Eastern Research Group, Inc.

Remote Sensing Measurements of Light-Duty Vehicle Emissions at Multiple California Locations

Draft Report

Version 5

Prepared for:

California Air Resources Board

April 11, 2024

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Alan Stanard
Sandeep Kishan
Eastern Research Group

In Cooperation with:
Denver University
Opus Group

Prepared for the California Air Resources Board

Disclaimer

Acknowledgment

ERG would like to acknowledge Dr. Gary Bishop of Denver University and Niranjan Vescio and his team at Opus Inspection for their work in safely and successfully completing remote sensing device (RSD) deployments across California during this project.

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This Report was submitted in fulfillment of Project 20RD001, Remote Sensing Measurements of Light-Duty Vehicle Emissions at Multiple California Locations, by ERG under the sponsorship of the California Air Resources Board.

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Abstract

Remote sensing devices (RSD) were used to measure and analyze the pollutant emissions from on-road vehicles as a part of the long-term efforts of the California Air Resources Board (CARB) to understand air pollution sources and help improve air quality across California. This study involved conducting RSD campaigns, each approximately one week in duration, in 8 California cities. ERG partnered with Denver University (DU), whose staff conducted the RSD measurements at 3 of the sites, and Opus Inspection, who conducted the RSD measurements at the remaining 5 sites. One additional campaign was previously conducted by DU, and this data was provided in cooperation by the Coordinating Research Council (CRC), which funded that campaign.

In addition to adding to CARB's existing body of RSD data for general emission quantification purposes, the project had the key goals of identifying emissions trends and electric-vehicle prevalence in socioeconomically disadvantaged communities (DACs), extending the long-running emissions measurements at DU's West Los Angeles site, evaluating the emissions of cross-border vehicles operating in Southern California, evaluating heavy-duty vehicle (HDV) emissions, and evaluating the emissions trends of vehicles registered in the different Smog Check program areas. Measurement results indicated that light-duty vehicles (LDVs) registered in DACss did tend to have elevated emissions compared to the vehicle registered in non-DACs, even when accounting for model year differences. Electric vehicles were also observed to be less prevalent in the fleet of vehicles registered in disadvantaged communities. At the West Los Angeles RSD site, the average nitric oxide (NO) emission rates continued to decline, while the average carbon monoxide (CO) and hydrocarbon (HC) emission rates increased from their levels measured during the previous 2018 campaign. Vehicles registered in Mexico did tend to have higher emission rates than vehicles registered in California even though their model years tended to be similar. The findings of the Smog Check program indicated that overall, vehicles registered in the Enhanced areas of the Smog Check program emit at lower rates than vehicles registered in the Change of Ownership area.

Executive Summary

Background

This research project was conducted to continue and expand the long-term efforts of the California Air Resources Board (CARB) to measure and analyze the pollutant emissions from on-road vehicles using remote sensing devices (RSD). CARB has been setting and tightening emissions standards for California vehicles since 1990 and RSD measurement can track the effectiveness of these standards over time. In this work, measurement campaigns took place at sites in 9 California cities, including one campaign funded by Coordinating Research Council (CRC), who cooperatively shared the resulting data. Each RSD campaign was conducted by either Denver University (DU) or Opus Inspection. This work was motivated, in part, by CARB's legislated directives to improve the air quality in socioeconomically disadvantaged communities (DACs). Senate Bill 535 (SB535, 2012) requires funding for air quality improvement projects in DACs. More recently, the CARB Board selected specific communities to develop and implement local community emissions reduction plans pursuant to Assembly Bill 617 (AB617, 2017) across various air districts. The project provided an evaluation of the Smog Check program, which requires an emissions inspection every two years for most vehicles except those registered in less populous areas, which are only inspected at a change of ownership. In this work, weeklong RSD campaigns were conducted in Bakersfield, City of Industry, El Centro, Fresno, Oakland, Riverside, San Ysidro, Stockton, and West Los Angeles. Most RSD sites were near or within DAC and AB617 communities.

Objectives and Methods

This project had six key objectives to be addressed by RSD measurement. The first was evaluating trends in emission rates for light-duty vehicles (LDVs) registered in DACs and evaluating the prevalence of electric vehicles registered in those communities. Additionally, this work extended the long-term emissions trends at the West LA site where DU has been making periodic measurements for two decades, evaluated cross-border vehicle emission rates in Southern California, and quantified heavy-duty vehicle (HDV) emission rates. A subset of this work was performed for the Bureau of Automotive Repair (BAR) to evaluate Smog Check Program attributes, including investigating emissions trends across vehicles registered in different program areas and understanding emissions trends in vehicles throughout the registration cycle.

The RSD measurement functions by measuring the level of attenuation of emitted light at various wavelengths corresponding to the absorbance of different exhaust pollutants and estimate's the ratio of emitted pollutants' mass to emitted carbon dioxide (CO_2) mass. Measurements are made of each passing vehicle by a half-second snapshot of its exhaust plume. The RSD campaigns varied in number of measurements from less than 9,000 to greater than 50,000.

Results

The RSD campaigns measured increased emission rates from vehicles registered in DACs or AB617 communities compared to all other vehicles. Figure ES-1 presents the average LDV emission rates for hydrocarbon (HC), nitric oxide (NO), and carbon monoxide (CO) for non-DAC, DAC and AB617 for the City of Industry campaign (shown as an example as it had the largest number of measurements). Error bars indicate 95% confidence intervals. The AB617 vehicles tend to have significantly higher emission rates than the other communities' vehicles.

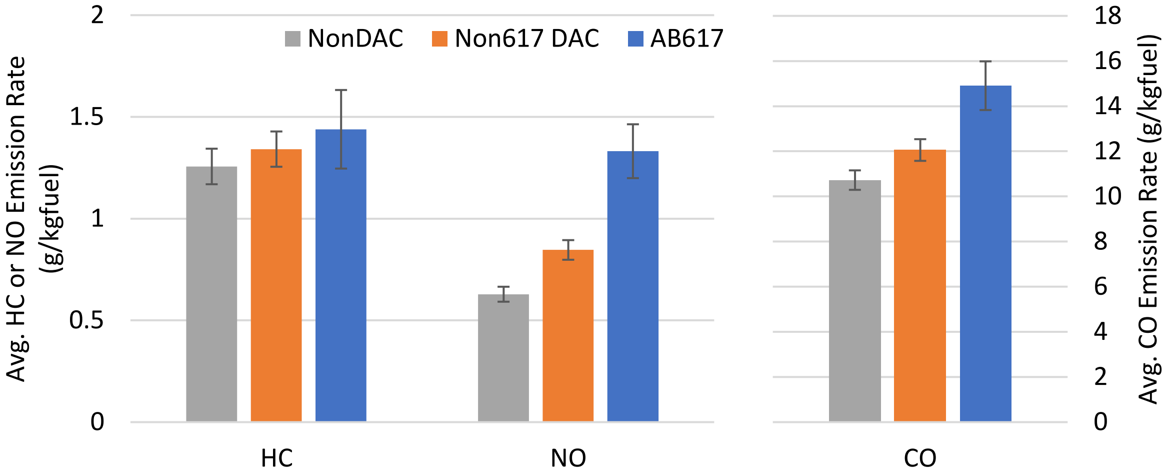

Figure ES-1. The average LDV emission rates for non-DAC, DAC, and AB617 community status for HC, NO, and CO at City of Industry

Figure ES-2 presents the prevalence of different observed fuel types for non-DAC and DAC registered vehicles. The electric vehicle fraction (normalized with each campaign weighted equally) is 1% for non-DAC and 0.3% for DAC.

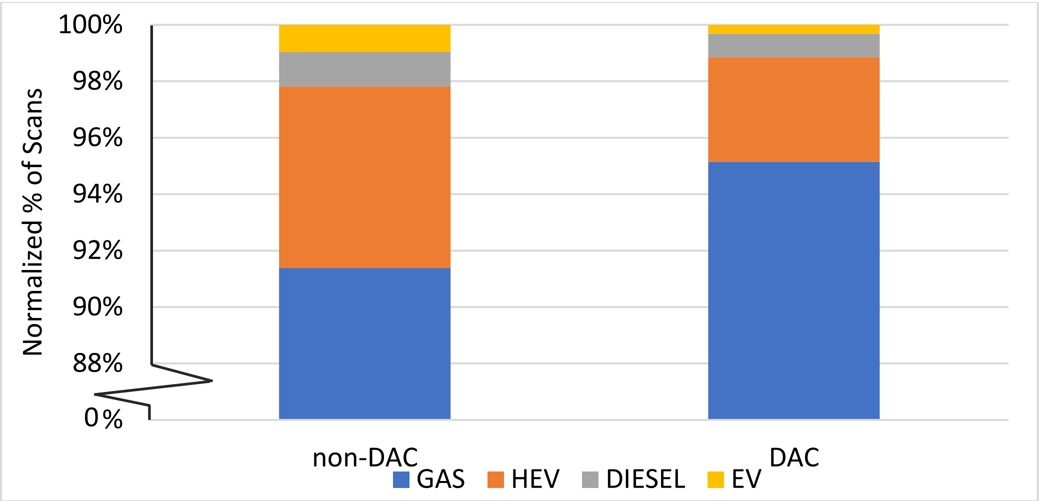

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Figure ES-3 presents the overall average emission rates of HC, NO, and CO for each campaign that DU has conducted at the West Los Angeles site at La Brea Ave., with the most recent data point from this project. Note the average NO is continuing to decline while the HC and CO are no longer decreasing; average HC has been increasing in the most recent two campaigns.

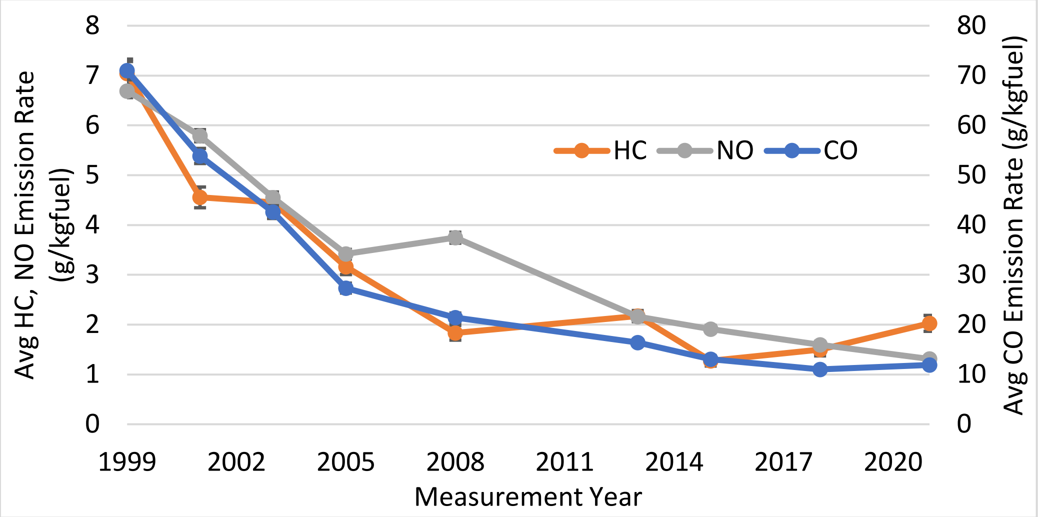

Figure ES-3. The overall-average emission rates of HC, NO, and CO at each West Los Angeles campaign conducted by DU.

Figure ES-4 presents the emission rate comparison between California-registered and Mexico-registered vehicles operating at the two border campaigns. While the model year distributions tended to be very similar for the two fleets of vehicles, the NO and CO emission rates were significantly higher for the Mexico-registered vehicles.

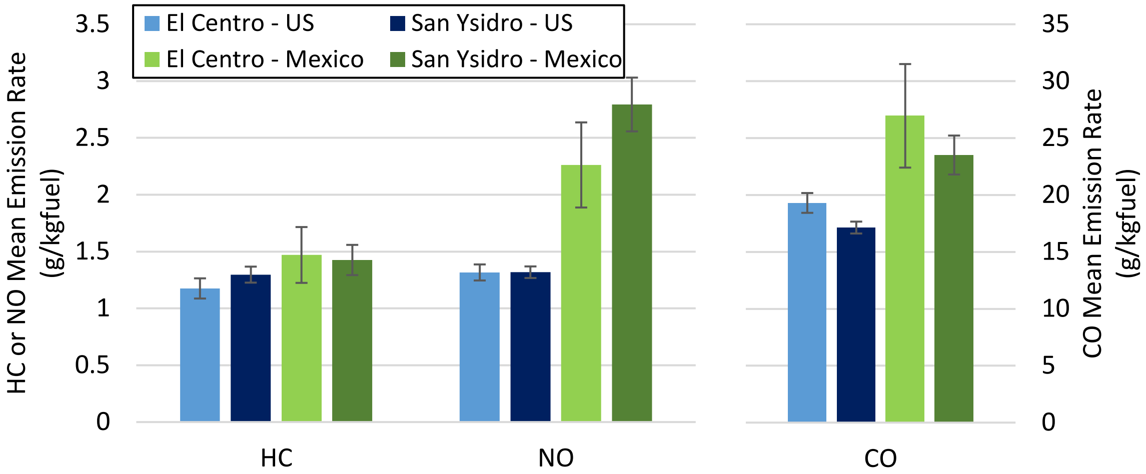

Figure ES-4. The average emission rates for the CA and Mexican fleets of vehicles at each border site. Error bars represent 95% confidence intervals.

HDVs were more challenging to measure by RSD than LDVs, largely because many of the higher-weight trucks use updraft exhausts that were not seen by the RSD setup in this work. Figure ES-5 presents the average HDV emission rate by model year bin and truck class for all fuel types observed at the City of Industry campaign. City of Industry is shown as it had the largest number of valid HDV measurements.

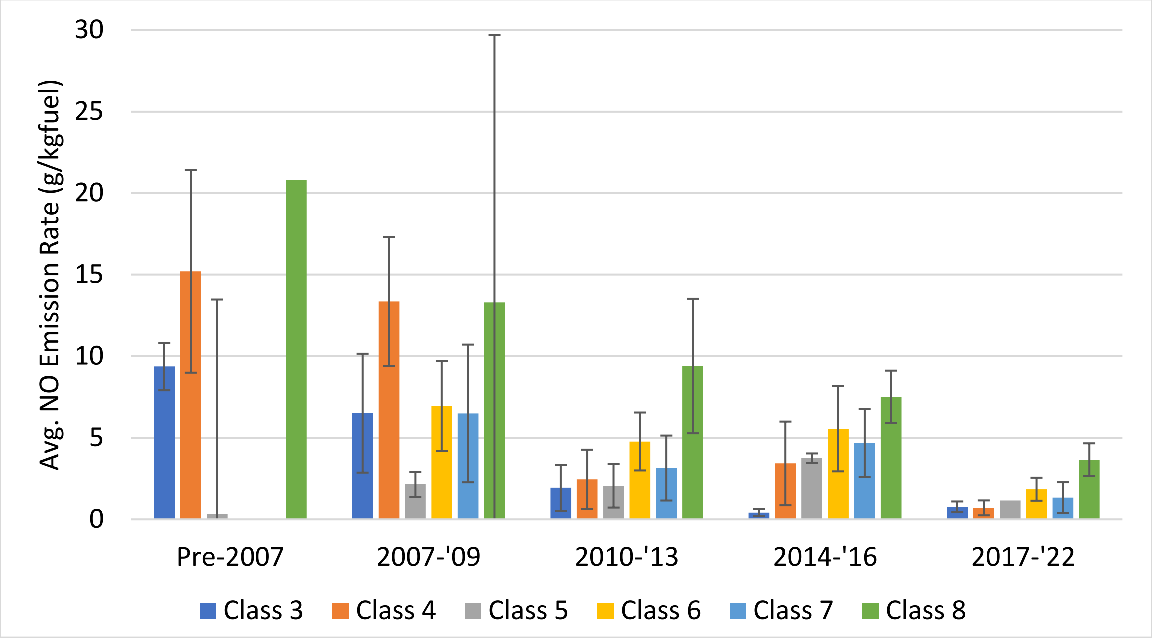

Figure ES-5. The average HDV emission rate for HDVs of each class across model year bins at the City of Industry campaign.

Figure ES-6 presents the average NO emission rate of vehicles registered in the Smog Check change of ownership (COO) area as compared to the more stringent Enhanced area, as observed at the El Centro campaign. El Centro is presented here as that campaign had the greatest number of COO-registered vehicles (which were not frequently seen at the other campaign sites).

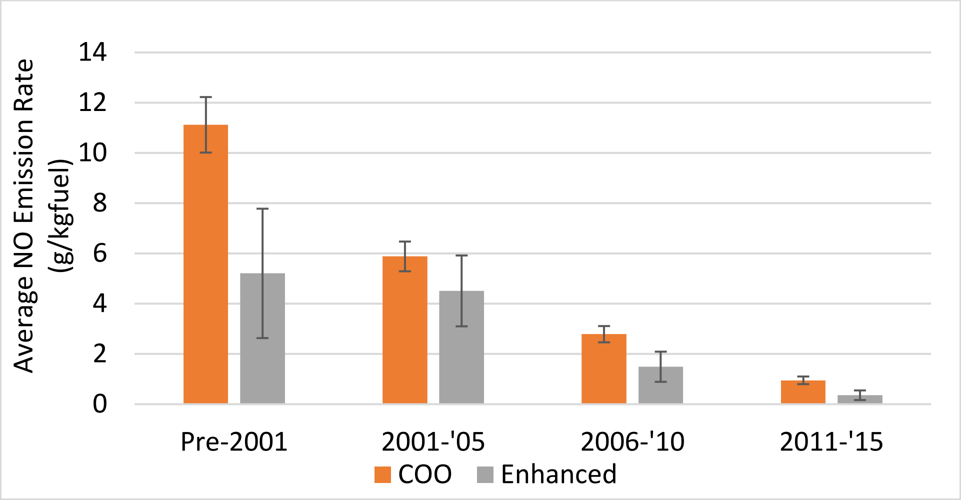

Figure ES-6. The average NO emission rates for LDVs registered within the Enhanced Smog Check area as compared to the COO area at the El Centro campaign.

Conclusions

This project used RSD measurement to investigate six analysis topics relevant to CARB's goal of quantifying and reducing mobile source air pollutants.

- Compared to non-DAC vehicles, the emission rates of vehicles registered in DACs can range up to 50% higher depending on pollutant and community type. DACs do tend to have older vehicles, but their emissions are elevated even when accounting for model year differences. ERG estimated the contribution of the model year shift to be 30 to 48 percent of the emission rate difference depending on pollutant.
- ERG also analyzed the prevalence of EVs registered in DAC and non-DAC areas and evaluated their impact to the fleet emissions by community. EVs were much less prevalent in DACs, for which LDVs tended to be more than 95% gasoline-powered non-hybrid vehicles. At less than 0.5% of the vehicle population, EVs had a minimal effect on reducing DAC fleet emissions.
- DU has been making periodic measurements of the La Brea Ave. site in West Los Angeles for over two decades. This project's West Los Angeles campaign continued the trends observed during the previous campaign, conducted in 2018. On an overall basis, average readings for NO continue to trend downward, while CO is relatively unchanged, and HC has trended slightly upwards.
- In the comparison between California-registered and Mexico-registered LDVs operating at the two border campaigns, the Mexican vehicles tended to have higher emissions, and this difference was statistically significant for NO and CO. Based on overall averages, the vehicles from Mexico averaged 18% higher for HC, 38% higher for CO, and 92% higher for NO.
- RSD campaigns in this project included provision to measure HDV emissions where possible. However, these measurements were made for only downdraft-exhaust trucks, limiting the quantity of vehicles available for measurement. Despite the relatively few valid measurements of HDVs, the resulting emissions trends did fit with expectations; lighter trucks and newer model years tended to have the lowest emissions. Diesel-powered trucks tended to have higher emission rates than either their gasoline-(prevalent in the lighter truck classes) or natural gas-(prevalent for the heavier truck classes) powered counterparts.
- The RSD data was used to investigate various aspects of the Smog Check program and its effectiveness. However, many analyses were statistically inconclusive.
  - Emission rates of CO and NO were significantly higher for vehicles registered in COO areas (where inspections are only required on ownership change), as compared to the areas requiring biennial emissions tests. It is worth noting that this finding was confounded by the high prevalence of DACs in the COO areas; it was not possible to determine whether the effect was due to the Smog Check program or the DAC effect.
  - ERG analyzed the data to determine if any Smog Check stations issued passing results to vehicles that were later found to have elevated emissions; it was not possible to conclusively indicate any stations with suspect results.
  - The RSD data indicated that vehicles from the COO areas tend to diverge from biennial vehicles in emission rates at about 8 years of vehicle age, indicating the emissions

impact of exempting vehicles newer than 8 years old from Smog Check requirements is likely, though not provably, minimal.

Main Report

Introduction

This research project was conducted to continue and expand on the long-term efforts of the California Air Resources Board (CARB) to measure and analyze the pollutant emissions from on-road vehicles using remote sensing devices (RSD). This project involved continued measurements at long-standing RSD sites as well as making measurements at new sites. This study involved conducting RSD campaigns, each approximately one week in duration, in 8 California cities. Additionally, the Coordinating Research Council (CRC) provided RSD data from a similar 1-week campaign that it funded in Fresno, CA.[1] A subset of this work was performed for the Bureau of Automotive Repair (BAR) to investigate emissions trends associated with the Smog Check Program.

RSD measurement functions by measuring the level of attenuation of emitted light at various wavelengths corresponding to the absorbance of different exhaust pollutants.[2,3,4] The light source and detector units are positioned on opposite sides of a single lane road such that the emitted light passes through the exhaust plume of passing vehicles. The system measures the ratios of various exhaust pollutants to carbon dioxide (CO_2), which can be used to calculate the ratio of emitted mass of various pollutants to emitted CO_2 mass.

In this work, ERG partnered with Denver University (DU) and Opus Inspection for the execution of the RSD measurement campaigns. DU has been conducting RSD measurements in California and other states since the 1990s using their Fuel Efficiency Automobile Test (FEAT) device, developed and patented by Dr. Stedman and Dr. Bishop.[5] The Opus team also has decades of RSD experience with their RSD devices after acquiring Envirotest, and their equipment uses the same principle of operation to FEAT.[6,7]

California has experienced dramatic increases in air quality over the past few decades, with decreases in measured ozone levels across the state. Despite these improvements, more than half of Californians reside in areas that exceed the most stringent 0.07 parts per million (ppm), ozone standard, established by EPA in 2015.[8,9] Nineteen areas in California are not in attainment of that standard, and these nonattainment areas include over 99 percent of California's socioeconomically disadvantaged communities (DACs).

This work was motivated, in part, by CARB's legislated directives to continue to improve the air quality in DACs. Senate Bill 535, passed in 2012, includes the requirement for minimum funding levels for climate investments aimed at improving public health, quality of life, and economic opportunity in DACs.[10,11] This resulted in the development of the California Environmental Health Screening Tool (CalEnviroScreen, or CES), which models various pollutant, health, and economic factors to geographically assign a CES score to every census tract in the state, indicating prevalence of exposure or vulnerability to pollution-linked health issues.[12] Under SB 535, CalEPA is charged with designating DACs in California and utilizes the CES in doing so. More recently, the CARB Board selected specific communities to develop and implement local community emissions reduction plans pursuant to Assembly Bill 617 (2017) across various air districts and there is a need to track the effectiveness of actions and strategies in these plans in improving air quality in these communities.[13] Figure 1 depicts the AB-617 communities at the time of this report; it is expected that more communities will be added in the future. Where possible, RSD measurements made in this work may inform these legislated priorities for CARB.

Figure 1. The AB-617 communities, with surrounding air districts shaded in blue.[14]

The RSD campaigns conducted in this work, in addition to expanding CARB's emission quantification, have specific analysis opportunities based on their location. The key research topics addressed by RSD in this work were:

Emission rate disparities in Disadvantaged Communities. A priority of CARB is to investigate the air quality disparities across communities of varying socioeconomic status (SES). In this work, CalEnviroScreen was used to assign a SES level to each vehicle and to determine whether the address of registration was within a DAC. From matching a measured vehicle's license plate to its address of registration, CARB was able to look up and provide ERG a CES percentile, DAC status, and AB 617 status (registered in an AB 617 community or not) for each vehicle. The analyses in this report include various approaches to quantifying differences in emission rates across California communities.

Continue the long-term measurement campaign at the West Los Angeles (LA) location. DU has been conducting measurements at the onramp to I-10 from La Brea Avenue since the 1990s.[15,16,17,18] One goal of this work was to continue populating this long-term dataset with measurements from a new campaign.

Evaluate emissions of cross-border traffic. RSD from campaigns near the U.S. – Mexico border was used to determine emissions trends between California-and Mexico-registered vehicles.

Evaluate electric vehicle (EV) fleet penetration in DACs. The RSD data was used to determine prevalence of EVs across communities of varying SES levels and evaluate their impact on fleet emissions at community level.

Heavy-duty vehicle (HDV) profiles. RSD measurements were analyzed for the presence of HDVs and emissions measurements from each campaign were compared and contrasted for observable trends. HDVs in this work consisted of vehicles registered as class 3 and above (the registration did not include the information necessary to separate classes 2a and 2b).

Observations of the Smog Check program attributes. The RSD data was used in concert with records from the Smog Check inspection program to determine observable trends. ERG investigated whether emissions effects were observable in vehicles before and after their inspection date as well as whether any trends in individual inspection stations could be identified.

This report presents the measurements, results, and analysis from RSD campaigns at the locations presented in Table 1. The analysis goals of each measurement site are also included in the table.

Table 1. RSD Campaign Locations and their measurement contractor and specific site analysis goals.

Campaign Location	Subcontractor	Analysis Purposes
Stockton	DU	DAC analyses, HDV profiles, Evaluate Smog Check
West LA	DU	Extend measurements made since ~1999, DAC analyses, HDV profiles, Evaluate Smog Check
Bakersfield	Opus	DAC analyses, HDV profiles, Evaluate Smog Check
Oakland	DU	DAC analyses, HDV profiles, Evaluate Smog Check
San Ysidro	Opus	Evaluate border crossing, DAC analyses, HDV profiles, Evaluate Smog Check
El Centro	Opus	Evaluate border crossing, DAC analyses, HDV profiles, Evaluate Smog Check
Diamond Bar	Opus	DAC analyses, HDV profiles, Evaluate Smog Check
Riverside	Opus	DAC analyses, HDV profiles, Evaluate Smog Check
Fresno[a]	DU	DAC analyses, Evaluate Smog Check

[a] – This campaign was funded under CRC Project RW-117, and data was provided by CRC in cooperation for further analysis in this work.

Materials and Methods

RSD Measurement Methods

The RSD instruments used in this study operate on the principle of measuring the level of light attenuation at various wavelengths that correspond with the absorbance range of different pollutants in engine exhaust. RSD instruments consist of a non-dispersive infrared (NDIR) component for detecting carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbon (HC)[19] and may be equipped with twin-dispersive ultraviolet (UV) spectrometers (0.26 nm/diode resolution) for measuring oxides of nitrogen (NO and NO_2), sulfur dioxide (SO_2) and ammonia (NH_3)[20],[21]. Collinear beams of infrared (IR) and UV light are passed across the roadway into the IR detection unit then focused through a dichroic beam splitter, which separates the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC and a reference. The UV light is then reflected from the surface of the dichroic beam splitter and focused onto the end of a quartz fiber bundle mounted to a coaxial connector on the side of the detector unit. A picture of a typical RSD roadside measurement is presented in Figure 2.

Figure 2. An Opus roadside RSD unit set up on a highway onramp.

RSD has been used to measure pollutant emission rates in vehicle exhaust for over three decades.[22] Past studies have shown that the remote sensor is capable of measurements that agree with the values reported by an on-board gas analyzer to within ±5% for CO and ±15% for HC.[23,24] For NO, published literature indicates RSD has a detection limit of 25 ppm, with an accuracy of ±5%.[3] A 1997 study investigated RSD emission rate measurements as compared to measurements made over the IM240 exhaust emissions inspection cycle and found the results to be linearly correlated.[25] A more recent study involved the parallel exhaust measurement by RSD and portable emissions measurement systems (PEMS) and found favorable correlation.[26]

The exhaust plume path length and density of the observed plume are highly variable across vehicle measurements, and depend on the exhaust pipe height, exhaust flowrate, wind, and the vehicle shape.[18] Because of this, the remote sensor only measures ratios of CO, HC, NO, NH_3 or

NO_2 to CO_2. The molar ratios of CO, HC, NO, NH_3 or NO_2 to CO_2 respectively, are constant for a given exhaust plume. This study primarily reports measured emissions as grams/kilogram of fuel (g/kg of fuel). The HC measurement is calibrated with propane, a C_3 hydrocarbon. Based on measurements using flame ionization detection (FID) of gasoline vehicle exhaust, the remote sensor is only half as sensitive to exhaust hydrocarbons on a per carbon atom basis as it is to propane on a per carbon atom basis as demonstrated by Singer et al[27]. To calculate mass emissions, the %HC values reported were first multiplied by 2 to account for these "unseen" hydrocarbons, under the assumption that the fuel used is gasoline.

In addition to emissions measurements, freeze-frame images of the front and rear license plates of each vehicle were taken by cameras and associated with the timestamp of each vehicle's pass. In typical RSD campaigns, only a single camera is used to capture a rear-view image of each passing vehicle. However, in this work, front and rear cameras were used in each campaign to increase the likelihood of successful recording of HDV plates. The rear license plates of HDVs are often obscured from successful recording by the presence of a trailer in tow or vehicle features related to its vocation; this was addressed by an additional front camera for use in helping identify HDVs.

The speed and acceleration of each vehicle was measured by a pair of infrared emitters and detectors generating two parallel infrared beams passing across the road.[18] The beams are six feet apart and mounted just above the roadway. Vehicle speed was calculated from the time that passes between the front of the vehicle blocking the first and the second beam, and the acceleration was estimated by the difference in that speed and a second speed calculated by the rear of the vehicle unblocking the first and the second beams.

After the time of measurement, the RSD software system evaluates the measurement for validity, both for the emission measurement and the speed/acceleration measurement. In the event that there is a large amount of noise in a given pollutant's ratio to CO_2 throughout the measurement interval, the system automatically flags the measurement of that channel to be invalid. Likewise, if the speed is zero or negative, or the acceleration value is unreasonable, the speed/accel would be marked as invalid by the system. This occurs automatically and immediately at the time of each vehicle passing. In this work, if an RSD pass is flagged as invalid by the RSD processing software, the pass is left in the dataset for vehicle counts. If the pass is invalid for speed or acceleration measurement, all emission values are removed and not considered in any further analyses. If the pass is invalid for a certain pollutant measurement only, the emission measurement for that pollutant is removed but all other pollutants for that pass remain.

In general, the operation of the two contractors' RSD systems was very similar during this work. However, there were minor differences in operation, notably the manner by which they handled measurement of heavy-duty vehicles, especially as relates to high-stack (i.e. exits near the top rear of the cab) or downdraft (i.e. exits at the truck's frame level pointed down toward the pavement) exhaust outlets:

- For DU, only heavy-duty trucks with valid emission measurements were tag-edited (i.e. their license plate photos were transcribed into the dataset). As a result, all high-stack exhaust passes and any invalid downdraft trucks were excluded from the dataset. All RSD measurements were triggered at the conclusion of each beam block (i.e. unblocking). One RSD unit was used, and scans were matched to data from two cameras: one capturing vehicles' rear license plates, and another capturing front plates.
- Opus used a different signal to trigger a measurement for the front and rear license plate reader systems. Opus used two RSD units to make measurements. The rear system, which was used primarily for light-duty vehicles (LDVs), used the beam unblocking to initiate the measurement just as was done by DU. Their front plate measurement system was used primarily for HDVs, and measurements were triggered by an elevated reading of CO_2 instead of beam unblocking. This approach was chosen due to the more frequent interruption of the light beam by HDV components such as additional tires/axles, mudflaps, trailer chains, or other truck components. These can confound the successful time alignment of the time of measurement with the exhaust plume. In the case of HDVs with downdraft exhausts for the front camera, a much higher percentage of measurements were marked as invalid as compared to LDVs, and this is likely due to these components frequently interrupting the light beam during the measurement interval, obscuring successful measurement. Also, as a result of this approach, high-stack trucks were not logged by the front LPR system and were generally not identifiable in the beam-block trigger for the rear camera.

RSD Campaigns

ERG's subcontractors executed 8 RSD campaigns during this work, and CRC provided the measurements from another similarly conducted campaign. At the onset of the project, CARB provided the cities and/or regions of interest for each campaign, and ERG assigned either DU or Opus to each, depending on staff availability. Most of the cities and/or regions selected by CARB were within or near DAC and/or AB617 communities. Figure 3 presents a map of California including the locations of the RSD campaigns presented in this work.

Figure 3. A map of California presenting the 9 campaign regions in this work.

For each region, the assigned subcontractor generated a list of potential sites to conduct measurements. Daily traffic volumes at each site were estimated, either by using Caltrans Performance Measurement System (PeMS)[28] or by visiting in person and conducting timed traffic counts. The candidate sites were presented to the CARB Project Advisory Committee by teleconference, and the committee selected the preferred location(s) for sampling. In most cases, a single location for each region was selected, however, for some sites, the campaign was divided roughly equally in time between measurements at two different sites. Sites were also surveyed for any possible future construction activities that could interfere with the measurement campaigns.

Based on CARB's requirements and the experience of Gary Bishop of DU and Niranjan Vescio of Opus Inspection, the project team developed the following key considerations and priorities for site selection as follows:

- Single lane locations with ample room on each shoulder to safely locate the instrumentation and the support vehicle
- Sites where vehicles would generally be accelerating or driving at a steady speed uphill with a positive load on the engine, to avoid the highly variable tailpipe emissions that can occur under deceleration

- Sampling locations should have similar driving conditions to the long-standing La Brea site in West LA (used for RSD study since 1999) such as an uphill road grade, speeds from 20 to 30 mph, and minimal effect of control light signals on acceleration
- Unobtrusive positioning of the RSD equipment to avoid motorists braking suddenly
- Absence of cold start vehicle operating conditions that would cause atypically high emissions
- Absence of high engine loads that could result in atypically high emissions
- High traffic volume (i.e., in excess of 5000 vehicles/day between 7 a.m. and 7 p.m.)
- Where possible, sites were chosen so that they are near areas which are likely to get traffic of vehicles registered in DACs (i.e. communities with high CES-scores)

Each RSD campaign was conducted for approximately 1 week including both weekends and weekdays. Measurements were conducted for approximately 8-10 hours per day, with the goal for each campaign being to achieve 25,000 RSD measurements in total.

The sites considered for each region are presented below, with the selected site in bold. Most sites are highway onramps or connecting ramps, with direction indicated by northbound (NB), southbound (SB), etc. All selected sites were within or bordering DACs.

Bakersfield

Six sites were considered for the Bakersfield area:

- NB CA-184 to WB CA-58
- SB CA-184 to EB CA-58
- SB CA-204 to EB CA-178
- **WB CA-178 to SB CA-99**
- WB California Ave to SB CA-58
- EB California Ave to NB CA-58

The WB CA-178 to SB CA-99 cloverleaf interchange was selected for optimal space for equipment setup, traffic counts, and accessibility of lower SES census tracts. The Bakersfield measurement campaign ran from 10/18/21 – 10/29/21.

