APPENDIX AVAILABLE ON THE HEI WEBSITE

Research Report 199

Real-World Vehicle Emissions Characterization for the Shing Mun Tunnel in Hong Kong and Fort McHenry Tunnel in the United States

Xiaoliang Wang et al.

Appendix C. Additional Results

This Appendix was reviewed solely for spelling, grammar, and cross-references to the main text. It has not been formatted or fully edited by HEI. This document was reviewed by the HEI Review Committee.

Correspondence may be addressed to Dr. Xiaoliang Wang, Desert Research Institute, 2215 Raggio Pkwy., Reno, NV 89512; e-mail: *xiaoliang.wang@dri.edu*.

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APPENDIX C. ADDITIONAL RESULTS

Additional Measured Concentration and Emission Factor Results

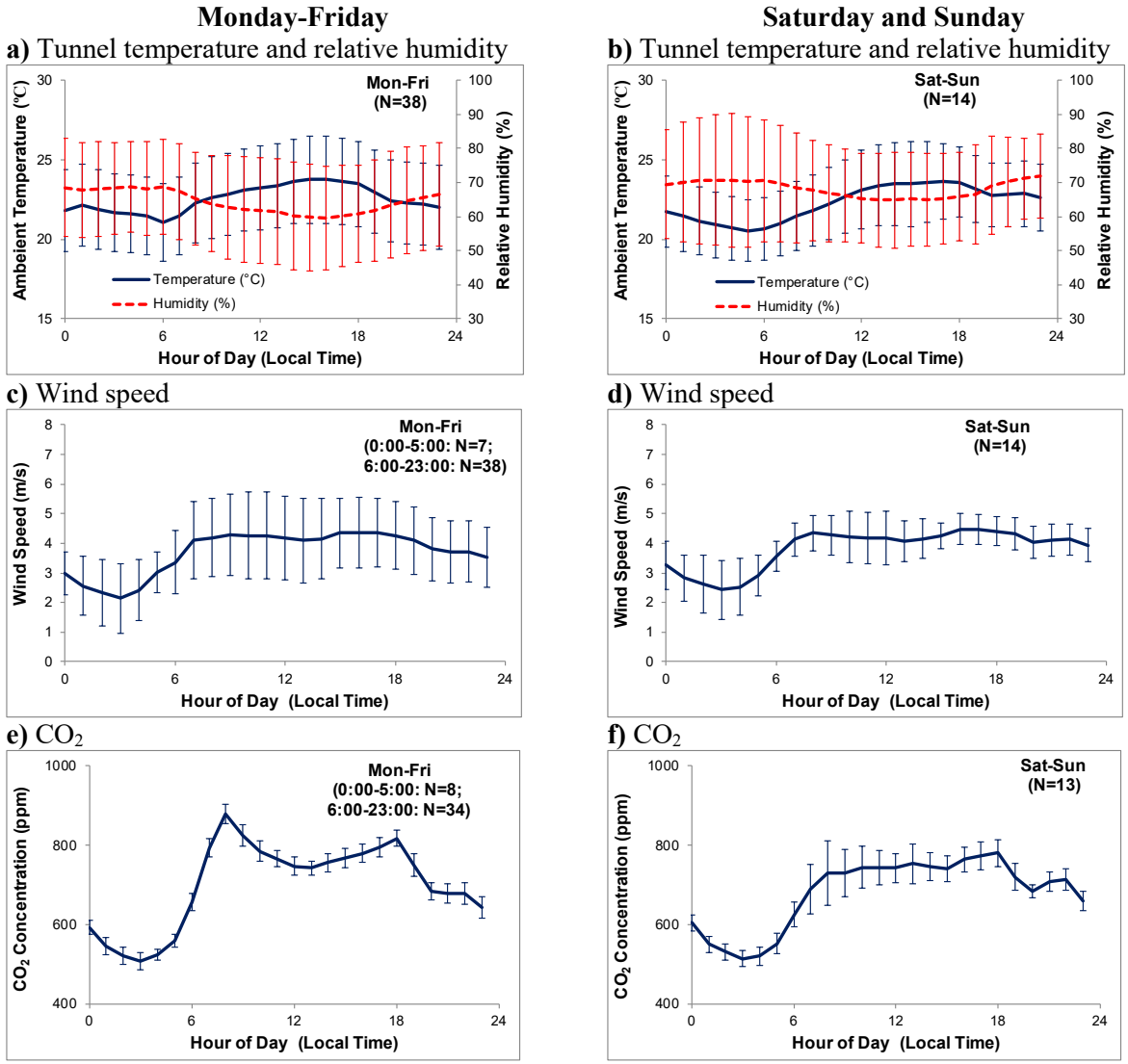


Figure C.1. Diurnal variations (hourly average) of SMT outlet measurements in 2015: tunnel ambient temperature and relative humidity (a and b); wind speed (c and d); and CO_2 concentrations (e and f) during weekdays (left panels) and weekends (right panels). Error bars represent the standard deviation of the hourly average data, and N represents the number of days when the indicated measurement is available. Because one of the bores was closed for cleaning and maintenance during 0000-0500 LDT on Monday-Thursday and all traffic was redirected to the other bore, only Friday data were averaged for 0000-0500 LDT on weekdays.

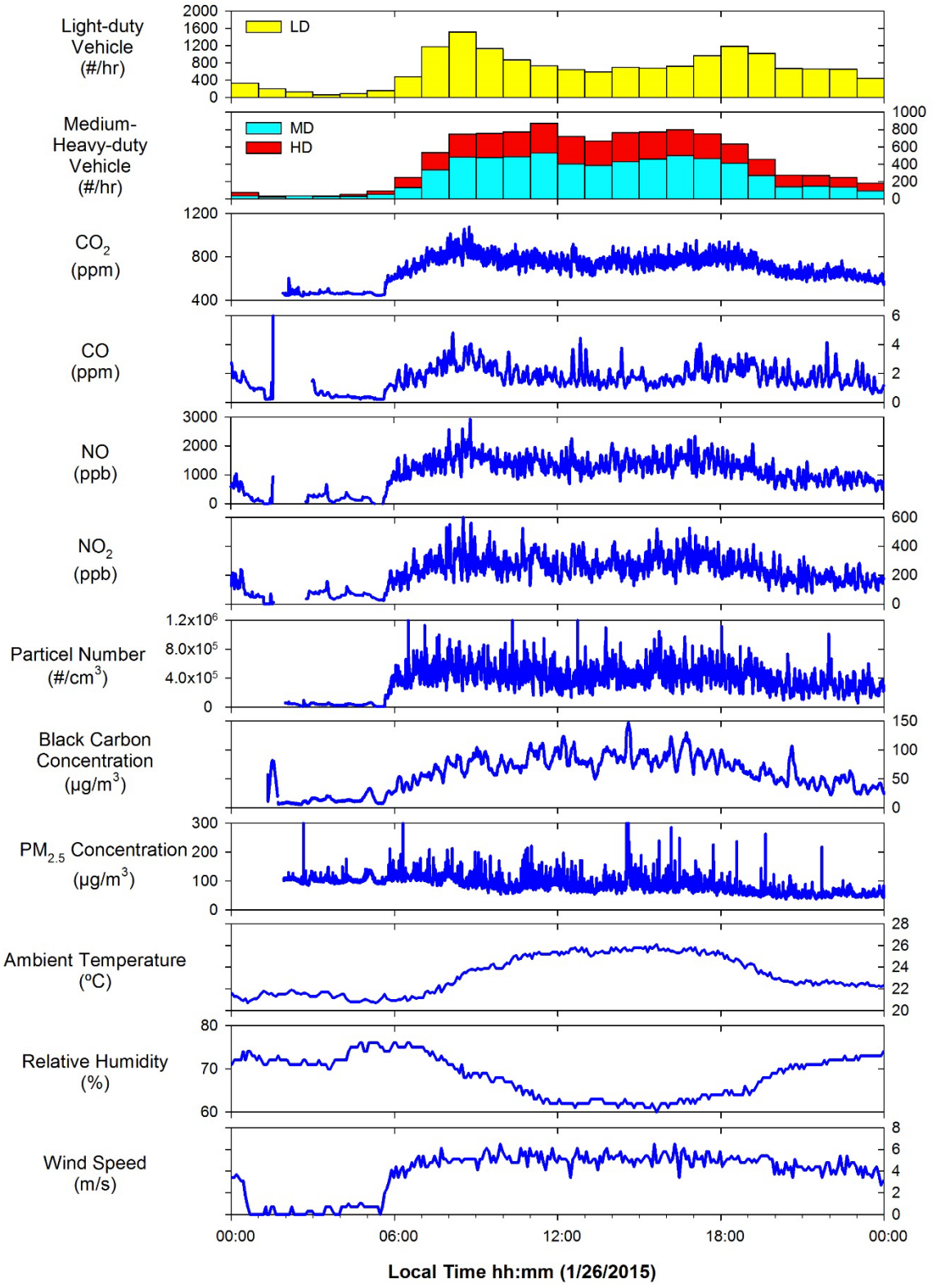


Figure C.2. An example of parameter temporal variation on 1/26/2015 (Monday) measured by continuous instruments at the outlet sampling location in the SMT.

Table C.1. Pearson Correlation Coefficients (*r*) Among Pollutant Concentrations and Vehicle Categories in the SMT[a]

Parameter	CO_2	CO	NO	NO_2	SO_2	$PM_{2.5}$	PM_{10}	LD	MD	HD
CO_2	1.00									
CO	0.76	1.00								
NO	0.99	0.67	1.00							
NO_2	0.98	0.64	0.99	1.00						
SO_2	0.99	0.71	0.99	0.98	1.00					
$PM_{2.5}$	0.97	0.59	0.98	0.98	0.98	1.00				
PM_{10}	0.96	0.57	0.98	0.98	0.97	1.00	1.00			
LD	**0.94**	**0.91**	**0.89**	**0.87**	**0.90**	**0.83**	**0.81**	1.00		
MD	**0.92**	**0.53**	**0.94**	**0.95**	**0.94**	**0.97**	**0.98**	0.77	1.00	
HD	**0.94**	**0.53**	**0.96**	**0.97**	**0.96**	**0.99**	**0.99**	0.77	0.99	1.00

[a] Green font indicates $r > 0.9$, and red font indicates $r \leq 0.9$ between pollutant concentration and vehicle categories.

Table C.2. Comparison of Distance-Based Emission Factors (EF_D; in g/vehicle/km) for Gases and $PM_{2.5}$ Measured at SMT and FMT with Earlier Studies (The EF_D is reported as fleet-average when not labeled specifically for LD or HD.)

Year	Location	EF_D (g/vehicle/km)							Traffic	References
		CO	NH_3	NO	NO_2	NO_x (as NO_2)	SO_2	$PM_{2.5}$		
2015	Shing Mun Tunnel, Hong Kong	1.80 ± 0.13	0.019 ± 0.001	0.87 ± 0.08	0.24 ± 0.02	1.58 ± 0.14	0.047 ± 0.002	0.025 ± 0.003	13% LPG, 45% GV, and 42% DV	This study
2015 Winter	Ft. McHenry Tunnel, Maryland	0.69 ± 0.05 (LD) 0.66 ± 0.17 (HD)	0.015 ± 0.002 (LD) 0.012 ± 0.005 (HD)	NA	NA	0.24 ± 0.11 (LD) 3.45± 0.36 (HD)	NA	0.016 ± 0.024 (LD) 0.093 ± 0.076 (HD)	>97% LD in Bore 3 and 8-45% HD in Bore 4	This study
2015 Summer	Ft. McHenry Tunnel, Maryland	0.67 ± 0.07 (LD) 0.94 ± 0.25 (HD)	0.024 ± 0.002 (LD) 0.009 ± 0.006 (HD)	NA	NA	0.09 ± 0.06 (LD) 1.94 ± 0.19 (HD)	NA	0.001 ± 0.003 (LD) 0.065 ± 0.010 (HD)	>97 LD in Bore 3 and 8-45% HD in Bore 4	This study
2013 2014	Zhujiang Tunnel, Guangzhou, China	3.10 ± 0.68	0.230 ± 0.014	1.15 ± 0.18	0.14 ± 0.03	1.89 ± 0.28	0.021 ± 0.003	0.083 ± 0.028	27% LPG, 61% GV, and 12% DV	(Liu et al. 2014; Zhang et al. 2015)
2010	Caldecott Tunnel, California[1]	1.09 ± 0.05 (LD)	NA	NA	NA	0.145 ± 0.006 (LD)	NA	0.0029 ± 0.0008 (LD)	>99% GV	(Dallmann et al. 2013)
2006	Caldecott Tunnel, California[2]	2.92 ± 0.24 (LD)	0.049 ± 0.004 (LD)	NA	NA	0.36 ± 0.02 (LD)	NA	0.008 ± 0.002 (LD)	>99% GV	(Ban-Weiss et al. 2008a; 2008b; Kean et al. 2009)
2003-2004	Shing Mun Tunnel, Hong Kong	1.88 ± 0.11	0.017± 0.003	0.98 ± 0.08	0.22 ± 0.03	1.72 ± 0.13	0.21 ± 0.02	0.131 ± 0.037	9% LPG, 41% GV, and 50% DV	(Cheng et al. 2006; HKPolyU 2005)
2001	Caldecott Tunnel, California[2]	5.25 ± 0.16	NA	NA	NA	0.67 ± 0.02	NA	NA	>99% GV	(Kean et al. 2002)
1999	Caldecott Tunnel, California[2]	6.35 ± 0.41	0.078 ± 0.006	NA	NA	0.80 ± 0.03	NA	NA	>99% GV	(Kean et al. 2000a)
1999	Tuscarora Tunnel, Pennsylvania	1.94 ± 0.68 (LD)	NA	0.28 ± 0.04 (LD) 7.79±1.26 (HD)	NA	0.23 ± 0.04 (LD) 13.81±2.44 (HD)	NA	0.014 ± 0.013 (LD) 0.135 ± 0.018 (HD)	9.6-83% HD	(Gertler et al. 2002)
1997	Caldecott Tunnel, California[3]	NA	NA	NA	NA	0.94 ± 0.02	NA	0.011 ± 0.001	>99% GV	(Ban-Weiss et al. 2008b; Kirchstetter et al. 1999)
		NA	NA	NA	NA	19.63 ± 2.41	NA	0.930 ± 0.103	3.9-4.8% MD+HD	

Table C.2 *continued.*

Year	Location	EF_D (g/vehicle/km)							Traffic	References
		CO	NH_3	NO	NO_2	NO_x (as NO_2)	SO_2	$PM_{2.5}$		
1992	Ft. McHenry Tunnel, Maryland	3.94 ± 0.34 (LD) 6.11 ± 1.75 (HD)	NA	0.29 ± 0.04 (LD) 5.26 ± 0.20 (HD)	0.056 ± 0.042 (LD) 0.90 ± 0.20 (HD)	0.50 ± 0.06 (LD) 8.97 ± 0.28 (HD)	NA	NA	>99 LD in Bore 3, and ~17% HD in Bore 4	(Pierson et al. 1996)
1992	Tuscarora Tunnel, Pennsylvania	3.04 ± 0.30 (LD) 3.44 ± 1.00 (HD)	NA	0.17 ± 0.09 (LD) 7.40 ± 0.31 (HD)	0.00 ± 0.13 (LD) 0.74 ± 0.43 (HD)	0.24 ± 0.16 (LD) 12.09±0.53 (HD)	NA	NA	6-80% (average 18%) HD	(Pierson et al. 1996)

[1]Assuming fuel economy 9.7 km/L, gasoline fuel density 0.742 kg/L, and gasoline carbon content 0.824 kgC/kg fuel. The emission values excluded MD and HD contributions.
[2]Assuming fuel economy 6.1 km/L, gasoline density 0.74 kg/L, and gasoline carbon content 0.85 kgC/kg fuel (Kean et al. 2009).
[3]Assuming fuel economy 8.3 and 2.8 km/L for LD and MD+HD, gasoline and diesel density 0.74 and 0.84 kg/L, respectively (Ban-Weiss et al. 2008b; Kirchstetter et al. 1999).

Table C.3. Gas and $PM_{2.5}$ Carbon-Based Emission Factors (EF_C in g/kg-C) and Comparison with a Few Selected Earlier Studies (The EF_C is reported as fleet-average when not labeled specifically for LD or HD.)

Year	Location	EF_C (g/kg-C)							Traffic	References
		CO	NH_3	NO	NO_2	NO_x (as NO_2)	SO_2	$PM_{2.5}$		
2015 Winter/ Spring	Shing Mun Tunnel, Hong Kong	22.5 ± 0.6	0.24 ± 0.01	11.3 ± 0.5	3.2 ± 0.2	20.5 ± 0.9	0.57 ± 0.03	0.30 ± 0.03	13% LPG, 45% GV, and 42% DV	This study
2015 Winter	Ft. McHenry Tunnel, Maryland	10.0 ± 0.8 (LD) 5.2 ± 2.4 (HD)	0.21±0.02 (LD) 0.10±0.07 (HD)	NA	NA	4.8 ± 1.7 (LD) 34.0 ± 5.4 (HD)	NA	0.26 ± 0.32 (LD) 0.93 ± 1.0 (HD)	>97% LD in Bore 3 and 8-45% HD in Bore 4	This study
2015 Summer	Ft. McHenry Tunnel, Maryland	9.7 ± 0.9 (LD) 8.7 ± 3.0 (HD)	0.34±0.02 (LD) 0.03±0.08 (HD)	NA	NA	1.9 ± 0.5 (LD) 20.6 ± 3.0 (HD)	NA	0.03 ± 0.04 (LD) 0.70 ± 0.12 (HD)	>97 LD in Bore 3 and 8-45% HD in Bore 4	This study
2014	Aberdeen Tunnel Hong Kong	26.2	NA	NA	NA	19.3	NA	0.51	26% LPG, 41% GV, and 33% DV	(Brimblecombe et al. 2015)
2014	Lion Rock Tunnel, Hong Kong	15.8	NA	NA	NA	26.7	NA	0.41	13% LPG, 53% GV, and 34% DV	
2014	Tai Lam Tunnel Hong Kong	13.0	NA	NA	NA	28.5	NA	0.61	6% LPG, 48% GV, and 46% DV	

Table C.3 *continued.*

Year	Location	EF_C (g/kg-C)							Traffic	References
		CO	NH_3	NO	NO_2	NO_x (as NO_2)	SO_2	$PM_{2.5}$		
2014	Aberdeen, Lion Rock, and Tai Lam Tunnels, Hong Kong	33.2 ± 5.6 (NDV) 11.0 ± 9.8 (DV)	NA	NA	NA	3.9 ± 3.7 (NDV) 33.7 ± 6.4 (DV)	NA	-0.15 ± 0.11 (NDV) 0.83 ± 0.20 (DV)	6-27% LPG, 43-57% GV, and 29-42% DV	(Brimblecombe et al. 2015)
2010	Caldecott Tunnel, California[1]	17.3 ± 0.9 (LD)	NA	NA	NA	2.3 ± 0.1 (LD)	NA	0.046 ± 0.012 (LD)	>99% GV	(Dallmann et al. 2013)
2006	Caldecott Tunnel, California[2]	28.2 ± 2.4	0.47 ± 0.02	NA	NA	3.5 ± 0.2	NA	0.082 ± 0.023	>99% GV	(Ban-Weiss et al. 2008a; 2008b; Kean et al. 2009)
		93.1 ± 17.2	0.20 ± 0.17	NA	NA	46.0 ± 3.4	NA	1.61 ± 0.34	7% MD+HD	
2003-2004	Shing Mun Tunnel, Hong Kong	26.1 ± 8.3	0.35 ± 0.14	10.5 ± 2.8	3.1 ± 0.6	19.2 ± 4.8	3.43 ± 0.76	1.75 ± 0.50	9% LPG, 41% GV, and 50% DV	(Cheng et al. 2006; HKPolyU 2005)
2001	Caldecott Tunnel, California[2]	50.9 ± 1.6	NA	NA	NA	6.5 ± 0.2	NA	NA	>99% GV	(Kean et al. 2002)
1999	Caldecott Tunnel, California[2]	61.5 ± 4.0	0.76 ± 0.05	NA	NA	7.7 ± 0.3	NA	NA	>99% GV	(Kean et al. 2000a)
1997	Caldecott Tunnel, California[2]	NA	NA	NA	NA	10.6 ± 0.2	NA	0.129 ± 0.011	>99% GV	(Ban-Weiss et al. 2008b; Kirchstetter et al. 1999)
			NA	NA	NA	65.5 ± 8.0	NA	3.10 ± 0.34	3.9-4.8% MD+HD	
1992	Ft. McHenry Tunnel, Maryland[3]	72.6 ± 6.6 (LD) 7.7 ± 23.5 (HD)	NA	NA	NA	14.7 ± 2.0 (LD) 50.2 ± 7.2 (HD)	NA	NA	>99 LD in Bore 3, and ~17% HD in Bore 4	(Pierson et al. 1996)
1992	Tuscarora Mountain Tunnel, Pennsylvania[4]	55.4 ± 10 (LD) 1.3 ± 27.9 (HD)	NA	NA	NA	19.6 ± 3.7 (LD) 53.6 ± 10.3 (HD)	NA	NA	6-80% (average 18%) HD	(Pierson et al. 1996)

[1]Assuming gasoline carbon content 0.824 kgC/kg fuel. The emission values excluded MD and HD contributions (Dallmann et al. 2013).
[2]Assuming fuel carbon content 0.85 and 0.87 kgC/kg fuel for gasoline and diesel, respectively (Ban-Weiss et al. 2008b).
[3]Assuming fuel economy 30.4 and 7.0 mil/gal for LD and HD, respectively; gasoline is assumed to have a formula of $C_nH_{1.825n}$ with a density of 0.74 g/cm3; and diesel is assumed to have a formula of C_nH_{2n} with a density of 0.77 g/cm^3 (Pierson et al. 1996).
[4]Assuming fuel economy 37.0 and 5.71 mil/gal for LD and HD, respectively (Pierson et al. 1996).

