Atmospheric Environment 258 (2021) 118491

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Real-world emissions of carbonyls from vehicles in an urban tunnel in south China

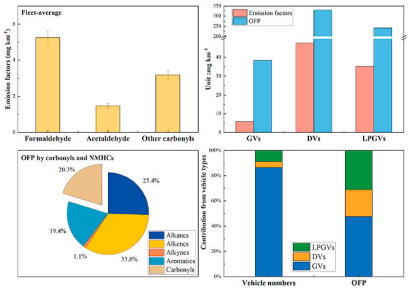
Zhenfeng Wu [a,b], Yanli Zhang [a,c,*], Chenglei Pei [b,d], Zuzhao Huang [e], Yujun Wang [d], Yanning Chen [d], Jianhong Yan [f], Xiaoqing Huang [a,b], Shaoxuan Xiao [a,b], Shilu Luo [a,b], Jianqiang Zeng [a,b], Jun Wang [a,b], Hua Fang [a,b], Runqi Zhang [a,b], Sheng Li [a,b], Xuewei Fu [a,b], Wei Song [a], Xinming Wang [a,b,c,**]

[a] State Key Laboratory of Organic Geochemistry and Guangdong Key Laboratory of Environmental Protection and Resources Utilization, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, China
[b] University of Chinese Academy of Sciences, Beijing, 100049, China
[c] Center for Excellence in Regional Atmospheric Environment, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, 361021, China
[d] Guangzhou Environmental Monitoring Center, Guangzhou, 510030, China
[e] Guangzhou Environmental Technology Center, Guangzhou, 510030, China
[f] Guangzhou Tunnel Development Company, Guangzhou, 510133, China

HIGHLIGHTS

- Real-world vehicular carbonyl emissions were tested in an urban tunnel.
- Formaldehyde was the major species accounting for over half of carbonyl emissions.
- EFs for each fuel type vehicles were obtained via multiple regession analysis.
- Carbonyls could contributed ~20% of the total OFP by vehicular NMHCs and VOCs.
- The OFP of carbonyls from LPGVs was about 5 times that from GVs on average.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Carbonyls
Emission factor
Vehicle exhaust
Tunnel test
On-road vehicles
Ozone formation potential (OFP)

ABSTRACT

Carbonyls play a vital role in atmospheric photochemistry. Vehicle emission is among most important primary emission sources of carbonyls in urban areas, yet knowledge is quite scarce about real-world emissions of carbonyls with the changing on-road vehicle fleets. In this study, emissions of carbonyls were characterized based on tests in a busy urban tunnel in south China. Emission factor (EF) of carbonyls was measured to be 9.89 ± 0.65 mg km^{-1} on average, in which formaldehyde alone shared 53.1% with an EF of 5.25 ± 0.35 mg km^{-1}, followed by acetaldehyde with an EF of 1.47 ± 0.13 mg km^{-1}. Glyoxal and methylglyoxal showed identical EFs of 0.18 ± 0.02 mg km^{-1}. Multiple linear regression retrieved total carbonyl EFs of 5.68, 47.71 and 35.09 mg km^{-1} and ozone formation potentials (OFPs) of 38.4, 329.3, and 242.4 mg km^{-1} for gasoline, diesel and liquefied

* Corresponding author. State Key Laboratory of Organic Geochemistry and Guangdong Key Laboratory of Environmental Protection and Resources Utilization, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, China. ,.
** Corresponding author. State Key Laboratory of Organic Geochemistry and Guangdong Key Laboratory of Environmental Protection and Resources Utilization, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, China.
E-mail addresses: zhang_yl86@gig.ac.cn (Y. Zhang), wangxm@gig.ac.cn (X. Wang).

https://doi.org/10.1016/j.atmosenv.2021.118491
Received 26 March 2021; Received in revised form 10 May 2021; Accepted 15 May 2021
Available online 26 May 2021

petroleum gas vehicles (LPGVs), respectively. The unexpectedly high carbonyl emissions from LPGVs were largely attributed to the lack of after-treatment systems or the inefficiency of the after-treatment systems. Among vehicle-emitted non-methane hydrocarbons and carbonyls, carbonyls could contribute ~20% of the total OFPs while they only accounted for 7.1% of the total mass.

1. Introduction

As an important subset of volatile organic compounds (VOCs), carbonyl compounds play key roles in atmospheric chemistry (Carlier et al., 1986; Atkinson et al., 2003; Mellouki et al., 2015; Zhang et al., 2019b). As important ozone precursors, carbonyls could contribute 17–50% of the ozone formation potential (OFP) (Duan et al., 2008; Yuan et al., 2012; Han et al., 2019), and were often found to be among precursors with the highest relative incremental reactivity (RIR) based on observation-based model simulation (Cheng et al., 2010; Yang et al., 2018b). Some carbonyls, such as formaldehyde and acetaldehyde, have been identified as air toxics that are known to cause adverse health effects (World Health Organization, 2000). Carbonyls are substantial contributors to primary organic aerosol (POA) (Jakober et al., 2008), while the uptake of carbonyls on aerosols is also an important pathway for secondary organic aerosol (SOA) formation (Fu et al., 2008; Kawamura et al., 2013; Toda et al., 2014; Mitsuishi et al., 2018; Ling et al., 2020; Xu et al., 2020).

A large fraction of carbonyls occurring in ambient air is secondarily formed via photochemical oxidation of VOCs (Chen et al., 2014; Wang et al., 2015; Yang et al., 2017; de Gouw et al., 2018; Huang et al., 2019a, 2020a), but they can also be emitted primarily from various emission sources, including vehicle exhaust (Tsai et al., 2012; Yao et al., 2015a, b), industrial processes (Kim et al., 2008; Ma et al., 2016), biomass burning (Cerqueira et al., 2013; Yang et al., 2019), interior finish (Huang et al., 2019b), cooking activities (Huang et al., 2011; Cheng et al., 2016) and biogenic emissions (Seco et al., 2007; Sindelarova et al., 2014). Among them, vehicular exhaust is an important source of carbonyls particularly in urban areas. As reported by Chen et al. (2014), vehicle emission could account for 16.6–26.6% of carbonyls in urban Beijing. However, studies on vehicular emissions of VOCs were focused more on non-methane hydrocarbons (NMHCs) than on these carbonyls, and characterizing vehicular emissions of carbonyls would benefit a comprehensive assessment of vehicle emission impacts on urban air chemistry.

Vehicular emissions of carbonyls can be measured by chassis and engine dynamometer test (Dong et al., 2014; Zhou et al., 2015) and on-board emission measurements (Yao et al., 2015a, b; Cao et al., 2016). However, results from different studies showed large variations in the percentages of carbonyls in the total vehicle-emitted VOCs either for gasoline vehicles (GVs) and liquefied petroleum gas vehicles (LPGVs) (Adam et al., 2011; Cao et al., 2016; Li et al., 2019), or for diesel vehicles (DVs) (Tsai et al., 2012; Yao et al., 2015b; Mo et al., 2016), partly due to a limited number of vehicles were tested in the studies. Tunnel test is another widely adopted approach to study emissions of carbonyls from vehicles (Sagebiel et al., 1996, 1998, 1998; Zielinska et al., 1996; Fraser et al., 1998; Staehelin et al., 1998; Grosjean et al., 2001; Kean et al., 2001; Kristensson et al., 2004; Martins et al., 2006; Ho et al., 2007; Legreid et al., 2007; Ban-Weiss et al., 2008; Gentner et al., 2013; Nogueira et al., 2015; Zhang et al., 2016). The advantage of this approach is that it gets involved a large number of vehicles, and that results can represent emissions under real-world operation conditions. Although the number of motor vehicles in China has increased rapidly by approximately four times in the last decade (China statistical Yearbook, 2020), the emissions of carbonyls from vehicles are understudied, and till present only two tunnel studies for vehicular carbonyl emissions are available in China: Ho et al. (2007) reported vehicular emissions of mono-carbonyls based on tests in the Shing Mun Tunnel in 2003 in Hong Kong, and Zhang et al. (2016) reported emissions of dicarbonyls based on tests in the Zhujiang Tunnel in 2014 in Guangzhou.

Many megacities in the world are confronted with surface ozone pollution (Liu and Wang, 2020), and vehicle emission largely hold accountable for the ozone pollution particularly in urban areas where ozone formation is typically sensitive to VOCs. While vehicle-emitted NMHCs have been identified to contribute substantially to ozone formation potential (Huang et al., 2017, 2020b; Zhang et al., 2019a; Hui et al., 2020; Li et al., 2020a; Wang et al., 2020a, b), the role of vehicle-emitted carbonyls in forming ozone is poorly understood due to the lack of studies to characterize vehicular emission of carbonyls. In fact, previous studies have demonstrated that vehicle emission could significantly contribute to carbonyls in urban air especially during rush hours (Feng et al., 2005; Liu et al., 2015). Moreover, as emission standards and vehicle fleet compositions change dramatically in China in the last decade, it is imperative to understand current status of carbonyl emissions from on-road vehicles under real world driving conditions, which were tested about 10 years ago based on tunnel tests in the Pearl River Delta (PRD) region in south China (Ho et al., 2007; Zhang et al., 2016).

In this study, a field campaign was carried out in the Zhujiang Tunnel during October 13–19, 2019 to characterize emissions of carbonyls from on-road vehicles under real world driving conditions. The fleet average EFs of carbonyls were obtained, and average EFs of carbonyls for GVs, DVs and LPGVs were further derived through multiple linear regression. The ozone formation potential of vehicle-emitted carbonyls were compared with those of vehicle-emitted NMHCs.

2. Experimental methods

2.1. Field measurement site

Field measurements were conducted in the Zhujiang Tunnel, which is a densely trafficked underwater tunnel that crosses the Pearl River in the urban area of Guangzhou, China (Zhang et al., 2015). The tunnel is 1238.5 m long with a 721 m flat underwater section and has a total of four lanes of traffic contained in the two separate bores. During sampling, the tunnel's ventilation supply system was turned off, so ventilation was only induced by the flow of traffic through the tunnel and prevailing winds. Two sites were set, 50 m from each end of the flat underwater section, to simultaneously quantify the emissions of gaseous and particulate pollutants from vehicles. The vehicle speed limits in Zhuajing Tunnel are 50 km h^{-1}, and the most typical vehicle speed is 40–50 km h^{-1}. Traffic volumes and compositions of the vehicle fleet travelling through the tunnel were recorded visually with a video camera throughout the campaign. The diurnal variations of total vehicle numbers, as well as numbers of GVs, electric vehicles (EVs), DVs and LPGVs were shown in Fig. 1. In this campaign, approximately 36000 vehicles passed through the tunnel each day. On average GVs accounted for 75% of the total vehicle numbers, followed by EVs (13%), LPGVs (8%) and DVs (4%) during the whole campaign.

