Supporting Information for

A method for using stationary networks to observe long term trends of on-road emissions factors of primary aerosol from heavy duty vehicles

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Contents of this file

Introduction

In S1 and S2, we provide additional details describing the traffic data used in this work. In S3, we define regional signal in more detail than in the main text and explore the sensitivity of derived emissions factors to the time window used to derive regional signal. In S4, we compare weekend and weekday truck flow, total flow, PM enhancement, and CO enhancement to demonstrate the sensitivity of PM and CO enhancement at each site to traffic signal. In S5, we detail the fitting process used to determine enhancement ratio and show fits for each site and time period. In S6, we show the mean diel cycles of boundary layer height and windspeed used to model enhancement of PM from HDV both near roadways and regionally. In S7, we show modeled PM from HDV. In S8, we show data from Laney College, near-highway site with signal interference from a nearby large parking lot and discuss the importance of using isolated sites for this analysis. In S9, we explore the possible impacts of LDV emissions on our calculations.

Text S1: Transportation Data

The Caltrans Performance Measurement System consists of a network of in-road sensors (magnetic loop) that detect car and truck flow rate across the state of California. PeMS derives truck portion at a given site using vehicle length estimates (Kwon, 2003). Comparisons of this method with weigh-in-motion technology finds error in this method to be ~5%. (Kwon, 2003) Although network density varies across the state of California, coverage in the San Francisco Bay Area is quite dense, with over 1800 measurement sites along major highways (Figure S1). Total vehicle flow rate and truck percentage were retrieved from (http://pems.dot.ca.gov). For each near-highway BAAQMD site, traffic data was taken from the two closest (primary) PeMS sites (one in either direction). In cases when PeMS data from the closest sites were not available, data was (if possible) filled in with median values for hour of week for the given site and year (excluding 2020), or retrieved from pairs of second closest (secondary) or third closest (tertiary) sites on the same highway. PeMS site codes in Table S1. Example flow rates are shown below in Figure S2.

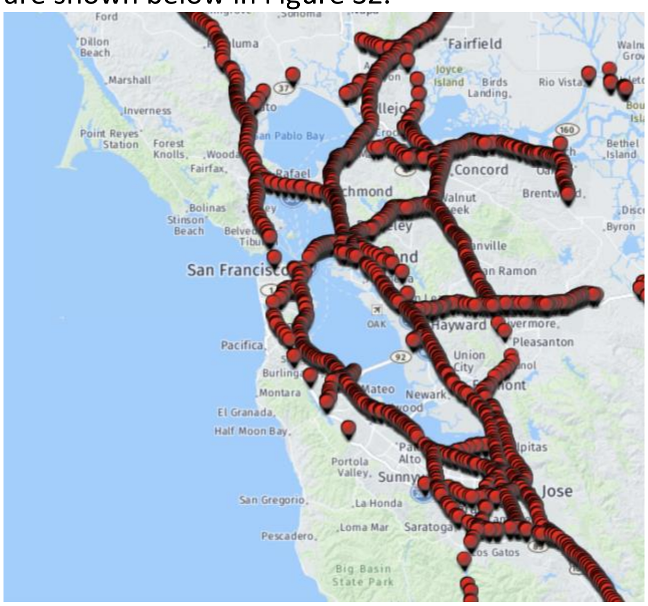


Fig S1: Map of Caltrans PeMS loop detector sites in the SF Bay Area from http://pems.dot.ca.gov. Copyright © 2022 State of California.

BAAQMD Site	PeMS – DIR 1 (primary)	PeMS – DIR 2 (primary)	PeMS – DIR 1 (secondary)	PeMS – DIR 2 (secondary)	PeMS – DIR 1 (tertiary)	PeMS – DIR 2 (tertiary)
Laney College (LC)	408138	400835	400609	400980	401710	400682
San Rafael (SR)	403317	403316	403314	403315	402412	402139
Redwood City (RWC)	404572	405673	401875	401874	401873	405679
Berkeley (BM)	400176	400728	400009	400432		
Pleasanton (PL)	402016	401006	400892	402018	402444	407964

Table S1: PeMS stations used in this study to capture truck flow near BAAQMD sites.

Text S2: Example weekly truck flow and truck percent at sites of interest.
Hourly flow rates and truck percent are found by combining data from paired traffic sensors in each direction of flow. Peak weekday flow rates vary substantially from site to site from ~300 to ~1000 trucks / hr.

