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

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Appendix D. Additional Discussion

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APPENDIX D. ADDITIONAL DISCUSSION

Influence of High Emitters on the FMT Regression Results

Restriction of the HD traffic to Bore 4 of the FMT allowed investigation of emission factors for LD vehicles using real time data. Unfortunately, no CO_2 real time data were available during the winter campaign and the CO monitors did not perform well during both campaigns; the analysis was thus restricted to NO_x EFs during the summer campaign. The real time CO_2 and NO_x data were averaged to 5-min intervals corresponding to the traffic data. In summer, there were 204 five-minute observations during which no HD vehicles were present in Bore 3 of the FMT. This amounts to the total of 17 h during which 16552 LD vehicles passed through Bore 3. Using real time CO_2 data, fleet-average EFs for NO_x were calculated for each of the 204 LD-only periods. A histogram of EFs during these periods is shown in Figure D.1.

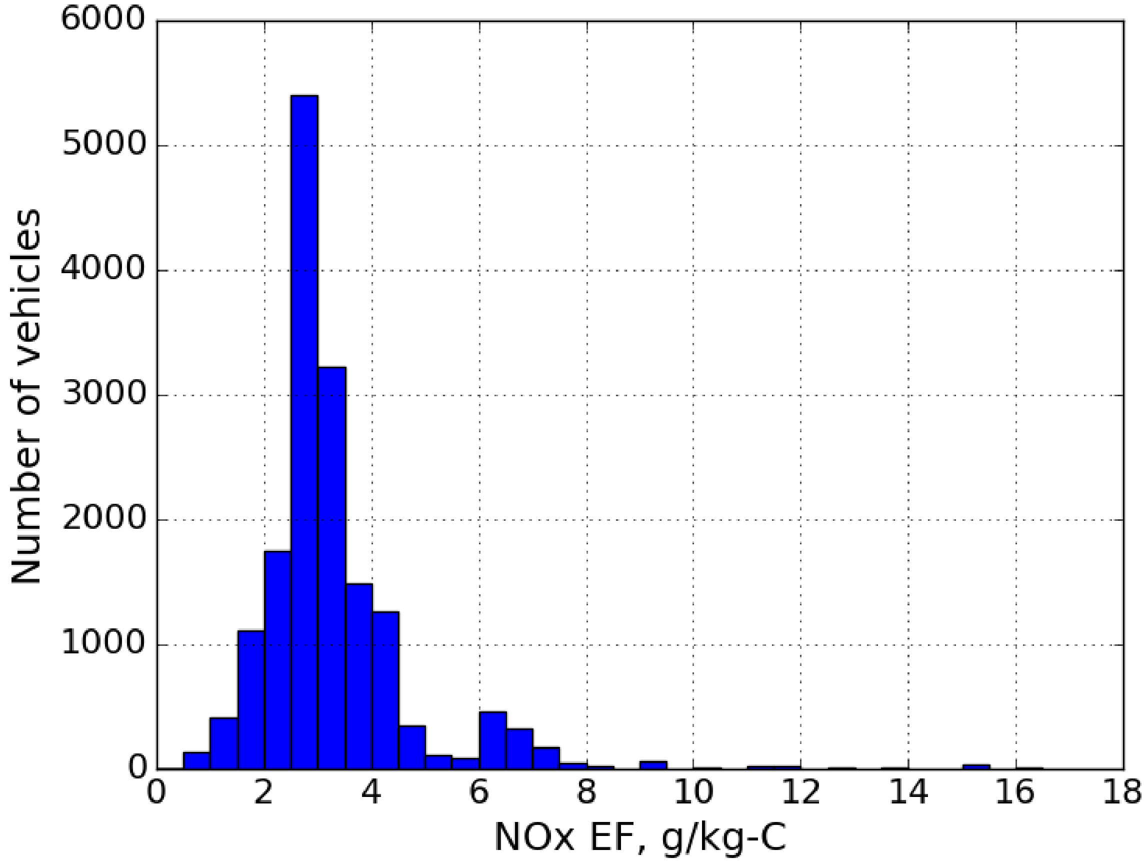


Figure D.1. NO_x emission factors for LD vehicles calculated for periods with no HD traffic during the 2015 FMT study.

The mean NO_x EF for LD-only periods was 3.33 g/kg-C, which was close to 1.9 ±0.5 g/kg-C obtained by the regression method of all traffic composition data. The distribution of EFs, however, showed two peaks, one with the mean of 2.97 g/kg-C and another with the mean of 6.59 g/kg-C, as well as a relatively small number of even higher emitters. The first peak represented 92% of all LD vehicles and 82.2% of the total LD emissions, the second represented 6.7% of LD vehicles and 13.4% of all LD emissions. Vehicles with EFs higher than 9 g/kg-C comprised only 1.3% of the LD fleet, but were responsible for 4.4% of all LD emissions.

