Response to comments from anonymous referee #1

This is an interesting paper presenting average emission factors of light duty and heavy duty vehicles in the LA region by measuring in-freeway pollutant concentrations. The method is indeed a cost-effective method as the authors suggest. However, there are some significant limitations with such an approach, which are not at all discussed by the authors. The main ones are:

1. *Equation 1 requires a 'background' level of concentrations so that concentration incremental increases on the roadway are calculated. Therefore, the whole calculation is very sensitive to the background concentration selected. The authors should: (i) discuss how background concentrations were determined in each location, (ii) estimate the uncertainty in the background concentration, and (iii) estimate the uncertainty that this induces on the emission factor calculation.*

Please see our response to Referee #4, comment #1 about background concentration determination.

An uncertainty analysis in the conventional sense does not apply to the background values estimated using the percentile approach because we cannot modify the distributional aspects of our calculations in a straightforward manner. However, we could have introduced a bias if we under- or over-estimated the freeway background concentrations. Figure R1 below shows that the lowest CO2 concentrations were quite stable across the majority of runs, i.e., choosing the 2nd percentile, for example, did not change the CO_2 concentration for about half the runs and 5 ppm or less for the rest.

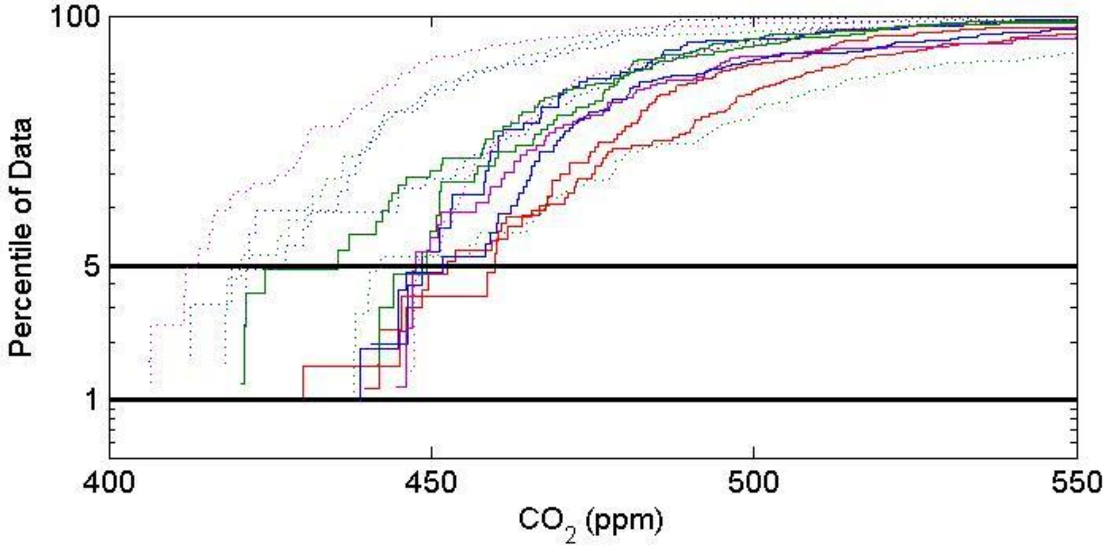


Figure R1: CO2 concentrations for a subset of runs on LDG only traffic freeway (SR-110)

2. Equation S.1 is critical in the calculation. It basically assumes that the ratio of pollutant over CO2 concentrations for gasoline vehicles remains constant in all freeways measured. The corresponding diesel ratios are then estimated using this assumption. However, it is well known that pollutant over CO2 ratios substantially differ for gasoline vehicles depending on the driving conditions. For example, 20-fold CO/CO2 ratios can be observed for different VSPs (EPA - Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission System, p.69). Similarly, the authors have measured significant differences in these ratios over the 110 freeway. Hence, it cannot be unanimously assumed that the average ΔP/ΔCO2 ratio over the 110 freeway holds for all other freeways/times of day/driving conditions. Ideally, the authors should estimate the contribution of the uncertainty in the ΔP/ΔCO ratio to the uncertainty of the emission factors calculated. At a minimum this should be clearly identified as a limitation to the study.

