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Cost effective determination of vehicle emission factors using on-road measurements

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Abstract

To evaluate the success of vehicle emissions regulations, trends in both fleet-wide average emissions as well as high-emitter emissions are needed, but it is challenging to capture the full spread of vehicle emission factors (EFs) with chassis dynamometer, tunnel or remote sensing studies. We developed an efficient and cost-effective method using real-time on-road pollutant measurements from a mobile platform, which when linked with real-time traffic data, allows calculating both the average and spread of EFs for light-duty gasoline-powered vehicles (LDV) and heavy-duty diesel-powered vehicles (HDV). This is the first study in California to report EFs under a wide range of real-driving conditions on multiple freeways and it captured much or most of the variability in EFs due to inter-vehicle differences. Fleet average LDV EFs were generally in agreement with most recent studies and an order of magnitude lower than HDV EFs, but over an order of magnitude or more spread was observed for both LDV and HDV EFs. HDV EFs reflected relatively rapid decreases occurring in diesel emissions in Los Angeles/California, and HDV EFs on I-710, a primary route used for goods movement and a focus of additional truck fleet turnover incentives, were lower than on other freeways. When freeway emission rates (ER) were quantified as the product of EF and vehicle activity rates per mile of freeway, ERs were found to be generally similar in magnitude. Despite a two- to three-fold difference in HDV fractions between freeways, higher LDV volumes largely offset this difference.

1 Introduction

Monitoring of emissions from mobile sources is not only relevant to assessing the public health impacts, but also for evaluating the efficacy of regulatory measures and maintaining accurate emission inventories. Particularly in California, where mobile emissions are the single largest source of nitrogen oxides (NO_x) and carbon monoxide

(CO) emissions, and therefore closely regulated, there is a need to accurately measure mobile emissions that reflect a full range of realistic driving conditions.

Over the last two decades, gasoline-powered vehicle tailpipe and evaporative emissions have been targeted by multiple regulations (e.g. fuel reformulation, inspection and maintenance programs, tighter emission standards and better control technology) that have resulted in large reductions in light-duty vehicle (LDV) emissions. For example in the Los Angeles Air Basin, NO_x and CO emissions (both tons per day and percent contribution) from light duty passenger cars (PC) have significantly decreased over the last decade. Notable regulations affecting fleet emissions during this time include the LEV (Low Emission Vehicle, regulations for 2003 and older cars) and LEVII (for 2004 to 2010 cars) that further tightened fleet emission standards and sharply reduced NO_x, CO and non-methane hydrocarbon emissions. In addition, fleet turnover to newer cars meeting OBDII requirements (On-Board Diagnostics) facilitated emissions control maintenance procedures and diagnostics. Based on California Air Resources Board estimates (CARB, 2009), despite increase in total PC activity, PC contribution to NO_x emissions from mobile sources decreased from 34 % in 2000 to 20 % in 2010, and they only emitted 40 % as much CO in 2010 as they did in 2000. Consequently, heavy-duty diesel vehicles (HDV) have become disproportionate contributors to on-road emissions (Harley et al., 2005) and a principal focus of regulations and control technology improvements. For example, from 2000 to 2010, heavy duty diesel trucks surpassed PCs as the top source of NO_x (CARB, 2009).

In Los Angeles (LA), port-related diesel-engine activity has been the target of especially aggressive regulations at the Port of Los Angeles (PoLA) and Port of Long Beach (PoLB), such as the San Pedro Bay Ports Clean Air Action Plan (PoLA and PoLB, 2010a). These measures are expected to eliminate 72 % of diesel particulate matter and 22 % of NO_x from port-related sources by 2014 (PoLA and PoLB, 2010b) through progressive bans on older engine years and by only allowing heavy duty diesel trucks meeting 2007 federal emission standards to operate on ports after 1 January 2012. Furthermore, the California Air Resources Board implemented drayage (short haul) truck regulations that required retrofitting with diesel particulate filters and that banned pre-1994 engines, with the expected benefit of accelerated fleet turn-over and 85 % reduction in particulate matter emissions from trucks by 2013 (for engine years 1994 through 2006) (CARB, 2011a). Since these regulations are expected to have the largest impact on and near major port truck routes such as I-710, it is also important to compare I-710 HDV emissions to other freeways to ascertain if fleet turnover incentives are having the desired effect.

Accurate emission factors (EFs) are challenging to measure but necessary for historical trend analysis. Of the studies that have quantified trends in vehicle emissions in California, most have employed either tunnel measurements (Kirchstetter et al., 1999a; Ban-Weiss et al., 2008, 2009, 2010) or a remote sensing approach (Bishop and Stedman, 2008; Bishop et al., 2010). Despite their merits, both of these approaches have significant limitations, discussed below, but described in more detail in Zavala et al. (2006) and Wenzel et al. (2000).