Real time data were also used to assess NO_x EFs of HD vehicles. The following analysis was performed. The LD EF was fixed at a certain value (the pure LD EF of 3.33 g/kg-C was used as an initial guess) and "effective" emission factors for HD vehicles were calculated for 5 min data collected in both bores using the following formula:

$$EF_{HD,i} = [EF_{FA,i} - (1-f_{HD,i})\times EF_{LD}] / f_{HD,i} \qquad (D.1)$$

where $EF_{HD,i}$ is the "effective" EF of HD vehicles during observation i, $EF_{FA,i}$ is the corresponding fleet-averaged EF, $f_{HD,i}$ is the fuel-efficiency-weighed fraction of HD vehicles during observation i, and EF_{LD} is the emission factor of LD vehicles that is fixed at a certain value. The key to this approach is that $EF_{HD,i}$ should not depend on the fraction of HD, $f_{HD,i}$, i.e., the assumption is that HD vehicles of different emission characteristics are randomly distributed over all observations. If plotted vs. $f_{HD,i}$ should be randomly (and normally) distributed around the mean EF of the HD fleet.

A plot of $EF_{HD,i}$ vs. $f_{HD,i}$ in Bore 3 for EF_{LD} = 3.33 g/kg-C is shown in Figure D.2. The noise in the effective values is strongest at the low $f_{HD,i}$ values, because division by small $f_{HD,i}$ values amplifies any variability in fleet EFs, as well as experimental uncertainty. As $f_{HD,i}$ increases, the noise decreases and $EF_{HD,i}$ values converge to a mean value of about 12 g/kg-C. This value is almost 2 times lower than the HD EF of 20.6 g/kg-C obtained by the regression method. A closer observation of the plot at $f_{HD,i} > 0.2$ shows that EF_{HD} are biased high relative to the asymptotic value of 12 g/kg-C and decrease with increasing f_{HD}. This suggests that EF_{LD} is underestimated in this f_{HD} range (as the fraction of LD vehicle decreases, deviation from the asymptotic value decreases). Indeed, fixing EF_{LD} at 5.5 g/kg-C removes the bias of EF_{HD} relative to its asymptotic value at $f_{HD,i} > 0.2$. It should be noted that this f_{HD} range contains most HD vehicles and thus should weigh more in derivation of EF_{HD} than the high LD fraction range. Increasing EF_{LD} to 7.8 g/kg-C causes the EF_{HD} to be biased low at $f_{HD,i} < 0.2$, indicating that in that range LD vehicles have a lower EF. Indeed, EF_{LD} = 3.33 g/kg-C provides a symmetric spread around some mean value in that range (see Figure D.2, left panel).

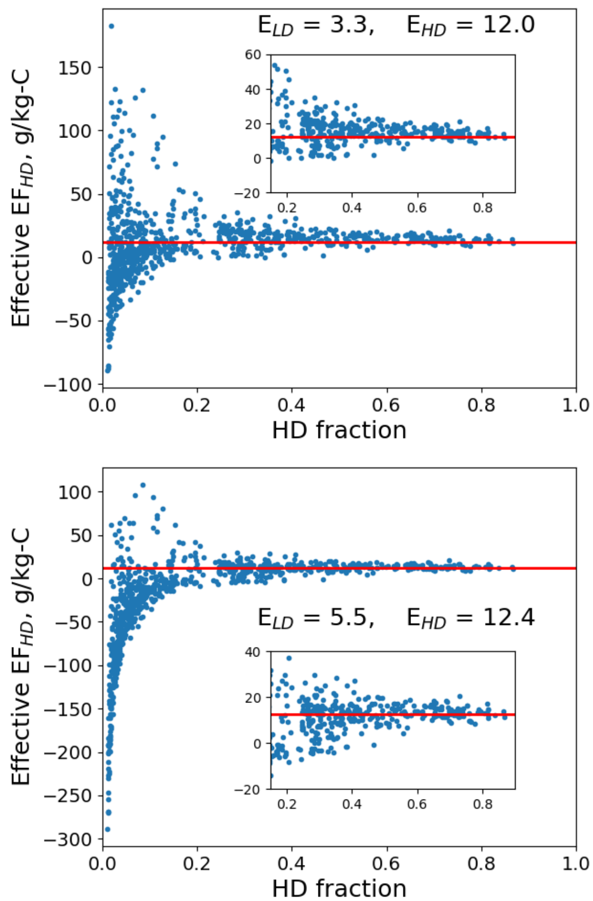


Figure D.2. Effective NO_x emission factors for HD vehicles calculated for Bore 3 of FMT during the 2015 study. The top panel shows effective EF_{HD} for a fixed EF_{LD} = 3.3 g/kg-C; the bottom panel for EF_{LD} = 5.5 g/kg-C. Note a better convergence to the asymptotic value (red line) at larger HD fractions in the right panel.