We agree that an ΔP/ΔCO2 varies across freeways, and differs by time of day or driving conditions. We therefore used a distribution of EFs calculated by freeway segment and run. We first conducted 25 runs on SR-110 to capture LDG EF variability under various times of day and traffic conditions. Each of these 25 values was then used as a ΔP/ΔCO2 probability distribution that was coupled with ΔP/ΔCO2 for each of 61 mixed-fuel fleet segment ΔP/ΔCO2 ratios.

To clarify these procedures, the edited Lines 16-21/Page 18722 now read as:

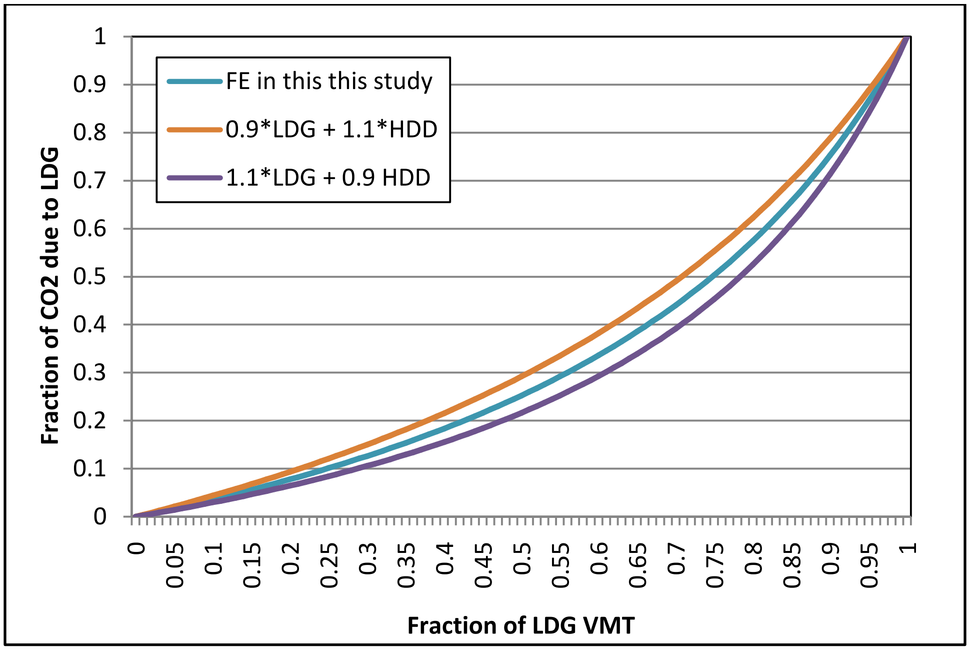
> "A total of 25 runs were made on SR-110, which is the only thoroughfare with just LDG traffic, and has been previously used for curbside measurements to study LDG emissions in Los Angeles (e.g. Kuhn et al., 2005a, b). We assumed that these 25 runs captured the expected spread of LDG emissions, based on the spread of EFs being comparable to other studies of individual LDG EFs. The likely impact of not having adequately captured the high end of LDG emissions in the 25 runs would be a mis-assignment of some fraction of LDG emissions to HDDs. We estimated total LDG emissions on other freeway links from runs on SR-110, and the remaining emissions were attributed to HDDs, producing a distribution of possible HDD EFs for each of the 61 other freeway runs. Each run reflected a different fleet composition not only in terms of fraction that was HDD, but also a new set of vehicles under a new set of driving conditions."

This comment brings up a key advantage of our approach in that we were capturing vehicle EFs over a range of operating conditions that reflect real-world driving. With the exception of dynamometer tests, other methods capture closer to an instantaneous EF that reflects a specific speed and power situation. If this situation involves grade or consistent accelerations states, such as an on-ramp, then EFs are biased.

<u>It is important to distinguish between uncertainty and variability in our work.</u> We attempted to characterize the variability in EFs that exist in real-world driving conditions. It was beyond the scope of our study to resolve EF variability into components. Rather, we wanted to ensure that these factors were included in a manner representative of real-world driving.

Separate from the sources of variability, uncertainty in our EF calculations resulted from (a) instrument related uncertainty; (b) average value for fuel efficiency; and (c) the 'fraction of HDV' estimate, which is reported to be 6% by PEMS. In our EF calculation, an error in fuel efficiency firstly affects the apportionment factor non-uniformly across its range (please see figure below) and secondly affects the factors for converting EFs from g/kg-fuel to g/mile units. EFs reported in g/kg of fuel burnt are not as sensitive to fuel efficiency. In fact, to calculate EF for LDG vehicles fuel efficiency is not required. It is only required to convert EFs to g/mile units.