2.2. Sampling and analysis

The concentrations of carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide (NO_x), sulfur dioxide (SO_2) at the inlet and outlet stations were continuously monitored by an optical filter CO_2 analyzer (model 410i, Thermo, USA), gas filter correlation CO analyzer (model 48i, Thermo, USA), a low source chemiluminescence NO–NO_2-NO_x analyzer (model 42i, Thermo, USA) and a high level pulsed fluorescence SO_2

analyzer (model 43i, Thermo, USA), respectively. The wind speed parallel to the tunnel was sensed by a 3-D sonic anemometer (Campbell, USA).

During October 13–19, 2019, carbonyl samples were collected by drawing air through a 2,4-dinitrophenylhydrazine (DNPH)-impregnated silica gel cartridge (Sep-Pak DNPH-Silica Cartridge, Waters, USA) at a constant flow of 2 L min^{-1} during time intervals of 00:00–02:30, 02:30–05:00, 05:00–06:00, 06:00–07:00, 07:00–08:00, 08:00-9:00, 09:00–10:00, 10:00–11:00, 11:00–12:00, 12:00–13:00, 13:00–14:00, 14:00–15:00, 15:00–16:00, 16:00-17:00, 17:00–18:00, 18:00–19:00, 19:00–20:00, 20:00–21:00, 21:00–22:00, 22:00–23:00, 23:00–00:00 in each day. A potassium iodide (KI) oxidant scrubber and a filter were connected before the cartridge to prevent the interference of ozone and remove the particulate matter, respectively. After sampled, each cartridge was wrapped with aluminum foil and zipped in a Teflon bag, and stored in a refrigerator at 4 °C until analysis.

Sample treatments and analytical procedures are described elsewhere (Feng et al., 2005; Lv et al., 2009, 2010, 2010; Liu et al., 2013). Briefly, the sampled cartridges were eluted slowly with 2 ml of acetonitrile (ACN) into a 2 ml volumetric flask and then stored in refrigerated conditions at 4 °C. The carbonyl compounds were measured by the high-performance liquid chromatography (HPLC) system (HP1200, Agilent, USA). A 10 μl aliquot was injected in to the HPLC system and the analytical conditions were as follows: Agilent SB-C18 reverse column (250 mm × 4.6 mm × 5 μm); gradient mobile phase: 60–65% ACN of water solution for 25 min, 65–100% ACN for 3 min, 100% ACN for 7 min, 100–60% ACN for 1 min and then 60% ACN for 7 min; mobile–-phase flow rate: 0.8 ml min^{-1}; detector: ultraviolet detector at 360 nm for monocarbonyls and 420 nm for dicarbonyls.

Except for collecting the carbonyl samples, on 13 October 2019, non-methane hydrocarbons (NMHCs) were sampled simultaneously, by taking air into cleaned and evacuated 2 L stainless steel canisters by a model 910 canister sampler (Xonteck Inc., California, USA). After taken the canisters back to the laboratory, they were analyzed by using a preconcentrator (model 7100, Entech Instruments Inc., USA) coupled to an Agilent 5973 N gas chromatograph with a mass selective detector and a flame ionization detector (GC-MSD/FID, Agilent Technologies, USA) as described in Zhang et al. (2013) and Yang et al. (2018a).

2.3. Quality control and quality assurance for carbonyls

Before the sampling, breakthrough tests were conducted by drawing standard mixtures (with concentrations of formaldehyde and acetaldehyde all over 50 μg m^{-3}) through two cartridges connected in series in the same way as field samples. The concentration of carbonyls (DNPH derivative) detected in the second cartridge had no significant difference from the field blank samples, indicating the collecting efficiencies of carbonyls were nearly 100% without breakthrough.

To prepare calibration standards of the monocarbonyls (as DNPH derivative), two composite stock standard solutions containing 22 monocarbonyl-DNPH derivatives, including Mix 1 (100 μg ml^{-1} in ACN, ChemService, USA), Mix 2 (100 μg ml^{-1} in ACN, ChemService, USA), 2-butanone-DNPH derivative (100 μg ml^{-1} in ACN, Sigma-Aldrich, USA) and methacrolein-DNPH derivative (100 μg ml^{-1} in ACN, Sigma-Aldrich, USA) and concentrations of monocarbonyls-DNPH derivatives in the standard solutions ranged from 0.05 μg ml^{-1} to 20.0 μg ml^{-1}. For calibration standards of the dicarbonyls (DNPH derivative), glyoxal and methylglyoxal (Mix 3, 1000 μg ml^{-1} in ACN, AccuStandard, USA) were mixed with 200 μg ml^{-1} DNPH under weak acid condition, and then the mixed solution was placed at room temperature for at least 6 h for the complete derivation of glyoxal and methylglyoxal by DNPH, and then after dilution we got the standard solutions with dicarbonyl concentrations ranging from 0.05 μg ml^{-1} to 4.0 μg ml^{-1}. Calibration curves were obtained by running the calibration standards with the HPLC system in the same way as the cartridge extracts and then linearly correlating responses (peak areas) with the amounts of carbonyls ($R^2 >$ 0.995). The detail carbonyl species and their method detection limits were also shown in Table S1.

3. Results and discussion

3.1. Emission factors

Among the 23 carbonyls (Table S1) in the standard solutions, only 14 of them were detected in tunnel air samples and the rest of them showed levels below their method detection limits (MDLs). On average total carbonyl concentrations were 27.42 ± 0.88 μg m^{-3} at the inlet and

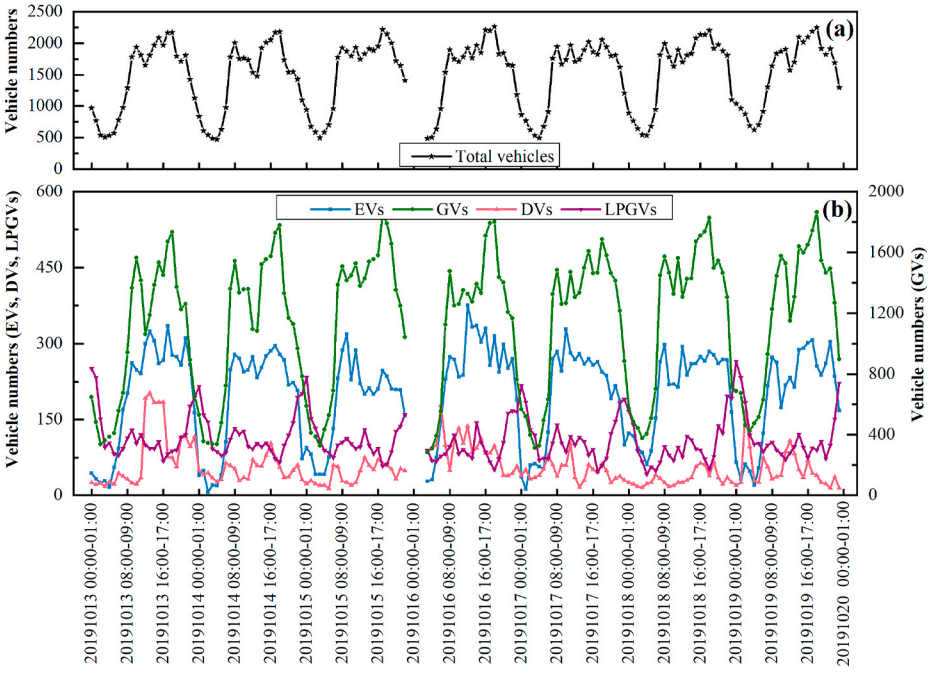


Fig. 1. Time series of traffic volumes of gasoline vehicles (GVs), electric vehicles (EVs), diesel vehicles (DVs) and liquefied petroleum gas vehicles (LPGVs) during the sampling period.

37.64 ± 1.12 μg m^{-3} at the outlet (Table 1). Acetone was the most abundant species at the inlet with an average concentration of 11.24 ± 0.43 μg m^{-3}, followed by formaldehyde (6.87 ± 0.20 μg m^{-3}) and acetaldehyde (3.59 ± 0.10 μg m^{-3}); at the outlet formaldehyde was the most abundant species (12.57 ± 0.42 μg m^{-3}), followed by acetone (12.21 ± 0.43 μg m^{-3}). The average concentrations of glyoxal and methylglyoxal were 0.44 ± 0.03 and 1.23 ± 0.06 μg m^{-3} at the inlet against that of 0.61 ± 0.03 and 1.35 ± 0.05 μg m^{-3} at the outlet, respectively. Differences between inlet-outlet pairs indicates that formaldehyde, acetaldehyde and acetone were the most abundant carbonyls emitted from vehicles, while vehicle emission is an anthropogenic source of glyoxal and methylglyoxal.

The total fleet EFs of carbonyls could be calculated according to the method described in detail by Pierson and Brachaczek (1983) and Pierson et al. (1996):

$$EF_{fleet} = \frac{(C_{out} - C_{in}) \times T \times \nu \times A}{N \times l}, \quad (1)$$

where $\mathbf{EF_{fleet}}$ is the average vehicle emission factors in unit of mg km^{-1}, $\mathbf{C_{out}}$ and $\mathbf{C_{in}}$ represent the mass concentrations of specific carbonyls at the tunnel outlet and inlet in mg m^{-3}, $\boldsymbol{\nu}$ is the wind speed parallel to the tunnel in m s^{-1}, **A** is the tunnel cross section in m^2 (A = 52.8 m^2), **N** is the total traffic number passing through the tunnel within the time internal **T** (s), and ***l*** is the distance between the two monitoring sites in km (***l*** = 0.621 km).