Table C.4. Gas and $PM_{2.5}$ Fuel-Based Emission Factors (EF_F in g/kg fuel) and Comparison with a Few Selected Earlier Studies (The EF_F is reported as fleet-average when not labeled specifically for LD or HD.)

Year	Location	EF_F (g/kg fuel)							Traffic	References
		CO	NH_3	NO	NO_2	NO_x (as NO_2)	SO_2	$PM_{2.5}$		
2015 Winter/ Spring	Shing Mun Tunnel, Hong Kong[1]	19.1 ± 0.5	0.20 ± 0.01	9.6 ± 0.4	2.7 ± 0.2	17.4 ± 0.7	0.48 ± 0.02	0.25 ± 0.03	13% LPG, 45% GV, and 42% DV	This study
2015 Winter	Ft. McHenry Tunnel, Maryland	8.5 ± 0.6 (LD) 4.6 ± 2.0 (HD)	0.18±0.02 (LD) 0.09±0.06 (HD)	NA	NA	4.1 ± 1.5 (LD) 29.6 ± 4.7 (HD)	NA	0.22 ± 0.28 (LD) 0.81 ± 0.89 (HD)	>97% LD in Bore 3 and 8-45% HD in Bore 4	This study
2015 Summer	Ft. McHenry Tunnel, Maryland	8.3 ± 0.7 (LD) 7.5 ± 2.6 (HD)	0.29±0.02 (LD) 0.03±0.07 (HD)	NA	NA	1.7 ± 0.4 (LD) 17.9 ± 1.4 (HD)	NA	0.028 ± 0.030 (LD) 0.61 ± 0.11 (HD)	>97 LD in Bore 3 and 8-45% HD in Bore 4	This study
2014	Aberdeen, Lion Rock, and Tai Lam Tunnels, Hong Kong	28.9 ± 4.9 (NDV) 9.6 ± 8.5 (DV)	NA	NA	NA	3.4 ± 3.2 (NDV) 29.3 ± 5.6 (DV)	NA	-0.13 ± 0.10 (NDV) 0.72 ± 0.17 (DV)	6-27% LPG, 43-57% GV, and 29-42% DV	(Brimblecombe et al. 2015)
2014	Aberdeen Tunnel Hong Kong	22.8	NA	NA	NA	16.8	NA	0.44	26% LPG, 41% GV, and 33% DV	
2014	Lion Rock Tunnel, Hong Kong	13.7	NA	NA	NA	23.2	NA	0.36	13% LPG, 53% GV, and 34% DV	
2014	Tai Lam Tunnel Hong Kong	11.4	NA	NA	NA	24.8	NA	0.53	6% LPG, 48% GV, and 46% DV	
2013	Zhujiang Tunnel, Guangzhou, China[2]	53.2 ± 11.7	3.95 ± 0.24	19.7 ± 3.1	2.4 ± 0.5	32.5 ± 4.8	0.36 ± 0.05	1.42 ± 0.49	27% LPG, 61% GV, and 12% DV	(Liu et al. 2014; Zhang et al. 2015)
2010	Caldecott Tunnel, California	14.3 ± 0.7 (LD)	NA	NA	NA	1.9 ± 0.08 (LD)	NA	0.038 ± 0.010 (LD)	>99% GV	(Dallmann et al. 2013)
2006	Caldecott Tunnel, California	24 ± 2	0.40±0.02	NA	NA	3.0 ± 0.2	NA	0.07 ± 0.02	>99% GV	(Ban-Weiss et al. 2008a; 2008b; Kean et al. 2009)
		81 ± 15	0.17±0.15	NA	NA	40 ± 3	NA	1.4 ± 0.3	7% MD+HD	
2003-2004	Shing Mun Tunnel, Hong Kong[1]	22.2 ± 7.1	0.30 ± 0.12	8.9 ± 2.4	2.6 ± 0.5	16.3 ± 4.1	2.91 ± 0.65	1.48 ± 0.42	9% LPG, 41% GV, and 50% DV	(Cheng et al. 2006; HKPolyU 2005)

Table C.4 *continued.*

Year	Location	EF_F (g/kg fuel)							Traffic	References
		CO	NH_3	NO	NO_2	NO_x (as NO_2)	SO_2	$PM_{2.5}$		
2002-2004	Squirrel Hill Tunnel, Pennsylvania	NA	0.183-0.274	NA	NA	8-18	NA	0.158-0.437	6-15% HD	(Grieshop et al. 2006)
2001	Caldecott Tunnel, California[3]	43.2 ± 1.4	NA	NA	NA	5.5 ± 0.1	NA	NA	>99% GV	(Kean et al. 2002)
1999	Caldecott Tunnel, California	52.3 ± 3.4	0.64±0.04	NA	NA	6.55 ± 0.23	NA	NA	>99% GV	(Kean et al. 2000a)
1997	Caldecott Tunnel, California	NA	NA	NA	NA	9.0 ± 0.2	NA	0.11 ± 0.01	>99% GV	(Ban-Weiss et al. 2008b; Kirchstetter et al. 1999)
		NA	NA	NA	NA	57 ± 7	NA	2.7 ± 0.3	3.9-4.8% MD+HD	
1993	Van Nuys Tunnel, California	173	0.51	NA	NA	NA	NA	NA	~70% GV and 30% DV; ~80% with TWC	(Fraser and Cass 1998)
1992	Ft. McHenry Tunnel, Maryland	68.4 ± 5.8 (LD) 23.4 ± 6.7 (HD)	NA	5.1 ± 0.6 (LD) 20.1 ± 0.8 (HD)	1.0 ± 0.7 (LD) 3.4 ± 0.8 (HD)	8.7 ± 1.0 (LD) 34.3 ± 1.1 (HD)	NA	NA	>99 LD in Bore 3, and ~17% HD in Bore 4	(Pierson et al. 1996)
1992	Tuscarora Mountain Tunnel, Pennsylvania	64.2 ± 6.4 (LD) 11.7 ± 3.1 (HD)	NA	3.5 ± 2.0 (LD) 23.1 ± 1.0 (HD)	0.0 ± 2.8 (LD) 2.3 ± 1.3 (HD)	5.1 ± 3.4 (LD) 37.7 ± 1.6 (HD)	NA	NA	6-80% HD with an average of 18%	(Pierson et al. 1996)

[1]Assuming fuel carbon content 0.85.
[2]Assuming fuel consumption rate: 12.7 km/L and fuel density of 0.74 kg/L (Liu et al. 2014).
[3]Assuming fuel density 0.74 kg/L.

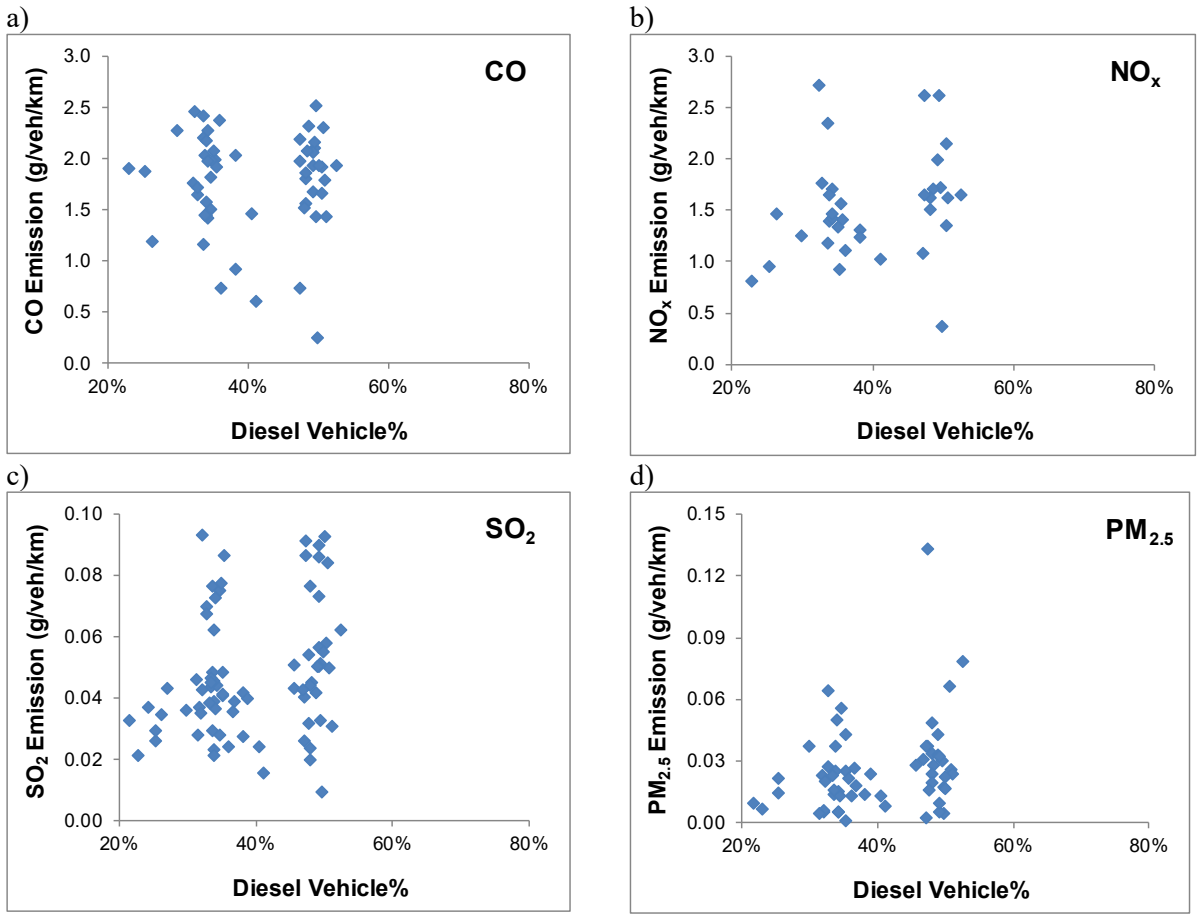


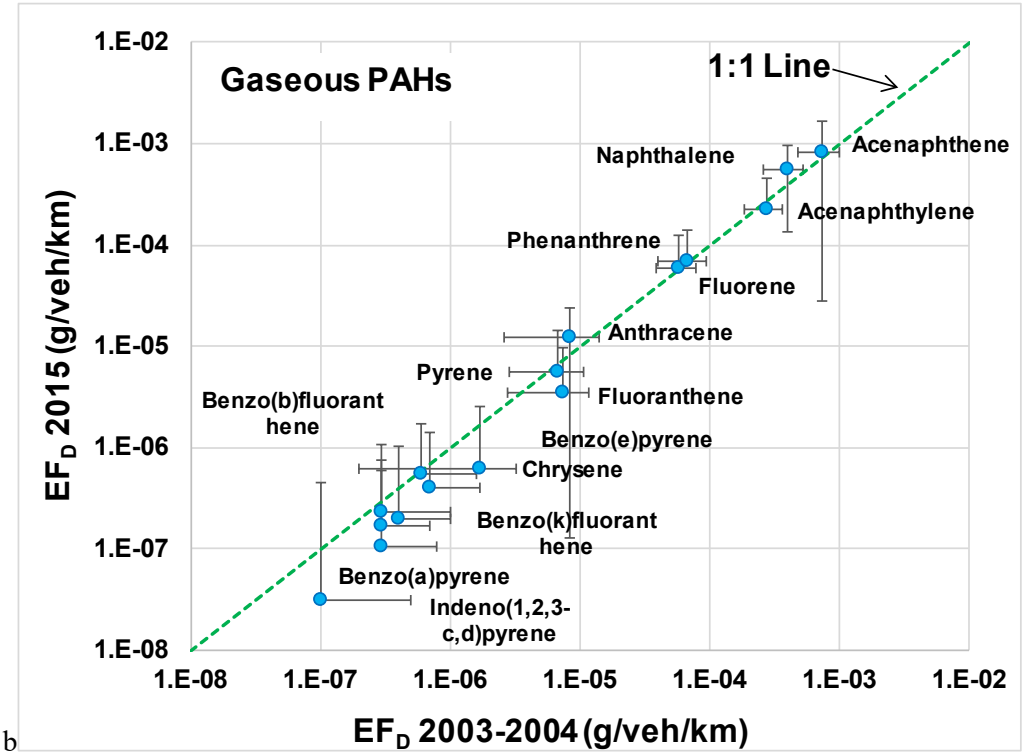
Figure C.3. Fleet-average emission factor (EF_D) vs. diesel vehicle fraction measured in SMT in 2015.

Table C.5. Distance-Based Emission Factors (EF_D; Average ± Standard Error in g/vehicle/km) for Gases and $PM_{2.5}$ Apportioned by Positive Matrix Factorization (PMF) for the 2015 Study and by Linear Regression for the 2003–2004 Study in SMT.

Year	Vehicle Category	EF_D (g/vehicle/km)						
		CO	NO	NO_2	NO_x	NMHCs	SO_2	$PM_{2.5}$
2015	LPG	1.68±0.26	0.49±0.10	0.11±0.02	0.87±0.18	0.150±0.026	0.009±0.002	0.011±0.001
	Gasoline	0.90±0.25	0.15±0.05	0.02±0.01	0.25±0.08	0.035±0.010	0.021±0.007	0.007±0.001
	Non-diesel (NDV)	1.09±0.24	0.23±0.05	0.04±0.01	0.40±0.09	0.062±0.012	0.018±0.006	0.008±0.001
	Diesel (DV)	0.29±0.04	1.23±0.21	0.37±0.07	2.26±0.39	0.035±0.007	0.044±0.008	0.043±0.003
2003–2004	Non-diesel (NDV)	NA[a]	NA[a]	NA[a]	0.03±0.45	NA[a]	NA[a]	0.017±0.029
	Diesel (DV)	NA[a]	NA[a]	NA[a]	3.97±0.58	NA[a]	NA[a]	0.257±0.031

[a]Not available

a)



b

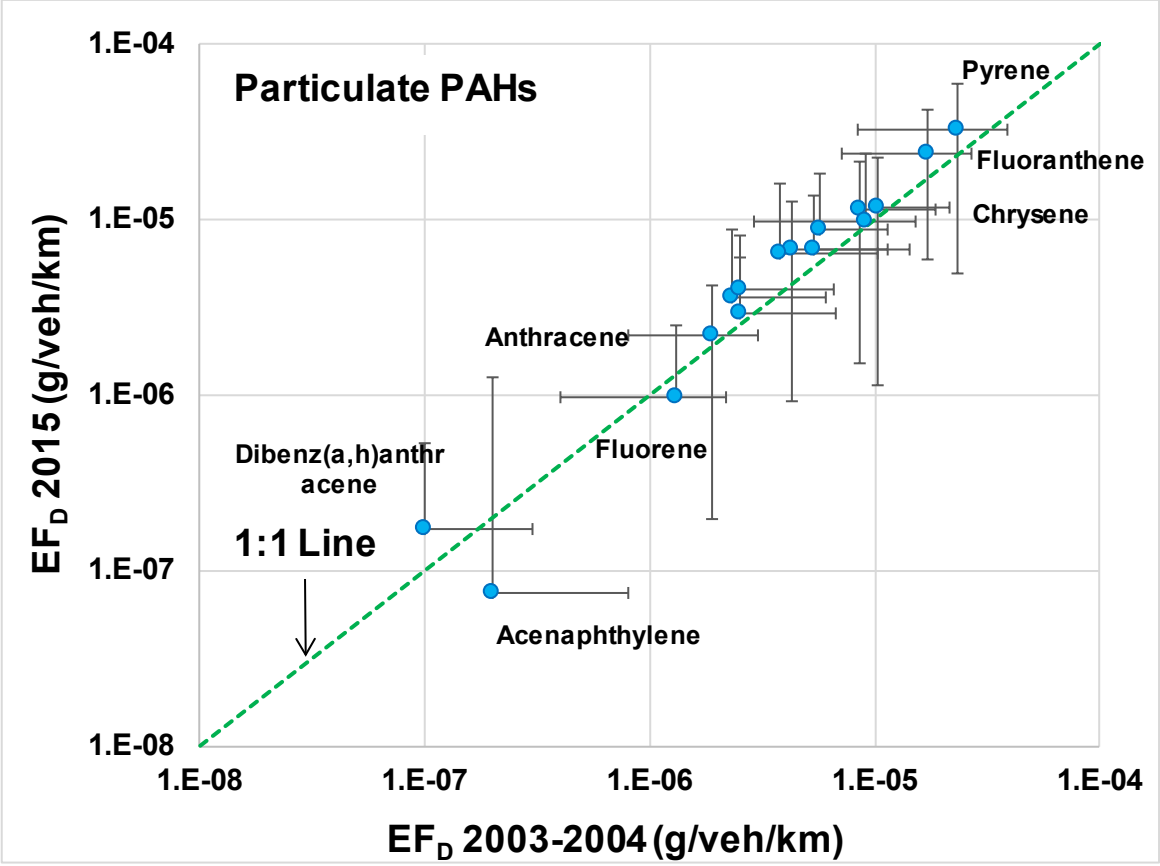


Figure C.4. Comparison of (a) gaseous PAHs and (b) particulate PAHs emission factors (EF_D) in SMT between 2015 and 2003–2004.

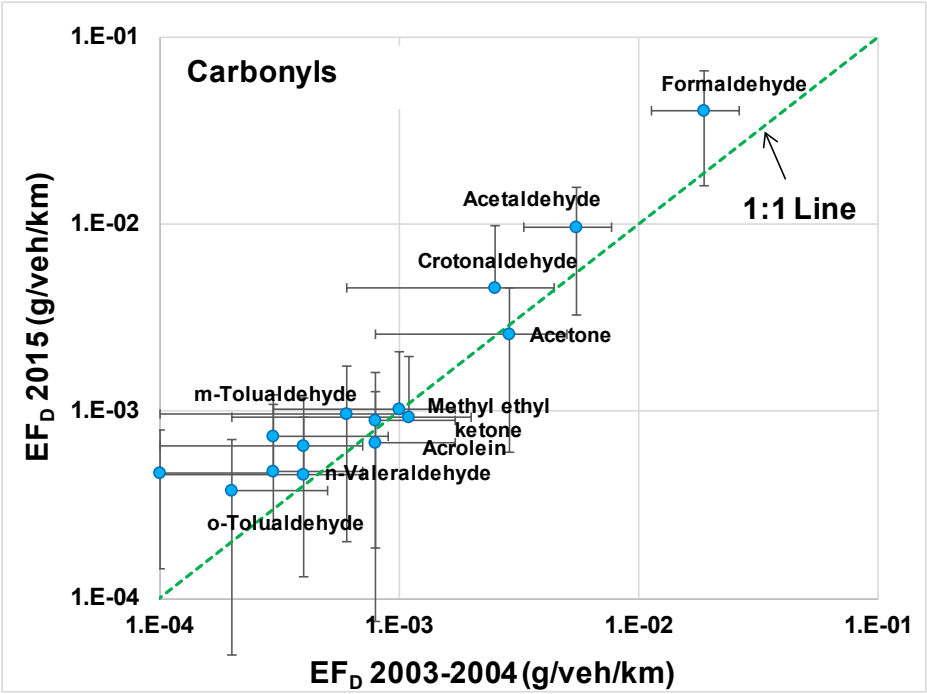


Figure C.5. Comparison of carbonyl emission factors (EF_D) in SMT between 2015 and 2003–2004.