While calculating HDD EFs, fuel efficiency is required to calculate the CO_2 apportionment factor. However there are few data available on how fleet wide aggregate fuel efficiency differs by driving mode, probably the largest source of uncertainty of the three. To address the uncertainty concern, we decided to conduct a sensitivity analysis to see how a ±10% difference in the average fuel efficiency values we used would affect our EF estimates. Results are shown in the figure below. A 10% mis-estimation of fleet wide average will lead to at maximum error of 0.05 in apportionment factor, which will occur when one of the fuel efficiency is over- and other under-estimated. Also, the effect is not uniform across the apportionment factor range. In our study, the maximum truck HDV was 0.4 and corresponding maximum error in CO_2 apportionment factor is ±0.04.



Using mean square error propagation technique, maximum uncertainty in EFs resulting from instrument accuracy, error in CO_2 emission apportionment and error in HDD/LDG fraction of VMT was calculated. Values have been reported in Table 1, and are summarized below. Please also see our response to Comment 3 regarding uncertainty in emission rates (ERs).

	Uncertainty in EFs				
	NOx	NO	PN	BC	PB-PAH
LDG	4%	5%	20%	11%	13%
HDD	10%	10%	30%	17%	20%

The following sentence has been added to the manuscript.

> "Using mean square error propagation, maximum uncertainty in EFs resulting from instrument accuracy, error in CO_2 emission apportionment and error in attribution HDD/LDG fraction of VMT was calculated. Values have been reported in Table 1."

3. *Freeway emission rates have been calculated per mile of freeway and unit time, using constant fuel economy values which represent the average fuel economy in the LA region. Fuel economy may substantially differ according to driving conditions hence this*

value is far from constant per mileage driven on freeways. Similarly to point #2 above, the impact of this on emission factor uncertainty should be estimated or at minimum be clearly discussed. This is particularly true to the diurnal emission rate variation (section 3.4.1). I would suggest that all these are discussed on a separate (new) section of this paper.

There are few data available on how fleet wide aggregate fuel efficiency differs by driving mode, which makes it difficult to weigh fuel efficiency by driving mode and come up with better estimates than an average used in this study to calculate emission rates (ER). Our goal with ER calculation was to demonstrate that despite a several-fold difference in truck fraction on freeways, total emissions can be comparable. It is highly likely that fuel efficiency changes due to speed will not be a strong function of the freeway being driven if the pattern of speed on freeways is similar. However, by ignoring effects of speed on EFs, we likely understated emissions during rush hours where speed is most reduced and stop-and-go conditions occur, but these diurnal differences in speed in Los Angeles are very similar across freeways, so our comparisons between freeways are still valid. We have updated Section S.4 in the Supporting information to include a graph that compares the average diurnal speed trend on freeways. For the sake of clarity, all other freeways have been averaged and compared to I-710, since the observation we are making is that I-710 is not an exceptionally high emitter. Also, we have included the following sentence in the discussion to acknowledge this limitation.

> "…there were no significant seasonality aspects to consider. While average fuel efficiency was used to calculate ERs and changes in fuel efficiency due to difference in driving conditions were not taken into account, it is likely that changes in efficiency would be similar across freeways and that a comparison based on average fuel efficiency is applicable because the diurnal profile of speed on freeways is similar (See Figure S5 in the Supplement).Figure 5 ….."

4. *The authors report that the study average EFs are generally in good agreement with recent studies, which are assumed to be shown in Table 1 (l.227-8). I have a number of questions on Table 1:*
    a. *I see no emission factors for other studies in Table 1.*

Table 1 has been edited to include results from the latest and comparable publications.

b. The average values shown seem rather inconsistent with the distribution statistics. For example, average CO of 39 g/kg fuel and median of 89 g/kg fuel. Do the authors confirm these large differences?