Times series of EFs for some important carbonyls, including formaldehyde, acetaldehyde, glyoxal and methylglyoxal, were presented in Fig. 2. As shown in Table 1, calculated total carbonyl emissions factor was 9.89 ± 0.65 mg km^{-1} on average, in which formaldehyde shared 53.1% with an average EF of 5.25 ± 0.35 mg km^{-1}, and acetaldehyde and acetone ranked the second and the third with EFs of 1.47 ± 0.13 and 1.16 ± 0.12 mg km^{-1}, respectively. A comparison of the EFs for the five important carbonyl species from this study in the Zhujiang Tunnel in comparison with literature data from other tunnel tests was presented in Table 2, and the comparison of the rest carbonyls was showed in Table S2. The EFs of formaldehyde, acetaldehyde and acetone from this study were lower than that from most of previous studies (Fraser et al., 1998; Kristensson et al., 2004; Ho et al., 2007), but near that from tests in the Tuscarora Mountain Tunnel, Pennsylvania, USA (Grosjean et al., 2001). The EFs of the two dicarbonyls, glyoxal and methylglyoxal, were all 0.18 ± 0.02 mg km^{-1}, which were decreased by over 80% when compared to that measured in 2014 in the same tunnel (Zhang et al., 2016). The reduced EFs of carbonyls from on-road vehicles might be largely resulted from the upgrade of the emission standards or exhaust treatment technology in recent years (Kaspar et al., 2003; Granger et al., 2011).

Table 1
The average concentrations of carbonyls and their emission factors (EFs) in the measurement of Zhujiang Tunnel.

Carbonyls	Concentration ±95%CI (μg m^{-3})		EFs ± 95%CI (mg km^{-1})
	Inlet	Outlet	
Formaldehyde	6.87 ± 0.20	12.57 ± 0.42	5.25 ± 0.35
Acetaldehyde	3.59 ± 0.10	5.15 ± 0.18	1.47 ± 0.13
Acetone	11.24 ± 0.43	12.21 ± 0.43	1.16 ± 0.12
Propanal	0.38 ± 0.02	0.65 ± 0.03	0.25 ± 0.02
2-Butanone	1.10 ± 0.09	1.42 ± 0.07	0.33 ± 0.04
Butanal	0.49 ± 0.05	0.54 ± 0.02	0.21 ± 0.02
Benzaldehyde	0.48 ± 0.03	0.73 ± 0.04	0.23 ± 0.02
Pentanal	0.15 ± 0.03	0.38 ± 0.46	0.25 ± 0.06
2,5-Dimethyl-benzaldehyde	< MDL[a]	0.33 ± 0.04	0.41 ± 0.03
Octanal	0.17 ± 0.01	0.26 ± 0.01	0.10 ± 0.01
Nonanal	1.19 ± 0.04	1.29 ± 0.04	0.14 ± 0.01
Decanal	0.10 ± 0.01	0.13 ± 0.01	0.04 ± 0.01
Glyoxal	0.44 ± 0.03	0.61 ± 0.03	0.18 ± 0.02
Methylglyoxal	1.23 ± 0.06	1.35 ± 0.05	0.18 ± 0.02
Sum of carbonyls	**27.42 ± 0.88**	**37.64 ± 1.12**	**9.89 ± 0.65**

[a] Method detection limits.

The ratios of formaldehyde/acetaldehyde (F/A) and acetaldehyde/propanal (A/P) were widely used to characterize carbonyls from different sources or in ambient air. Generally, F/A ratios vary from 1 to 2 in urban areas to about 10 in forested areas. Propanal is considered to be associated only with anthropogenic emissions, so A/P ratios would be high in remote areas and low in urban areas. Fig. 3 shows the average F/A and A/P ratios in comparison with those reported previously in vehicle exhaust and in ambient air in China's megacities. The F/A and A/P ratios from this tunnel study were 3.57 and 7.22, respectively. They fall between those from previous tunnel studies (Fraser et al., 1998; Grosjean et al., 2001; Kristensson et al., 2004; Ho et al., 2007), but it is interesting to find that these ratios from all tunnel studies seem to be higher than those tested by chassis and engine dynamometers or from on-board emission measurements (Schauer et al., 1999; Siegl et al., 1999; Adam et al., 2011; Tsai et al., 2012; Zhang et al., 2013; Dong et al., 2014; Yao et al., 2015a, b; Mo et al., 2016; Li et al., 2019), implying this kind of tunnel test for on-road emissions is necessary. As illustrated in Fig. 3 and references therein, the average F/A ratio from this study was slightly higher than those observed in ambient air in China's megacities including Hongkong, Guangzhou, Shanghai and Beijing, probably due to a shorter tropospheric lifetime of formaldehyde than acetaldehyde (Seinfeld and Pandis, 1998) and faster degradation of formaldehyde during photochemical ageing. The average A/P ratio from this study was close to that observed in the megacities (Fig. 3), further demonstrating vehicle emission should be a major primary emission source of carbonyls in urban areas.

3.2. Reconstructed EFs for GVs, DVs and LPGVs

Since EVs were free of carbonyl emissions, the fleet average EFs of carbonyls at time interval ***i***, $\mathbf{EF_{fleet,\,i}}$, could be linked with the average EFs for GVs, DVs and LPGVs as below:

$$EF_{fleet,\,i} = \alpha_i \times EF_{GVs} + \beta_i \times EF_{DVs} + (1 - \alpha_i - \beta_i) \times EF_{LPGVs} \quad (2)$$

where $\boldsymbol{\alpha_i}$ and $\boldsymbol{\beta_i}$ are the number fractions of GVs and DVs in the vehicle fleet during time interval ***i***; $\mathbf{EF_{GVs}}$, $\mathbf{EF_{DVs}}$ and $\mathbf{EF_{LPGVs}}$ are the average emission factors for GVs, DVs and LPGVs, respectively. With the fleet average EFs and fleet composition data, average EFs for GVs, DVs and LPGVs could be retrieved through multiple linear regression based on the above equation (2). A comparison between observed and reconstructed fleet average EFs was shown in Fig. S1. The retrieved EFs of individual carbonyls for different fuel type vehicles are presented in Table S3. The results revealed that EFs of carbonyls totalled 5.68, 47.70, 35.09 mg km^{-1} for GVs, DVs, and LPGVs, respectively. As shown in Table 2, all the tunnel studies agreed with each other in the fact that DVs or high-duty vehicles had much higher EFs than GVs or light-duty vehicles, and that formaldehyde was the most abundant carbonyls in vehicle exhaust. EFs of monocarbonyls measured in this study fell in the range of those from tunnel studies in USA (Zielinska et al., 1996; Sagebiel et al., 1996; Grosjean et al., 2001; Kean et al., 2001; Ban-Weiss et al., 2008), but lower than that from tunnel tests in Hong Kong (Ho et al., 2007).

For GVs, the total EFs of monocarbonyls on average was 5.51 mg km^{-1}, in which formaldehyde (3.06 ± 0.33 mg km^{-1}), acetone (0.66 ± 0.12 mg km^{-1}), acetaldehyde (0.65 ± 0.13 mg km^{-1}), 2,5-dimethylbenzaldehyde (0.31 ± 0.04 mg km^{-1}) and pentanal (0.23 ± 0.07 mg km^{-1}) were the top 5 species. For DVs, the total average EFs of monocarbonyls was 45.42 mg km^{-1}, and the top five species instead were formaldehyde (22.73 ± 4.55 mg km^{-1}), acetaldehyde (6.76 ± 1.73 mg

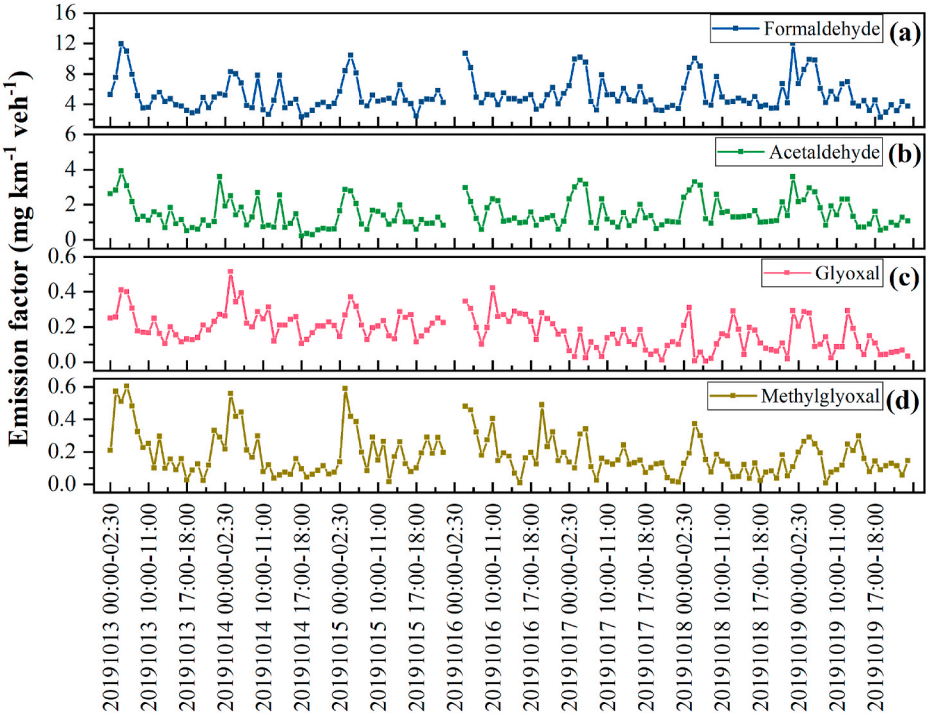


Fig. 2. Times series of emission factors for formaldehyde, acetaldehyde, glyoxal and methylglyoxal.

km^{-1}), acetone (3.75 ± 1.71 mg km^{-1}), 2,5-dimethyl-benzaldehyde (2.44 ± 0.57 mg km^{-1}) and butanal (2.41 ± 0.39 mg km^{-1}). For LPGVs, No EFs of carbonyls from tunnel tests have been reported before. From this study, total EF of monocarbonyls for LPGVs reached 33.92 mg km^{-1}, which was unexpectedly much higher than that of GVs. This result was different from the results reported by Adam et al. (2011) and Zhou et al. (2015) who observed lower EFs from LPGVs than from GVs based on chassis and engine dynamometer testing. This higher EFs of carbonyl for LPGVs than for GVs might be due to, as demonstrated in a previous study (Feng et al., 2020), the lack of after-treatment systems or the inefficiency of the after-treatment systems for LPGVs in Guangzhou. For dicarbonyls, the EFs of glyoxal were 0.10 ± 0.02, 0.92 ± 0.23 and 0.50 ± 0.13 mg km^{-1} for GVs, DVs and LPGVs, while the EFs of methylglyoxal were 0.07 ± 0.02, 1.36 ± 0.30 and 0.67 ± 0.17 mg km^{-1} for GVs, DVs and LPGVs, respectively.