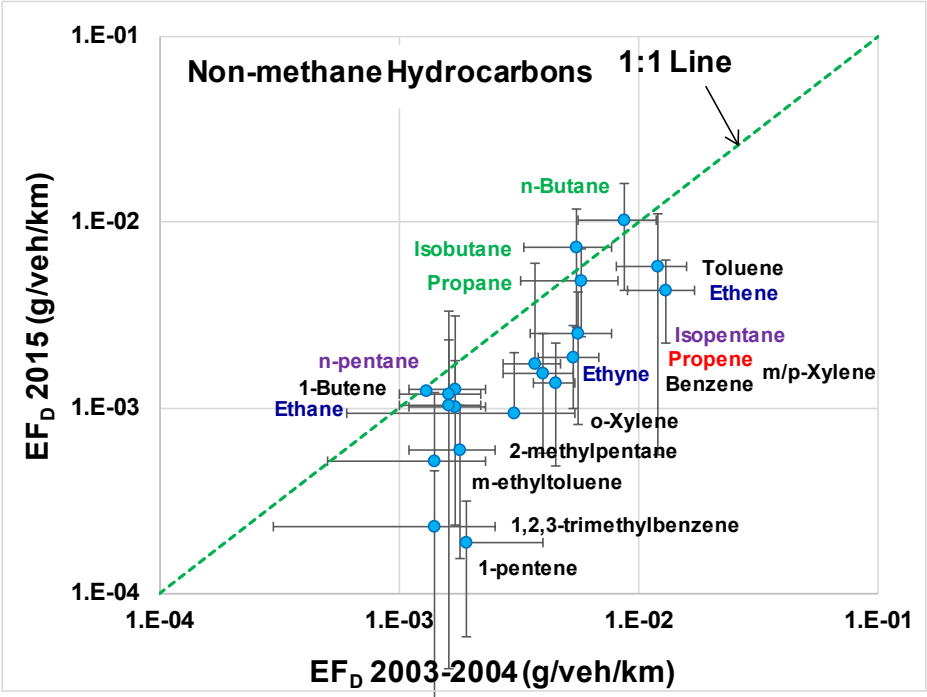
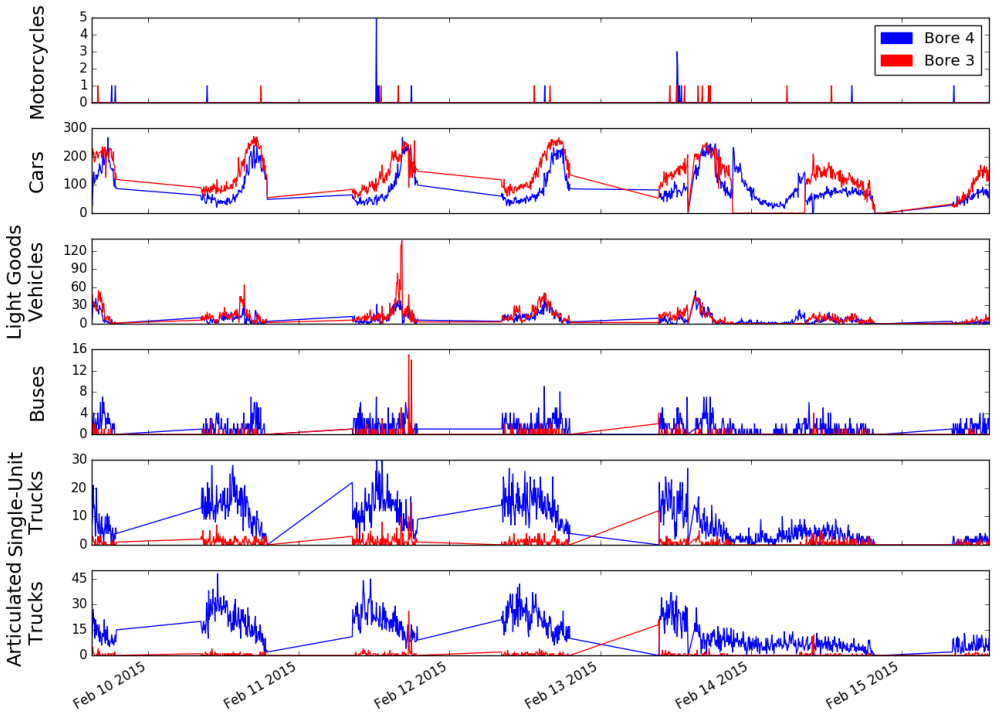


Figure C.6. Comparison of non-methane hydrocarbon emission factors (EF_D) in SMT between 2015 and 2003–2004. *n*-Butane, isobutane, and propane are LPG markers (in green); *n*-pentane and isopentane are gasoline markers (in purple); propene is a diesel marker (in red); and ethyne, ethene, and ethane are tailpipe emission markers (in blue) (Lyu et al. 2017).

a) Winter



b) Summer

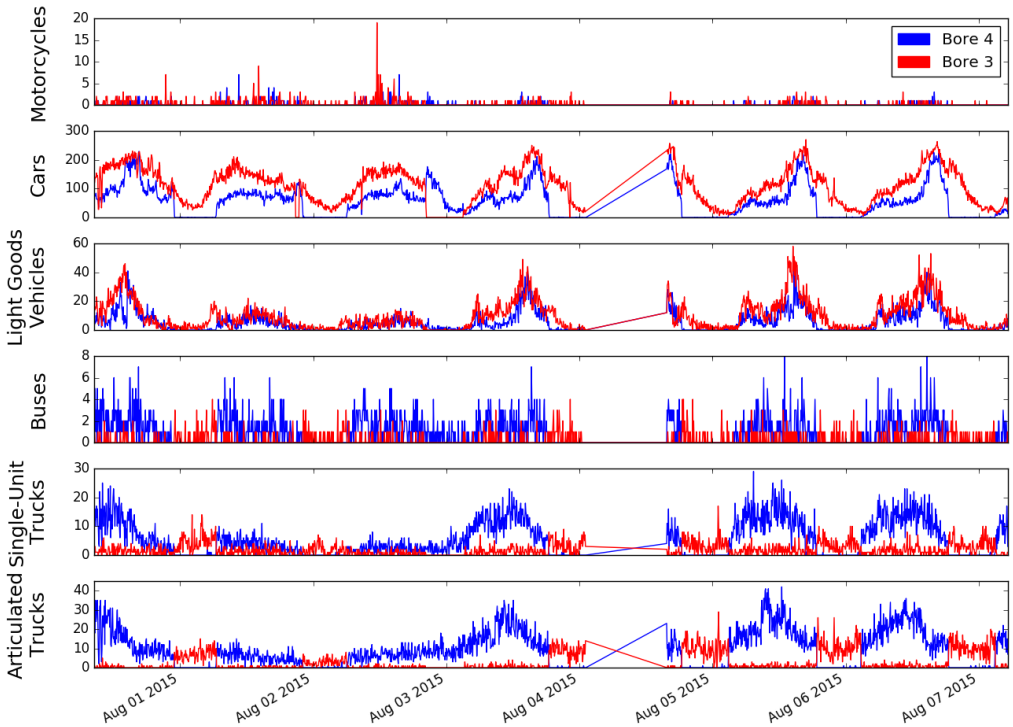


Figure C.7. Traffic patterns for different vehicle categories during (a) winter and (b) summer campaigns at the FMT in 2015. Plots show vehicle counts per 5 minutes.

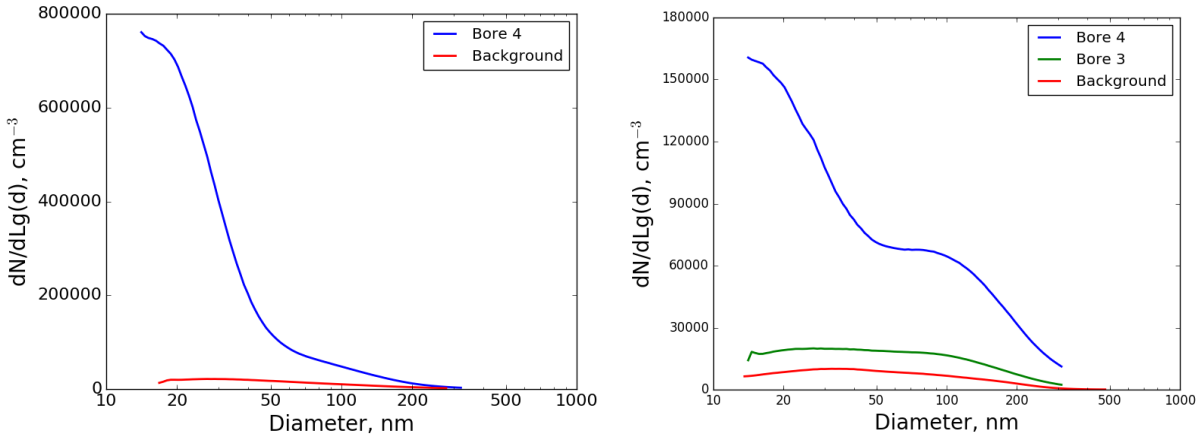


Figure C.8. Campaign-average aerosol size distributions measured during winter (left) and summer (right) campaigns in the FMT in 2015. No SMPS measurements were available in Bore 3 during the 2015 winter campaign.

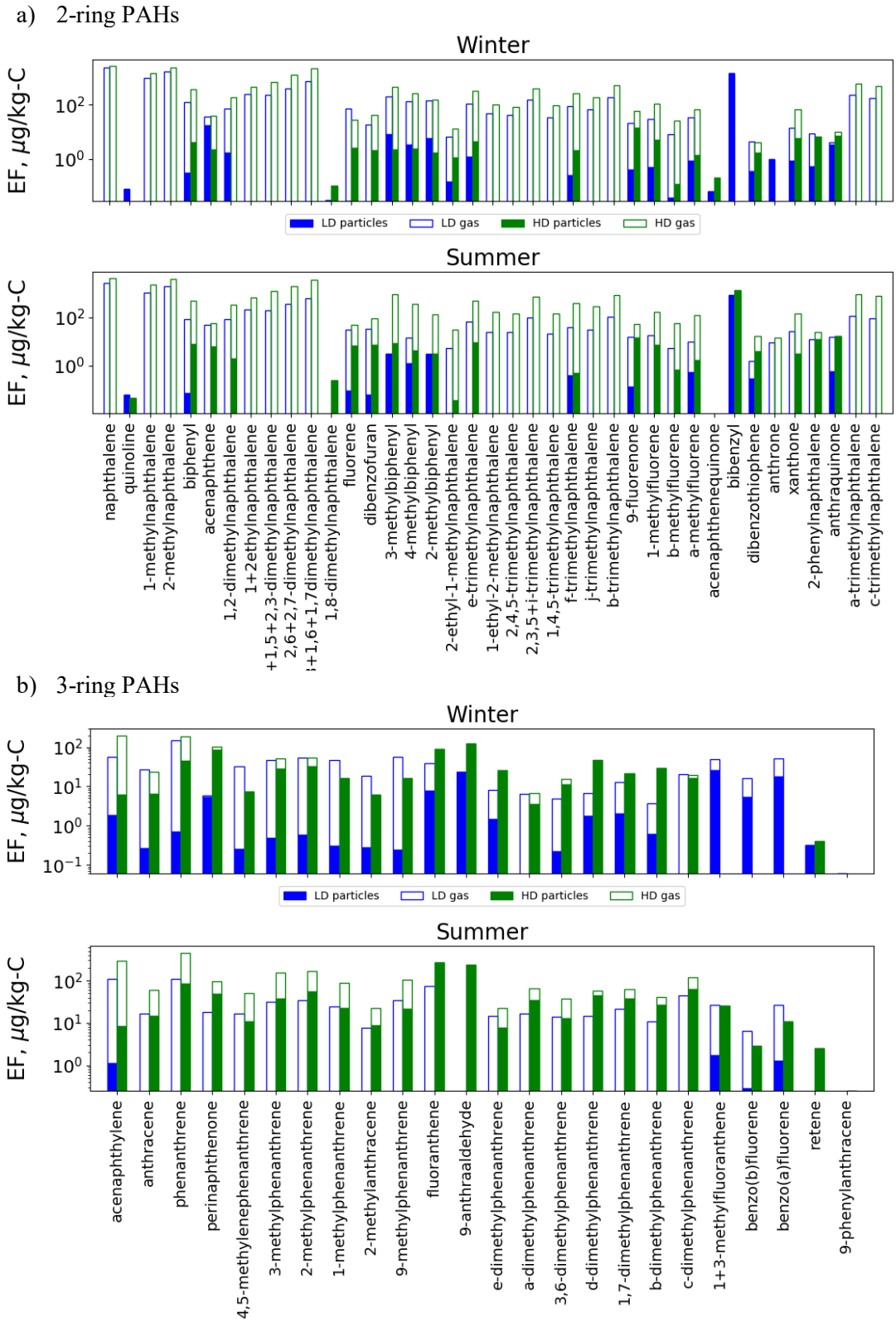
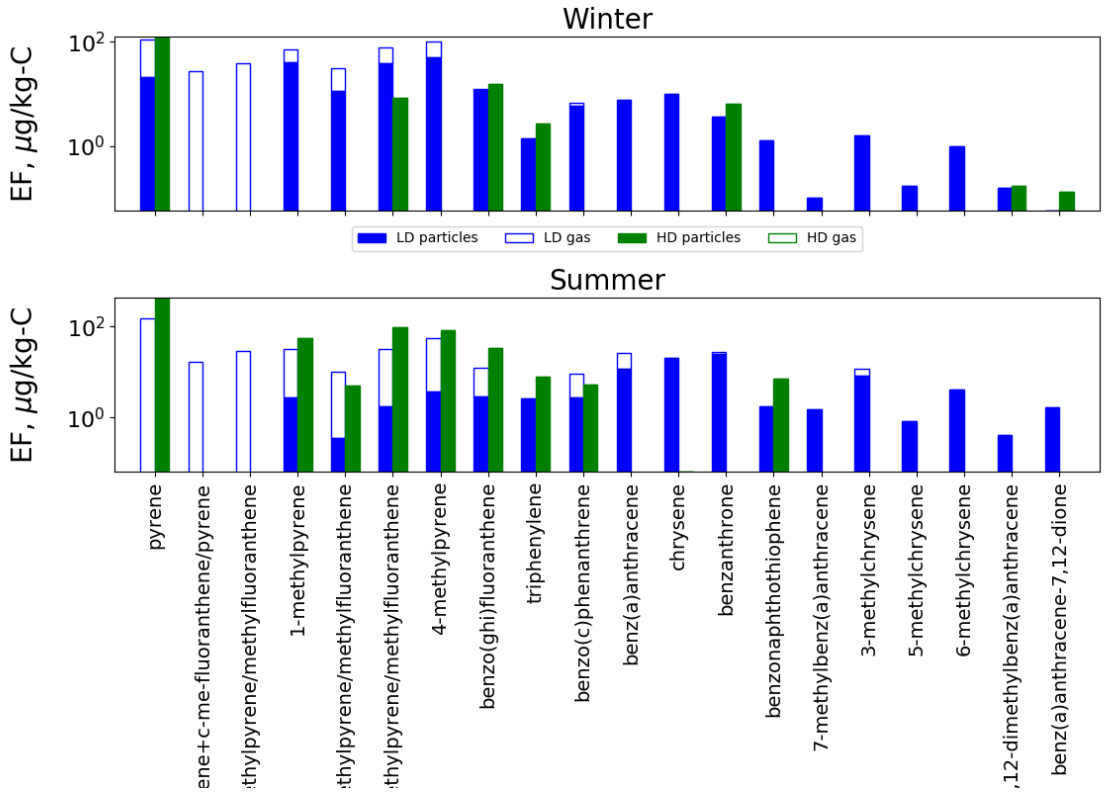


Figure C.9. Emission factors (EF_C) for (a) 2-ring, (b) 3-ring, (c) 4-ring, and (d) 5-, 6-, and 7-ring PAHs measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. Empty and solid bars represent gas and particle phase pollutants, respectively.

c) 4-rings PAHs



d) 5-, 6-, and 7-ring PAHs

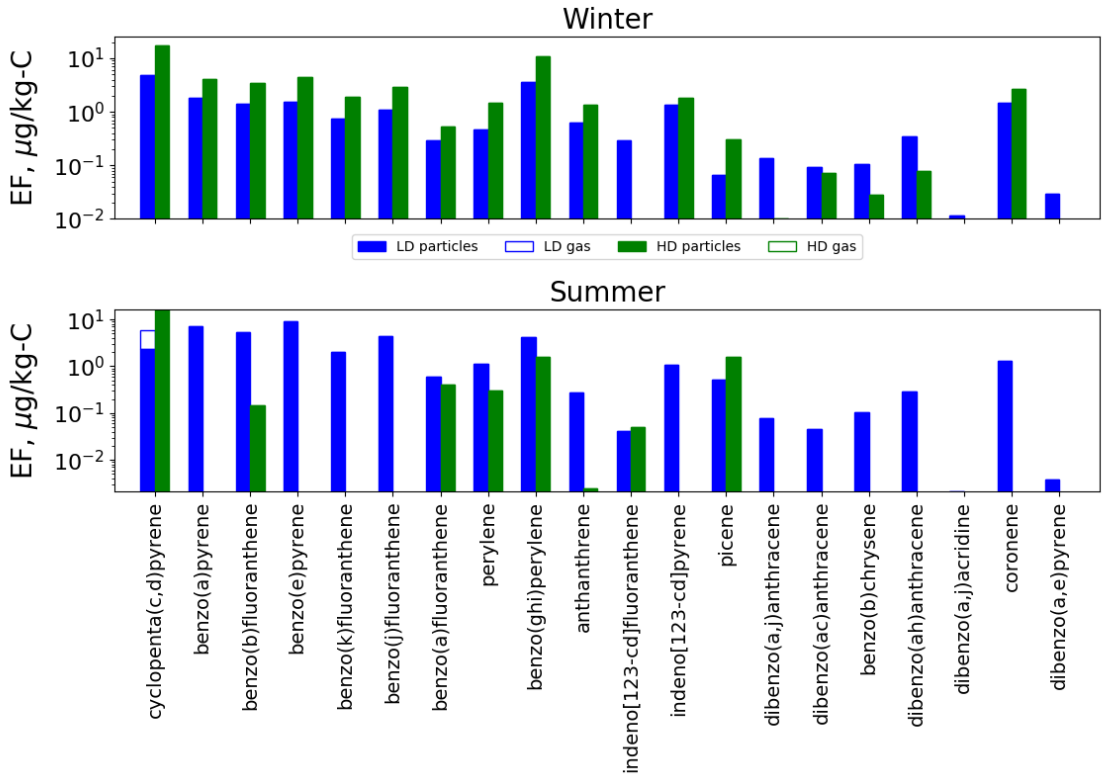


Figure C.9 *continued.*

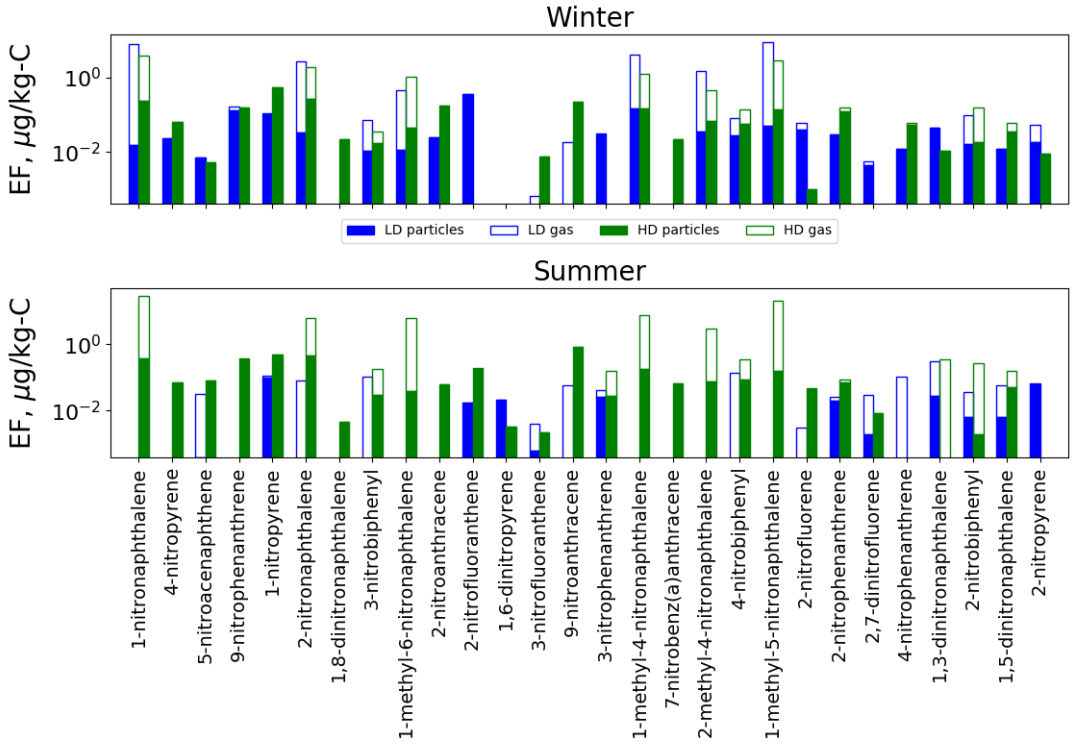


Figure C.10. Emission factors (EF_C) for nitro-PAHs measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. Empty and solid bars represent gas and particle phase pollutants, respectively.