Diamond Bar/City of Industry

Initially, three candidate sites were selected for the relatively small city of Diamond Bar, but measurements at all sites were likely to be negatively impacted by the presence of ramp metering signals, which would be likely to capture a high percentage of decelerating or off-throttle vehicle operation. So, an additional location in City of Industry was identified for consideration.

- NB Diamond Bar Blvd to WB CA-60
- Fairway Dr to WB CA-60
- SB Fairway Dr to EB CA-60

- **S 7th Ave to WB CA-60**

The S 7th Ave to WB CA-60 onramp in City of Industry was selected for this campaign. This site is relatively near the Diamond Bar area, is likely to include traffic from low SES communities, has relatively high traffic flow, and does not have a metered ramp. The campaign at City of Industry ran from 2/19/23 - 2/22/23 before being interrupted by heavy rain such that Opus paused the campaign. It was restarted and ran from 3/2/23 – 3/4/23.

El Centro/Imperial County

Opus considered five candidate sites in this region extending from El Centro to Calexico:

- EB Heber St/CA-86 to SB CA-111
- NB CA-111 to WB I-8
- SB CA-111 to EB I-8
- **4th Ave/CA-86 to WB I-8**
- **4th Ave/CA-86 to EB I-8**

Because of the uncertainty in traffic counts in this region, two sites were selected for measurements, and approximately half of the campaign was conducted at each. The two onramps from 4th Ave/CA-86 to I-8 in each direction were selected due to proximity to low SES areas and likelihood of higher traffic counts, while still being likely to capture some cross-border vehicles. The measurement location was moved from the WB site to the EB site during the middle of the campaign and traffic volumes were higher at the new site. The El Centro campaign ran from 10/4/22 – 10/14/22.

Fresno

The Fresno site was selected by CRC and DU during CRC project RW-117, and the data from this site was provided for this project by CRC. The Fresno site is located on the cloverleaf interchange from:

- **NB CA-41 to WB CA-180**

Because the Fresno data was collected for a different project, the data is not necessarily equivalent and care should be taken in its further analysis. For example, no front license plate reader was used at the Fresno site, so there will be a different bias in the prevalence of heavy-duty vehicles in that set as trucks with their rear license plates obscured (i.e. from towing) will not be successfully identified for use in analysis. Also, there was no prioritization of counting and/or including electric vehicles (EVs) in that set, so it is likely that EV passes were excluded at the time of sampling and dropped from further analysis. So, in contrast with the other campaigns of this project, the Fresno data should not be used for equivalent heavy-duty or EV and engine-off hybrid-electric vehicle (HEV) analyses. Also, the Fresno campaign was shorter in duration and has lower measurement counts than the other campaigns. The Fresno measurements took place from 6/7/21 – 6/12/21.

Oakland

This region included the following sites from Richmond and Oakland identified by DU:
- Richmond Parkway to WB I-80
- John Muir Pkwy (CA-4) to SB I-80
- 12th Ave to EB I-980
- **27th Street to EB I-980**
- Davis St to NB I-880

The first two sites in Richmond were presented to the project committee, but a preferred candidate was not found due to the uniformly high SES of the area and limited space for safe equipment setup. DU later proposed the other three options in the Oakland area and the project team selected the onramp from 27th Street to EB I-980. The Oakland campaign ran from 3/31/22 – 4/6/22.

Riverside

Two sites were considered for the Riverside area:
- **NB CA-91 to WB CA-60**
- WB Arlington Ave to NB CA-91

The NB CA-91 to WB CA-60 cloverleaf interchange was selected due to its high traffic flow, optimal roadway characteristics for RSD, and proximity to a large number of Smog Check stations. The Riverside campaign ran from 11/13/22 – 11/19/22.

San Ysidro

Opus considered five candidate sites for San Ysidro:
- **Via de San Ysidro to NB I-5**
- NB I-5 to WB CA-905/Tocayo Ave.
- **Picador Blvd to WB CA-905**
- Smythe Ave to EB CA-905
- NB I-805 to WB CA-905

The project committee prioritized two of the sites, the Via de San Ysidro onramp, which would be likely to include some cross-border vehicles, and the Picador Blvd onramp, which had ample space and would be likely to include vehicles from nearby communities. The project committee directed Opus to split the campaign week approximately in half and conduct the first half of measurements at the Via de San Ysidro to NB I-5 site, and the rest of the week at the Picador Blvd to WB CA-905 site. The San Ysidro campaign ran from 4/2/23 – 4/8/23.

Stockton

Two candidate sites were considered by DU for the Stockton area as follows:

- **Charter Way to NB I-5**
- Alpine Way Ave to NB I-5

The Charter Way onramp was selected for its higher traffic volumes, large amount of room for safe equipment setup, and likelihood of traffic to and from lower SES census tracts. The Stockton measurement campaign ran from 6/13/21 – 6/19/21.

West LA

Only one candidate was considered for DU's West LA campaign, which was the long-standing RSD site at the cloverleaf-style onramp from:

- **SB La Brea Ave to EB I-10.**

This site has been in use since 1999 and provides long-term historical emissions data. This West LA measurement campaign ran from 10/26/21 – 11/1/21.

Each campaign lasted approximately one week in duration. Equipment was set up each morning and taken down at the end of each measurement day. QA calibrations were performed at least twice daily in the field unless observed voltage readings or meteorological changes were judged to warrant additional calibrations. For the multi-species instrument, three calibration cylinders are used. The first contains CO, CO_2, propane (C_3H_8) and NO; the second contains ammonia and propane; and the final cylinder contains NO_2 and CO_2. To calibrate, a puff of gas is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (i.e., Air Liquide or PraxAir). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure, and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by RSD are reported as propane equivalents.[18]

Table 2 presents a summary of each campaign including the overall date range, number of days of measurements within the range, and the number of RSD passes with readable tag-edited license plates.

Table 2. Summary of Each RSD Campaign

Campaign	Date Range	# Test Days	# Readable Passes
Bakersfield	10/18/21 - 10/29/21	10	35,509
City of Industry	2/19/23 – 3/4/23	7	56,166
El Centro	10/7/22 – 10/14/22	8	21,929
Fresno	6/7/21 - 6/12/21	6	8,763
Oakland	3/31/22 - 4/6/22	7	27,616
Riverside	11/13/22 – 11/19/22	7	34,259
San Ysidro	4/2/23 – 4/8/23	7	33,358
Stockton	6/13/21 - 6/19/21	7	30,055
West LA	10/26/21 - 11/1/21	7	19,842

As mentioned previously, the City of Industry campaign was interrupted due to rain; the RSD instrument cannot operate effectively with rain present in the light beam.[29] The high-level weather conditions, such as average daily temperature, ambient pressure, humidity, and wind speed for each campaign day and location are presented in Appendix A.

Analysis Methods

QA Process

At the completion of each campaign, the logged RSD datasets were subject to a QA review, by both the respective subcontractor and ERG staff. The following summarizes the QA steps applied to the data in this work:

- Each contractor implemented similar requirements to establish measurement validity. To establish validity, in general, the signal strength must be above a certain threshold, and there must be a certain level of linearity between each pollutant and CO2 throughout the measurement interval.
- Various data channels, primarily pollutant signals, were reviewed graphically versus time during the campaign period. This review was for outliers, errors in logged date or time, or for any apparent overall trends that may need investigation.
- Each variable was reviewed for its range and overall trends. Character variables were reviewed for all discreet values (where practical). Numeric variables were reviewed for max, min, mean, and graphical distribution to identify unexpected trends or outliers.
- The frequencies of either emission or speed/accel validity being flagged was evaluated for different vehicle types or times/dates for each site to evaluate any unexpected trends in assigned validity for each RSD pass.
- Measurement validity was inspected as a function of vehicle speed and it was found that there was no effect of vehicle speed on emission measurement validity.
- All RSD passes with invalid speed or acceleration or speed equal to zero were eliminated from further emissions analysis.

- One of the priorities of this project was tracking proportions of electric vehicles. Because RSD measurements of EVs (and HEVs when their engine is not operating) match the background, they are generally flagged as invalid due to a high level of error in the ratio of each pollutant to CO_2 (similar to division by zero error). As a result, ERG took the following steps during the QA process to ensure that EVs and HEVs remained in the datasets:
    - If a vehicle was registration-matched as an EV, the emission rates for all pollutants were set to zero irrespective of measurement validity such that they would be included in all relevant fleet-level analyses
    - If a vehicle was registration-matched as an HEV and flagged with invalid pollutant measurements the emission rates were set to zero only if the Max CO_2 value was below a given threshold, indicating that it was likely that the CO_2 was near or equivalent to background.
- Vehicle specific power (VSP), a relative measure of the ratio of a vehicle's engine power output to its total mass[30], was estimated by the software of both contractors, however no data was excluded or marked as invalid based on VSP.
- Both contractors' systems logged negative measurements for all pollutants due to the nature of the error profiles of the instruments. No measurements were excluded due to negative values and, to avoid bias, they were not set to zero.

HC Offset

Over the years of continued development of the RSD measurement process, DU has developed an adjustment referred to as the "HC offset" to account for a systematic offset in the HC measurement channel.[31] The offset is determined by taking a subset of only the newest gasoline vehicles and assuming their exhaust HC is, in general, functionally zero. The offset consists of a single value for each campaign, and is calculated by determining the mean, median and mode of the newest vehicles and using the lowest value that does not render the new-vehicle mean negative. The offset value is then subtracted from all HC measurements for vehicles of all model years. Gary Bishop calculated the HC offsets for the DU sites, and ERG calculated offsets for the Opus sites based on Dr. Bishop's method. Unless otherwise stated, the analyses of the HC measurements in this report use the offset-adjusted data. The offsets used for the data from each site are presented in Table 3.

Table 3. HC offset values for each campaign, presented in terms of concentration percent.

Campaign	HC Offset (Concentration %)
Bakersfield	0.0012
City of Industry	0.0008
El Centro	0.0025
Fresno	0.0010
Oakland	0.0034
Riverside	0.0004
San Ysidro	0.0014
Stockton	0.0029
West LA	0.0042

Calculations

In this report, emissions are generally presented on the basis of grams of pollutant per kilogram of fuel burned. The RSD instrument logs the concentration of the various pollutants throughout the scan after the vehicle passes the light beam. During the period of time of the measurement (0.5s), the exhaust plume disperses but the relative concentrations of each exhaust pollutant to exhaust CO_2 remain constant. By principle of carbon balance, the ratios of each pollutant to the total of all carbon-containing exhaust constituents can also be calculated in terms of mass of pollutant per mass of fuel burned, expressed as g/kg_{fuel}. Because results are expressed on the basis of fuel mass, no assumption is needed regarding the density of the fuel. The mass emission rates for the pollutant are derived based on an assumed fuel carbon to hydrogen ratio of 2 (i.e. the fuel is stoichiometrically equivalent to CH_2) for gasoline and diesel and are calculated as follows:[32,33]

$$CO\left[\frac{g}{kg_{fuel}}\right] = \frac{\frac{28\cdot CO[\%]}{CO_2[\%]}}{\frac{CO[\%]}{CO_2[\%]} + 1 + 6\cdot\frac{HC[\%]}{CO_2[\%]}} \cdot \frac{860[\frac{gC}{kg_{fuel}}]}{12}$$

$$HC\left[\frac{g}{kg_{fuel}}\right] = \frac{\frac{44\cdot HC[\%]}{CO_2[\%]}}{\frac{CO[\%]}{CO_2[\%]} + 1 + 6\cdot\frac{HC[\%]}{CO_2[\%]}} \cdot \frac{860[\frac{gC}{kg_{fuel}}]}{12}$$

$$NO\left[\frac{g}{kg_{fuel}}\right] = \frac{\frac{30\cdot NO[\%]}{CO_2[\%]}}{\frac{CO[\%]}{CO_2[\%]} + 1 + 6\cdot\frac{HC[\%]}{CO_2[\%]}} \cdot \frac{860[\frac{gC}{kg_{fuel}}]}{12}$$

$$NO_2\left[\frac{g}{kg_{fuel}}\right] = \frac{\frac{46 \cdot NO_2[\%]}{CO_2[\%]}}{\frac{CO[\%]}{CO_2[\%]} + 1 + 6 \cdot \frac{HC[\%]}{CO_2[\%]}} \cdot \frac{860[\frac{gC}{kg_{fuel}}]}{12}$$

where,

- 28, 44, 30, 46 are the molecular weights of the respective pollutants
- 12 is the molecular weight of carbon
- 860 approximates the mass of carbon (g) per kg of fuel (calculated as the molecular weight of carbon divided by the molar mass of CH_2 [~0.014 kg])
- 6 represents a factor of two (due to the RSD instrument being sensitive to only half of total exhaust HC) multiplied by 3, the atomic carbon content of propane.

NOx is calculated as the sum of the concentrations of NO and NO_2. In exhaust measurement, NOx is typically presented on a mass basis assuming the same molecular weight as NO_2, which is 46.[34] Thus, NOx can be calculated on a mass basis using the same equation as presented above for NO_2, except the summed NOx concentration is used in the numerator.

As referenced above, and consistent with previous RSD studies, measurements of HC are doubled due to RSD HC readings being known to be approximately 50% of the readings of laboratory analyzers. So, a factor of two is applied to the raw emissions concentration reading prior to mass calculation. This correction is separate from the HC offset described above.

Additionally, some emissions data in this report is presented on the basis of VSP. This value was calculated based on the equation proposed by Jimenez[30], which is calculated as follows:

$$VSP = 4.39 \cdot \sin(slope) \cdot v + 0.22 \cdot v \cdot a + 0.0954 \cdot v + 0.0000272 \cdot v^3$$

where,

- *VSP* is the vehicle specific power in kW/metric tonne
- *slope* is the slope of the roadway
- *v* is vehicle speed in mph
- *a* is vehicle acceleration in mph/s.

The RSD contractors measured the slope gradient of the roadway at each measurement site. Table 4 presents the roadway slope at each measurement site; for those campaigns with multiple measurement locations, the values are provided for the range of dates at each location.

Table 4. Roadway slope at each measurement site

Campaign	Site Dates	Roadway Slope (deg)
Bakersfield	All	1.3°
City of Industry	All	1.9°
El Centro	10/7/22-10/10/22	1.6°
El Centro	10/11/22-10/14/22	1.7°
Fresno	All	1.8°
Oakland	All	1.4°
Riverside	All	3.3°
San Ysidro	4/2/23-4/5/23	1.8°
San Ysidro	4/6/23-4/8/23	2.0°
Stockton	All	2.0°
West LA	All	2.0°

Parallel Measurements

While the main priority of the RSD measurements was to measure emissions from light-duty vehicles, one of the project's research topics was to determine the emissions profiles of heavy-duty vehicles where possible. This was the primary reason for capturing pictures of vehicles' front license plates, as the front license plate is often the only way to identify a heavy-duty vehicle in an RSD photo, especially if it is towing a trailer. As described previously, the two RSD subcontractors used different methods in making measurements of heavy-duty vehicles. For the Opus data, RSD scans required merging data from the two separate RSD units used in parallel during each campaign. Because measurements were being made by the two systems in parallel, most vehicle passes involved two separate measurements in the data outputs (depending on the activation of the CO_2-based measurement trigger). ERG developed a process to determine which one of each parallel measurement should be used for analysis. In general, if one or the other measurement had an invalid gas or speed/acceleration reading, that one was dropped. In the less likely event that both were valid, the measurement from the instrument intended for light-duty vehicles, which was triggered on beam blocks, was used for analysis. Because DU did not use two instruments in parallel, this process did not need to be performed for data from the DU sites.

Registration and Smog Check Datasets

ERG utilized vehicle registration data from California and Mexico as well as BAR Smog Check records for the data analysis. ERG matched the tag-edited license plates from RSD to the registration and Smog check datasets by license plate and where applicable, date.

Registration Data

Registration data was used in this project to determine vehicle information based on the license plates recorded with every RSD scan. For all sites, vehicle information was sourced from the California vehicle registration database and CalEnviroScreen. Additionally, for the cross-border analyses performed on the El Centro and San Ysidro data, registration data from various areas of the Baja region of Mexico were also used in the analysis.

After tag-editing of a given campaign was complete, ERG provided a list of all unique license plates to CARB staff. To preserve individual motorists' privacy, CARB staff provided a subset of those plates' registration data back to ERG that was scrubbed of personally identifying information. The registration data provided back to ERG included:

- Vehicle model information such as make, model, model year, engine displacement, and specific model trimline/series information
- The 9-digit anonymized vehicle identification number (VIN) stem
- Specifics of the vehicle registration such as the body style, the fuel type, empty weight, gross vehicle weight rating (GVWR) class, whether the registration was current, and the registration expiration date
- The due date of the vehicle's next Smog Check visit
- The Smog Check program that the vehicle was subject to based on registration location, i.e. Enhanced, Basic, or Change of Ownership (COO) only
- Information about the location that the vehicle was registered in including the census tract ID and the latitude and longitude of the centroid of that census tract
- CalEnviroScreen information such as the CES score and CES percentile. The dataset also indicated whether the vehicle's registered address was within an AB 617 community.

ERG considered all vehicles with registration indicating a top 25% CES score to be registered in DACs. All vehicles with lower CES scores were considered non-DAC (i.e. the bottom 75%). This criterion was based on the original and largest category of CalEPA's DAC assignment criteria and was most readily applied with the data available to ERG.[35] AB617 communities may or may not fall within this definition of DAC. So, in this work, a given vehicle will have a DAC status based on CES percentile and an AB617 status based on whether it is registered within one of the specifically defined AB617 communities. In some analyses, all combinations of the two community assignment types are analyzed separately but, for some analyses with fewer measurement counts, they may be combined - the manner in which they are combined will be described with the respective analysis findings.

Smog Check Data

The Smog Check Program classifies California vehicles into one of four program area types[36]:

- Basic, in which all vehicles must undergo emissions testing upon initial registration in California, on change of ownership, and also biennially. These areas are generally moderately populated areas between urban and rural locations.
- Enhanced, in which all Basic inspections must also be performed, but 36% of vehicles must have their biennial tests performed at STAR certified locations. These are generally

more urban or densely populated areas that are not in attainment of federal or state air quality standards.
- COO, in which vehicles must undergo emissions testing upon initial registration in California and on change of ownership only. These tend to be the least densely populated areas of the state.
- Not required, in which vehicles are not subject to emissions testing requirements (largely comprised of vehicles registered on Catalina Island).

The Program has exemptions for vehicles based on model year and fuel type that are relevant to this RSD study and analyses. Gasoline vehicles do not require a biennial inspection if eight model years old or less and do not require a change-of-ownership inspection if four model years old or less. Diesel vehicles are only exempted if older than 1997 model year and all vehicles are exempted if older than the 1975 model year.

ERG provided the list of unique California license plates to BAR for the purpose of matching with Smog Check program records. BAR provided Smog Check records for each license plate for the range from 6/1/2019 through 6/23/2023. This date range was selected to provide at least one complete two-year cycle prior to this program's first campaign, which began in June 2021.

The Smog Check data was organized in rows for each visit of a vehicle to an inspection station and included the following data fields:

- Inspection Test ID or inspection key number, date and time
- Inspection test cycle, indicating OBD (onboard diagnostic) or tailpipe test type
- Station number/ID and the test type including Star or referee, etc.
- Vehicle information such as VIN stem, make, model, model year, and odometer reading
- The inspection reason: biennial, initial registration, change-of-ownership, etc.
- HC, CO, and NOx emission measurement values for tailpipe tests
- Scanned OBD diagnostic trouble codes (DTCs)
- Test results for visual inspection, emissions, functional checks, and the overall test

Cross-Border Analysis

In the El Centro and San Ysidro data, the vehicles identified as having Mexican license plates were matched with registration data sourced from Mexico. For a previous CARB project involving RSD measurements of Mexican vehicles, ERG worked with Baja California's Ministry of Environment and Sustainable Development to obtain registration data for Baja areas including Ensenada, Mexicali, Rosarito, Tecate, Tijuana, and others.[37],[38] This registration data was not as extensive as the California registration data, including only vehicle model year, vehicle class, vehicle type, and fuel type. Approximately 77% of the plates identified as being from Mexico had a match in the registration data from Mexico. Based on a review of those matches, the vast majority (99+%) appeared to be light-duty vehicles based on the indicated vehicle class and type.

Results

This section presents the results of the RSD measurements and analyses. Results are presented on various bases as appropriate, either at the fleet level, by model year, by vehicle or fuel type, etc. The first section provides an overview of the observed trends in the vehicles observed during the RSD campaigns and their emissions. The remaining sections address the project's specific analysis topics.

Fleet Statistics and Initial Emissions Findings

Fleet Statistics

This section presents a context for the analysis topic results that follow by presenting various measures of the characteristics of the fleets of vehicles observed at each site. The first step in the process of understanding the fleet characteristics was matching the observed vehicles' license plates to the registration data, as no vehicle information would be available without this match. Table 5 presents the match rates with California registration data for vehicles observed in each campaign. The match rate with the vehicle information is different than the match rate for the CES data, and the CES match rate is generally lower. There are multiple potential causes for this, including the presence of California-registered vehicles with an out-of-state mailing address or issues caused during geolocation of the registration address in CES, such as when a PO Box could otherwise cause a flag of an incorrect residence lookup location. In those cases, information about the vehicle is available, but CES data is not.

Table 5. California Registration and CES Plate Match Rates

Campaign	Scans with Read Plates	Registration Matched (% of read)	CES Score Match (% of read)
Fresno	8,763	8,558 (98%)	7,729 (88%)
Stockton	30,055	29,271 (97%)	26,344 (88%)
Bakersfield	35,509	31,866 (90%)	28,963 (82%)
West LA	19,842	19,309 (97%)	17,358 (87%)
Oakland	27,616	27,026 (98%)	24,668 (89%)
El Centro	21,929	16,631 (76%)	14,283 (65%)
Riverside	34,259	30,487 (89%)	28,132 (82%)
City of Industry	56,166	49,234 (88%)	45,895 (82%)
San Ysidro	33,358	25,750 (77%)	22,573 (68%)

The RSD setups used in this project were designed to measure LDVs and HDVs with downdraft exhaust. HDVs with updraft exhaust may not have successfully triggered RSD measurement events and so counts and distributions of HDVs presented in this work should not be taken as representative of the entire HDV fleet. Figure 4 presents the percentage of RSD passes by LDVs observed at each campaign; all remaining readings were identified HDVs. Counts of all RSD scans with registration-matching license plate readings were included irrespective of whether the emission measurement was valid.

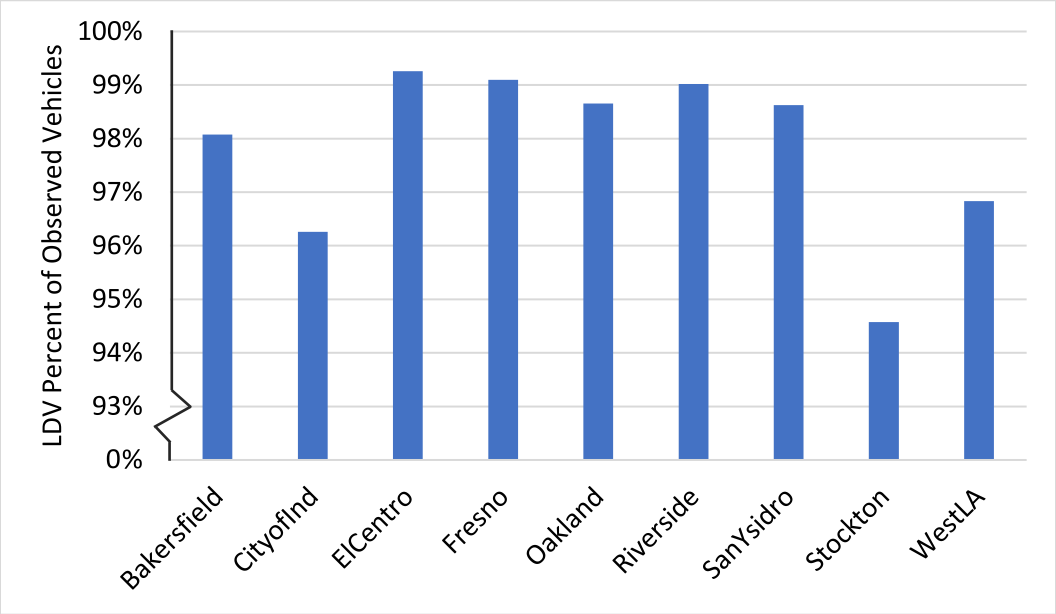

Figure 4. LDV percentage of RSD passes with readable and registration-matching license plates by campaign.

Two of the main analysis topics in this work involve making the determination whether a given vehicle is registered in a DAC and also whether it is registered in an AB617 community. As described previously, ERG assigned the DAC status based on whether a vehicle had a top 25% CES score in the plate-matching data returned by CARB. Further, vehicles were assigned whether they are registered in an AB617 community; this assignment was included in the registration data provided by CARB staff. Note that most AB617-community-registered vehicles will likely be DAC vehicles, but there is overlap across the categories that varies by campaign. The percentage of vehicles in each combination of categories is presented in Figure 5, with the percentage of vehicles for which CES information was not available included in the Missing category. As with many analyses of DAC status, the figure only presents the findings for LDVs, as it is likely that HDVs, which tend to be commercial vehicles, will not be registered at an individual home address and therefore the community status may not reflect that of the owner or operator.

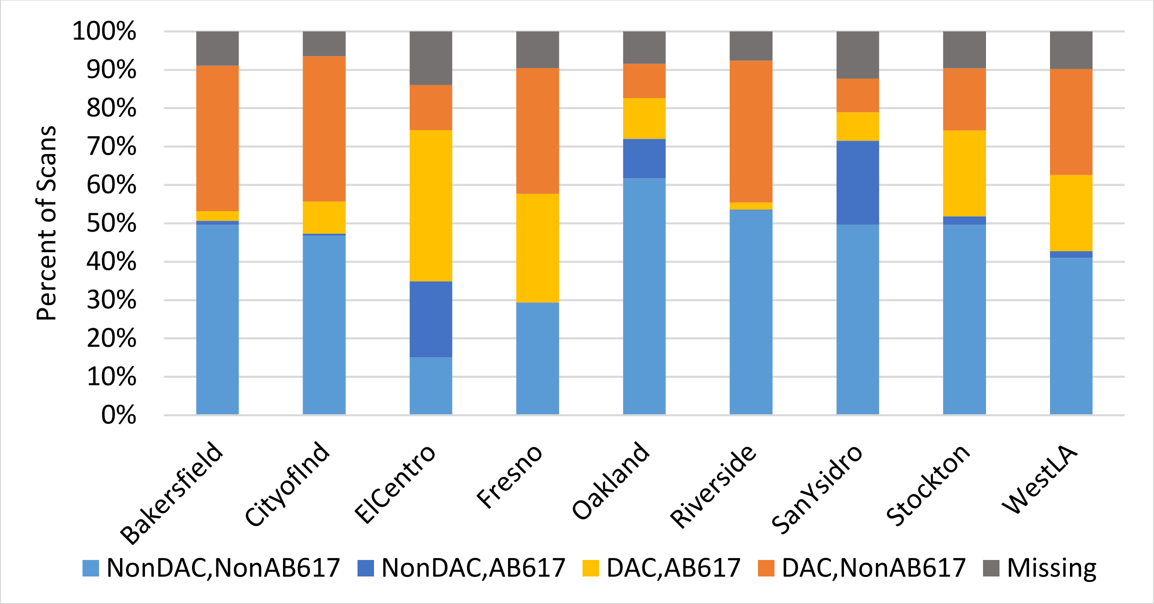

Figure 5. The percentage of LD vehicles from each combination of DAC and AB617 community status by campaign.

In analyzing RSD data, model year of a given vehicle is one of the most important factors influencing emission rates. Because of this, it is important to present model year distributions for different analysis groups, not just the emission rates of those groups. Figure 6 presents a comparison of model year distributions for all LDV scans during the RSD campaigns (each vehicle scan weighted equally and multiple scans of a given vehicle are all included) as well as for all California-registered LDVs. Model year distributions for both groups are separated by those registered in DAC/non-DAC based on CES percentile. The DAC vehicles tend to be older in model year than the non-DAC vehicles for both groups, and the overall registration distribution tends to be older than those vehicles observed by RSD. This is likely because newer vehicles tend to be driven more often and are therefore more likely to have been seen by RSD. The vehicles that are driven more frequently are more likely to be seen by RSD and contribute more to total fleet emissions. The overall average model years for all four groups are presented in Table 6.

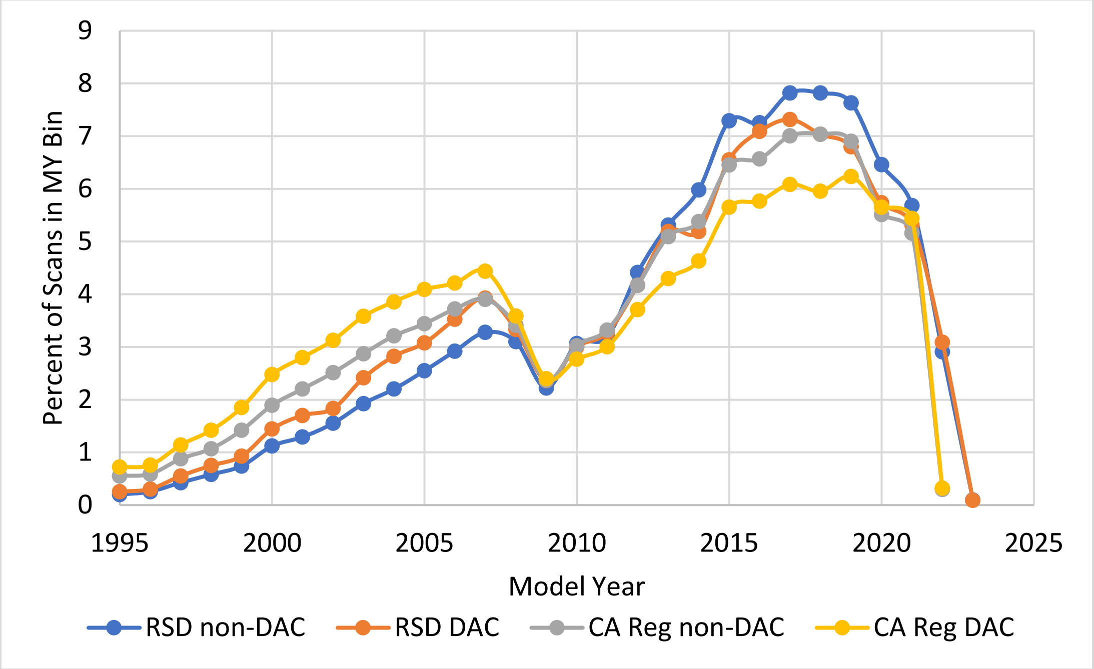

Figure 6. The model year distributions for all RSD-observed LDVs and for all CA-registered LDVs, presented for DAC and non-DAC vehicles.

Table 6. The average model years for all RSD-observed LDVs and for all CA-registered LDVs, presented for DAC and non-DAC vehicles

	non-DAC	**DAC**
All Observed RSD	2013.5	2012.9
CA Registration	2012.0	2011.1

Each campaign had a different number of observed vehicles and each one varied in its model year distribution. Figure 7 presents the average LDV model years observed at each campaign for DAC and non-DAC vehicles. Error bars in the figure (and in all figures in this work) indicate the 95% confidence interval (CI) of the mean. The observed DAC vehicles were significantly older in model year at each campaign. Bakersfield and West LA had the largest differences in model year, while El Centro and San Ysidro had the smallest. ERG further separated the data into all four of the two-way combinations of DAC status and AB617 community designations. Within the DAC vehicles, the AB617 vehicles tend to be slightly older than the non-617 vehicles. Appendix B includes all model year distributions for each campaign for the four combinations of DAC/AB617 categories.

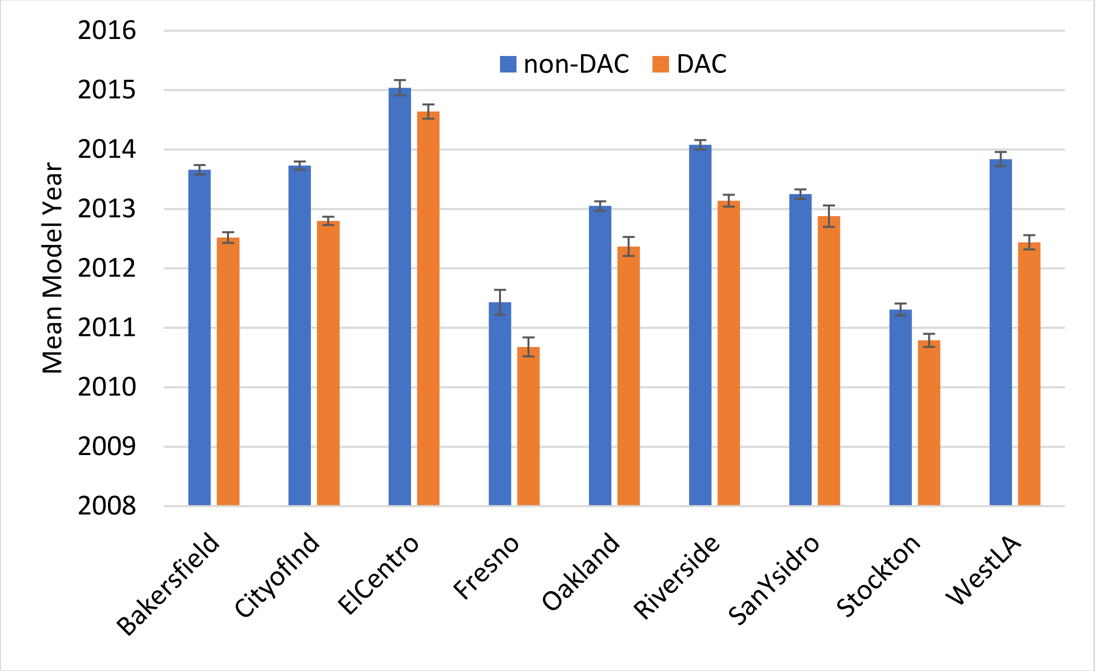

Figure 7. The average model years of DAC and non-DAC LDVs observed at each campaign. Error bars indicate 95% confidence interval.

The campaigns in this project took place over a period of about two years. As a result, there is some confounding of vehicle age against model year that is inevitable in the data analysis as not all vehicles of a given model year will be of the same age when compared across campaigns. To illustrate this, Figure 8 presents the average age of the LDV DAC and non-DAC fleets observed at each campaign. Note especially that Fresno and Stockton had the oldest model years but are close to the other campaigns in terms of average vehicle age. El Centro had the newest model years and, given that the campaign was late in the project, also had the lowest average vehicle age. These ages are presented for context; where applicable, vehicle model year will be the basis of most analyses in this work. Appendix B includes the average ages for the same vehicles, further divided into DAC/non-DAC and AB617 community designation. For many campaigns the DAC, AB617 vehicles tended to be the oldest, but trends across the other combinations tended to vary across the campaigns.