A similar situation is observed in Bore 4 (Figure D.3). Using EF_{LD} = 5.3 g/kg-C (Figure D.3 left panel), most observations in Bore 4, including the lowest f_{HD} values, are normally distributed around the asymptotic line of 12.8 g/kg-C, a value close to that in Bore 3. However, there is another band of observations that is biased high. The bias, again, decreases with increasing f_{HD}, indicating that EF of LD in that fraction of observations is underestimated. An EF of 22 g/kg-C is required for these observations to be normally distributed around a constant value of 22 g/kg-C, which corresponds to EF_{HD} of that group. This value is somewhat higher than the EF_{HD} value obtained by the regression method (20.6 ±3 g/kg-C). These observations suggest that there are several groups of both LD and HD vehicles (or different driving regimes) that have emission factors different from those derived with the regression method. The average EF_{HD} could be actually lower than the regression-derived value of 20.6 g/kg-C, while EF_{LD} either increases in the presence of HD vehicles (probably due to a more erratic, brake-accelerate driving) or higher polluting LD vehicles tend to follow HD vehicles. If any of this is the case, it could bias the regression method, underestimating LD emissions and over-estimating HD emissions. More research is needed to verify these observations.

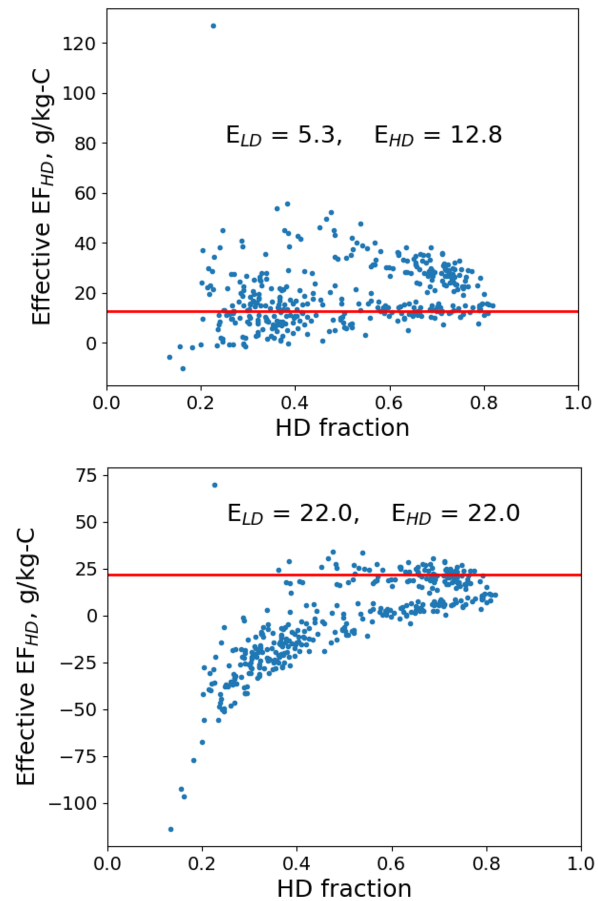
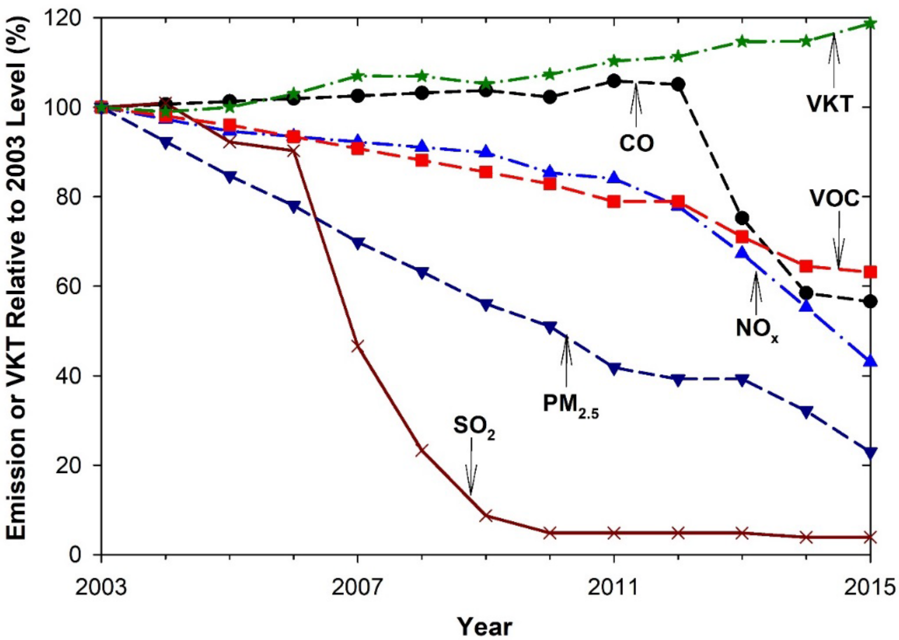


