268 shading), and NO_x; (c) CO; (d) THC; (e) PM; and (f) PN EFs for each machine type under different
269 operating modes. Error bars indicate standard deviation.

270 **3.2 Speciated PM emissions**

271 The speciated PM collected and analyzed in all of the modes, and the analyzed results
272 are representing the whole operation process. The fractional mass contributions of main
273 category of various PM chemical components are shown in Fig. 3 (a); the detailed fractions
274 of speciated PM are summarized in Table 4. The PM filter for EX_2 was contaminated
275 during the sampling process, so PM data is not available for this machine. OM and EC
276 were the main PM components in the diesel construction machinery exhaust. OM
277 accounted for 41 ± 17%, 52.3 ± 15%, 50.9%, and 46.6% of the total PM mass for the
278 excavator, loader, bulldozer and roller, respectively, while EC contributed 47.2 ± 8%, 34.5
279 ± 15%, 19.6%, and 37.1%.

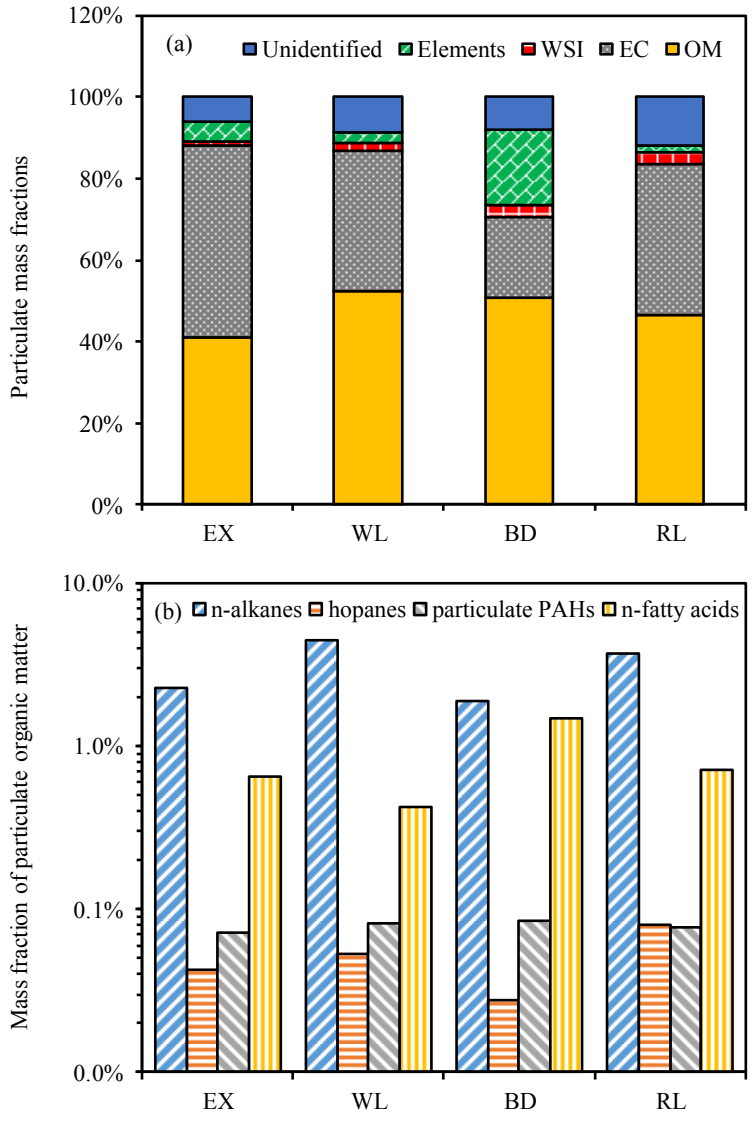
280 The contributions of WSIs to PM mass were relatively lower, with an average of 1.9 ±
281 1%. WSIs from the test machines consisted primarily of NO_3^-, which accounted for 1.3 ± 1%
282 of the total PM mass, followed by SO_4^{2-}. These results are consistent with Ma et al. (2018).
283 However, SO_4^{2-} was the dominant contributor to PM mass, far outweighing NO_3^-, in diesel
284 vehicle and machinery exhaust in previous studies in China (Zhang et al., 2015; Cui et al.,
285 2017); these differences may be attributed to the diesel fuel sulfur content in these studies,
286 which reached up to 500 and 1300 ppm, respectively. The quality of diesel fuel has
287 improved in recent years; diesel sulfur content is currently controlled to < 50 ppm, which
288 generally reduces the fraction of SO_4^{2-} in PM emissions in diesel exhaust.