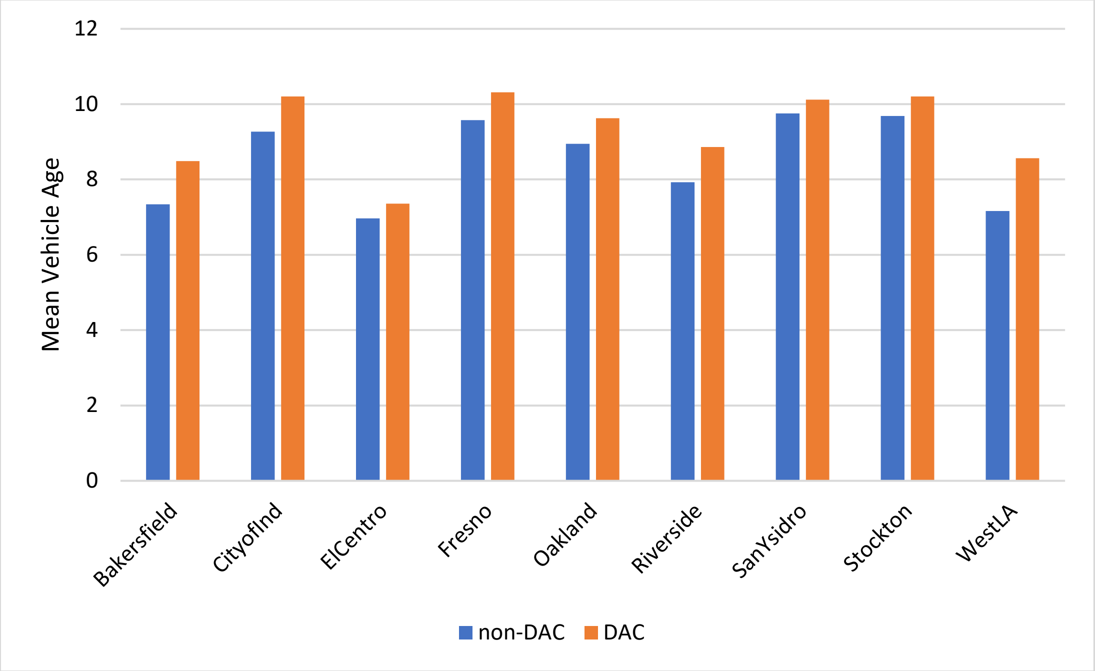

Figure 8. The average DAC and non-DAC LDV age for each campaign.

The registration data also provided the fuel type for each vehicle, including whether the vehicle was a hybrid-electric or pure electric. Figure 9 presents the percentages of each fuel type for DAC and non-DAC LDVs observed over all campaigns. The registration also included some alternative-fueled vehicles such as liquefied propane gas (LPG), fuel cell, or natural gas (NAG), but these made up less than 0.1% of observed vehicles and so are not included in the figure. The DAC vehicles tended to have a greater percentage of gasoline vehicles, with lower percentages of all gasoline alternatives. Further information and specifics regarding fuel type prevalence is presented in Analysis Topic 4, and detailed fuel type distributions by campaign are presented in Appendix C.

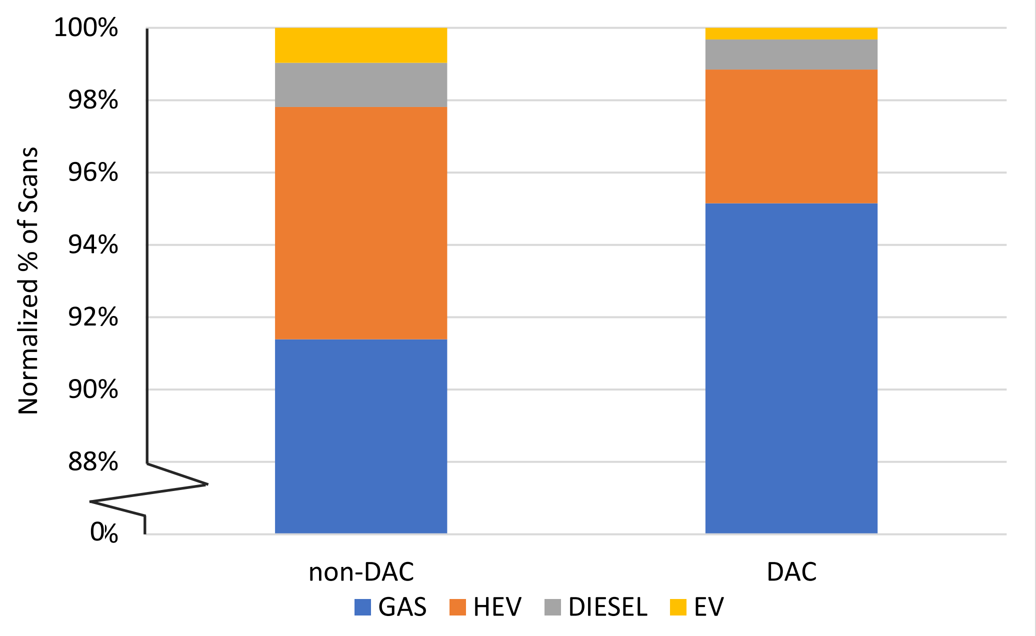

Figure 9. The percentage of observed LDVs of each fuel type for non-DAC and DAC vehicles. The gasoline bars extend down to zero percent.

The CES information for each license plate lookup also included the resident's census tract and the latitude and longitude for the centroid of that census tract. Using this data, ERG was able to calculate an approximate distance from the registered address to the RSD site for each observed vehicle. Figure 10 presents a stacked bar chart displaying the percent of observed RSD passes falling in three bins of distance from registered address to RSD site: less than 3 mi, 3 to 9 mi, and greater than 9mi. These findings give an indication of how the relative distances that each vehicle may have traveled vary across campaigns. For example, San Ysidro and El Centro tended toward having the observed (registration-matching) vehicles domiciled closer to the RSD sites than Oakland or West LA. Vehicles domiciled very near the RSD location may be more likely to be operating under cold-start conditions (with associated elevated emissions)[39,40], but there is no way to make this determination using RSD data. In the FTP-75 emissions cycle for LDVs, vehicles travel 3.6 miles after a cold start before entering what is considered the "stabilized" phase of the cycle.[41] Likewise, a recent study indicated that test vehicle catalyst temperatures for a stabilized within approximately the first 2 miles (3.2 km) of driving, and the engine coolant temperature stabilized in the first 3 miles (4.8 km) of driving.[42] The upper bin is chosen to be nine miles and greater to describe non-local traffic; this is approximately the width of cities such as Fresno or Stockton. The distance information given in the figures is not used in any further analyses in this work; it is shown here to provide context to differences across campaigns.

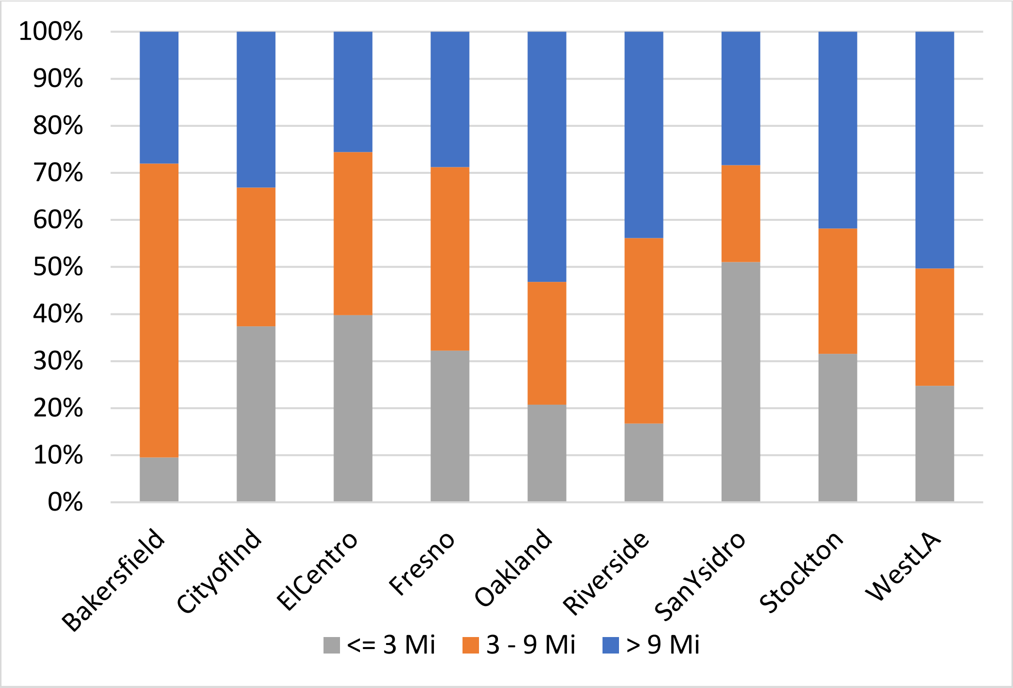

Figure 10. The fraction of vehicles observed in each campaign that were registered at various distances from the RSD site (≤ 3 mi, 3 – 9 mi, > 9mi)

Initial Emissions Findings

ERG initially reviewed the emission rates for LDVs on a by-campaign basis to get an overview of the trends observed throughout the project. Figure 11 presents the average emission rates of HC and NO for all LDVs observed during each campaign. Compared with other recent studies conducted by DU for CRC Project E-123 at Chicago[43] and Tulsa[44], the average observed HC emission rate of 1.4 g/kgfuel across campaigns is somewhat lower than the averages of 2.8 g/kgfuel and 1.9 g/kgfuel for Chicago and Tulsa, respectively. The campaign-average value for NO was 1.1 g/kgfuel in this work, which agrees with the averages of 0.94 g/kgfuel and 1.1 g/kgfuel for Chicago and Tulsa, respectively.

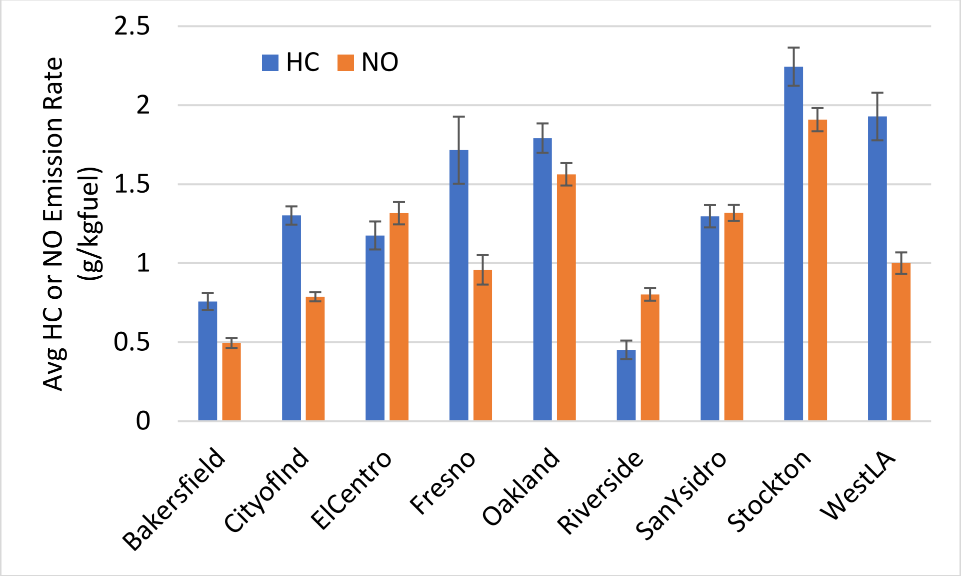

Figure 11. The average HC and NO emission rates observed for all LDVs at each campaign. Error bars indicate 95% confidence interval.

Likewise, Figure 12 presents the average CO emission by campaign for all observed LDVs. The average of all campaigns of 15 g/kgfuel is higher than the Chicago and Tulsa averages of 10.9 g/kgfuel and 11.6 g/kgfuel. For all 3 pollutants, however, there is a notable level of variability across the nine campaigns. The error bars within each campaign's average indicate relatively low variability within each campaign by comparison to the level of variability across campaigns. Broadly, the level of variability indicates an approximate factor of 4 from the lowest campaign value to the highest. By means of comparison, the most recent measurement campaigns for the three cities[45] in CRC Project E-123 had a factor of approximately 1.5 from the low to high average measurement for HC and NO, and a factor of approximately 2.5 from low to high for CO.

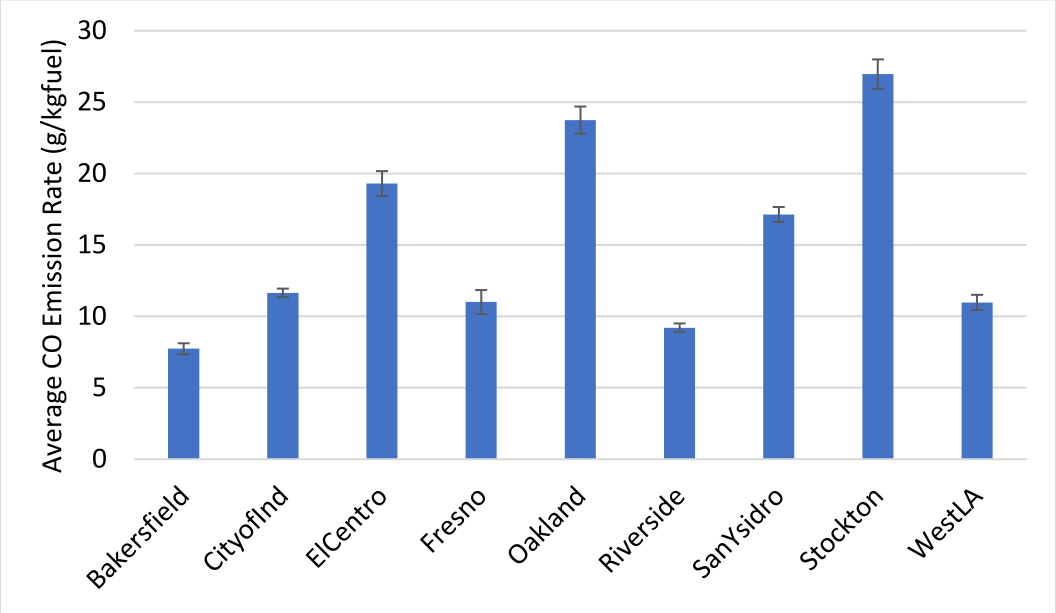

Figure 12. The average CO emission rate observed for all LDVs at each campaign. Error bars indicate 95% confidence interval.

ERG conducted further analysis of the potential causes of the site-to-site variability. These analyses are presented in the Discussion section; these campaign-level graphs are presented here to summarize the initial findings and indicate potential shortcomings in bringing together the data from multiple campaigns.

Throughout this project, the DU instrument included the capability to measure NO and NO_2, which can be summed to calculate the NOx emission rate as described previously. However, at the start of this project, the Opus instrument did not have the capability to measure NO_2. This functionality was added by Opus after their first campaign at Bakersfield. As a result, only NO can be compared across all sites, not NOx. The following two figures aim to describe trends observed in the relationship between NO and NOx; all remaining analyses will be presented based on NO only such that all sites can be compared on an equivalent basis.

Figure 13 presents the ratio of the average concentration of NO to the concentration of NOx by campaign and model year bin for gasoline-powered LDVs. Note that the figure is based on pollutant concentration instead of emission mass per kg fuel as in most graphs in this report. The NO/NOx ratio is presented on the basis of concentration to prevent confusion regarding the convention of calculating NOx mass based on the molecular weight of NO_2, which would result in the NO fraction appearing lower than it actually is by concentration. Bakersfield is excluded from the plot because Opus did not yet have capability for NO_2 measurement at that time; West LA is also excluded because of elevated levels of error and negative measurements in the NO_2 channel confounding the results. It can be seen that NO generally makes up the majority of NOx as measured by RSD. There is an observably different trend by model year bin in the DU vs Opus measurement campaigns. In the Opus campaigns, the NO ratio tends to be lower in the newer model years. However, for DU, the NO ratio tends to be more constant across the model year ranges. Literature indicates that a moderate decrease in the NO percentage is to be expected in newer vehicles, and published values for gasoline vehicles are within the range from 0.9 to 1.[46] The NO/NOx ratio may also be expected to increase over time as newer vehicles age.,[47]

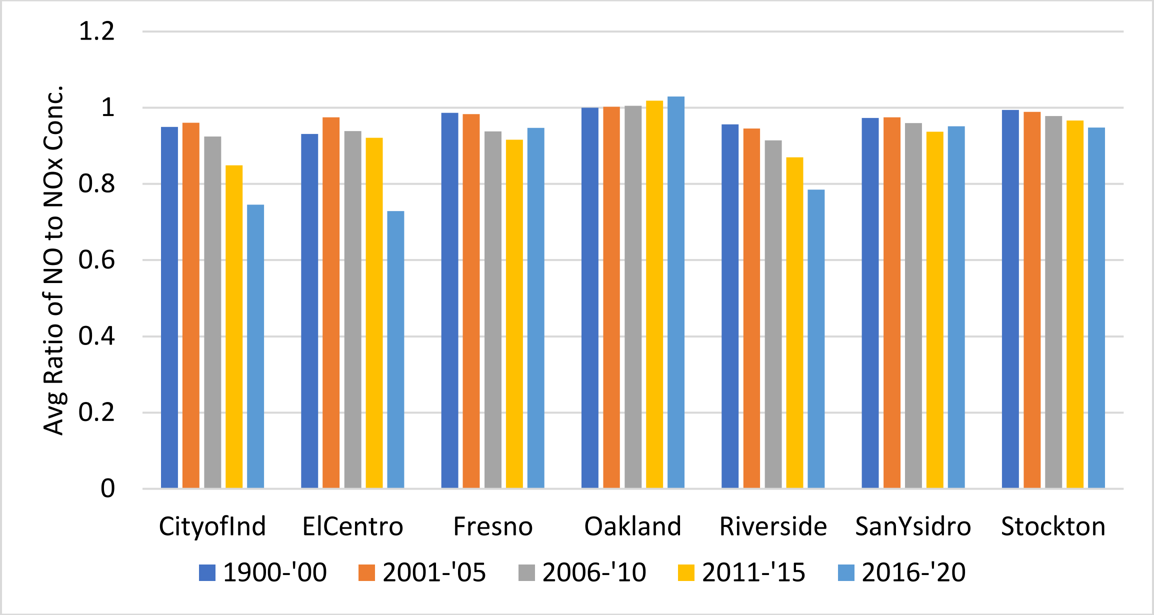

Figure 13. Average ratio of NO to NOx concentration for gasoline-powered LDVs by model year bin and campaign.

Figure 14 presents similar data for diesel-powered LDVs. For diesel vehicles, the NO percentage tends to be lower, meaning NO_2 tends to comprise a larger part of the total NOx. This lower percentage is consistent with trends reported in literature, with one study showing a range of values from approximately 0.7 to 0.9.[46,48,49] Similar trends across model years appear for the diesel vehicles, with newer vehicles having a lower percentage of NO as measured by the Opus instruments. ERG also investigated the NO to NOx ratio for diesel-powered HDVs. As with the diesel-powered LDVs, the NO tends to make up approximately 80% of the NOx by concentration, with variation across campaigns and model years. The average ratios of NO to NOx for diesel-powered HDVs by model year and campaign are included in Appendix D.

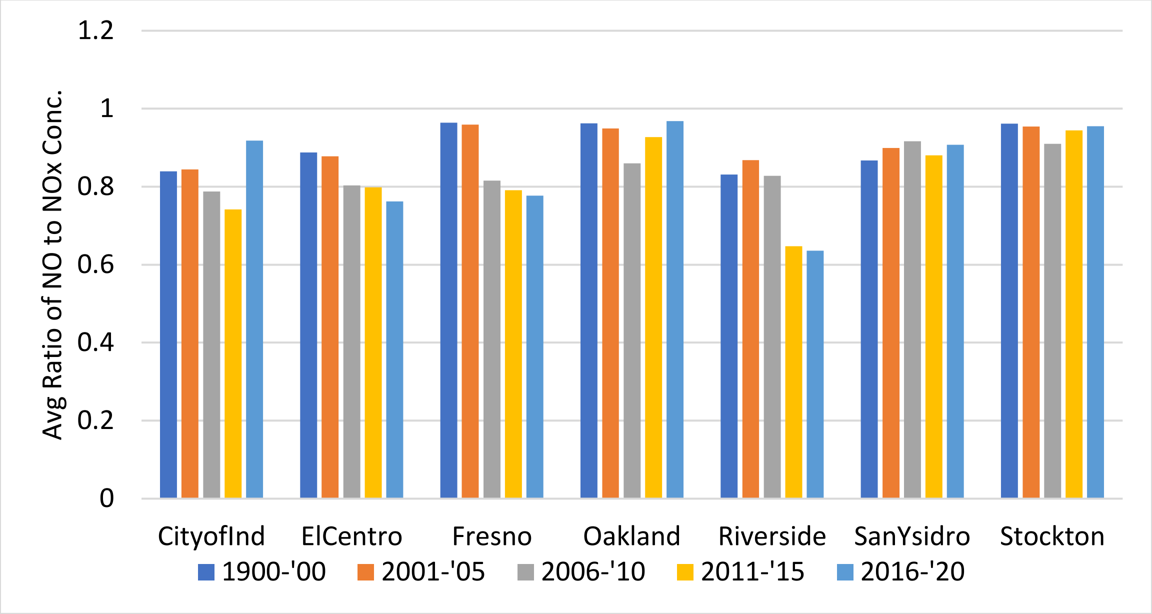

Figure 14. Average ratio of NO to NOx concentration for diesel-powered LDVs by model year bin and campaign.

In general, the NO_2 measurements by the RSD tend to be noisier with a higher coefficient of variation than NO, and there is a notably different trend across model years between the DU and Opus instruments. NO_2 is generally less prevalent in exhaust than NO and it also has multiple wavelength peaks[50] (whereas NO has only 1 wavelength peak) which means RSD instruments are less sensitive to it resulting in higher measurement noise. The DU and Opus systems use different light emitter types and measure the NO_2 signal at different wavelength peaks, which is a potential cause of the observed differences in trends across the two instrument types. The increased noise also manifests itself with some of the bars in Figure 13 being greater than 1, especially for newer model years; this implies that the average NO_2 measurement was negative. To be able to make comparisons across all sites and to reduce noise in the analyses, the remaining emissions analyses in this work are presented for NO, not NOx, and are presented on a g/kgfuel basis.

The DU instrument was also capable of measuring vehicle NH_3 emissions, while the Opus unit did not have that capability. Ammonia from vehicle exhaust can contribute to secondary particulate matter formation in the atmosphere, and vehicle emission rates of NH_3 may be higher than previously thought.[51] Due to the limited measurement data for this pollutant, however, NH_3 findings for the various analysis topics are presented in Appendix E.

Analysis Topic 1, Emission Rate Disparities in DACs

This section presents the investigation into the emissions differences from vehicles registered in different areas based on SB535 DAC status or AB617 community assignment. The previous section presented the differences in model years of vehicles from these various communities; this section will present the emissions differences and attempt to quantify how much of the difference is attributable to the model year trends versus other factors. All analyses in this section are of LDVs only and include all fuel types.

In the analyses in this section, the vehicle community assignments will be based on either DAC/non-DAC only (i.e. CES-based), or, when greater specificity is appropriate, the three categories of non-DAC, AB617 (irrespective of SB535 DAC status), and non-AB617 DAC. These categories are intended to allow for differences to be seen where they exist while minimizing the noise and unneeded complexity in the resulting figures that would exist if all 4 combinations of DAC and AB617 status were included.

While all RSD campaigns in this work were conducted on highway onramps or highway interchanges, the conditions at each site were likely different in various ways that could affect the passing vehicles' emission rates. Figure 15 presents the average HC emissions by site for non-DAC, AB617, and non-617 DAC. The HC averages have large variability across sites, especially for the non-DAC population, which ranges from less than 0.5 g/kgfuel to about 2.25 g/kgfuel. One or both types of DACs tend to have higher emission rates than the corresponding non-DAC populations.

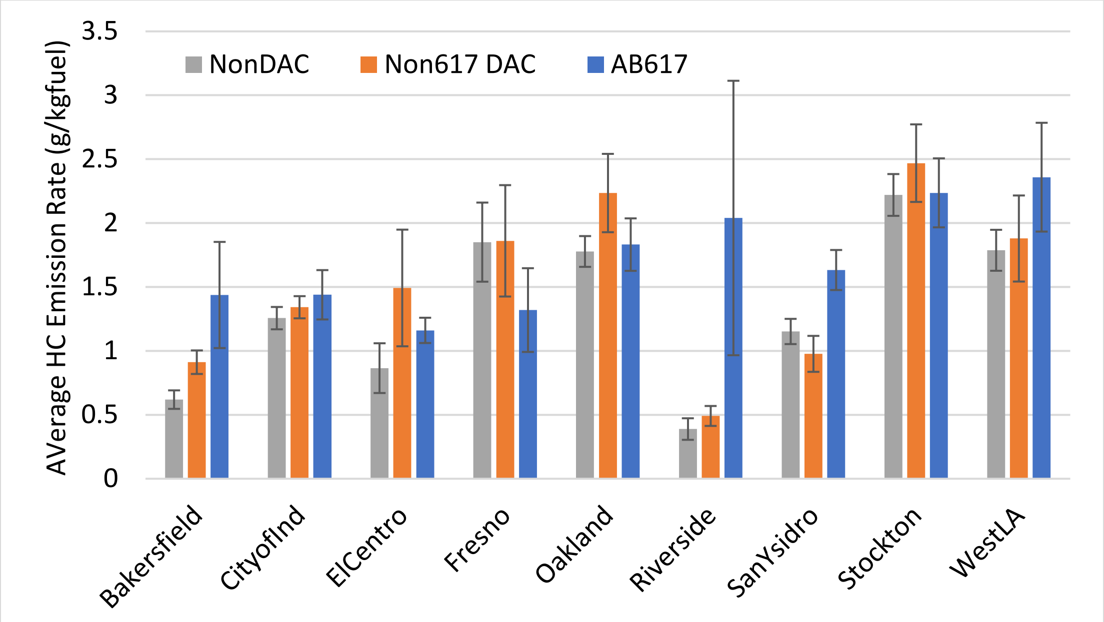

Figure 15. The average HC emission rates for non-DAC, AB617, and non-617 DAC by RSD campaign. Error bars indicate 95% confidence intervals.

Figure 16 presents the by-campaign CO emissions for the populations from non-DAC, AB617, and non-617 DAC. Within each campaign, the relative emission rates are less variable than for HC, with non-DAC tending to have the lowest emissions, non-617 DAC having somewhat elevated emissions, and the AB617 vehicles having the highest emissions (at most sites).

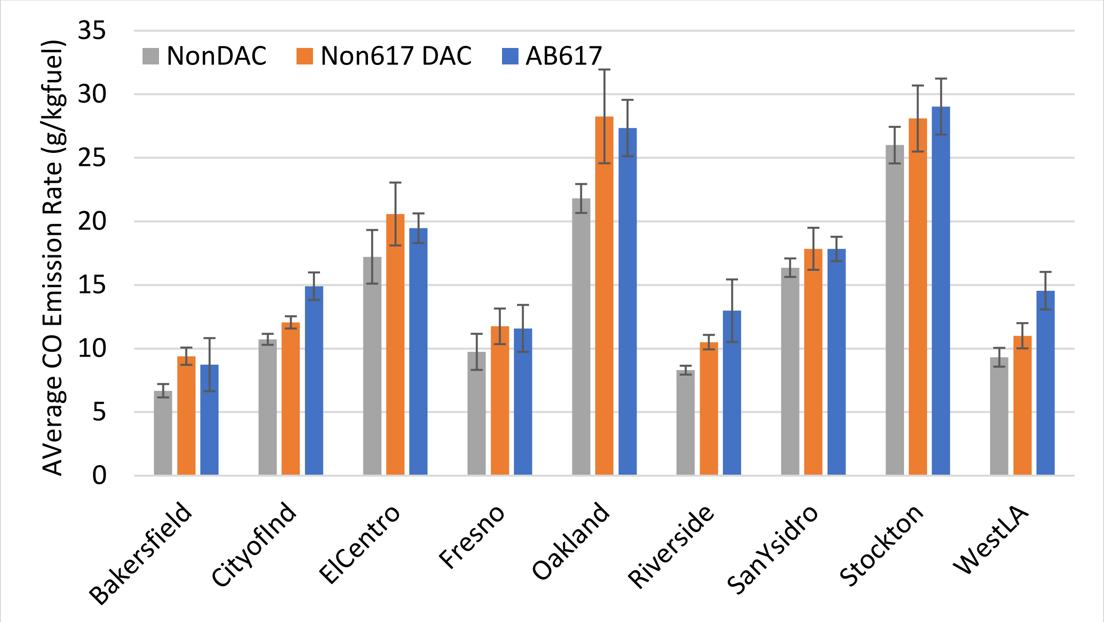

Figure 16. The average CO emission rates for non-DAC, AB617, and non-617 DAC by RSD campaign. Error bars indicate 95% confidence intervals.

Figure 17 presents the by-campaign average NO emissions for each of the same three population groups. Six of the sites display the trend seen at most sites for CO, with non-DAC having the lowest emission rates, followed by Non-617 DAC, with AB617 having the highest emissions. Of the other sites, only Fresno's non-DAC population had the highest emission rates of the three populations, and it was not significantly different than the Non-617 DAC emission rate.

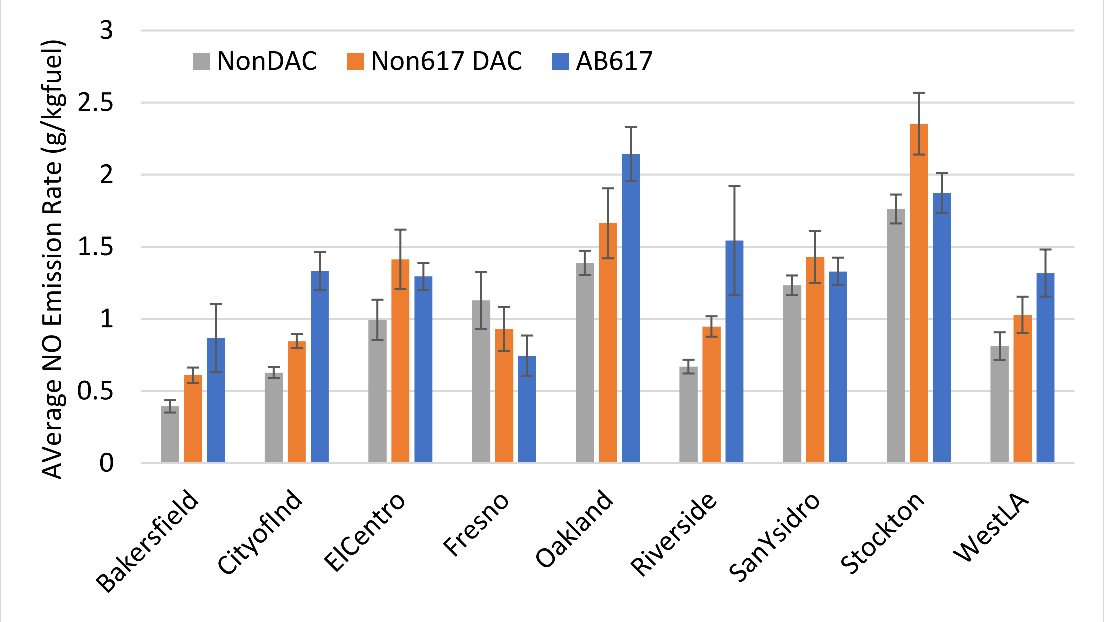

Figure 17. The average NO emission rates for non-DAC, AB617, and non-617 DAC by RSD campaign. Error bars indicate 95% confidence intervals.

ERG investigated the level of variability across sites (see Discussion, Cross-Campaign Variability for details). For a given community type, the factor between the lowest emission rate campaign to the highest ranged from 2.5-4 times. This level of variability means that, due to variations in model year distribution and specific operational conditions at each site, care should be taken if calculating and analyzing overall-average emission rates, and direct comparisons within like groups may be more appropriate.

The differences in model year distributions among campaigns and communities were presented in the previous section, and these model year differences can be expected to affect the overall average emission rates. To maximize the statistical power and reduce noise in the remaining DAC-related analyses, the communities will be grouped into only non-DAC and DAC, which will included both SB535- and AB617-defined communities. Figure 18 presents the average HC emission rates by model year for DAC and non-DAC vehicles observed in the San Ysidro campaign. San Ysidro is shown here as representative of the trends observed at other campaigns; similar findings for all campaigns are presented in Appendix F. The average DAC emission rates are higher than the respective non-DAC emissions for most model years, though for almost all years this difference is not statistically significant.

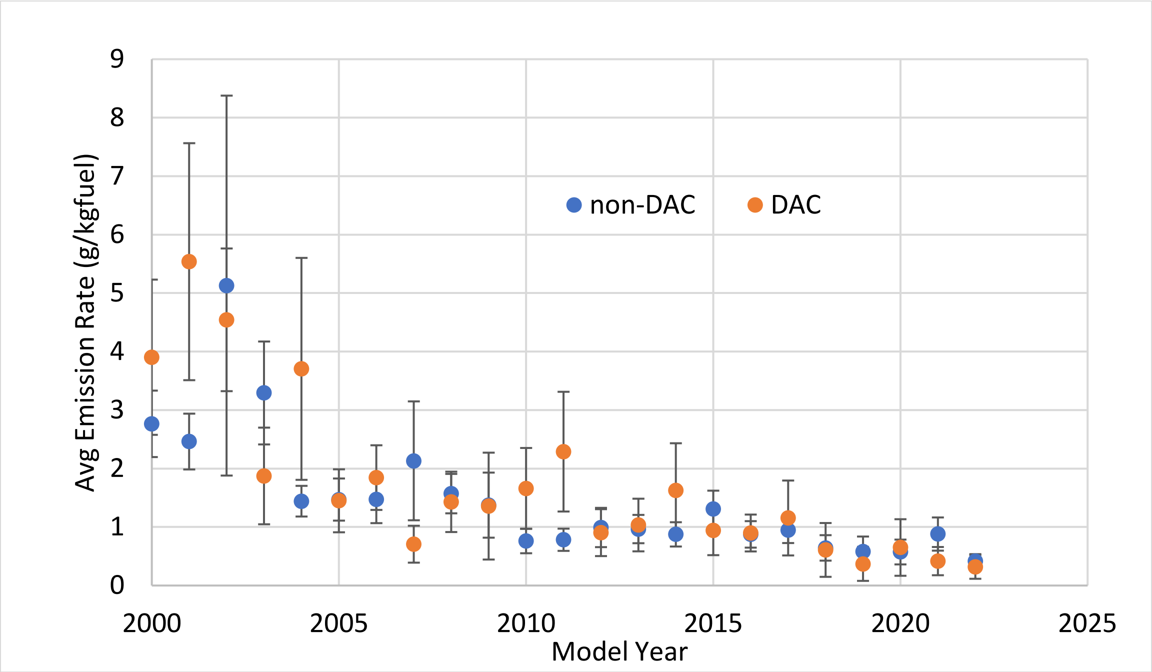

Figure 18. HC emission rates for non-DAC and DAC LDVs averaged by model year for the San Ysidro campaign. Error bars indicate 95% confidence intervals.

Figure 19 presents the emission rates for CO, averaged by model year for the Oakland campaign. The Oakland findings are presented as an example as there are multiple model years for which the DAC emissions were significantly higher than the non-DAC emissions; most other campaigns did not resolve as many significant differences. Similar CO plots for all campaigns are presented in Appendix F. As observed for HC, the emission rate difference between DAC and non-DAC tends to be small for relatively new vehicles and become wider for older model years.