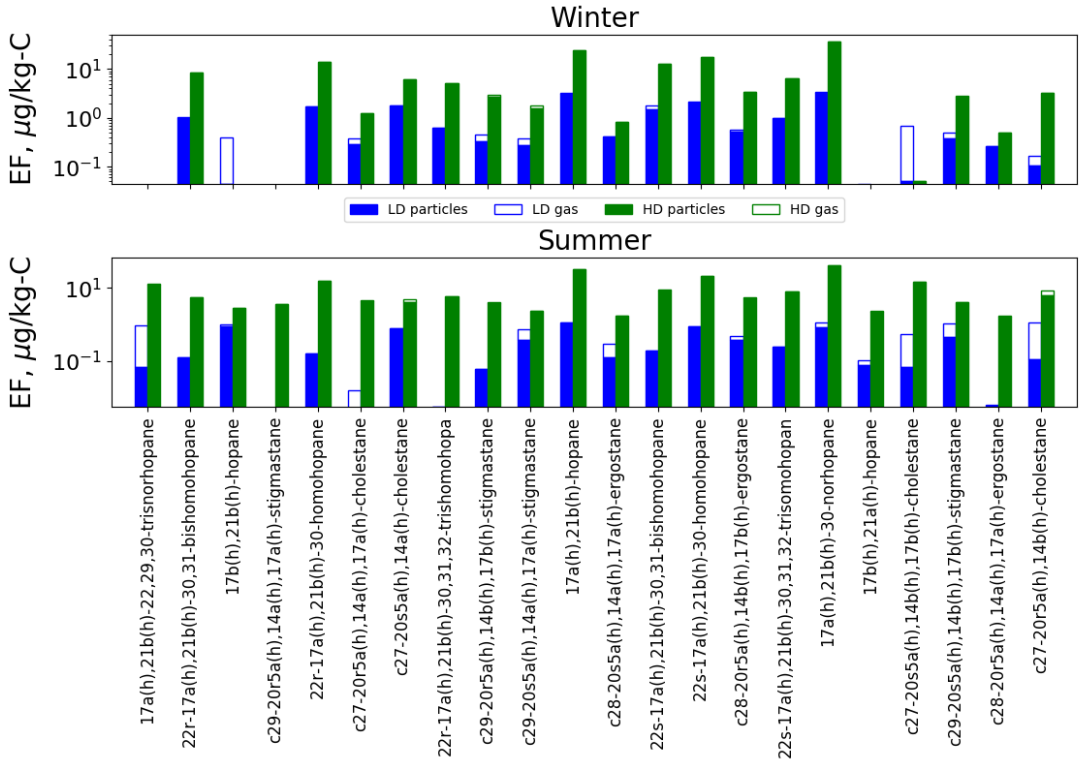


Figure C.11. Emission factors (EF_C) for hopanes and steranes measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. Empty and solid bars represent gas and particle phase pollutants, respectively.

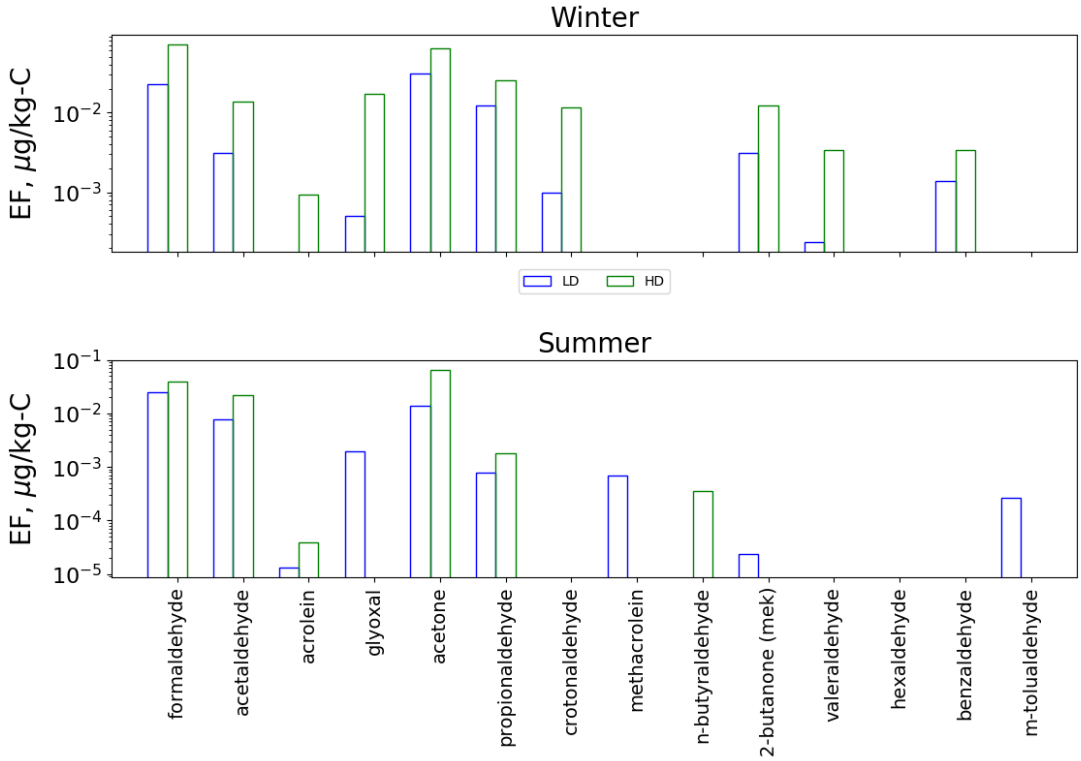


Figure C.12. Emission factors (EF_C) for carbonyl compounds measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. All components were in the gas phase.

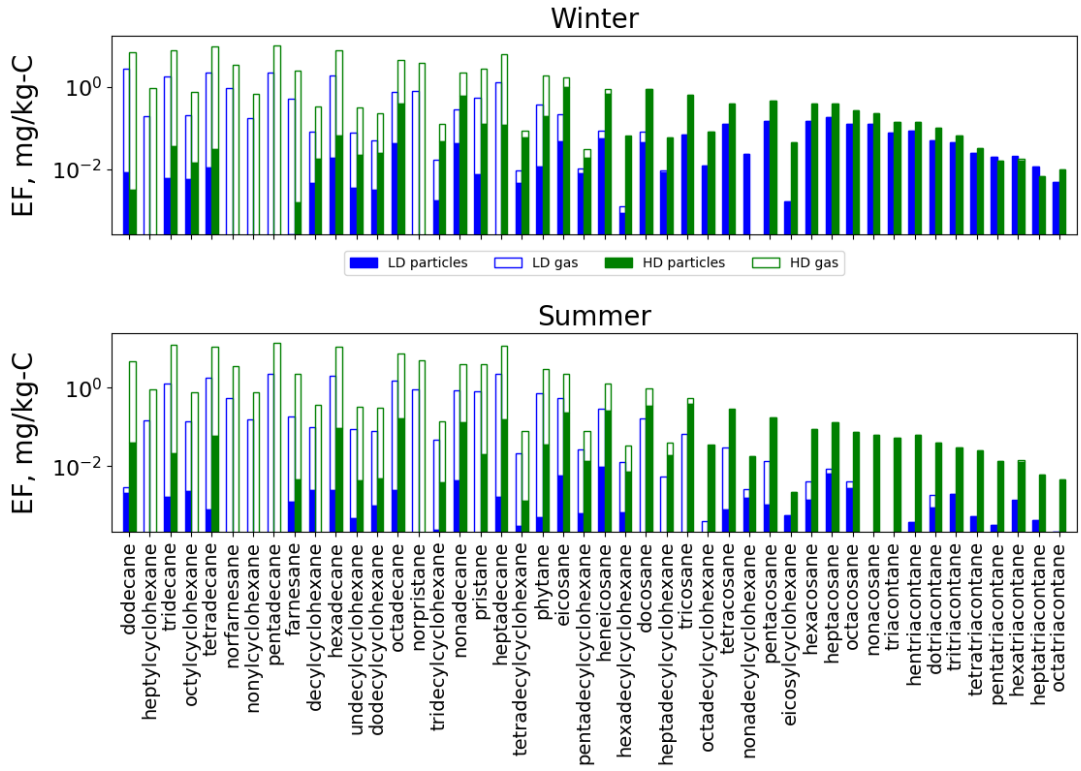


Figure C.13. Emission factors (EF_C) for semi-volatile alkanes measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. Empty and solid bars represent gas and particle phase pollutants, respectively.

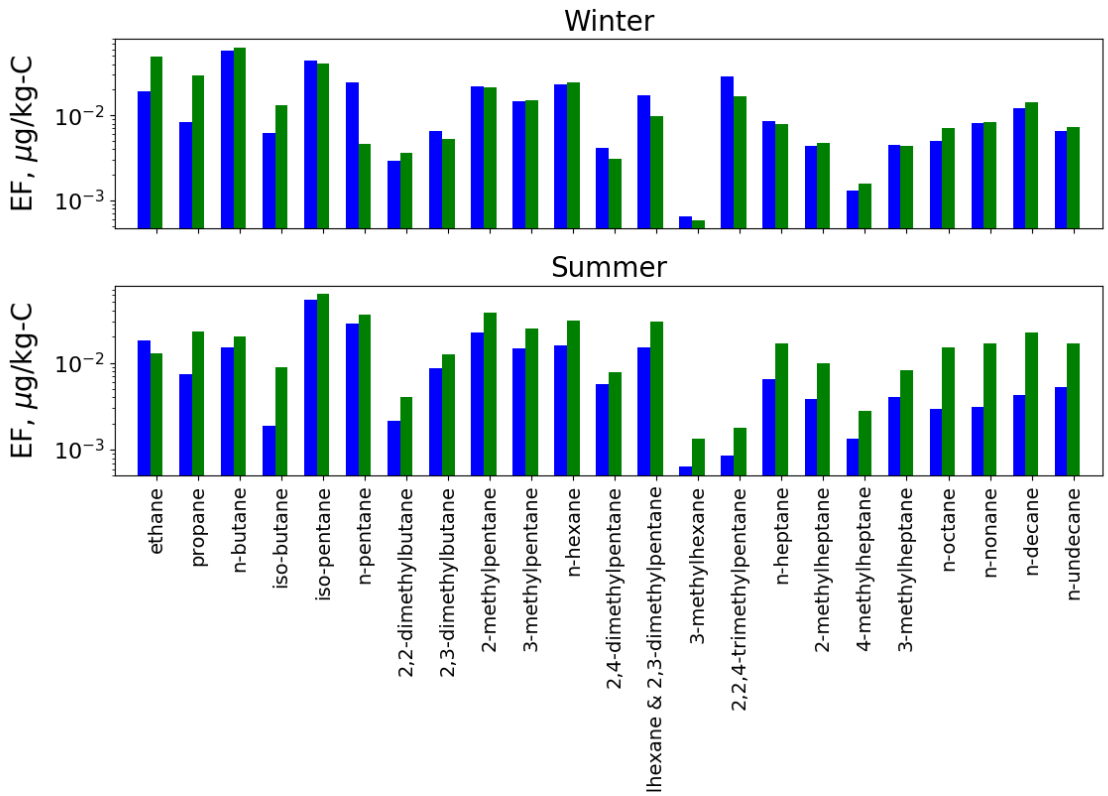


Figure C.14. Emission factors (EF_C) for light alkanes (C2–C11) measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. All components were in the gas phase.

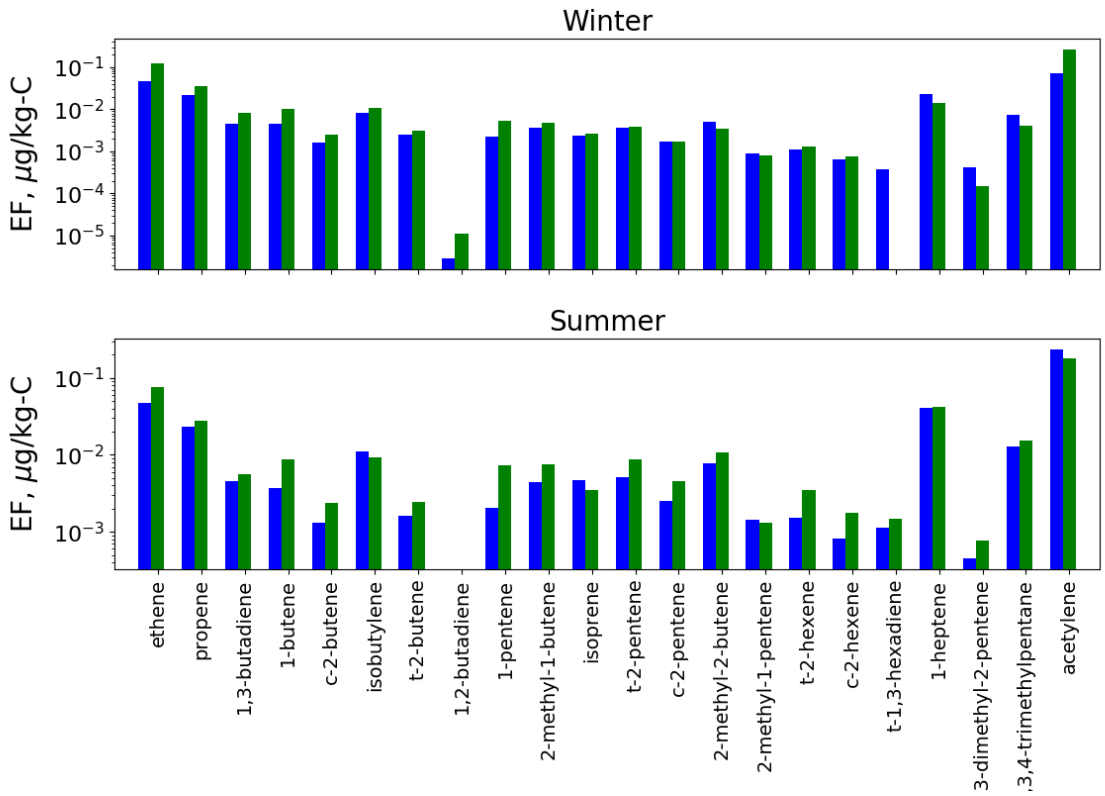


Figure C.15. Emission factors (EF_C) for light alkenes and alkynes measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. All components were in the gas phase.

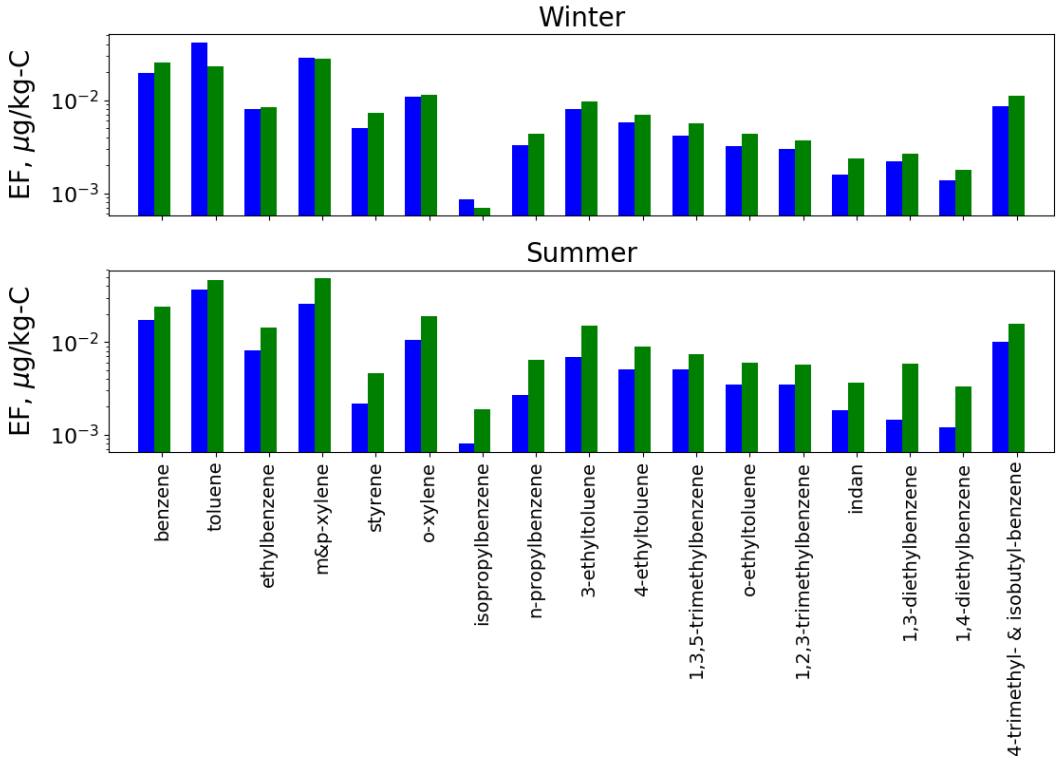


Figure C.16. Emission factors (EF_C) for aromatic VOCs measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. All components were in the gas phase.

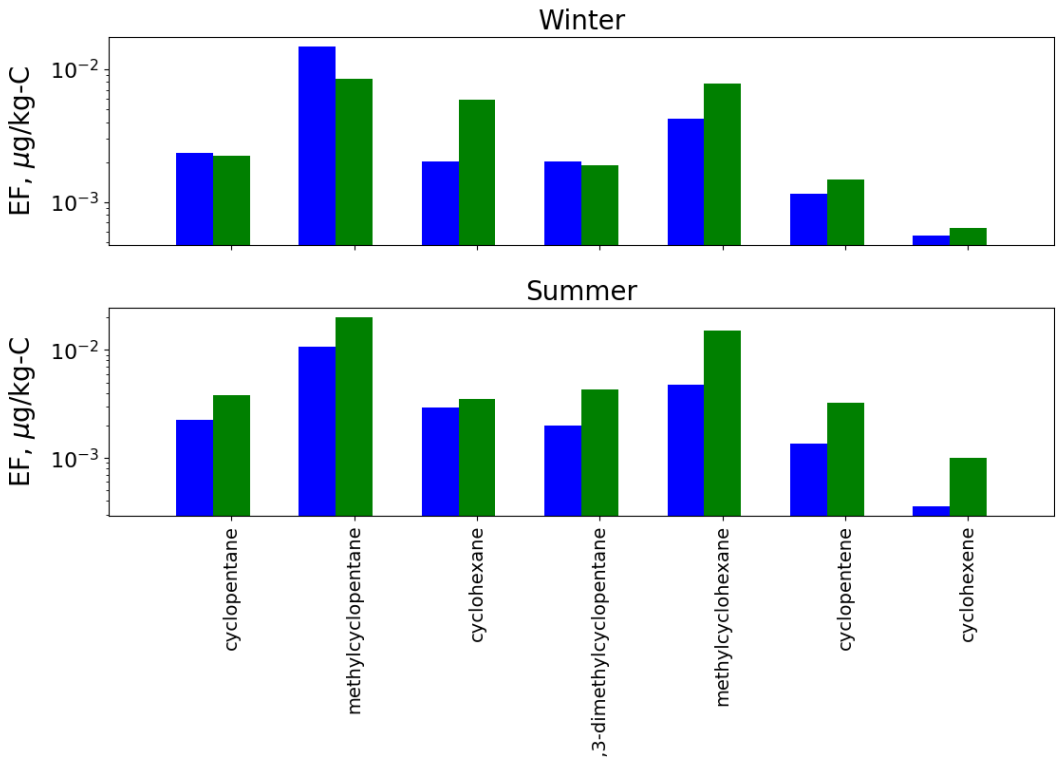


Figure C.17. Emission factors (EF_C) for cycloalkanes and cycloalkenes measured in the FMT in 2015. Blue bars represent LD vehicles; green bars represent HD vehicles. All components were in the gas phase.