289 The elemental component fractions varied between the different types of machinery.

290 Elements constituted 4.9 ± 2%, 2.6 ± 0.9%, and 1.8%, respectively of the excavator, wheel
291 loader, and roller emissions; Si was the dominant elemental component, accounting for 3.5
292 ± 1.9%, 1.2 ± 1.1%, and 1.1% of the total PM mass. The elemental fraction was much
293 higher for the bulldozer than for the other machine types, reaching 18.5% of the total PM
294 mass. The major elements emitted from the bulldozer were Si, Ca, Al, and Fe, which
295 accounted for 5.1%, 5.1%, 2.4%, and 1.8%, respectively, of the total PM mass. These
296 elements are generally derived primarily from diesel fuel impurities (Wang et al., 2003).
297 Thus, the inferior quality of the diesel fuel used in the test bulldozer may explain the high
298 elemental emissions. The PM SO_4^{2-} fraction emitted from the test bulldozer, which
299 measured up to 1.2%, was much higher than the SO_4^{2-} fractions emitted from the other
300 machinery types (0.1% - 0.3%).

301 The fractional contributions of various OM species to total PM organic mass are shown
302 in Fig. 3 (b). Altogether, 21 *n*-alkanes, 10 hopanes, 21 particulate PAHs, and 21 *n*-fatty
303 acids were quantified in the PM samples (see Table 4). OM species contributed
304 approximately 2.4% - 6.4% of the total PM mass. *n*-Alkanes were the dominant organic
305 component, accounting for 2.26 ± 0.2%, 4.48 ± 2%, 1.87%, and 3.71% of the total PM
306 mass from the excavators, wheel loaders, bulldozer, and roller, respectively; *n*-fatty acids
307 were the second most abundant category, contributing 0.65 ± 0.4%, 0.42 ± 0.4%, 1.47%,
308 and 0.71% of the total PM mass. The average PM mass fractions of hopanes and particulate
309 PAHs were 0.049 ± 0.03% and 0.078 ± 0.02%, respectively. Cui et al. (2017) reported
310 *n*-alkane and particulate PAH fractions reaching 5.14% and 0.098%, slightly higher than
311 the proportions found herein; this may be attributed to the use of high-sulfur fuel in that

312 study. The *n*-alkanes found herein consisted primarily of C18-C23 compounds, except for
313 those emitted from the bulldozer, which contained more high-carbon components
314 (C20-C24), as shown in Table 4. Hopanes can be used as organic tracers for oil combustion
315 processes. 17a(H)21ß(H)-hopane (C30H) and 17a(H)21ß(H)-30-norhopane (C29H) were
316 the most abundant hopanes, contributing 0.016 ± 0.01% and 0.009 ± 0.004% of the total
317 PM mass, respectively, which is similar to the hopane composition of PM emissions from
318 diesel vehicles and ships (Schauer et al., 1999; Sippula et al., 2014; Cui et al., 2017).



319

320 **Fig. 3.** (a) Fractional contributions various species to total PM mass, and (b) fractional contributions of

organic matter species to total organic mass.

Table 4. Fractional chemical and organic matter of PM composition for each test machine (%).