Tunnel studies in California have been primarily conducted at the Caldecott Tunnel (Kirchstetter et al., 1999a; Ban-Weiss et al., 2008, 2009, 2010), but results reflect the 4 % upgrade, which increases engine load and emissions for HDVs, thus introducing a bias. Kean et al. (2003) conducted measurements at Caldecott tunnel and showed that driving uphill approximately doubled EFs for CO and NO_x compared to the downhill direction. Furthermore, tunnel studies can only provide estimates of central tendency and not variability, as they report averages of large numbers of vehicles. Though the results are useful to evaluate fleet-wide average trend, without information on vehicle-to-vehicle differences in EFs it is not possible to determine whether reduction in vehicle emissions can best be achieved through targeting high emitters (e.g. drayage truck replacement) or fleet-wide measures such as new vehicle standards.

In contrast to tunnel studies, remote sensing allows determining individual vehicle EFs, but this technique is not mobile, so it can only make measurements at one location at a time, also a limitation unless large numbers of locations are sampled in a manner representative of real world driving modes. Moreover, it is applicable to only some gaseous pollutants. For example, Bishop and Steadman et al. (2008) and Bishop et al. (2010) conducted remote sensing studies in West LA, and, more recently, at the Port of Los Angeles (Wilmington, CA) and Peralta weigh station (Anaheim, CA) (Bishop et al., 2012). In these studies, the West LA measurements were conducted on a traffic-light-controlled freeway ramp (I-10/La Brea Ave) at a positive grade with reported mean vehicle speed less than 20 miles h^{-1} and acceleration greater than 1.9 miles $h^{-1} s^{-1}$, i.e. conditions of high power. Similarly, heavy duty diesel trucks emissions were measured either at a zero grade, low speed, and high acceleration condition at the Port of Los Angeles or on a 1.8 degree incline with trucks in an accelerating mode at Peralta. Therefore, in these studies, high-load conditions were likely to bias EFs upward.

An alternative and more efficient approach is on-road measurements during real-world driving with a mobile platform, procedures similar to those used by Zavala et al. (2006, 2009a) and Jiang et al. (2005). Here, pollutant concentration ratios to CO_2 concentrations are used to calculate both fleet as well as individual emission factors (EFs). Wang et al. (2012, 2011) used a similar approach to measure individual vehicle EFs with a similar suite of instruments as this study. Park et al. (2011), using the mobile platform approach in Los Angeles, found that inter-vehicle variability exceeded that due to different driving modes and that inter-vehicle variability in LDV EFs was less than that in heavy duty truck EFs. However, with numerous accelerations from arterial stop lights and relatively little freeway driving, the Park et al. (2011) study did not provide representative coverage of HDV on freeways where most HDV miles occur.

In a somewhat different approach (capturing vehicle plumes with a stationary set-up) Ban Weiss et al. (2009) made an important observation. They measured emissions from 226 individual vehicles and reported a large skew in inter-vehicle EF distribution, with the highest emitting 10 % of trucks emitting 40 % of total BC and particle number emissions. This suggests that studies extrapolating fleet-wide level emission inventories or trends based on individual vehicle measurements have to be based on large sample sets. This is cost prohibitive for dynamometer methods as well as vehicle chase techniques. Our study used a hybrid approach, combining individual plume impacts into longer averages that still managed to capture the spread and skew of individual EFs.

Our study had two main objectives: the first was to evaluate the impact of recent HDV regulations by measuring EFs that capture actual inter-vehicle variability as well as including realistic mix of driving conditions (e.g. speed and acceleration) and roadway conditions (e.g. grade). The second objective was to compare freeway segments by taking total vehicle volumes and speed into account by calculating total freeway emission rates (ERs), potentially a more direct means of evaluating relative impacts from different freeways.

2 Methods

2.1 Mobile platform measurements

A hybrid vehicle (2010 Honda Insight) was used as a mobile measurement platform. All the continuous instruments, listed in Table S1 in the Supplement, sampled air from a duct installed across the rear windows. The mobile platform was driven in "Green" mode which automatically turns off the engine at idling, eliminating the possibility of sampling our own emissions.

Several procedures were used to improve data accuracy. Data from each instrument were aligned with respect to the fastest instrument to adjust for any delayed response after times were synchronized to be within 1 s to the Global Positioning System (GPS) device time (Garmin GPSMAP 76CSC). Ten second averages were used to determine the concentration on freeway segments which were demarcated based on location information collected using the GPS. Quality assurance procedures included regular flow and zero reading checks. A correction was applied to particle number (PN) concentrations exceeding 10^5 particles cm^{-3} (similar to Westerdahl et al., 2005), as reported by Condensation Particle Counter (TSI CPC 3007), to account for coincidence. Black Carbon (BC) data collected using Magee Scientific microAeth AE 51 was corrected for filter

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loading (same as Kirchstetter and Novakov, 2007). This instrument is susceptible to interference from vibration, and mechanical shocks result in sharp concentration spikes, usually large positive and negative pairs that last up to several seconds. The spikes are readily discernible because they exceed the preceding and succeeding values by an order of magnitude and are unaccompanied by corresponding changes in concentration of co-pollutants. Such instances were identified and censored while processing the BC data, but data loss was less than 3 %.