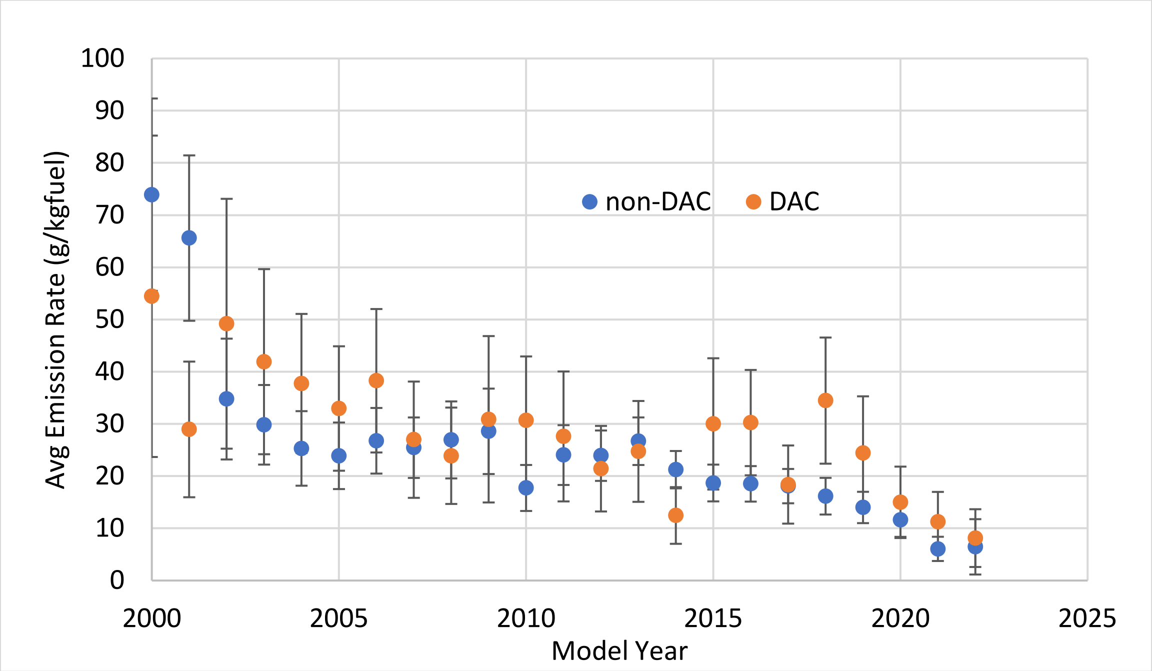

Figure 19. CO emission rates for non-DAC and DAC LDVs averaged by model year for the Oakland campaign. Error bars indicate 95% confidence intervals.

Figure 20 presents the by-model year average emissions for NO for the El Centro campaign, presented as typical of the trends observed in other campaigns (also presented in Appendix F). As with the other pollutants, the DAC means tend to be higher but for most years the difference is not statistically significant. Differences between the emissions of the two community types are less for the newer model year vehicles.

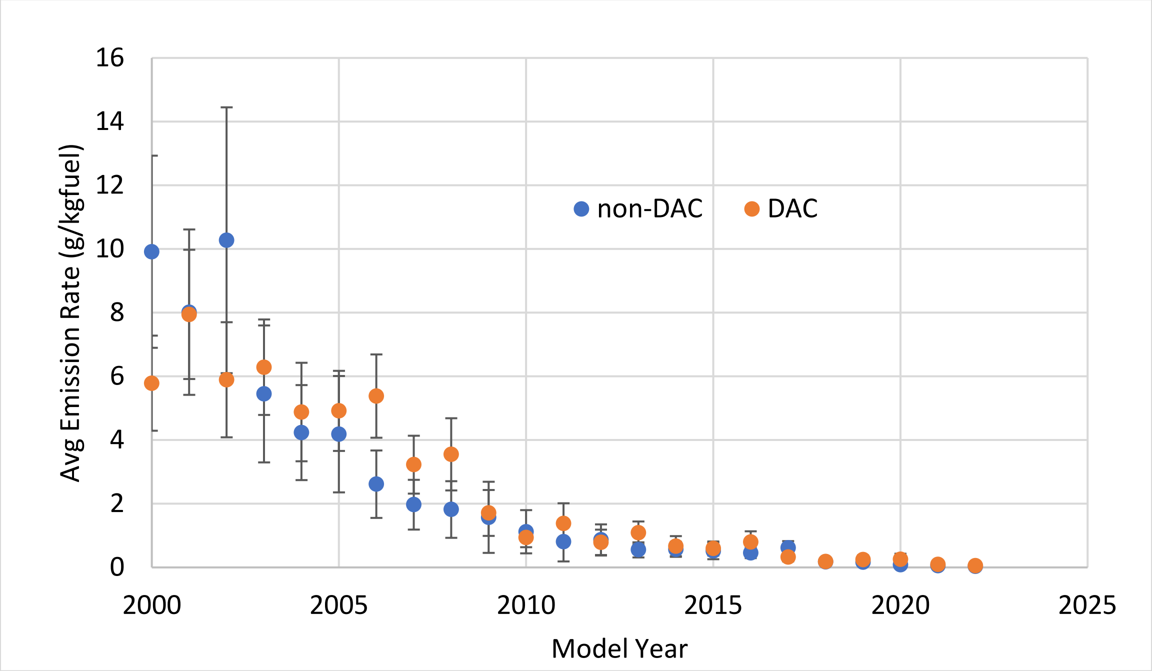

Figure 20. NO emission rates for non-DAC and DAC LDVs, averaged by model year for the El Centro campaign. Error bars indicate 95% confidence intervals.

The previous three figures, which were typical of the broad trends observed in other campaigns, indicate that the elevated overall average emissions for DAC vehicles are not only due to their older model years. Even within a given model year, emission rates for vehicles from these communities tend to be elevated, especially for older vehicles.

ERG also investigated how emissions rates are distributed across the different communities' vehicles. Appendix G presents the distributions of measurements of HC, CO, and NO for each community type at each campaign. Counts of RSD measurements are presented by emission rate as well as cumulatively. These types of plot generally indicate that, as compared to the other community-type fleets, a lower percentage of the AB617 vehicles emit near zero, and a greater percentage of these vehicles appear in the elevated emission rate bins. The DAC and non-617 DAC populations are more similar, while the non-DAC vehicles have a greater proportion of vehicles emitting near zero.

Previously in this section, the analysis showed that differences in DAC emissions are caused partly by differences in model year distribution and partly by some factor(s) not specific to the model year distributions. One method to estimate the percent of DAC emissions differences that are explained by the model year difference is to calculate the total emissions by campaign if the non-DAC emission rates were re-weighted by the DAC model year distribution. ERG performed this analysis as follows:

1. Determine the average non-DAC emission rate by model year for each campaign
2. Determine the DAC model year distribution for each campaign
3. Multiply the non-DAC emission rates by the DAC model year distribution and sum this value for each campaign to get a hypothetical total emission rate
4. Divide the by-site hypothetical emission rate sum by the total counts in the model year distribution (or 100% if using percent instead of counts)
5. Determine the difference between the hypothetical model-year shifted emission increase and the measured DAC emissions increase

The results of this analysis are presented in Table 7 for each pollutant of interest. There is a large amount of noise in the results across each site, but the overall average by campaign ranges from 30% to 48%. Negative values exist in the table where the model year trends indicated an opposite expected emissions trend from that observed, likely due to noise in the calculated model-year-averaged emission rates. For San Ysidro, the model year distributions for DAC/non-DAC were closer than many other sites and the negative CO value is likely due to noise. In the case of the Fresno NO value, the DAC vehicles tended to be older than the non-DAC vehicles (as was typical), however the measured DAC emission rates were less than the measured non-DAC emission rate across most of the model year spectrum, resulting in the negative value in the table. This trend was not observed at any other campaign and ERG found that it did not relate to fuel types or the breakdown of passenger cars and light trucks and so was unable to determine a cause. In the case of values exceeding 100%, this was due to the model years indicating a larger expected increase in emissions from non-DAC to DAC than that observed in the measurements (which were likely lower in those few cases only because of measurement noise).

Table 7. The estimated percent of the DAC and non-DAC emissions difference due to the shift in model year

Campaign	HC	CO	NO
Bakersfield	21%	30%	44%
City of Industry	156%	49%	66%
El Centro	7%	5%	13%
Fresno	7%	35%	-44%
Oakland	36%	31%	56%
Riverside	35%	31%	56%
San Ysidro	1%	-2%	13%
Stockton	119%	36%	75%

West LA	49%	55%	123%
Average	**48%**	**30%**	**45%**

ERG also analyzed the ratio of DAC to non-DAC emission rates as a function of model year. Previously presented plots of DAC and non-DAC emission rates by model year indicate a smaller difference in emission rates for newer vehicles. Given that newer vehicles are cleaner than older vehicles, however, it may be instructive to determine whether the ratio of the emission rates changes with model year. As a simple investigation into this, ERG determined the ratio of DAC emissions to non-DAC emissions by model year for each campaign. Then, this by-model year ratio for each campaign was averaged into a single ratio by model year for each pollutant. The variation of this average ratio is presented in Figure 21. ERG investigated the outlying HC values but was unable to determine a cause outside of measurement noise. A linear trendline is fitted to each group, and all three trendlines have a negative slope (though the slope for NO is much flatter than for HC and CO). The data suggest that DAC and non-DAC emission rates are more similar for newer model years, even when accounting for newer vehicles emitting less.

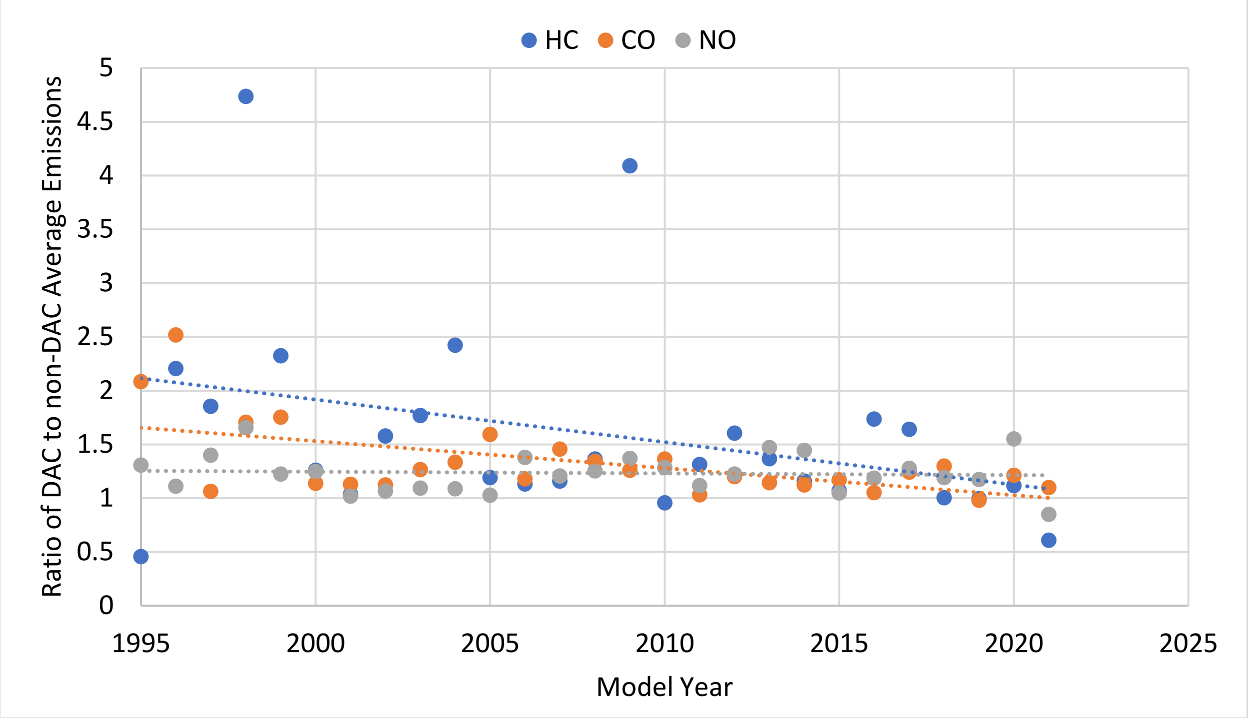

Figure 21. The campaign-averaged ratio of DAC to non-DAC emission rates by model year for HC, CO, and NO.

Analysis Topic 2, Extend Historical West LA RSD Data

The DU team has been periodically conducting RSD campaigns at the highway onramp from La Brea Avenue since 1999 and has now completed 9 total campaigns.[15,16,17] Findings and historical trends from these campaigns have most recently been provided to CARB in DU's 2019 final report for project 17RD015.[18] This section adds the measurements from the 2021 campaign to those historical findings, presented on a similar basis to DU's previous report for consistency.

Figure 22 presents the all-vehicle average emissions measured during each historical campaign year for the three pollutants HC, NO (left axis) and CO (right axis). Average readings for NO continue to trend downward in recent measurements, while CO is relatively unchanged and HC has trending upwards in the two most recent campaigns.

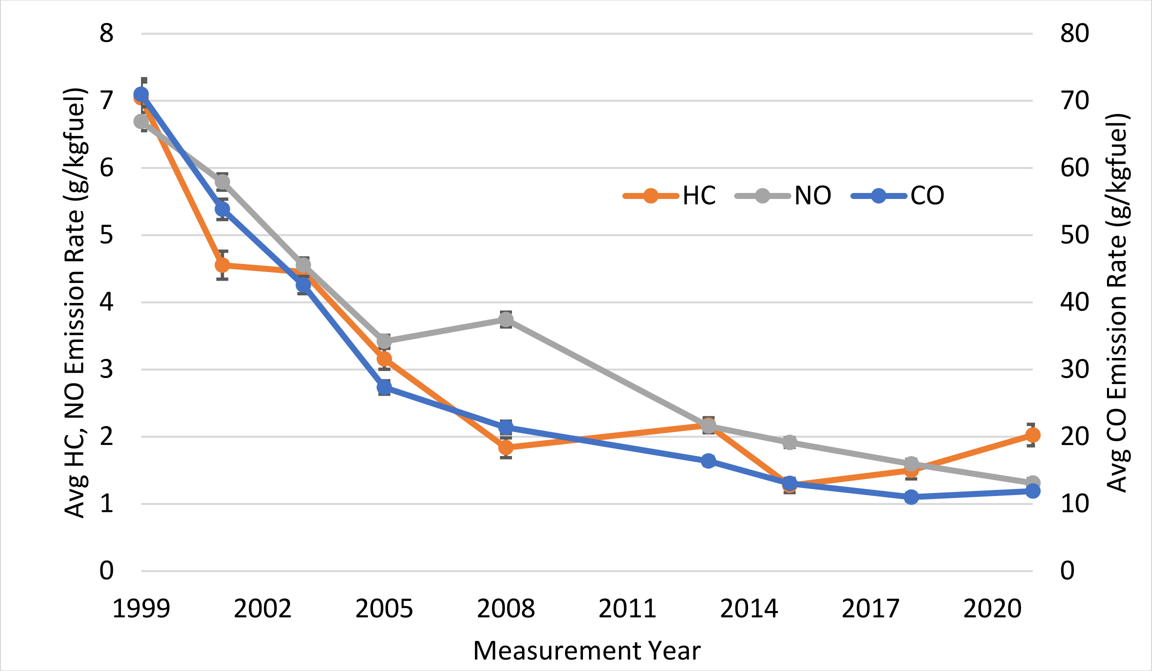

Figure 22. Overall average emissions measured at the La Brea Site by measurement year. Error bars indicate 95% confidence intervals.

Given that the historical dataset spans over 20 years, the fleet makeup may have changed during that time. Figure 23 presents the percent of heavy-duty (i.e. class 3 and above) vehicles successfully measured during each year's campaign as well as the percent of vehicles that were diesel-powered. Both the HDV and diesel vehicle percentages have been increasing in the two most recent campaigns. It should be noted that previous campaigns did not include a front camera, so that is likely the cause of some of the increase in valid, registration-matching HDV measurements in the 2021 campaign. Also, within LDVs, the percentage of passenger cars compared to Class 1 and 2 trucks declined recently from 60% in 2013 and 2015 to 54% in 2021, which could be related to the recent increase in emission rates of CO and HC.

It would be of interest to observe the growing fraction of hybrid and electric vehicles across the historical data from the La Brea site, however the RSD system was not set up to ensure the capture of these vehicles until the most recent campaign. Therefore, one limitation of this historical dataset is the inability to determine the rate of market penetration of those powertrain types.

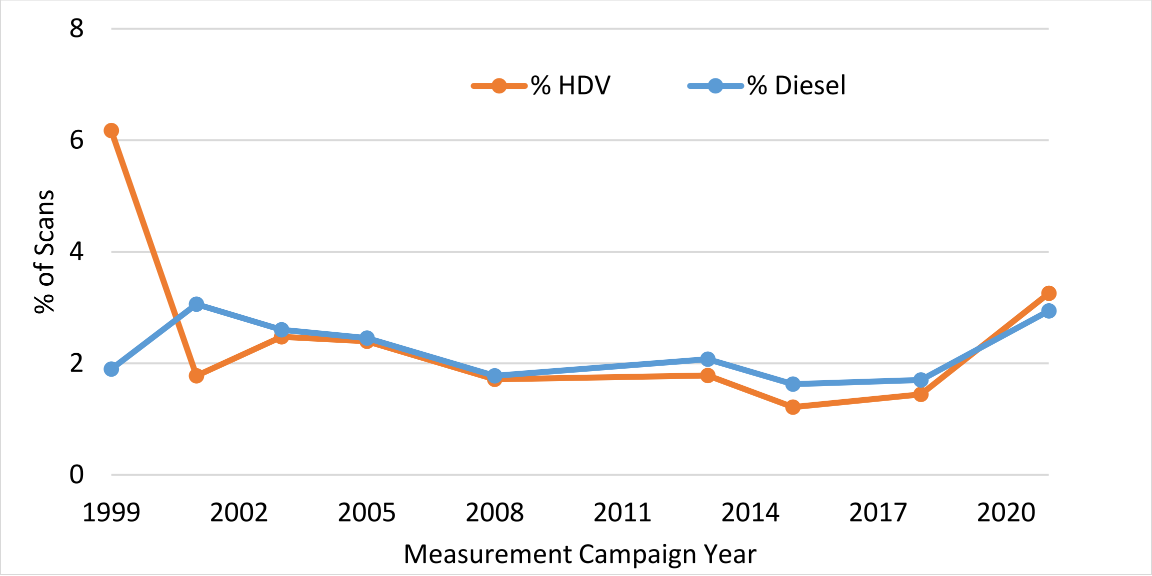

Figure 23. The percentage of heavy-duty vehicles as well as diesel-powered vehicles of all successful measurements in each West LA campaign year.

As the on-road vehicle fleet continues to turn over to newer and lower-emitting vehicles, the proportion of total emissions from the small number of high emitters tends to grow. Figure 24 presents the fraction of the total measured emissions that were emitted by the top 1%-emitting fraction of the vehicles by each pollutant. The percent of NO emitted by the highest emitters can be seen to have been steadily increasing; however the trend for HC and CO has begun to decline as average emission rates of these pollutants have stabilized.

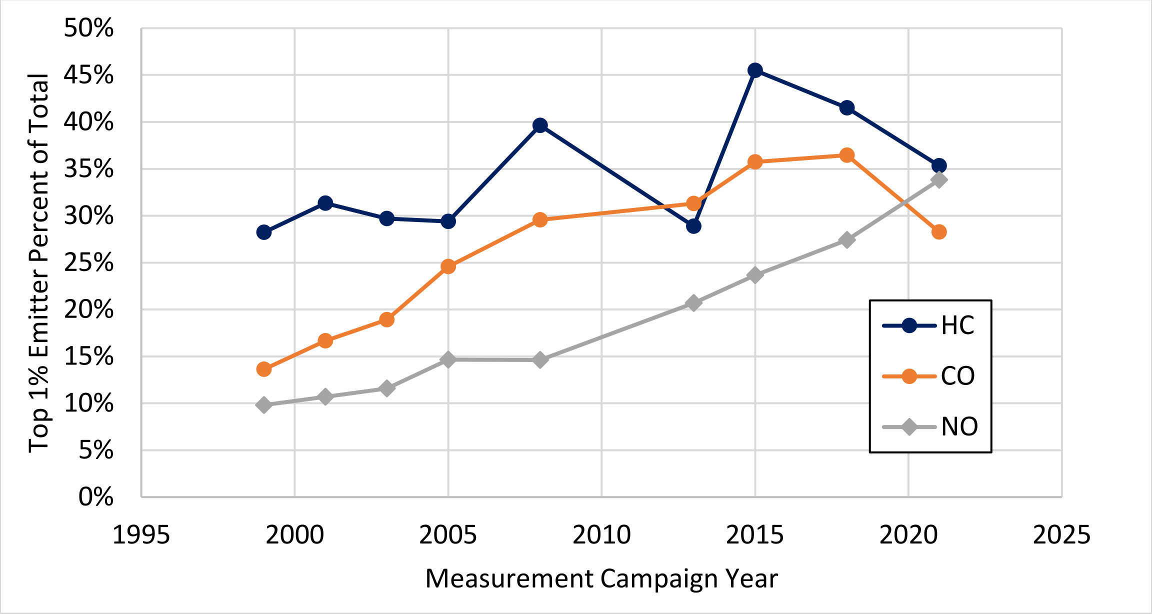

Figure 24. Emissions from the top 1% of emitters as a percent of total measured emissions

ERG also analyzed the historical La Brea Ave data on the basis of vehicle age. Presenting emissions on the basis of vehicle age allows for the determination of relative levels of emissions deterioration over time. To reduce clutter, plots by vehicle age in this section are limited to alternating measurement years. Axes range from left to right over decreasing vehicle age. Figure 25 presents the HC emissions by vehicle age over different measurement years. The plot depicts the decreased emissions deterioration rates observed in newer fleets of vehicles.

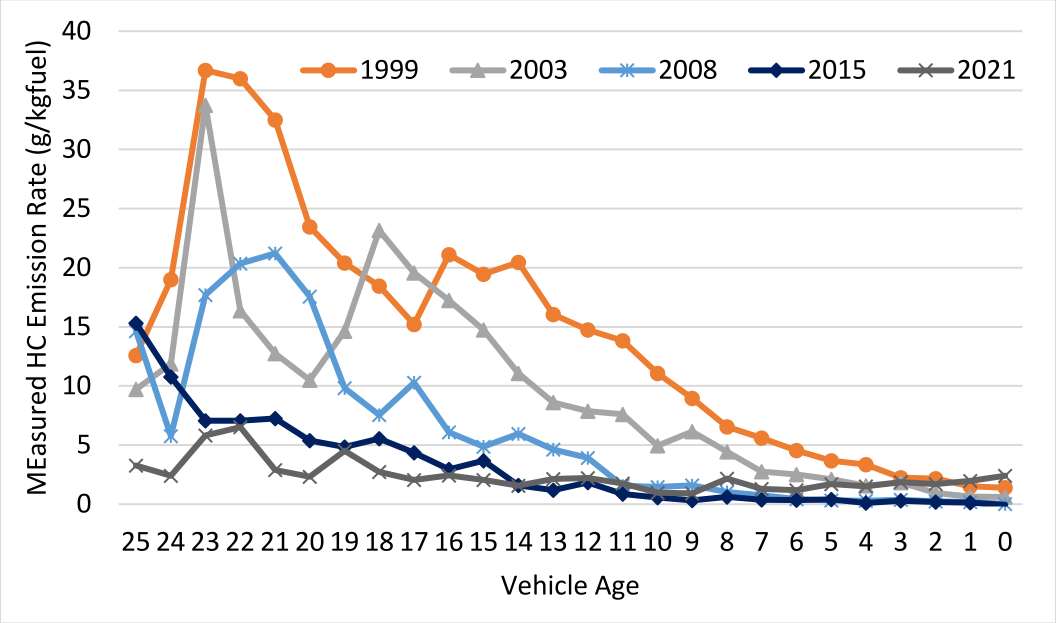

Figure 25. Average HC emission rates by vehicle age for the different measurement years

Figure 26 and Figure 27 present similar by-age results for CO, and NO, respectively. Similar trends are observed to HC, with the level of emissions deterioration decreasing steadily over more recent measurement campaigns.

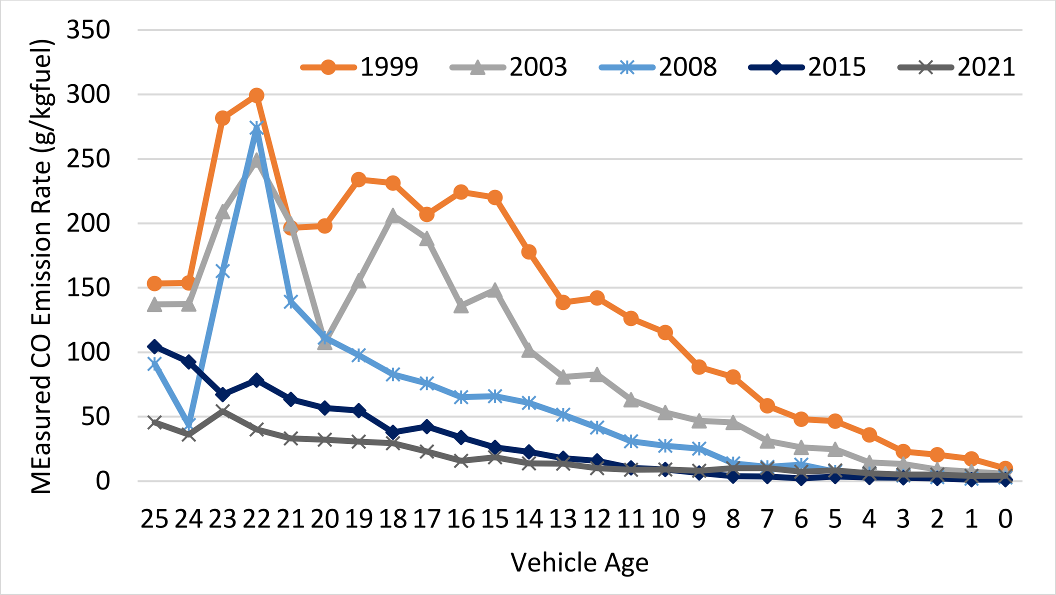

Figure 26. Average CO emission rates by vehicle age for the different measurement years

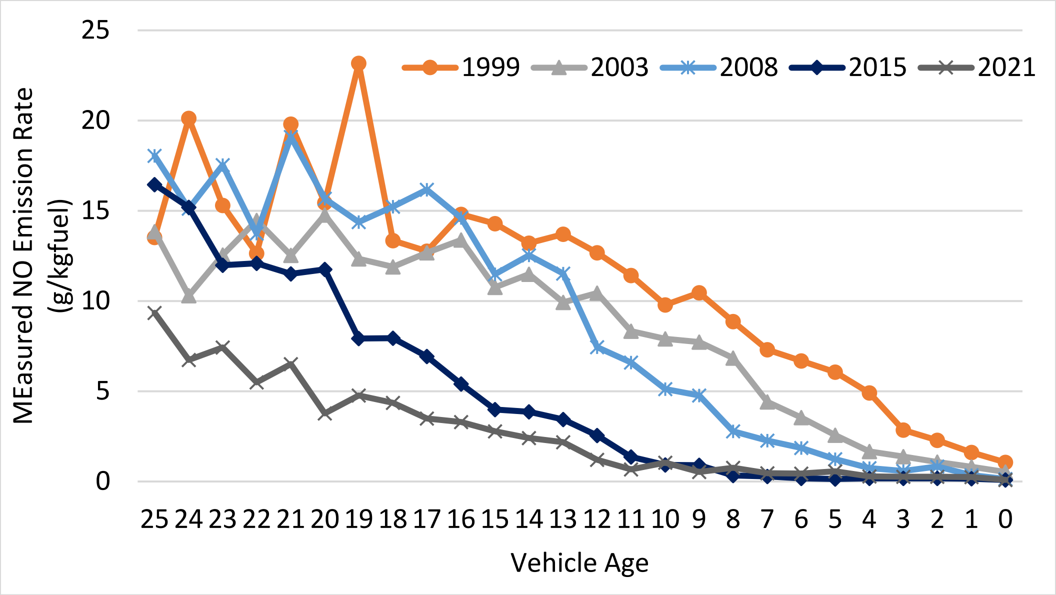

Figure 27. Average NO emission rates by vehicle age for the different measurement years

DU has also presented the La Brea Ave emission measurements as a function of estimated VSP in earlier historical reports. Emission rates can be expected to trend with VSP[52], though this effect can be confounded in RSD because measurements are on the basis of fuel consumption rate. For comparison with historical data, it should be noted that the observed acceleration rate distribution in the 2021 measurement year was different than in prior years, resulting in much lower calculated VSP values. Figure 28 presents the changing VSP distributions over time, with the distribution for 2021 trending lower compared to the other years. The distribution for 2013 is the closest to 2021, with all other years showing much greater agreement with each other at higher VSP levels. In both the 2013 and 2021 campaigns, DU noted that the traffic metering signal was inoperative. It was functional in all other measurement years, so this is likely to be the cause of the two outlying distributions. Notably in the 2021 data, there was only one measurement in the 25 kW/tonne bin, leading to large potential error in reported emissions for that bin. It is possible that the lower VSP levels of the 2021 measurement year contributed to the increasing trends in mean emissions of CO and HC, given that, at particularly low VSP levels, emissions of those two pollutants were observed to be higher in terms of $g_{pollutant}/kg_{fuel}$.

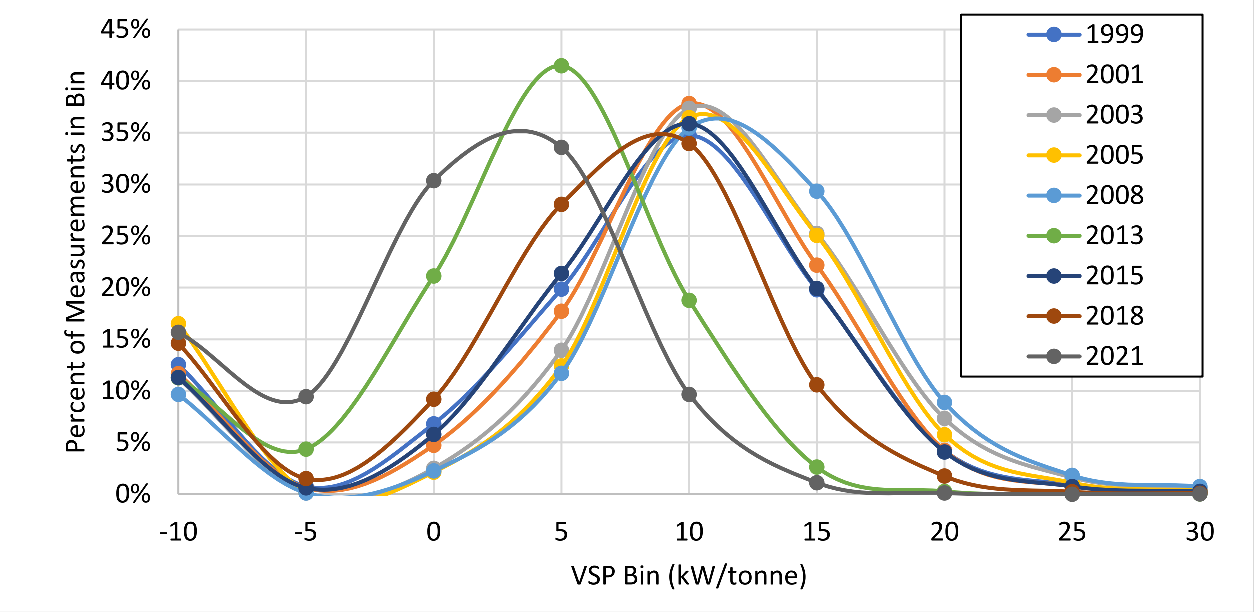

Figure 28. Distribution of estimated VSP in each measurement year.

Figure 29 - Figure 31 present the historical average VSP-binned emission rates across measurement years for HC, CO, and NO, respectively. Note that only one data point was measured for the 25 kW/tonne bin for 2021, likely resulting in high error for that point in all three plots. That point contains the lowest mean emission rates for all three pollutants, which, as with all other measurements in this work, are left as negative values and not adjusted to zero. The figures indicate that HC and CO tend to be elevated at very low levels of VSP, whereas NO does not have a corresponding increase. This, coupled with the lower VSPs observed in the most recent measurement year, may be the cause of the increased HC (and to a lesser extent, CO) emission rate observed in the 2021 campaign. Similarly, the increase in observed HC emission rate from 2008 to 2013 (depicted in Figure 22) may also have been caused by the lower VSPs observed in the 2013 campaign. It should be noted that, while the measured emission rates of HC and CO trend upwards at very low VSP, these measurements are on the basis of fuel consumed, which trends down at low VSP; the findings do not suggest that the absolute or time-based mass emission rate is higher at low VSP.

