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ON-ROAD REMOTE SENSING OF AUTOMOBILE EMISSIONS IN THE FRESNO, CA AREA: Spring 2021

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On-Road Remote Sensing of Automobile Emissions in the Fresno, CA Area: Spring 2021

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EXECUTIVE SUMMARY

The University of Denver carried out six days of remote sensing in the Fresno, CA area in June of 2021. Measurements were collected Monday, June 7, to Saturday, June 12, between the hours of 9:00 and 18:00 on the uphill interchange ramp from NB US 41 to WB US 180. This is the same location previously used for measurements in the spring of 2008. The remote sensor used in this study measures the ratios of CO, HC, NO, SO_2, NH_3 and NO_2 to CO_2 in motor vehicle exhaust. From these ratios, one can calculate the percent concentrations of CO, CO_2, HC, NO, SO_2, NH_3 and NO_2 in the exhaust that would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. Mass emissions per mass or volume of fuel can also be determined and are generally the preferred units for analysis. The equipment used in this study was configured to determine vehicle speed and acceleration, and included a video system to record license plate information. The latter was subsequently used to obtain non-personal vehicle registration information.

A database was compiled containing 8,621 records for which the State of California provided registration information. All of these records contained valid measurements for at least CO and CO_2, and most records contained valid measurements for the other species as well. The database, as well as others compiled by the University of Denver, can be found at https://digitalcommons.du.edu/feat/.

The 2021 mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured in this study were 10.3 ± 0.5 g/kg of fuel (0.08%), 1.9 ± 0.2 g/kg of fuel (49 ppm), 1.14 ± 0.06 g/kg of fuel (80 ppm), 0.29 ± 0.01 g/kg of fuel (36 ppm) and 0.07 ± 0.01 g/kg of fuel (3 ppm) respectively (see Figure ES1). The 2021 Fresno measurements show reductions for all of the species measured when compared with the 2008 values. Fuel specific emission factors (g/kg of fuel) decreased for CO (49%), HC (44%), NO (62%), NH_3 (40%), NO_2 (50%) and NO_x (62%) despite the age of the fleet increasing 1.8 years. Fleet mean emissions remain dominated by a few high emitting vehicles. For the 2021 data set the highest emitting 1% of the measurements (99th percentile) are responsible for 30%, 31%, 33%, 14% and 41% of the overall fleet CO, HC, NO, NH_3 and NO_2 emissions, respectively.

Overall, as mentinoned we have observed a 40% reduction in the mean NH_3 emissions since 2008 (0.49 ± 0.01 to 0.29 ± 0.01). The 2008 measurements show the classic peak NH_3 emissions around 15 year old vehicles after which the three-way catalytic converters on average started to lose their ability to reduce NO to NH_3 and NH_3 emissions in the exhaust declined. The 2021 measurements show the increase in the durability of the newer catalytic converters in that there is no obvious peak in NH_3 emissions indicating converter life beyond 25 years.

However, the NH_3 fleet reduction pattern in Fresno is similar to observations in other locations in that it lags behind the rate for tailpipe NO emissions. Total fixed nitrogen emissions have been

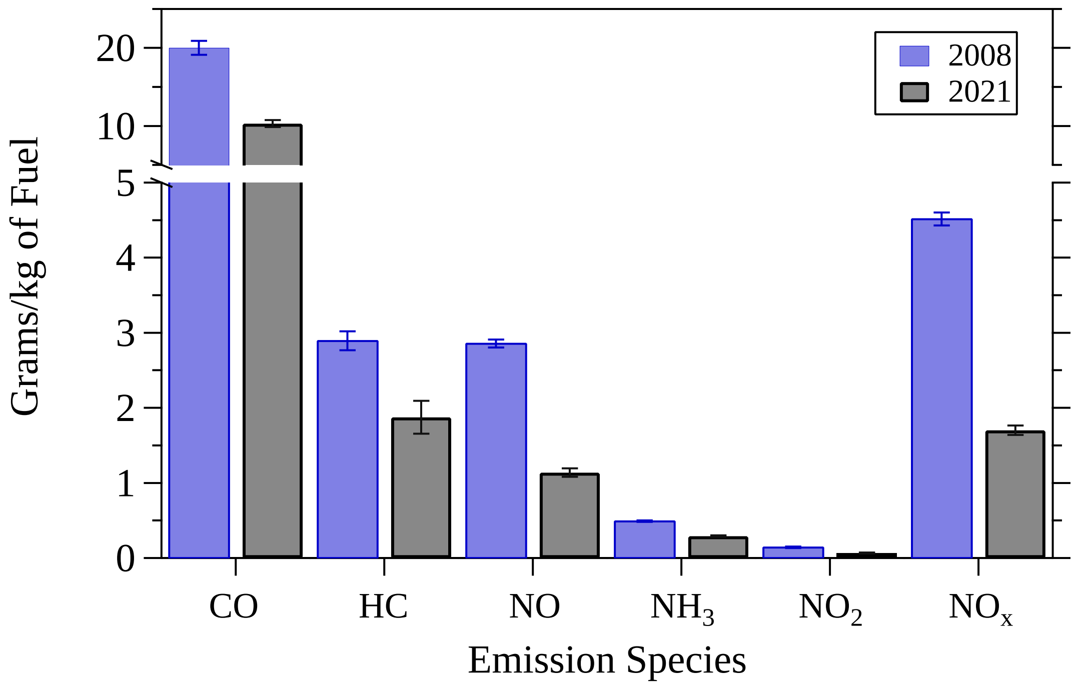

Figure ES1. Mean emission comparison between the 2008 (left blue bars) and the 2021 (right black bars) Fresno, CA measurements using a split y-axis. Uncertainties are standard error of the mean calculated using the daily means. NO is grams of NO and NO_2 and NO_x are grams of NO_2.

on a steep decline since the mid-nineties in the on-road fleet and are continuing to show decreases in the newest model years in this data set as well (see Figure ES2). The percent of fixed nitrogen made up of NH_3 had been on the rise with the introduction of LEV II vehicles to where NH_3 for a time was the dominate species. However, consistent with observations at our other sampling sites across the U.S. toward the end of the LEV II models and with the introduction of LEV III vehicles NO_x emissions have once again become the majority species. It is not known what if anything is behind this preference now for nitrogen oxidation (NO_x) at the tailpipe over reduced nitrogen (NH_3) in the newest vehicles but catalyst formulation is an important factor that can influence NH_3 production.

99^{th} percentile emission levels much like the mean values, have continued to drop though the 99^{th} percentile emissions are still large multiples of the mean values. The 99^{th} percentile values for 10 year old vehicles (2011 model years) in the 2021 database for CO are more than a factor of 8 larger than their mean emissions (76 vs 9 gCO/kg of fuel). For HC the 99^{th} percentile is a factor of 15 larger (25.6 vs 1.7 gHC/kg of fuel) and for NO it is more than a factor of 9 larger (4.9 vs 0.5 gNO/kg of fuel). For CO and especially for NO there has been a noticeable improvement since the introduction of the LEV II vehicles.

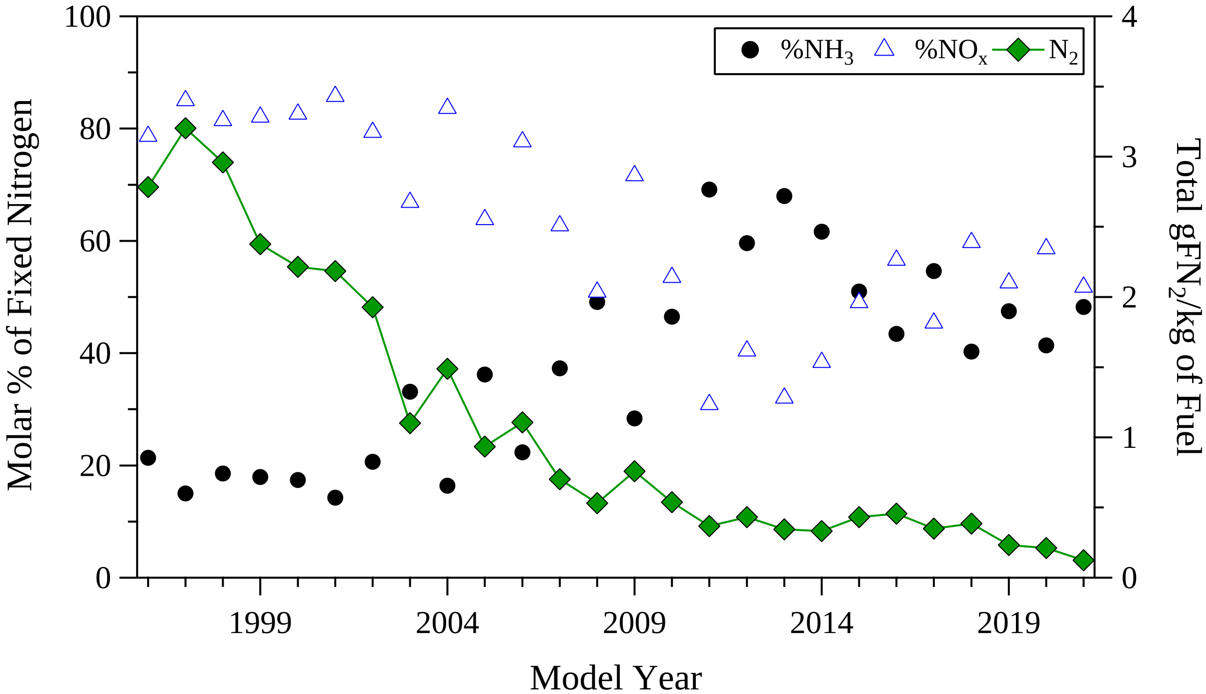

Figure ES2. Total fixed nitrogen in gN/kg of fuel (diamonds, right axis) with the molar percent composition distributed between the molar $\%NH_3$ (circles, left axis) component and the molar $\%NO_x$ component (triangles, left axis) by model year for the 2021 measurements.