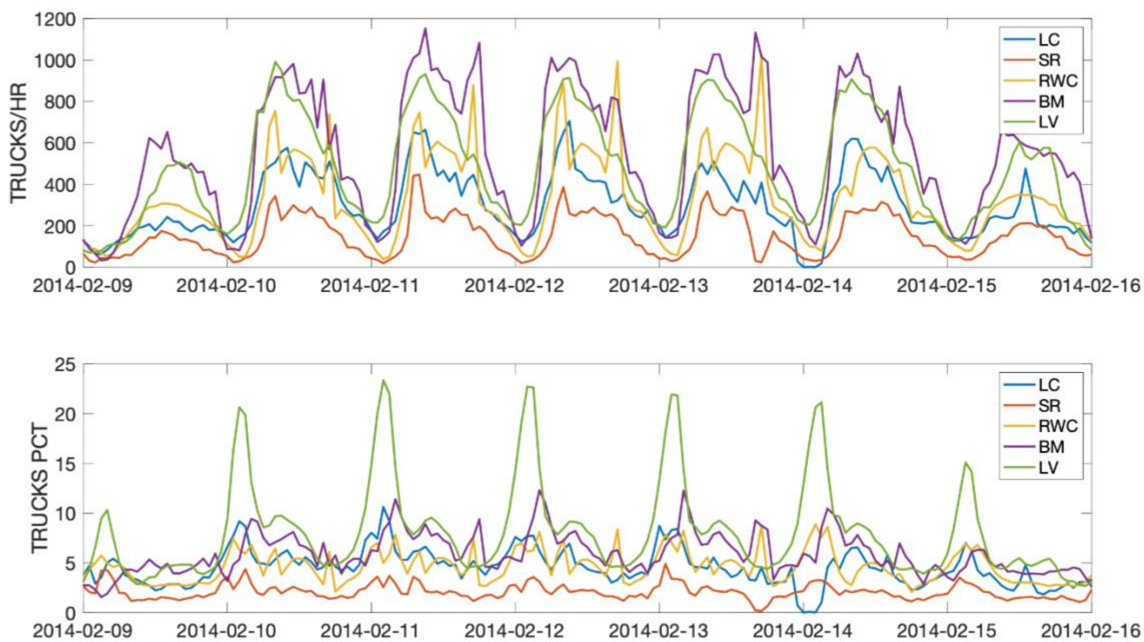


Fig S2: Hourly truck flow and truck % for PeMS sites located closes to the near-highway BAAQMD sites below.

Text S3: Sensitivity of Results to Regional Signal method

We define regional signal of $PM_{2.5}$ as including $PM_{2.5}$ transported to the Bay Area from elsewhere, $PM_{2.5}$ emitted from area point, and line sources far enough away from a site to have mixed through the area, and $PM_{2.5}$ formed in the atmosphere through secondary chemical processes. We make the assumption that by taking the 10^{th} percentile of the signal from all sites, that we are able to approximate this regional signal, as in Shusterman (2018). By subtracting the regional signal from total signal at a given site, we are able to isolate enhancements that result from localized emissions. We furthermore make the assumption that within the nearfield of a highway during morning rush hour, that both $PM_{2.5}$ and CO enhancements are dominated by highway emissions. $PM_{2.5}$ emissions not from the highway should not correlate well with enhancements in CO and are eliminated from our analysis by taking the median value of $PM_{2.5}$ enhancement for each CO bin.

We choose to take a the 10^{th} percentile of a five hour window, based on the size of the region we are trying represent, but we recognize that depending on meteorology, different time windows may be more appropriate. In figure S3, we explore the sensitivity of emissions factors to the time window used to derive regional signal. While we observe some dependence of HDV emissions factors on time window, we note that with the exception of San Rafael in 2009-2011, (1) temporal trends for a given site are unchanged, and (2) the spatial pattern of differences in emissions factors for a given time period are unchanged.

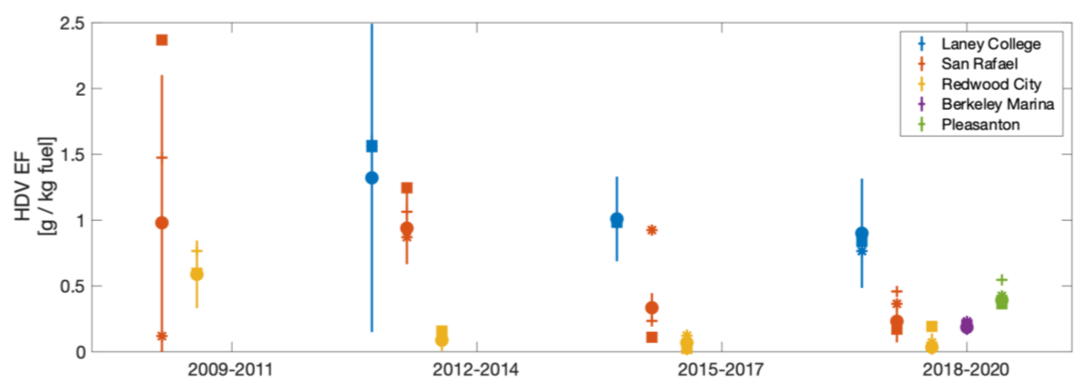


Figure S3: HDV emissions factors derived at each site during each time period, as in Figure 4 of the main text. Colors denote BAAQMD site: yellow denotes San Rafael, purple denotes Redwood City, blue denotes Laney College, and red denotes Berkeley. Each symbol represents a different time window used to derive regional signal: plus denotes one hour, square denotes three hours, circle denotes five hours, and the asterisk denotes seven hours. Error bars denote error calculated for 5 hour window.

Text S4: Dependence of PM and CO enhancement on roadway emissions.
To illustrate the dependence of PM enhancement of HDV traffic and CO enhancement on total traffic, we show differences in truck flow, vehicle flow, PM enhancement, and CO enhancement at 8AM in Redwood City across all time periods in Figure S4. Although there is a large spread in enhancement of both PM and CO, weekend and weekday populations are distinct.