There was a typographical error in the table. The label for “Emission factor distribution statistics” was supposed to read “All freeways (HDV)” instead of “I-110 (LDV only)”. The numerical values reported are correct.

c. *What does the variability range shown for the g/kg-fuel values express? Is it standard deviation? In any case, this is a huge variability, even without taking into account the uncertainties discussed in the previous points. Some discussion on the sources and reasons for this variability should be given.*

The values have been reported as average ± standard deviation. There is a large variability in real-world emissions, and the reported value is representative of this variation. (Please see the response to Comment 2 and 3 above.) The standard deviation we are reporting is not comparable to that reported by tunnel or remote sensing studies. Tunnel studies report standard deviation of day-to-day variation in average concentrations in the tunnel. Remote sensing studies report the standard error of their dataset. Also, the following sentence has been added to the manuscript to draw attention to this aspect.

> “Important statistics for HDV EFs are summarized in Table 1. Though the averages were in agreement, it is worth noting that our study appeared to capture nearly a magnitude of real-world intra-fleet variation in an efficient manner without having to measure individual vehicles.”

Also see our discussion on variability and uncertainty in response to Comment #2 by Referee 1.

d. *Despite this, the distance-based emission factors are given in Table 1 without any variability. This is inconsistent and has to be corrected.*

Uncertainty for distance-based emission factors has been added to the edited Table 1, which is now Table S.4. Due to space constraints, emission factor distribution statistics and distance based emission factors have been moved to the Supplement as Table S.4.

5. *The discussion in lines 253 to 262 (HDV Fleet EFs : : :only lower emissions by 20%) is not at all understood. First, I do not see substantial evidence from Fig. 2 that NOx/NO is much closest to normal distribution than BC. If this is indeed the case, the relevant statistics (e.g. goodness of fit) should be presented to support the argument.*

None of the EF distributions were statistically normal. We have replaced the term “normal” in the manuscript with “least skewed” and the discussion in lines 253 to 262 was removed. The revised text now reads as:

"Of all the pollutants measures, HDD fleet EFs were least skewed for NOx and NO. EF skew in this study does not strictly result from only 'high emitting' vehicles but a combination of vehicle differences and driving conditions. However, given that EF is based on median elevated concentration, it is less likely to be influenced by a transient driving condition like a hard acceleration and more likely by sustained effects like having a high emitter vehicle in the fleet mix. This difference in distribution skews may have important implications for regulatory purposes—a substantial reduction in NOx and NO emission is probably more efficiently achieved through regulations aimed towards lowering fleet-wide NOx and NO emissions, while control of BC or particle species emissions, with larger skews in EFs, are likely more effectively reduced by identifying and replacing or retrofitting specific high emitters."

6. *Second, the authors make the implicit assumption that the frequency of observation (and not 'fraction of observation' as erroneously stated in Fig. 8 and 9) is equal to the frequency of high emitters. However, the authors do not monitor individual vehicles but individual road sections. Hence, high emissions are not delivered by individual vehicles but by individual driving conditions.*

   Please see the previous response.

7. *The authors imply in section 3.3 that a different HDV mix operates on I-710 than other freeways, mostly composed of newer vehicles. If this is the case, then this should be reflected to an improvement in fuel economy as well. Hence, retaining the original LA wide fuel economy for HDVs also on I-710 introduces a bias to average emission rates estimated in section 3.4.2. Can the authors estimate its impact?*

   We could not find reliable estimates of improved fuel efficiency for newer HDDs in the literature. However, please see our response to Comment 3, regarding the impact of fuel efficiency in EF calculations.

   We calculated the maximum uncertainty in EF (g/mile) unit that will result due to instrument accuracy, error in fuel economy and error in estimating HDD fraction of traffic. These are listed below. When assuming a 10% error in fuel economy, maximum uncertainty in g/mile EF solely due to that in fuel efficiency is10.8%.

	NOx	NO	PN	BC	PB-PAH
Instrument Accuracy	2%	3%	20%	10%	13%
LDG EF Uncertainty (g/mile)	11%	11%	23%	15%	17%
HDD EF Uncertainty (g/mile)	14%	14%	31%	20%	22%

8. *Minor points l.268: “2012” not “2102” l.182.: No “Ban-Weiss et al. 2008” reference included in the references list. Is it the 2008 or the 2009 paper the authors refer to? l.300: Correct syntax*

   Required corrections have been made to the revised version. We were referring to Ban-Weiss et al, 2008, which is listed in the references.