3.3. Ozone formation potential of VOCs from vehicles exhaust

In this study, 66 species of NMHCs, including 29 alkanes, 19 alkenes, 1 alkyne and 17 aromatics, were also determined on October 13, 2019. As shown in Fig. S2, the composition of NMHCs was similar to that observed in the same Zhujiang tunnel in 2014 (Zhang et al., 2018), but the total EF of NMHCs in this study on average (122.9 ± 38.5 mg km^{-1}) was only 27.4% of that in 2014. To compare the ozone formation potential (OFP) of carbonyls with that of NMHCs, OFPs of the carbonyls and NMHCs in vehicle exhaust could be calculated as:

$$OFP = \sum_i EF_i \times MIR_i, \quad (3)$$

where $\mathbf{EF_i}$ and $\mathbf{MIR_i}$ are the emission factor and the maximum incremental reactivity for species $\boldsymbol{i}$ (Carter, 2009).

As presented in Fig. 4, the total OFP of all measured VOCs from vehicles was 340.3 mg km^{-1}, in which alkenes contributed most (114.9 mg km^{-1}) with a share of 33.8%, followed by alkanes (25.5%, 86.6 mg km^{-1}), carbonyls (20.3%, 69.1 mg km^{-1}) and aromatics (19.4%, 66.1 mg km^{-1}). It is worth noting that carbonyls only accounted for 7.1% of mass in all measured VOCs (NMHCs and carbonyls), but contributed about one fifth of the total OFPs. Formaldehyde was the major contributor with OFP of 49.63 mg km^{-1} and ranked second among all the detected VOCs. As reported previously, approximately 17–41% of OFP from VOCs was attributed to vehicle exhaust in the urban areas (Cai et al., 2010; An et al., 2017; Huang and Hsieh, 2019; Ma et al., 2019; Li et al., 2020b), carbonyls from vehicles could account for about 3–8% of the total OFP.

With the average emission factor of carbonyls of each fuel type vehicles and the average fleet compositions during our field campaign, the contribution to OFP of carbonyls by GVs, DVs and LPGVs could be further calculated. Results revealed that 47.6% of OFP by carbonyls was attributed to GVs (33.22 ± 0.43 mg km^{-1}). This larger share is reasonable since 75% of vehicles travelling through the tunnel during the campaign were GVs although GVs had a smaller average EFs of carbonyls. DVs and LPGVs, contributed 21.2% (14.81 ± 1.75 mg km^{-1}) and 31.1% (21.71 ± 2.22 mg km^{-1}) of OFP by carbonyls although they only accounted for 4% and 8% in fleet number compositions. In Guangzhou, all LPG-fueled vehicles were taxi cars that had been converted from gasoline-driven to LPG-driven with retrofitted gasoline-LPG bi-fuel engines to reduce the emission of particulate matters and photochemically reactive VOC species. Due to the lack of exhaust treatment systems or the inefficiency of the exhaust treatment systems, while a previous study shows that OFPs by NMHCs from LPGVs were not reduced when compared to GVs (Feng et al., 2020), results from this study further demonstrate that on average the OFP of carbonyls from LPGVs was about 5 times that from GVs, suggesting that poor maintenance of LPGVs would instead increase the emissions of ozone precursors relative to GVs.

4. Conclusions

In this study, we updated the EFs of carbonyls from on-road vehicles by a tunnel test campaign in Zhujiang Tunnel, Guangzhou. Formaldehyde was found to contribute over half of carbonyl emissions with a fleet-average EF of 5.25 ± 0.35 mg km^{-1}, followed by acetaldehyde (1.47 ± 0.13 mg km^{-1}) and acetone (1.16 ± 0.12 mg km^{-1}), while glyoxal and methylglyoxal, as the important precursors of SOA, both had

Table 2
Emission factors of carbonyls based on measurements in the Zhujiang Tunnel in comparison with literature data from other tunnel tests.

Tunnel		Formaldehyde	Acetaldehyde	Acetone	Glyoxal	Methylglyoxal
Emission factor (mileage-based in mg km^{-1})						
FortMcHenry Tunnel, Baltimore, USA, 1992[a]	LDVs[p]	4.31 ± 1.06	1.31 ± 0.31			
	HDVs[q]	32.9 ± 5.88	20.1 ± 1.75			
Tuscarora Mountain Tunnel, Pennsylvania, USA, 1992[b]	LDVs	3.91 ± 1.38				
	HDVs	27.0 ± 4.54				
Gubrist tunnel, Switzerland, 1993[c]	GVs	10.5 ± 8.06	2.33 ± 1.12	1.10 ± 1.80	0.17 ± 0.88	0.07 ± 0.91
	DVs	67.8 ± 36.5	14.6 ± 5.09	7.95 ± 8.13	0.00 ± 3.42	0.81 ± 3.53
Tuscarora Mountain Tunnel, Pennsylvania, USA, 1999[d]	Total fleet	5.41 ± 2.22	2.19 ± 0.68	2.14 ± 0.81	0.18 ± 0.07	0.23 ± 0.17
	LDVs	2.57 ± 1.05	0.64 ± 0.27	1.69 ± 0.73	0.02 ± 0.01	0.03 ± 0.14
	HDVs	6.73 ± 2.04	3.95 ± 0.59	2.49 ± 1.42	0.32 ± 0.03	0.51 ± 0.32
Söderledstunnel, Stockholm, Sweden, 1998–1999[e]	Total fleet	13 ± 3	3.1 ± 0.8	1.4 ± 0.6		
	LDVs	4.9 ± 4.6	1.4 ± 1.8	1.5 ± 1.8		
	HDVs	215 ± 137	50 ± 35	14 ± 27		
Janio Quadros tunnel, Sao Paulo, Brazil, 2004[f]	Total fleet	48.4 ± 35.1	45.7 ± 29.1	9.3 ± 4.4		
Shing Mun Tunnel, Hong Kong, China, 2003[g]	Total fleet	18.8 ± 7.5	3.1 ± 0.8	1.4 ± 0.6		
	NDVs[r]	3.5 ± 5.2	1.4 ± 1.8	1.5 ± 1.8		
	DVs	38.3 ± 6.5	50 ± 35	14 ± 27		
Gubrist tunnel, Switzerland, 2004[h]	Total fleet		2.40 ± 0.39	0.78 ± 0.09		
	LDVs		2.10 ± 0.60	0.57 ± 0.13		
	HDVs		5.30 ± 6.60	3.94 ± 1.54		
Janio Quadros tunnel, Sao Paulo, Brazil, 2011[i]	LDVs	5.7 ± 1.7	7.4 ± 2.7			
	HDVs	28 ± 8	20 ± 16			
Zhujiang Tunnel, Guangzhou, China, 2014[j]	Total fleet				1.18 ± 0.43	0.32 ± 0.26
	GVs				1.64 ± 1.03	0.17 ± 0.33
	DVs				0.10 ± 3.49	1.68 ± 1.20
	LPGVs				0.58 ± 2.37	0.70 ± 0.66
Zhujiang Tunnel, Guangzhou, China, 2019[k]	Total fleet	5.25 ± 0.35	1.47 ± 0.13	1.16 ± 0.12	0.18 ± 0.02	0.18 ± 0.02
	GVs	3.06 ± 0.33	0.65 ± 0.13	0.66 ± 0.12	0.10 ± 0.02	0.07 ± 0.02
	DVs	22.7 ± 4.55	6.76 ± 1.73	3.75 ± 1.71	0.92 ± 0.23	1.36 ± 0.30
	LPGs	17.6 ± 2.53	6.72 ± 0.96	4.72 ± 0.95	0.50 ± 0.13	0.67 ± 0.17
Emission factor (fuel-based in mg L^{-1})[t]						
Van Nuys Tunnel, Los Angeles, USA, 1993[l]	Total fleet	128	29		27	27
Caldecott tunnel, San Francisco, USA, 1999[m]	LDVs	31.0 ± 4.00	8.00 ± 0.80	4.00 ± 0.50	0.09 ± 0.03	0.75 ± 0.15
Caldecott tunnel, San Francisco, USA, 2010[n]	GVs	4.51 ± 7.4	9.92 ± 3.32	6.12 ± 3.05		
	DVs	28.80 ± 1.46		78.7 ± 79.3		
Zhujiang Tunnel, Guangzhou, China, 2019[k]	Total fleet	61.2 ± 4.04	17.1 ± 1.53	13.5 ± 1.38	2.06 ± 0.19	2.11 ± 0.25
	GVs	35.7 ± 3.89	7.53 ± 1.48	7.66 ± 1.46	1.22 ± 0.20	0.81 ± 0.26
	DVs	265 ± 53.1	78.9 ± 20.2	43.8 ± 19.9	10.8 ± 2.68	15.9 ± 3.50
Emission factor (fuel-based in mg kg^{-1})[u]						
Caldecott tunnel, San Francisco, USA, 1999[o]	LDVs	43.0 ± 5.0	11.0 ± 1.0	5.60 ± 0.70	0.12 ± 0.04	1.00 ± 0.20
Caldecott tunnel, San Francisco, USA, 2001[o]	LDVs	42.0 ± 3.0	9.0 ± 0.5	6.70 ± 0.40	0.17 ± 0.03	0.91 ± 0.10
Caldecott tunnel, San Francisco, USA, 2006[o]	LDVs	16.0 ± 1.4	7.0 ± 0.7	3.50 ± 1.10	0.10 ± 0.02	0.29 ± 0.10
	MDVs[s]/HDVs	129 ± 18.0	46.0 ± 12.0	ND	1.00 ± 0.50	2.60 ± 1.70
Zhujiang Tunnel, Guangzhou, China, 2019[k]	GVs	48.2 ± 5.25	10.2 ± 2.00	10.4 ± 1.97	1.65 ± 0.26	1.09 ± 0.35
	DVs	312 ± 62.5	92.8 ± 23.8	51.5 ± 23.4	12.7 ± 3.15	18.7 ± 4.11

[a] Zielinska et al. (1996).
[b] Sagebiel et al. (1996).
[c] Staehelin et al. (1998).
[d] Grosjean et al. (2001).
[e] Kristensson et al. (2004).
[f] Martins et al. (2006).
[g] Ho et al. (2007).
[h] Legreid et al. (2007).
[i] Nogueira et al. (2015).
[j] Zhang et al. (2016).
[k] This study.
[l] Fraser et al. (1998).
[m] Kean et al. (2001).
[n] Gentner et al. (2013).
[o] Ban-Weiss et al. (2008).
[p] Light-duty vehicles.
[q] High-duty vehicles.
[r] Non-diesel Vehicles.
[s] Medium-duty vehicles.
[t] The average fuel consumption of vehicles was estimated to be 8.57 L per 100 km (2018 new data analysis on real-world driving and fuel consumption for passenger cars in China, http://www.icet.org.cn/admin/upload/2019081537990401.pdf).
[u] we assumed a gasoline oil density of 0.74 g mL^{-1} and a diesel oil density of 0.85 g mL^{-1} (Zhang et al., 2016).