Figure D.3. Effective NO_x emission factors for HD vehicles calculated for Bore 4 of FMT during the 2015 study. The top panel shows effective EF_{HD} for a fixed E_{LD} = 5.3 g/kg-C; the bottom panel, for EF_{LD} = 22.0 g/kg-C.

Table D.1. Vehicle emission reduction measures in Hong Kong, 1999-2015 (HKEPD 2017d; Lau et al. 2015)

Year	Actions
1999	Dynamometer smoke test for light-duty vehicles
2000	Diesel to liquefied petroleum gas (LPG) taxi Trap/diesel oxidation catalyst (DOC) retrofitting for Pre-Euro light-duty vehicles (LDV) Ultra-low sulfur diesel (ULSD, 50 ppmw S) The fine of fixed penalty ticket raised to $1000
2001	Euro III standard phase-in
2002	Dynamometer smoke test for heavy-duty vehicles Diesel to LPG light bus
2003	Trap/DOC retrofit for Pre-Euro light- and heavy-duty diesel vehicles
2005	Reduce petroleum sulfur (S) from 150 to 50 ppmw
2006	Euro IV standard phase-in
2007	Replacement of Pre- Euro I commercial vehicles Euro V diesel (10 ppm S)
2008	DPF retrofitting for Euro II/III franchised buses
2010	Replacement of Euro II diesel commercial vehicles Euro V standard phase-in Euro V motor vehicle fuels (10 ppmw S)
2011	Switch off the engines while the vehicles are stationary
2012	Euro V standard for all vehicles
2014	Phase out of Pre-Euro IV diesel commercial vehicles Hybrid and electric bus pilot program Replacement of LPG vehicle catalytic converters Monitor gasoline and LPG emissions using roadside remote sensing equipment Incentive-cum-regulatory approach for vehicle replacement
2015	SCR retrofitting for Pre-Euro IV franchised buses

a)



b)

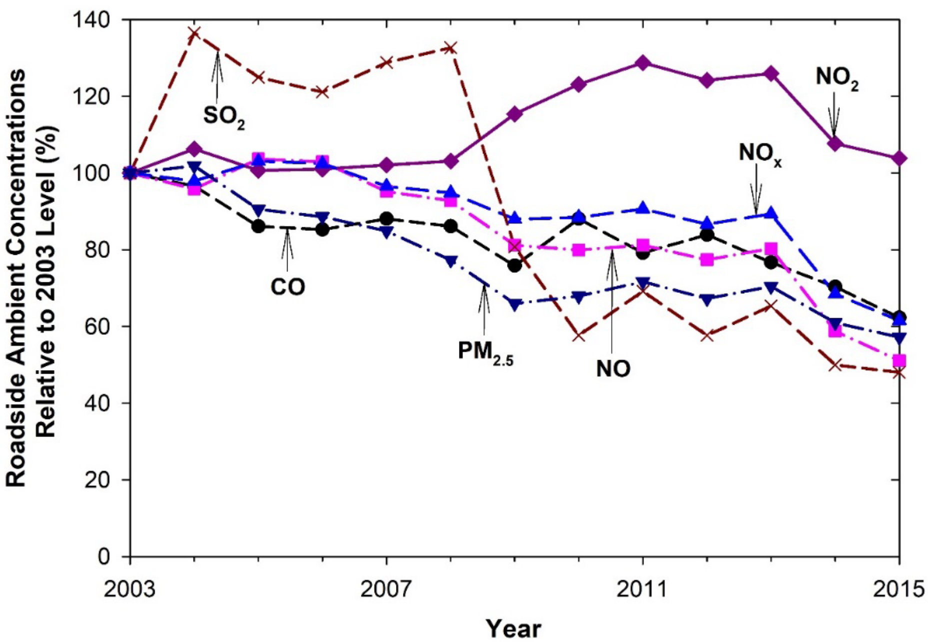


Figure D.4. Trends of (a) estimate of criteria pollutant emissions by the road transport sector and vehicle kilometer travelled (VKT) in Hong Kong relative to 2003 level (HKEPD 2017e; HKTD 2016) ; and (b) ambient concentrations measured from roadside sites in Hong Kong. The *y*-axis shows levels normalized by 2003 values.