Species	EX_1	EX_3	EX_4	WL_1	WL_2	WL_3	BD_1	RL_1
OC	**19.6**	**47.9**	**35**	**57.9**	**37.9**	**34.9**	**42.4**	**38.8**
EC	**47.1**	**36.2**	**34.7**	**19.7**	**43**	**23.6**	**16.4**	**30.9**
SO_4^{2-}	0.1	0.2	0.2	0.3	0.1	0.2	1.2	0.3
NO_3^-	0.5	0.0	1.6	1.8	1.8	1.4	1.3	2.1
Cl^-	0.0	0.1	0.1	0.4	0.2	0.0	0.3	0.2
NH_4^+	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.2
ΣWSIs	**0.6**	**0.3**	**1.9**	**2.6**	**2.1**	**1.7**	**2.9**	**2.7**
Na	0.1	0.0	0.2	0.2	0.2	0.4	1.2	0.0
Mg	0.5	0.0	0.3	0.0	0.1	0.0	0.0	0.0
Al	0.8	0.5	0.8	0.4	0.5	0.0	2.4	0.3
Si	3.6	1.5	5.3	0.4	2.5	0.6	5.1	1.2
K	0.1	0.0	0.0	0.0	0.0	0.3	1.0	0.0
Ca	0.1	0.1	0.0	0.2	0.1	0.6	5.1	0.2
Ti	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
V	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mn	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Fe	0.1	0.1	0.0	0.1	0.1	0.2	1.8	0.0
ΣElements	**5.3**	**2.4**	**7.0**	**1.7**	**3.5**	**2.5**	**18.5**	**1.8**
$C_{16}H_{34}$	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0
$C_{17}H_{36}$	0.1	0.0	0.1	0.3	0.1	0.0	0.0	0.0
$C_{18}H_{38}$	0.2	0.1	0.3	0.7	0.2	1.2	0.0	0.3
$C_{19}H_{40}$	0.4	0.3	0.5	1.1	0.4	1.6	0.1	0.7
$C_{20}H_{42}$	0.4	0.6	0.4	1.2	0.4	1.1	0.2	0.9
$C_{21}H_{44}$	0.4	0.5	0.3	0.9	0.3	0.7	0.4	0.7
$C_{22}H_{46}$	0.3	0.3	0.2	0.6	0.2	0.4	0.4	0.4
$C_{23}H_{48}$	0.2	0.2	0.1	0.4	0.1	0.2	0.3	0.3
$C_{24}H_{50}$	0.1	0.1	0.1	0.2	0.1	0.1	0.3	0.1
$C_{25}H_{52}$	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.1
$C_{26}H_{54}$	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
$C_{27}H_{56}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C_{28}H_{58}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C_{29}H_{60}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C_{30}H_{62}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C_{31}H_{64}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C_{32}H_{66}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C_{33}H_{68}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Species	EX_1	EX_3	EX_4	WL_1	WL_2	WL_3	BD_1	RL_1
$C_{34}H_{70}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C_{35}H_{72}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C_{36}H_{74}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Σ*n*-alkanes	**2.5**	**2.2**	**2.2**	**5.5**	**1.9**	**6.0**	**1.9**	**3.7**
Ts	0.002	0.002	0.005	0.004	0.002	0.009	0.002	0.005
Tm	0.002	0.001	0.004	0.003	0.002	0.006	0.002	0.005
C29H	0.006	0.006	0.015	0.009	0.006	0.014	0.005	0.010
ba-C29H	0.000	0.000	0.001	0.000	0.001	0.002	0.002	0.001
C30H	0.009	0.009	0.025	0.009	0.011	0.032	0.008	0.028
ba-C30H	0.001	0.001	0.003	0.001	0.001	0.005	0.001	0.004
C31H-S	0.003	0.003	0.006	0.005	0.000	0.011	0.003	0.010
C31H-R	0.002	0.002	0.005	0.002	0.000	0.007	0.002	0.006
C32H-S	0.002	0.002	0.004	0.002	0.000	0.009	0.002	0.006
C32H-R	0.001	0.001	0.003	0.001	0.000	0.006	0.001	0.005
Σhopanes	**0.03**	**0.03**	**0.07**	**0.03**	**0.02**	**0.10**	**0.03**	**0.08**
Phenanthrene	0.022	0.004	0.009	0.005	0.019	0.009	0.003	0.008
Anthracene	0.002	0.001	0.001	0.001	0.002	0.001	0.001	0.001
Fluoranthene	0.017	0.010	0.005	0.008	0.007	0.012	0.009	0.009
Acephenanthrene	0.004	0.002	0.001	0.002	0.002	0.003	0.001	0.002
Retene	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.001
Pyrene	0.039	0.021	0.021	0.038	0.028	0.036	0.014	0.035
Benzo[ghi]fluoranthene	0.004	0.001	0.001	0.002	0.001	0.002	0.005	0.002
Cyclopenta[cd] pyrene	0.001	0.000	0.000	0.001	0.000	0.001	0.001	0.001
Benz[a]anthracene	0.002	0.001	0.001	0.001	0.001	0.002	0.003	0.001
Chrysene	0.004	0.002	0.001	0.002	0.002	0.003	0.006	0.002
Benzo[b+k]fluoranthene	0.004	0.001	0.003	0.007	0.004	0.003	0.009	0.002
Benzo[a]fluoranthene	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.001
1,3,5-triphenylbenzene	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.001
Benzo[e]pyrene	0.003	0.001	0.001	0.002	0.003	0.003	0.006	0.002
Benzo[a]pyrene	0.002	0.001	0.002	0.002	0.000	0.002	0.003	0.002
Perylene	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Anthanthracene	0.001	0.000	0.000	0.001	0.000	0.002	0.003	0.001
Benzo[123-cd]pyrene	0.002	0.000	0.001	0.002	0.000	0.003	0.004	0.001
Dibenz[ah]anthracene	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000
Benzo[ghi]perylene	0.005	0.001	0.002	0.003	0.001	0.005	0.009	0.003
Coronene	0.001	0.000	0.001	0.001	0.001	0.001	0.002	0.000
Σparticulate PAHs	**0.12**	**0.05**	**0.05**	**0.08**	**0.07**	**0.09**	**0.09**	**0.08**
Σfatty acids	**0.4**	**1.1**	**0.5**	**0.8**	**0.4**	**0.1**	**1.5**	**0.7**

3.3 OC and EC emissions

On average, the OC and EC measured in the test machine emissions herein contributed

39.3 ± 11% and 37.7 ± 13% of the total PM mass, as shown in Fig. 4. The average OC/EC ratio was 1.24 ± 0.7, which is similar to the average excavator OC/EC ratio (1.18) measured by Cui et al. (2017), lower than the ratios measured for diesel fork lifts (FL, 2.71) and generators (GE, 2.73) by Chow et al. (2011), and higher than the ratios (0.43-0.57) measured in diesel truck exhaust in China (Zhang et al., 2015; Wu et al., 2016). Previous studies have indicated that engine load affects OC and EC emissions considerably (Liu et al., 2005; Wu et al., 2016; Cui et al., 2017); OC/EC ratios are much higher under low engine load, such as during idling, than under high engine load, as OC is generated predominantly at low temperatures in fuel-rich zones. The diesel trucks evaluated by Zhang et al. (2015) and Wu et al. (2016) were operated at high speed (high load), resulting in relatively low OC/EC ratios compared with construction machinery in this and previous studies (Chow et al., 2011; Cui et al., 2017).