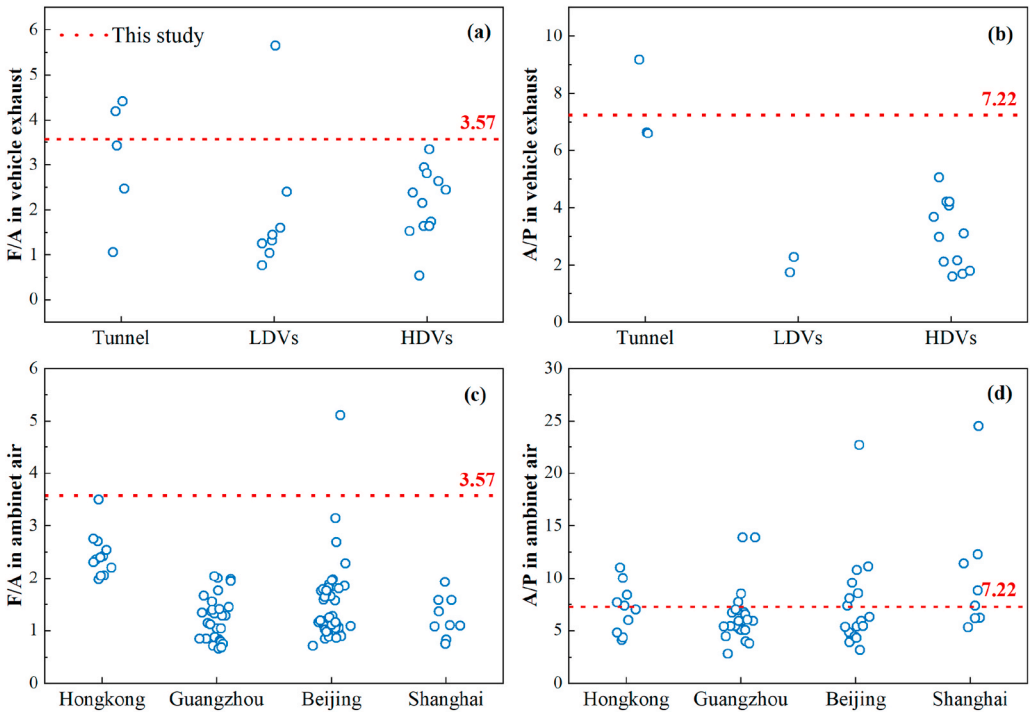


Fig. 3. The ratio of formaldehyde/acetaldehyde (F/A) and acetaldehyde/propanal (A/P) for vehicle emissions and urban observation.
Data from: Tunnel; Fraser et al. (1998), Grosjean et al. (2001), Kristensson et al. (2004), Martins et al. (2006) and Ho et al. (2007);
Light-duty vehicles (LDVs): Adam et al. (2011), Zhang et al. (2013) and Li et al. (2019);
Heavy-duty vehicles (HDVs): Schauer et al. (1999), Siegl et al. (1999), Tsai et al. (2012), Dong et al. (2014), Yao et al. (2015a,b) and Ma et al. (2016);
Hongkong: Lee et al. (2001), Ho et al. (2002), Cheng et al. (2014), Lui et al. (2017) and Yang et al. (2020);
Guangzhou: Feng et al. (2004, 2005, 2007), Yu et al. (2008), Lv et al. (2009, 2010), Wang et al. (2009), Hu et al. (2010), Zhuang et al. (2011), Liu et al. (2013) and Ho et al. (2015);
Beijing: Pang and Mu (2006), Xu et al. (2006), Shao et al. (2009), Xu and Gao (2009), Xu et al. (2010), Wang et al. (2011), Duan et al. (2012), Zhang et al. (2012a,b), Altemose et al. (2015), Ho et al. (2015), He et al. (2016), Rao et al. (2016), Sheng et al. (2018), Yang et al. (2018b), Huang et al. (2020a) and Liu et al. (2020).
Shanghai: Huang et al. (2008, 2009) and Ho et al. (2015).

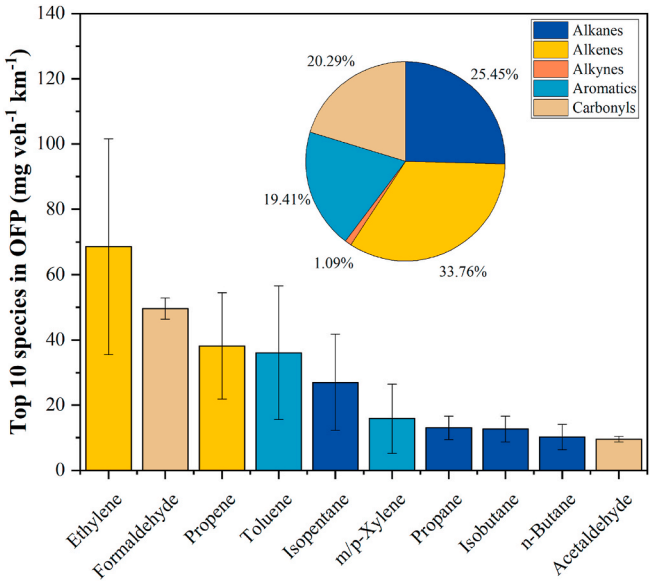


Fig. 4. Contribution percentages by different groups to OFPs (pie chart) and top 10 species among the vehicle-emitted NMHCs and carbonyls in their OFPs (bar charts).

EFs of 0.18 ± 0.02 mg km^{-1}. Multiple linear regression was used to retrieve the average EFs of carbonyls for GVs, DVs and LPGVs. The EFs of DVs were much higher than that of GVs, which was consistent with results in the previous studies. However, the average EF of total carbonyls for LPGVs were 35.09 mg km^{-1}, which was about 5 times higher than that of GVs. As for the impact on ozone formation, though carbonyls only contributed 7.1% of mass in all measured NHMCs and carbonyls, they could account for one fifth of the total OFPs by the vehicle-emitted NMHCs and carbonyls. This signals the importance to take carbonyls into consideration in the control of vehicular ozone precursors. Among all the fuel type vehicles, GVs accounted for 47.6% of OFP because 75% of vehicles travelling through the tunnel were GVs; LPGVs contributed 31.1% of OFP with only 8% in fleet, while DVs contributed 21.2% of OFP with only 4% in fleet. The unexpected higher carbonyl emissions from LPGVs suggest installing exhaust treatment systems or improve the performance of exhaust treatment systems for LPGVs will also benefit reducing vehicular emission of carbonyls that are important ozone precursors in urban areas.

CRediT authorship contribution statement

Zhenfeng Wu: Writing – original draft, Methodology, Formal analysis, Writing – review & editing. **Yanli Zhang:** Writing – review & editing. **Chenglei Pei:** Methodology. **Zuzhao Huang:** Methodology. **Yujun Wang:** Methodology. **Yanning Chen:** Methodology. **Jianhong Yan:** Methodology. **Xiaoqing Huang:** Investigation, Data curation. **Shaoxuan Xiao:** Investigation, Data curation. **Shilu Luo:** Investigation, Data curation. **Jianqiang Zeng:** Investigation, Data curation. **Jun Wang:** Investigation, Data curation. **Hua Fang:** Investigation, Data curation. **Runqi Zhang:** Investigation, Data curation. **Sheng Li:** Investigation, Data curation. **Xuewei Fu:** Investigation, Data curation. **Wei Song:** Investigation, Data curation. **Xinming Wang:** Project administration, Conceptualization, Writing, Funding acquisition, Supervision, review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the National Natural Science Foundation of China, China (Grant No. 41530641/41961144029), the National Key Research and Development Program, China (2016YFC0202204), the Chinese Academy of Sciences, China (Grant No. QYZDJ-SSW-DQC032/XDA23010303), Youth Innovation Promotion Association of the Chinese Academy of Sciences, China (2017406), and Department of Science and Technology of Guangdong Province, China (2017B030314057/2017BT01Z134/2019B121205006).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2021.118491.

References

Adam, T.W., Astorga, C., Clairotte, M., Duane, M., Elsasser, M., Krasenbrink, A., Larsen, B.R., Manfredi, U., Martini, G., Montero, L., Sklorz, M., Zimmermann, R., Perujo, A., 2011. Chemical analysis and ozone formation potential of exhaust from dual-fuel (liquefied petroleum gas/gasoline) light duty vehicles. Atmos. Environ. 45, 2842–2848.

Altemose, B., Gong, J.C., Zhu, T., Hu, M., Zhang, L.W., Cheng, H., Zhang, L., Tong, J., Kipen, H.M., Ohman-Strickland, P., Meng, Q.Y., Robson, M.G., Zhang, J.F., 2015. Aldehydes in relation to air pollution sources: a case study around the Beijing Olympics. Atmos. Environ. 109, 61–69.

An, J.L., Wang, J.X., Zhang, Y.X., Zhu, B., 2017. Source apportionment of volatile organic compounds in an urban environment at the Yangtze River Delta, China. Arch. Environ. Contam. Toxicol. 72, 335–348.

Atkinson, R., Arey, J., 2003. Atmospheric degradation of volatile organic compounds. Chem. Rev. 103, 4605–4638.

Ban-Weiss, G.A., McLaughlin, J.P., Harley, R.A., Kean, A.J., Grosjean, E., Grosjean, D., 2008. Carbonyl and nitrogen dioxide emissions from gasoline- and diesel-powered motor vehicles. Environ. Sci. Technol. 42, 3944–3950.

Cai, C.J., Geng, F.H., Tie, X.X., Yu, Q.O., An, J.L., 2010. Characteristics and source apportionment of VOCs measured in Shanghai, China. Atmos. Environ. 44, 5005–5014.

Cao, X.Y., Yao, Z.L., Shen, X.B., Ye, Y., Jiang, X., 2016. On-road emission characteristics of VOCs from light-duty gasoline vehicles in Beijing, China. Atmos. Environ. Times 124, 146–155.