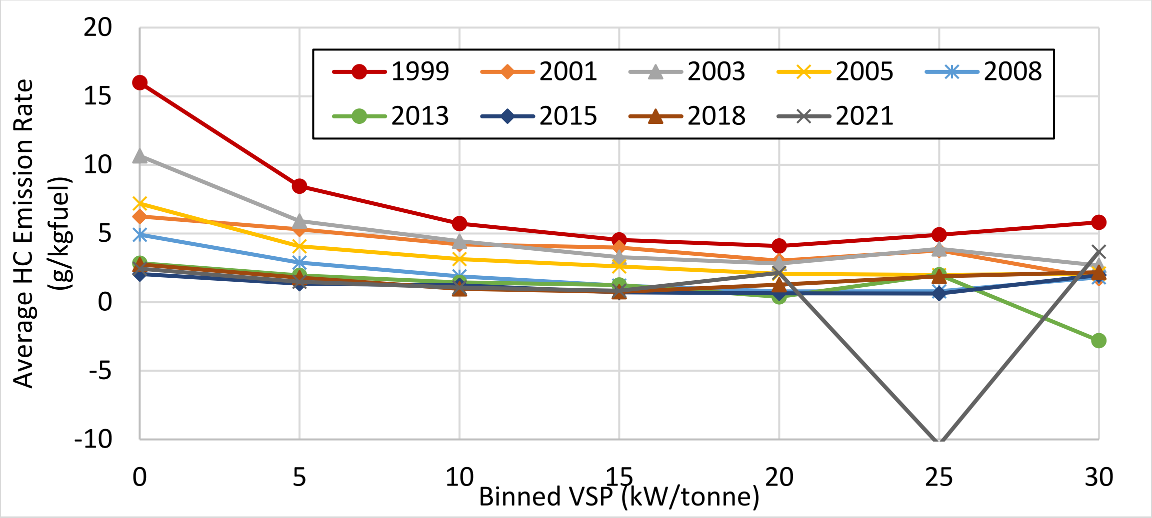

Figure 29. Average VSP-binned HC emission rates by measurement year

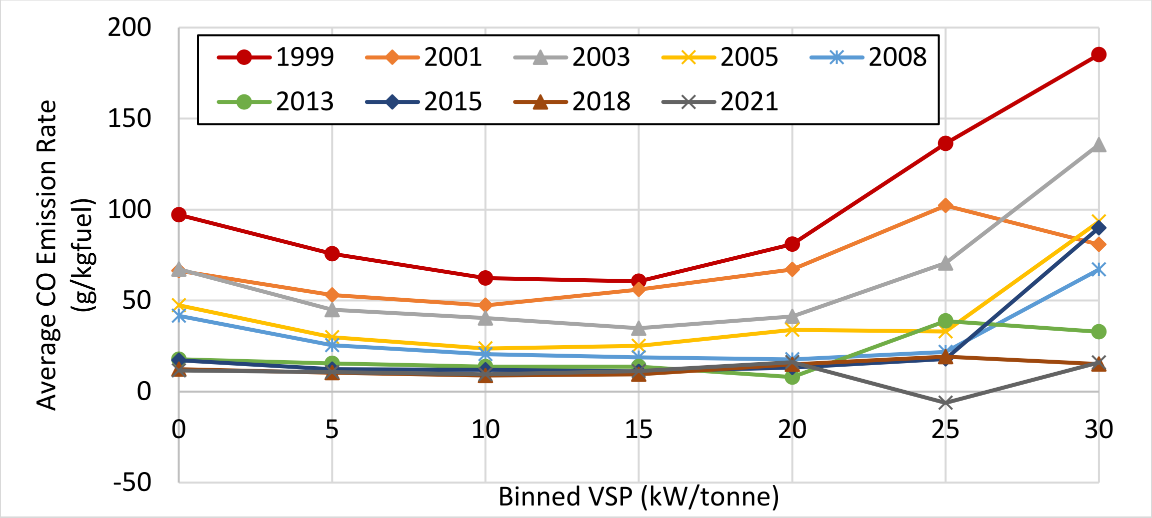

Figure 30. Average VSP-binned CO emission rates by measurement year

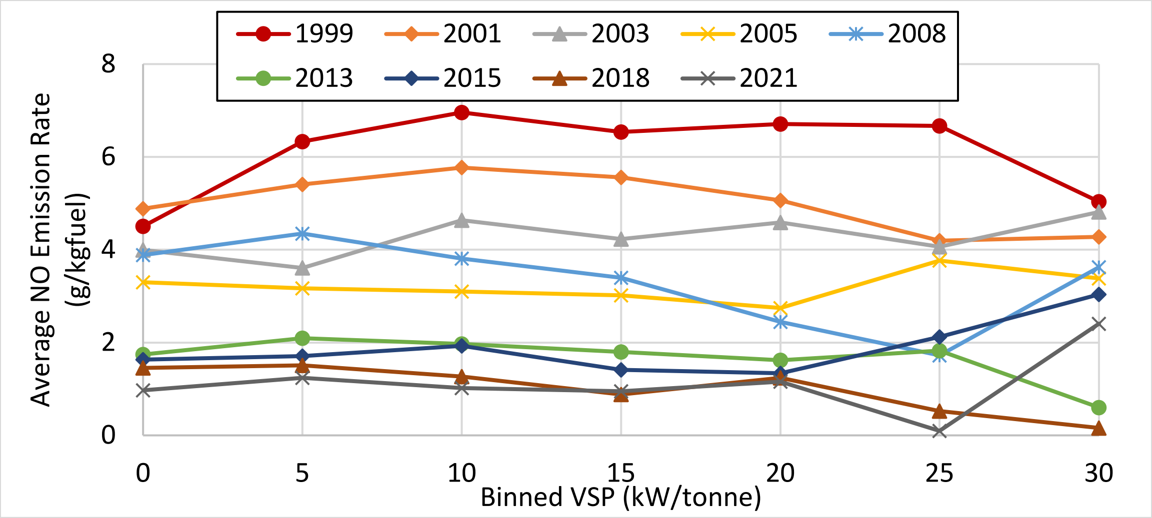

Figure 31. Average VSP-binned NO emission rates by measurement year

Analysis Topic 3, Evaluate Emissions of In-state and Cross-border Vehicles

RSD campaign measurements near the U.S. – Mexico border were used to examine emissions differences between California-registered vehicles vs. out-of-country vehicles. The El Centro measurement sites were located approximately 8 miles from the border crossing, and the two San Ysidro sites were located approximately 1 and 3 miles from the border, respectively. Approximately 6% of the readable El Centro plates and approximately 9% of the readable San Ysidro plates were identified as being from Mexico. At the time of the initiation of the two border campaigns, ERG was already in possession of recent Mexican vehicle registration from the Baja area and was able to find matches in that data for approximately 77% of the border crossing vehicles. This section presents information about the vehicle types, the model year distributions, and the emissions measurement results.

The Mexican registration data used by ERG in this work included information about LDVs and HDVs of a variety of fuel types. However, based on a review of the Mexican registration-matched vehicles that were observed during the RSD campaigns, the vast majority (99+%) appeared to be light-duty vehicles based on the indicated vehicle class and type. As a result, all analyses in this section compare the observed Mexican vehicles to only the LDV fraction of the observed CA-registered vehicles. Over 99% of the Mexican registration-matched vehicles were gasoline powered, with about 1-2% of those vehicles being hybrids.

Table 8 presents the average model year for the two fleets of vehicles observed during the two border campaigns. Within each campaign, the average model years of the two fleets are not significantly different at 95% confidence. The distributions of model years for each fleet at each campaign are presented in Figure 32.

Table 8. The average model years of the CA- and Mexico-registered fleets observed during each border RSD campaign

Site	Avg. CA-Fleet MY	Avg. Mexican-Fleet MY
El Centro	2014.8	2015.1
San Ysidro	2013.2	2011.5

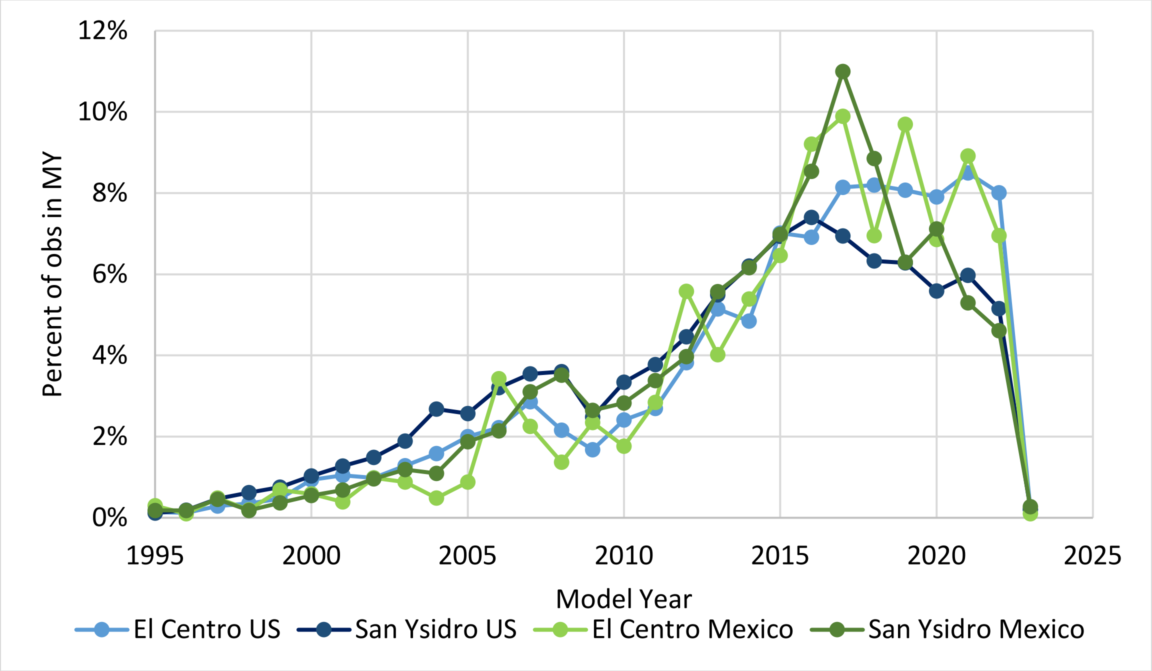

Figure 32. The distributions of model year for the CA- and Mexico-registered fleets at El Centro and San Ysidro.

The overall emission rates of HC, NO, and CO are presented in Figure 33. For all three pollutants, the Mexican fleet had higher mean emission rates, though the differences are only significant at 95% confidence for NO and CO.

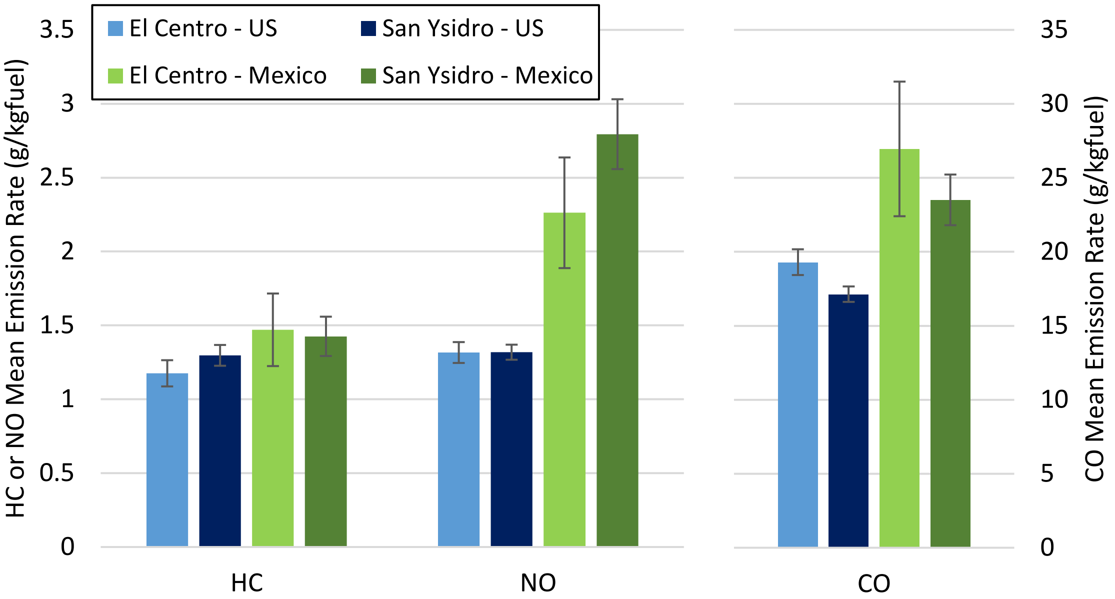

Figure 33. The average emission rates for the CA and Mexican fleets of vehicles at each border site. Error bars represent 95% confidence intervals.

Figure 33 indicated that the emission rates tended to be significantly different between the CA and Mexico based fleets. Figure 34 presents the average emission rates by model year for the two fleets (with the El Centro and San Ysidro campaigns taken together). The emission rates tend to be more different in the older model years.

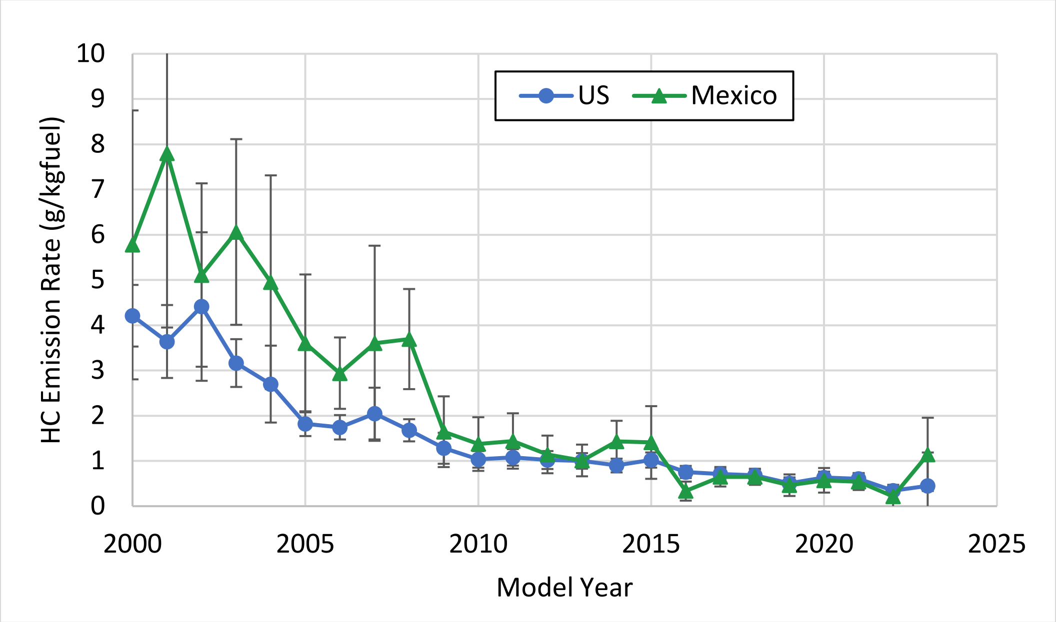

Figure 34. The average HC emission rates for the CA and Mexico registered fleets by model year. Error bars indicate 95% confidence intervals.

Likewise, Figure 35 presents the model-year average emissions for CO for the two fleets, and Figure 36 presents the by-model year average emissions of NO. As with HC, the emission rates of the two fleets tend to diverge more at older model years. For CO, many of the model years do not have significantly different emission rates at 95% confidence; however for NO, the emission rates become significantly different at about model year 2012 and older and remain so back through model year 1995 and beyond.

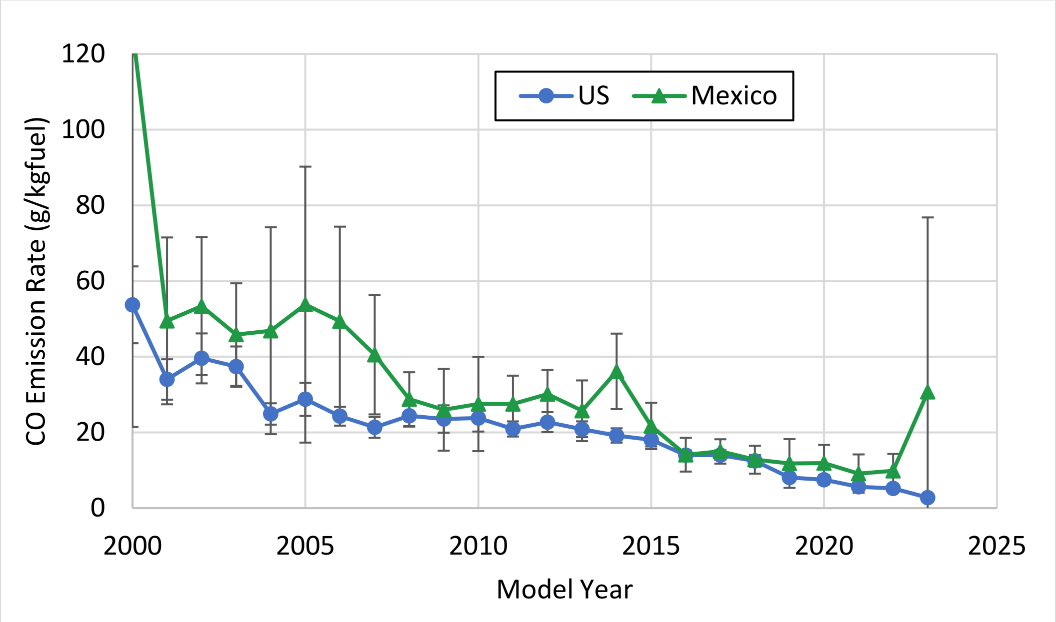

Figure 35. The average CO emission rates for the CA and Mexico registered fleets by model year. Error bars indicate 95% confidence intervals.

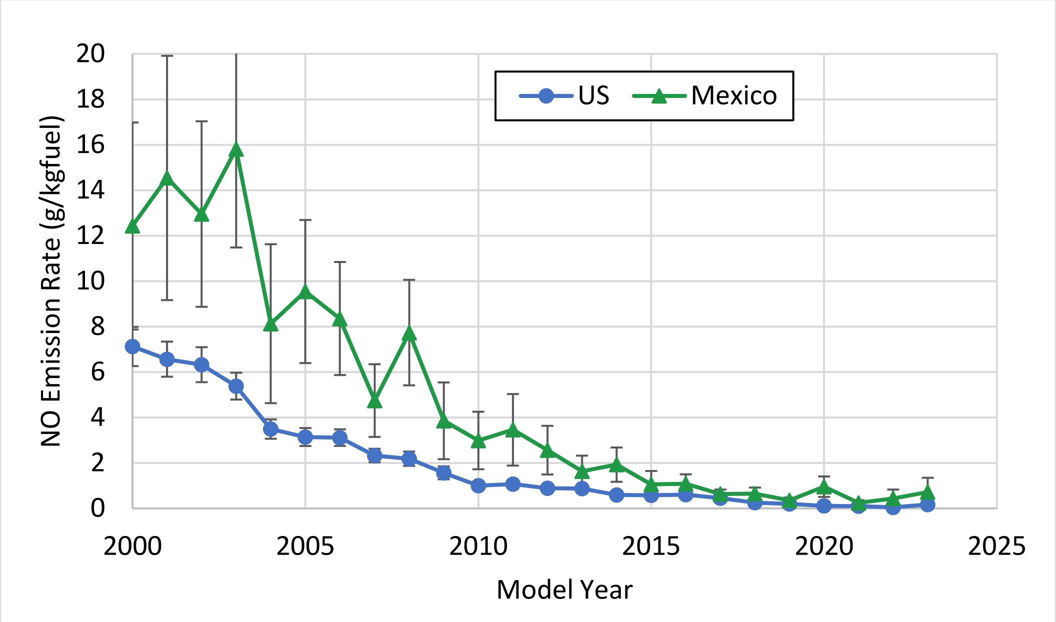

Figure 36. The average NO emission rates for the CA and Mexico registered fleets by model year. Error bars indicate 95% confidence intervals.

Analysis Topic 4, Evaluate Electric Vehicle Fractions in DAC and non-DAC

Figure 9 presented the fractions of different fuel types overall for DAC and non-DAC. Analysis Topic 4 involves a more specific investigation into the prevalence of EVs in different communities and how often these vehicles were observed at RSD sites. The EV prevalence varied widely across the different groups of observed vehicles. Figure 37 presents the percentage of EVs observed in each combination of DAC and AB617 status for LDVs. Oakland had the highest prevalence of EVs across all community types, with El Centro and San Ysidro having relatively few. At all campaigns, the non-DAC/nonAB617 communities had the highest EV fractions. The AB617 communities generally had the lowest fraction of EVs, whether they were DAC or non-DAC. Note that Fresno is not included in the figure because, as described previously, EVs were not included in the data from that campaign.

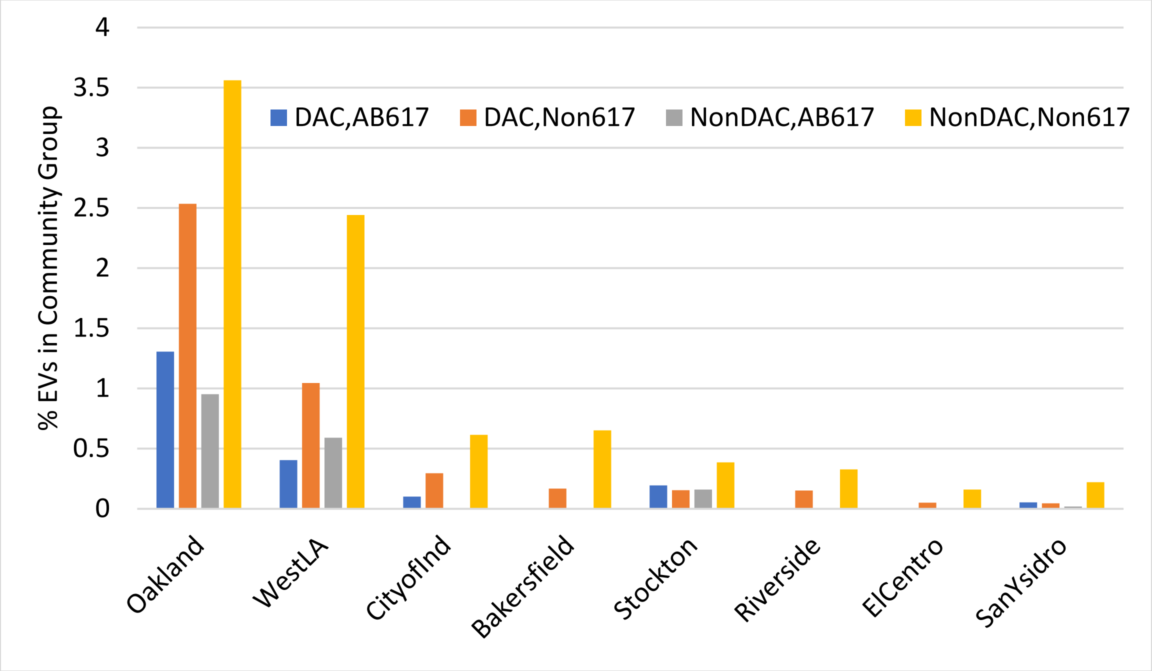

Figure 37. The percentage of EVs observed in each combination of DAC/AB617 for the different campaigns.

ERG also evaluated the effect of the presence of EVs on the average emissions for each campaign by calculating the averages including and excluding EVs (which were assigned emission rates of zero). Figure 38 presents the approximate percent reduction in calculated average emission rates when including EVs compared to the average of all other LDVs by campaign and DAC status. Only one figure is shown because the percentage factors for each combination of DAC status and campaign are approximately equal for all pollutants, varying only slightly due to minor variations in measurement validity rate across pollutants. As would be expected, Oakland and West LA have the largest factors due to the higher prevalence of EVs observed at those campaigns. Fresno is again excluded because EV measurements did not take place. It should be noted, however, that Figure 38 may be an overestimate of the emission reduction due to the presence of EVs. The EV fleet is much newer in model year than the average vehicle in the California fleet so it is possible that, if motorists had not chosen an EV, they would have selected another recent model year, and thus relatively low emitting, vehicle, limiting the criteria pollutant emissions benefits of selecting an EV.

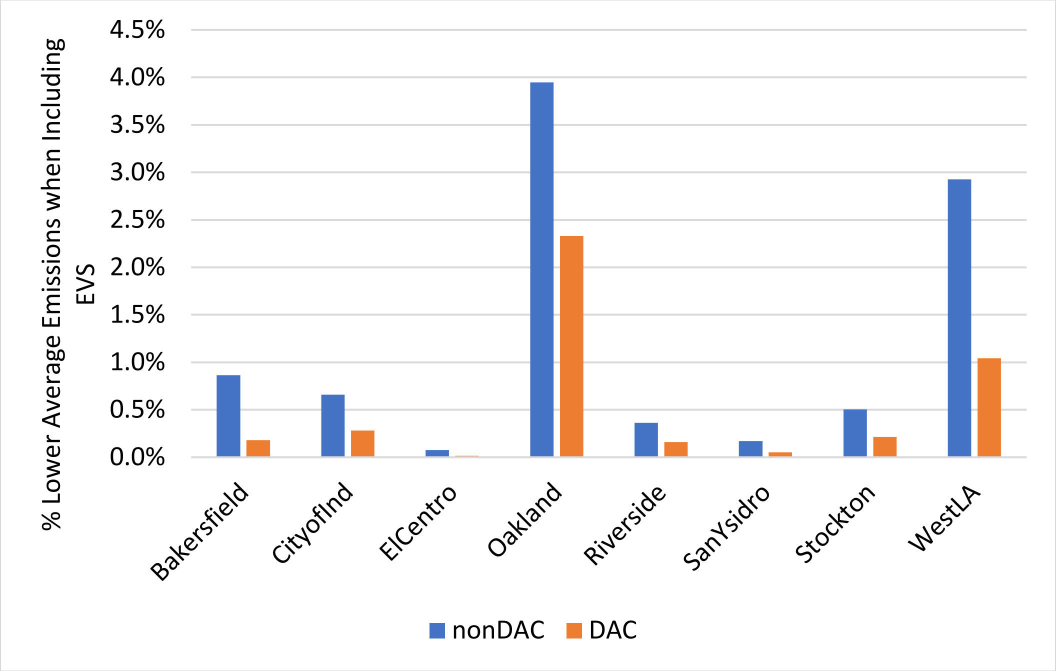

Figure 38. The percent lower average emission rate for each campaign by including or excluding EVs from the calculation, presented for DAC and non-DAC.

ERG reviewed the model year distributions for EVs registered in and outside of DACs. Figure 39 presents the EV model year distribution (LDVs only) for vehicles registered in DAC (SB535 and AB617 taken together) and non-DAC. The model year distributions do not appear to be notably different, and the mean model years of the two populations were not significantly different at 95% confidence. ERG also reviewed this distribution for all 4 combinations of SB535 and AB617 communities, but the distributions were extremely noisy due to the relatively few datapoints in each of the four groups.

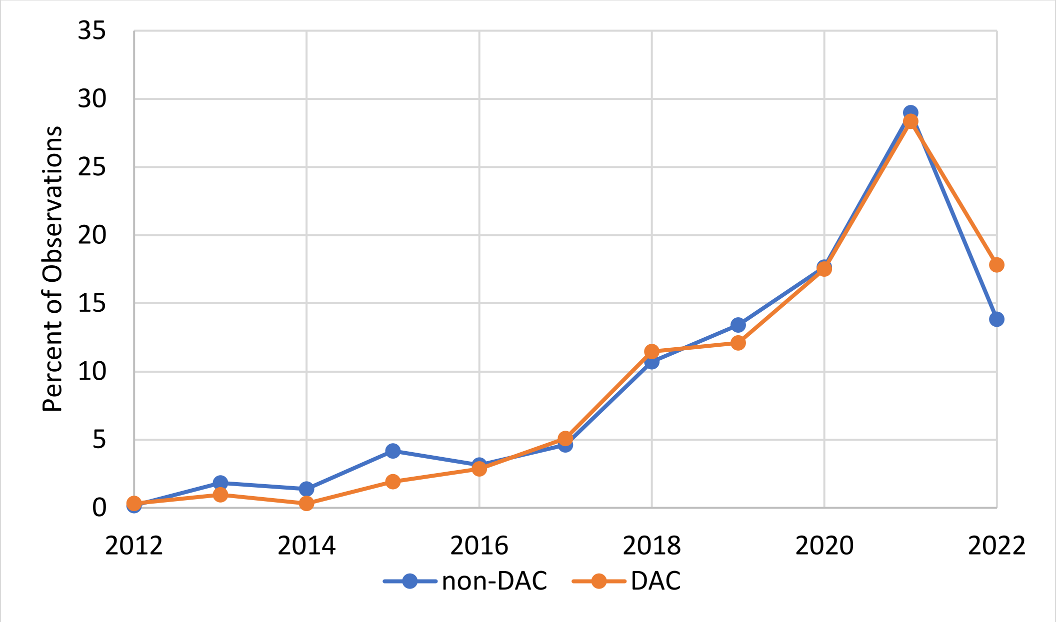

Figure 39. The model year distribution of LDV EVs, DAC and non-DAC

Analysis Topic 5, HDV Profiles and Emissions Trends

As described previously, measurement of HDVs by RSD is generally more challenging than measuring light-duty vehicles. During HDV measurement, it is more likely that the RSD light beam will be interrupted multiple times per vehicle pass by additional axles, mudflaps, and trailer components, etc. This increases measurement error and leads to a greater percentage of invalid measurements that are outside of QA limits. It also adds uncertainty to when a measurement interval should begin, resulting in a greater chance of low signal strength. Also, updraft exhausts were not readable by this project's experimental setup, which was based on near-roadway measurement. As a result, analysis of HDVs generally had very few valid measurements, with an associated elevated level of uncertainty. Figure 40 presents the percentage of valid emissions measurements for each truck class combined for all campaigns. It can be seen that the lighter truck classes are more likely to result in valid measurements; this is likely due to their exhaust systems being more similar in location and orientation to light-duty vehicles, which were the measurement priority for this program.

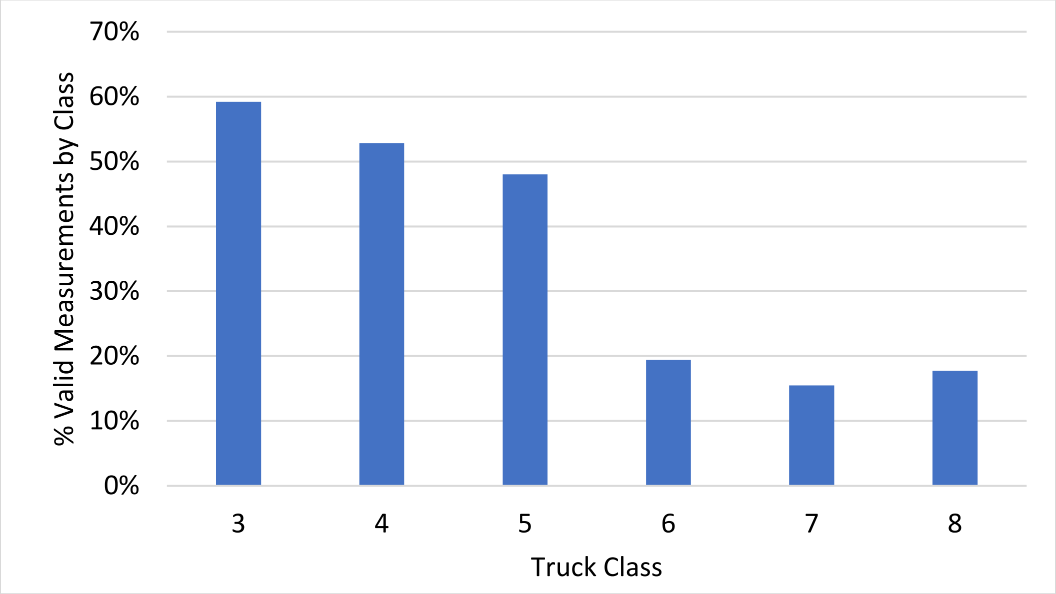

Figure 40. Percentage of valid measurements in the program for HD trucks by class (all campaigns).

To further illustrate the lower measurement validity, Figure 41 presents a comparison by campaign of the valid measurement percentage for LDVs and HDVs. The LDV measurement validity was higher at all campaigns, with the differences at some campaigns averaging about 30 percentage points. The figure indicates that care should be taken when interpreting the HDV emissions results as the emissions data is drawn from a relatively small percentage of all observed HDVs.

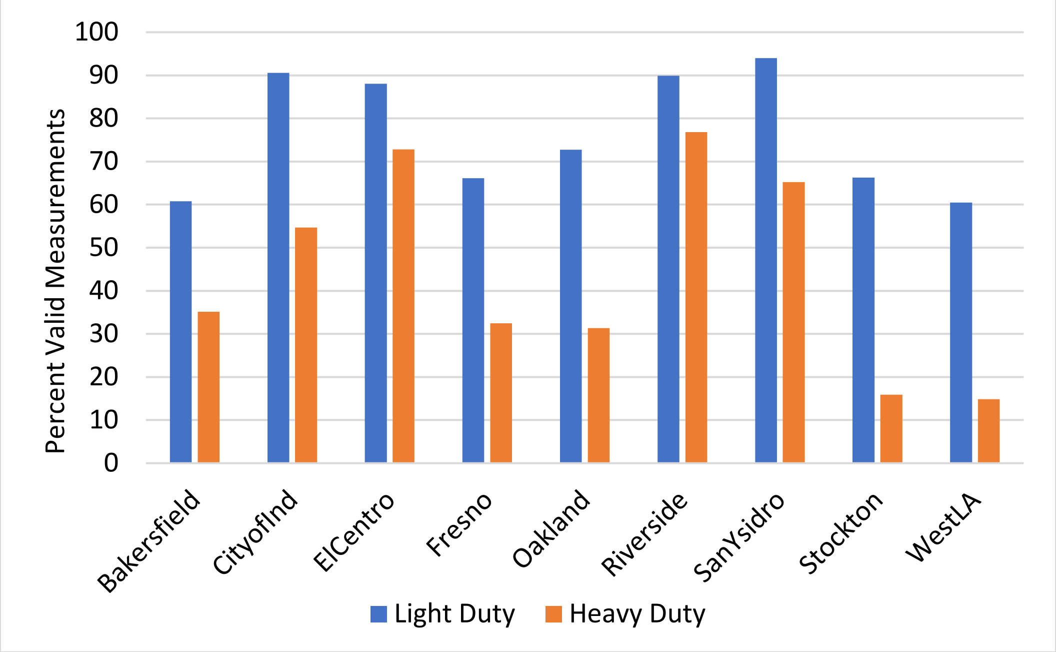

Figure 41. The percentage of valid measurements for HDVs and LDVs by campaign.

Figure 42 presents the distribution of truck classes for all observed HDVs at each site. The figure presents the percentages for all observed, registration-matching HDVs, and includes both valid and invalid measurements. Note, however, that it is likely that fewer HDVs have successful plate readings than do LDVs, for the same reasons as already described for HDVs having fewer valid emissions measurements. So, Figure 42 should not necessarily be used to estimate the fraction of HDV classes actually in operation on the road. Class 3 generally makes up the largest portion of observed vehicles, with Class 7 generally being the least common. Two campaigns had elevated numbers of Class 8 trucks; both had numerous observed trailer-towing tractors and City of Industry also had numerous observed refuse haulers.

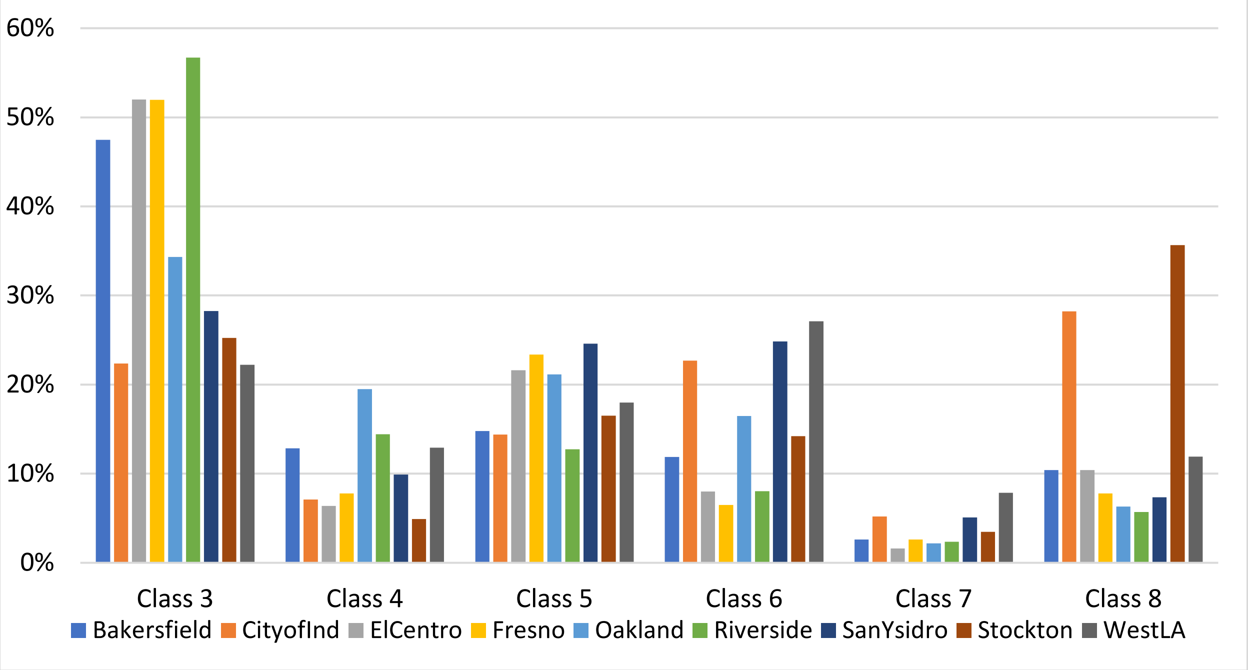

Figure 42. Distribution of the percentage of HDVs in each truck class by campaign.