Table C.6. Average Vehicle Emission Factors at 80 km/hr for the Major 2015 Fleet Categories in Hong Kong and in California as Estimated by EMFAC-HK and EMFAC, Respectively, Aggregated Over All Model Years in the Respective Fleets

EFMFAC-HK Code[a]	EMFAC Code[b]	Fuel	EF_D by EMFAC-HK (g/veh/km)			EF_D by EMFAC (g/veh/km)		
			CO	NO_x	$PM_{2.5}$	CO	NO_x	$PM_{2.5}$
PC	LDA	gasoline	0.75	0.07	0.002	0.87	0.08	0.001
PC	LDA	diesel	0.34	0.35	0.030	0.17	0.20	0.012
TAXI		LPG	2.67	0.52	0.000			
LGV3	LDT1	gasoline	7.81	1.25	0.005	2.04	0.22	0.002
LGV3	LDT1	diesel	0.16	0.59	0.010	0.73	0.91	0.086
LGV4	MDV	gasoline	2.55	0.15	0.003	1.29	0.17	0.001
LGV4	MDV	diesel	0.17	0.67	0.022	0.11	0.10	0.006
LGV6	LHDT1	diesel	0.34	2.56	0.050	0.44	3.36	0.016
HGV7	MHDT	diesel	0.45	2.79	0.037	0.63	3.66	0.132
HGV8	HHDT	diesel	1.32	4.49	0.123	0.66	4.24	0.099
PLB		diesel	0.41	3.49	0.204			
PLB		LPG	13.37	1.21	0.000			
NFB8	OBUS	diesel	1.67	5.27	0.146	0.90	4.83	0.177
FBSD	SBUS	diesel	1.76	3.97	0.091	0.17	4.92	0.039
FBDD	UBUS	diesel	1.65	6.03	0.112	0.22	4.86	0.007
MC	MCY	gasoline	20.57	0.87	0.018	13.11	0.74	0.001

[a]Refer to Table A.6 for the corresponding vehicle description.
[b]Refer to Appendix 4 of EMFAC2017 User's Guide for EMFAC vehicle categories (CARB 2018b).

Additional EMFAC-HK and MOVES Modeling Results

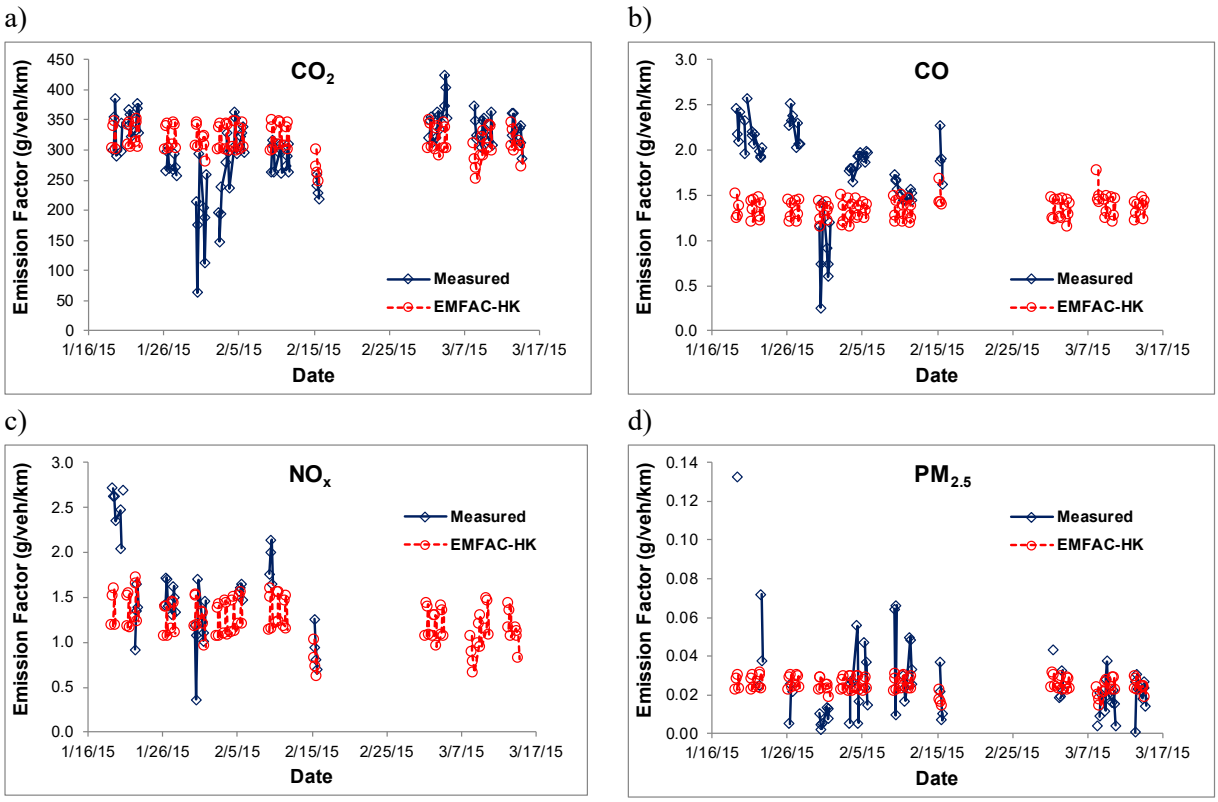


Figure C.18. Comparison of time series of measured emission factors (EF_D) with EMFAC-HK model estimates during the 2015 SMT sampling periods.

Table C.7. Average hourly vehicle count and emission factors (g/vehicle/km) by vehicle class estimated by EMFAC-HK V3.3 for (a) 2003 and (b) 2015 SMT study periods.

a) 2003 SMT Study Periods

Vehicle Class\Species	Hourly Vehicle Count	Average EF_D in 2003 by EMFAC-HK (g/veh/km)							
		CO_2	CO	NO_x	NMHCs Exhaust	NMHCs Evaporation	NMHCs Total	$PM_{2.5}$	PM_{10}
MC	34	61.1	24.691	0.755	2.027	0.925	2.952	0.018	0.024
PC	680	167.1	3.196	0.731	0.089	0.084	0.173	0.002	0.003
TAXI	158	193.6	4.174	1.470	0.073	0.000	0.073	0.001	0.001
LGV3	3	200.2	8.192	2.101	0.470	0.439	0.910	0.036	0.039
LGV4	90	234.2	0.589	1.278	0.055	0.008	0.063	0.087	0.094
LGV6	96	387.5	0.599	3.773	0.141	0.000	0.141	0.096	0.104
HGV7	294	453.4	0.710	5.124	0.232	0.000	0.232	0.124	0.135
HGV8	62	811.0	2.203	9.355	0.347	0.000	0.347	0.506	0.550
PLB	48	421.5	1.523	3.612	0.150	0.000	0.150	0.329	0.357
PV4	3	299.8	0.475	2.078	0.143	0.000	0.143	0.175	0.190
PV5	3	421.0	1.224	4.346	0.144	0.000	0.144	0.059	0.064
NFB6	8	457.1	0.716	3.366	0.147	0.000	0.147	0.122	0.133
NFB7	8	540.2	2.304	9.089	0.353	0.000	0.353	0.112	0.122
NFB8	3	740.6	1.617	9.790	0.362	0.000	0.362	0.302	0.328
FBSD	2	795.3	0.887	6.543	0.123	0.000	0.123	0.150	0.163
FBDD	87	1021.3	1.694	9.229	0.185	0.000	0.185	0.215	0.234
Gasoline	718	162.0	4.228	0.734	0.180	0.125	0.305	0.003	0.003
LPG	162	198.1	4.433	1.464	0.088	0.000	0.088	0.000	0.000
Diesel	698	526.7	0.929	5.320	0.190	0.000	0.190	0.179	0.195
Fleet Average	1578	323.7	2.797	2.805	0.176	0.057	0.233	0.080	0.087

Table C.7 *continued.*

b) 2015 SMT Study Periods

Vehicle Class\Species	Hourly Vehicle Number	Average EF_D in 2015 by EMFAC-HK (g/veh/km)							
		CO_2	CO	NO_x	NMHCs Exhaust	NMHCs Evaporation	NMHCs Total	$PM_{2.5}$	PM_{10}
MC	38	86.3	8.351	0.444	0.668	0.626	1.294	0.007	0.009
PC	722	174.2	0.790	0.078	0.012	0.021	0.032	0.002	0.002
TAXI	192	201.6	2.670	0.470	0.043	0.000	0.043	0.000	0.000
LGV3	2	232.0	0.929	0.612	0.051	0.007	0.058	0.010	0.011
LGV4	159	235.7	0.251	0.618	0.016	0.001	0.017	0.021	0.023
LGV6	87	387.5	0.343	2.409	0.072	0.000	0.072	0.050	0.054
HGV7	238	453.4	0.450	2.626	0.058	0.000	0.058	0.037	0.041
HGV8	51	811.0	1.317	4.239	0.110	0.000	0.110	0.123	0.133
PLB	34	384.3	9.359	1.772	0.429	0.000	0.429	0.063	0.068
PV4	2	224.6	2.883	0.574	0.055	0.014	0.069	0.042	0.045
PV5	8	409.3	3.376	1.130	0.147	0.000	0.147	0.028	0.030
NFB6	7	457.2	0.615	2.274	0.084	0.000	0.084	0.071	0.077
NFB7	5	540.2	1.187	4.531	0.157	0.000	0.157	0.043	0.046
NFB8	8	740.6	1.666	4.969	0.077	0.000	0.077	0.146	0.159
FBSD	2	795.3	1.760	3.740	0.058	0.000	0.058	0.091	0.099
FBDD	94	1021.3	1.648	5.688	0.066	0.000	0.066	0.112	0.122
Gasoline	757	169.4	1.178	0.094	0.043	0.050	0.093	0.002	0.002
LPG	218	222.1	3.977	0.541	0.110	0.000	0.110	0.000	0.000
Diesel	672	505.7	0.634	2.713	0.056	0.000	0.056	0.057	0.062
Fleet Average	1647	314.5	1.310	1.236	0.057	0.023	0.080	0.024	0.027

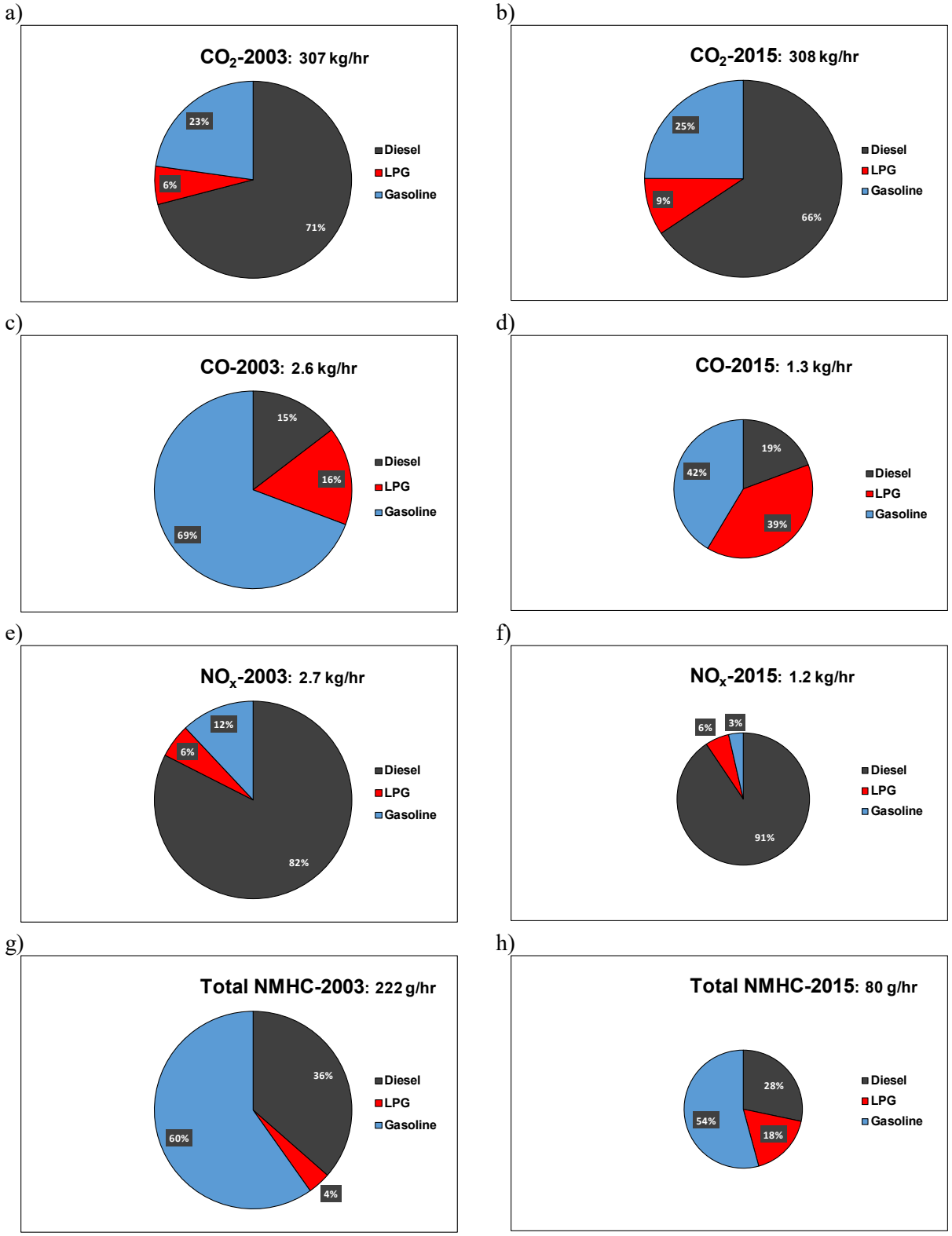
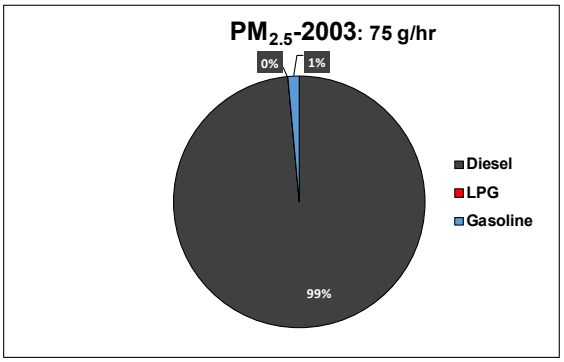
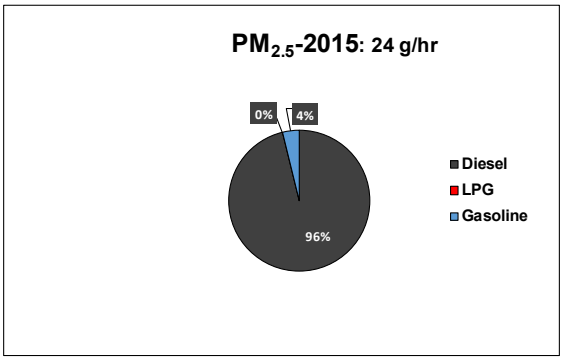


Figure C.19. Breakdown of CO_2, CO, NO_x, total NMHCs, $PM_{2.5}$, and PM_{10} hourly average emissions in the SMT in 2003 (left) and 2015 (right) by gasoline-, LPG-, and diesel-fueled vehicles. The EMFAC-HK model was applied to the total emissions throughout the 2003 and 2015 tunnel monitoring periods. The 2015 pie areas were normalized to those of 2003 based on the fleet-average hourly emission rates.

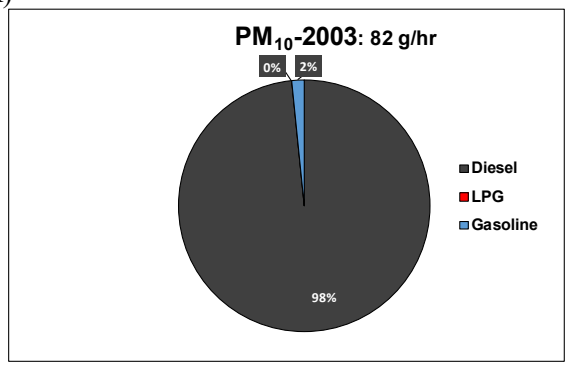
i)



j)



k)



l)

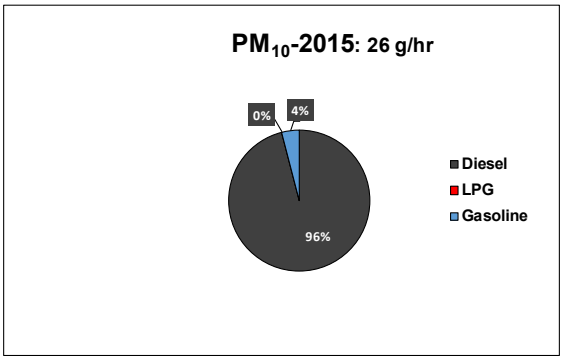


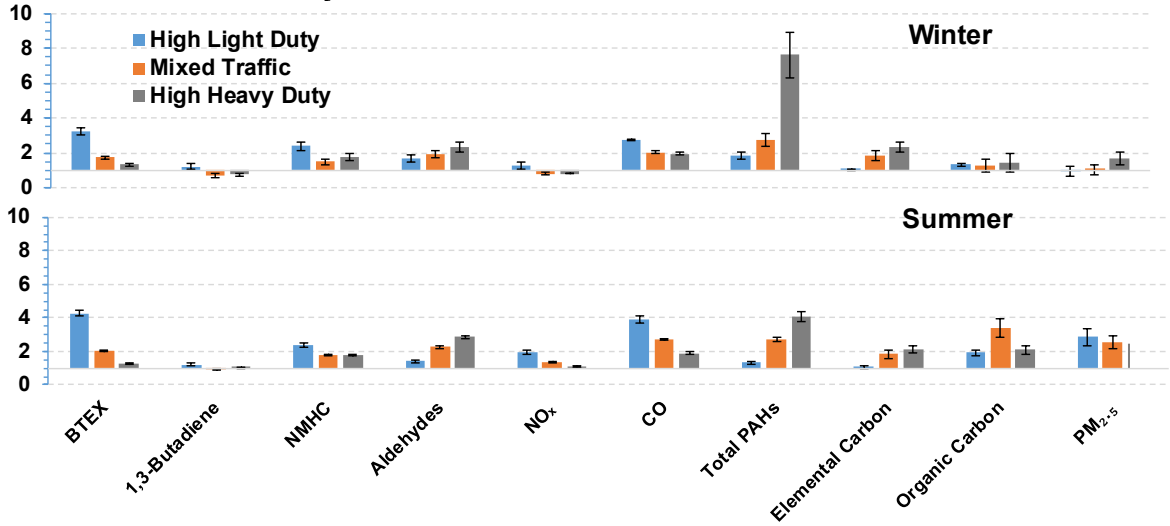
Figure C.19 *continued.*

Table C.8. Change in Fuel-Based Emission Factors (g/kg-C) with Ambient Temperature and Relative Humidity as Predicted by MOVES2014 and Measured at Fort McHenry Tunnel in 2015.