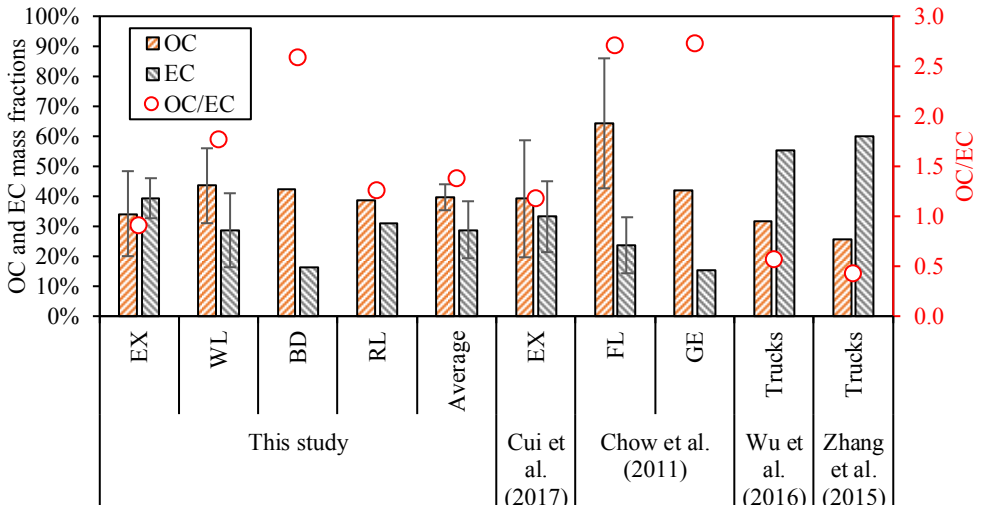


Fig. 4. OC and EC mass fractions and OC/EC ratios for emissions from different types of machinery in this study and in previous studies on construction machinery and diesel trucks in China.

3.4 PAH emissions

The fuel-based EFs of the speciated PAHs were classified by the number of benzene

rings, as shown in Fig. 5(a). The average fuel-based EF for the test machinery was 382 ± 264 g kg-fuel^{-1}. Compounds with 3 or 4 benzene rings were dominant, accounting for 34.9% and 52.3%, respectively, of the total particulate PAHs. Pyrene, phenanthrene, and fluoranthene were the most abundant particulate PAH compounds emitted from the test machines, constituting 37.1%, 12.6%, and 12.2%, respectively, of the total PAHs. Other important compounds included benzo[b+k]fluoranthene (BbkF), benzo[ghi]perylene (BghiP), chrysene (Chr), benzo[e]pyrene (BeP), and benzo[ghi]fluoranthene (BghiF). The distributions of individual particulate PAH species, as well as compounds with given numbers of rings, were consistent with previous studies on diesel excavators (Cui et al., 2017) and trucks (Cui et al., 2017; Zheng et al., 2017) in China, as shown in Fig. 5.

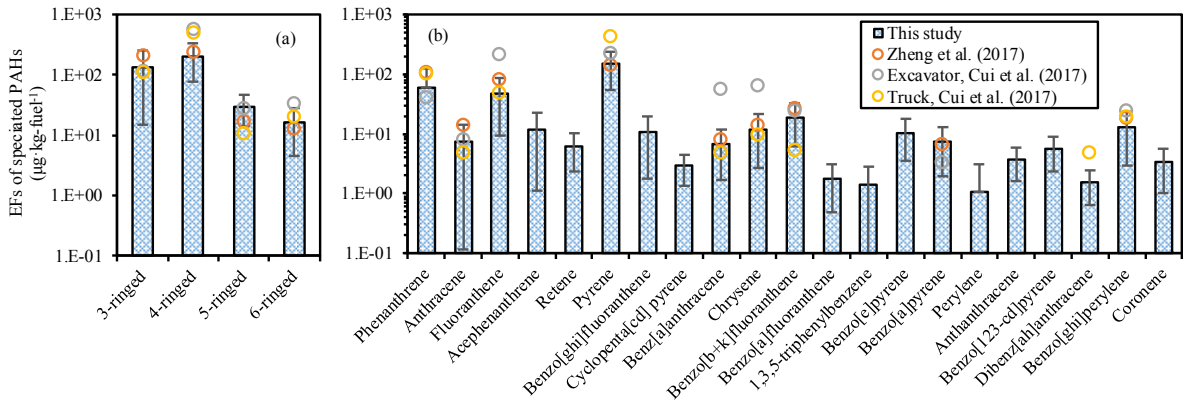


Fig. 5. Fuel-based EFs for speciated PAHs classified by (a) the number of benzene rings and (b) the speciated components, as compared with previous studies in China.

