		**0.89**	0.42	**0.84**	0.14	0.52	–0.65	**0.71**		0.21
o-Xylene	0.57	0.66		0.68	0.49	0.47	**0.73**	0.63	–0.15	
Eigenvalue	14.40	3.19	2.42	15.28	2.82	2.67	10.80	5.83	2.66	1.42
%Total variance	65.47	14.50	10.99	69.45	12.82	12.15	49.09	26.49	12.07	6.47
Cumulative %	65.47	79.97	90.96	69.45	82.27	94.42	49.09	75.58	87.65	94.12
Source	vehicle exhaust (heavy-duty gasoline engines)/ aircraft exhaust	vehicle exhaust (diesel engines)	vehicle exhaust (light-duty gasoline engines)	aircraft exhaust/ vehicle exhaust (heavy-duty gasoline engines)	vehicle exhaust (light-duty gasoline engines)	others	vehicle exhaust (light-duty gasoline engines)/ aircraft exhaust	vehicle exhaust (heavy-duty gasoline engines)	vehicle exhaust (diesel engines)	others

high loadings of isoprene, acetylene, ethylene, and benzene are related to aircraft exhaust (Profile #1098, Profile #1217, Profile #1216) (EPA, 2011; Schürmann *et al.*, 2007), whereas n-butane, n-propane, n-pentane, i-pentane, 2-methyl pentane and 3-methyl pentane are related to emissions from heavy-duty gasoline engines (Profile #1186) (EPA, 2011). FC2, which accounted for 12.82% of total variance, is associated with emissions from light-duty gasoline engines, with high loadings of n-hexane, i-butane, 2,3-dimethyl butane, and 2,2,4-trimethyl pentane (Profile #2521) (EPA, 2011). Additionally, FC3, accounted for 12.15% of total variance, is associated with the others, and sources of toluene and styrene were difficult to identify.

During early winter, the following four factors at the airport apron accounted for approximately 94.12% of total variance (Table 5): vehicle exhaust from light-duty gasoline engines/aircraft exhaust (FC1: 49.09%); vehicle exhaust from heavy-duty gasoline engines (FC2: 26.49%); vehicle exhaust from diesel engines (FC3: 12.07%); and exhaust from other sources (FC4: 6.47%).

The APCS receptor model was then applied to quantify the contributions of these sources at the airport apron. Exhausts from heavy-duty gasoline engines and aircraft contributed most (46.55 ± 30.82%), followed by exhaust from light-duty gasoline engines (30.49 ± 29.46%), and diesel engines (22.96 ± 18.31%) in summer (Fig. 3(a)). Vehicle exhaust from light-duty gasoline engines contributed most (45.43 ± 26.94%), followed by aircraft exhaust/exhaust from heavy-duty gasoline engines (42.06 ± 24.18%), and other emission sources (12.51 ± 29.79%) in autumn (Fig. 3(b)). In early winter, exhaust from diesel engines contributed most (41.06 ± 21.05%), followed by exhaust from light-duty gasoline engines/aircraft (33.96 ± 29.76%), vehicle exhaust from heavy-duty gasoline engines (23.94 ± 14.38%), and exhaust from other sources (1.04 ± 1.01%) (Fig. 3(c)).

APCS indicate that only vehicular emissions and aircraft exhaust were the dominant sources of ambient VOCs at the airport apron. However, other sources were difficult to identify. When emission contributions excluded combined similar sources (i.e., vehicle exhaust/aircraft exhaust), the contribution of vehicle exhaust to TVOC was estimated to contribute about 45.43–65% during the three seasons. Notably, these values may vary from case to case, since atmospheric VOC levels at the airport apron were influenced by many factors, including the amount of airport exhaust, seasons, photochemical reactions, wind speed, wind direction, and other pollution sources. We suggest that ground vehicle exhaust was higher than aircraft exhaust at the airport apron (Fig. 3).