Figure 43 presents the breakdown of fuel types for each truck class, averaged for all scans from all campaigns. Class 3 is almost exactly half gasoline and half diesel. Classes 6 and above are about 90 percent diesel, with gasoline representing most of the balance for class 6 and natural gas representing most of the balance for class 8.

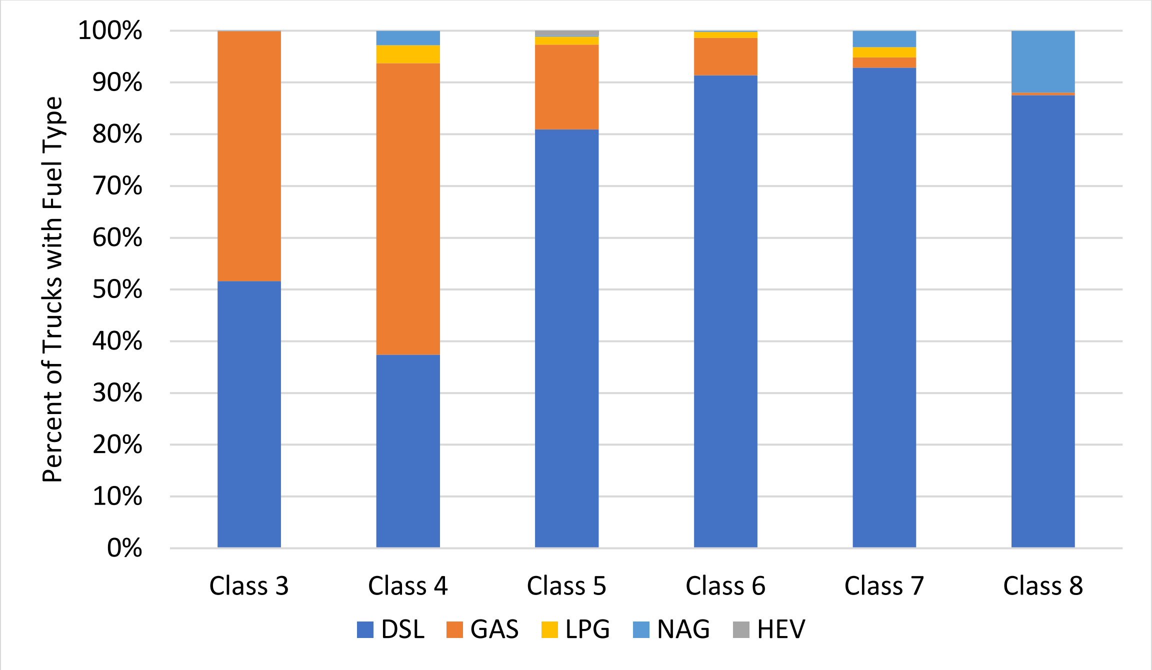

Figure 43. The percentage of registration-matching trucks with each fuel type by truck class. Data represents all campaigns and counts are by scan.

Trucks were grouped by model year to increase the statistical power of the analysis of the relatively small number of valid measurements. Even with the model years binned into groups of 4 years, most campaigns did not have measurement coverage across all or even most combinations of truck class and model year bin. Also, as a result of the smaller sample sizes, the variability in HDV NO emissions across campaigns was larger than observed for LDVs. City of Industry had the largest population of measured HDVs and the widest coverage of truck class and model year bin, so it was the primary campaign used for emissions analysis. Figure 44 presents the average emission rate by model year bin for each truck class observed at City of Industry. All fuel types are included in the averages, and error bars indicate the 95% confidence interval of each mean. Missing bars indicate that no valid observations took place; missing error bars indicate that there were not enough observations to calculate the confidence interval (i.e. less than 4 measurements).

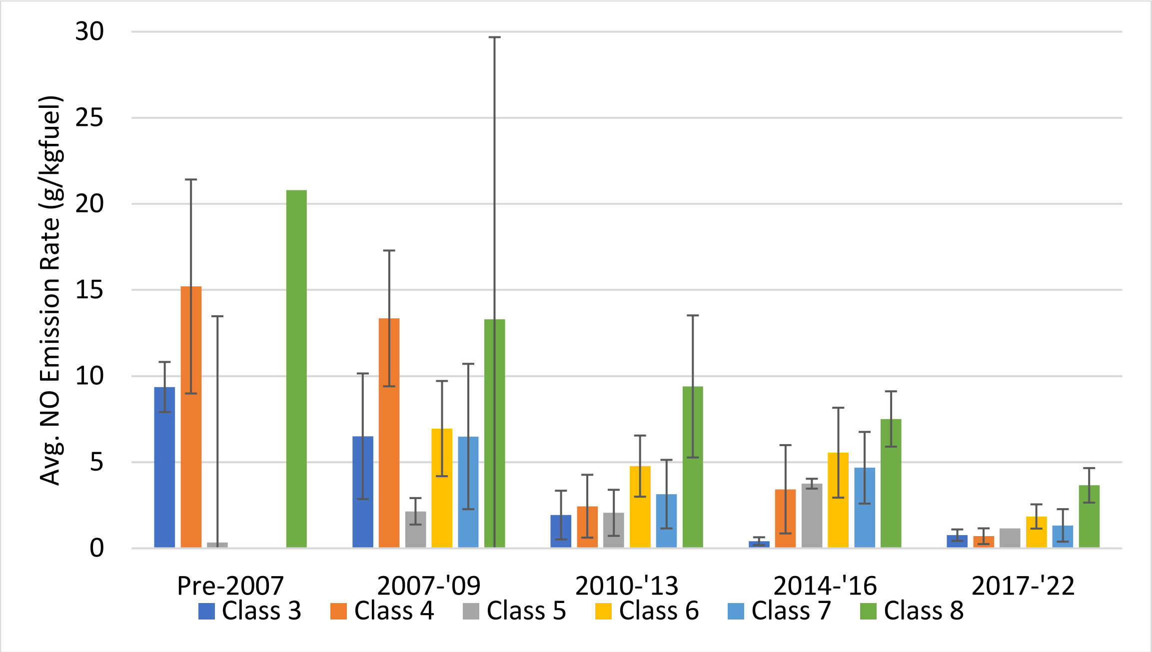

Figure 44. The average emission rate for all HDVs by each truck class and model year bin for all fuels, observed at the City of Industry campaign. Error bars indicate 95% confidence intervals.

The majority of observed HDVs were diesel-powered. Figure 45 presents the average NO emission rates by model year bin and truck class for the diesel-powered trucks operating at City of Industry. Isolating to only diesel trucks generally results in higher calculated emission rates. This is driven primarily by the lighter truck classes which tend more frequently to be gasoline powered and have correspondingly lower emission rates. The heavier truck classes are more similar when comparing the diesel graph and the all-fuel graph as most of the heavier trucks are diesel powered. Stockton had fewer valid HDV NO measurements but was the only other campaign with noteworthy measurement coverage across combinations of truck class and model year bin. The corresponding all-fuel and diesel-only figures for Stockton are presented in Appendix D along with City of Industry for comparison.

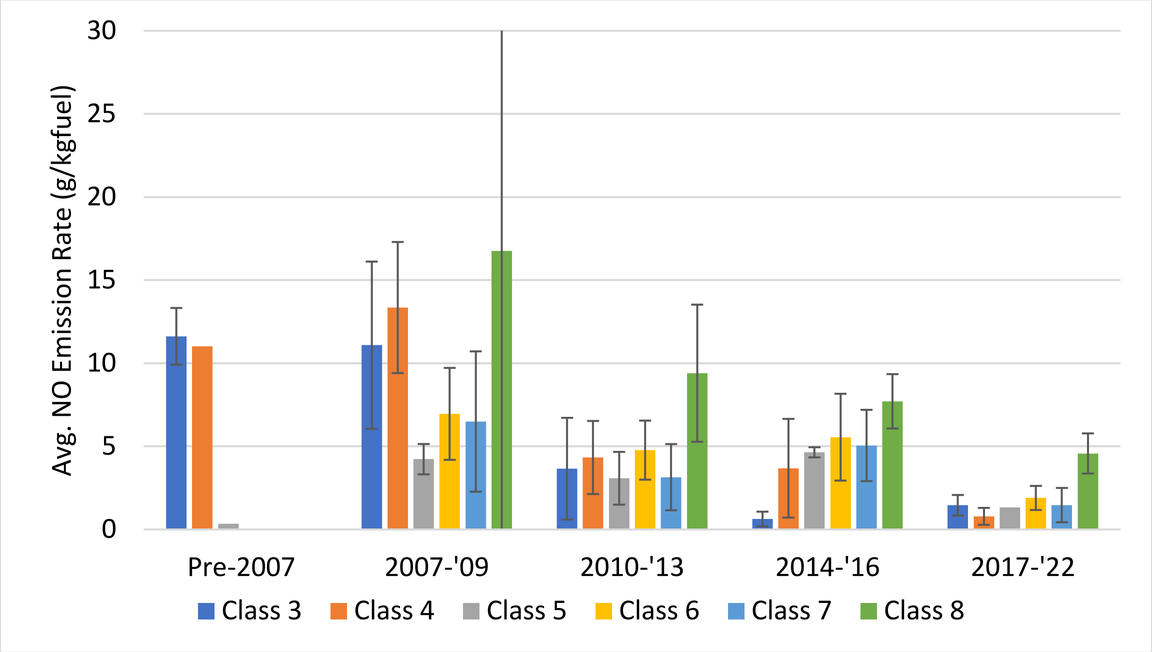

Figure 45. The average emission rate for all HDVs by each truck class and model year bin for diesel trucks only, observed at the City of Industry campaign. Error bars indicate 95% confidence intervals.

The analysis of heavy-duty vehicle emissions is made more complex by the wide differences across truck classes and the very different distribution of fuel types within each. Rather than presenting further graphs of trends by single fuel for HDVs, Figure 46 presents the average HDV NO emission rates at the City of Industry campaign by fuel type and model year bin for each truck class. The error bars indicate 95% confidence intervals of each mean. Fuel types are included for each truck class if enough valid measurements were made to calculate confidence intervals in more than one model year bin. Bars without error bars indicate that there were not enough measurements in that group to calculate a confidence interval. In almost all cases, the diesel trucks have higher emission rates than the other fuels observed in each truck class. Note also that no valid measurements of registration-matching Class 8 pre-2007 diesel-powered trucks were made.

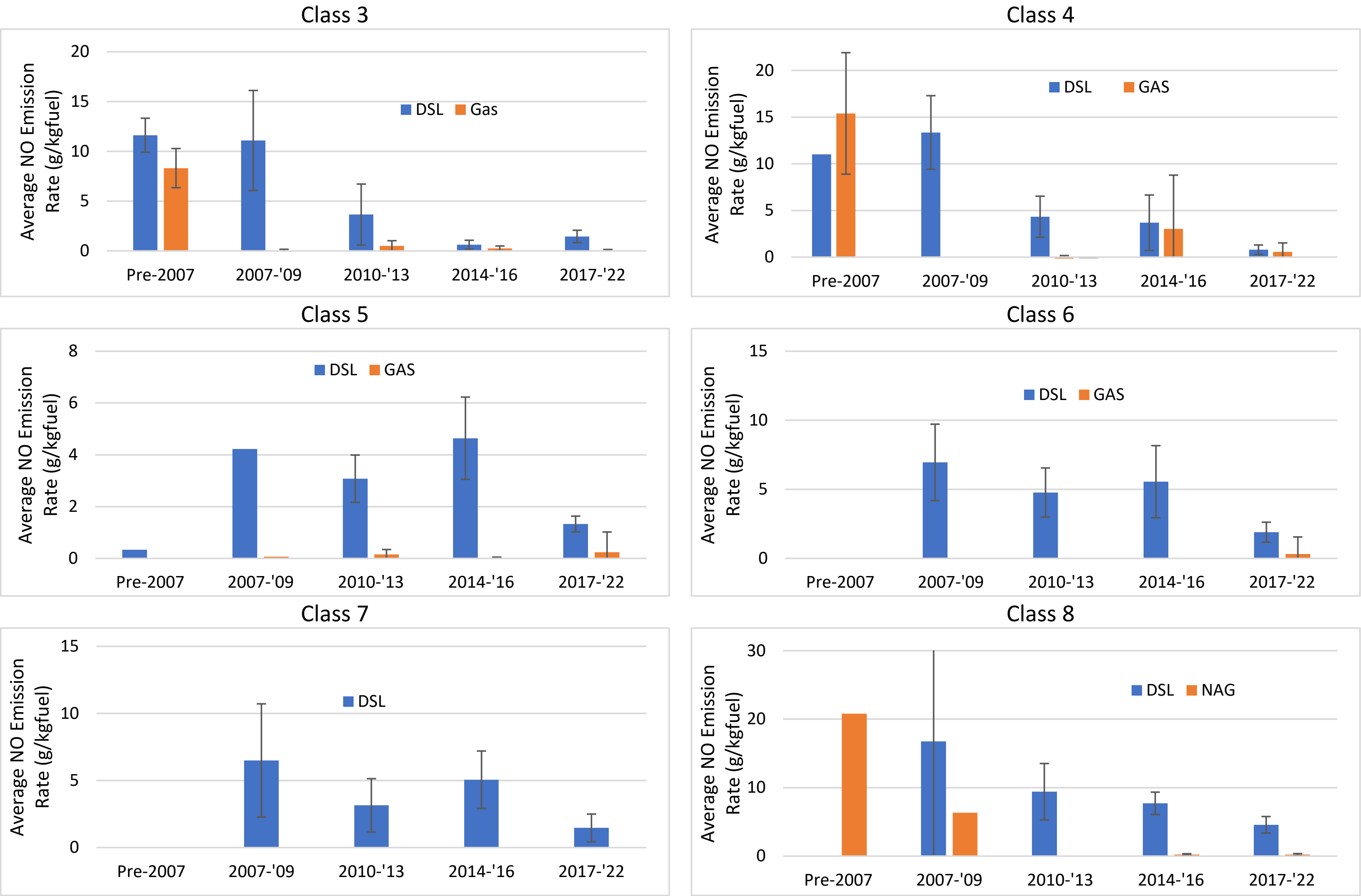

Figure 46. HDV average NO emission rates by model year, truck class and fuel type, for the City of Industry campaign

Analysis Topic 6, Compare RSD to Smog Check Records

This analysis topic included the evaluation of various aspects of the Smog Check program, with the following analysis goals:

1. Evaluate the emissions of COO area vehicles compared to Enhanced and Basic (i.e. biennial test) area vehicles
2. Compare unregistered and out-of-state (US) vehicle emission rates to in-state
3. Evaluate RSD emission rates vs. station pass rates to determine if any stations have significant numbers of passing vehicles that later have elevated emissions
4. Determine if any trends exist in how emission rates vary throughout vehicles' biennial inspection period
5. Determine if the RSD data indicates an observable effect of the 8-model-year exemption

Analyses 1, 2, and 5 required only the RSD and registration data; items 3 and 4 required merging the Smog Check data into the registration-matched RSD data. Table 9 presents the match rate of registration-matched RSD data to the Smog Check dataset, which contained records of all Smog Check tests by California vehicles in recent years. Note that, due to the 8-year model year exemption for new gasoline-powered vehicles, there is a low match rate for newer vehicles; the match rate is much higher for 8+ year old vehicles and is similar to the match rate with the CA registration data.

Table 9. Counts and match rate between Registration-Matching RSD'd LDVs and entries in Smog Check Records for all vehicles and 8+ year old vehicles

	All Vehicles			8+ MY Vehicles		
Campaign	**LD RSD Scans**	**Scans Matching Smog Check**	**% Match**	**LD RSD Scans**	**Scans Matching Smog Check**	**% Match**
Bakersfield	42,044	17,352	41%	13,018	12,086	93%
City of Ind	54,324	24,272	45%	25,300	22,513	89%
El Centro	21,804	2,595	12%	6,156	1,580	26%
Fresno	10,644	5,607	53%	4,710	4,427	94%
Oakland	30,609	14,306	47%	13,177	11,843	90%
Riverside	33,961	14,653	43%	13,256	12,043	91%
SanYsidro	33,004	13,769	42%	14,319	12,449	87%
Stockton	33,904	17,470	52%	14,759	13,493	91%
West LA	25,103	9,456	38%	7,559	7,018	93%

Some of the Smog Check analyses are subject to similar considerations relating to the emission rate variability across campaigns that have been previously presented, and care must be taken in interpreting findings. Also, there are numerous potential confounding factors to the Smog Check analyses. A significant factor is that the model year exemptions for gasoline fuel types do not apply to diesel vehicles, meaning that newer vehicles with biennial smog check tests will likely be all or almost all diesel-powered. There is also a significant geographical overlap of DACs with the COO program area. Additionally, of the RSD campaign sites in this program, only

El Centro is in a COO area. All other campaign sites were within Enhanced areas – no sites were within Basic areas. This significantly reduces the utility of the other campaign sites in drawing conclusions regarding trends across the different program areas.

Figure 47 presents the percentage of RSD-scanned vehicles subject to each Smog Check program area observed during each campaign. Note that the percentage calculated in the figure is based only on the total number of registration-matching LDV scans. Some LDVs in the registration did not have a program area listed; these vehicles are represented in the Unknown category. Only the El Centro campaign has more than 2% COO vehicles; it has approximately 83% of LDVs registered in the COO area. ERG was unable to determine the program area of the vehicles marked as Partial (indicating their approximate location could overlap with more than one program area), so these vehicles will be excluded from emissions analysis. No sites had more than 4% of vehicles registered in Basic areas and, as a result, it is unlikely that any statistically significant conclusions will be able to be drawn for that program area type.

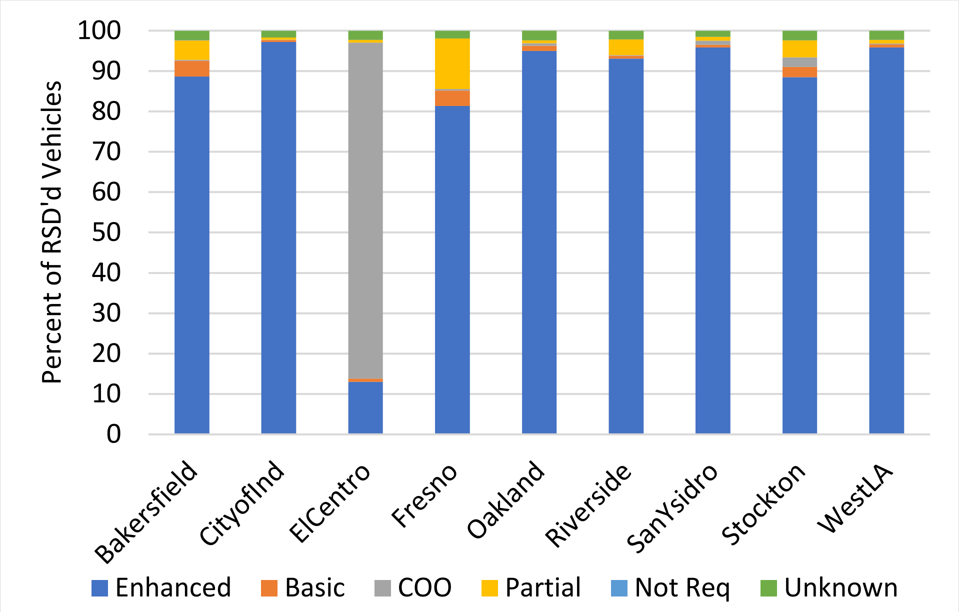

Figure 47. The percentage of RSD-scanned vehicles assigned to each Smog Check program area by campaign

ERG analyzed the RSD data to determine differences in emission rates for the Enhanced, Basic, and COO program areas. ERG first analyzed only the Enhanced vs Basic areas as these areas have similar fuel- and model year-based exemptions and requirements. This analysis was challenged by the rarity of Basic area vehicles, which made up a small portion of the RSD-scanned LDV fleet at all campaigns. Figure 48 presents the average NO emissions by model year bin for Basic-area and Enhanced-area gasoline-powered vehicles at each campaign. The vehicles included in the analysis were 8 model years and older to avoid including exempted vehicles. Error bars represent 95% confidence intervals, and they are relatively large due to the very limited number of measurements from Basic areas. Missing bars indicate that no vehicles were in the given model year bin, and missing error bars indicate that too few observations were present to calculate a confidence interval. While some differences within campaigns and model year groups appear statistically significant, no clear overall trends can be drawn from the data. For completeness, ERG also calculated the averages within each model year bin by taking data from all campaigns together (despite this possibly confounding the findings due to cross-campaign variability) and also found no statistically significant differences using that approach. ERG also developed similar plots for HC and CO that indicated similar findings; these are not shown. Finally, ERG performed a similar analysis of diesel LDVs across all campaigns (including newer model years that are not exempt for diesels) and found a similar result; due to the even fewer diesel LDV observations, it is not possible to determine any statistically significant difference in emissions trends between the Basic and Enhanced program areas.

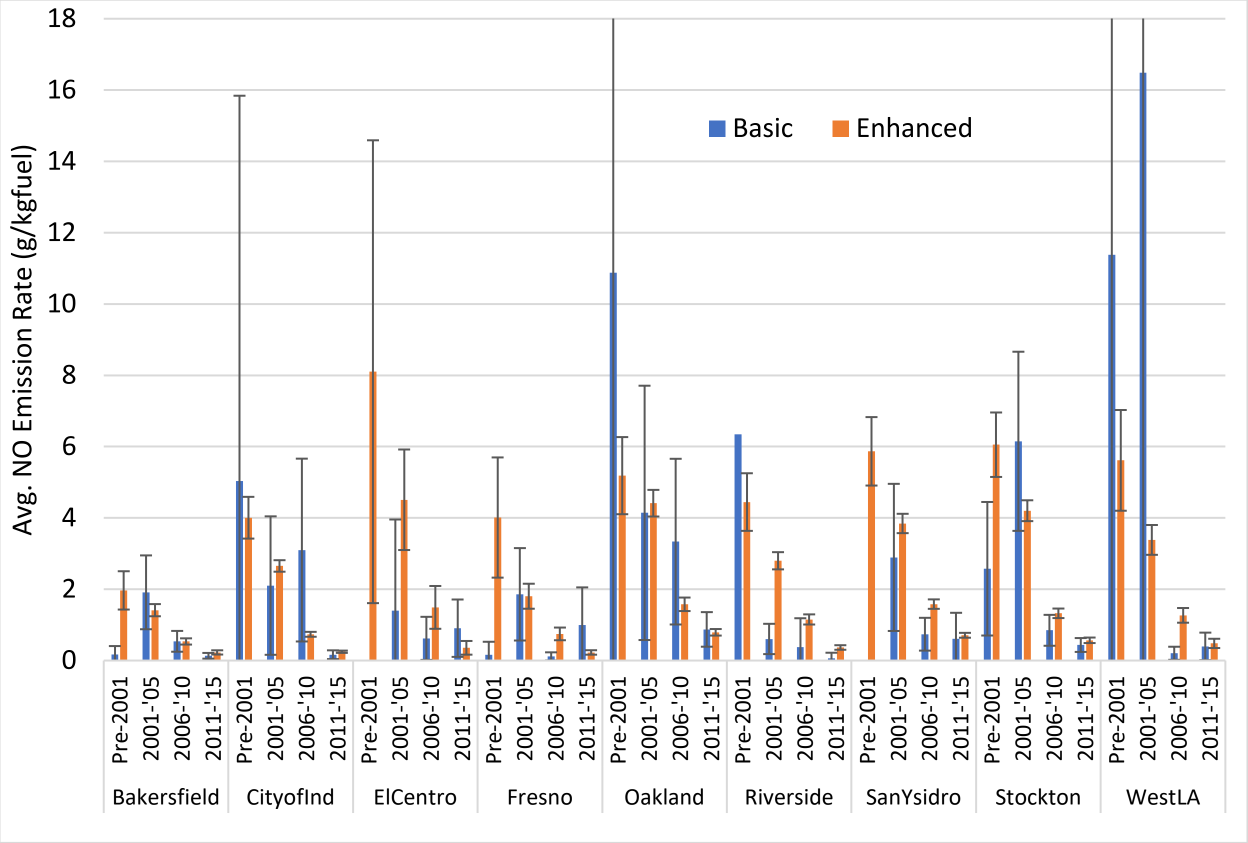

Figure 48. Average NO emissions by model year bin of Enhanced-area gasoline-powered LDVs vs Basic-area gasoline powered vehicles across all campaigns.

ERG then compared the Enhanced-area vehicles to the COO-area vehicles. Because the only campaign with a noteworthy number of COO vehicles was El Centro, ERG used data from only that campaign for the most direct possible comparison without the confounding of emissions variation across campaigns. Figure 49 presents the average HC emission rates by model year bin for gasoline-powered vehicles observed during the El Centro campaign. For most model year bins, it is not possible to resolve significant differences in emission rates between the two program areas' vehicles; only the newest model year bin indicates that COO vehicles have higher average emissions than Enhanced area vehicles.

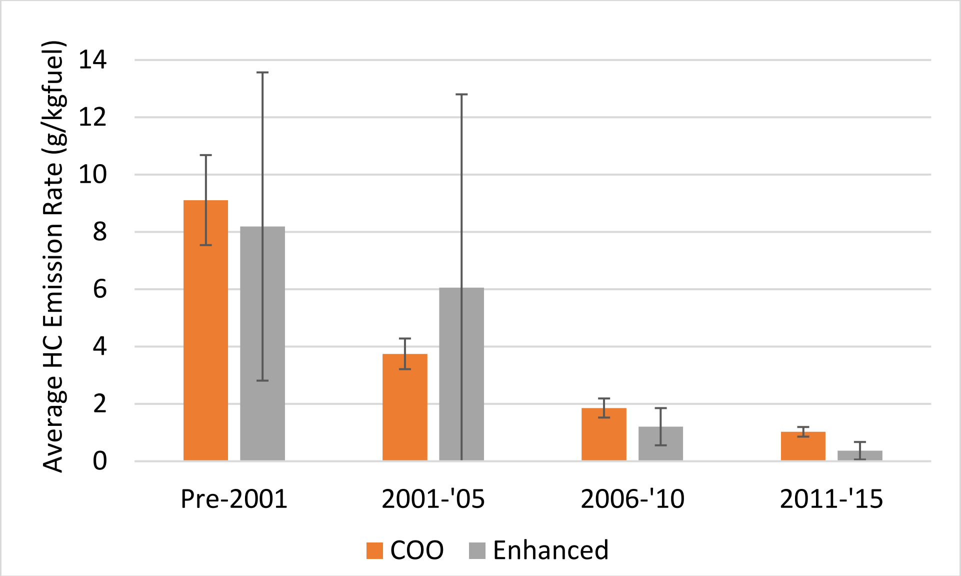

Figure 49. HC emission rate by model year bin for COO and Enhanced areas, averaged for gasoline vehicles observed at El Centro

Figure 50 and Figure 51 present similar plots for CO and NO emissions, respectively. For these two pollutants, more of the model year bins indicate significantly higher emission rates for COO vehicles. The oldest model year bin indicates the greatest emissions differences for CO and NO. ERG also developed similar plots for diesel vehicles; however the relatively few data points meant that no significant differences could be determined between program areas and so these graphs are not shown.

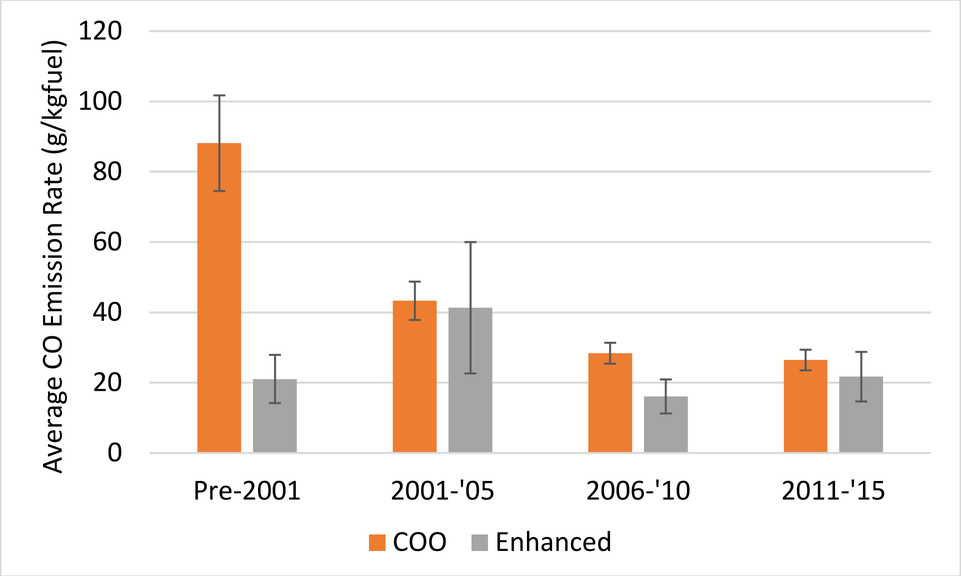

Figure 50. CO emission rate by model year bin for COO and Enhanced areas, averaged for gasoline vehicles observed at El Centro

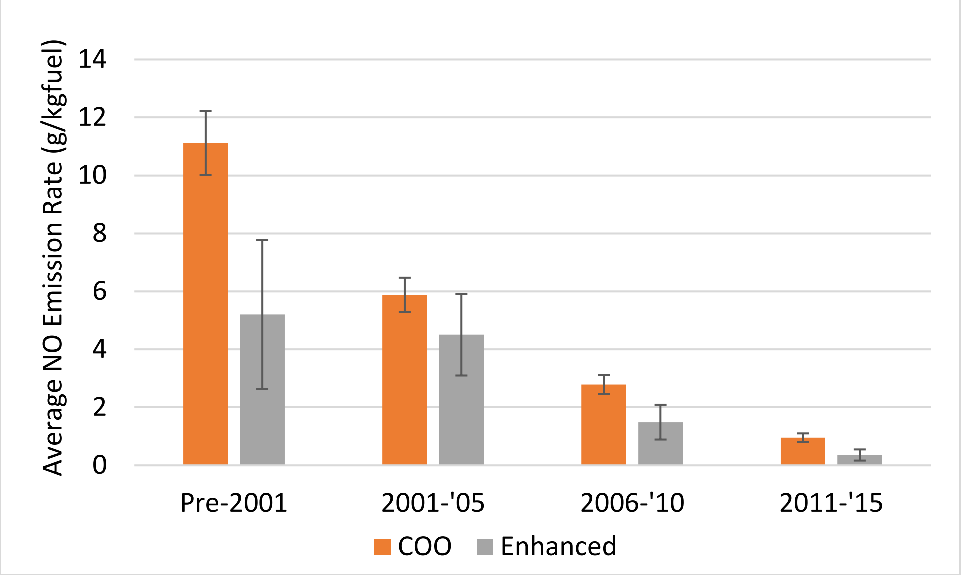

Figure 51. NO emission rate by model year bin for COO and Enhanced areas, averaged for gasoline vehicles observed at El Centro

The second task within this analysis topic was to determine if any conclusions could be drawn about comparing out-of-state vehicle emissions to in-state vehicle emissions. However, ERG was not able to determine any information about out of state vehicles such as model year or fuel type. As a result, no direct comparison of these vehicles was possible. Also, less than 0.5% of readable LDV plates were from states outside of California (excluding Mexico, the comparison to which was presented in Analysis Topic 3). So, even if it were possible to decode the plates for meaningful comparisons, the analysis would have minimal statistical power.

Task 3 of the Smog Check analysis topic was to determine if any smog check stations were associated with a large number of vehicles that were issued passing emissions test results but then had elevated RSD emissions. To do this, ERG conducted the following steps:

1. Isolate all vehicles that had an RSD scan where the previous smog check event was a passing test result.
2. Bin the model years of these vehicles and find outliers with elevated emissions exceeding 2.5 standard deviations from the mean in each.
3. Count the number of outlying vehicles from each inspection station and determine the percentage of each station’s tested vehicles that those outliers represent. Determine if any station has large numbers of counts or a high percentage of outliers.

This analysis did not successfully yield a list of potentially suspect stations. There are a large number of Smog Check stations in California, and over 6,000 stations were visited by the vehicle population that was scanned by RSD during this project. As a result, individual stations did not have a particularly large group of RSD-scanned after-pass vehicles, limiting the statistical power of this analysis. The few stations that did have some high-emitting after-pass vehicles could easily be due to happenstance given the large number of stations and vehicles that were evaluated. As a result, these stations are not identified in this report as there is not statistical cause to draw their work into question.

The fourth task of the Smog Check analysis was to determine if the RSD data could be used to determine if emission rates vary throughout the biennial inspection period. Only Smog Check visits with a test reason of “Biennial” were used in these analyses, and diesel-powered vehicles were excluded. Also, only the earliest 5 RSD campaigns were analyzed so that at least one year of Smog Check data after the RSD measurement would be available for each vehicle in the analysis. ERG conducted multiple analyses on this subset of data in an attempt to quantify the emissions trends throughout this period, but all were inconclusive. ERG matched the Smog Check data to the RSD data, and then isolated the data to only the Smog Check test for each eligible vehicle that was closest in time to the RSD campaign (either before or after). This resulted in having one or more RSD scans for each matching vehicle, along with the length of time before or after the corresponding inspection. In the first of the biennial trend analyses, ERG assigned all measurements into two main categories, those for which the RSD was after the inspection by up to 2 months, and all other RSDs from either before the inspection or from more than 2 months up to 14 months in either direction. The purpose of this analysis was to determine if the time immediately after inspection was the “cleanest” or lowest emission period. However, there was no conclusive finding. Figure 52 presents these findings for CO by model year group for the five campaigns with a year of available smog check data prior-to and after the campaign. Error bars indicate 95% confidence intervals. There is limited data in each bin and, as a result the data is noisy with large error bars preventing conclusions from being drawn. ERG performed similar analyses for HC and NO; these were inconclusive as well. ERG also performed this analysis with all five campaigns taken together (despite the limitations caused by the cross-campaign variability) with similar results; for the oldest two model year groups, the mean emission rates tended to be lower for the post-Smog vehicles, but these differences were not significant at 95%. The results of that type of analysis for HC and CO were similar. None are shown so as to avoid confounding the cross-campaign variability with the effects of the Smog Check program.