Carlier, P., Hannachi, H., Mouvier, G., 1986. The chemistry of carbonyl compounds in the atmosphere -A review. Atmos. Environ. 20, 2079–2099.

Carter, W.P.L., 2009. Update Maximum Incremental Reactivity Scale and Hydrocarbon Bin Reactivities for Regulatory Application. Prepared for California Air Resources Board Contract, 07-339.

China Statistics Press, 2020. China Statistical Yearbook 2020. China (in Chinese).

Cerqueira, M., Gomes, L., Tarelho, L., Pio, C., 2013. Formaldehyde and acetaldehyde emissions from residential wood combustion in Portugal. Atmos. Environ. 72, 171–176.

Chen, W.T., Shao, M., Lu, S.H., Wang, M., Zeng, L.M., Yuan, B., Liu, Y., 2014. Understanding primary and secondary sources of ambient carbonyl compounds in Beijing using the PMF model. Atmos. Chem. Phys. 14, 3047–3062.

Cheng, H.R., Guo, H., Wang, X.M., Saunders, S.M., Lam, S.H.M., Jiang, F., Wang, T.J., Ding, A.J., Lee, S.C., Ho, K.F., 2010. On the relationship between ozone and its precursors in the Pearl River Delta: application of an observation-based model (OBM). Environ. Sci. Pollut. Res. 17, 547–560.

Cheng, J.H., Lee, Y.S., Chen, K.S., 2016. Carbonyl compounds in dining areas, kitchens and exhaust streams in restaurants with varying cooking methods in Kaohsiung, Taiwan. J. Environ. Sci. 41, 218–226.

Cheng, Y., Lee, S.C., Huang, Y., Ho, K.F., Ho, S.S.H., Yau, P.S., Louie, P.K.K., Zhang, R.J., 2014. Diurnal and seasonal trends of carbonyl compounds in roadside, urban, and suburban environment of Hong Kong. Atmos. Environ. 89, 43–51.

de Gouw, J.A., Gilman, J.B., Kim, S.W., Alvarez, S.L., Dusanter, S., Graus, M., Griffith, S. M., Isaacman-VanWertz, G., Kuster, W.C., Lefer, B.L., Lerner, B.M., McDonald, B.C., Rappengluck, B., Roberts, J.M., Stevens, P.S., Stutz, J., Thalman, R., Veres, P.R., Volkamer, R., Warneke, C., Washenfelder, R.A., Young, C.J., 2018. Chemistry of volatile organic compounds in the Los Angeles Basin: formation of oxygenated compounds and determination of emission ratios. J. Geophys. Res. Atmos. 123, 2298–2319.

Dong, D., Shao, M., Li, Y., Lu, S.H., Wang, Y.J., Ji, Z., Tang, D.G., 2014. Carbonyl emissions from heavy-duty diesel vehicle exhaust in China and the contribution to ozone formation potential. J. Environ. Sci. 26, 122–128.

Duan, J.C., Guo, S.J., Tan, J.H., Wang, S.L., Chai, F.H., 2012. Characteristics of atmospheric carbonyls during haze days in Beijing, China. Atmos. Res. 114, 17–27.

Duan, J.C., Tan, J.H., Yang, L., Wu, S., Hao, J.M., 2008. Concentration, sources and ozone formation potential of volatile organic compounds (VOCs) during ozone episode in Beijing. Atmos. Res. 88, 25–35.

Feng, J.J., Zhang, Y.L., Song, W., Deng, W., Zhu, M., Fang, Z., Ye, Y.Q., Fang, H., Wu, Z. F., Lowther, S., Jones, K.C., Wang, X.M., 2020. Emissions of nitrogen oxides and volatile organic compounds from liquefied petroleum gas-fueled taxis under idle and cruising modes. Environ. Pollut. 267.

Feng, Y.L., Chen, Y.J., Wen, S., Sheng, G.Y., Fu, J.M., 2007. Characteristics of carbonyl compounds in the atmosphere of Guangzhou. Environ. Sci. Technol. 30, 51–54 (in Chinese).

Feng, Y.L., He, Q.S., Wen, S., Sheng, G.Y., Fu, J.M., 2004. Preliminary research on carbonyl pollution in Guangzhou. Guangzhou Environmental Sciences 19 (2), 15–17 (in Chinese).

Feng, Y.L., Wen, S., Chen, Y.J., Wang, X.M., Lu, H.X., Bi, X.H., Sheng, G.Y., Fu, J.M., 2005. Ambient levels of carbonyl compounds and their sources in Guangzhou, China. Atmos. Environ. Times 39, 1789–1800.

Fraser, M.P., Cass, G.R., Simoneit, B.R.T., 1998. Gas-phase and particle-phase organic compounds emitted from motor vehicle traffic in a Los Angeles roadway tunnel. Environ. Sci. Technol. 32, 2051–2060.

Fu, T.M., Jacob, D.J., Wittrock, F., Burrows, J.P., Vrekoussis, M., Henze, D.K., 2008. Global budgets of atmospheric glyoxal and methylglyoxal, and implications for formation of secondary organic aerosols. J. Geophys. Res. Atmos. 113, 17.

Gentner, D.R., Worton, D.R., Isaacman, G., Davis, L.C., Dallmann, T.R., Wood, E.C., Herndon, S.C., Goldstein, A.H., Harley, R.A., 2013. Chemical composition of gas-phase organic carbon emissions from motor vehicles and implications for ozone production. Environ. Sci. Technol. 47, 11837–11848.

Granger, P., Parvulescu, V.I., 2011. Catalytic NO_x abatement systems for mobile sources: from three-way to lean burn after-treatment technologies. Chem. Rev. 111, 3155–3207.

Grosjean, D., Grosjean, E., Gertler, A.W., 2001. On-road emissions of carbonyls from light-duty and heavy-duty vehicles. Environ. Sci. Technol. 35, 45–53.

Han, C., Liu, R.R., Luo, H., Li, G.Y., Ma, S.T., Chen, J.Y., An, T.C., 2019. Pollution profiles of volatile organic compounds from different urban functional areas in Guangzhou China based on GC/MS and PTR-TOF-MS: atmospheric environmental implications. Atmos. Environ. 214, 9.

He, X.L., Tan, J.H., Guo, S.J., Ma, Y.L., He, K.B., 2016. Chemical characteristics and sources of atmospheric carbonyls during the 2014 Beijing APEC. Environ. Sci. 37 (3), 801–806 (in Chinese).

Ho, K.F., Ho, S.S.H., Cheng, Y., Lee, S.C., Yu, J.Z., 2007. Real-world emission factors of fifteen carbonyl compounds measured in a Hong Kong tunnel. Atmos. Environ. 41, 1747–1758.

Ho, K.F., Ho, S.S.H., Huang, R.J., Dai, W.T., Cao, J.J., Tian, L., Deng, W.J., 2015. Spatiotemporal distribution of carbonyl compounds in China. Environ. Pollut. 197, 316–324.

Ho, K.F., Lee, S.C., Louie, P.K.K., Zou, S.C., 2002. Seasonal variation of carbonyl compound concentrations in urban area of Hong Kong. Atmos. Environ. 36, 1259–1265.

Hu, P., Wen, S., Wei, S.L., Liu, Y.L., Bi, X.H., Sheng, G.Y., Fu, J.M., 2010. Character of carbonyl compounds and their source in Guangzhou Wanqingsha atmosphere. Ecology and Environmental Sciences 19 (6), 1387–1391 (in Chinese).

Huang, J., Feng, Y.L., Li, J., Xiong, B., Feng, J.L., Wen, S., Sheng, G.Y., Fu, J.M., Wu, M. H., 2008. Characteristics of carbonyl compounds in ambient air of Shanghai, China. J. Atmos. Chem. 61, 1–20.

Huang, J., Feng, Y.L., Xiong, B., Fu, J.M., Sheng, G.Y., 2009. Ambient levels of carbonyl compounds in Shanghai, China. Environ. Sci. 30 (9), 2701–2706 (in Chinese).

Huang, X.F., Wang, C., Zhu, B., Lin, L.L., He, L.Y., 2019a. Exploration of sources of OVOCs in various atmospheres in southern China. Environ. Pollut. 249, 831–842.

Huang, X.F., Zhang, B., Xia, S.Y., Han, Y., Wang, C., Yu, G.H., Feng, N., 2020a. Sources of oxygenated volatile organic compounds (OVOCs) in urban atmospheres in North and South China. Environ. Pollut. 261, 114152.

Huang, X.Y., Zhang, Y.L., Yang, W.Q., Huang, Z.Z., Wang, Y.J., Zhang, Z., He, Q.F., Lü, S. J., Huang, Z.H., Bi, X.H., Wang, X.M., 2017. Effect of traffic restriction on reducing ambient volatile organic compounds (VOCs): observation-based evaluation during a traffic restriction drill in Guangzhou, China. Atmos. Environ. 161, 61–70.

Huang, X.Y., Zhang, Y.L., Wang, Y.J., Ou, Y.B., Chen, D.H., Pei, C.L., Huang, Z.Z., Zhang, Z., Liu, T.Y., Luo, S.L., Huang, X.Q., Song, W., Ding, X., Shao, M., Zou, S.C., Wang, X.M., 2020b. Evaluating the effectiveness of multiple emission control measures on reducing volatile organic compounds in ambient air based on observational data: a case study during the 2010. Guangzhou Asian Games. Sci. Total Environ. 723, 9.

Huang, Y., Ho, S.S.H., Ho, K.F., Lee, S.C., Yu, J.Z., Louie, P.K.K., 2011. Characteristics and health impacts of VOCs and carbonyls associated with residential cooking activities in Hong Kong. J. Hazard Mater. 186, 344–351.

Huang, Y.S., Hsieh, C.C., 2019. Ambient volatile organic compound presence in the highly urbanized city: source apportionment and emission position. Atmos. Environ. 206, 45–59.

Huang, Y., Su, T., Wang, L.Q., Wang, N., Xue, Y.G., Dai, W.T., Lee, S.C., Cao, J.J., Ho, S.S. H., 2019b. Evaluation and characterization of volatile air toxics indoors in a heavy polluted city of northwestern China in wintertime. Sci. Total Environ. 662, 470–480.

Hui, L.R., Liu, X.G., Tan, Q.W., Feng, M., An, J.L., Qu, Y., Zhang, Y.H., Deng, Y.J., Zhai, R.X., Wang, Z., 2020. VOC characteristics, chemical reactivity and sources in urban Wuhan, central China. Atmos. Environ. 224, 15.