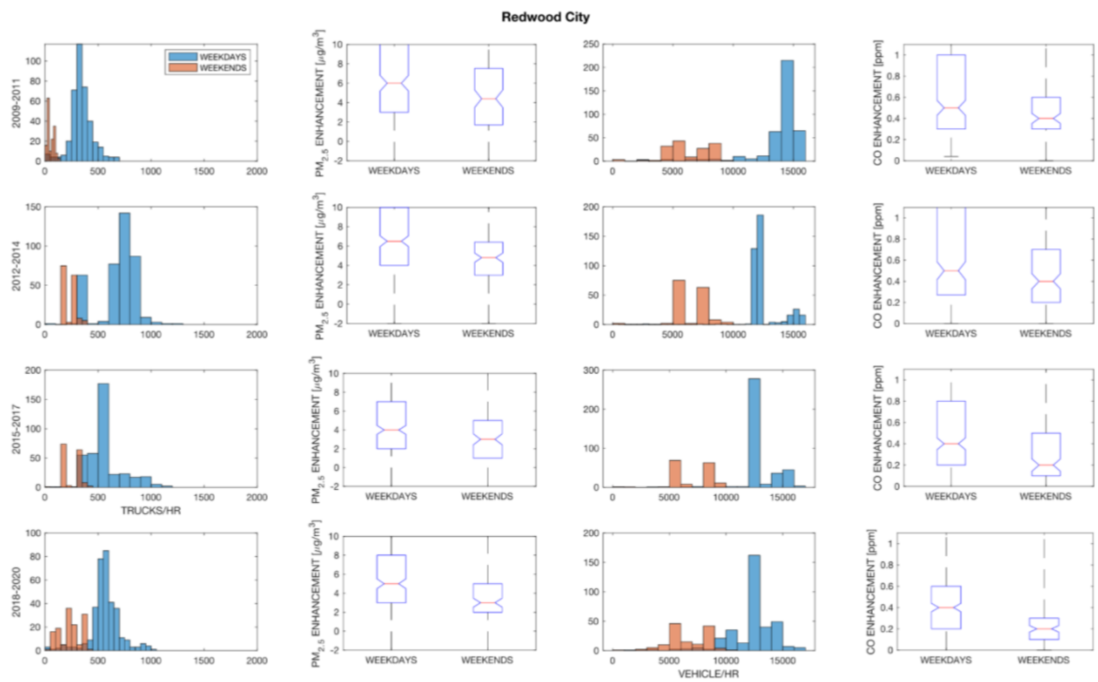


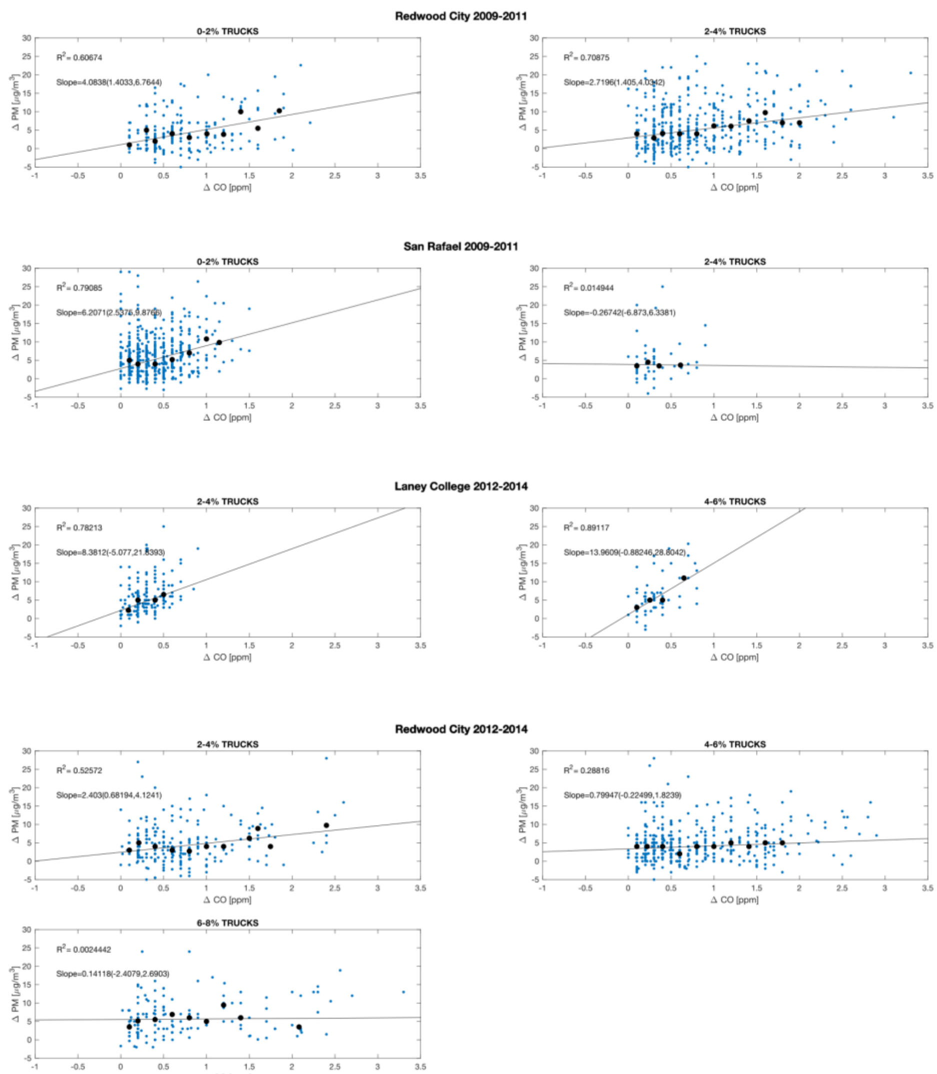
Figure S4: Truck and total flow rates, as well as $PM_{2.5}$ and CO enhancements on weekdays and weekends at 8 AM at RWC site during all time periods considered in this study.