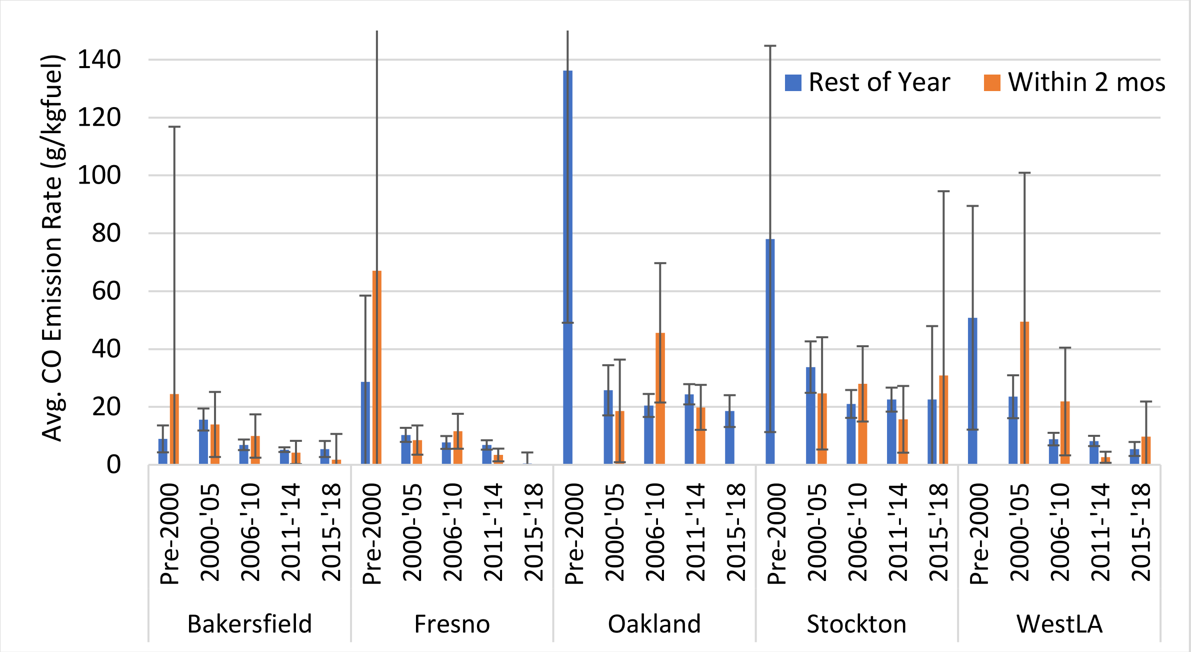

Figure 52. The average CO emissions of vehicles immediately following their Smog Check test as compared to all others by model year.

ERG also divided the data into larger time scale bins; Figure 53 presents the average emissions for vehicles RSD-scanned up to one year prior to a Smog Check inspection as compared to emissions for vehicles up to one year after an inspection. The figure presents the data for CO with error bars indicating 95% confidence intervals. Of all combinations of campaign and model year bin, only one of the differences of before/after is significant at 95% confidence (2011-2014 West LA the before inspection is significantly higher). The findings for HC and NO are also generally inconclusive; the analysis of those two pollutants indicates only one campaign and model year bin combination has a statistically significant difference, and in that case the after inspection NO average for 2011-2014 at West LA is higher.

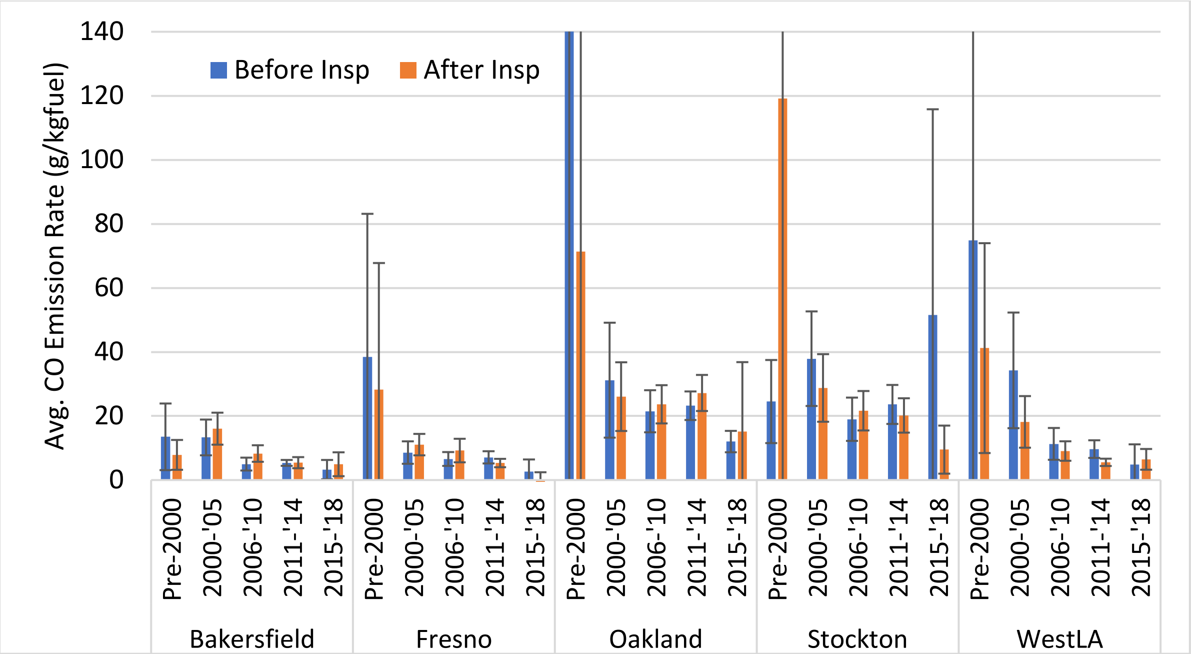

Figure 53. Average emission rates by model year bin for non-diesel vehicles with RSD up to one year prior to Smog Check inspection vs. vehicles with RSD up to one year after inspection.

The final task of the Smog Check analysis topic was to determine if there is an observable effect of the 8-year model year testing exemption. The most straightforward way to investigate this is to determine emission rates by age for vehicles registered inside versus outside of Biennial areas. As in previous analyses, the El Centro campaign allows for the most unbiased comparison of these two program area vehicle populations, and removing diesel-powered vehicles is appropriate as there is no age exemption for those vehicles. Figure 54 presents this comparison of HC emission rates by vehicle age for gasoline-powered LDV’s measured during the El Centro campaign. It can be seen that the emission rates are similar for the newer vehicles but do diverge around 8 years of vehicle age. Based on the confidence intervals, there are not statistically significant differences in the emission rates of the two groups until about 12 years of vehicle age.

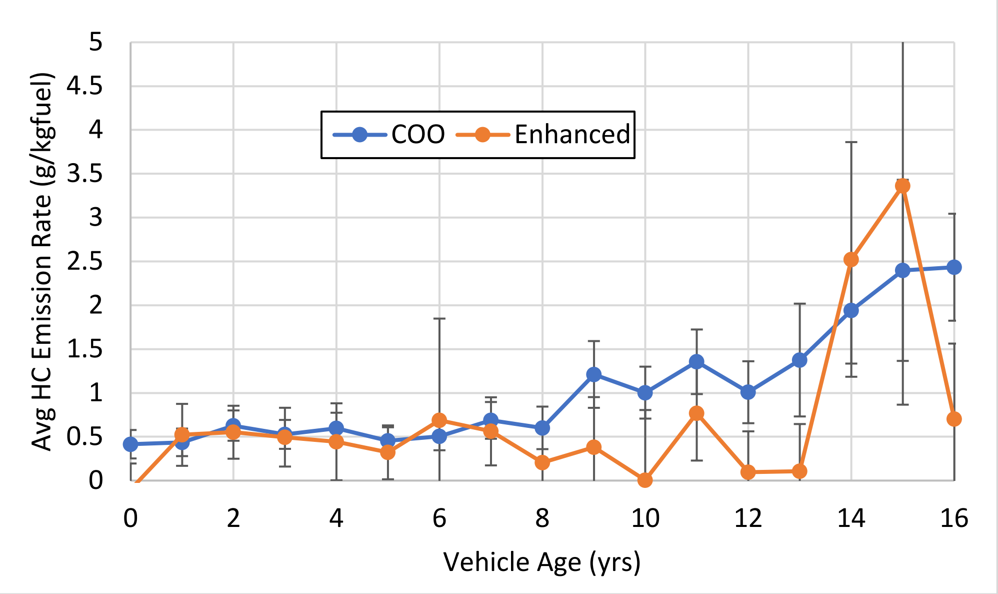

Figure 54. Average gasoline-powered LDV HC emissions by vehicle age, El Centro campaign. Error bars represent 95% confidence intervals.

Figure 55 presents similar results for CO. The emission rates tend to diverge starting at around 9 years of vehicle age, with a significant difference observed at 12 years. Figure 56 presents the corresponding findings for NO. As with the other pollutants, there are no significant differences for the newer vehicles but, for NO, the COO vehicles have significantly higher emission rates at 9, 11, and 16 years of age.

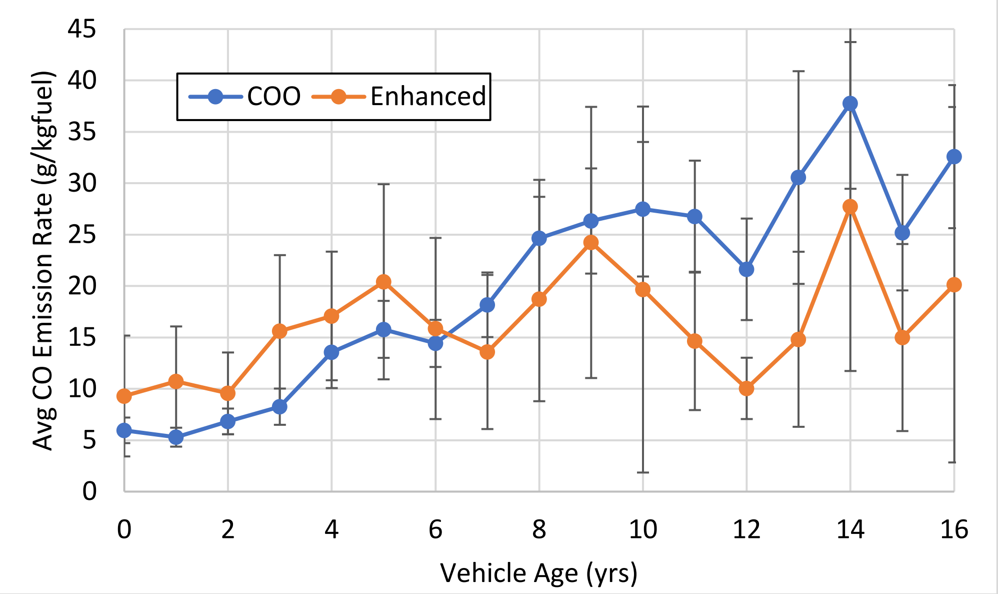

Figure 55. Average gasoline-powered LDV CO emissions by vehicle age, El Centro campaign. Error bars represent 95% confidence intervals.

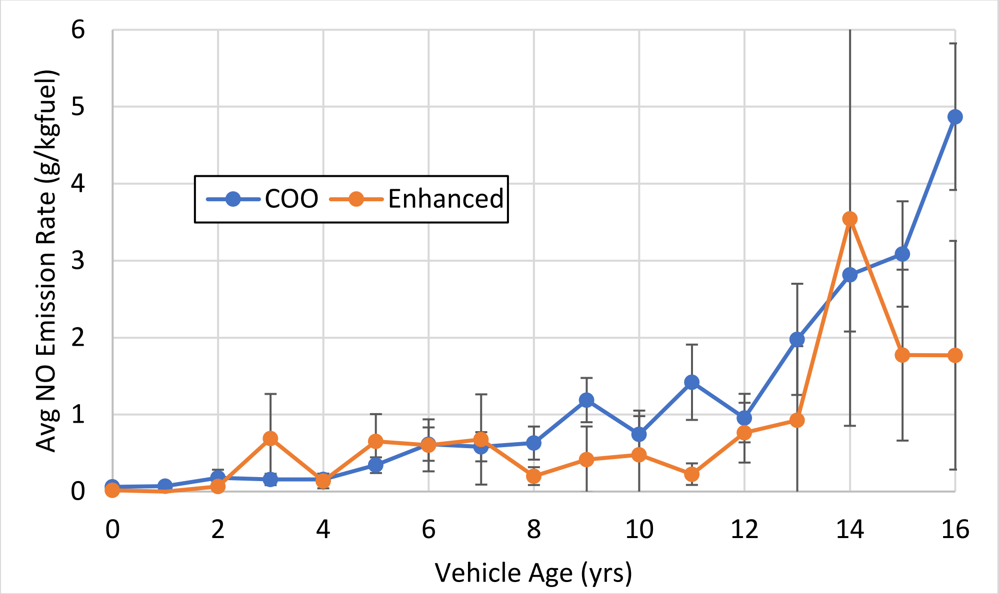

Figure 56. Average gasoline-powered LDV NO emissions by vehicle age, El Centro campaign. Error bars represent 95% confidence intervals.

The previous three figures do not necessarily indicate whether there is an emissions effect of the 8-year model year exemption for gasoline vehicles. However, they do indicate that the Enhanced and COO vehicles tend to have similar emission rates throughout the period of the 8-model-year exemption. After that, the COO vehicles tend to increase in their emission rates faster than vehicles in the Enhanced program.

Discussion

The use of RSD allows for the emissions measurement of large numbers of on-road vehicles operating in-use with minimal invasiveness to motorists. Each measurement is only a half-second snapshot of the vehicle operation, however, so measurements are subject to more noise than can be expected by other emissions measurement methods such as the IM240 inspection test cycle. Given that the RSD unit is stationary at a given location, it is also possible that unknown aspects of the specific site can affect the observed overall exhaust emissions rates.

Emissions and Fuel Type Trends of DAC Vehicles

The emissions findings of this work confirmed that vehicles registered in DACs tended to have measurably higher emission rates than non-DAC vehicles. The DAC fleet of vehicles tend to be slightly older in model year, and the emission rates are elevated even when accounting for that difference. The AB617 community vehicles also tended to have higher emissions than even other DAC vehicles.

This work also investigated the prevalence of EV's registered in DACs. These rates varied greatly across the different campaign locations, but in almost all cases, the EV prevalence was much lower for DAC vehicles than non-DAC. AB617 community vehicles had an even lower percentage of EVs compared to other DACs. In general, all alternative LDV powertrain types were less represented in DACs, which tended to be comprised of almost all gasoline-powered non-hybrids.

In this work, the quantity of measurements at each site was adequate to statistically separate the overall DAC emissions from non-DAC emissions. However, when attempting to isolate all four permutations of DAC/non-DAC within and outside of AB617 communities, the data quantity at most campaigns was more marginal for statistical analysis. This is, in part, because of the relatively small size of the AB617 communities. Also, depending on the location in California, there is a nonzero number of vehicles registered in an AB617 community that are otherwise not considered DACs based on CES score; this even smaller population tended to yield limited statistical power for analysis.

Historical West LA data

When comparing the RSD findings for this project's West LA campaign as compared to data taken periodically at the same site over the last two decades, the findings were generally consistent with recent trends. The average measured emission rates of NO continue to decline, but consistent with the previous West LA campaign, emissions of CO and HC have leveled off and may even be slightly increasing. Newer vehicle emission rates also tend to stay lower for longer as vehicles age.

The average emission rates across the 9 campaigns in this work tended to be more variable than initially expected by CARB and ERG. Notably, the West LA data was reasonably consistent with the previous West LA campaigns. This may be an indication that the variability is due to real differences across sites and not just measurement variability. If it were only variability, it would be reasonable to expect more inconsistency with the previous recent West LA measurements.

Cross-border analysis

Emissions from cross-border vehicles were analyzed at two campaigns in Southern California. The cross-border population of vehicles at each border campaign was similar in model year to the observed California-registered vehicles. However, the emission rates tended to be statistically significantly higher for the vehicles registered in Mexico. This is likely due to the less stringent new-vehicle emissions standards in Mexico, as well as the requirements of the California Smog Check program resulting in more emissions-related maintenance for California vehicles. The light-duty emissions standards currently in place for new vehicles sold in Mexico require meeting either the Tier 2 standards in place in the U.S. between 2009-2017 or the

European Euro 3/4 standards (in place during approximately the same period).[53,54] The new-vehicle standards for U.S. vehicles have continued to decrease since that time.

The cross-border analysis included only vehicles with readable license plates that matched either the California registration data or the Mexican licensing entities' data that was available to ERG. ERG was not able to make any determination about vehicles that did not have traceable registration as there was no way to know if the vehicle in a given RSD observation was operating under invalid registration or whether it had a valid registration to a different state (either in the U.S. or Mexico).

The data quantity for both of the cross-border campaigns was adequate to allow for resolving statistically significant emissions differences in the two fleets.

HDV Emissions Trends

This work presented the NO emissions trends for HDVs observed at the City of Industry campaign, which had the highest quantity of valid HDV measurements. HDV measurement by RSD was challenged by many previously-described factors, with the outcome being that relatively few valid measurements were able to be made of trucks heavier than about Class 4 or 5. For those measurements that were valid, the trends of emission rates across vehicle age were consistent with expectations. Newer and lighter trucks were generally lower emitting.

The measurement quantities in this work were generally not adequate for statistical power in terms of HDV emissions analysis. Results were presented by model year bin and truck class for City of Industry, as for other campaigns many of the combinations of truck class and model year bin had very few or no measurements for analysis (Stockton has the second highest quantity of HDV measurements and so is included in Appendix D). Overall, there were relatively few valid observations within each of the many permutations of truck class and model year, resulting in large uncertainties. This was exacerbated by the test setup being limited to only downdraft exhaust trucks.

Smog Check Evaluation

The evaluation of the Smog Check analysis topic was challenged by a number of confounding factors. Only one campaign in this work was deployed within a COO area; all others were within the Enhanced area (and only 3 were in the proximity of any Basic areas). So, the data from only one site was relevant to the analysis of trends across Enhanced and COO areas, and extremely limited analysis could be performed on the few observed vehicles from Basic areas. Further, the COO vehicles tended also to be registered in DACs, which confounded the source of emission rate differences. So, while the COO-area vehicles tended to have significantly higher emissions than other vehicles, it is not possible to definitively attribute this to the Smog Check program.

ERG also conducted an analysis of Smog Check station performance, investigating whether any stations were associated with passing vehicles that were later observed by RSD to have elevated emission rates. Unfortunately, due to the large number of Smog Check stations and the previously mentioned confounding factors, the data quantities were not large enough to draw statistically significant conclusions. Due to the nature of RSD measuring a very limited snapshot of emissions in time, it is particularly useful in comparing general trends across measurements of large populations of vehicles. In the case of the Smog Check station analysis, each vehicle was analyzed on an individual basis. The individual measurements exhibited relatively high levels of noise, limiting their usefulness for this type of analysis. That is a potential limitation of RSD data use; it would likely be better mitigated by fewer campaigns that were longer in duration, potentially resulting in higher numbers of measurements of each individual vehicle.

There were also many confounding factors in the analysis of the emissions trends of Enhanced-area vehicles throughout their biennial emissions cycle. This analysis did not yield any observable trends – either due to their not actually being any trend or alternatively due to the many confounding factors affecting the comparison of Smog Check data and RSD. This type of analysis may be improved by periodically conducting RSD campaigns at the same location over a two-year period. This would potentially allow for direct comparison of each individual vehicle throughout the time period. In the analysis in this work, the reverse was performed in which each vehicle was only observed one or more times during a week and these measurements were associated only with when that was in the respective vehicle's biennial cycle. That was an indirect approach and did not yield meaningful results.

Finally, ERG investigated whether there were any observable effects of the 8-model-year exemption. In this analysis, ERG compared the by-model year emission rates of vehicles in Enhanced vs. COO areas. The results indicated that Enhanced and COO vehicles tend to be similar in emission rates over the first 8 model years. As they age further, the emission rates begin to diverge with COO-area vehicles exhibiting more elevated emission rates, and these differences are in some cases statistically significant. This result did not specifically indicate an effect of the 8-model-year exemption; however, the gradual divergence in COO and Enhanced vehicle emissions after 8 years of age suggests that Enhanced-area vehicle emissions do not suddenly drop at the end of the exemption period when subject to Smog Check requirements. This could be interpreted as indicating limited potential utility in subjecting less than 8-year-old vehicles to the Smog Check program. The datasets were large enough for this type of analysis, though larger datasets may have allowed for resolving the significance of emissions differences in more of the age bins.

The design of experiment for an RSD program intended to resolve the emissions effects of the Smog Check program is more challenging than for many of the other analyses in this work. The geographic overlap between COO and DAC areas is a key aspect of this challenge. An ideal RSD site for this type of resolution would be in an area proximate to all 4 permutations of Enhanced/COO and DAC/non-DAC areas and community types. This type of area may be difficult to find and would necessarily be in a less populated area (as the most populous areas are completely in the Enhanced program) and so would be challenged by fewer possible measurements per campaign day.

Cross-Campaign Variability

The relative quantities of many factors observed during each campaign, such as counts of vehicles, proportions of DAC/non-DAC, fuel types, etc. are to an extent happenstance. The analyses in the Results section investigated the data from various perspectives, notably by-campaign, to mitigate the effects of the differences amongst the campaigns to present results and allow for overall conclusions to be drawn that were unaffected by cross-campaign variability.

The average measurements of LDV emission rates of HC, CO, and NO varied significantly across the nine campaigns analyzed in this work, with an approximate ratio of 3.5 to 4 between the highest campaign and lowest campaign for each. This limited the statistical power of most analyses, as it was not necessarily appropriate to bring data from all campaigns together. ERG attempted to determine the cause of the variation and its implication for interpretation of the project results. It is important to note that the RSD unit captures only ½ second of operation of each passing vehicle at one specific location for each measurement site. Vehicle emissions are highly variable during the course of a trip, and a small change in the time of measurement can yield a large difference in the result.

As a first step in the variability analysis, it is instructive to review the distribution of measured emission rates at each campaign to determine if the shapes of the distributions provide any information about the reasons for variation in the means. Figure 57 presents the distribution of NO emission rate measurements (shown as an example, HC and CO trends are similar) for LDVs measured at each campaign. The distributions vary notably in width; the DU distributions tend to be narrower than the distributions for Opus. However, they all have their peaks at zero or 0.05 and none appear shifted up or down from one another. So, it is likely that the variability across campaigns is due to the specifics of the shapes of each distribution, not due to the entire group of measurements being shifted along the emission rate axis.

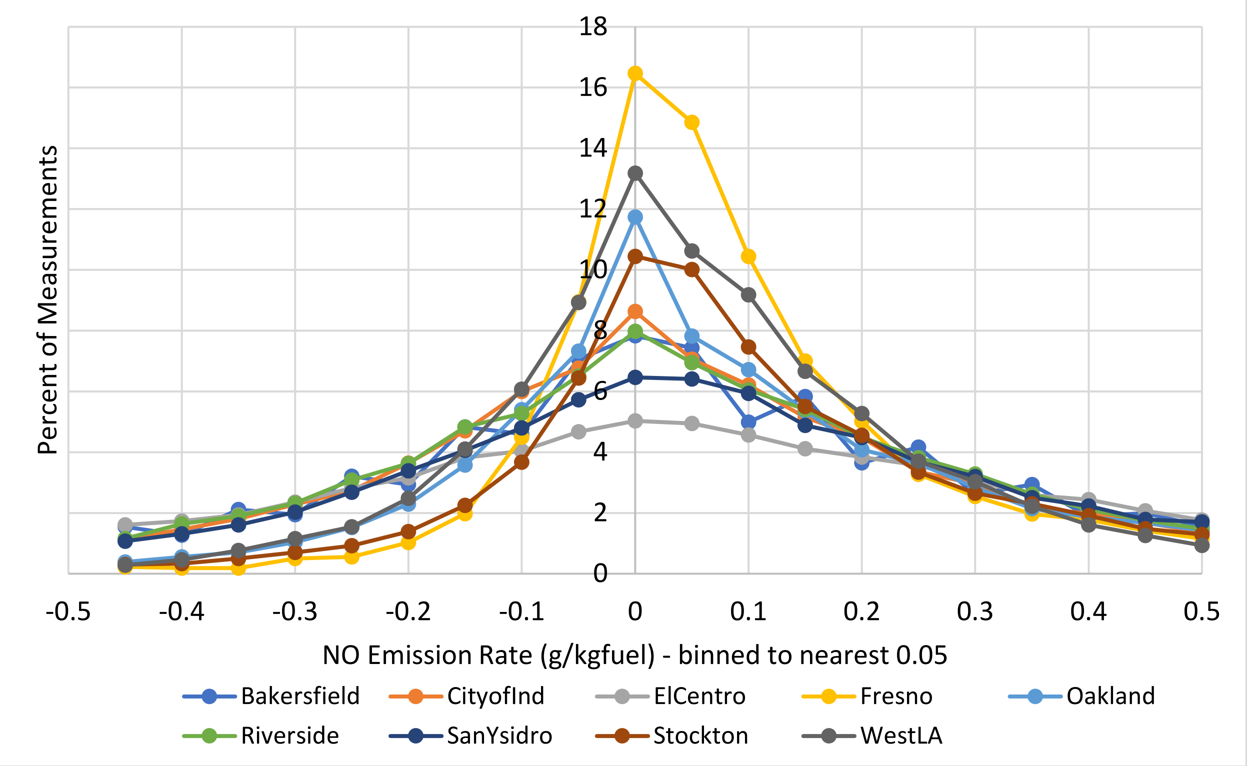

Figure 57. The distribution of NO emission rate measurements for LDVs at each campaign.

ERG isolated potential causes of site-to-site emissions variability and grouped them into two categories, measurable factors present in the RSD data and other factors that are not quantifiable or otherwise not available in the logged data. The following are examples of the types of factors in each category.

- Factors quantified in the registration-matched RSD dataset
    - Model Year
    - Fuel type
    - RSD subcontractor and specific Instrument ID
    - Vehicle type, passenger car or truck class
    - Registered Smog Program Area
    - DAC status
    - Weather effects such as temperature, humidity, pressure and wind speed
    - Variables in VSP calculation such as speed, acceleration, site road grade
- Factors not known or quantifiable in RSD dataset
    - Vehicle recent cold start
    - Presence of an OBD check engine light or other mal-maintenance
    - Any other potential optical, magnetic or other environmental characteristics of the particular site that could affect the measurement instrument and not necessarily the passing vehicle

The non-quantifiable variables may contribute to site-to site variability, but it is not possible to isolate their effects in the RSD data; their contribution to variability must remain unknown. The quantifiable variables are more straightforward to analyze. ERG investigated various methods of attempting to isolate the effect of the quantifiable factors in the site- to site variability.

ERG reviewed the daily average emissions readings for each instrument at each campaign. This would give an indication of whether the variability exists on a day-to-day basis or was more likely to be caused by campaign or site related causes. Figure 58 presents the average LDV CO emission rate by subcontractor (DU and Opus), instrument ID (which varies only for the Opus, or "O", campaigns), and campaign test day (D#). The figure shows that the variability across campaigns tends to be much greater than the variability from day-to-day within each. This also indicates that instrument noise is likely to not be the main cause of the variability. The differences across sites, be they related to the vehicle population differences, roadway and operational differences, or environmental differences are likely to be more important.

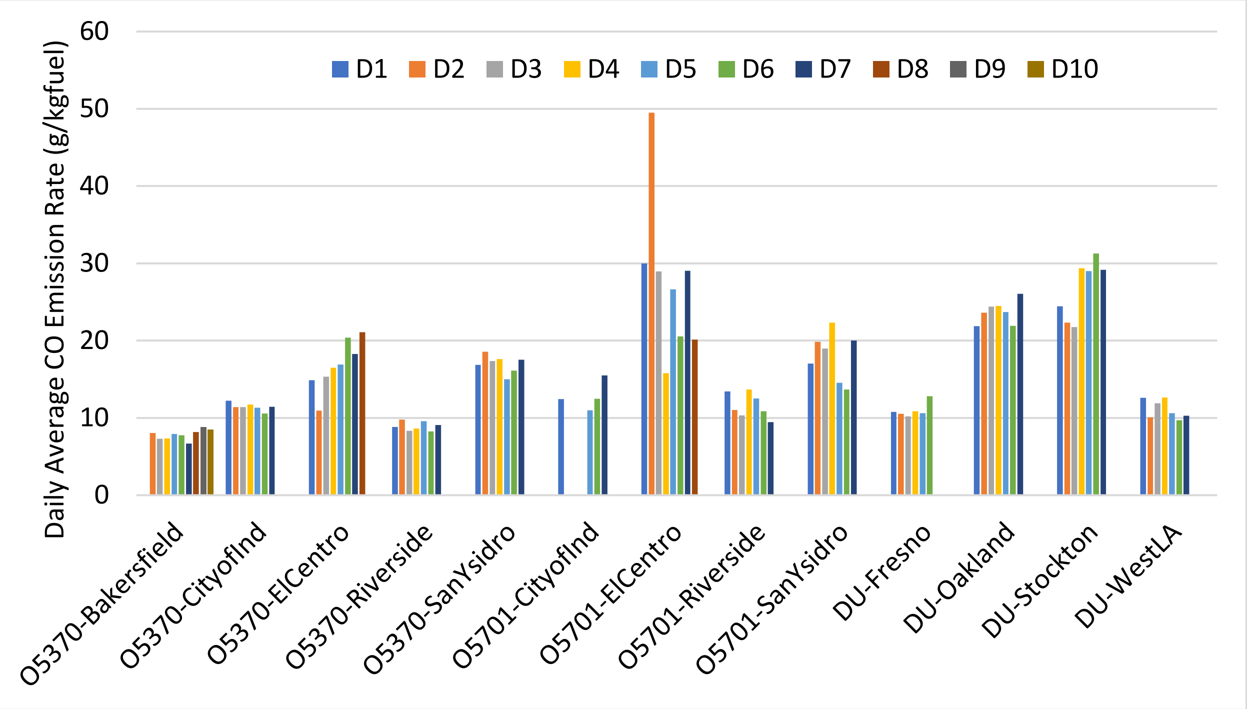

Figure 58. The average LDV CO emission rate by Subcontractor/Instrument and campaign, by campaign test day number (D#).

The operational differences of the vehicles observed at each campaign may be important in causing campaign-level variability. ERG investigated this by reviewing the VSP and emissions trends across campaigns. Figure 59 presents the distribution of VSP observed for LDVs observed at each campaign. West LA tended to have most observations at the low end of the VSP range, and Oakland had VSPs at the higher end of the range, with the other campaigns in between.

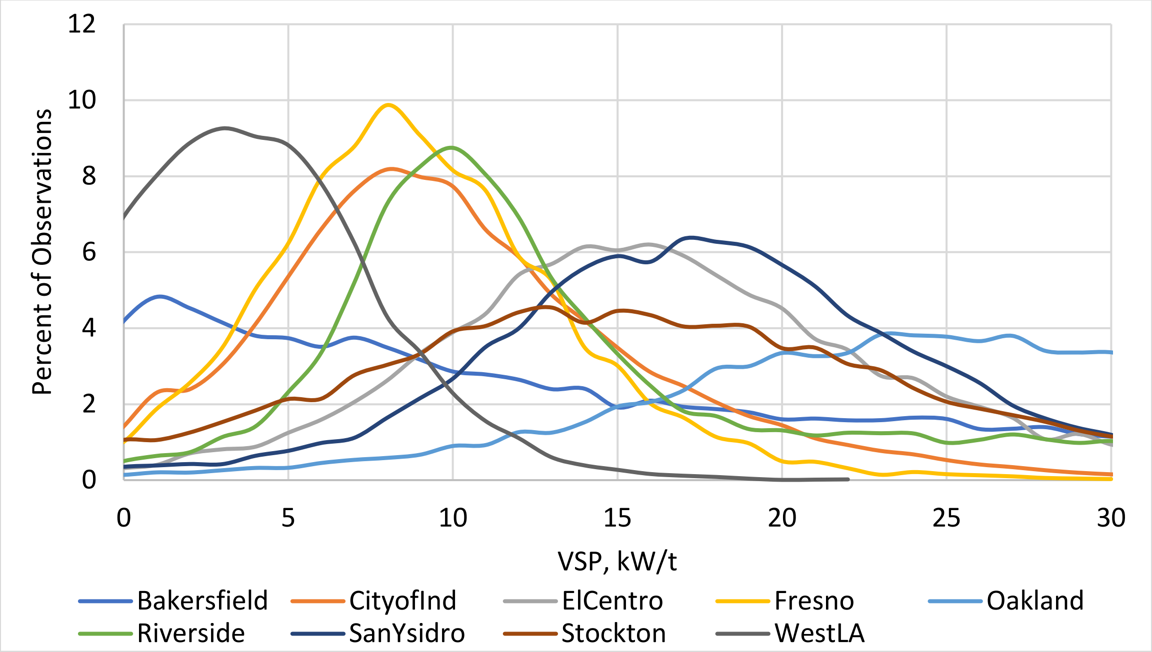

Figure 59. The distributions of LDV VSP observed during each campaign.

Figure 60 presents an example of NO emission rate versus VSP for City of Industry (selected for its low day-to-day variability and clearly defined trend). It can be seen that older vehicles tend to increase in emission rate with VSP, but newer vehicles' emissions generally remain relatively constant and low across the VSP range. So, it can be expected that VSP influences emission rates only for vehicles older than around 2008 model year.

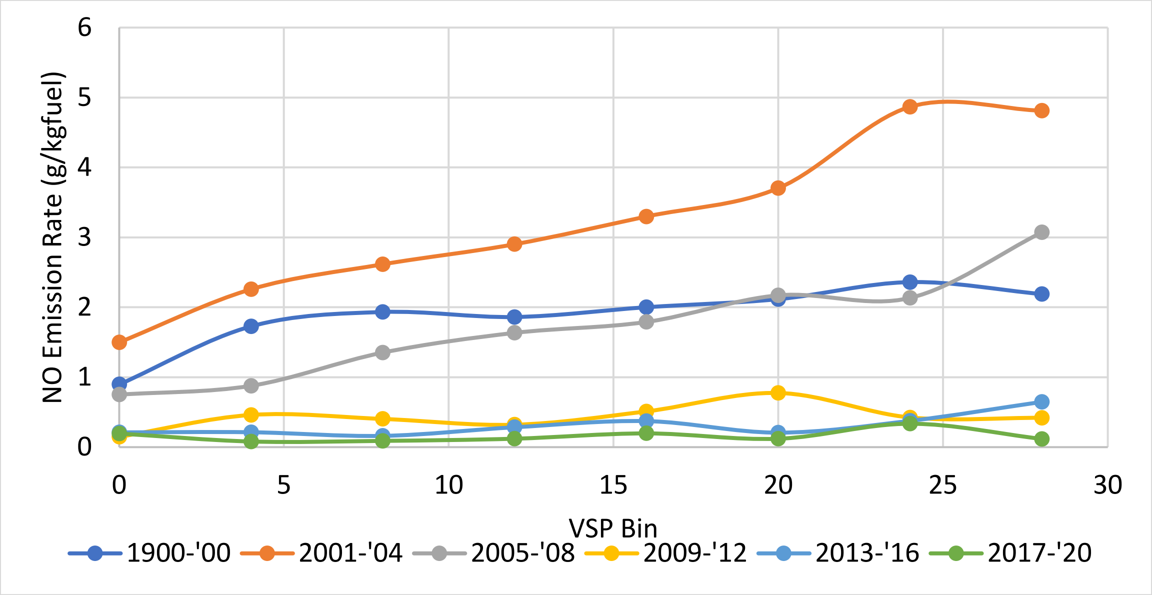

Figure 60. The trend in NO emission rate against VSP bin by model year bin for the City of Industry campaign.