Vehicle Category	T (°F)	RH (%)	CO	NO_x	Running Exhaust NMHCs	Evaporative NMHCs	Total NMHCs	$PM_{2.5}$	EC
MOVES Sensitivity									
Passenger cars	20 → 90	20	39.4%	-1.8%	-1.7%	1.6%	-0.4%	-66.9%	-83.3%
Passenger cars	90	20 → 70	15.3%	-25.7%	-1.0%	-7.8%	-3.8%	-7.8%	-7.8%
Comb. long-haul truck	20 → 90	20	-11.5%	-15.8%	-11.5%	NA	-11.5%	-11.5%	-11.5%
Comb. long-haul truck	90	20 → 70	-7.2%	-25.4%	-7.2%	NA	-7.2%	-7.2%	-7.2%
Seasonal variations									
MOVES (>97% LD)	43 → 85	31 → 34	28%	-19%	NA	NA	17%	-33%	-29%
measured (>97% LD)	43 → 85	31 → 34	-1%	-82%	NA	NA	18%	-180%*	-28%
MOVES (30–40% HD)	43 → 85	31 → 34	24%	-25%	NA	NA	10%	9%	0%
Measured (30–40% HD)	43 → 85	31 → 34	26%	-71%	NA	NA	10%	-19%*	9%

* measured $PM_{2.5}$ emission rates shown have been adjusted to remove estimated contribution from road sanding, which is not accounted for by MOVES.

a) MOVES/Measured Ratio for Major Pollutants



b) MOVES/Measured Ratio for PAHs

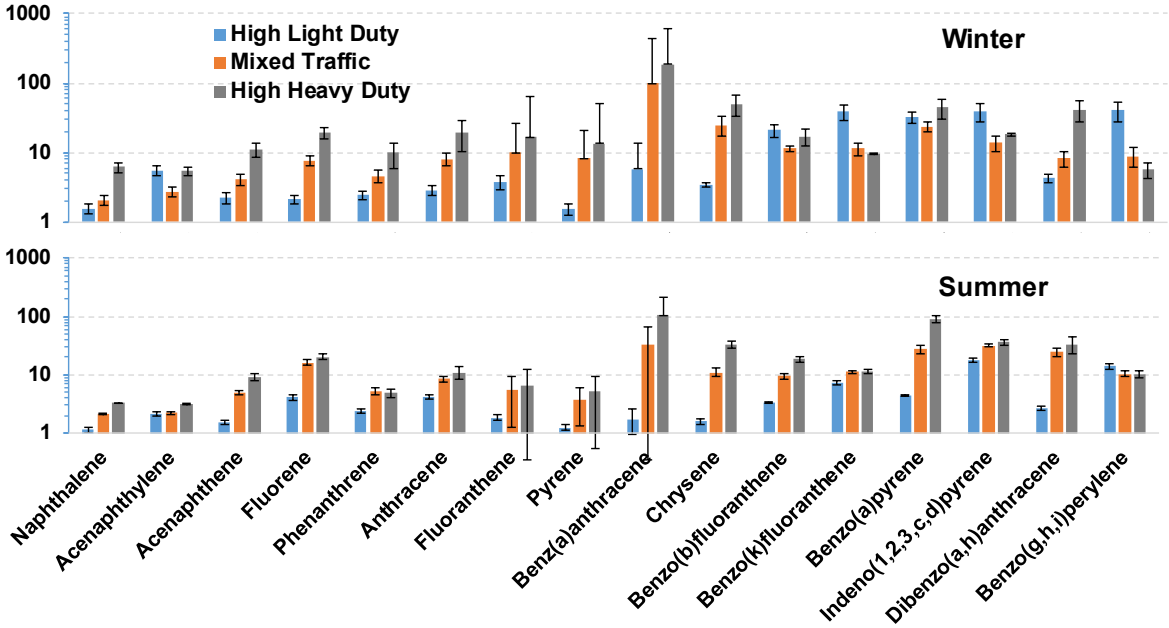


Figure C.20. Ratios of carbon-based emission factors (EF_C) calculated by MOVES using the default vehicle fleet composition ("sourcetypeagedistribution" in the MOVES2014a) to fleet average EF_C measured in the FMT in 2015 for (a) major pollutants and (b) PAHs. Results for three fleet compositions are shown: high light duty (⩾97%), mixed traffic (8-15% heavy duty), and high heavy duty (> 30%).

Additional Source Profile and Source Apportionment Results

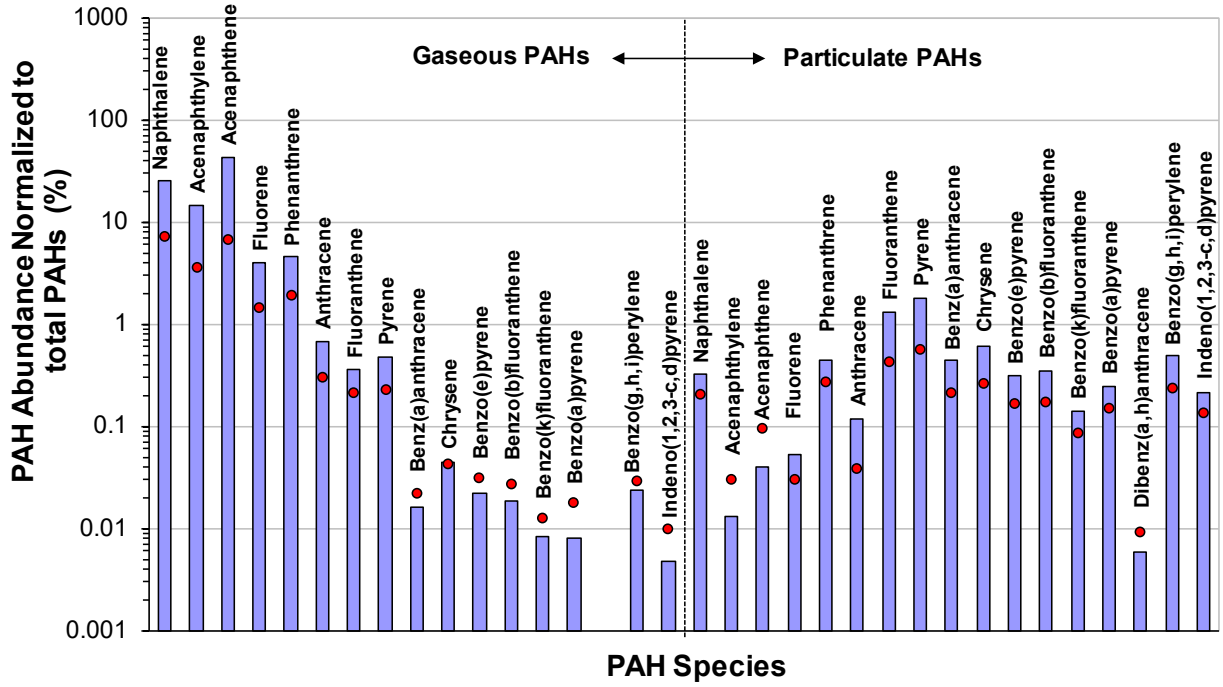


Figure C.21. Abundance of gaseous and particulate PAHs measured in the SMT in 2015. (The height of each bar indicates the average abundance, while the dot shows the standard deviation of the 70 filter-XAD samples.)

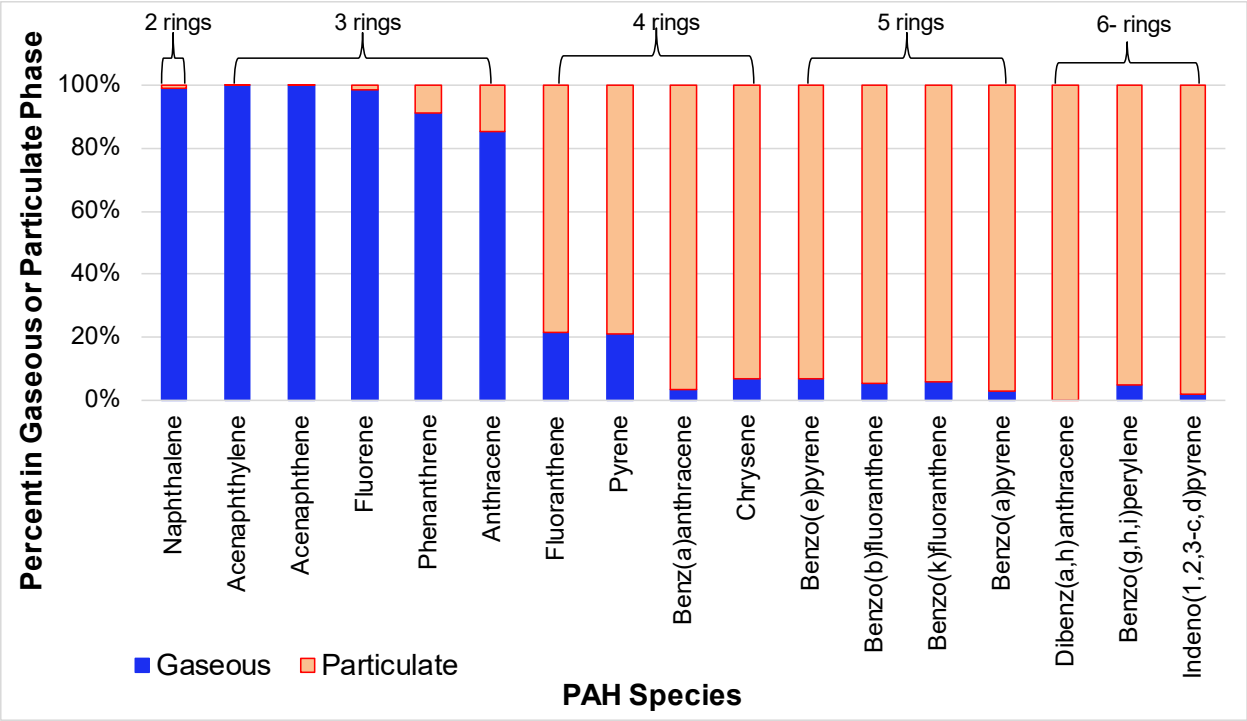


Figure C.22. Distribution of individual PAHs in gaseous and particulate phases measured in the SMT in 2015.

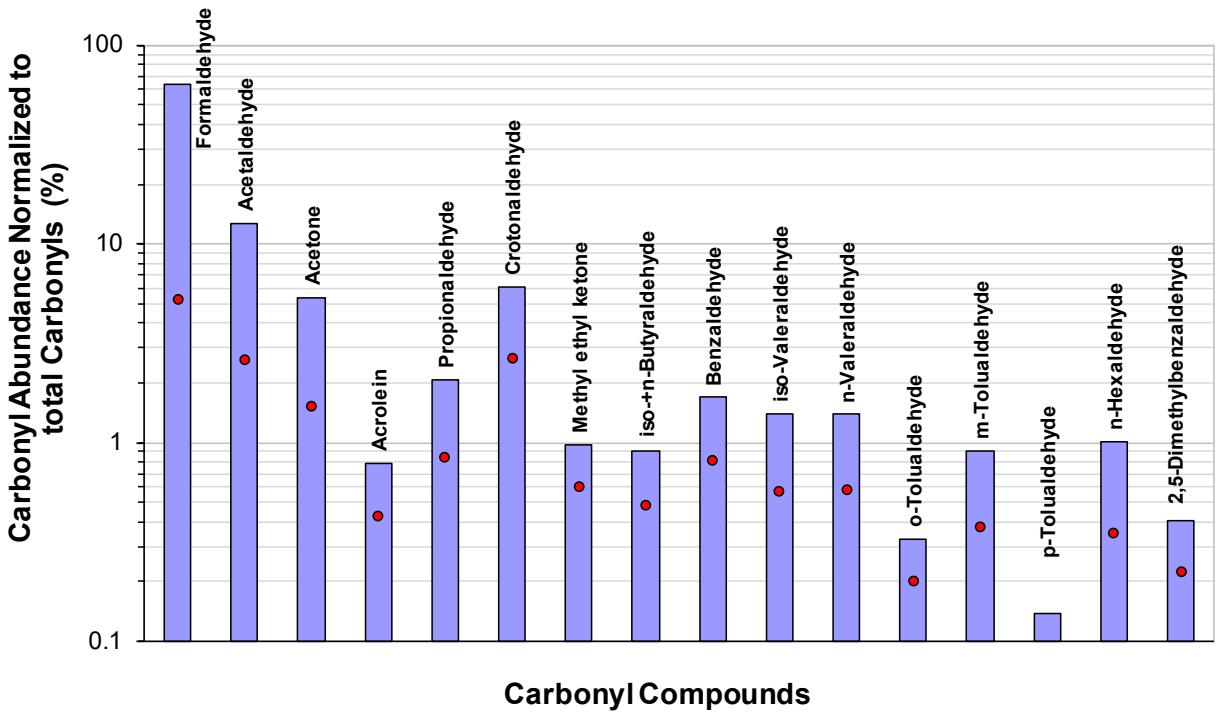


Figure C.23. Abundance of carbonyl compounds measured in the SMT in 2015. (The height of each bar indicates the average abundance, while the dot shows the standard deviation of the 59 DNPH samples.)

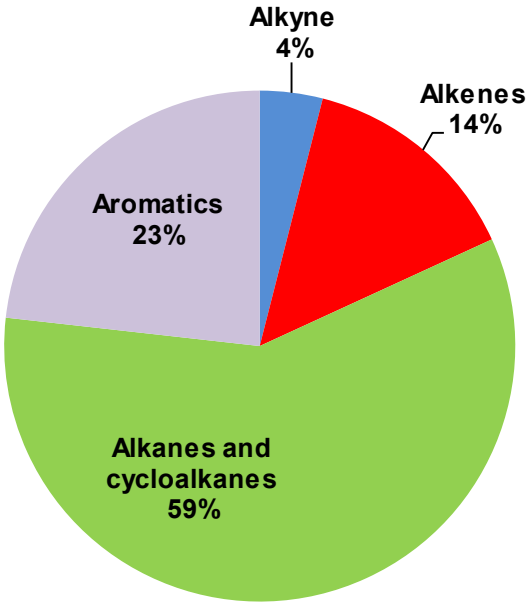


Figure C.24. Percentage of non-methane hydrocarbon (NMHC) groups measured in the SMT in 2015 normalized to the total measured NMHCs mass concentration.

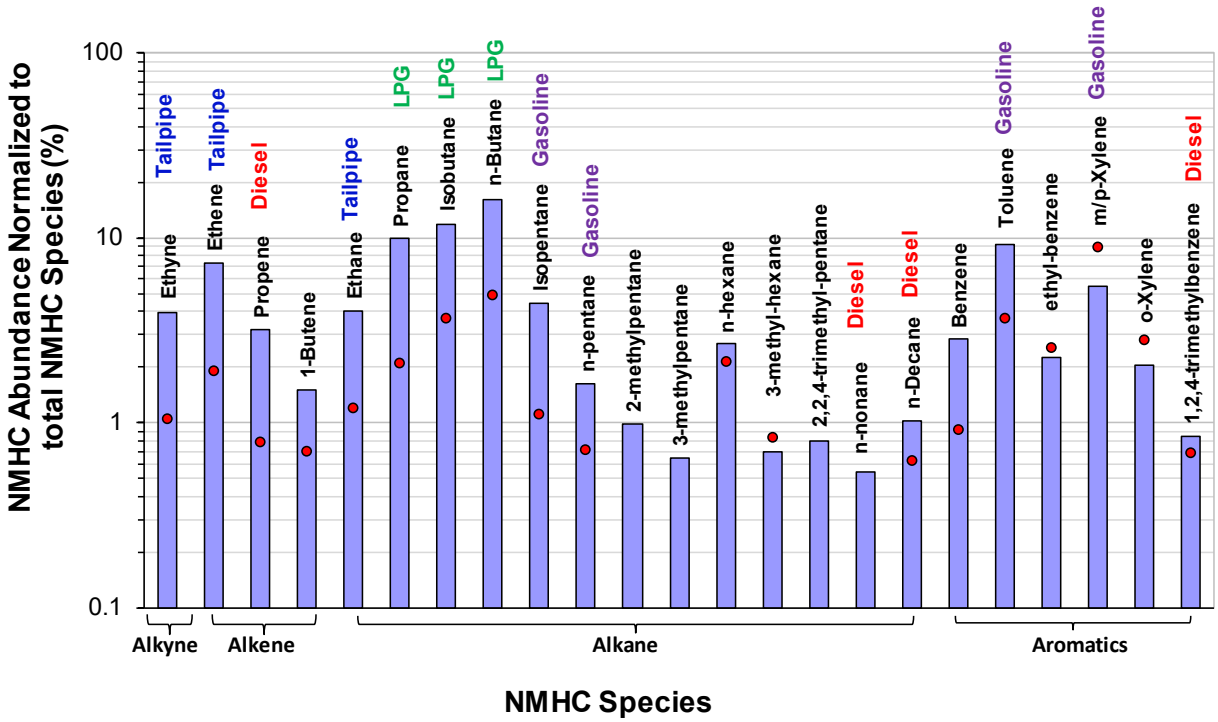


Figure C.25. Average non-methane hydrocarbon (NMHC) tunnel source profiles in the SMT in 2015. Only species with abundances >0.5% of total NMHC species are plotted. (The height of each bar indicates the average abundance, while the dot shows the standard deviation of the 96 canister samples. The colored labels indicate markers for LPG, gasoline, diesel, or tailpipe emissions.)

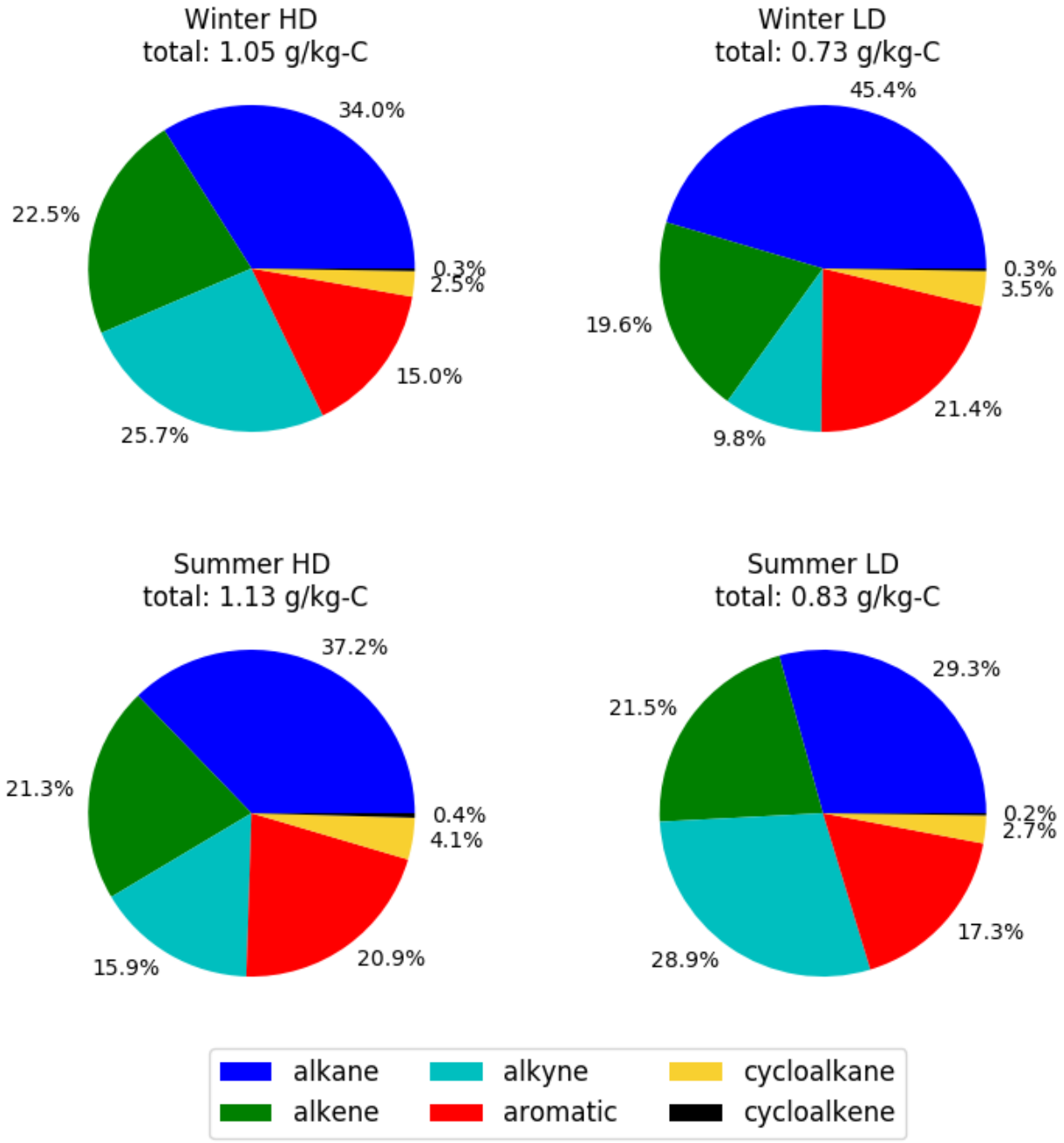


Figure C.26. Contribution of different compound classes to NMHC emissions in the FMT in 2015.