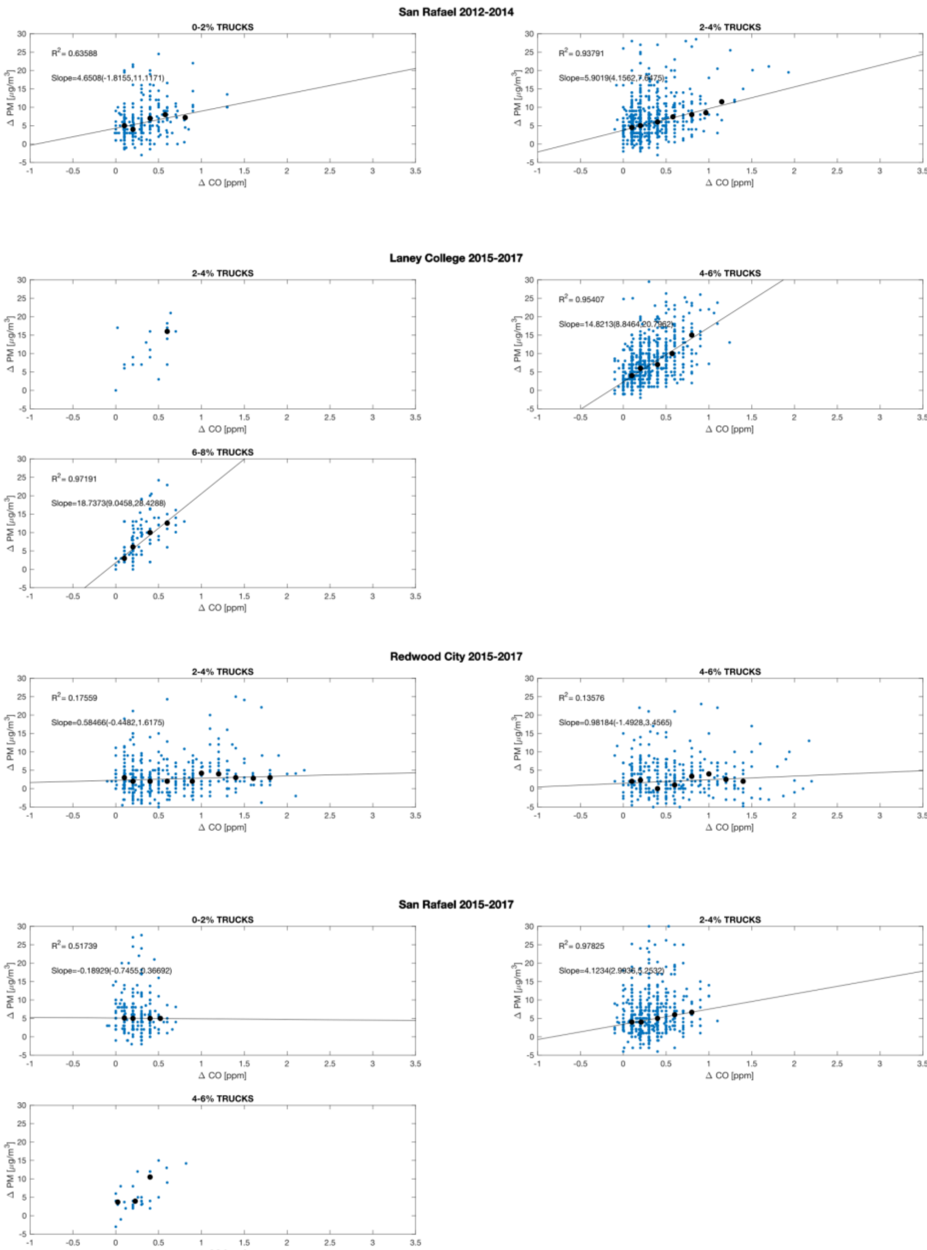
Text S5: Determining Emissions Factors

As described in the main body of the text, we use enhancement in local CO over background as a tracer for $PM_{2.5}$ emitted by HDV on the highway. Although most of the CO comes from LDV, when averaging over the course of an hour, $PM_{2.5}$ emissions from HDV and CO emissions from LDV and HDV can be thought of as originating from the same location and can be thought to have the same, meteorologically dependent dilution from the roadway. Using our knowledge of truck percentage and total flow rate from PeMS and assuming a fleet-wide emissions factor for CO from HDV and LDV, we use enhancement ratios of $PM_{2.5}$ to CO to find HDV emissions factors for $PM_{2.5}$, as described in the main text. Here we detail the process used to find these enhancement ratios.

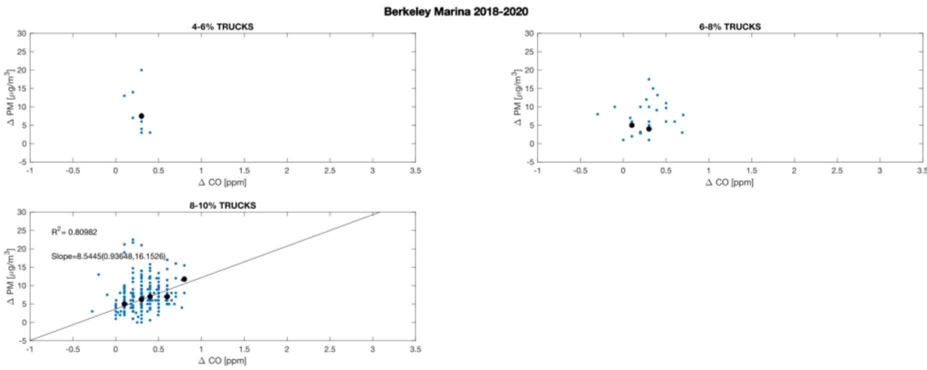
(1) In figure S5, we show median $PM_{2.5}$ enhancement for every CO enhancement for each time period and truck percentage bin. (We insist on 5 data points to find a median.) These median $PM_{2.5}$ enhancements are fit to a line to find the enhancement ratio.