Jakober, C.A., Robert, M.A., Riddle, S.G., Destaillats, H., Charles, M.J., Green, P.G., Kleeman, M.J., 2008. Carbonyl emissions from gasoline and diesel motor vehicles. Environ. Sci. Technol. 42, 4697–4703.

Kaspar, J., Fornasiero, P., Hickey, N., 2003. Automotive catalytic converters: current status and some perspectives. Catal. Today 77, 419–449.

Kawamura, K., Okuzawa, K., Aggarwal, S.G., Irie, H., Kanaya, Y., Wang, Z., 2013. Determination of gaseous and particulate carbonyls (glycolaldehyde, hydroxyacetone, glyoxal, methylglyoxal, nonanal and decanal) in the atmosphere at Mt. Tai. Atmos. Chem. Phys. 13, 5369–5380.

Kean, A.J., Grosjean, E., Grosjean, D., Harley, R.A., 2001. On-road measurement of carbonyls in California light-duty vehicle emissions. Environ. Sci. Technol. 35, 4198–4204.
Kim, K.H., Hong, Y.J., Pal, R., Jeon, E.C., Koo, Y.S., Sunwoo, Y., 2008. Investigation of carbonyl compounds in air from various industrial emission sources. Chemosphere 70, 807–820.
Kristensson, A., Johansson, C., Westerholm, R., Swietlicki, E., Gidhagen, L., Wideqvist, U., Vesely, V., 2004. Real-world traffic emission factors of gases and particles measured in a road tunnel in Stockholm, Sweden. Atmos. Environ. Times 38, 657–673.
Lee, S.C., Ho, K.F., Chan, L.Y., Zielinska, B., Chow, J.C., 2001. Polycyclic aromatic hydrocarbons (PAHs) and carbonyl compounds in urban atmosphere of Hong Kong. Atmos. Environ. 35, 5949–5960.
Legreid, G., Reimann, S., Steinbacher, M., Staehelin, J., Young, D., Stemmler, K., 2007. Measurements of OVOCs and NMHCs in a swiss highway tunnel for estimation of road transport emissions. Environ. Sci. Technol. 41, 7060–7066.
Li, Q.Q., Su, G.J., Li, C.Q., Liu, P.F., Zhao, X.X., Zhang, C.L., Sun, X., Mu, Y.J., Wu, M.G., Wang, Q.L., Sun, B.H., 2020a. An investigation into the role of VOCs in SOA and ozone production in Beijing, China. Sci. Total Environ. 720, 14.
Li, W.S., Sha, Q.E., Yuan, Z.B., Wang, R.C., Lin, X.H., Zheng, Z.Y., Shao, M., 2019. Emission characteristics of VOCs from light-duty gasoline vehicles at constant speed in the Pearl River Delta. Acta Sci. Circumstantiae 39 (1), 243–251 (in Chinese).
Li, Y.D., Yin, S.S., Yu, S.J., Yuan, M.H., Dong, Z., Zhang, D., Yang, L.M., Zhang, R.Q., 2020b. Characteristics, source apportionment and health risks of ambient VOCs during high ozone period at an urban site in central plain, China. Chemosphere 250, 9.
Ling, Z.H., Xie, Q.Q., Shao, M., Wang, Z., Wang, T., Guo, H., Wang, X.M., 2020. Formation and sink of glyoxal and methylglyoxal in a polluted subtropical environment: observation-based photochemical analysis and impact evaluation. Atmos. Chem. Phys. 20, 11451–11467.
Liu, Y.F., Song, M.D., Liu, X.G., Zhang, Y.P., Hui, L.R., Kong, L.W., Zhang, Y.Y., Zhang, C., Qu, Y., An, J.L., Ma, D.P., Tan, Q.W., Feng, M., 2020. Characterization and sources of volatile organic compounds (VOCs) and their related changes during ozone pollution days in 2016 in Beijing, China. Environ. Pollut. 257, 13599-13599.
Liu, Y.M., Wang, T., 2020. Worsening urban ozone pollution in China from 2013 to 2017-Part 2: the effects of emission changes and implications for multi-pollutant control. Atmos. Chem. Phys. 20, 6323–6337.
Liu, Y., Yuan, B., Li, X., Shao, M., Lu, S., Li, Y., Chang, C.C., Wang, Z., Hu, W., Huang, X., He, L., Zeng, L., Hu, M., Zhu, T., 2015. Impact of pollution controls in Beijing on atmospheric oxygenated volatile organic compounds (OVOCs) during the 2008 Olympic Games: observation and modeling implications. Atmos. Chem. Phys. 15, 3045–3062.
Liu, Y.L., Bi, X.H., Chan, L.Y., Wen, S., Wang, X.M., Sheng, G.Y., Fu, J.M., 2013. Characteristics, loss and gain of atmospheric carbonyl compounds in winters of 2008-2010 in Pearl River Delta region, China. J. Atmos. Chem. 70, 53–67.
Lui, K.H., Ho, S.S.H., Louie, P.K.K., Chan, C.S., Lee, S.C., Hu, D., Chan, P.W., Lee, J.C.W., Ho, K.F., 2017. Seasonal behavior of carbonyls and source characterization of formaldehyde (HCHO) in ambient air. Atmos. Environ. 152, 51–60.
Lv, H.X., Cai, Q.Y., Wen, S., Chi, Y.G., Guo, S.J., Sheng, G.Y., Fu, J.M., Antizar-Ladislao, B., 2009. Carbonyl compounds in the ambient air of hazy days and clear days in Guangzhou, China. Atmos. Res. 94, 363–372.
Lv, H.X., Cai, Q.Y., Wen, S., Chi, Y.G., Guo, S.J., Sheng, G.Y., Fu, J.M., 2010. Seasonal and diurnal variations of carbonyl compounds in the urban atmosphere of Guangzhou, China. Sci. Total Environ. 408, 3523–3529.
Ma, Y., Diao, Y.W., Zhang, B.J., Wang, W.W., Ren, X.R., Yang, D.S., Wang, M., Shi, X.W., Zheng, J., 2016. Detection of formaldehyde emissions from an industrial zone in the Yangtze River Delta region of China using a proton transfer reaction ion-drift chemical ionization mass spectrometer. Atmos. Meas. Tech. 9, 6101–6116.
Ma, Z.B., Liu, C.T., Zhang, C.L., Liu, P.F., Ye, C., Xue, C.Y., Zhao, D., Sun, J.C., Du, Y.M., Chai, F.H., Mu, Y.J., 2019. The levels, sources and reactivity of volatile organic compounds in a typical urban area of Northeast China. J. Environ. Sci. 79, 121–134.
Martins, L.D., Andrade, M.F., D Freitas, E., Pretto, A., Gatti, L.V., Albuquerque, E.L., Tomaz, E., Guardani, M.L., Martins, M.H.R.B., Junior, O.M.A., 2006. Emission factors for gas-powered vehicles traveling through road tunnels in Sao Paulo, Brazil. Environ. Sci. Technol. 40, 6722–6729.
Mellouki, A., Wallington, T.J., Chen, J., 2015. Atmospheric chemistry of oxygenated volatile organic compounds: impacts on air quality and climate. Chem. Rev. 115, 3984–4014.
Mitsuishi, K., Iwasaki, M., Takeuchi, M., Okochi, H., Kato, S., Ohira, S.I., Toda, K., 2018. Diurnal variations in partitioning of atmospheric glyoxal and methylglyoxal between gas and particles at the ground level and in the free troposphere. ACS Earth Space Chem 2, 915–924.
Mo, Z.W., Shao, M., Lu, S.H., 2016. Compilation of a source profile database for hydrocarbon and OVOC emissions in China. Atmos. Environ. 143, 209–217.
Nogueira, T., de Souza, K.F., Fornaro, A., Andrade, M.D., de Carvalho, L.R.F., 2015. On-road emissions of carbonyls from vehicles powered by biofuel blends in traffic tunnels in the Metropolitan Area of Sao Paulo, Brazil. Atmos. Environ. 108, 88–97.
Pang, X.B., Mu, Y.J., 2006. Seasonal and diurnal variations of carbonyl compounds in Beijing ambient air. Atmos. Environ. 40, 6313–6320.
Pierson, W.R., Brachaczek, W.W., 1983. Emissions of ammonia and amines from vehicles on the road. Environ. Sci. Technol. 17, 757–760.
Pierson, W.R., Gertler, A.W., Robinson, N.F., Sagebiel, J.C., Zielinska, B., Bishop, G.A., Stedman, D.H., Zweidinger, R.B., Ray, W.D., 1996. Real-world automotive emissions - summary of studies in the fort McHenry and Tuscarora mountain tunnels. Atmos. Environ. 30, 2233–2256.
Rao, Z.H., Chen, Z.M., Liang, H., Huang, L.B., Huang, D., 2016. Carbonyl compounds over urban Beijing: concentrations on haze and non-haze days and effects on radical chemistry. Atmos. Environ. 124, 207–216.
Sagebiel, J.C., Zielinska, B., Pierson, W.R., Gertler, A.W., 1996. Real-world emissions and calculated reactivities of organic species from motor vehicles. Atmos. Environ. 30, 2287–2296.
Schauer, J.J., Kleeman, M.J., Cass, G.R., Simoneit, B.R.T., 1999. Measurement of emissions from air pollution sources. 2. C-1 through C-30 organic compounds from medium duty diesel trucks. Environ. Sci. Technol. 33, 1578–1587.
Seco, R., Penuelas, J., Filella, I., 2007. Short-chain oxygenated VOCs: emission and uptake by plants and atmospheric sources, sinks, and concentrations. Atmos. Environ. 41, 2477–2499.
Seinfeld, J.H., Pandis, S.N., 1998. Atmospheric Chemistry and Physics: from Air Pollution to Climate Change. Taylor & Francis Group.
Shao, M., Lu, S.H., Liu, Y., Xie, X., Chang, C.C., Huang, S., Chen, Z.M., 2009. Volatile organic compounds measured in summer in Beijing and their role in ground-level ozone formation. J. Geophys. Res. Atmos. 114, 13.
Sheng, J.J., Zhao, D.L., Ding, D.P., Li, X., Huang, M.Y., Gao, Y., Quan, J.N., Zhang, Q., 2018. Characterizing the level, photochemical reactivity, emission, and source contribution of the volatile organic compounds based on PTR-TOF-MS during winter haze period in Beijing, China. Atmos. Res. 212, 54–63.
Siegl, W.O., Hammerle, R.H., Herrmann, H.M., Wenclawiak, B.W., Luers-Jongen, B., 1999. Organic emissions profile for a light-duty diesel vehicle. Atmos. Environ. 33, 797–805.
Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Muller, J. F., Kuhn, U., Stefani, P., Knorr, W., 2014. Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years. Atmos. Chem. Phys. 14, 9317–9341.
Staehelin, J., Keller, C., Stahel, W., Schlapfer, K., Wunderli, S., 1998. Emission factors from road traffic from a tunnel study (Gubrist tunnel, Switzerland). Part III: results of organic compounds, SO2 and speciation of organic exhaust emission. Atmos. Environ. 32, 999–1009.
Toda, K., Yunoki, S., Yanaga, A., Takeuchi, M., Ohira, S.I., Dasgupta, P.K., 2014. Formaldehyde content of atmospheric aerosol. Environ. Sci. Technol. 48, 6636–6643.
Tsai, J.H., Chang, S.Y., Chiang, H.L., 2012. Volatile organic compounds from the exhaust of light-duty diesel vehicles. Atmos. Environ. 61, 499–506.
World Health Organization (WHO), 2000. Guidelines for Air Quality. World Health Organization, Geneva, Switzerland.
Wang, B.G., Liu, C., Lv, W.M., Shao, M., Zhang, Y.H., 2009. Character of volatile carbonyl compounds and their source in Guangzhou ambient air. Environ. Sci. 30 (3), 631–636 (in Chinese).
Wang, M., Chen, W.T., Shao, M., Lu, S.H., Zeng, L.M., Hu, M., 2015. Investigation of carbonyl compound sources at a rural site in the Yangtze River Delta region of China. J. Environ. Sci. 28, 128–136.
Wang, M., Hu, K., Chen, W.T., Shen, X.Y., Li, W.J., Lu, X.D., 2020a. Ambient non-methane hydrocarbons (NMHCs) measurements in Baoding, China: sources and roles in ozone formation. Atmosphere 11, 17.
Wang, M., Qin, W., Chen, W.T., Zhang, L., Zhang, Y., Zhang, X.Z., Xie, X., 2020b. Seasonal variability of VOCs in Nanjing, Yangtze River delta: implications for emission sources and photochemistry. Atmos. Environ. 223, 11.
Wang, Q., Shao, M., Wei, Q., Chen, W.T., Lu, S.H., Zhao, Y., 2011. Spatial and temporal variations of ambient carbonyl compounds in Beijing and its surrounding areas. Environ. Sci. 32 (12), 3522–3530 (in Chinese).
Xu, J.J., Gao, Y., 2009. Seasonal variations of carbonyl compounds in urban atmosphere of Beijing. Environ. Sci. 30 (3), 625–630 (in Chinese).
Xu, R.J., Li, X., Dong, H.B., Wu, Z.J., Chen, S.Y., Fang, X., Gao, J., Guo, S., Hu, M., Li, D. Q., Liu, Y.C., Liu, Y., Lou, S.R., Lu, K.D., Meng, X.X., Wang, H.L., Zeng, L.M., Zong, T. M., Hu, J.L., Chen, M.D., Shao, M., Zhang, H.Y., 2020. Measurement of gaseous and particulate formaldehyde in the yangtze River Delta, China. Atmos. Environ. 224, 11.
Xu, Z., Liu, J.F., Zhang, Y.J., Liang, P., Mu, Y.J., 2010. Ambient levels of atmospheric carbonyls in beijing during the 2008 olympic games. J. Environ. Sci. 22, 1348–1356.
Xu, Z., Pang, X.B., Mu, Y.J., 2006. Measurement of carbonyl compounds in Beijing ambient air and rain. Acta Sci. Circumstantiae 26 (12), 1948–1954 (in Chinese).
Yang, W.Q., Zhang, Y.L., Wang, X.M., Li, S., Zhu, M., Yu, Q.Q., Li, G.H., Huang, Z.H., Zhang, H.N., Wu, Z.F., Song, W., Tan, J.H., Shao, M., 2018a. Volatile organic compounds at a rural site in Beijing: influence of temporary emission control and wintertime heating. Atmos. Chem. Phys. 18, 12663–12682.
Yang, X., Xue, L.K., Wang, T., Wang, X.F., Gao, J., Lee, S.C., Blake, D.R., Chai, F.H., Wang, W.X., 2018b. Observations and explicit modeling of summertime carbonyl formation in Beijing: identification of key precursor species and their impact on atmospheric oxidation chemistry. J. Geophys. Res. Atmos. 123, 1426–1440.
Yang, X., Xue, L.K., Yao, L., Li, Q.Y., Wen, L., Zhu, Y.H., Chen, T.S., Wang, X.F., Yang, L. X., Wang, T., Lee, S.C., Chen, J.M., Wang, W.X., 2017. Carbonyl compounds at mount tai in the north China plain: characteristics, sources, and effects on ozone formation. Atmos. Res. 196, 53–61.
Yang, X., Zhang, G.Q., Sun, Y.M., Zhu, L., Wei, X.F., Li, Z., Zhong, X.L., 2020. Explicit modeling of background HCHO formation in southern China. Atmos. Res. 240, 10.
Yang, X.J., Ma, Y.F., Wang, G.Y., Alvarado, E.C., Tigabu, M., Ju, Y.H., Guo, F.T., 2019. Characterization of pollutants emitted during burning of eight main tree species in subtropical China. Atmos. Environ. 215, 12.
Yao, Z.L., Jiang, X., Shen, X.B., Ye, Y., Cao, X.Y., Zhang, Y.Z., He, K.B., 2015a. On-road emission characteristics of carbonyl compounds for heavy-duty diesel trucks. Aerosol Air Qual. Res. 15, 915–925.