2.2 Sampling routes

Emissions from motor vehicles were measured on five Los Angeles freeways – CA SR-110, I-110, I-405, I-710 and CA SR-91, highlighted in Fig. S1 in the Supplement. The mobile measurement platform was driven in the central freeway lane, when possible. HDVs are prohibited on the northern segment of I-110 (called CA SR-110, linking downtown LA to Pasadena) and this northern segment was used to measure LDV-only emissions. Based on California Department of Transportation (CALTRANS) 2009 annual average daily traffic and truck data (counts trucks 2-axle or higher), trucks constitute less than 1 % of the total vehicle flow on SR-110. On southern I-110, the fraction is 5.0 % (Caltrans, 2009), while freeways I-710, SR-91 and I-405 have 12, 7.6, and 3.8 % truck fractions, respectively. Days and hours of sampling and meteorological conditions during the measurement period are summarized in Table S2 in the Supplement (Sect. S1). In general, sampling periods were well distributed to cover both rush and non-rush hour activity.

2.3 Mathematical calculations and equations

2.3.1 Emission factors (EF)

Fuel-based EFs were calculated for every run at freeway segment level using carbon balance approach, shown in Eq. (1):

$$\mathrm{EF} = 10^3 \left(\frac{\Delta[P]}{\Delta[\mathrm{CO_2}] + \Delta[\mathrm{CO}] + \Delta[\mathrm{BC}]} \right) \times w_\mathrm{c} \qquad (1)$$

where EF is the emission factor (g or number emitted per kg fuel burned) for pollutant P, $\Delta\,[P]$ ($\mathrm{g\,m^{-3}}$ or particle number $\mathrm{m^{-3}}$) is the increase in the concentration of pollutant P above the background roadway concentration, and $\Delta[\mathrm{CO_2}]$, Δ [CO] and Δ [BC] are the increases in the concentrations of carbon combustion products above roadway background. The mass fraction of carbon in fuel, w_c, was 0.85 for gasoline and 0.87 for diesel fuel (Ban Weiss et al., 2008). Roadway background values in Eq. (1) were estimated as the first percentile of pollutant concentration observed on each freeway link. This approach took differences in fuel density, carbon fraction, and fuel economy into account, similar to the approach of Ban-Weiss et al. (2008). More details are given in Sect. S2 in the Supplement.

A total of 25 runs were made on SR-110 and we assumed these runs captured the expected spread of LDV emissions on other freeways based on the spread of EFs being compared to other studies of individual LDV EFs and lack of any evidence suggesting LDV fleet composition on SR-110 to be significantly different from other freeways measured. Furthermore, SR-110 is the only known thoroughfare with only LDV traffic and long enough to adequately capture the combined emissions from multiple vehicles. Curbside measurements on SR-110 have been previously used to study LDV emissions in Los Angeles (e.g. Kuhn et al., 2005a, b). Results from each of the 25 runs on SR-110 were used to estimate LDV emissions on other freeway links, and the remaining emissions were attributed to HDVs, producing a distribution of possible HDV EFs for each of the 61 other freeway runs.

2.3.2 Real-time traffic characterization

The total and hourly vehicle miles travelled (VMT) on freeway links, further categorized into HDV and LDV, were obtained from aggregate data over all lanes of the freeway reported by the CALTRANS Performance Measuring System (PeMS) (Choe et al., 2002), which is publicly available and gives real-time traffic data averaged at approximately one point every mile on the segments studied. Further details are provided in Sect. S2 in the Supplement.

2.3.3 Freeway emission rates

Freeway emission rates (ERs), i.e. pollutant mass or particle number emitted per mile of freeway per unit time (g or number $\mathrm{h^{-1}}$ freeway-$\mathrm{mile^{-1}}$) were calculated using Eq. (2), where $\mathrm{VMT_{HDV}}$ and $\mathrm{VMT_{LDV}}$ are expressed as vehicle miles travelled per unit time normalized by freeway segment length (vehicle-miles $\mathrm{h^{-1}}$ freeway-$\mathrm{mile^{-1}}$), $\mathrm{EF_{HDV}}$ and $\mathrm{EF_{LDV}}$ are emission factors for pollutants per kg of fuel burned, $\mathrm{FE_{HDV}}$ and $\mathrm{FE_{LDV}}$ are fuel economies in miles $\mathrm{l^{-1}}$, and ρ_g and ρ_d are fuel densities expressed as $\mathrm{kg\,l^{-1}}$. Fuel density values used were $0.74\,\mathrm{kg\,l^{-1}}$ and $0.84\,\mathrm{kg\,l^{-1}}$ for gasoline and diesel fuel, respectively, similar to other studies (Ban-Weiss et al., 2008). The values for fuel economy used in this study were 5.1 miles $\mathrm{l^{-1}}$ and 2.0 miles $\mathrm{l^{-1}}$ for gasoline and diesel fuel engines, respectively, based on Los Angeles fuel usage figures, obtained from CARB Emission Factors Model (EMFAC, 2011) (CARB, 2011b).