INTRODUCTION

Since the early 1970's, many heavily populated U.S. cities have been unable to attain the National Air Quality Standards (NAAQS) established by the Environmental Protection Agency (EPA) pursuant to the requirements of the Federal Clean Air Act.[1, 2] Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas, and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). Ambient levels of particulate emissions can result either from direct emissions of particles or semi-volatile species or from secondary reactions between gaseous species, such as ammonia and nitrogen dioxide. As of 2017, on-road vehicles continued to be estimated as one of the larger sources for major atmospheric pollutants, contributing approximately 38% of the CO, 13% of the VOC's, 3% of the NH_3 and 35% of the NO_x to the national emission inventory.[3]

The use of the internal combustion engine (and its combustion of carbon-based fuels) as a primary means of transportation, makes it a significant contributor of species covered by the NAAQS. For a description of the internal combustion engine and causes of pollutants in the exhaust, see Heywood.[4] Properly operating modern vehicles with three-way catalysts are capable of partially (or completely) converting engine-out CO, HC and nitric oxide (NO) emissions to carbon dioxide (CO_2), water, and nitrogen. Control measures to decrease mobile source emissions in non-attainment areas, beyond Federal and California certification standards, include inspection and maintenance programs, reformulated and oxygenated fuel mandates, and transportation control measures, but the effectiveness of these measures is difficult to quantify. Many areas remain in non-attainment for ozone. The further tightening of the federal eight-hour ozone standards (first introduced by the EPA in 1997 (80ppb), lowered in 2008 (75ppb) and again in 2015 (70ppb)) means that many new locations are likely to continue to have difficulty meeting the standards in the future.

The University of Denver first visited Fresno, CA in March of 2008 as part of a California Air Resources Board project and collected seven days of measurements on the uphill interchange ramp from northbound US 41 to westbound US 180 (see Figure 1) using the University of Denver's FEAT optical remote sensing unit.[5] Fresno, CA is a community of approximately 500,000 people located in California's central San Joaquin Valley. The Central Valley is an area in California that regularly exceeds the NAAQS for particulate matter and ozone. Mobile sources are one of many factors that contribute either with direct particulate emissions or indirectly with ozone pre-cursor emissions of CO, volatile organic compounds and oxides of nitrogen emissions ($NO_x \equiv NO + NO_2$) to these air quality problems.

A new visit to the 2008 site was requested and the University of Denver returned for a series of new measurements in the spring of 2021. The ramp originally used in Fresno is not a high volume site but it was determined that despite this fact the new measurements should be carried out at the same location previously used.

Figure 1. A satellite view of the Fresno interchange ramp from northbound US 41 to westbound US 180 with the approximate locations of the motor home (large rectangle), the remote sensing detector, source (small rectangles) and camera (circle).

MATERIALS AND METHODS

The FEAT remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust; it has been extensively discussed in the literature.[6-8] The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC and twin dispersive ultraviolet (UV) spectrometers (0.26 nm/diode resolution) for measuring oxides of nitrogen (NO and NO_2), SO_2 and NH_3. The source and detector units are positioned on opposite sides of a single lane road in a bi-static arrangement. 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 reference.

The UV light is 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. The quartz fibers in the bundle are divided in half to carry the UV signal to two separate spectrometers. The first spectrometer's wavelength ranges from 227nm down to 198nm to measure the species of NO, SO_2 and NH_3. The absorbance from each respective UV spectrum of SO_2, NH_3, and NO is compared to a calibration spectrum using a classical least squares fitting routine in the same region to obtain the vehicle emissions. The second spectrometer measures only NO_2 by measuring an absorbance band at 438nm in the UV spectrum and comparing it to a calibration spectrum in the same region.[9] All species are sampled at 100Hz. Since the removal of sulfur from US gasoline and diesel fuel, SO_2 emissions have become negligibly small. While SO_2 measurements were collected as a part of this study, they will not be reported or discussed because the sensor was not calibrated for SO_2 emissions.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and depend on, among other things, the height of the vehicle's exhaust pipe, engine size, wind, and turbulence behind the vehicle. For these reasons, the remote sensor measures directly only 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, termed Q^{CO}, Q^{HC}, Q^{NO}, Q^{NH3} and Q^{NO2} respectively, are constant for a given exhaust plume; they are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as grams/kilogram of fuel (g/kg of fuel) or as molar %CO, %HC, %NO, %NH_3 and %NO_2 in the exhaust gas, corrected for water and excess air not used in combustion. 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.[10] To calculate mass emissions as described below, the %HC values reported are first multiplied by 2.0 as shown below to account for these "unseen" hydrocarbons, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the following equations.

$$\text{gm CO/gallon} = 5506 \bullet \%\text{CO} / (15 + 0.285 \bullet \%\text{CO} + 2(2.87 \bullet \%\text{HC})) \quad (1a)$$
$$\text{gm HC/gallon} = 2(8644 \bullet \%\text{HC}) / (15 + 0.285 \bullet \%\text{CO} + 2(2.87 \bullet \%\text{HC})) \quad (1b)$$
$$\text{gm NO/gallon} = 5900 \bullet \%\text{NO} / (15 + 0.285 \bullet \%\text{CO} + 2(2.87 \bullet \%\text{HC})) \quad (1c)$$
$$\text{gm NH}_3\text{/gallon} = 3343 \bullet \%\text{NH}_3 / (15 + 0.285 \bullet \%\text{CO} + 2(2.87 \bullet \%\text{HC})) \quad (1d)$$
$$\text{gm NO}_2\text{/gallon} = 9045 \bullet \%\text{NO}_2 / (15 + 0.285 \bullet \%\text{CO} + 2(2.87 \bullet \%\text{HC})) \quad (1e)$$

These equations show that the relationships between emission concentrations and mass emissions are: (a) linear for NO_2 and NH_3, (b) nearly linear for CO and NO and (c) linear at low concentrations for HC. Thus, the percent difference in emissions calculated from the concentrations of pollutants reported here is equivalent to a difference calculated from masses. Note that NO is reported as grams of NO, while vehicle emission factors for NO_x are normally reported as grams of NO_2, even when the actual compound emitted is nearly 100% NO in the case of gasoline-fueled vehicles.

The major relationship reported here is the direct conversion from the measured pollutant ratios to g/kg of fuel. This is achieved by first converting the pollutant ratio readings to moles of pollutant per mole of carbon in the exhaust using the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 6HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q^{CO}, 2Q^{HC}, Q^{NO}...)}{Q^{CO} + 1 + 6Q^{HC}} \quad (2)$$

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in the fuel, assuming gasoline is stoichiometrically CH_2. Again, the HC/CO_2 ratio must use two times the reported HC (see above) because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading.[10]

$$\text{gm CO/kg} = (28Q^{CO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3a)$$
$$\text{gm HC/kg} = (2(44Q^{HC}) / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3b)$$
$$\text{gm NO/kg} = (30Q^{NO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3c)$$
$$\text{gm } NH_3\text{/kg} = (17Q^{NH3} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3d)$$
$$\text{gm } NO_2\text{/kg} = (46Q^{NO2} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3e)$$

Quality assurance calibrations are performed at least twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant additional calibrations. The multi-species instrument used in this study requires three calibration cylinders. The first contains 6% CO, 6% CO_2, 0.6% propane and 0.3% NO; the second contains 0.1% NH_3 and 0.6% propane and the final cylinder contains 0.05% NO_2 and 15% CO_2. A puff of gas is released into the instrument's path, and the measured ratios from the instrument are compared to those certified by the cylinder manufacturer (Praxair and Air Liquide). 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 the remote sensor are reported as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[11, 12] The NO channel used in this study has been extensively tested by the University of Denver, but has not been independently validated in an extensive double-blind study and instrument intercomparison. Tests involving a late-model low-emitting vehicle indicate a detection limit (3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations.[7] A list of criteria for determining data validity is shown in Appendix A.

The remote sensor is accompanied by a video system to record a freeze-frame image of the license plate of each vehicle measured. The emissions information for the vehicle and a time and date stamp are also recorded on the video image. The images are stored digitally, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate two parallel infrared beams passing across the road, six feet apart and approximately two feet above the surface. Vehicle speed is calculated (reported to 0.1 mph) from the time that passes between the front of the vehicle blocking the first and the second beam. To measure vehicle acceleration, a second speed is determined from the time that passes between the rear of the vehicle unblocking the first and the second beam. Acceleration is calculated (reported to 0.001 mph/sec) from these two speeds and the time difference between the two speed measurements. Appendix B defines the database format used for the data set.

RESULTS AND DISCUSSION

Measurements were made on parts of six consecutive days, from Monday, June 7, to Saturday, June 12, between the hours of 9:00 and 18:00 on the uphill interchange ramp from NB US 41 to WB US 180. Equipment problems on the first two days of sampling restricted the measurements to only the afternoon time period. The instrument was located in the uphill portion of the ramp at the approximate location of the 2008 measurements. It was not possible to unequivocally determine the 2008 location as the outside portion of the ramp had been reconstructed with a concrete jersey barrier that eliminated the guard rail used in 2008 for the location measurements. Figure 2 shows a photograph of the setup. Plates that appeared to be in state and readable were sent to the California Air Resources Board to be matched against the state non-personal vehicle registration information. The resulting database contains 8,621 records with make and model year information and valid measurements for at least CO and CO_2. The database and all previous databases compiled for CRC E-106 and CRC E-23-4 campaigns can be found at https://digitalcommons.du.edu/feat/.

The data reduction process of the measurements is summarized in Table 1. The table details the steps beginning with the number of attempted measurements and ending with the number of records containing both valid emissions measurements and vehicle registration information. An attempted measurement is defined as a beam block followed by a half second of data collection. If the data collection period is interrupted by another beam block from a close following vehicle, the measurement attempt is aborted and a new attempt is made to measure the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement. The first significant data losses occur from invalid measurement attempts when the vehicle plume misses the sampling beam, is highly diluted or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit (See Appendix A). The second significant loss of data occurs during the plate reading process, when out-of-state vehicles and vehicles with unreadable plates (obscured, rusted, missing, dealer, out of camera field of view) are omitted from the database.

Figure 2. The Fresno monitoring site in 2021 showing the monitoring vehicle and the remote sensing detectors and speed and acceleration bars.