Yao, Z.L., Shen, X.B., Ye, Y., Cao, X.Y., Jiang, X., Zhang, Y.Z., He, K.B., 2015b. On-road emission characteristics of VOCs from diesel trucks in Beijing, China. Atmos. Environ. 103, 87–93.

Yu, Y.X., Wen, S., Lv, H.X., Feng, Y.L., Wang, X.M., Sheng, G.Y., Fu, J.M., 2008. Characteristics of atmospheric carbonyls and VOCs in forest park in south China. Environ. Monit. Assess. 137, 275–285.

Yuan, B., Chen, W.T., Shao, M., Wang, M., Lu, S.H., Wang, B., Liu, Y., Chang, C.C., Wang, B.G., 2012. Measurements of ambient hydrocarbons and carbonyls in the Pearl River delta (PRD), China. Atmos. Res. 116, 93–104.

Zhang, X.F., Yin, Y.Y., Wen, J.H., Huang, S.L., Han, D.M., Chen, X.J., Cheng, J.P., 2019a. Characteristics, reactivity and source apportionment of ambient volatile organic compounds (VOCs) in a typical tourist city. Atmos. Environ. 215, 13.

Zhang, Y.J., Mu, Y.J., Liu, J.F., Mellouki, A., 2012a. Levels, sources and health risks of carbonyls and BTEX in the ambient air of Beijing, China. J. Environ. Sci. 24, 124–130.

Zhang, Y.J., Mu, Y.J., Liang, P., Xu, Z., Liu, J.F., Zhang, H.X., Wang, X.K., Gao, J., Wang, S.L., Chai, F.H., Mellouki, A., 2012b. Atmospheric BTEX and carbonyls during summer seasons of 2008-2010 in Beijing. Atmos. Environ. 59, 186–191.

Zhang, Y.L., Wang, X.M., Wen, S., Herrmann, H., Yang, W.Q., Huang, X.Y., Zhang, Z., Huang, Z.H., He, Q.F., George, C., 2016. On-road vehicle emissions of glyoxal and methylglyoxal from tunnel tests in urban Guangzhou, China. Atmos. Environ. 127, 55–60.

Zhang, Y.L., Yang, W.Q., Simpson, I., Huang, X.Y., Yu, J.Z., Huang, Z.H., Wang, Z.Y., Zhang, Z., Liu, D., Huang, Z.Z., Wang, Y.J., Pei, C.L., Shao, M., Blake, D.R., Zheng, J. Y., Huang, Z.J., Wang, X.M., 2018. Decadal changes in emissions of volatile organic compounds (VOCs) from on-road vehicles with intensified automobile pollution control: case study in a busy urban tunnel in south China. Environ. Pollut. 233, 806–819.

Zhang, Y.L., Wang, X.M., Barletta, B., Simpson, I.J., Blake, D.R., Fu, X.X., Zhang, Z., He, Q.F., Liu, T.Y., Zhao, X.Y., Ding, X., 2013. Source attributions of hazardous aromatic hydrocarbons in urban, suburban and rural areas in the Pearl River Delta (PRD) region. J. Hazard Mater. 250, 403–411.

Zhang, Y.L., Wang, X.M., Li, G.H., Yang, W.Q., Huang, Z.H., Zhang, Z., Huang, X.Y., Deng, W., Liu, T.Y., Huang, Z.Z., Zhang, Z.Y., 2015. Emission factors of fine particles, carbonaceous aerosols and traces gases from road vehicles: recent tests in an urban tunnel in the Pearl River Delta, China. Atmos. Environ. 122, 876–884.

Zhang, Y.N., Xue, L.K., Dong, C., Wang, T., Mellouki, A., Zhang, Q.Z., Wang, W.X., 2019b. Gaseous carbonyls in China's atmosphere: tempo-spatial distributions, sources, photochemical formation, and impact on air quality. Atmos. Environ. 214, 15.

Zhou, M., Gong, D.C., Zhu, D., Wang, H., Zhou, L., Feng, Q., Shuang, J.R., Zhang, Z.J., Ouyang, X.W., Wang, B.G., 2015. Measurement of carbonyls in exhaust gases of light-duty vehicles in China using pentafluorophenyl hydrazine derivatisation and GC/MS analysis. J. Environ. Anal. Chem. 95, 390–402.

Zhuang, Y.J., Wang, B.G., Liu, C., 2011. Preliminary research on the carbonyl compounds under of sea-land breeze at the west coast of the Pearl River Estuary. China Environ. Sci. 31 (4), 568–575 (in Chinese).

Zielinska, B., Sagebiel, J.C., Harshfield, G., Gertler, A.W., Pierson, W.R., 1996. Volatile organic compounds up to C-20 emitted from motor vehicles; Measurement methods. Atmos. Environ. 30, 2269–2286.