$$\mathrm{ER} = \mathrm{VMT_{HDV}} \times \mathrm{EF_{HDV}} \times \left(\frac{1}{\mathrm{FE_{HDV}}}\right) \times \rho_\mathrm{d} + \mathrm{VMT_{LDV}} \times \mathrm{EF_{LDV}} \times \left(\frac{1}{\mathrm{FE_{LDV}}}\right) \times \rho_\mathrm{g} \qquad (2)$$

3 Results and discussion

3.1 LDV fleet emission factors

LDV EFs on SR-110 showed more than an order of magnitude range, as shown in Fig. 1. This variation was due to differences in speed (also shown in Fig. 1), acceleration, grade, and inter-vehicle variability. We assumed this variability captured most of same sources of LDV variability on other freeway segments. The resulting EF distribution variability generally spans the range reported by Park et al. (2011) for individual LDVs. For comparison, results from other recent California studies are plotted in Fig. 1.

Study average EFs were generally in good agreement with recent studies (listed in Table 1). However, the mean values reported by remote sensing studies (Bishop et al., 2008, 2010) were substantially higher than mean values in this study or Caldecott 2006 measurements, likely due to Bishop et al. (2010) measuring plumes from vehicles under strong acceleration. Furthermore, the standard error for EFs reported by Bishop et al. (2010) is unrealistically tight. In contrast, latest Caldecott tunnel study (Ban Weiss et al., 2008, 2009; measurements conducted in summer 2006), reported average EFs agreed well with the mode of our EF distributions. However, they only captured a small fraction of the observed spread in EFs, as is expected from the well-mixed aspects of tunnel emissions.

3.2 HDV fleet emission factors

HDV emission factors (per mile) exceeded LDV EFs by at least an order of magnitude for all pollutants. On average the HDV fleet on freeways other than I-710 emitted 4 times higher NO_x, 12 times higher PN, and 20 times higher BC per quantity of fuel burned than LDVs. When differences in fuel efficiency were taken into account, the disparity between HDV and LDV emission factors further increased. Important statistics for HDV EF are summarized in Table 1. The distribution of speed for these measurements is shown in Fig. S2 in the Supplement.

Similar to the distributions for LDV EFs, significant variation was observed in HDV EFs, as shown in Fig. 2. Only data from freeways other than I-710 are plotted in the histogram in Fig. 2. In absolute terms, HDV EFs had much broader variability than the LDV EFs. Combined with being an order of magnitude higher than in LDV, the variability in HDV EFs is therefore more consequential in determining the overall variability in freeway EFs.

HDV fleet EFs were least variable for NO_x/NO, and closest to being normally distributed of the six pollutants measured. This finding may have important implications for regulatory purposes – a substantial reduction in NO_x/NO emission is perhaps more efficiently achieved through regulations aimed towards lowering fleet-wide NO_x/NO emissions, while control of BC or particle species emissions may be more effective by identifying and replacing or retrofitting specific high emitters. For example, removing the highest emitting 10 % of BC or particle bound polycyclic aromatic hydrocarbons (PB-PAH) emitters would lower average fleet EF by 60 % and 40 %, respectively, but a similar approach with NO_x would only lower emissions by 20 %.

In comparison to recent studies, the average HDV EFs in this study were lower (except for CO). Colored bars in Fig. 2 represent results from the four most recent and relevant studies conducted in the state of California, measuring individual vehicle EFs (Ban-Weiss et al., 2009, 2010; Bishop et al., 2012; Dallmann et al., 2011). The remote sensing-based measurements of Bishop et al. (2012) at a location in the Port of Los Angeles, and at a truck weigh station (Peralta) on CA SR-91 were much higher (than I-710) or comparable (only NO on freeways other I-710) for NO_x/NO than measured in this study, likely due to acceleration only conditions in remote sensing studies. Dallmann et al. (2011) measured EFs for individual vehicles in the Port of Oakland (Oakland, California) area and reported NO_x EF values around 15 g kg-fuel^{-1}, in excellent agreement with this study. Though the PN EF mode agreed well with both Caldecott 2006 results (i.e. the fleet average and individual truck measurements-based mean) it is worth noting that due to the volatile nature of vehicle exhaust particles (especially ultrafine particles of diameter less than 100 nm) and the markedly reduced dilution in tunnels, EFs measured in tunnel studies may not be a representative measure of real-world EFs.