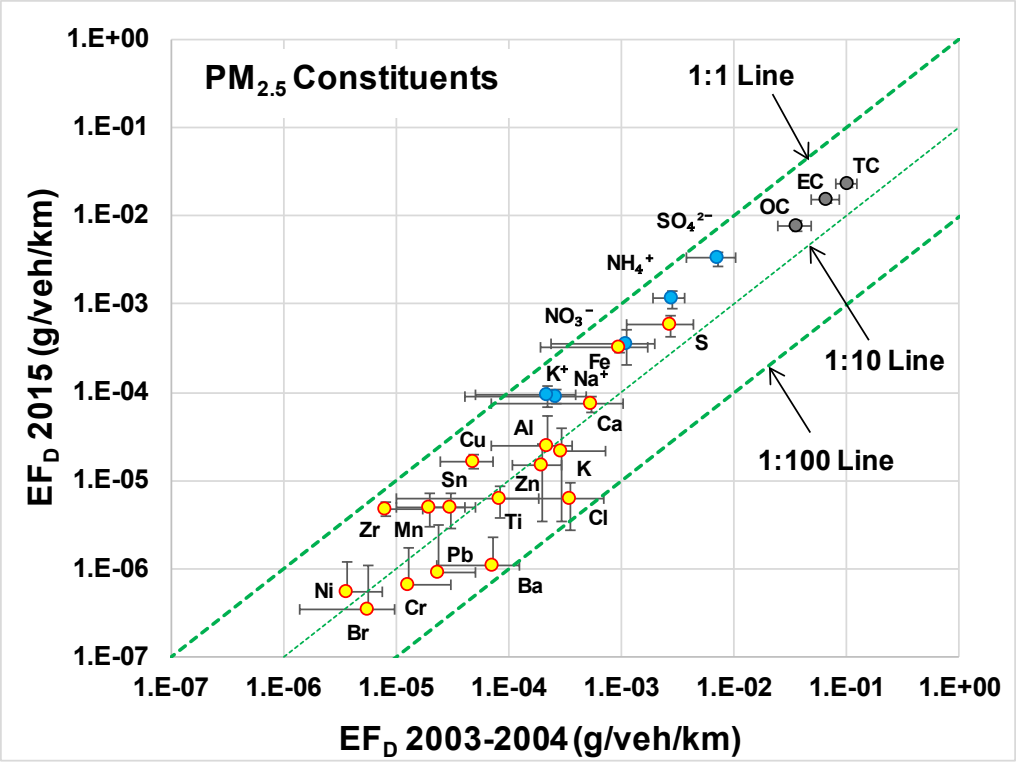


Figure C.27. Comparison of $PM_{2.5}$ elements (yellow), ions (blue), and carbon (grey) emission rates measured between 2003–2004 and 2015 in the SMT. Error bars represent standard error of the mean.

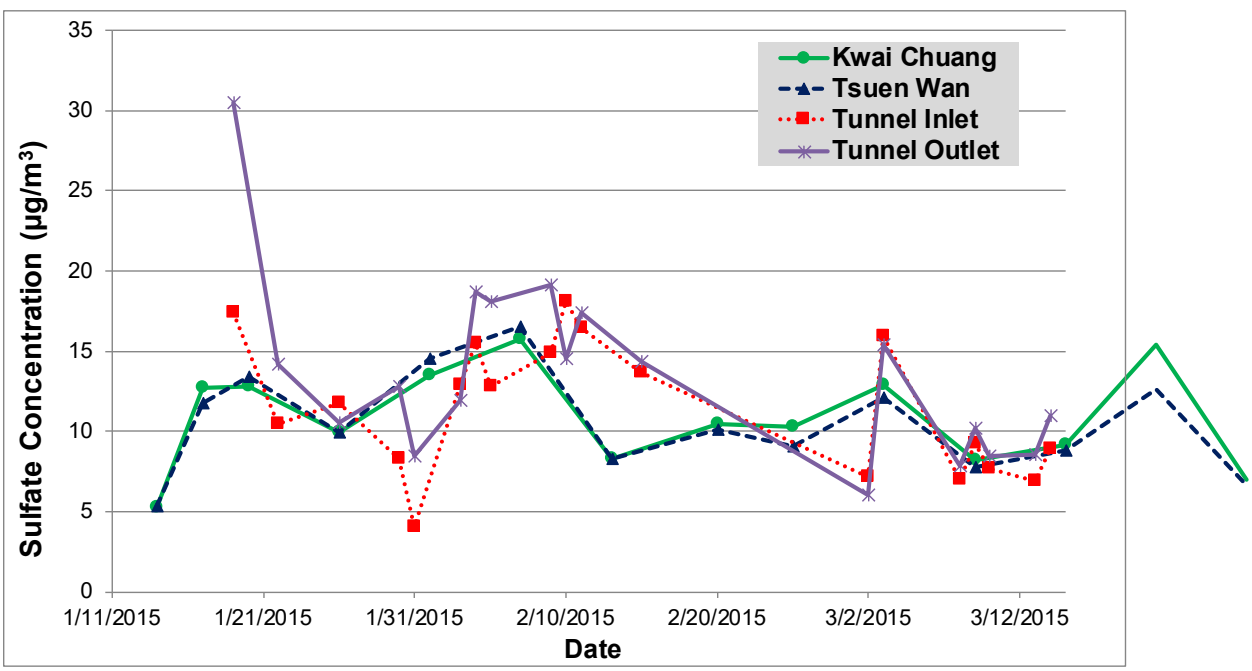


Figure C.28. Sulfate concentrations measured at the inlet and outlet of the SMT and two ambient monitoring stations near the SMT during the 2015 tunnel measurement period.

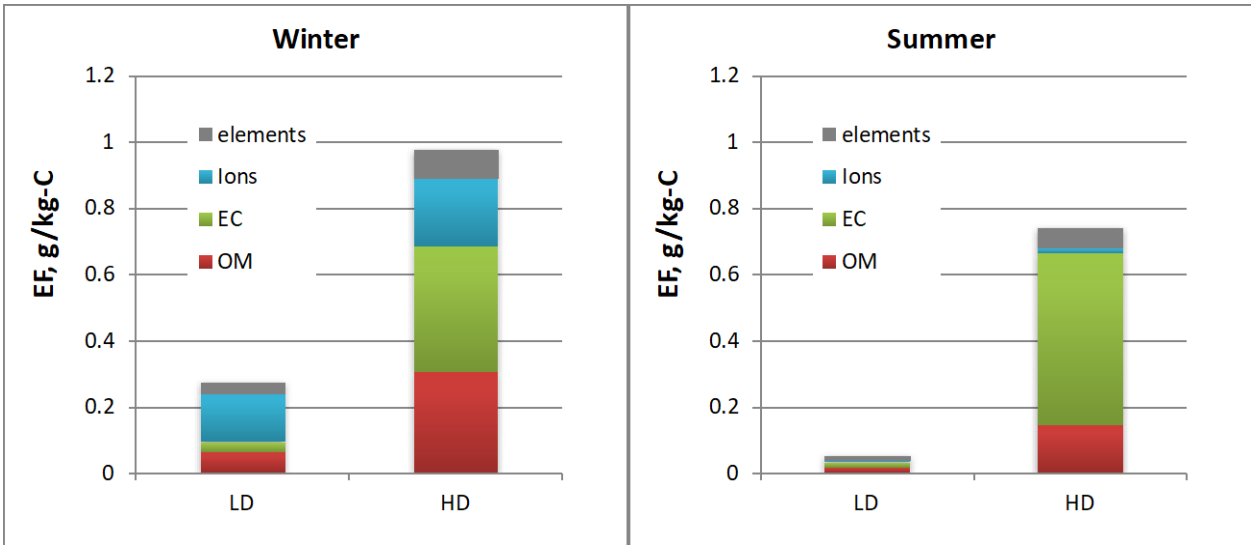


Figure C.29. Contribution of the main aerosol species to $PM_{2.5}$ measured at the FMT in 2015.

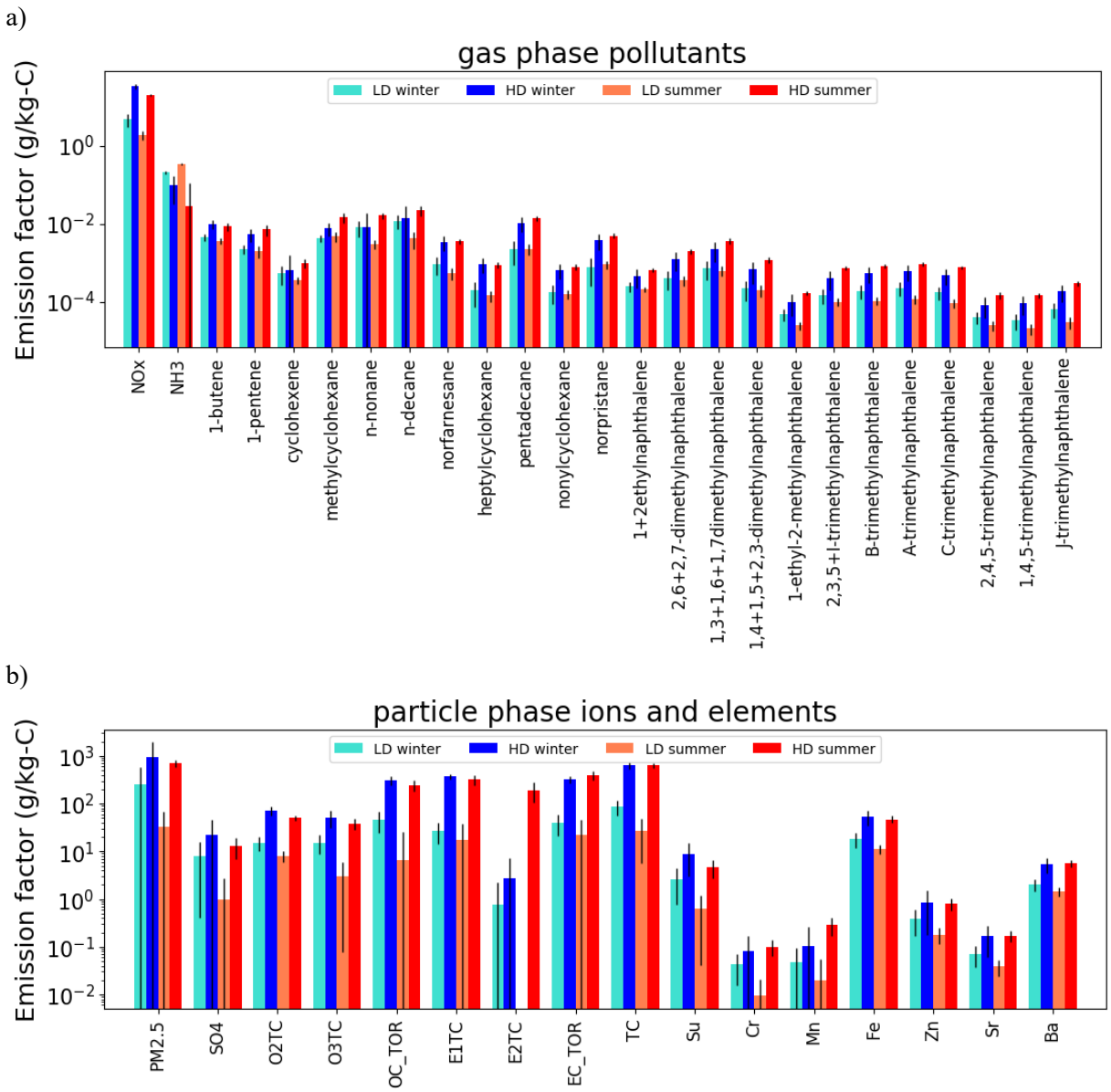
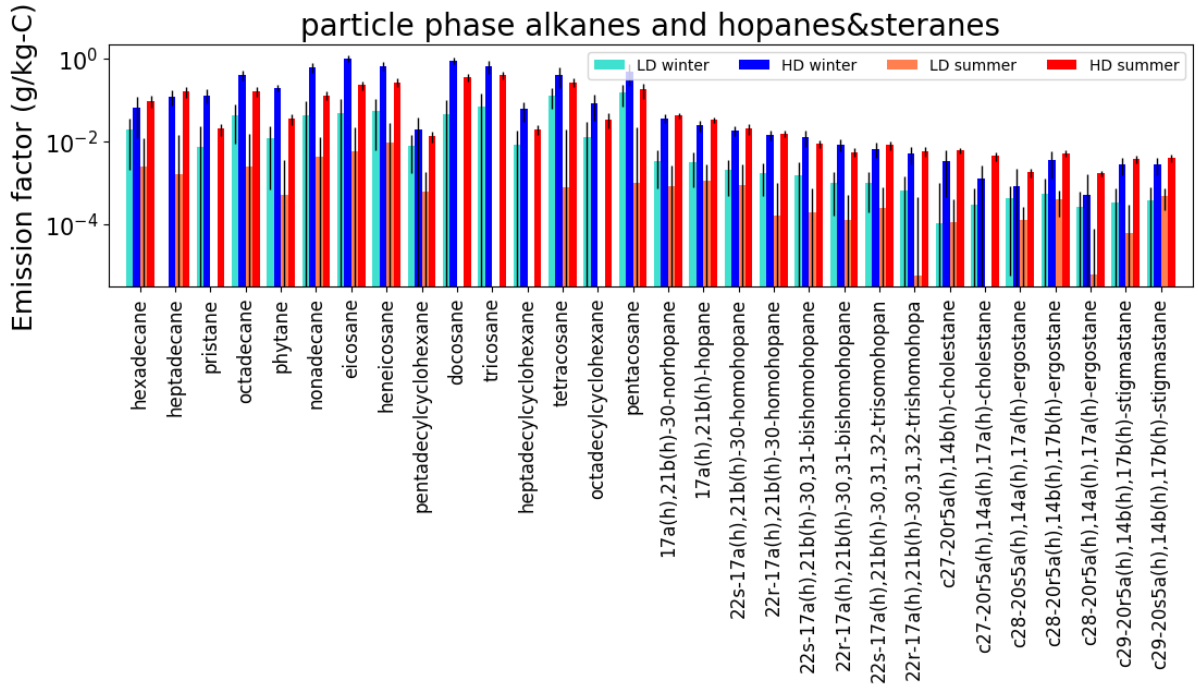


Figure C.30. FMT emission profiles of (a) gaseous pollutants; (b) inorganic $PM_{2.5}$ species; (c) particle phase alkanes, hopanes, and steranes species; (d) particle phase PAH species; (e) total (gas and particle phase) alkanes, hopanes, and steranes species; and (f) total (gas and particle phase) PAH species measured in 2015.

c)



d)

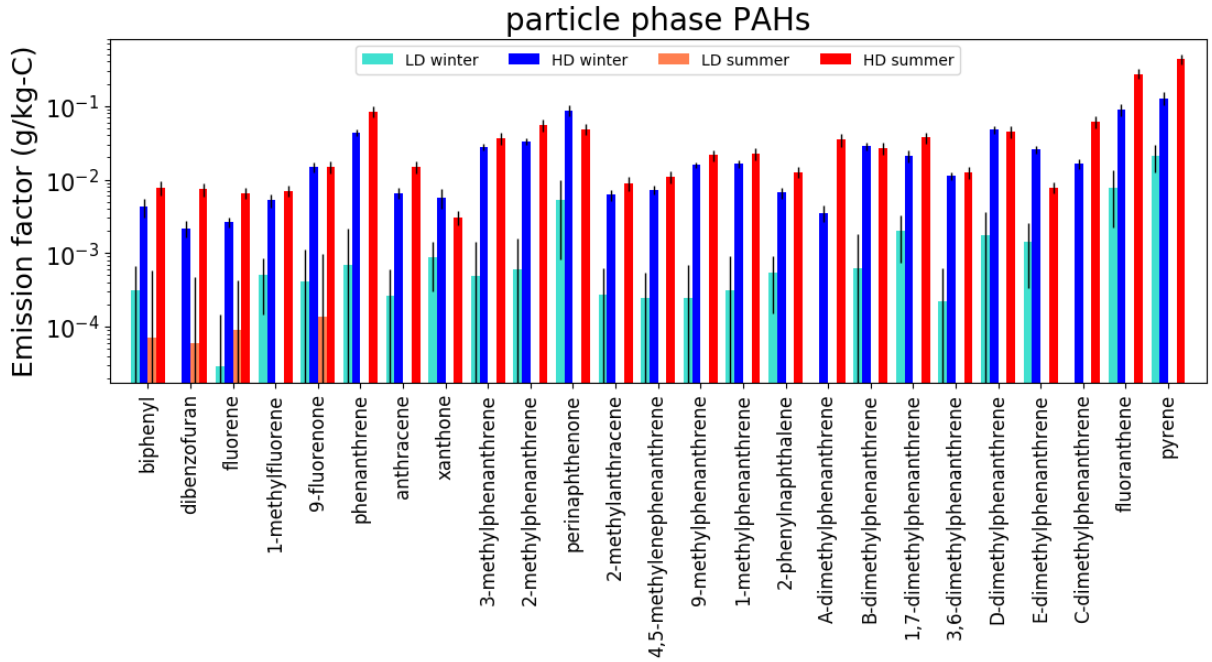
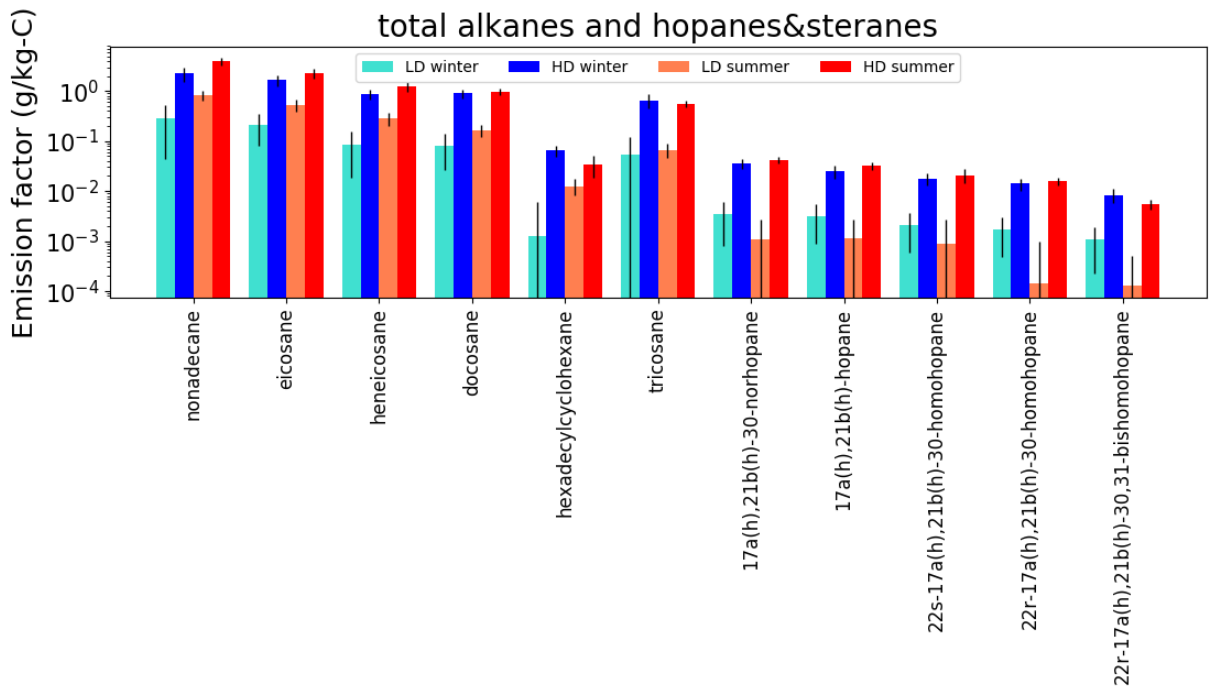