Molecular diagnostic ratios (MDRs), which consist of ratios of two individual PAHs, have been used as organic markers for various anthropogenic sources (Katsoyiannis et al., 2011) and can also be used in primary organic aerosol source apportionment (Shrivastava et al., 2007). MDRs consisting of common PAHs (e.g., Fluoranthene/(Pyrene+Fluoranthene): Flu/(Pyr+Flu); Anthracene/(Phenanthrene+Anthracene): Ant/(Phe+Ant);

Benzo[a]anthracene/(Chrysene + Benzo[a]anthracene): BaA/(Chr+BaA); Benzo[a]pyrene/Benzo[ghi]perylene: BaP/BghiP) have been used to estimate source contributions from diesel exhaust, as shown in Table 5. The overall Flu/(Pyr+Flu) ratio in this study was 0.25 ± 0.07, similar to values reported by Shah et al. (2005) and Pakbin et al. (2009), but lower than those reported by Schauer et al. (1999), Cui et al. (2017), and Zheng et al. (2017). Katsoyiannis et al. (2011) suggested that Flu/(Pyr+Flu) MDRs between 0.40 and 0.50 represent pyrogenic sources (e.g., fuel combustion). Yunker et al. (2002) and Ravindra et al. (2008) found that Flu/(Pyr+Flu) MDRs of 0.39 ± 0.1 and > 0.5, respectively, could be used to distinguish diesel combustion sources. Our measurements indicate much lower thresholds than those recommended by previous studies, which may introduce substantial uncertainties in the use of these ratios to infer diesel combustion sources. The average Ant/(Phe+Ant) and BaA/(Chr+BaA) ratios in this study were 0.12 ± 0.02 and 0.36 ± 0.02, which are both similar to the recommended MDR lower limits (0.1 and 0.35) used to identify fuel combustion sources in Katsoyiannis et al. (2011). The MDR results herein are similar to measurements in Zheng et al. (2017), but lower than those reported by Pakbin et al. (2009), Liu et al. (2015), and Cui et al. (2017). The overall BaP/BghiP ratio in this study was 0.63 ± 0.5 on average, comparable to the MDR (> 0.6) suggested for traffic emission sources by Katsoyiannis et al. (2011) and the range (0.5-0.6) suggested by Ravindra et al. (2008). The organic markers emitted from diesel machinery and vehicles varied widely with vehicle type, fuel quality, operating mode, and control technology, as shown in Table 5. In addition, the markers recommended in previous studies cannot be used to distinguish on-road emissions from non-road diesel exhaust. Therefore, we suggest that

Source	Vehicle type	Flu/(Pyr+Flu)	Ant/(Phe+Ant)	BaA/(Chr+BaA)	BaP/BghiP
Measured MDRs from diesel combustion					
This study	Excavator	0.27 ± 0.07	0.12 ± 0.02	0.34 ± 0.01	1.01 ± 0.5
	Wheel loader	0.21 ± 0.03	0.11 ± 0.01	0.38 ± 0.01	0.33 ± 0.3
	Bulldozer	0.38	0.15	0.35	0.30
	Roller	0.20	0.13	0.38	0.72
Schauer et al. (1999)	Diesel vehicle	0.39	0.19	0.33	N/A
Shah et al. (2005)	Diesel vehicle	0.28 (creep), 0.26 (transit), and 0.26 (cruise)	0.07 (creep), 0.05 (transit), and 0.03 (cruise)	0.53 (creep), 0.50 (transit), and 0.51 (cruise)	N/A
Pakbin et al. (2009)	Diesel vehicle	0.22 (UDDS) and 0.26 (cruise)	0.20 (UDDS) and 0.21 (cruise)	0.44 (UDDS) and 0.41 (cruise)	N/A

organic markers be applied carefully during diesel emissions source apportionment until additional real-world PAH emissions data can be obtained for on- and non-road diesel vehicles.

Table 5. Molecular diagnostic ratios (MDRs) for particulate PAHs from diesel construction machinery and trucks in this and previous studies.

Liu et al. (2015)	Non-road diesel engine	0.19	0.16	0.44	0.81
Cui et al. (2017)	Excavator	0.48	0.17	0.47	0.13
Zheng et al. (2017)	Diesel vehicle	0.40	0.10	0.33	0.35
Recommended MDRs for source apportionment					
Katsoyiannis et al. (2011)	Fuel combustion	0.40-0.50	> 0.1	> 0.35	
	Traffic emission				> 0.6
Yunker et al. (2002)	Diesel combustion	0.39 ± 0.1			
Ravindra et al. (2008)	Diesel combustion	> 0.5			
	Traffic emission				0.5-0.6