3.3 HDV fleet emission factors on I-710

I-710 is a major route used for goods movement and the trucks involved are a target of recent California Air Resources Board regulation efforts in addition to regulations by the ports themselves (i.e. Clean Air Action Plan). For this reason, it was useful to see whether I-710 EFs might now reflect a newer, cleaner population of HDVs serving the ports compared to other freeways. Figure 3 shows that there is some evidence to support this claim. Though the spread of EFs on I-710 and other freeways was similar, lower EFs were observed more frequently on I-710. Median EFs on I-710 were 50–70 % of that on other freeways. (Average HDV EFs are compared in Table 1.) However, only the NO distributions were statistically significantly different (Kolmogorov-Smirnov test, 5 % significance level). Average NO EFs on I-710 were about half of that observed on all other freeways, while NO_x emissions were comparable. This suggests the NO_2/NO_x fraction may have increased on I-710, similar to that reported by Bishop et al. (2012) for Port of Los Angeles. Continuously-regenerating particle trap technology has been reported to produce higher NO_2/NO_x fractions (Heeb et al., 2010; Herner et al., 2009; Velders et al., 2011).

3.4 Freeway emission rates

3.4.1 Diurnal variation in freeway emission rates

Total emissions from freeways depend not only on average EFs by also vehicle miles traveled (VMT), which takes into account traffic volume and diurnal shifts in traffic mix. VMT and its HDV fraction vary most with time of the day, and diurnal LDV activity patterns (either VMT or number of vehicles) are typically bimodal, peaking during morning and afternoon rush hour. In Los Angeles, during midday (10:00–13:00 LT) a drop in

LDV vehicle activity is often observed, more strongly in vehicle volume (number of vehicles per hour) than in VMT because higher non-rush hour speeds accumulate more miles (see Fig. S3 in the Supplement). However, HDV activity in Los Angeles increases and peaks during midday hours. The emissions from increased HDV activity seem to compensate for reductions in emission due to fewer LDV (or even a reduction in total VMT), thereby producing distinctly uni-modal profiles for emission rates, such as shown in Fig. 4. Mean hourly VMT and f_{HDV} on the freeway segments during the month May 2011 were used to generate Fig. 4. These diurnal patterns differ strongly from on-road or near roadway concentration profiles, which tend to be bi-modal as rush hour generally coincides with lower wind speeds and reduced dilution (Hudda et al., 2010; Moore et al., 2009; Ntziachristos et al., 2007).

3.4.2 Average emission rates

Assuming that diurnal meteorology patterns are similar across the Los Angeles basin, ERs can be used to compare across freeways the overall impact of vehicular emissions on near-roadway communities. Total pollutant emission rates for four freeways were computed using Eq. (2). Daily VMT per freeway mile within Los Angeles (and the fraction due to HDV) during the 215 working days from 1 December 2010–30 November 2011 were used to generate average hourly emission rates, plotted in Fig. 5. (Daily time series for VMT and HDV VMT are shown in Fig. S4 in the Supplement.) The error bars represent the standard deviation due to daily variation in VMT. Except for a summer-to-fall increase in port related goods movement on I-710, there were no significant seasonality aspects to consider. Figure 5 shows that while I-710 has often been studied and observed as a high end of freeway emissions (Fruin et al., 2008), ER results indicate that on per mile of freeway basis, the highest emitting freeway is SR-91, due to both high VMT and high HDV fraction, and that emissions per mile from I-110 and I-405 are roughly comparable to I-710 for NO, NO_x and PN.

The above discussion illustrates that the common assumption – that freeways with the highest truck volume fractions are the worst sources of pollution – may be too simple. Total VMT on several low-fraction HDV freeways in Los Angeles are high enough for total emissions to be comparable to I-710. As an additional illustration, in Fig. 6 the NO ERs have been plotted against total VMT (vehicle miles per mile of freeway during May 2011) for two freeways – I-710 and I-405. Despite much lower HDV fraction of I-405 versus I-710 (3.8 % versus 12 %), total emissions were comparable for almost all hours of the day. Figure 6 shows that hypothetically reducing HDV fraction by more than two-thirds on I-710 would likely provide little if any total NO reductions if VMT simultaneously doubled. Hence, while HDV fraction is an important factor in determining overall freeway ER, at currently high Los Angeles VMT levels, LDV contributions to total freeway emissions can be comparable to HDV. Furthermore, continuing future growth VMT growth will likely offset much of the emissions reduction benefits of a cleaner HDV fleet.