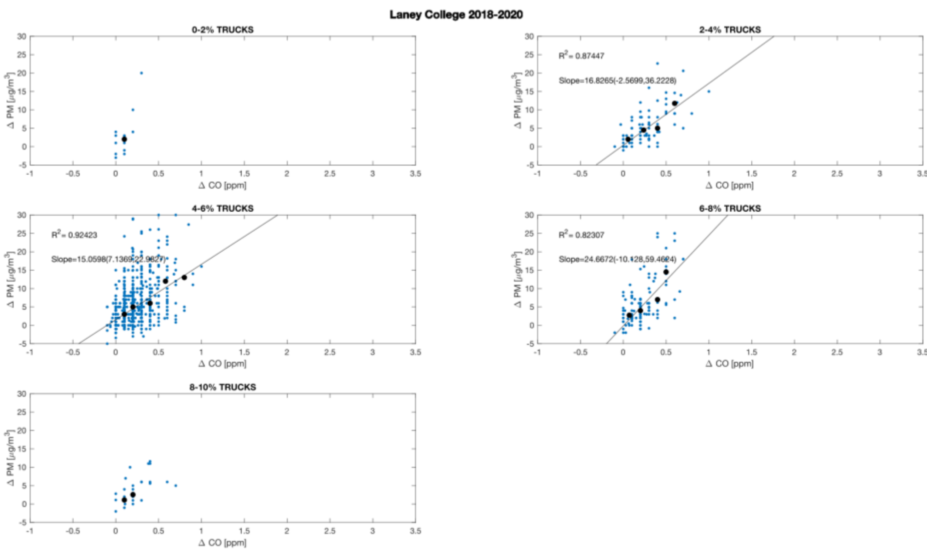
(2) We use the 95[th] percent confidence interval values from the fit and to define uncertainty in the slopes.

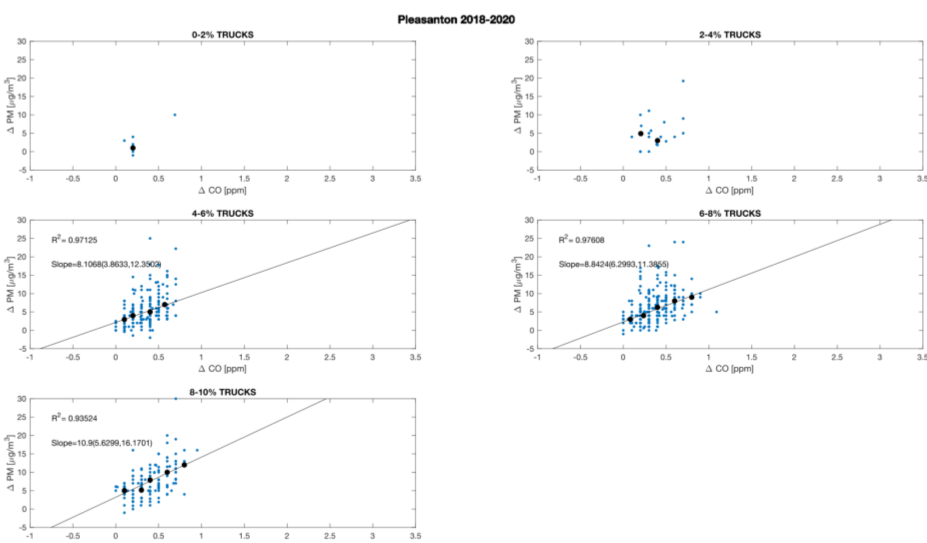




San Rafael 2012-2014
0-2% TRUCKS
R² = 0.63588
Slope=4.6508(-1.8155,11.1171)
2-4% TRUCKS
R² = 0.93791
Slope=5.9019(4.1562,7.6475)
Laney College 2015-2017
2-4% TRUCKS
4-6% TRUCKS
R² = 0.95407
Slope=14.8213(8.8464,20.7962)
6-8% TRUCKS
R² = 0.97191
Slope=18.7373(9.0458,28.4288)
Redwood City 2015-2017
2-4% TRUCKS
R² = 0.17559
Slope=0.58466(-0.4482,1.6175)
4-6% TRUCKS
R² = 0.13576
Slope=0.98184(-1.4928,3.4565)
San Rafael 2015-2017
0-2% TRUCKS
R² = 0.51739
Slope=-0.18929(-0.7455,0.36692)
2-4% TRUCKS
R² = 0.97825
Slope=4.1234(2.9936,5.2532)
4-6% TRUCKS
Δ PM [μg/m³]
Δ CO [ppm]


Berkeley Marina 2018-2020
4-6% TRUCKS
6-8% TRUCKS
8-10% TRUCKS
R^2= 0.80982
Slope=8.5445(0.93648,16.1526)
Δ PM [μg/m^3]
Δ CO [ppm]


Laney College 2018-2020
0-2% TRUCKS
2-4% TRUCKS
R^2= 0.87447
Slope=16.8265(-2.5699,36.2228)
4-6% TRUCKS
R^2= 0.92423
Slope=15.0598(7.1369,22.9827)
6-8% TRUCKS
R^2= 0.82307
Slope=24.6672(-10.128,59.4624)
8-10% TRUCKS
Δ PM [μg/m^3]
Δ CO [ppm]


Pleasanton 2018-2020
0-2% TRUCKS
2-4% TRUCKS
4-6% TRUCKS
R^2= 0.97125
Slope=8.1068(3.8633,12.3502)
6-8% TRUCKS
R^2= 0.97608
Slope=8.8424(6.2993,11.3855)
8-10% TRUCKS
R^2= 0.93524
Slope=10.9(5.6299,16.1701)
Δ PM [μg/m^3]
Δ CO [ppm]