4 Conclusions

This study presents detailed EFs and PM chemical composition measurements from an on-board emission measurement system for nine diesel construction machines in China. NO_x, CO, THC, PM, and PN EFs and fractional contributions of PM components (including OC, EC, WSIs, elements, and OM) were determined for each test machine under real-world conditions, including idling, moving, and working. The particulate and gaseous EFs were generally consistent with previous studies. The machines possessed much higher FC rates, but slightly lower fuel-based EFs, when moving and working than they did while idling. Overall, emissions were prominent under moving and working conditions. Compared with newer machinery (under more stringent emissions standards), diesel construction machines used in China produced relatively high EFs due to a lag in emissions standards. OC was the most abundant particulate component, contributing 39.3 ± 11% of the total PM mass, followed by EC, which accounted for 37.7 ± 13% on average. The average proportions of WSIs and elements emitted from the test machines were 1.9 ± 1% and 5.3 ± 6%. NO_3^- was the most abundant WSI, while Si dominated the elemental content. Fuel quality had an adverse impact on WSI and element emissions; SO_4^{2-} and elements (e.g., Si, Ca, Al, and Fe) were emitted in higher quantities from machinery fueled with inferior diesel fuel. Organic matter species in PM, including *n*-alkanes, hopanes, particulate

PAHs, and *n*-fatty acids, contributed approximately 2.4 - 6.4% of the total PM mass. Compounds with 3 or 4 aromatic rings, including pyrene, phenanthrene, and fluoranthene, were dominant, accounting for 62% of the total particulate PAHs. Other major compounds included benzo[b+k]fluoranthene, benzo[ghi]perylene, chrysene, benzo[e]pyrene, and benzo[ghi]fluoranthene. The overall ratios of Flu/(Pyr+Flu), Ant/(Phe+Ant), BaA/(Chr+BaA), and BaP/BghiP released from the test machines were 0.25 ± 0.07, 0.12 ± 0.02, 0.36 ± 0.02, and 0.63 ± 0.5, respectively. The ratio of Flu/(Pyr+Flu) was not consistent with the MDRs suggested by previous studies, while the other ratios were comparable to the suggested ones. More measurements are needed to identify organic markers from non-road diesel machinery.

Acknowledgments

This work was supported by the National Key R&D Program of China (Grant No. 2016YFC0201501), the National Natural Science Foundation of China (Grant No. 21777101), the Science and Technology Commission of Shanghai Municipality Fund Project (Grant No. 16dz1206704).

References

Abolhasani, S., Frey, H.C., Kim, K., Rasdorf, W., Lewis, P., Pang, S., 2008. Real-world in-use activity, fuel use, and emissions for nonroad construction vehicles: a case study for excavators. J. Air Waste Manage. Assoc. 58(8), 1033-1046.

Ayhan, D., 2009. Political, economic and environmental impacts of biofuels: A review. Applied Energy. 86, S108-S117.

Campbell, P., Zhang, Y., Yan, F., Lu, Z.F., Streets, D., 2018a. Impacts of transportation sector emissions on future U.S. air quality in a changing climate. Part I: Projected emissions, simulation design, and model evaluation. Atmos. Environ. 238, 903-917.

Campbell, P., Zhang, Y., Yan, F., Lu, Z.F., Streets, D., 2018b. Impacts of transportation sector

emissions on future U.S. air quality in a changing climate. Part II: Air quality projections and the interplay between emissions and climate change. Atmos. Environ. 238, 918-930.

Cao, T., Durbin, T.D., Russell, R.L., Cocker III, D.R., Scora, G., Maldonado, H., Johnson, K.C., 2016. Evaluations of in-use emission factors from off-road construction equipment. Atmos. Environ. 147, 234-245.

Cao T., Russell, R.L., Durbin, T.D., Cocker III, D.R., Burnette, A., Calavita, J., Maldonado, H., Johnson, K.C., 2018. Characterization of the emissions impacts of hybrid excavators with a portable emissions measurement system (PEMS)-based methodology. Sci. Total Environ. 632, 112-119.

Chow, J.C., Watson, J.G., Chen, L.W.A., Chang, M.C.O., Robinson, N.F., Trimble, D., Kohl, S., 2007. The IMPROVE_A temperature protocol for thermal/optical carbon analysis: maintaining consistency with a long-term database. Journal of the Air & Waste Management Association 57, 1014-1023.

Chow, J.C., Watson, J.G., Green, M.C., Wang, X.L., Chen, L.W.A., Trimble, D.L., Cropper, P.M., Kohl, S.D., Gronstal, S.B., 2018. Separation of brown carbon from black carbon for IMPROVE and Chemical Speciation Network $PM_{2.5}$ samples. J. Air Waste Manage. 68(5), 494-510.

Cui, M., Chen, Y.J., Feng, Y.L., Li, C., Zheng, J.Y., Tian, C.G., Yan, C.Q., Zheng, M., 2017. Measurement of PM and its chemical composition in real-world emissions from non-road and on-road diesel vehicles. Atmos. Chem. Phys. 17(11), 6779-6795.

Feng, J.L., Guo, Z.G., Chan, C.K., Fang, M., 2007. Properties of organic matter in $PM_{2.5}$ at Changdao Island, China-a rural site in the transport path of the Asian continental outflow. Atmos. Environ. 41, 1924-1935.