4 Conclusions

Emission factors measured using a mobile measurement platform during real-world driving conditions and across multiple freeways suggest that individual HDV emission factors still exceed LDV emission factors by an order of magnitude. To further lower emissions from HDV, regulations that target a fleet-wide reduction would be most suitable for NO_x/NO, while significant reductions for particulate species (BC, PN, PB-PAHs) may still be attained through targeting high emitters specifically. In general, our results suggest that emission factors for HDV have decreased, in line with the trend reported by recent studies, with apparently greater reductions occurring on I-710 (for NO) due to additional regulations targeting goods movement and promoting accelerated fleet turnover. However, HDV fleet-wide NO emissions have lowered without any significant differences in NO_x emissions, suggesting an increase in NO_2 emissions, perhaps due to the adoption of particle trap control technology (Heeb et al., 2010; Herner et al., 2009; Velders et al., 2011). When study-wide mean EFs were used to calculate total emissions from freeways, emissions from I-710, I-110 and I-405 now appear to be comparable, despite a 3-fold range in HDV fraction. This underscores the importance of taking total vehicle activity into account. The assumption that freeways with the highest HDV fractions are significantly worse sources of total emissions is no longer true in Los Angeles.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/12/18715/2012/ acpd-12-18715-2012-supplement.pdf.

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Table 1. Emission Factors for LDV and HDV fleet.

	Pollutants					
	CO	NOX[1]	NO	PN[1]	BC	PAH
Units	g kg-fuel^{-1}	g kg-fuel^{-1}	g kg-fuel^{-1}	particles m^{-3} kg – fuel^{-1}	g kg-fuel^{-1}	g kg-fuel^{-1}
	Average emission factors					
I-110 (LDV only)	39 ± 22	3.8 ± 1.4	2.0 ± 0.8	$(4.3 \pm 2.6)10^{14}$	0.07 ± 0.05	0.0008 ± 0.00006
I-710 (HDV)	88 ± 96	15 ± 9.2	7.8 ± 3.8	$(4.2 \pm 3.4)10^{15}$	0.41 ± 0.21	0.005 ± 0.003
All other freeways (HDV)	163 ± 144	16 ± 10	12 ± 7.1	$(5.2 \pm 3.1)10^{15}$	1.33 ± 0.33	0.010 ± 0.016
Ratio of all other freeways to I-710	1.9	1.1	1.5	1.2	3.2	2
	Emission factor distribution statistics					
I-110 (LDV only)						
Median	89	14	8.7	3.8410^{15}	0.32	0.0049
75th–25th	147	11	7.1	3.2710^{15}	0.502	0.0049
Skewness	0.4	0.8	0.3	0.8	1.4	1.1
I-710 (HDV)						
Median	59	14	7.3	3.1010^{15}	0.24	0.0042
75th–25th	80	9	4.4	2.1610^{15}	0.21	0.003
Skewness	2.2	1.3	0.98	2.1	1.2	1.9
All other freeways (HDV)						
Median	125	15	11	4.6010^{15}	0.43	0.006
75th-25th	166	13	10	3.5610^{15}	0.52	0.007
Skewness	1.5	0.66	0.6	1	0.76	4.1
	Distance-based emission factors[3]					
	CO	NOX[1]	NO	PN[2]	BC	PAH
	g mile^{-1}	g mile^{-1}	g mile^{-1}	particles m^{-3} mile^{-1}	g mile^{-1}	g mile^{-1}
LDV	5.7	0.55	0.29	6.2210^{13}	0.01	0.00012
All HDV	55.4	6.4	4.1	1.9710^{15}	0.373	0.003
HDV/LDV ratio	10	12	14	32	38	25

[1] LDV fuel efficiency 5.1 miles l^{-1}; HDV fuel efficiency 2.0 miles l^{-1}

[2] Reported as NO_2 mass equivalent

[3] Measured using TSI CPC 3007, Dp > 10 nm

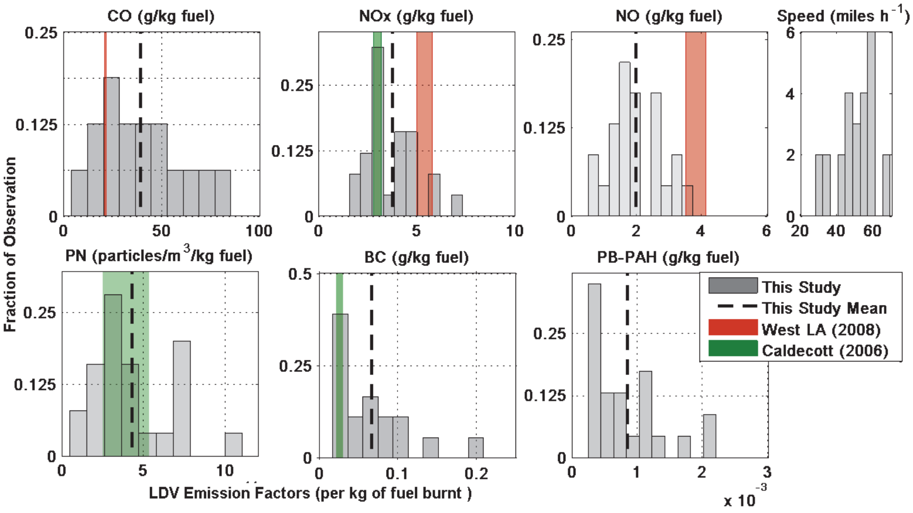

Fig. 1. LDV emission factors (measured on CA SR-110, total number of observations = 25). Caldecott 2006 refers to Ban-Weiss et al. (2008, 2010) results, and West LA (2008) refers to Bishop et al. (2010) results. The colored bars represent the reported one standard deviation range.