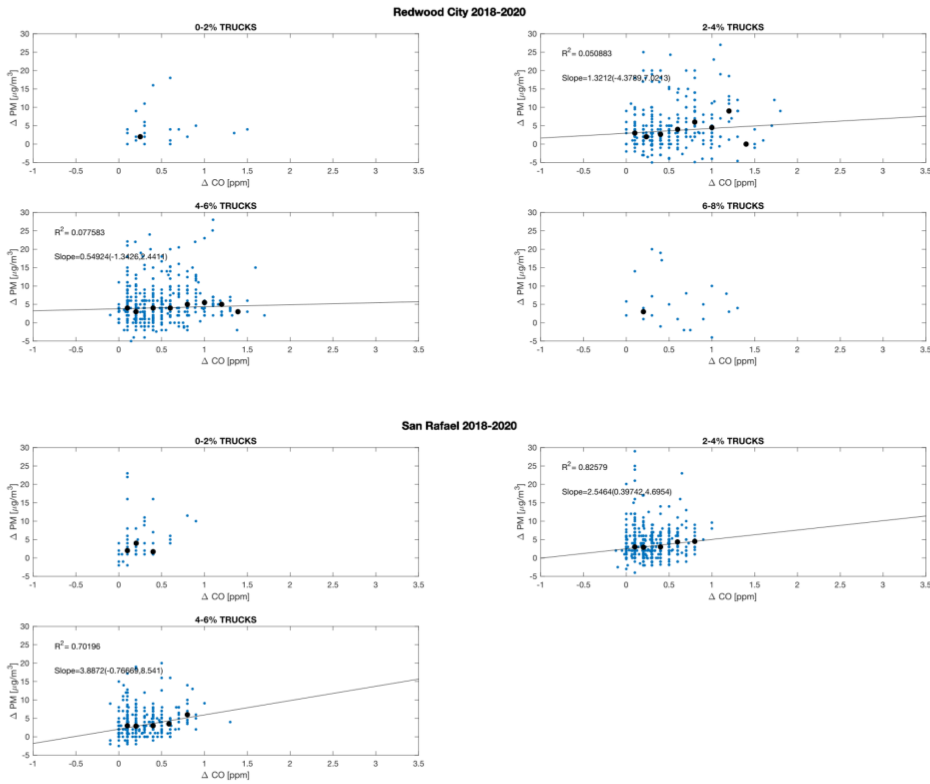


Figure S5: Binned PM enhancements and fits to CO enhancement.

Text S6: Meteorology Used in Modeled PM Enhancement
In the main text, we make estimates of near roadway enhancement, using the continuity equation and gaussian plume dispersion. Here, we show diel cycles of the meteorology used in these calculations. Meteorological variables were taken from ECMWF ERA5.

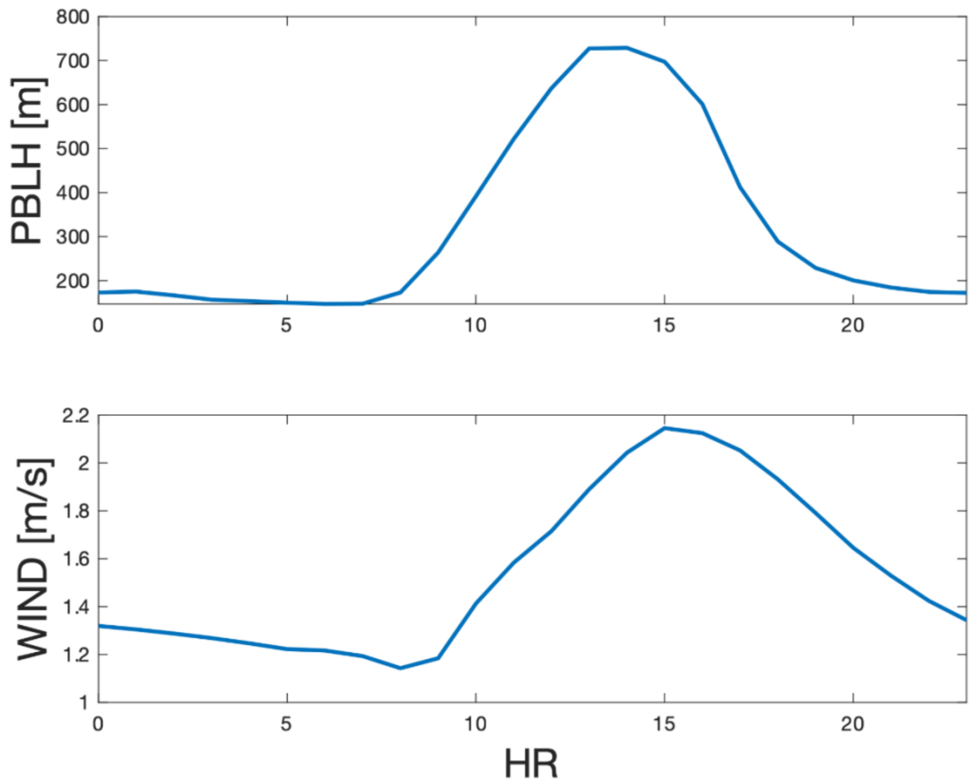


Figure S6: Mean diel cycle for total boundary layer height (top) and wind speed (bottom) in Bay Area during winter and spring. Data averaged across 2009-2018.

Text S7: As described in the text, we model PM enhancement from HDV across the region and as a function of distance from the highway.