Table 1. Fresno Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	10,711				
Valid Measurements	10,119	10,013	10,119	10,115	7,880
Percent of Attempts	94.5%	93.5%	94.5%	94.4%	73.6%
Submitted Plates	8,753	8,674	8,753	8,751	6,845
Percent of Attempts	81.7%	81.0%	81.7%	81.7%	63.9%
Percent of Valid Measurements	86.5%	86.6%	86.5%	86.5%	86.9%
Matched Plates	8,621	8,543	8,621	8,619	6,757
Percent of Attempts	80.5%	79.8%	80.5%	80.5%	63.1%
Percent of Valid Measurements	85.2%	85.3%	85.2%	85.2%	85.7%
Percent of Submitted Plates	98.5%	98.5%	98.5%	98.5%	98.7%

Table 2 provides an analysis of the number of vehicles that were measured repeatedly and the number of times they were measured. Of the 8,621 records used in this analysis, 5,919 (68.7%) were contributed by vehicles measured only once, and the remaining 2,702 (31.3%) records were from vehicles measured at least twice.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	5,919
2	694
3	230
4	81
5	44
6	11
7	2

Table 3 provides the data summary for the 2021 measurements along with a summary of previous 2008 measurements collected by the University of Denver at the Fresno site. It has been thirteen years since those previous measurements and all of the measured emission species have seen substantial reductions. Using the fuel specific means we find reductions of 48.5%, 43.5%, 62.1%, 40% and 50% for CO, HC, NO, NH_3, and NO_2 respectively despite the age of the fleet increasing 1.8 years. NO emissions show the largest reductions since the last visit. The mean HC values have been adjusted to remove a systematic offset in the measurements. This offset, restricted to the HC channel, has been reported in previous CRC reports. The offset is calculated by computing the mode and means of the newest model year vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. The offset adjustment subtracts this value from all of the hydrocarbon data. This process basically attempts to keep the median emissions of the newest and lowest emitting vehicles near zero but always slightly positive. Since it is assumed that the cleanest vehicles emit few hydrocarbons, this approximation will only err slightly towards clean as the true offset will be a value somewhat less than the average of the cleanest model year and make. Unless otherwise stated, the analysis of the HC measurements in this report use the offset adjusted data.

The inverse relationship between vehicle emissions and model year is shown in Figure 3 for data collected during the two campaigns. The HC data have been offset adjusted as previously described. The uncertainties for the 2021 measurements are standard error of the mean determined from the daily measurements. The thirteen year seperation between the two data sets results in only about half of the model years plotted overlapping between the two studies. The most noticable increases in emissions can be seen in the CO and NO emissions of the fourteen year old and older vehicles while the uncertainties in the HC measurements are larger than most of the differences. Another decernable feature is that the number of model years with mean

Table 3. Fresno Data Summary.

Study Year	2008	2021
Mean CO (%) (g/kg of fuel)	0.16 (20.0)	0.08 (10.3)
Median CO (%)	0.02	0.026
%Total CO from the 99th Percentile	30.8%	29.5%
Mean HC (ppm)* (g/kg of fuel)* Offset (ppm)	72 (2.9) 30	49 (1.9) 10
Median HC (ppm)*	40	40
%Total HC from the 99th Percentile	19.6%	31.2%
Mean NO (ppm) (g/kg of fuel)	202 (2.9)	80 (1.1)
Median NO (ppm)	12	6
%Total NO from the 99th Percentile	15.5%	35%
Mean NH_3 (ppm) (g/kg of fuel)	62 (0.5)	36 (0.3)
Median NH_3 (ppm)	21	14
%Total NH_3 from the 99th Percentile	12.5%	14.4%
Mean NO_2 (ppm) (g/kg of fuel)	7 (0.14)	3 (0.07)
Median NO_2 (ppm)	3.5	2
%Total NO_2 from the 99th Percentile	30.1%	41%
Mean Model Year	1999.8	2011.2
Mean Fleet Age (years)	8.8	10.6
Mean Speed (mph)	25.4	25.4
Mean Acceleration (mph/s)	0	0.35
Mean VSP (kw/tonne) Slope (degrees)	6.4 1.8°	8.3 1.8°
*Indicates values that have been HC offset adjusted as described in text.		

emissions near zero have more than doubled for all three species. The number of vehicles with near zero NO emissions may be triple depending on how one judges stability in the 2008 means.

The 2021 fleet vehicle emissions by model year, were divided into quintiles and plotted using the format originally presented by Ashbaugh et al.[13] This resulted in the plots shown in Figures 4 - 6. The bars in the top graphs represent the mean emissions for each quintile. The middle graphs the fraction of the Fresno fleet for each model year. The impact of the reduction in light-duty vehicle sales due to the economic recession is still evident in the model year fractions beginning in 2009

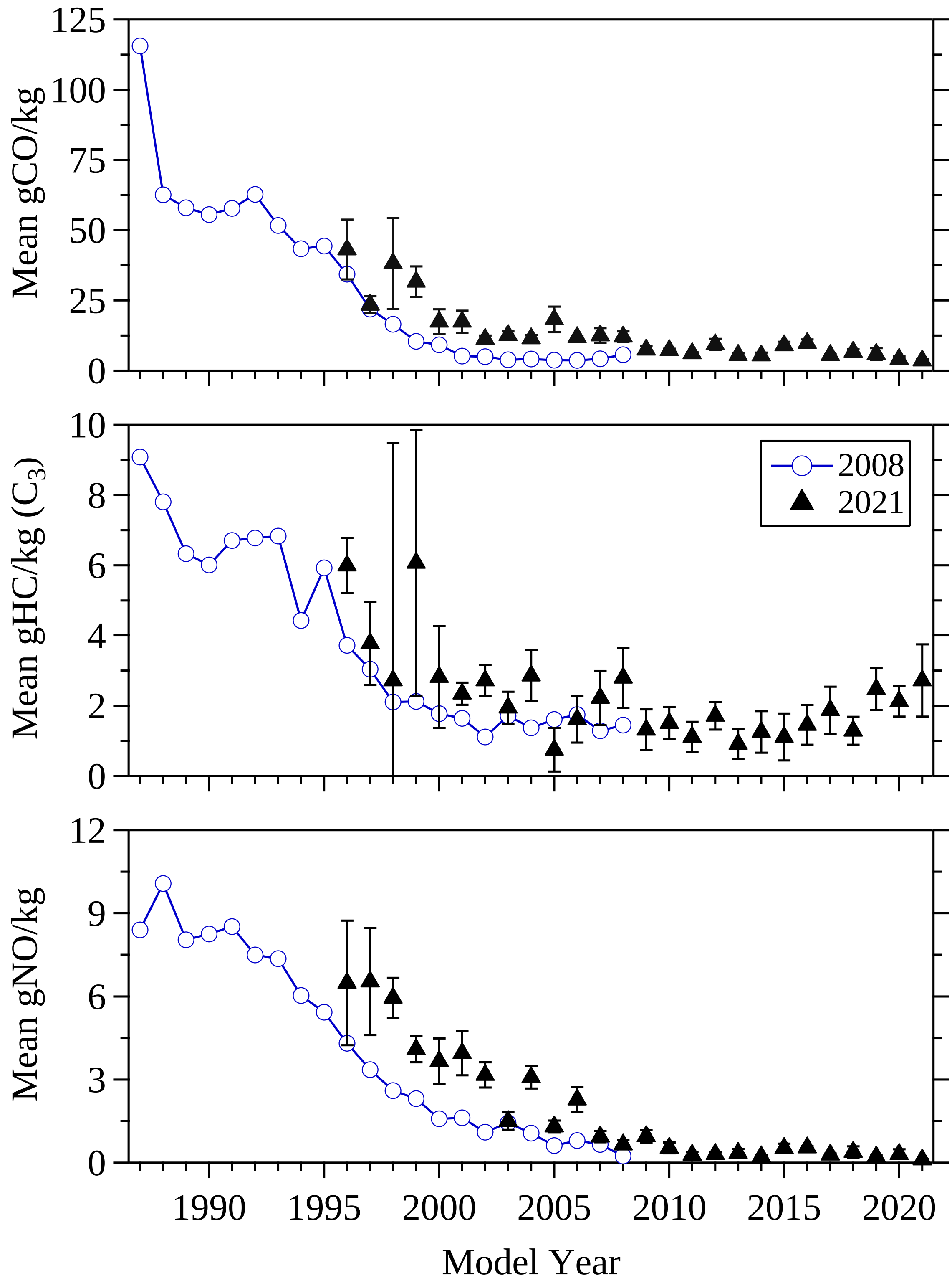

Figure 3. Fresno historical fuel specific mean vehicle emissions plotted as a function of model year. HC data have been offset adjusted as described in the text. Uncertainties are standard error of the mean determined from the daily means.