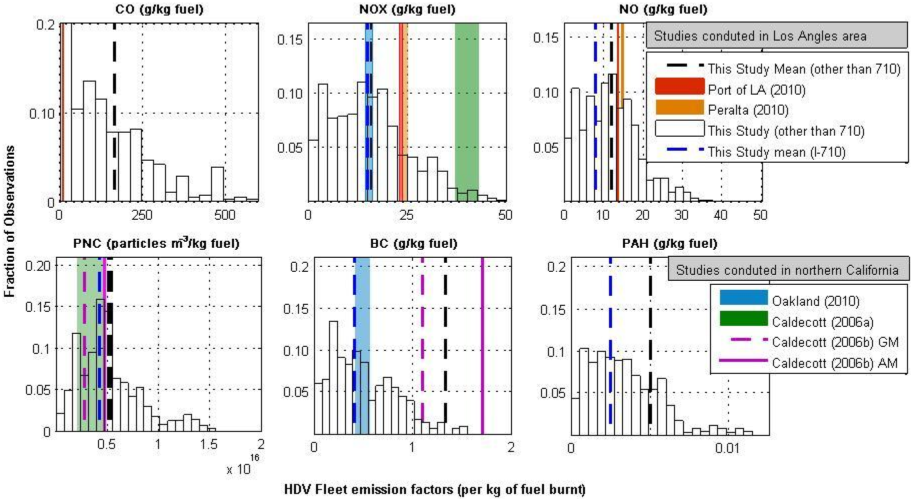

Fig. 2. HDV emission factors. Oalkand (2010) results represent individual vehicle plume averages reported by Dallmann et al. (2011), Caldecott 2006a refers to Ban-Weiss et al. (2009) results, Caldecott 2006b refers to Ban-Weiss et al. (2010) geometric and arithmetic means based on individual vehicles, and PoLA (2010) and Peralta (2010) refer to Bishop et al. (2012) results. Colored bars span the reported one standard deviation range. BC X-axis was truncated for clarity, values extend upto 15 g kg-fuel^{-1}.

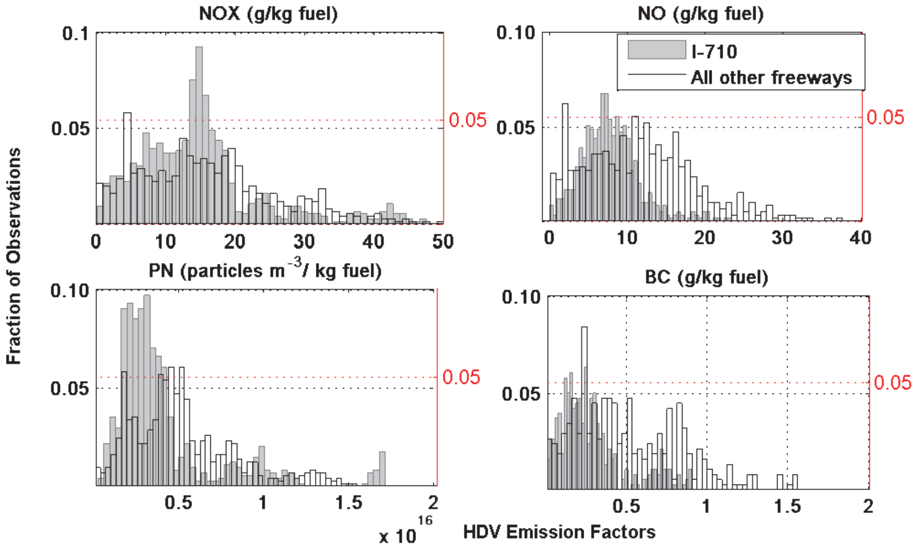

Fig. 3. Comparison of HDV fleet emission factors on I-710 to other mixed-fleet freeways (number of observations on I-710 = 32, all other freeways = 29).