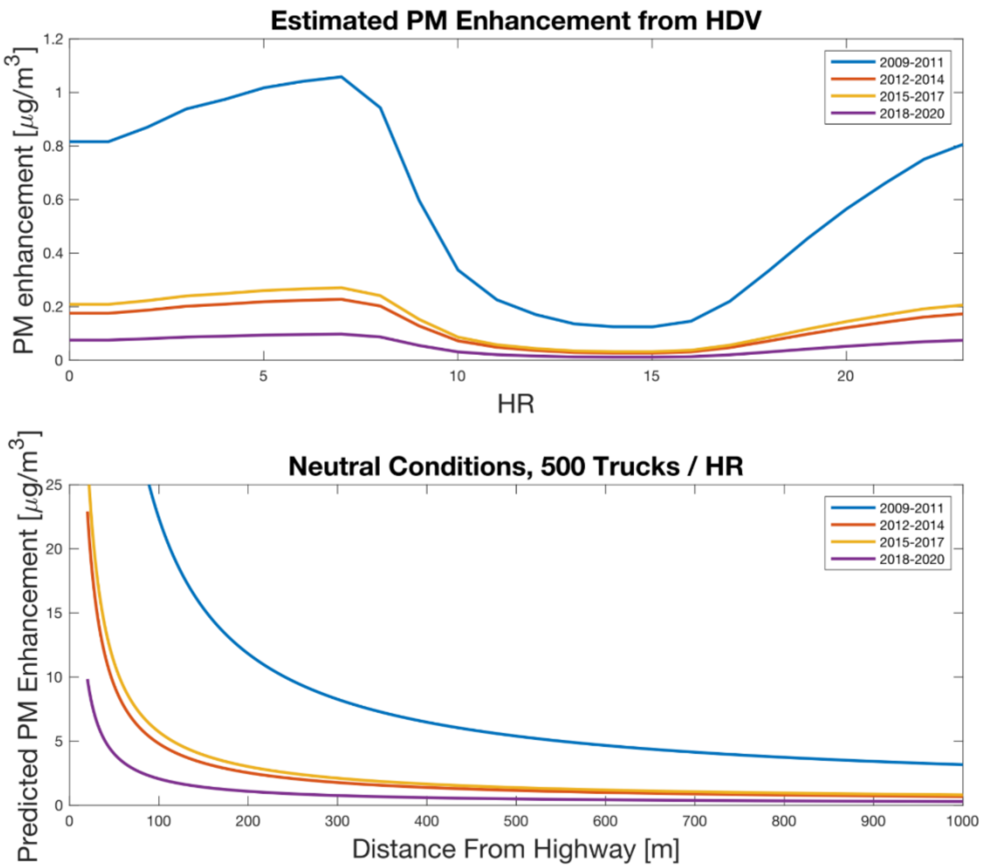


Figure S7: Modeled PM enhancement across Bay Area (top) and as a function of distance from a highway (bottom) during neutral conditions.

Text S8: Laney College is a near-highway BAAQMD site located in a large parking lot. We calculate much larger $EF_{PM(HDV)}$ than for other sites (FigS8, left). We believe that this is due, at least in part, to emissions from the parking lot. Here, we use EMFAC2017 emissions factors for PM and CO for both LDV and HDV, as well as typical 7 am LDV and HDV flow at that site to predict a PM:CO ratio due to highway traffic alone as well as the ratio that is expected from highway traffic plus 650 cars per hour driving into the parking lot at 5mph (FigS8, right). EMFAC2017 predicts $EF_{PM(LDV)}$ to be much higher at very low speeds, resulting in a substantially enhanced PM:CO ratio, that do not match, but are closer to the values measured at this site. This case highlights the need to screen near-highway sites for interfering emissions and the need to assess the role of slow moving LDV for their contribution to primary PM emissions.