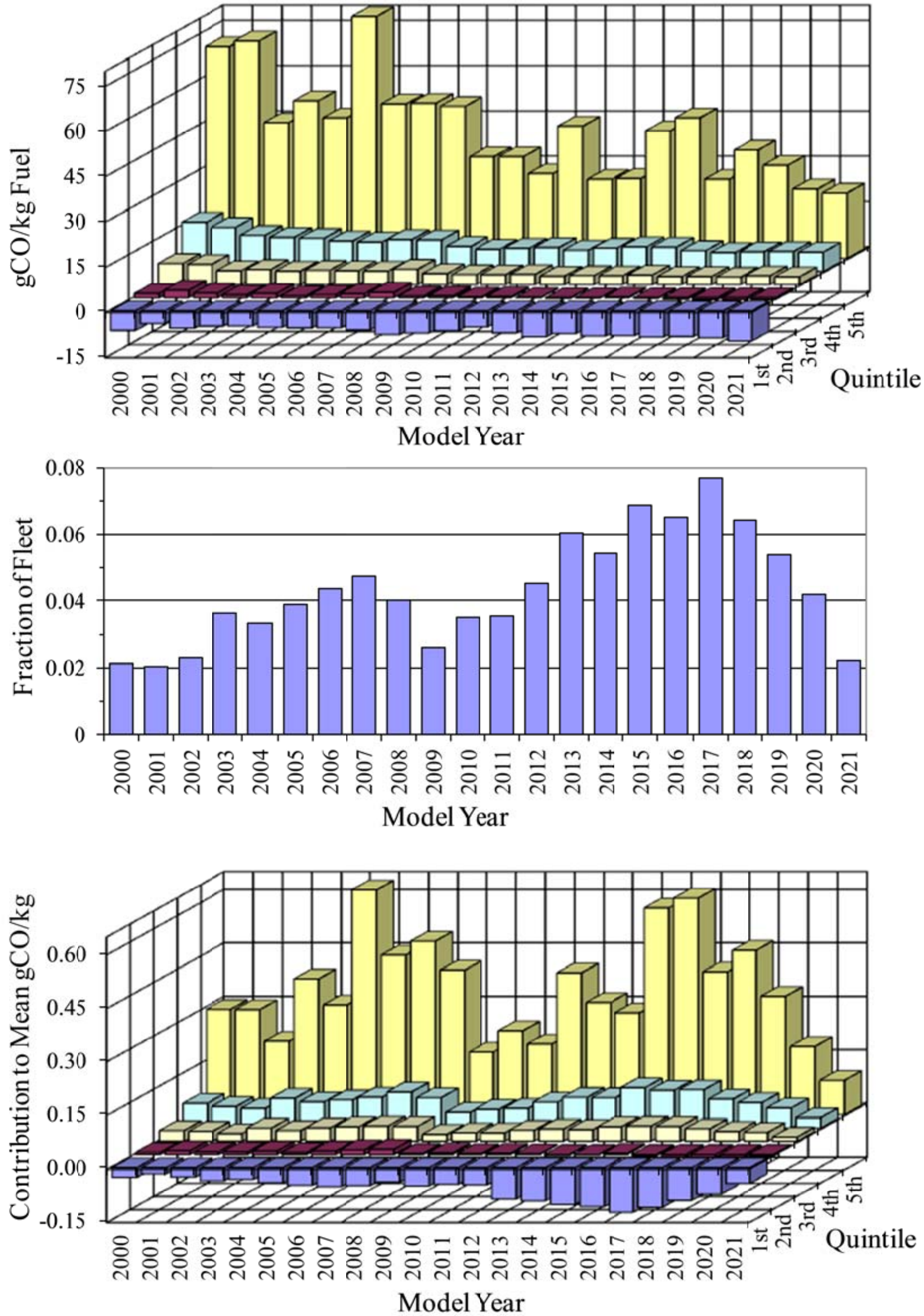

Figure 4. Fresno 2021 fuel specific CO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions by model year and quintile (bottom).

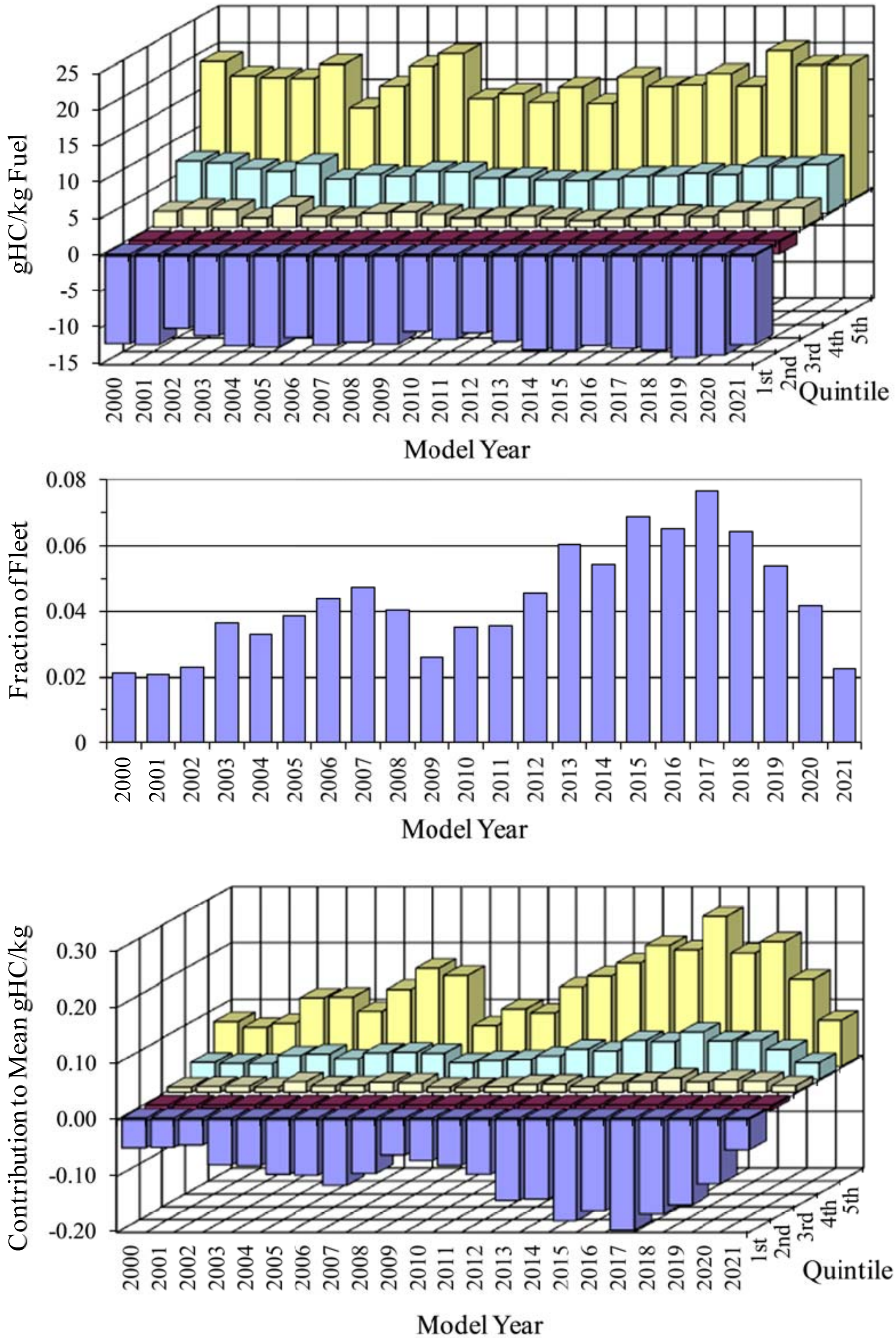

Figure 5. Fresno 2021 fuel specific HC emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions by model year and quintile (bottom).

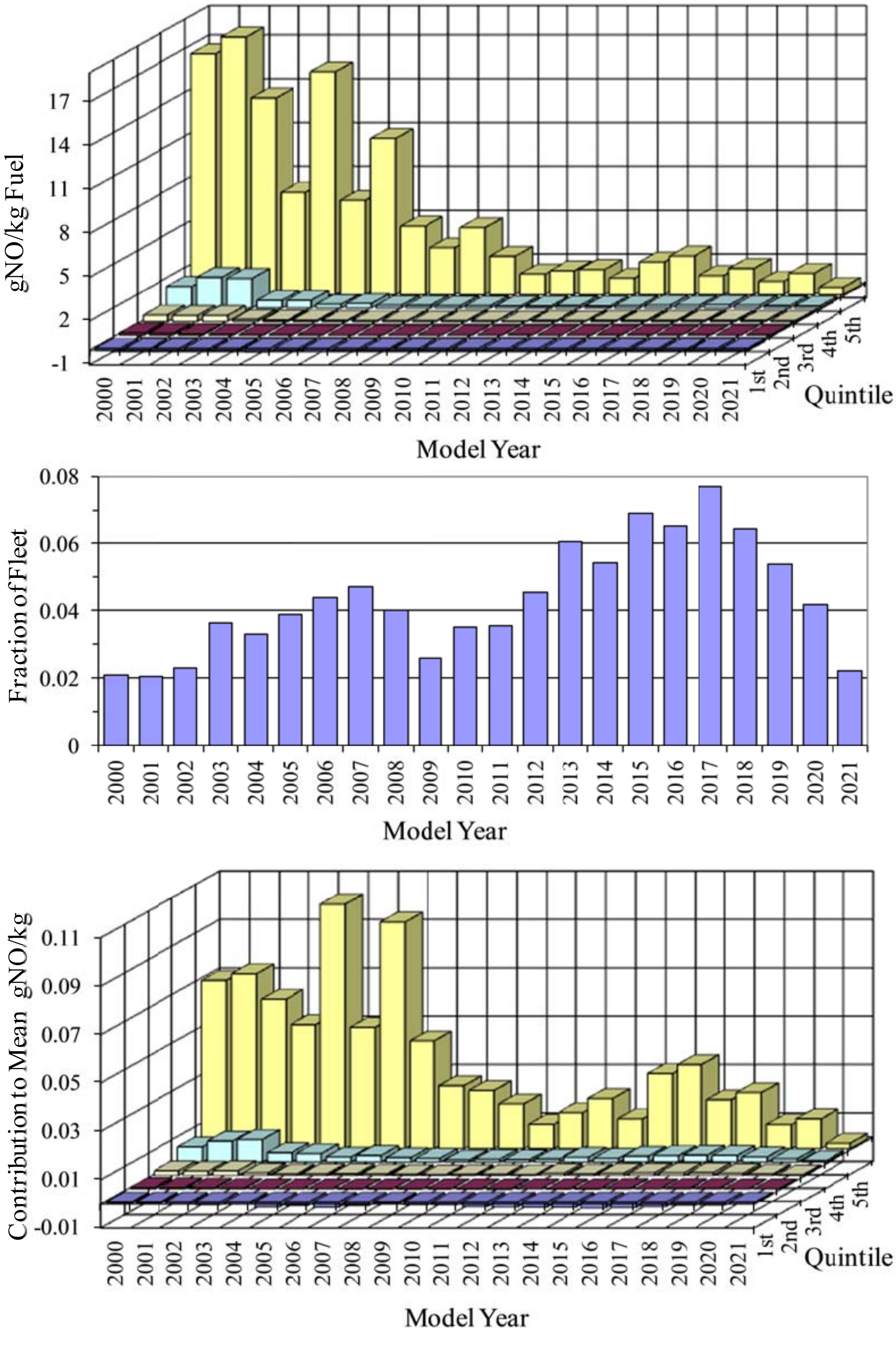

Figure 6. Fresno 2021 fuel specific NO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg of fuel emissions by model year and quintile (bottom).

and continuing through 2012. The bottom graphs, which are a product of the first two graphs, display the contribution each model year and quintile makes to the mean emissions. Model years older than 2000 that are not graphed account for 4.6% of the measurements and their contribution ranges between 11.3% (HC) to 24.8% (NO) of the emissions. The bottom graphs for each species illustrate that the first three quintiles of the measurements (60%) make an essentially negligible contribution to the mean emissions, regardless of model year. When the negative contributions are factored into the total for all three species only the last quintile now contributes significant amounts. The large accumulations of negative emissions in the first two quintiles are the result of ever decreasing emission levels. The instrument is designed such that when measuring a zero emission plume, half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to approach zero emissions, the negative emission readings will continue to grow toward half of all the measurements. The newest model years are at that stage now for all species.