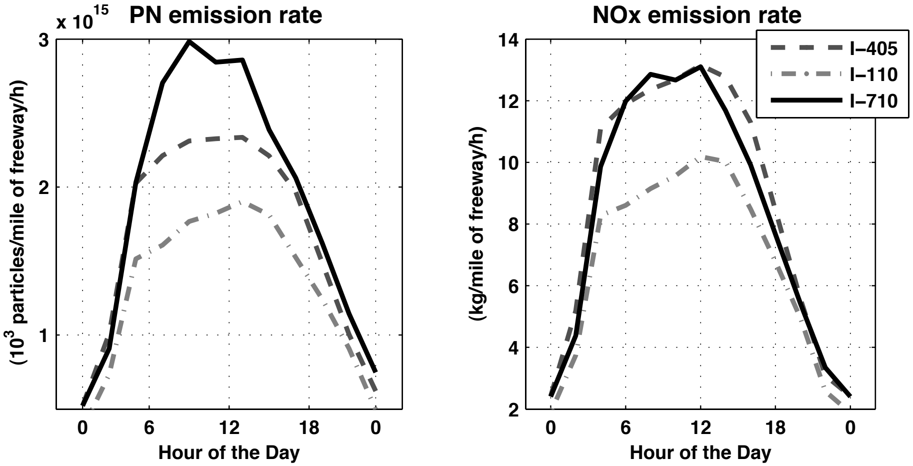

Fig. 4. Diurnal profile of I-110, I-710 and I-405 emission rates.

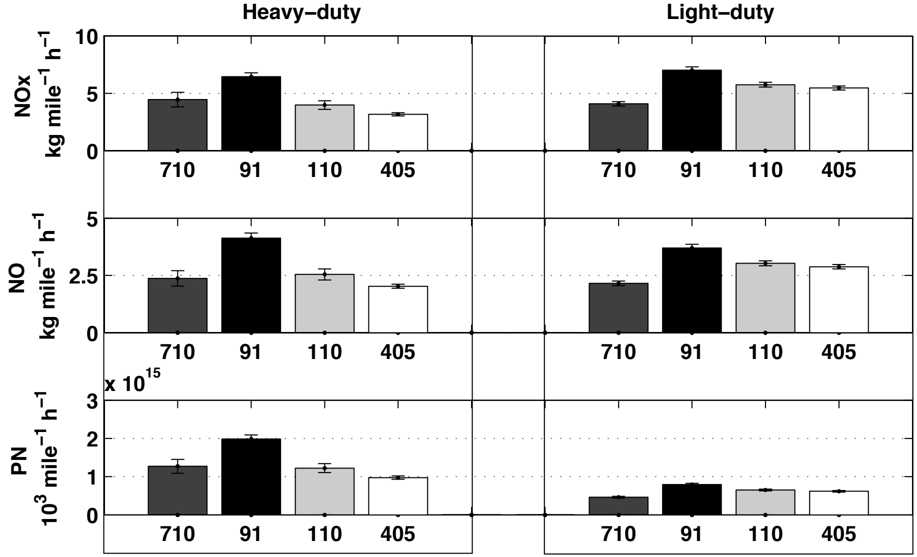

Fig. 5. Average hourly freeway emission rates for four freeways within LA County lines.

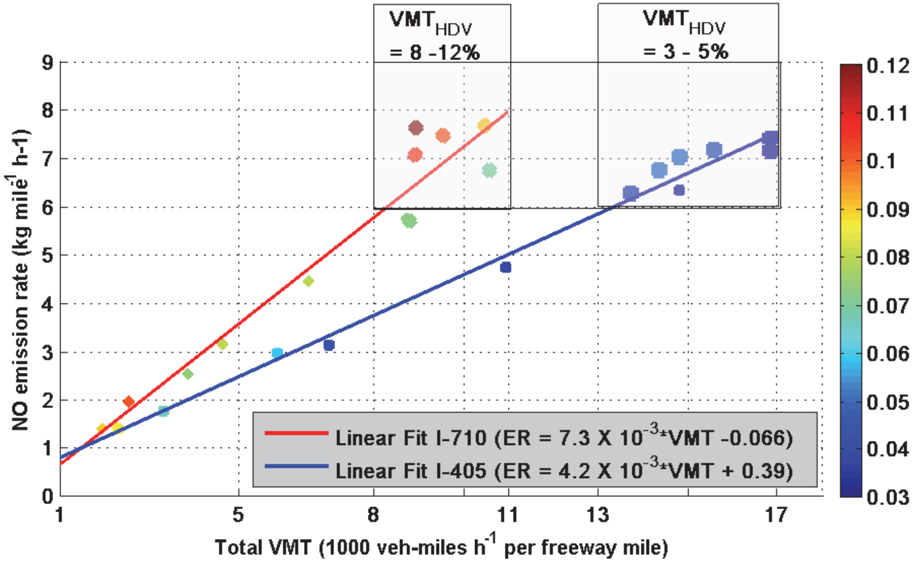

Fig. 6. Comparison of NO emission rates for low (I-405) and high (I-710) HDV fraction freeway. The color bar indicates the fraction of total VMT attributable to HDV.