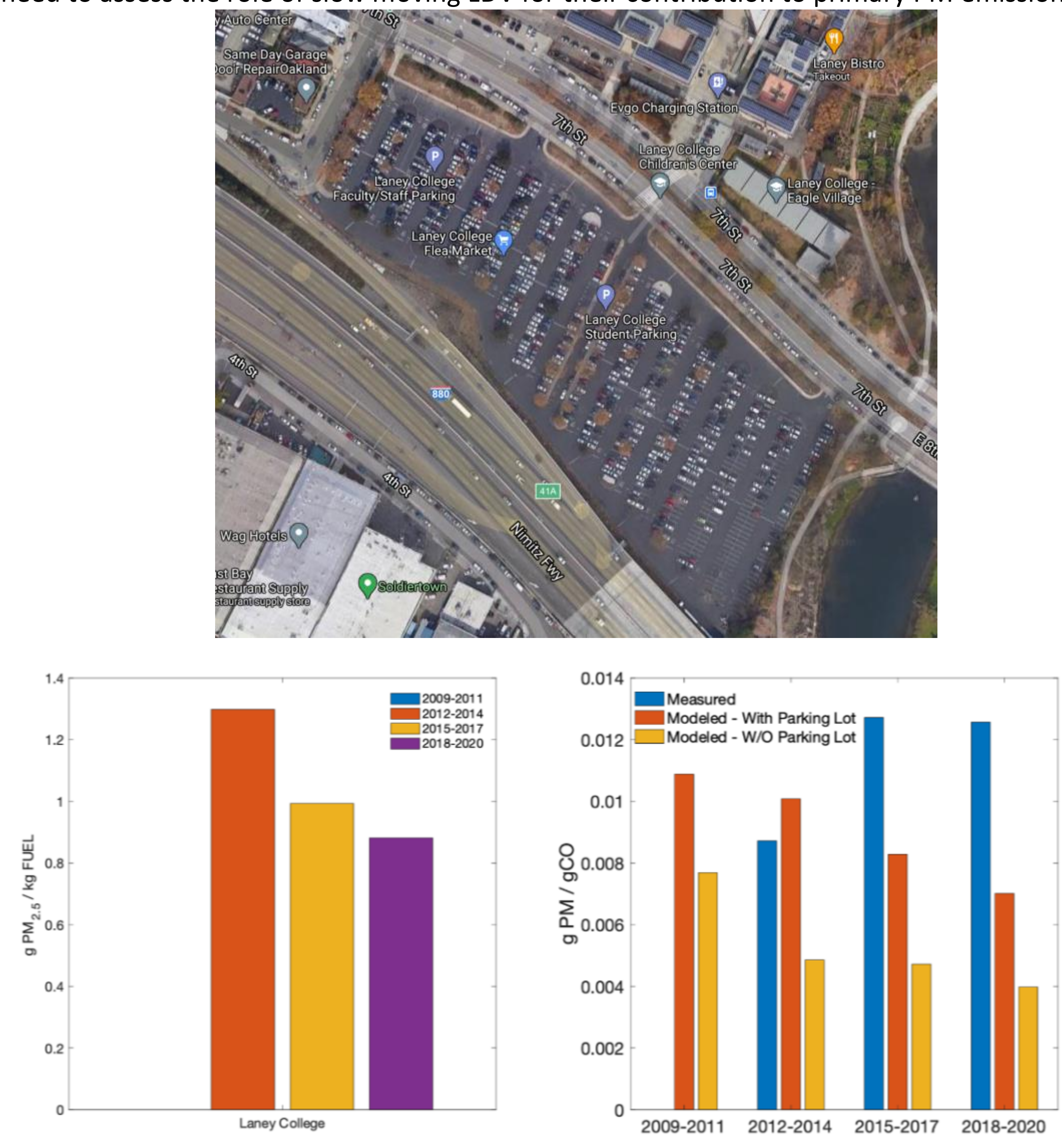


Figure S8: (top) Aerial photo of parking lot in which Laney College AQ sensors located. Image retrieved from google maps (© Google Maps 2021). (bottom left) $EF_{PM(HDV)}$ calculated by applying the procedure described in the text at Laney College. (bottom right) PM:CO ratios at Laney College site that are measured, modeled to include highway emissions only, or modeled to include both highway and parking lot emissions.

Text S9: In the procedure described in the main text, we assume that $EF_{PM(LDV)}$=0 and that all measured PM enhancements are due to HDV. This is a reasonable assumption in the early part of the period considered in our analysis when EF for HDV were measured to be 2-3 orders of magnitude larger than EF for LDV, but it is important to understand the impact of emissions from LDV during later time periods as emissions from HDV have dropped dramatically. We try to characterize $EF_{PM(LDV)}$ in two different ways.

1. We try to find $EF_{PM(LDV)}$, using the intercept of PM:CO ratios for all sites and truck bins during the 2018-2020 time period (Figure S9, right). We find this intercept to be within error of zero: -0.00087 (-0.005,0.004) g PM / g CO.
2. We use the idea that $EF_{PM(HDV)} \geq 0$ to constrain the possible impacts that PM from LDV might have on our results. If we do not assume that $EF_{PM(LDV)}$=0, our equation for calculating $EF_{PM(HDV)}$ becomes
   $EF_{PM(HDV)} = \gamma \frac{t \cdot EF_{CO,fleet} \cdot \frac{fuel\ fleet}{fuel\ HDV} - EF_{PM(LDV)}(1-t)}{t}$. (Equation S1)
   Applying Equation S1, and requiring $EF_{PM(HDV)} \geq 0$, we find that for highway driving, $EF_{PM(LDV)}$ should be less than 0.002 g PM / kg fuel in the 2018-2020 time period. Using the value of 0.002 for $EF_{PM(LDV)}$, Equation S1 in our analysis does little to change our final results (Figure S9, right).

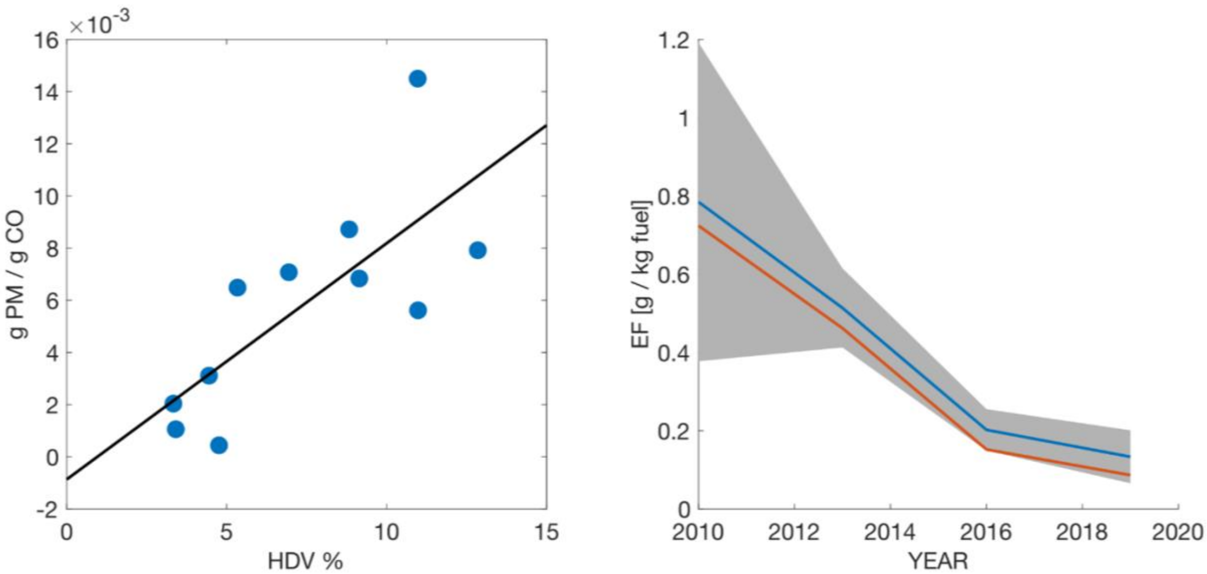


Figure S9: (Left) PM:CO ratio calculated from slope from for all HDV % bins and for BM, PL, RWC, SR during the 2018-2020 period. (Right) Trend in $EF_{PM(HDV)}$ for RWC and SR (as shown in Figure 1). The blue line indicates values calculated setting $EF_{PM(LDV)}$=0, while the orange line indicates values calculated using $EF_{PM(LDV)}$= 0.002 g PM / kg fuel.

References:

Kwon, Jaimyoung, Pravin Varaiya, and Alexander Skabardonis. "Estimation of truck traffic volume from single loop detectors with lane-to-lane speed correlation." *Transportation Research Record* 1856.1 (2003): 106-117.

Shusterman, A. A., Kim, J., Lieschke, K. J., Newman, C., Wooldridge, P. J., & Cohen, R. C. (2018). Observing local CO2 sources using low-cost, near-surface urban monitors. *Atmos. Chem. Phys*, *18*, 13773-13785.