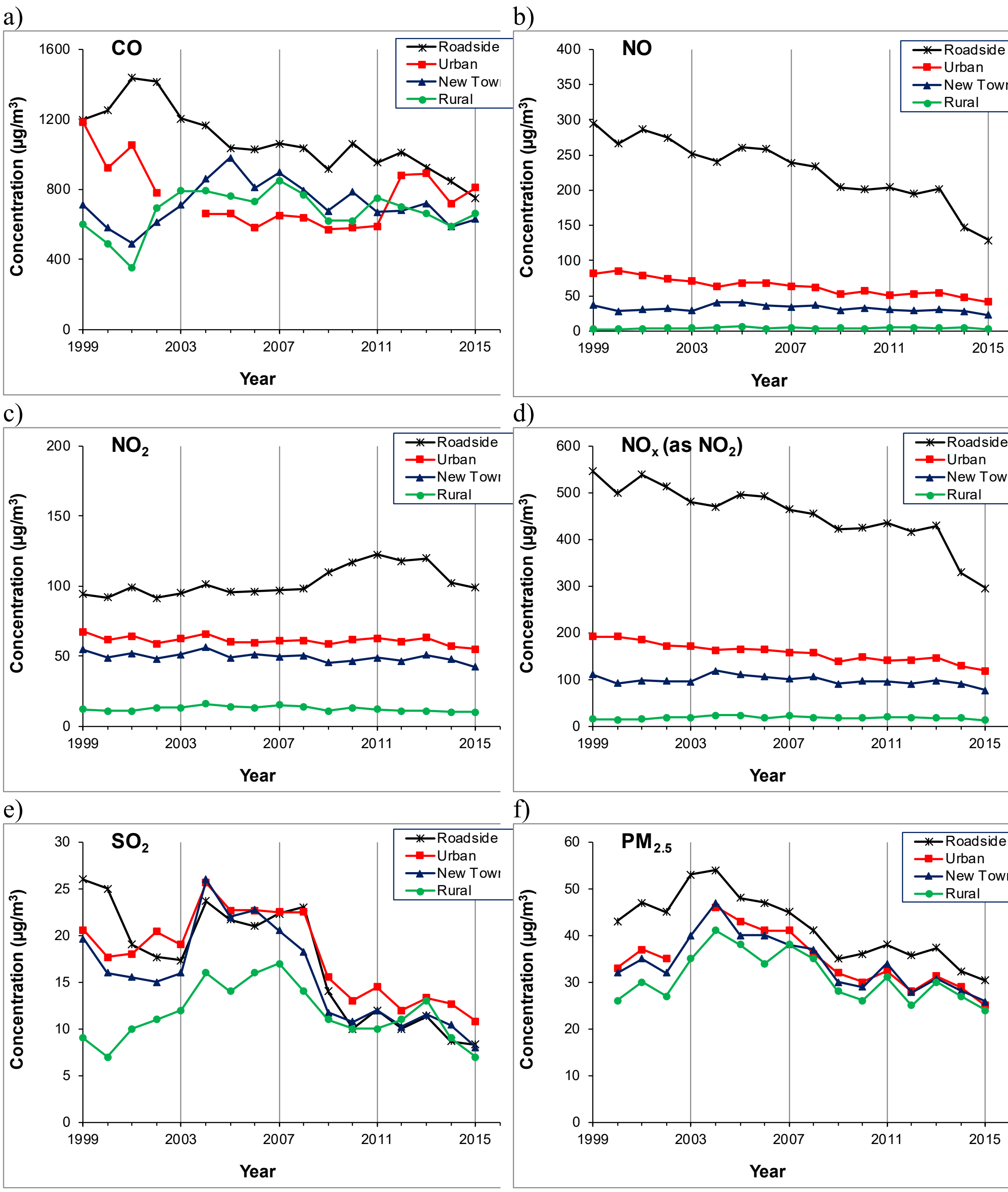


Figure D.5. Annual average ambient concentrations of (a) CO, (b) NO, (c) NO_2, (d) NO_x (as NO_2), (e) SO_2, and (f) $PM_{2.5}$ measured from air monitoring stations in Hong Kong over the period of 1999–2015. (HKEPD 2016, 2017a)