Frey, H.C., Kangwook, K., Pang, H.S., Rasdorf, W., Lewis, P., 2008. Characterization of real-world activity, fuel use, and emissions for selected motor graders fueled with petroleum diesel and B20 biodiesel. J. Air Waste Manage. Assoc. 58, 1274-1284.

Frey, H.C., Rasdorf, W., Lewis, P., 2010. Comprehensive field study of fuel use and emissions of nonroad diesel construction equipment. Transp. Res. Rec. (Issue 2158), 69-76.

Fu, M.L., Ge, Y.S., Tan, J.W., Zeng, T., Liang, B., 2012. Characteristics of typical non-road machinery emissions in China by using portable emission measurement system. Sci. Total Environ. 437, 255-261.

Hallquist, Å.M., Jerksjö, M., Fallgren, H., Westerlund, J., Sjödin, Å., 2013. Particle and gaseous

emissions from individual diesel and CNG buses. Atmos. Chem. Phys. 13(10), 5337-5350.

Huang, C., Lou, D.M., Hu, Z.Y., Feng, Q., Chen, Y.R., Chen, C.H., Tan, P.Q., Yao, D., 2013. A PEMS study of the emissions of gaseous pollutants and ultrafine particles from gasoline- and diesel-fueled vehicles. Atmos. Environ. 77, 703-710.

IARC (International Agency for Research on Cancer), 2012. Diesel Engine Exhaust Carcinogenic, WHO.

Ježek, I., Katrašnik, T., Westerdahl, D., Močnik, G., 2015. Black carbon, particle number concentration and nitrogen oxide emission factors of random in-use vehicles measured with the on-road chasing method. Atmos. Chem. Phys. 15(19), 11011-11026.

Katsoyiannis, A., Sweetman, A.J., Jones, K.C., 2011. PAH molecular diagnostic ratios applied to atmospheric sources: a critical evaluation using two decades of source inventory and air concentration data from the UK. Environ. Sci. Technol. 45, 8897-8906.

Li, Y.G., Huang, H.X.H., Griffith, S.M., Wu, C., Lau, A.K.H., Yu, J.Z., 2017. Quantifying the relationship between visibility degradation and $PM_{2.5}$ constituents at a suburban site in Hong Kong: Differentiating contributions from hydrophilic and hydrophobic organic compounds. Sci. Total Environ. 575, 1571-1581.

Li, Z., Zhang, K.S., Pang, K.L., Di, B.F., 2016. A fuel-based approach for emission factor development for highway paving construction equipment in China. J. Air Waste Manage. 66(12), 1214-1223.

Lindgren, M., Arrhenius, K., Larsson, G., Bäfver, L., Arvidsson, H., Wetterberg, C., Hansson, P., Rosell, L., 2011. Analysis of unregulated emissions from an off-road diesel engine during realistic work operations. Atmos. Environ. 45, 5394-5398.

Liu, Z.F., Lu, M.M., Birch, M.E., Keener, T.C., Khang, S.J., Liang, F.Y., 2005. Variations of the particulate carbon distribution from a nonroad diesel generator. Environ. Sci. Technol. 39(20), 7840-7844.

Liu, Z.G., Wall, J.C., Ottinger, N.A., McGuffin, D., 2015. Mitigation of PAH and nitro-PAH emissions from nonroad diesel engines. Environ. Sci. Technol., 49(6), 3662-3671.

Lu, J., Huang, C., Hu Q.Y., Yang, Q., Jing, B.L., Xia, Y., Lu, B., Tang, W., Lou, S.R., Tao, S.K., Li, L., 2017. Air pollutant emission inventory of non-road machineries in typical cities in Eastern China. Environmental Sciences. 38(7), 110-118. (in Chinese)

Ma, C.Y., Zhuang, T., Zhang, Z.Y., Wang, J., Yang, F., Qiao, C., Lu, M.M., 2018. Tailpipe emission

characteristics of $PM_{2.5}$ from selected on-road China III and China IV diesel vehicles. Aerosol Sci. Technol. 52(7), 799-808.

McDonald, B.C., Goldstein, A.H., Harley, R.A., 2015. Long-term trends in California mobile source emissions and ambient concentrations of black carbon and organic aerosol. Environ. Sci. Technol. 49(8), 5178-5188.

Moussa, S., A. Leithead, S. Li, T. Chan, J. Wentzell, C. Stroud, J. Zhang, P. Lee, G. Lu, J. R. Brook, K. Hayden, J. Narayan, and J. Liggio, 2016. Emissions of Hydrogen Cyanide from On-road Gasoline and Diesel Vehicles. Atmos. Environ. 131, 185-195

MEP (Ministry of Environmental Protection of China), 2018. China vehicle environmental management annual report 2018. Vehicle Emission Control Center of MEP, Beijing, 43.

Mohankumara, S., Senthilkumar, P., 2017. Particulate matter formation and its control methodologies for diesel engine: A comprehensive review. Renewable and Sustainable Energy Reviews, 80, 1227-1238.

Pakbin, P., Ning, Z., Schauer, J.J., Sioutas, C., 2009. Characterization of particle bound organic carbon from diesel vehicles equipped with advanced emission control technologies. Environ. Sci. Technol. 43(13), 4679-4686.