CONCLUSIONS

Concentrations of VOCs were investigated at the airport apron of the Taipei International Airport, Taiwan. The most
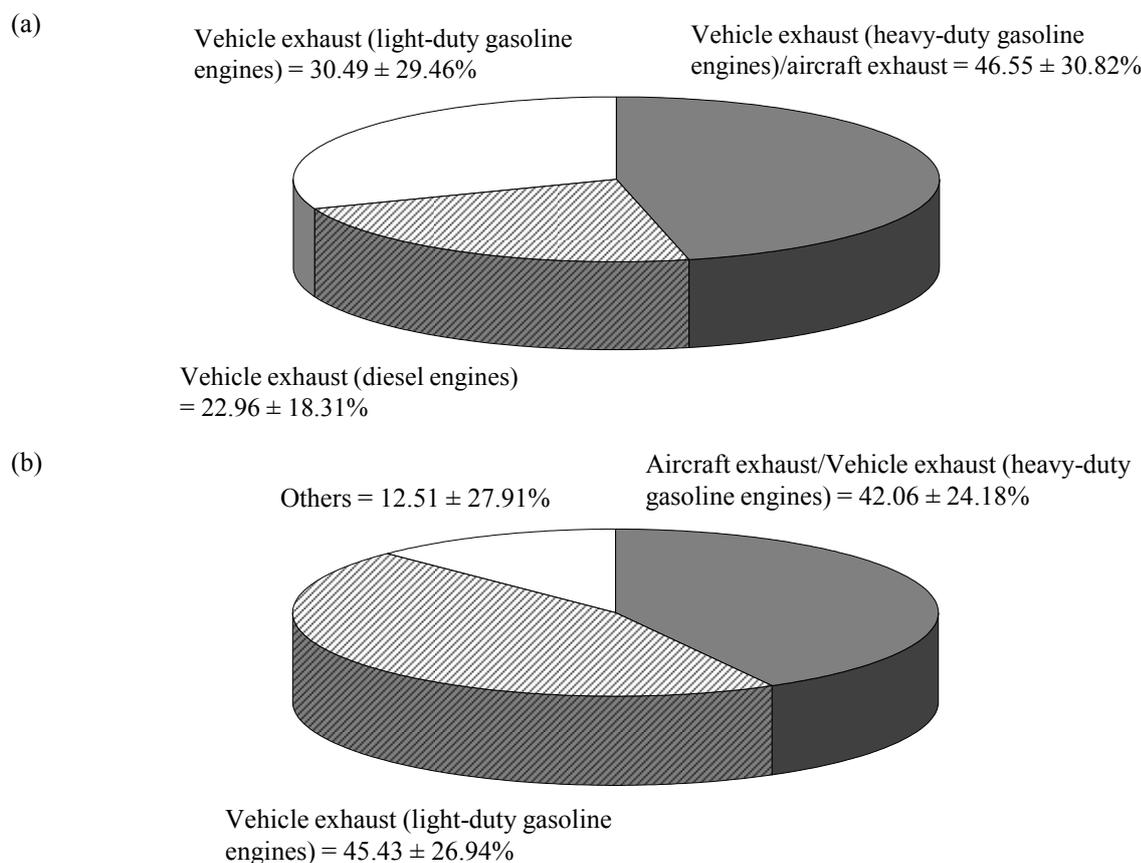

Fig. 3. Average source contributions (% of calculated mass ± SD) to TVOC by APCS results at the TSA airport apron in (a) summer, (b) autumn, and (c) early winter.
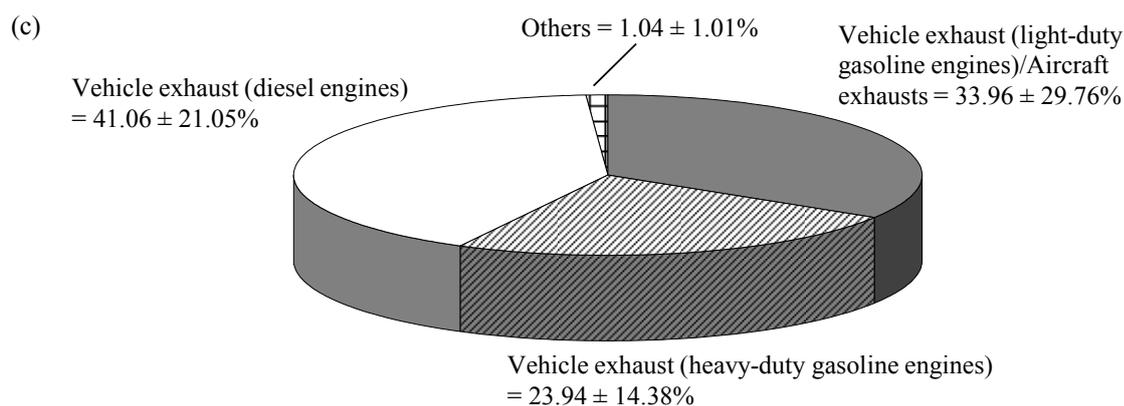
(c)

Others = 1.04 ± 1.01%

Vehicle exhaust (light-duty gasoline engines)/Aircraft exhausts = 33.96 ± 29.76%

Vehicle exhaust (diesel engines) = 41.06 ± 21.05%

Vehicle exhaust (heavy-duty gasoline engines) = 23.94 ± 14.38%

Fig. 3. *(continued).*

abundant species in the three seasons was toluene (14.50–17.17 $\mu g/m^3$). The next most abundant species were m,p-xylene, o-xylene, i-pentane and styrene, with concentrations in the range of 4.06–7.97 $\mu g/m^3$. Isoprene (2.41–3.11 $\mu g/m^3$) is emitted in significant amounts at the airport apron, and may be found in vehicle exhaust and produced by aircraft kerosene combustion. The B/T ratio was approximately 0.05–0.85 at the TSA airport apron, suggesting that VOC exhaust at the airport apron may be directly affected by aircraft ignition exhaust and that from ground vehicles. APCS demonstrate that vehicular emissions and aircraft exhaust are the dominant sources of ambient VOCs at the airport apron. In this study, ground vehicle exhaust was higher than aircraft exhaust at the airport apron. Furthermore, PCA/APCS receptor models may not be able to separate sources that are strongly correlated. Therefore, future studies can analyze local source profiles of airport emissions (e.g., exhaust from aircraft, airport ground traffic, cargo-handling vehicles, and aircraft taxiing) to assess the influence of VOCs on air quality.

ACKNOWLEDGMENTS

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