The impact of the 2008 recession is still very noticeable in the reduced fraction of the 2009 and 2010 model year vehicles as shown in the middle plots of Figures 4 - 6. What is also noticeable is that the fraction of 1 and 2 year old vehicles in Fresno (2020 and 2019) is also significantly reduced. Reductions in the 2020 models can likely be blamed on reduced demand during the pandemic but that cannot be used to explain the smaller fleet of 2 year old (2019) vehicles.

An equation for determining the instantaneous power demand of an on-road vehicle published by Jimenez[14], takes the form

$$\mathrm{VSP} = 4.39 \bullet \sin(slope) \bullet v + 0.22 \bullet v \bullet a + 0.0954 \bullet v + 0.0000272 \bullet v^3 \qquad (4)$$

where VSP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees, see Table 3), v is vehicle speed in mph, and a is vehicle acceleration in mph/s. This equation is derived from dynamometer studies and is necessarily an approximation. The first term represents the work required to climb the gradient, the second term is the $f = ma$ work to accelerate the vehicle, the third is an estimated friction term, and the fourth term represents aerodynamic resistance. This equation was used to calculate vehicle specific power for all measurements in each of the eleven years' databases. This equation, like all dynamometer studies, does not include any load effects arising from road curvature. The emissions data, binned according to vehicle specific power, are graphed in Figure 7. The uncertainty bars included in the plot are standard errors of the mean calculated from the daily averages. All of the specific power bins for 2021 contain at least 58 measurements and the HC data have been offset adjusted.

The VSP plots for all three species show the reductions in fuel specific emissions seen in the comparison of the mean emissions. In general over this range of VSP's CO and NO show slight increases in average emissions at the higher VSP bins but the uncertainties in the two highest bins, due to the small number of measurements, minimize the certainty of those trends. The HC

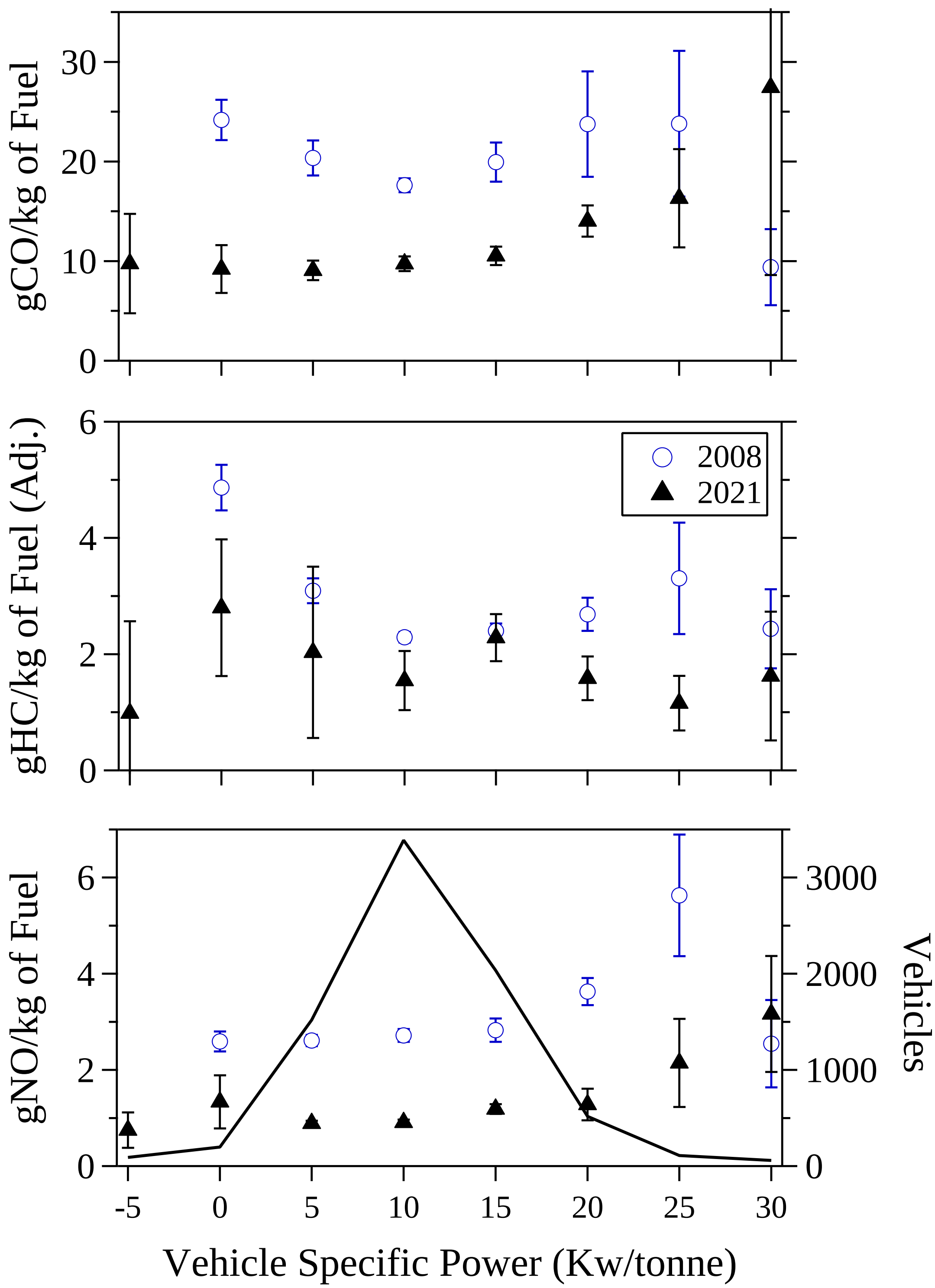

Figure 7. Vehicle emissions as a function of vehicle specific power for the two Fresno data sets. The uncertainties are plotted as the standard errors of the mean calculated from the daily means. The solid line without markers in the bottom panel is the vehicle count profile (right y-axis) for the 2021 data set.

emissions have the largest uncertainties, due to the higher noise levels incumbent in those measurements, and are flat across this range of driving modes.

The two data sets collected at the Fresno, CA site in general have very similar driving modes though the mean VSP from the 2021 is 22% larger than observed in 2008. We can use the 2008 VSP profile to normalize the driving mode of the 2021 fleet to gauge what if any effect the increased VSP has on the 2021 mean emissions. Table 4 shows the mean emissions for the vehicles in the 2008 and 2021 databases with specific powers between –5 and 25 kw/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire set of measurements in each data set, as shown in Table 3. Table 4 also shows the mean emissions for the two databases, adjusted for vehicle specific power that match the 2008 VSP distribution.

Table 4. Vehicle specific power emissions (-5 to 25 kw/tonne only) with standard errors of the means calculated using daily averages and means adjusted to the 2008 VSP distribution.

Year	Mean gCO/kg Measured (Adjusted)	Mean gHC/kg[a] Measured (Adjusted)	Mean gNO/kg Measured (Adjusted)
2008	19.6 ± 1.0 (19.6 ± 1.0)	4.1 ± 0.1 (2.8 ± 0.1)	2.7 ± 0.1 (2.7 ± 0.1)
2021	10.3 ± 0.5 (10.2 ± 0.5)	2.2 ± 0.2 (1.8 ± 0.2)	1.0 ± 0.05 (1.0 ± 0.05)

[a]HC emissions are offset adjusted as described in the text.

The normalization of the data to the 2008 driving mode is accomplished by applying the mean vehicle emissions for each VSP bin (between –5 and 20 kw/tonne) from a certain year's measurements to the vehicle distribution, by vehicle specific power, for each bin from the 2008 measurements. A sample calculation, for vehicle specific power-adjusted mean NO emissions, is shown in Appendix D. Because the VSP data are adjusted to the 2008 vehicle frequency distribution by VSP bin, the 2008 adjusted values are the same as the measured values except the HC data, which include the extra calculation to adjust for the yearly HC offset. Each measurement year's adjusted values for HC in Table 4 include this additional adjustment. As discussed with Figure 7 the influence of driving mode between -5 and 25 kw/tonne are small and the adjusted 2021 emissions did not change within the uncertainties when the 2008 VSP distribution was applied to the 2021 means in Table 4.

A similar normalization can be applied to a fleet of specific model year vehicles to track deterioration, provided a baseline of only the model years measured in 2008 is used. A sample calculation, for the model year adjusted mean NO emissions, is shown in Appendix E. Table 5 shows mean emissions for all vehicles from model year 1961 to 2008, as measured in 2008. Applying the vehicle frequency distribution by model year observed in 2008 to the mean emissions by model year from the 2021 study yields the model year adjusted fleet emissions.

Table 5. Measured and model year adjusted[a] fleet emissions. Uncertainties are standard error of the mean calculated from the daily means.

Year	Mean gCO/kg Measured (Age Adjusted)	Mean gHC/kg[a] Measured (Age Adjusted)	Mean gNO/kg Measured (Age Adjusted)	Vehicles
2008	20.0 ± 0.9 (20.0 ± 0.9)	4.1 ± 0.1 (2.9 ± 0.1)	4.4 ± 0.1 (4.4 ± 0.1)	13,365
2021	16.8 ± 1.3 (23.8 ± 1.9)	2.5 ± 0.2 (3.2 ± 0.2)	2.5 ± 0.2 (4.1 ± 0.3)	3,017

[a]To match the 2008 & older model year distribution observed during the 2008 measurements.

[b]HC emissions are offset corrected for all of the years adjusted data.

Only the CO and HC have age adjusted mean emissions for this model year grouping that have increased since the 2008 measurements (~+16% CO and +9% HC) though the HC increases are not significant at the 67% confidence level. The number of 2008 & older models has shrunk by 77% during the 13 years that have elapsed. The combination of vehicle attrition and emissions deterioration has resulted in very small increases in the overall emissions.

In 2008 Fresno became the fourth U.S. site to have the University of Denver collect fleet NH_3 measurements. The 2021 mean reported in Table 3 (0.29 ± 0.01) represents a ~40% reduction from the mean observed in 2008. Figure 8 is a graph of gNH_3/kg of fuel emissions by model year for the two Fresno data sets with NH_3 measurements. The uncertainties are standard error of the mean calculated using the daily means. In the 2008 data set you will notice that the NH_3 emissions rise faster than similarly aged vehicles do in the 2021 measurements. Also the 2008 data set has a noticeable peak around 15 year old vehicles (1993 model year vehicles) indicating that on average the three-way catalytic converters are starting to lose their ability to reduce NO to NH_3 after this age. In the 2021 data set there is no apparent peak indicating that three-way catalytic converters manufactured in the late 90's (23 years and older) are still fully functional.