Based on the previous two figures, it is possible that the interaction between the model year distributions and VSP distributions of each campaign may explain some of the variability in emission rates. Campaigns with higher VSPs may be expected to have higher emission rates if they also have older model years. Table 10 presents the top 4 campaigns for each of the following when averaged for observed LDVs: the highest VSP, the oldest model year, and the highest NO emissions. It can readily be seen that Oakland, San Ysidro, and Stockton appear in all three columns; El Centro appears in two of the columns. It is likely that the interaction of model year and VSP distribution explains some of the difference observed across campaigns. However, this type of analysis cannot predict the relative importance of these factors, nor does it demonstratively prove that the VSP and model year are causal to the NO emission rate variability.

Table 10. The top 4 campaigns in terms of LDV VSP distribution, oldest model years, and highest NO emission rate

Highest VSP Distributions	Oldest Vehicle MYs	Highest NO Emissions
Oakland	Fresno	Stockton
San Ysidro	Stockton	Oakland
El Centro	Oakland	San Ysidro
Stockton	San Ysidro	El Centro

The Opus instrument logged the ambient weather conditions (pressure, temperature, humidity, and wind speed) at the time of each measurement. The DU instrument did not have this capability. However, ERG did look up almanac weather conditions for each day of each campaign (for reference in Appendix A). ERG plotted emission rates of HC, CO, and NO against the various weather variables, both from the Opus system and the almanac, but did not observe any trends suggesting the equipment was affected by weather.

One key step that ERG took to continue to investigate the causes of cross-campaign variability was conducting various “narrow spectrum” analyses, in which measurements falling within a narrow range of each measurable variable were isolated, and the variability across campaigns recalculated. This process could help determine whether the cross campaign-variability was due primarily to the quantifiable RSD variables or outside factors. However, the narrow spectrum analyses that ERG performed did not reduce the variability observed across campaigns. In one example, typical of others, ERG isolated to only the following measurement characteristics:

- Model years 2009, 2010 and 2011
- Gasoline-powered
- Passenger cars, excluding light trucks
- Registered in Enhanced Smog Check program area
- Non-DAC
- VSP between 5 and 25 kW/ton
- For Opus campaigns, only instrument 5370 (the most commonly used LDV-oriented instrument)

Removing all LDV measurements outside of the above categories and ranges reduced the number of included measurements by about 99%. Table 11 presents the results of this example narrow spectrum analysis as compared to a similar calculation when all valid LDV measurements were included. For the all-valid statistics, ERG calculated the average emission rate by campaign for all LDV measurements, and then calculated the statics across those 9 results (i.e., the statistics are calculated on the by-campaign averages). Likewise, the narrow spectrum statistics are calculated on the 9 campaign-average values of only the measurements fitting the above criteria. The table presents two simple ways of interpreting the cross-campaign variability; the coefficient of variation and the simple ratio of the maximum campaign average to the minimum campaign average. By both measures, there is more variability in the narrow spectrum analysis, indicating that the variation across the RSD-quantifiable factors is not likely a primary cause of the observed cross-campaign variability. It is possible that the much smaller size of sample in the narrow spectrum example somewhat confounds this finding; but nonetheless, it is clear that variability is not reduced by narrowing the range of quantifiable factors. This example was typical of the findings of other narrow spectrum groupings that ERG investigated.

Table 11. Comparing statistics calculated on the campaign average NO emission rates (in g/kgfuel) for all LDV measurements and for only the example narrow-spectrum LDV measurements.

Statistic (Calculated on the 9 campaign averages)	All Valid LDV	Narrow Spectrum Example
Mean	1.2	0.68
Standard Deviation	0.43	0.30
Coefficient of Variation	0.36	0.44
Ratio of Maximum to Minimum	3.5	4.2

Regression Modeling

The previously described analysis of variability each were designed to investigate either one or two of the RSD-quantifiable variables (i.e. model year and VSP) or evaluate their potential effects entirely as a group (i.e. the narrow spectrum analysis. As a way to evaluate all of the individual variables concurrently, ERG also investigated the use of a large multiple regression model. This could potentially mitigate the quantifiable causes of cross-campaign variability allow for increased statistical power by using all campaign data together in a single analysis. Regression modeling offers the potential to mitigate the happenstance effects and site-to-site variation more effectively than taking direct overall averages.

Using Statistical Analysis Software (SAS), ERG used “Proc GLM” to develop a number of regression models to best isolate the effect of DAC vs non-DAC on vehicle emissions while controlling for the other happenstance variables in the RSD datasets.[55] One drawback of the regression modeling is that the output of the effect of DAC status on emission rate is given on a linear basis, not as a factor, i.e. the result is additive, not multiplicative. ERG investigated models with two sets of variables. The first model contained the following physical properties and measurable values from the campaigns:

- Model year
- Fuel type
- Vehicle speed
- Vehicle acceleration
- Road grade
- Instrument
- RSD contractor (DU, Opus)
- Weather conditions (temperature, barometer, wind)
- Vehicle class (passenger car, class 1 truck, class 2 truck)
- DAC Status

The resulting predicted emission rates for the models with these tangible variables tended to agree well with the measured emissions when averaged at the campaign level, despite the model not being trained on what site any individual scan was from. However, one variable, ambient pressure, was found to be a very significant parameter for HC emissions, but not for CO or NO. ERG was unable to determine any physical way for the ambient pressure to affect only HC measurement. For this and other reasons, ERG determined that it was likely that the models were overfitting to the tangible parameters, meaning that the model was assigning emissions variations to any parameter that happened to help the fit irrespective of any true understandable cause. To eliminate this, ERG developed a second type of model, in which the campaign name was included as a parameter variable, and any parameter that was not known to directly affect emissions was excluded, namely weather variables and vehicle speed. Using the campaign name means that the cause of site-to-site variability is unknown, but the model is trained on that variability and it affects the other parameters' emissions estimates less than in a simple average. ERG's next model used the following parameters:

- Campaign name
- Model year
- Fuel type
- Instrument
- RSD contractor (DU, Opus)
- Vehicle class (passenger car, class 1 truck, class 2 truck)
- DAC status

The model's output estimate for DAC status represents the additive difference in emissions from a non-DAC vehicle to a DAC vehicle, largely independent of all the other modeled parameters. Table 12 presents the regression model's estimate of the average additive emission level from non-DAC to DAC vehicles. These additive emission values represent averages that are independent of model year, meaning that they are an estimate of the difference that is not associated with the shifted model year distribution for DAC vehicles. The table also presents this value as a percentage of the average non-DAC vehicle emission rate.

Table 12. Regression model estimate of overall emissions delta between DAC and non-DAC, excluding the effect of shifted model year

HC, g/gkfuel (% of non-DAC mean)	CO, g/gkfuel (% of non-DAC mean)	NO, g/gkfuel (% of non-DAC mean)
0.10 (~8%)	1.37 (~10%)	0.10 (~11%)

The total non-DAC to DAC emission rate difference including the shift in model year can be estimated by dropping model year from the regression model. In this way, any differences in DAC/non-DAC emission rates, including those due to model year shift. are fit to just the DAC status parameter. The model estimates for doing so are presented in Table 13. As in the previous table, the additive emission rate as a percentage of the average non-DAC emission rate is also included in the table for reference.

Table 13. Regression model estimate of overall emissions delta between DAC and non-DAC, including the effect of shifted model year

HC, g/gkfuel (% of non-DAC mean)	CO, g/gkfuel (% of non-DAC mean)	NO, g/gkfuel (% of non-DAC mean)
0.18 (~14%)	2.15 (~15%)	0.26 (~27%)

Previous analyses above have shown that the non-DAC to DAC emissions difference varies across model year. To verify this using the regression modeling analysis, ERG also ran a model in which the DAC status parameter was interacted with the binned model year parameter; this would result in the model outputting a separate additive emissions value for each model year bin. ERG than calculated the ratio of the additive emissions estimate to the mean non-DAC emission rate to determine its trend against model year. Figure 61 presents the ratio of the emissions deltas to the average non-DAC emission rate by bins of 2 model years, with linear fits applied for each pollutant. As was observed in the analysis of the direct averages, the ratio does decrease with newer model years.

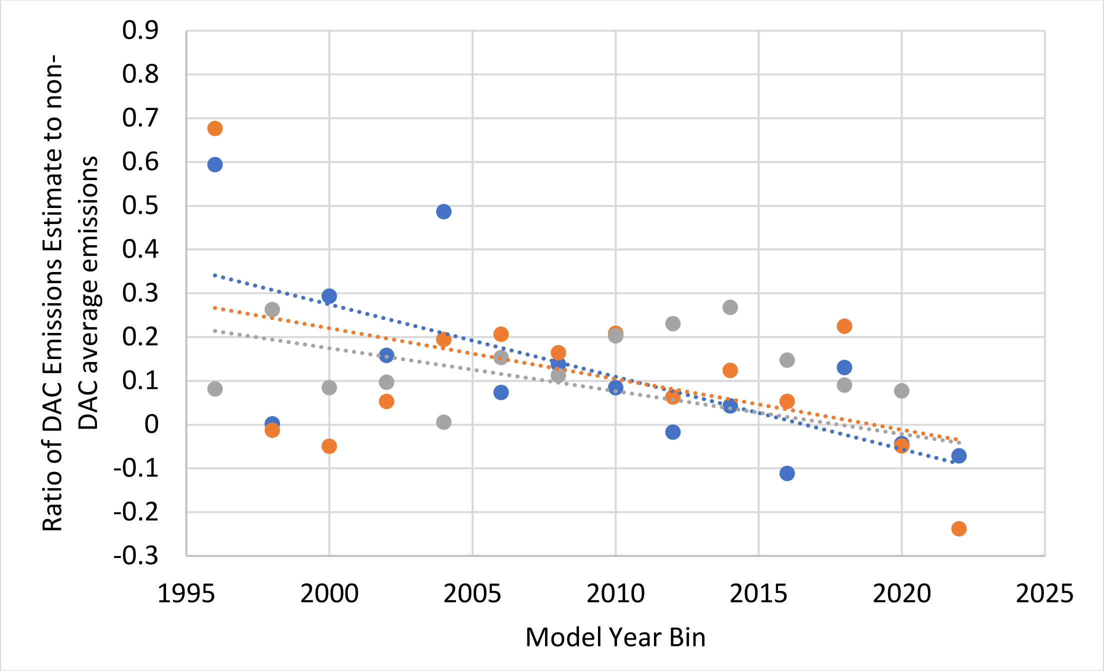

Figure 61. The ratio of the regression-modeled DAC status additive emission rate to the modeled non-DAC average emission rate by model year for each pollutant.

The regression modeling can help reduce the effects of the quantifiable sources of variability across campaigns and allow for the greater statistical power of performing analyses on all project measurements together as a single group. However, regression modeling may also be used to help understand the relative importance of the different quantifiable factors in causing the cross-campaign variability. To continue the cross-campaign variability investigation using regression modeling, ERG used not just the overall modeled emission rate outputs, but the individual coefficient outputs for each input (i.e. independent) variable as well.

The regression model outputs a coefficient for each input variable; for class variables (such as RSD subcontractor) the coefficient is additive and for continuous variables (such as VSP) the coefficient is multiplied by the value of the continuous variable for each modeled observation. The overall modeled output for each RSD observation is the sum of each corresponding additive value plus each multiplicative value multiplied by the associated input variable value. This is calculated by the model for every RSD measurement. ERG investigated the relative sizes of each term in the overall output equation for every RSD measurement to determine if it could inform the relative importance of each in causing cross-campaign variability. ERG averaged the contribution of each variable's term for all LDV measurements within each campaign. Figure 62 presents the findings of this contribution analysis on the basis of LDV emission rates of NO in g/kgfuel. Each campaign has three bars; the as-measured average, the as-modeled average, and the modeled average by component in which the relative sizes of each bar depict the extent to which the modeled average emission result depends on that variable. The dashed total model bar is equal to the sum of the component bars and is shown for comparison to the measured bar given that many sites have negative components (i.e. the dashed "Total Model" bar equals the sum of all modeled components). It is important to note that the depicted component sizes must be interpreted on a relative basis. The function of the model forces the components to add up to the modeled value; any unmodeled factors that affect the emissions must be accounted for by only the values that are present in the model.

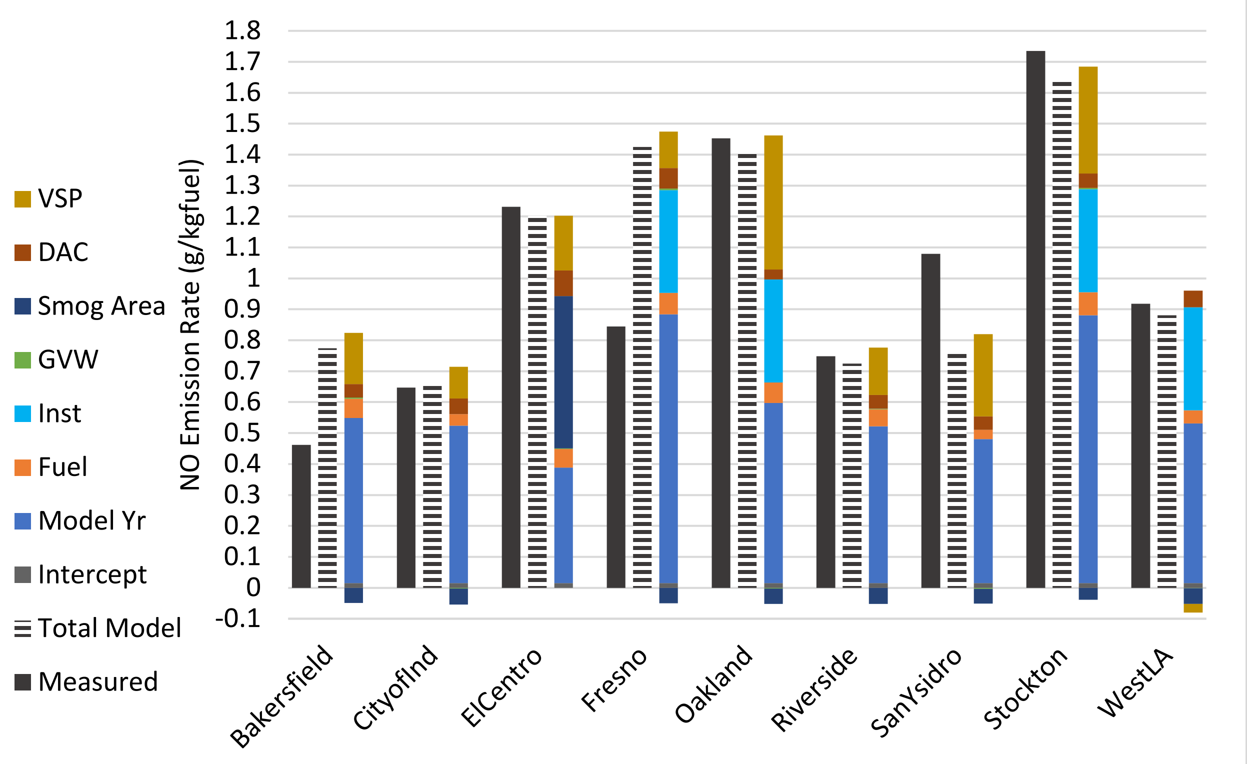

Figure 62. The campaign-average LDV NO emission rates as measured, as modeled, and separated into components for each quantifiable/categorical variable

Multiple regression analysis is subject to overfitting and other potential modeling errors, and it also has a limitation of having an additive value as its output. However, it does offer another avenue to understanding and describing the emissions effects between DAC and non-DAC vehicles observed during the RSD campaigns. It is included here as a supplement to the previously presented DAC analysis findings.

ERG's various analyses indicated that the measurable values were only able to describe a small part of the site-to site variability. ERG has extensive experience with other RSD projects and found that, compared to another example large multi-site RSD project, this level of variability across sites was not atypical, even when there would not be reason to expect significant variation in the nature of the vehicle fleets at each site.

Both the California BAR and Colorado Department of Health and Environment (CDPHE) have requirements on the RSD units using in screening for their emission inspection programs[56,57]. These requirements include accuracy thresholds for acceptance based on measurements of passing audit vehicles releasing known concentrations of calibration gas, and the instruments used in this program are typical of those that routinely meet these requirements. Pollutants must be read at the accuracy levels given in Table 14 for 98% of audit measurements for acceptance (if multiple requirements are included, meeting the greater of the two ranges is acceptable). The table represents a subset of requirements for illustrative purposes, it is not a complete list of all requirements. The accuracy requirements are fairly restrictive at elevated emission levels (i.e. within 10-15%), however at low emission levels, the absolute accuracy requirements apply and these are far less restrictive on a percentage error basis. They tend to be approximately equal in range to 2x the average emission readings for the typical campaign in this program.

Table 14. A subset of the accuracy requirements for RSD for BAR and CDPHE

Pollutant	BAR Accuracy Requirement	CDPHE Accuracy Requirement
HC	± 15% of gas conc. Or an absolute 250 ppm HC	± 15% of gas conc. Or an absolute 250 ppm HC
CO	± 10% of gas conc. or an absolute 0.25% CO	± 15% of gas conc. or an absolute 0.25% CO
NO	± 15% of gas conc. Or an absolute value of 250 ppm NO	± 15% of NOx gas conc. Or an absolute value of 250 ppm NOx

Conclusions

In this work, RSD was deployed at 8 weeklong campaigns across California, and CRC provided data from a similar campaign to allow for analysis of 9 cities across the state. RSD functions by measuring the level of attenuation of emitted light at various wavelengths corresponding to the absorbance of different exhaust pollutants. The light source and detector units are positioned on opposite sides of a single lane road such that the emitted light passes through the exhaust plume of passing vehicles. The system measured the ratios of various exhaust pollutants to CO_2, which can be used to calculate the ratio of emitted mass of various pollutants to emitted CO_2 mass and be presented on a per-unit-fuel basis. ERG partnered with DU and Opus Inspection for the execution of the RSD measurement campaigns. DU conducted four of the campaigns (one of which was separately funded by CRC), and Opus conducted the remaining five.

Part of the motivation for this work related to CARB’s legislated directives to improve the air quality in DACs. Senate Bill 535 and Assembly Bill 617 resulted in the assignment of DACs and CARB’s responsibility to both quantify and take action to improve air quality in those DACs. In addition to better understanding the emission rate differences in vehicles registered in and outside of DACs, this project also had the goals of quantifying EV prevalence in DACs, extending the long-running periodic RSD measurements at the West LA La Brea Ave. site, evaluating the emissions characteristics of the fleet of vehicles registered in Mexico that operate in California, evaluating HDV emission rates, and analyzing emissions effects of the different Smog Check program areas.

A key finding in this work was the determination of the increased emission rates from vehicles registered in DACs compared to all other vehicles. As an example of this, Figure 63 presents the average emission rates of NO at each campaign for non-DAC, DAC, and AB617 communities. While there is noise across campaigns, in most cases DAC and/or AB617 vehicles tend to have significantly higher emission rates than non-DAC vehicles at 95% confidence. These findings were similar for HC and CO emission rate measurements. The difference from non-DAC vehicles can range up to a 50% increase depending on pollutant and community type. The analyses in this work also showed that DACs do tend to have older vehicles, but their emissions are elevated even when accounting for model year differences. ERG estimated the contribution of the model year shift to be 30 to 48 percent of the emission rate difference depending on pollutant. ERG also analyzed the prevalence of different fuel types of DAC and non-DAC vehicles. The DAC vehicles tended to have a much lower prevalence of EVs than non-DAC and tended in general to have a higher proportion of gasoline-powered non-hybrid vehicles.

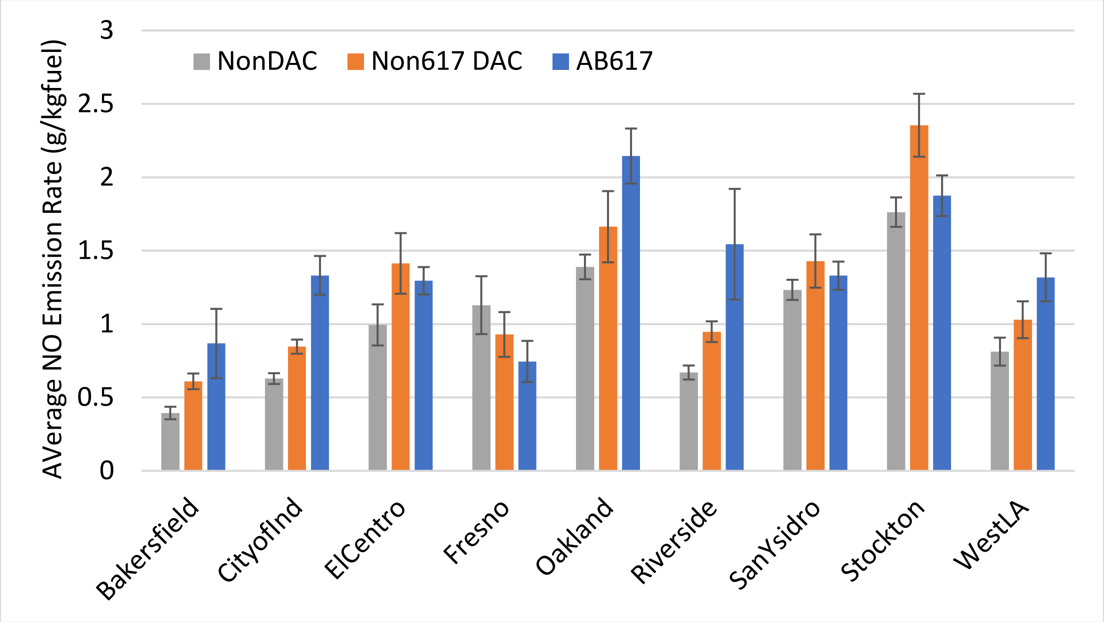

Figure 63. The average NO emission rates for non-DAC, DAC and AB617 status.

ERG also experimented with multiple linear regression modeling of emission rates based on various relevant variables available in the RSD datasets. This was performed to isolate the effects of community type on emission rates and mitigate (and also potentially quantify) the variability caused by the various independent RSD variables. Table 15 presents one finding of this analysis; the expected additive emission rate of NO for DAC LDVs as compared to non-DAC LDVs. Values are presented excluding or including the effect of the different model year distributions of the two communities (DACs tend to have older vehicles and could be expected to emit more on this basis alone).

Table 15. Regression-modeled estimate of the additive increase in expected NO emission rate from DAC-registered LDVs compared to non-DAC-registered ones (and expressed as a %)

	Modeled increase in NO emission rate, g/gkfuel (% of non-DAC mean)

Excluding effect of DAC model year shift	0.10 (~11%)
Including effect of DAC model year shift	0.26 (~27%)

ERG also analyzed the vehicles registered in Mexico that were operating in the areas of the two border campaigns in Southern California and compared them to the California-registered vehicles operating in the same locations. Figure 64 presents the primary findings of this analysis as the average emission rates for the two fleets of vehicles operating at the two border campaigns for HC, NO, and CO. While the model years tended to be very similar for the two fleets of vehicles, the NO and CO emission rates were significantly higher for the Mexico-registered vehicles. The vehicles from Mexico averaged 18% higher for HC, 38% higher for CO, and 92% higher for NO. This is likely due in part to the less restrictive new-vehicle certification rates applicable in Mexico.

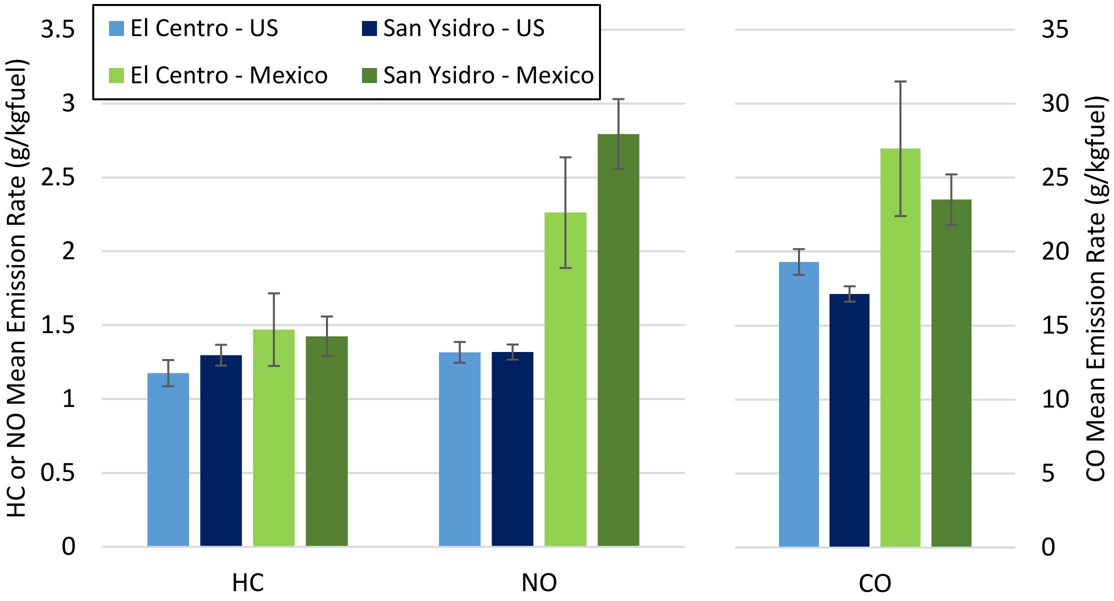

Figure 64. The average emission rates for the CA and Mexican fleets of vehicles at each border site. Error bars represent 95% confidence intervals.

The findings for HDV were limited by the relatively low valid RSD measurement rate for those vehicles. The emissions trends of the valid measurements followed the expected patterns; newer and lighter trucks tended to have lower emission rates than older and/or heavier trucks. The City of Industry campaign had the most valid HDV measurements and was the only campaign to have good measurement coverage across the truck class and model year range. Figure 65 presents the average NO emission rates for all fuel types by truck class and model year bin measured at City of Industry. Diesel-powered trucks tended to have higher emission rates than either their gasoline-(prevalent in the lighter truck classes) or natural gas-(prevalent for the heavier truck classes) powered counterparts.

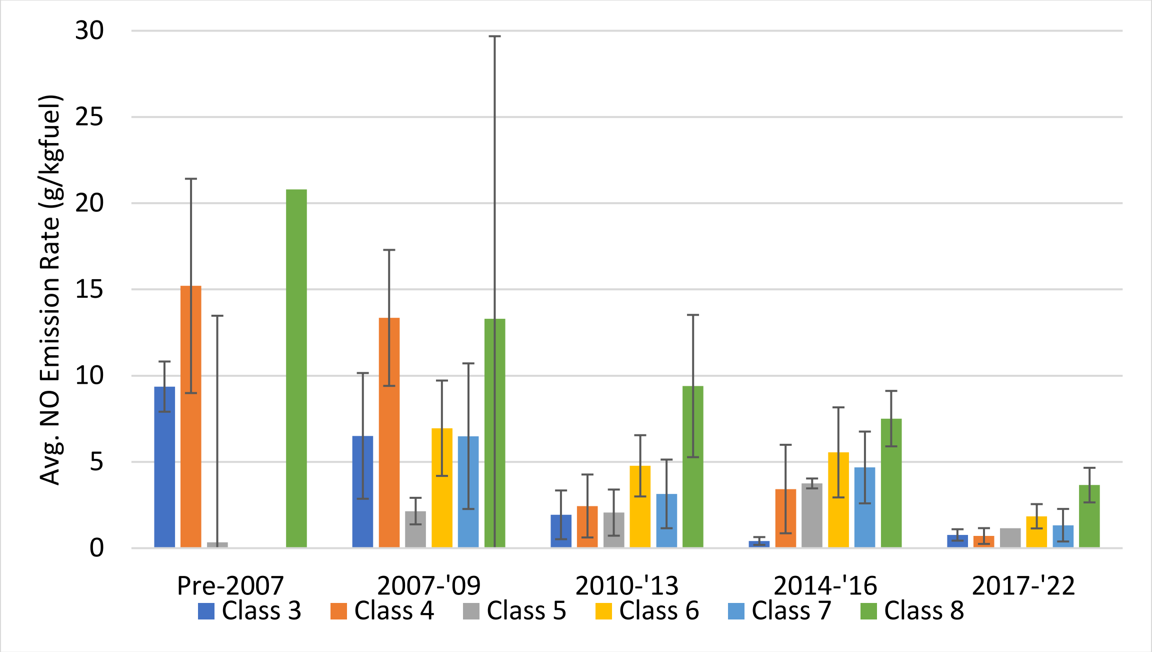

Figure 65. The average emission rate for all HDVs of each truck class and model year bin for all fuels at the City of Industry campaign. Error bars indicate 95% confidence intervals.

Finally, the RSD data was used to investigate various aspects of the Smog Check program and its effectiveness. Emission rates of CO and NO were significantly higher for vehicles registered in Change of Ownership (COO) areas, as compared to the areas requiring biennial emissions tests. However, this finding was confounded by the high prevalence of DACs in the COO areas; it was not possible to determine whether the effect was due to the Smog Check program or the DAC effect. ERG attempted to determine any emissions trends of vehicles throughout the biennial emissions cycle, but no apparent trends were found. ERG also analyzed for an effect of the 8-model year exemption. The RSD data indicated that vehicles from the COO areas to tend to diverge from biennial vehicles in emission rates at about 8 years of age, but the effect of the 8-model year exemption of this was not provable.

Recommendations

This project did result in lessons learned that could be applied to future RSD-based research projects. The ERG team and subcontractors experienced challenges prior to the RSD campaign deployments and also during the analysis of the data.

Site selection is a challenge for RSD deployment. In this project, there were multiple goals for the data analysis, and this did result in some confounding of various factors. For example, the evaluation of Smog Check program areas was very limited because most populated areas are in Basic or Enhanced programs. The DACs around El Centro were confounded with the COO area, preventing a clear interpretation of the causes of emission rate differences. In future multi-site RSD projects, care should be taken to establish potential confounding factors relating to the project goals prior to site selection. Finding locations within COO areas that do not confound with DACs or different vehicle ages in the population will always be difficult due to the nature of the COO area being relatively remote from most California population centers.

It will also be beneficial to continue RSD measurement campaigns into the future at the La Brea site. These campaigns have been conducted approximately every 3 to 4 years and provide a solid source of data for historical emissions trend investigation.

AB617 requires ongoing emissions and air quality measurements at specific communities around California. Continued RSD measurements in or near these communities, especially if at the same sites, can be one tool for CARB to track progress toward air quality goals for these areas.

The HDV measurements in this work were challenged by multiple previously-described factors. The most significant of which was that the RSD measurement location was near the roadway surface so was not able to measure trucks with high-stack exhaust. Consideration could be given to whether it would be feasible to set up an RSD campaign to measure high-stack exhausts. This may be challenged by varying exhaust stack heights, and light beam/mirror alignment may also be more difficult. However, it could allow for higher rates of successful HDV measurement, especially for the larger truck classes.

For most analyses in this work, there were enough measurements in each campaign to establish statistical significance in the results. However, for the Smog Check analyses, and some of the more specific analyses of the different categories of DAC, more data may have been helpful. As the number of combinations of analysis variables gets larger, the amount of data needed for statistical power can increase greatly.

As described previously, there was more variability in the mean emission rate across the different campaigns than expected. It was difficult to determine exactly how much of this variation was due to actual emissions differences across sites and how much was due to measurement error, noise, or other unknown effects. In the future, it may be beneficial to include controlled emissions releases periodically at different campaigns. For example, an EV could be equipped with a system to release different calibration gases as it drives through the RSD setup at each campaign. Having this as a reference could assist in determining how the environmental factors at a given site may affect the measurements.

Alternatively, it may also be illustrative to perform RSD measurements in locations that are geographically very near to each other but that otherwise have somewhat different driving conditions. This may help better understand the variability across different measurement locations. It is possible that specific driving conditions affect emissions measurements more than the differences across geographical areas.

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Glossary of Terms, Abbreviations, and Symbols

CalEnviroScreen (CES) – The software model, developed as a part of SB535, to assign a score of potential pollution exposure risk and socioeconomic disadvantage depending on geographic area in California.

Campaign – In this work, a city or region in which a week-long RSD measurement deployment was conducted. Each campaign consisted of measurements at a single or two sites in the region

Carbon Monoxide (CO) – Emissions made up of CO molecules

Coordinating Research Council (CRC) – A nonprofit, member-funded organization that directs research into environmental impacts of transportation. CRC funded the Fresno RSD data collection and shared it cooperatively for use in this work.

Disadvantaged Community (DAC) – A community as determined by either SB535 or AB617 as being economically or otherwise disadvantaged. In this work, a DAC as assigned by SB535 was taken to be all communities within the top 25% CES score.

Downdraft Exhaust – The exhaust pipe location of an HDV in which the exhaust pipe exits in the region of the truck's frame and the exhaust flows downwards.

High-Stack Exhaust – The exhaust pipe location of an HDV in which exhaust exits at the top rear of the cab, flowing either upwards or rearwards. High-stack exhaust vehicles were not measured by this programs RSD setups.

HC Offset – Developed by Denver University, the HC offset corrects for a potential offset error in RSD HC measurement. It involves subtracting a constant value so that the average of the cleanest fraction of vehicles is very nearly zero. This is not the same as the 2x factor that HC is adjusted by to account for its ability to "see" propane or other hydrocarbons in vehicle exhaust.

Hydrocarbon (HC) – Emissions of various carbon and hydrogen compounds. In RSD results, the HC compound is generally assumed to be propane.

Narrow Spectrum Analysis – In this work, this involved using only a small isolated group of common measurements in calculating by-campaign average emission rates to determine the effect on cross-campaign variability

NOx – Emissions of oxides of nitrogen. NOx consists of the sum of NO and NO_2 on a concentration basis. By convention, the molecular weight of NOx for mass calculation purposes is taken to be equal to that of NO_2.

Parallel measurements – To target both HDVs and LDVs, Opus used two RSD systems operating adjacently. Data for both was woven together, resulting in most vehicle passes appearing twice in the data. ERG used a single measurement for each RSD reading, selected first by which of the two measurements were valid and, in the case of both, using the appropriate system directed at the vehicle type being observed.

Parts per million (PPM) – The concentration of a specific compound within a sample, expressed as its fraction of a million molecules in the sample.

Portable Emissions Measurement System (PEMS) – An onboard exhaust measurement device consisting of miniaturized laboratory-style equipment that can measure exhaust emissions in real-time.

Remote Sensing Device (RSD) – A system that optically measures the concentration of various pollutants in vehicle exhaust compared to CO_2. The measurement occurs over a ½ second interval with minimal invasiveness or disturbance of the passing vehicle.

Site – In this work, a site was a particular location at which an RSD unit was set up. Most campaigns included measurements at only one site, but some campaigns consisted of measurements at two different sites.

Smog Check Program – The California statewide vehicle inspection program, which requires an emissions test during vehicle change of ownership and, depending on registered vehicle location, biennially. When applicable, a passing emissions test result is required to obtain current registration.

Tag-editing – The process by which an RSD contractor transcribes license plates into the RSD datasets. This process can be entirely manual, or can be automated with the automated plate interpretations manually checked by a staff member.

Vehicle specific power (VSP) – An estimate of a vehicle’s tractive power output divided by the vehicle mass. In RSD measurement, the true vehicle mass is unknown but an assumed value can be used.