Figure C.30 *continued.*

e)



f)

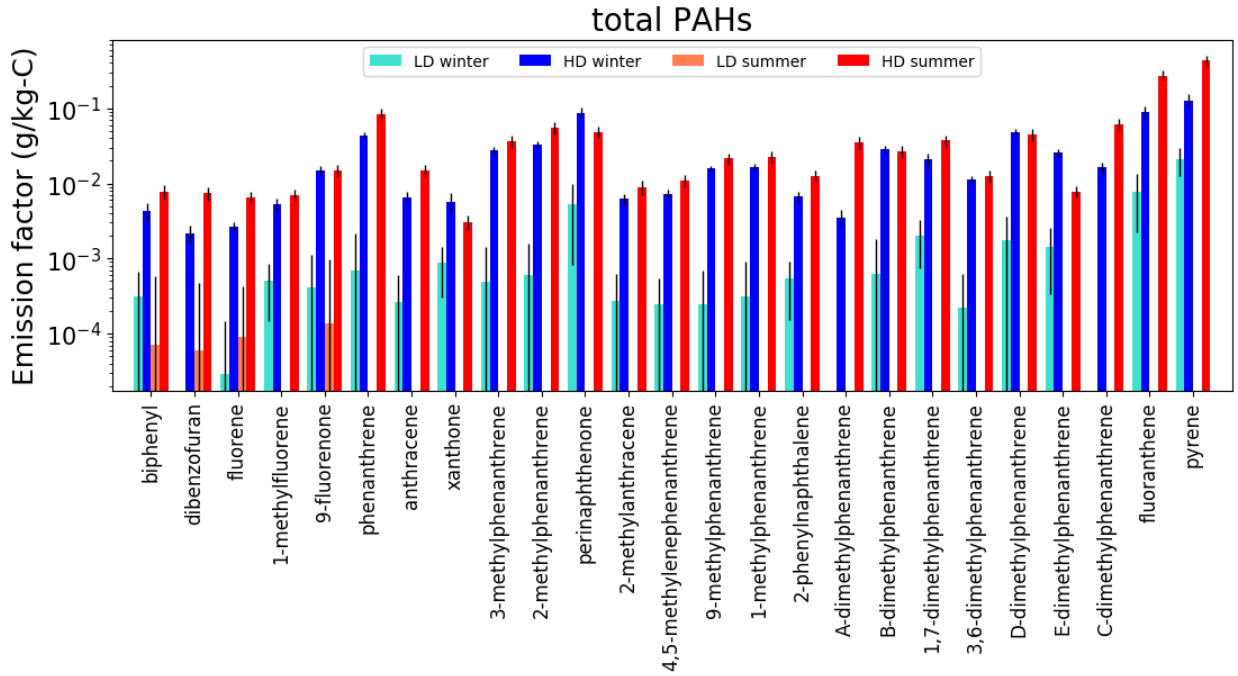


Figure C.30 *continued.*

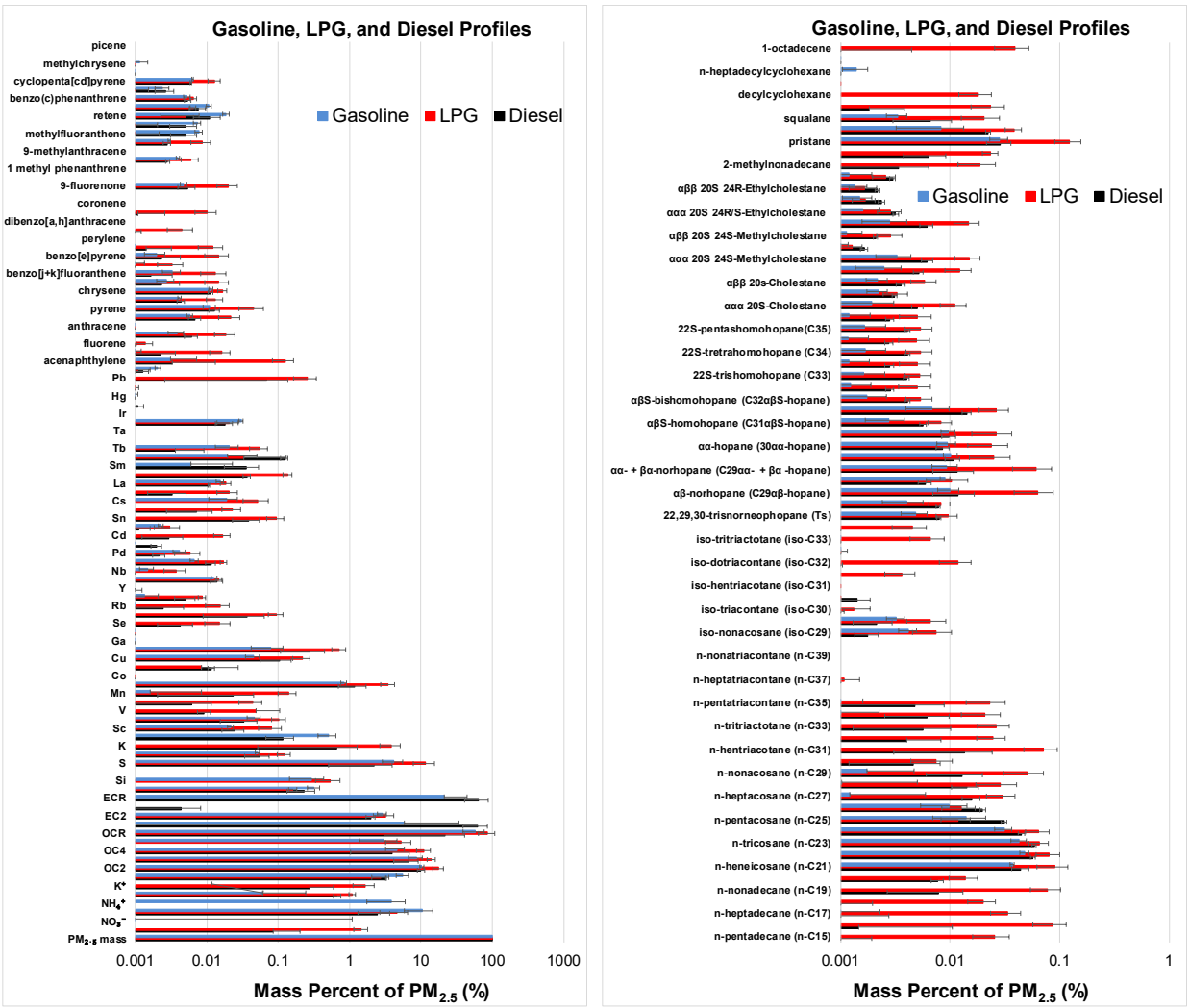


Figure C.31. PMF derived diesel and gasoline $PM_{2.5}$ profiles from the 2015 SMT tunnel study (left panel: ions, carbon, elements, and PAHs; right panel: alkanes, alkenes, hopanes, and steranes). Error bars indicate variability (standard deviation) from 10 replicate model runs.

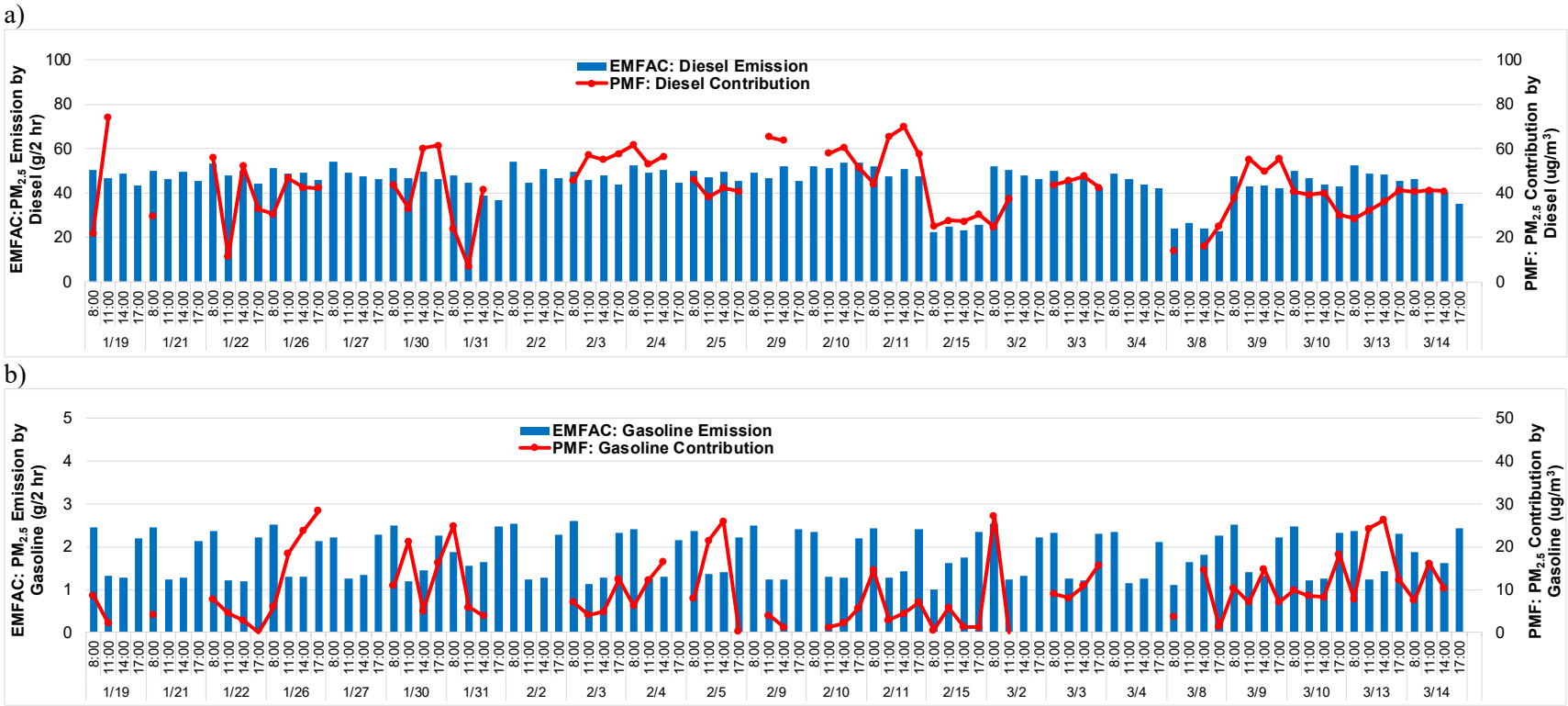


Figure C.32. EMFAC-HK-predicted $PM_{2.5}$ emissions (g in the 2-hour sampling periods) from (a) diesel (b) gasoline vehicles compared with the PMF-resolved concentration estimates at the outlet sampling location during the 2015 SMT study.

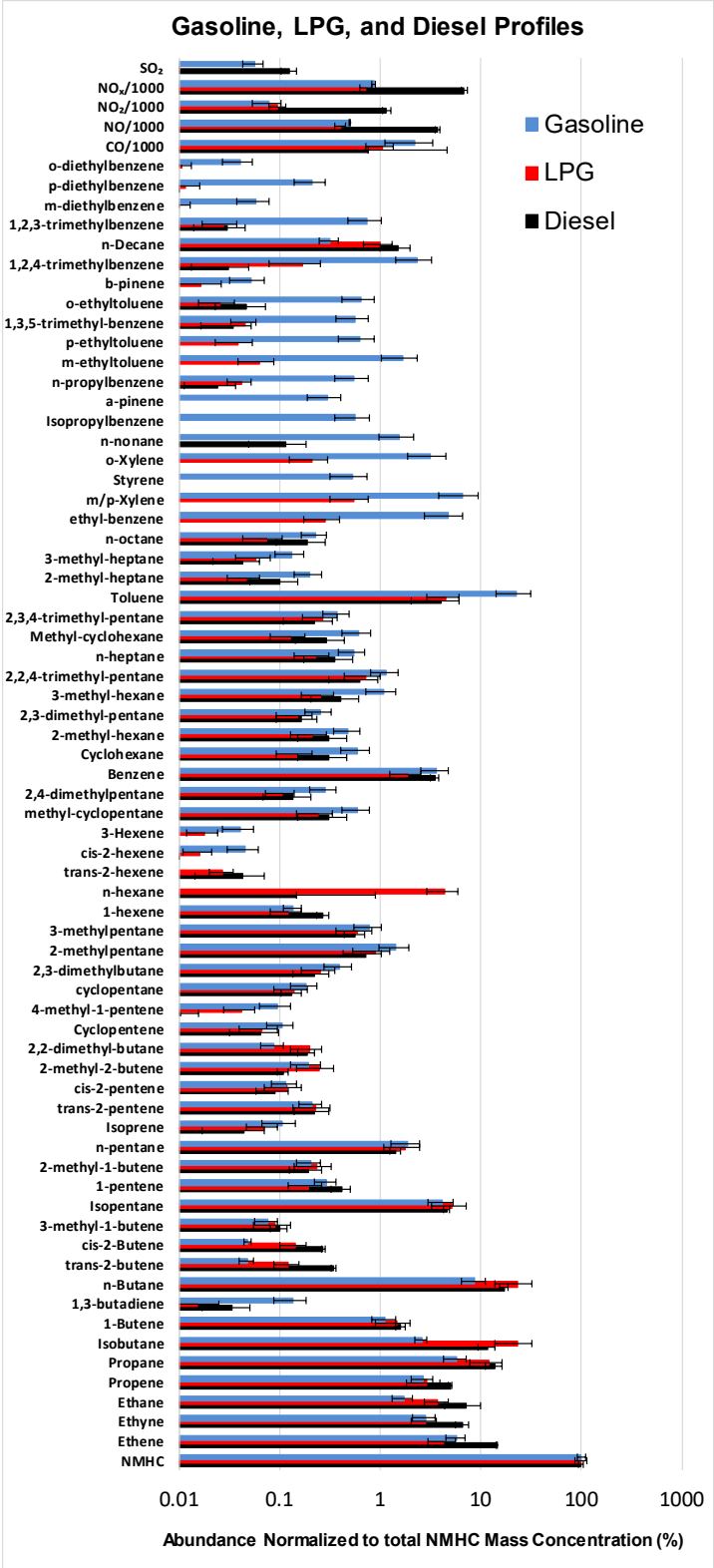


Figure C.33. PMF derived gasoline, LPG, and diesel profiles for NMHC, CO, NO_x, and SO_2 from the 2015 SMT tunnel study. Error bars indicate variability (standard deviation) from 10 replicate model runs.

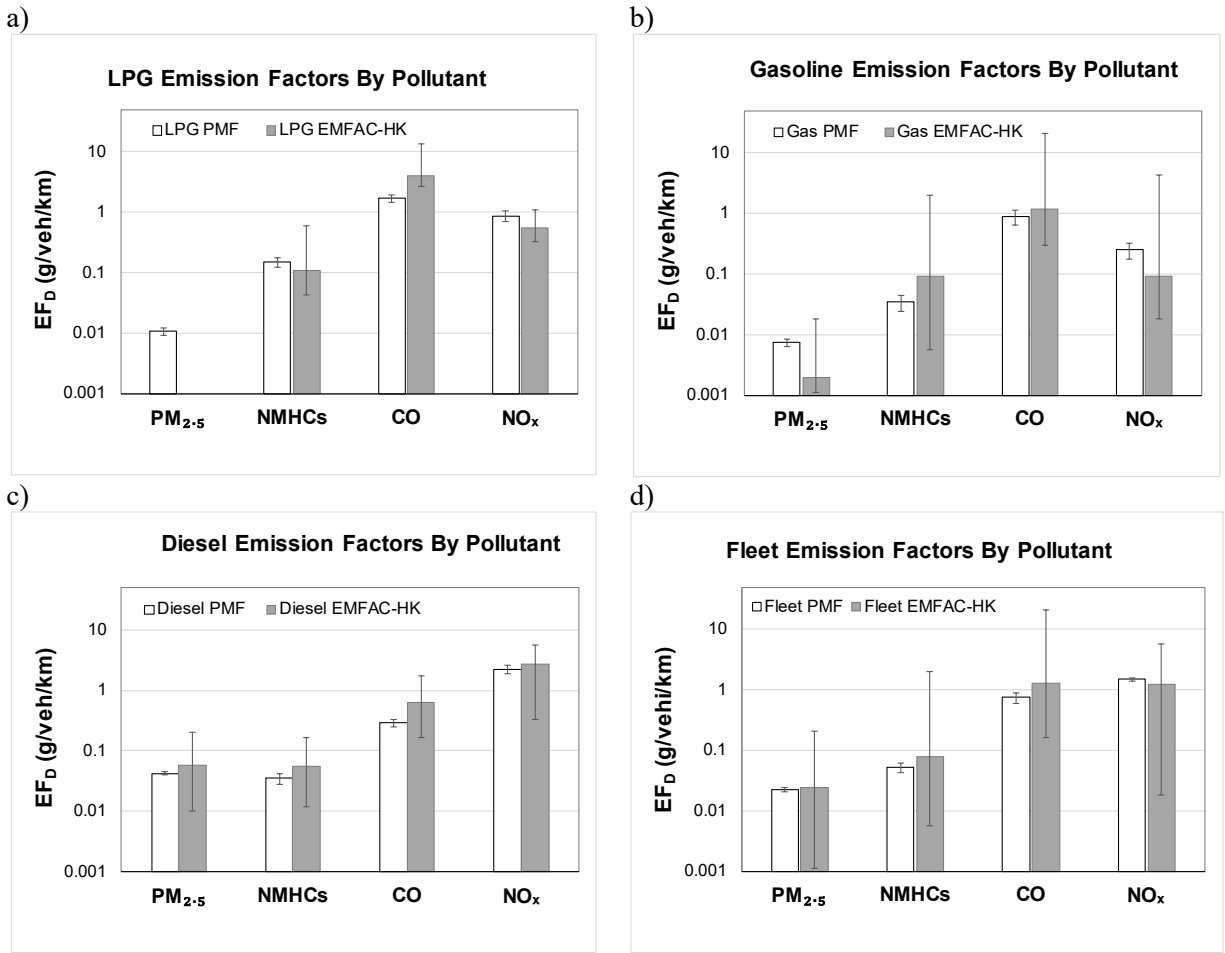


Figure C.34. Comparisons of (a) LPG, (b) gasoline, (c) diesel, and (d) fleet- average EF_D derived from PMF and EMFAC-HK by pollutant for the 2015 SMT study. The error bars for PMF represent standard error of the mean for all apportioned samples, and the error bars for EMFAC-HK represent the minimum and maximum EF_D of vehicle classes in each fleet.

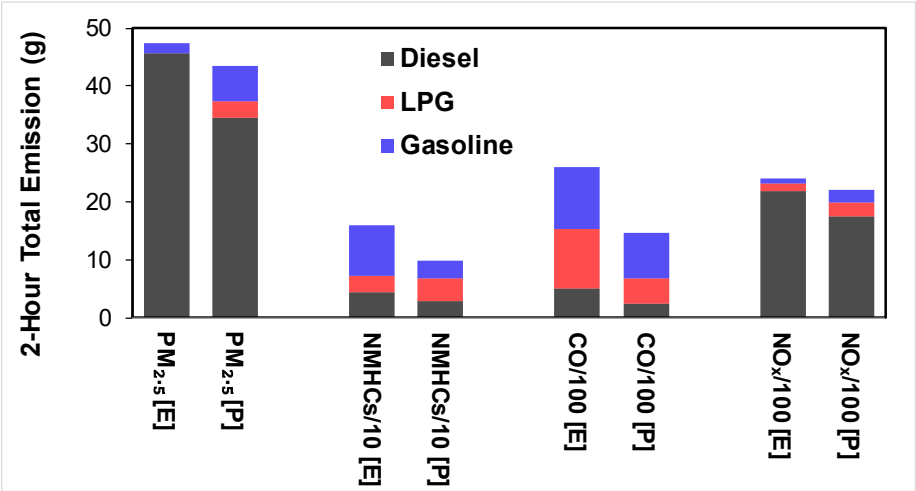


Figure C.35. Comparisons of average 2-hour emissions of $PM_{2.5}$, NMHCs, CO, and NO_x by fuel type, as predicted by EMFAC-HK [E] and PMF [P] source apportionment for the 2015 SMT study.