The percent ammonia of total fixed nitrogen was analyzed to see if the percentage of ammonia increased as total fixed nitrogen decreased with decreasing age, as has been shown in the analysis of other U.S. fleets. Total fixed nitrogen for this calculation neglects the minor contributions of nitrous oxide (N_2O) and nitrous acid (HONO) and is the sum of the moles of nitrogen contributed by NO, NO_2 and NH_3. The gNO_x/kg of fuel was calculated by converting the measured gNO/kg of fuel to gNO_2/kg of fuel equivalents and summing with the measured gNO_2/kg of fuel. The percent of ammonia in the total fixed nitrogen (FN_2), in g/kg of fuel, was calculated as shown by Burgard et al.[9] All of the N factors were converted to mole/kg of fuel.

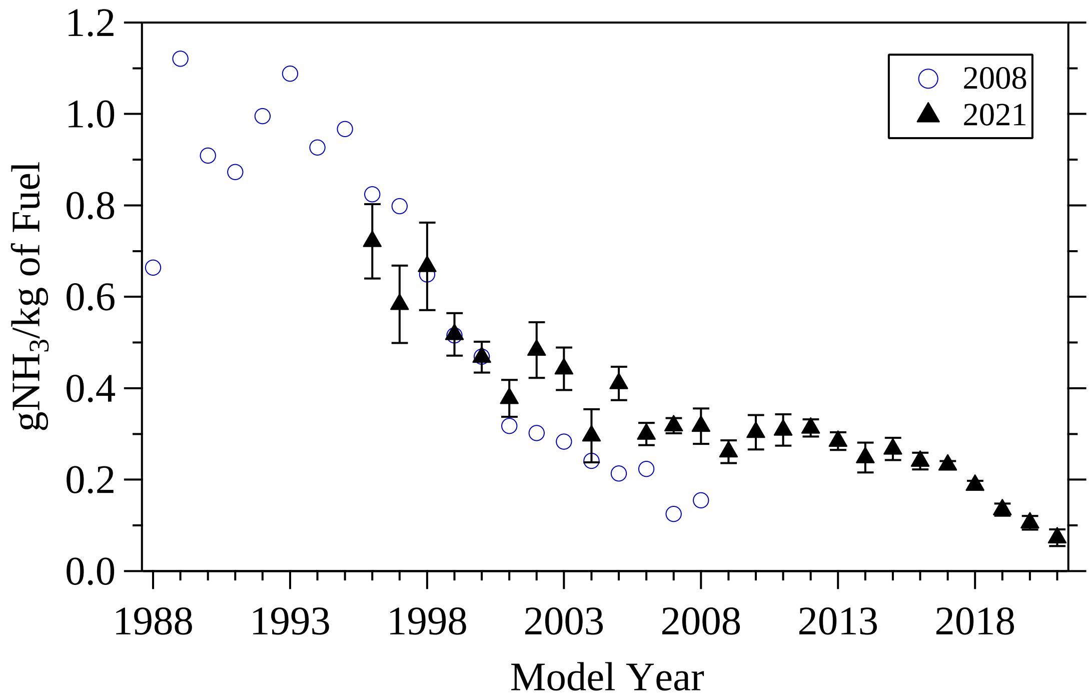

Figure 8. Comparison of gNH_3/kg of fuel emissions by model year for the 2008 and 2021 Fresno data sets. The uncertainties are standard error of the mean calculated using the daily means.

$$\text{Molar }\%NH_3\text{ in Total Fixed Nitrogen} = \frac{100 \text{ x } N_{NH_3}}{N_{NH_3} + N_{NO_x}} \qquad (5)$$

Figure 9 shows the results of these calculations for the Fresno 2021 data set. The molar $\%NO_x$ and $\%NH_3$ which total 100% are percentages of the gFN_2/kg of fuel values plotted by model year. The noise increases for the molar percentages in the newest model years is due to the shrinking amount of fixed nitrogen emissions. The total fixed nitrogen (filled diamonds, right axis) species continues to decrease with subsequent model year vehicles. The percent contributed by ammonia (●, left axis) had steadily increased in the Fresno fleet but peaked around the 2011 to 2013 model years and has since declined to where it is once again lower than the fixed nitrogen contributed by the NO_x (△, left axis) emissions. This pattern has now also been observed at all of the U.S. sites that the University of Denver has collected NH_3 emission measurements since 2019. There is a hypothesis that the apportionment between NH_3 and NO_x is affected by the precious metal makeup of the three-way catalyst. If catalyst formulation information was available that theory could be tested with these data sets.

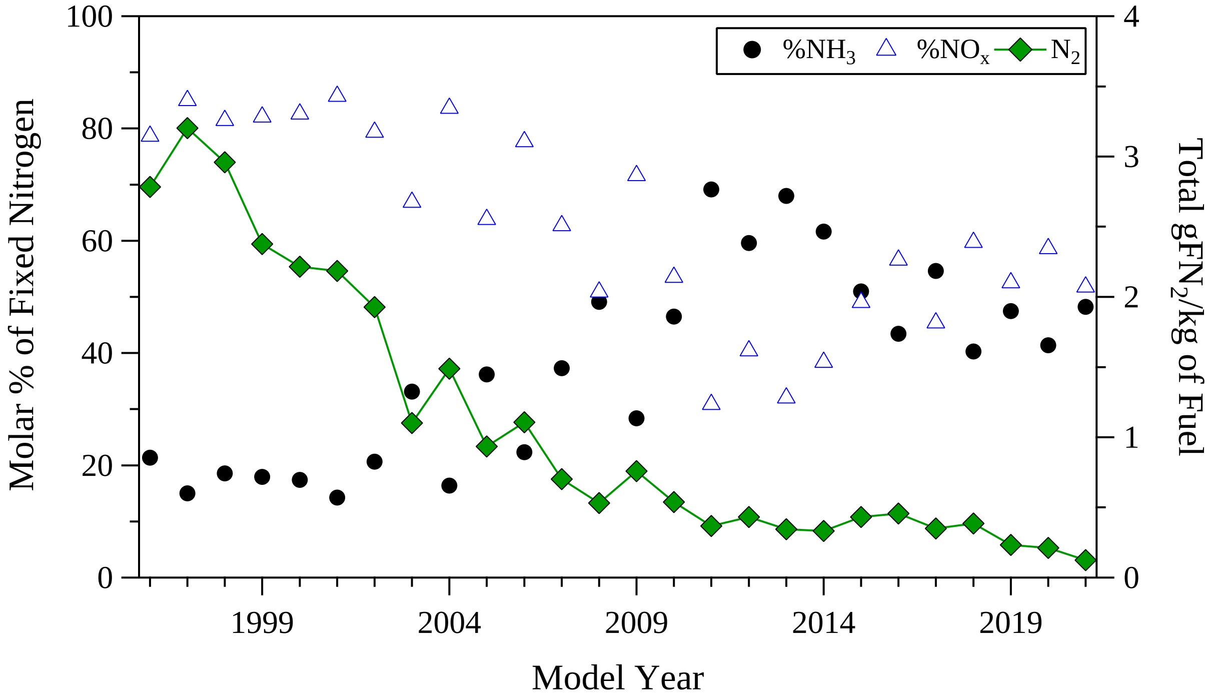

Figure 9. Total fixed nitrogen in gN/kg of fuel (diamonds, right axis) with the molar percent composition distributed between the molar $\%NH_3$ (circles, left axis) component and the molar $\%NO_x$ component (triangles, left axis) by model year for the 2021 measurements.

Figure 10 is a plot of the fuel specific CO (top panel), HC (middle panel) and NO (bottom panel) 99th percentiles by model year for the 2008 and 2021 Fresno data sets. The 99th percentile of the emissions distribution can be used to represent an emissions level that generally corresponds to vehicles in disrepair and are only displayed for model years with at least 100 measurements. Much like the mean values, the emissions of these vehicles have continued to drop along with the mean emissions though these vehicles emissions are still large multiples of the mean values. The 99th percentile values for 10 year old vehicles (2011 model years) in the 2021 database for CO are more than a factor of 8 larger than their mean emissions (76 vs 9 gCO/kg of fuel). For HC the 99th percentile is a factor of 15 larger (25.6 vs 1.7 gHC/kg of fuel) and for NO it is more than a factor of 9 larger (4.9 vs 0.5 gNO/kg of fuel). For CO and especially for NO there was a noticeable improvement with the introduction of the LEV II vehicles. It is quite remarkable that an improvement in durability, design and efficiencies of modern vehicles has also translated into the ability to cap emissions in vehicles that have obvious problems. However, for there to be future reductions in mean emissions, there will have to be additional reductions or elimination in the emissions of these extreme emitters and certainly for CO and HC the lower limit for the 99th percentile vehicles appears to have occurred.