Pirjola, L., Dittrich, A., Niemi, J.V., Saarikoski, S., Timonen, H., Kuuluvainen, H., Järvinen, A., Kousa, A., Rönkkö, T., Hillamo, R., 2016. Physical and chemical characterization of real-world particle number and mass emissions from city buses in Finland. Environ. Sci. Technol. 50(1), 294-304.

Pirjola, L., Rönkkö, T., Saukko, E., Parviainen, H., Malinen, A., Alanen, J., Saveljeff, H., 2017. Exhaust emissions of non-road mobile machine: real-world and laboratory studies with diesel and HVO fuels. Fuel. 202, 154-164.

Pitchford, M., Malm, W., Schichtel, B., Kumar, N., Lowenthal, D., Hand, J., 2007. Revised algorithm for estimating light extinction from IMPROVE particle speciation data. J. Air Waste Manage. 57(11), 1326-1336.

Ravindra, K., Sokhi, R., Van Grieken, R., 2008. Atmospheric polycyclic aromatic hydrocarbons: source attribution, emission factors and regulation. Atmos. Environ. 42, 2895-2921.

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(10), 1578-1587.

Seinfeld, J. H., Pandis, S. N., 2006. Atmospheric chemistry and physics: from air pollution to climate change, 2nd Edition. Wiley, New York. 265-266.

Shah, S.D., Ogunyoku, T.A., Miller, J.W., Cocker, D.R., 2005. On-road emission rates of PAH and *n*-alkane compounds from heavyduty diesel vehicles. Environ. Sci. Technol. 39(14), 5276-5284.

Shrivastava, M.K., Subramanian, R., Rogge, W.F., Robinson, A.L., 2007. Sources of organic aerosol: Positive matrix factorization of molecular marker data and comparison of results from different source apportionment models. Atmos. Environ. 41, 9353-9369.

Sippula, O., Stengel, B., Sklorz, M., Streibel, T., Rabe, R., Orasche, J., Lintelmann, J., Michalke, B., Abbaszade, G., Radischat, C., Gröger, T., Schnelle-Kreis, J., Harndorf, H., Zimmermann, R., 2014. Particle emissions from a marine engine: chemical composition and aromatic emission profiles under various operating conditions. Environ. Sci. Technol. 48(19), 11721-11729.

Smith, K.R., Jerrett, M., Anderson, H.R., Burnett, R.T., Stone, V., Derwent, R., Atkinson, R.W., Cohen, A., Shonkoff, S.B., Krewski, D., Pope III, C. A., Thun, M.J., Thurston, G., 2009. Health and Climate Change 5 Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. Lancet. 374(9707), 2091-2103.

Turpin, B.J., Lim, H.J., 2001. Species contributions to $PM_{2.5}$ mass concentrations: Revisiting common assumptions for estimating organic mass. Aerosol Sci. Technol. 35 (1), 602-610.

Wang, F., Li, Z., Zhang, K., Di, B., Hu, B., 2016. An overview of nonroad equipment emissions in China. Atmos. Environ. 132, 283-289.

Wang, Y.F., Huang, K.L., Li, C.T., Mi, H.H., Luo, J.H., Tsai, P.J., 2003. Emissions of fuel metals content from a diesel vehicle engine. Atmos. Environ. 37, 4637-4643.

Wu, B.B., Shen, X.B., Cao, X.Y., Yao, Z.L., Wu, Y.N., 2016. Characterization of the chemical composition of $PM_{2.5}$ emitted from on-road China III and China IV diesel trucks in Beijing, China. Sci. Total Environ. 551-552, 579-589.

Yunker, M.B., Macdonald, R.W., Vingarzan, R., Mitchell, R.H., Goyettee, D., Sylvestre, S., 2002. PAHs in the Fraser River basin: a critical appraisal of PAH ratios as indicators of PAH source and composition. Org. Geochem. 33, 489-515.

Zavala, M., Huertas, J.I., Prato, D., Jazcilevich, A., Aguilar, A., Balam, M., Misra, C., Molina, L.T., 2017. Real-world emissions of in-use off-road vehicles in Mexico. J. Air Waste Manage. 67(9), 958-972.

Zhang, Y.Z., Yao, Z.L., Shen, X.B., Liu, H., He, K.B., 2015. Chemical characterization of PM2.5 emitted from on-road heavy-duty diesel trucks in China. Atmos. Environ. 122, 885-891.

Zheng, X., 2016, Emission characteristics of black carbon and polycyclic aromatic hydrocarbon from heavy duty diesel vehicles based on PEMS method. Doctoral dissertation. Tsinghua University. Beijing, China

Zheng, X., Wu, Y., Zhang, S.J., Hu, J.N., Zhang, K.M., Li, Z.H., He, L.Q., Hao, J.M., 2017. Characterizing particulate polycyclic aromatic hydrocarbon emissions from diesel vehicles using a portable emissions measurement system. Sci. Rep. 7(1), 10058.