Instrument noise was measured by looking at the slope of the negative portion of the log plots in the same manner as described in the Phoenix, Year 2 report.[15] Such plots were constructed for all

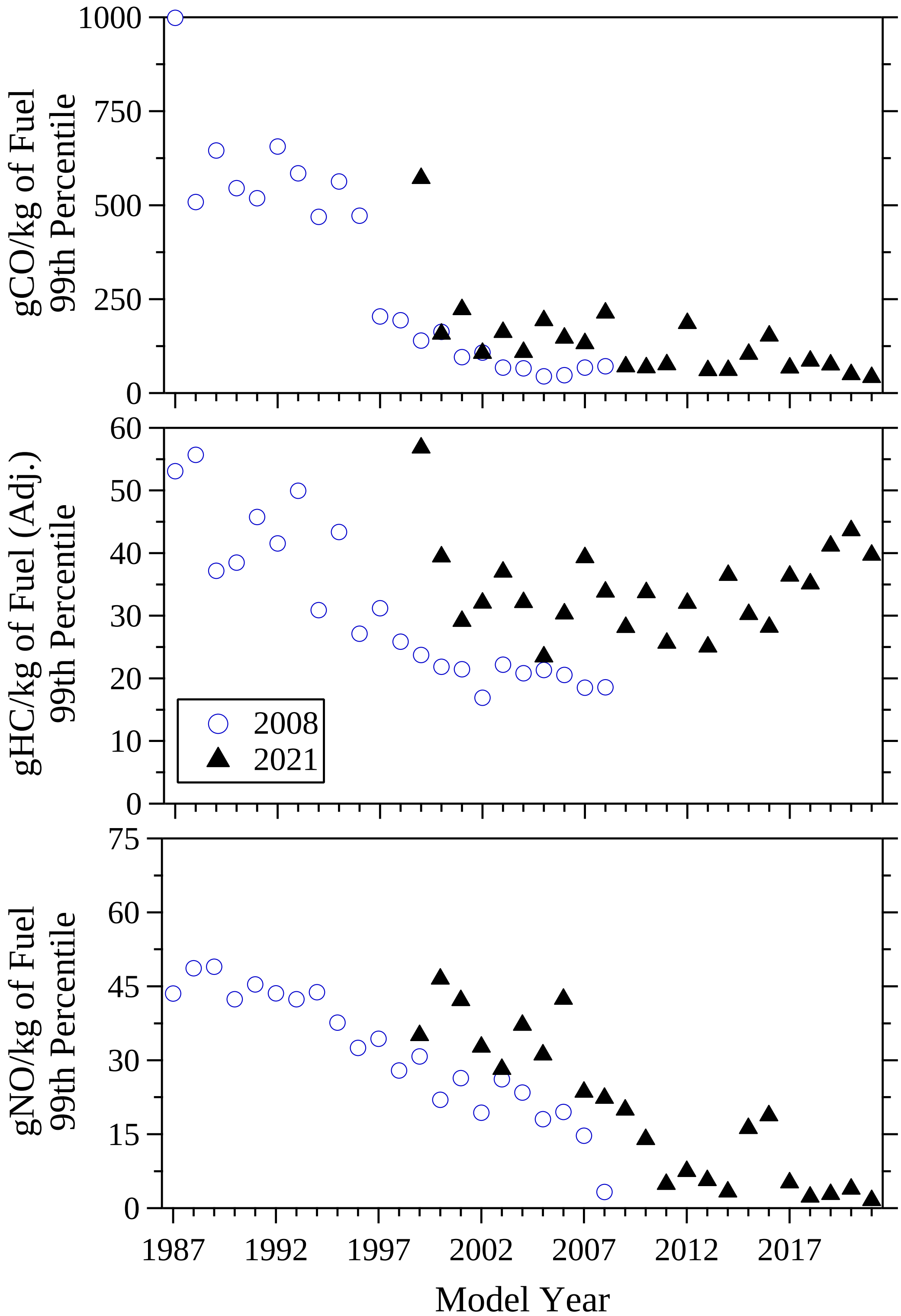

Figure 10. Fuel specific 99th percentiles by model year for CO (top), HC (middle) and NO (bottom) for the 2021 (triangles) and 2008 (circles) Fresno data sets. Note that vehicle age for the same model year is different for each data set.

of the measured species. Linear regression gave best-fit lines whose slopes correspond to the inverse of the Laplace factor, which describes the noise present in the measurements. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. The Laplace factors were 4.9, 6.2, 0.09, 0.02 and 0.3 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 7 gCO/kg of fuel (0.05%), 8.8 gHC/kg (205 ppm), 0.12 gNO/kg (10 ppm), 0.03 gNH_3/kg (3 ppm) and 0.5 gNO_2/kg (22 ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2 respectively. In terms of uncertainty in average values reported here, the numbers are reduced by a factor of the square root of the number of measurements. For example, with an average of 100 measurements, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages reduce to 0.7 gCO/kg of fuel, 0.9 gHC/kg, 0.01 gNO/kg, 0.003 gNH_3/kg and 0.05 gNO_2/kg, respectively.

CONCLUSIONS

The University of Denver carried out six days of remote sensing in the Fresno, CA area in June of 2021. Measurements were collected Monday, June 7, to Saturday, June 12, between the hours of 9:00 and 18:00 on the uphill interchange ramp from NB US 41 to WB US 180. This is the same location previously used for measurements in the spring of 2008. A database was compiled containing 8,621 records for which the State of California provided registration information. All of these records contained valid measurements for at least CO and CO_2, and most records contained valid measurements for the other species as well.

The 2021 mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured in this study were 10.3 ± 0.5 g/kg of fuel (0.08%), 1.9 ± 0.2 g/kg of fuel (49 ppm), 1.14 ± 0.06 g/kg of fuel (80 ppm), 0.29 ± 0.01 g/kg of fuel (36 ppm) and 0.07 ± 0.01 g/kg of fuel (3 ppm) respectively. The 2021 Fresno measurements show reductions for all of the species measured when compared with the 2008 values. Fuel specific emission factors (g/kg of fuel) decreased for CO (49%), HC (44%), NO (62%), NH_3 (40%), NO_2 (50%) and NO_x (62%) despite the age of the fleet increasing 1.8 years. Fleet mean emissions remain dominated by a few high emitting vehicles. For the 2021 data set the highest emitting 1% of the measurements (99^{th} percentile) are responsible for 30%, 31%, 33%, 14% and 41% of the overall fleet CO, HC, NO, NH_3 and NO_2 emissions, respectively.

Overall, as mentinoned we have observed a 40% reduction in the mean NH_3 emissions since 2008 (0.49 ± 0.01 to 0.29 ± 0.01). The 2008 measurements show the classic peak NH_3 emissions around 15 year old vehicles after which the three-way catalytic converters on average start to lose their ability to reduce NO to NH_3 and NH_3 emissions in the exhaust decline. The 2021 measurements show the increase in the durability of the newer catalytic converters in that there is no obvious peak in NH_3 emissions indicating converter life beyond 25 years.

However, the NH_3 fleet reduction pattern in Fresno is similar to observations in other locations in that it lags behind the rate for tailpipe NO emissions. Total fixed nitrogen emissions have been on a steep decline since the mid-nineties in the on-road fleet and are continuing to show decreases in the newest model years in this data set as well. The percent of fixed nitrogen made up of NH_3 had been on the rise with the introduction of LEV II vehicles to where NH_3 for a time was the dominate species. However, consistent with observations at our other sampling sites across the U.S. toward the end of the LEV II and with the introduction of LEV III vehicles NO_x emissions have once again become the majority species. It is not known what if anything is behind this preference now for nitrogen oxidation (NO_x) at the tailpipe over reduced nitrogen (NH_3) in the newest vehicles but catalyst formulation is an important factor that can influence NH_3 production.

99th percentile emission levels much like the mean values, have continued to drop though the 99th percentile emissions are still large multiples of the mean values. The 99th percentile values for 10 year old vehicles (2011 model years) in the 2021 database for CO are more than a factor of 8 larger than their mean emissions (76 vs 9 gCO/kg of fuel). For HC the 99th percentile is a factor of 15 larger (25.6 vs 1.7 gHC/kg of fuel) and for NO it is more than a factor of 9 larger (4.9 vs 0.5 gNO/kg of fuel). For CO and especially for NO there has been a noticeable improvement with the introduction of the LEV II vehicles.

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The author would like to take this opportunity to thank all of the individuals at the Coordinating Research Council and the Real World Emissions Committee that have contributed to the all of the on-road measurement programs since 1997. We also want to thank them for sponsoring RW-117 and the opportunity to return to Fresno, CA and repeat the 2008 measurements. We want to acknowledge Sandeep Kishan and James Fung-A-Fat for help repairing/replacing a failed power supply. We also thank Mrs. Annette Bishop whose plate reading skills are so important to the successful outcome of all the sampling campaigns and Chris Ruehl for help with the plate matching. Comments from the various reviewers of this report were also invaluable.

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APPENDIX A: FEAT criteria to render a reading "invalid" or not measured.

Not measured:

1) Beam block and unblock and then block again with less than 0.5 seconds clear to the rear. Often caused by elevated pickups and trailers causing a "restart" and renewed attempt to measure the exhaust. The restart number appears in the database.

2) Vehicle which drives completely through during the 0.1 seconds "thinking" time (relatively rare).

Invalid:

1) Insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms averages >0.25% CO_2 in 8 cm path length. Often HD diesel trucks, bicycles.

2) Excess error on CO/CO_2 slope, equivalent to $\pm$20% for %CO. >1.0, 0.2%CO for %CO<1.0.

3) Reported %CO <-1% or >21%. All gases invalid in these cases.

4) Excess error on HC/CO_2 slope, equivalent to $\pm$20% for HC >2500ppm propane, 500ppm propane for HC <2500ppm.

5) Reported HC <-1000ppm propane or >40,000ppm. HC "invalid".

6) Excess error on NO/CO_2 slope, equivalent to $\pm$20% for NO>1500ppm, 300ppm for NO<1500ppm.

7) Reported NO <-700ppm or >7000ppm. NO "invalid".

8) Excessive error on NH3/CO2 slope, equivalent to +50ppm.

9) Reported NH3 < -80ppm or > 7000ppm. NH3 "invalid".

10) Excess error on NO2/CO2 slope, equivalent to +20% for NO2 > 200ppm, 40ppm for NO2 < 200ppm

11) Reported NO2 < -500ppm or > 7000ppm. NO2 "invalid".

Speed/Acceleration valid only if at least two blocks and two unblocks in the time buffer and all blocks occur before all unblocks on each sensor and the number of blocks and unblocks is equal on each sensor and 100mph>speed>5mph and 14mph/s>accel>-13mph/s and there are no restarts, or there is one restart and exactly two blocks and unblocks in the time buffer.

APPENDIX B: Explanation of the Fresno_21.dbf database.

The Fresno_21.dbf is a Microsoft FoxPro database file, and can be opened by any version of MS FoxPro. The files can also be read by a number of other database management programs as well, and they are available from the DU library website at https://digitalcommons.du.edu/feat/. The following is an explanation of the data fields found in this database:

License	California license plate.
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Percent_CO	Carbon monoxide concentration, in percent.
CO_err	Standard error of the carbon monoxide measurement.
Percent_HC	Hydrocarbon concentration (propane equivalents), in percent.
HC_err	Standard error of the hydrocarbon measurement.
Percent_NO	Nitric oxide concentration, in percent.
NO_err	Standard error of the nitric oxide measurement.
PercentSO2	Sulfur dioxide concentration, in percent.
SO2_err	Standard error of the sulfur dioxide measurement.
PercentNH3	Ammonia concentration, in percent.
NH3_err	Standard error of the ammonia measurement.
PercentNO2	Nitrogen dioxide concentration, in percent.
NO2_err	Standard error of the nitrogen dioxide measurement.
PercentCO2	Carbon dioxide concentration, in percent.
CO2_err	Standard error of the carbon dioxide measurement.
Opacity	Opacity measurement, in percent.
Opac_err	Standard error of the opacity measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
HC_flag	Indicates a valid hydrocarbon measurement by a “V”, invalid by an “X”.
NO_flag	Indicates a valid nitric oxide measurement by a “V”, invalid by an “X”.
SO2_flag	Indicates a valid sulfur dioxide measurement by a “V”, invalid by an “X”.
NH3_flag	Indicates a valid ammonia measurement by a “V”, invalid by an “X”.
NO2_flag	Indicates a valid nitrogen dioxide measurement by a “V”, invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.
Max_CO2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor over an 8 cm path; indicates plume strength.

Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Tag_name	File name for the digital picture of the vehicle.
Vin	Vehicle identification number truncated by the State of California.
Make	Manufacturer of the vehicle.
Year	Model year.
Series	Vehicle series.
Model	Vehicle model within a particular series
Fuel	Fuel type G (gasoline), D (diesel), N (natural gas) and B (hybrid).
Disp_ci	DMV engine displacement cubic inches.
Weight	DMV unladen vehicle weight in pounds.
Gvw_code	DMV gross vehicle weight class code.
CO_gkg	Grams of CO per kilogram of fuel using 860 gC/kg of fuel.
HC_gkg	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and the molecular weight of propane which is our calibration gas.
NO_gkg	Grams of NO per kilogram of fuel using 860 gC/kg of fuel.
Nh3_gkg	Grams of NH_3 per kilogram of fuel using 860 gC/kg of fuel.
NO2_gkg	Grams of NO_2 per kilogram of fuel using 860 gC/kg of fuel.
NOx_gkg	Grams of NO_x per kilogram of fuel using 860 gC/kg of fuel.
HC_offset	Hydrocarbon concentrations after offset adjustment.
HCgkg_off	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and using the HC_offset value for this calculation.
VSP	Vehicles specific power calculating using the equation provided in the report.

APPENDIX C: Temperature and Humidity Data

Data Collected at the Fresno Yosemite International Airport

2008 Fresno Temperature and Humidity Data								
Time	3/08 °F	3/08 %RH	3/09 °F	3/09 %RH	3/10 °F	3/10 %RH	3/11 °F	3/11 %RH
6:53	48	83	47	80	48	74	51	74
7:53	51	77	49	77	54	62	55	64
8:53	55	69	55	67	59	54	58	62
9:53	60	56	61	52	64	43	61	58
10:53	65	□(□62	62	48	68	38	65	52
11:53	66	40	65	43	71	31	68	47
12:53	67	40	67	40	74	27	71	38
13:53	68	39	69	36	75	22	72	37
14:53	68	41	70	34	76	23	70	46
15:53	68	42	71	33	75	24	69	46
16:53	67	40	71	30	75	26	68	47
17:53	64	47	69	32	71	35	67	51

2008 Fresno Temperature and Humidity Data								
Time	3/12 °F	3/12 %RH	3/13 °F	3/13 %RH	3/14 °F	3/14 %RH		
6:53	51	86	56	67	47	83		
7:53	51	86	57	72	50	74		
8:53	55	80	58	70	54	67		
9:53	61	65	61	65	56	60		
10:53	63	65	64	54	58	49		
11:53	66	54	66	59	60	44		
12:53	69	49	68	59	60	43		
13:53	71	43	70	53	62	40		
14:53	71	41	70	49	63	35		
15:53	71	43	70	46	62	37		
16:53	69	41	69	44	61	38		
17:53	65	54	65	47	59	41		

2021 Fresno Temperature and Humidity Data								
Time	6/07 °F	6/07 %RH	6/08 °F	6/08 %RH	6/09 °F	6/09 %RH	6/10 °F	6/10 %RH
7:53	67	41	61	44	60	47	60	47
8:53	71	36	64	40	65	37	63	41
9:53	74	33	67	35	68	31	68	31
10:53	77	29	70	30	71	27	69	31
11:53	78	24	74	25	73	24	73	25
12:53	80	17	74	23	73	26	74	21
13:53	81	19	77	18	74	25	76	19
14:53	82	18	76	19	76	24	76	18
15:53	84	17	78	20	77	24	78	15
16:53	84	16	78	21	75	22	78	17
17:53	83	19	77	23	75	21	77	18

2021 Fresno Temperature and Humidity Data								
Time	6/11 °F	6/11 %RH	6/12 °F	6/12 %RH				
7:53	64	35	68	53				
8:53	69	31	72	44				
9:53	71	28	76	36				
10:53	76	23	80	29				
11:53	78	19	83	23				
12:53	80	17	84	24				
13:53	82	15	87	18				
14:53	81	14	89	19				
15:53	84	11	89	23				
16:53	84	11	90	24				
17:53	83	11	90	27				

APPENDIX D: Example Calculation of Vehicle Specific Power Adjusted Vehicle Emissions

1997 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	236	225	53200
	0	224	1609	360090
	5	307	4985	1531000
	10	431	6146	2648020
	15	548	2624	1438060
	20	590	456	269180
			16045	6299550
			Mean NO (ppm)	**393**
1998 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	233	137	31951
	0	239	784	187394
	5	265	3613	956613
	10	385	6685	2576433
	15	475	6012	2856195
	20	483	2392	1156320
			19623	7764906
			Mean NO (ppm)	**396**
1998 (Adjusted)	VSP Bin	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	-5	233	225	52474
	0	239	1609	384588
	5	265	4985	1319877
	10	385	6146	2368700
	15	475	2624	1246616
	20	483	456	220436
			16045	5592691
			Mean NO (ppm)	**349**

Note that the Mean NO readings listed here have been rounded to the nearest ppm values which results in the Total Emissions column appearing to not be a direct multiplication product. The -5 to 20 kw/tonne bins are chosen to preclude any "off-cycle" emissions.

The object of this adjustment is to have the 1998 fleet's emissions calculated as if they drove (VSP wise) like the 1997 fleet. This is accomplished by first binning and averaging the 1997 and 1998 data (the top two tables). We then combine the mean NO values from the 1998 fleet with the numerical VSP bin distribution from the 1997 fleet in the bottom table. The product of these two columns is summed and the sum total emissions are divided by the number of 1997 vehicles to produce the 1998 adjusted mean NO average. For this example, it shows that the 1998 fleet when driven like the 1997 fleet has lower NO emissions than the 1997 fleet.

APPENDIX E: Calculation of Model Year Adjusted Fleet Emissions

1997 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	690	398	274620
	84	720	223	160560
	85	680	340	231200
	86	670	513	343710
	87	690	588	405720
	88	650	734	477100
	89	610	963	587430
	90	540	962	519480
	91	500	1133	566500
	92	450	1294	582300
	93	460	1533	705180
	94	370	1883	696710
	95	340	2400	816000
	96	230	2275	523250
	97	150	2509	376350
			17748	7266110
			Mean NO (ppm)	**409**

1998 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	740	371	274540
	84	741	191	141531
	85	746	331	246926
	86	724	472	341728
	87	775	557	431675
	88	754	835	629590
	89	687	1036	711732
	90	687	1136	780432
	91	611	1266	773526
	92	538	1541	829058
	93	543	1816	986088
	94	418	2154	900372
	95	343	2679	918897
	96	220	2620	576400
	97	177	3166	560382
			20171	9102877
			Mean NO (ppm)	**451**

1998 (Adjusted)	Model Year	‘98 Mean NO (ppm)	‘97 No. of Meas.	Total Emissions
	83	740	398	294520
	84	741	223	165243
	85	746	340	253640
	86	724	513	371412
	87	775	588	455700
	88	754	734	553436
	89	687	963	661581
	90	687	962	660894
	91	611	1133	692263
	92	538	1294	696172
	93	543	1533	832419
	94	418	1883	787094
	95	343	2400	823200
	96	220	2275	500500
	97	177	2509	444093
			17748	8192167
			Mean NO (ppm)	**462**

APPENDIX F: Field Calibration Records.

2008 Fresno (FEAT 3002)							
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	SO_2 Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
3/8	12:10	1.41	1.25	1.11	0.87	1.01	0.75
3/9	9:25	1.87	1.69	1.58	0.95	1.01	1.32
3/9	11:25	1.54	1.41	1.31	1.25	1.01	0.56
3/10	7:25	2.29	2.07	1.90	1.85	1.01	2.01
3/10	9:20	1.75	1.60	1.36	1.43	1.01	1.23
3/10	14:10	1.33	1.22	0.96	0.99	1.01	0.93
3/11	7:45	2.01	1.84	1.64	1.74	1.02	1.71
3/11	9:10	1.81	1.64	1.37	1.54	1.02	1.43
3/11	14:20	1.45	1.22	1.25	1.21	1.02	1.30
3/12	7:30	2.27	2.16	1.72	1.11	0.99	1.71
3/12	9:50	1.85	1.69	1.40	1.28	0.99	1.39
3/12	12:30	1.54	1.40	1.02	1.06	0.99	1.01
3/12	14:40	1.37	1.26	0.90	1.02	0.99	0.85
3/13	7:20	2.04	1.83	1.67	1.73	0.94	1.49
3/13	10:00	1.72	1.55	1.27	1.52	0.94	1.13
3/13	12:30	1.55	1.35	1.14	1.26	0.94	1.02
3/13	14:20	1.46	1.25	1.06	1.13	0.94	0.95
3/14	7:25	2.02	1.87	1.56	1.15	0.93	1.74
3/14	9:15	1.70	1.57	1.32	1.03	0.93	1.47
3/14	12:10	1.50	1.41	1.11	1.06	0.93	1.24

2021 Fresno (FEAT 3002)						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
6/7	13:15	1.49	1.51	1.08	1.02	0.99
6/8	12:15	1.63	1.60	1.25	1.05	1.14
6/9	9:14	1.77	1.74	1.43	1.08	1.35
6/9	12:50	1.59	1.57	1.28	1.15	1.19
6/10	8:55	1.88	1.83	1.53	1.10	1.61
6/10	12:10	1.63	1.60	1.39	1.10	1.32
6/11	9:01	1.79	1.75	1.46	1.12	1.44
6/11	11:30	1.58	1.57	1.31	1.11	1.23
6/12	9:10	1.72	1.68	1.31	1.06	1.28
6/12	11:30	1.50	1.52	1.22	1.03	1.11