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ON-ROAD REMOTE SENSING OF AUTOMOBILE EMISSIONS IN THE PHOENIX AREA: Spring 2021

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On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Spring 2021

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EXECUTIVE SUMMARY

The University of Denver carried out five days of remote sensing in the Phoenix, AZ area in April of 2021. Measurements were collected Monday, April 12, to Friday, April 16, between the hours of 7:00 and 17:00 on the uphill interchange ramp from EB U.S. 60 to NB SH 101. The remote sensor used in this study measured the ratios of CO, HC, NO, SO_2, NH_3 and NO_2 to CO_2 in motor vehicle exhaust. Mass emissions per mass or volume of fuel are determined from these ratios and are the units used for the major results in this report. From these ratios, we can also 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 air. The system used in this study was configured to determine the speed and acceleration of the vehicle and was accompanied by a video system to record the license plate of the vehicle. Non-personal vehicle information was obtained from the State of Arizona and a database was compiled containing 18,294 records. The database, as well as others compiled by the University of Denver, can be currently found at https://digitalcommons.du.edu/feat/. 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. Since fuel sulfur has been nearly eliminated in US fuels, SO_2 emissions are generally below detection limits. While vehicle SO_2 measurements are routinely collected and archived for each data campaign, since 2014 we have not calibrated these measurements and they are not included in the discussion of the results.

The 2021 mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured in this study were 11.5 ± 0.2 g/kg of fuel (0.09%), 2.1 ± 0.1 g/kg of fuel (52 ppm), 1.38 ± 0.04 g/kg of fuel (98 ppm), 0.31 ± 0.01 g/kg of fuel (39 ppm) and 0.04 ± 0.01 g/kg of fuel (2 ppm) respectively. Figure E1 graphs the fuel specific emissions for CO, HC and NO versus model year for the Phoenix data. The fuel specific CO emissions are plotted in the top panel, the HC emissions in the middle panel and the NO emissions in the bottom panel. The HC data have been offset adjusted as previously described and the uncertainties plotted are standard error of the mean determined from the daily samples. As observed in previous measurements at other locations with the introduction of Tier II vehicles in 2009 fuel specific emissions for all three species are low and vary little even with age. With the phase-in of Tier III vehicles beginning with the 2017 model year, there appears to be some additional reductions in CO and NO emissions though small on an absolute basis. Despite increases in uncertainties due to fewer measurements, NO emissions show the largest increases in emissions for the model year 2008 and older vehicles with smaller increases observed in the CO and HC emissions.

The Phoenix AZ area was one of the original Coordinating Research Council's E-23 light-duty vehicle emissions measurement sites with measurements collected in 1998, 1999, 2000, 2002, 2004 and 2006 at a location near the Sky Harbor Airport. When measurements were paused after the 2006 measurements and the end of the E-23 program, the ramp used for the measurements in

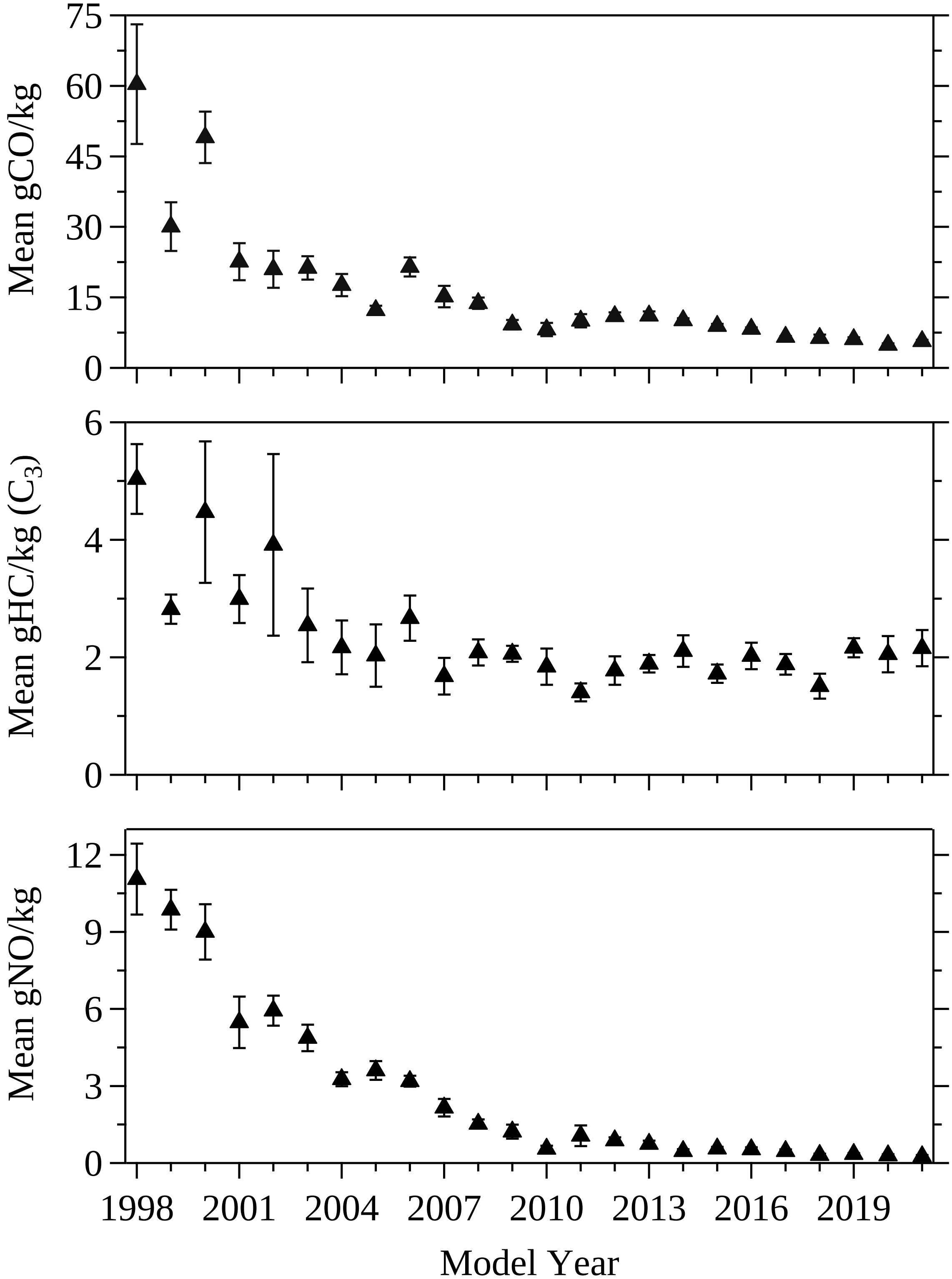

Figure E1. Phoenix fuel specific mean vehicle emissions plotted as a function of model year. HC data have been offset adjusted as described in the text. Uncertainties are standard error of the mean calculated using the daily samples.

Phoenix was eliminated by new road construction and a new site was not pursued when measurements were resumed in 2013 as part of the E-106 program. Figure E2 is a historical comparison for the fuel specific emissions of the three species collected in 2006 compared to the 2021 measurements. The 2021 Phoenix measurements showed reductions for CO (-15%), HC (-15%) and NO (-52%) when compared with the 2006 values collected at a different location. NO emissions show a significantly larger reduction than the other two species do to the higher NO emission levels present in the fleet prior to the introduction of Tier II vehicles in 2009. 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 28%, 19%, 32%, 19% and 49% of the overall fleet CO, HC, NO, NH_3 and NO_2 emissions, respectively.

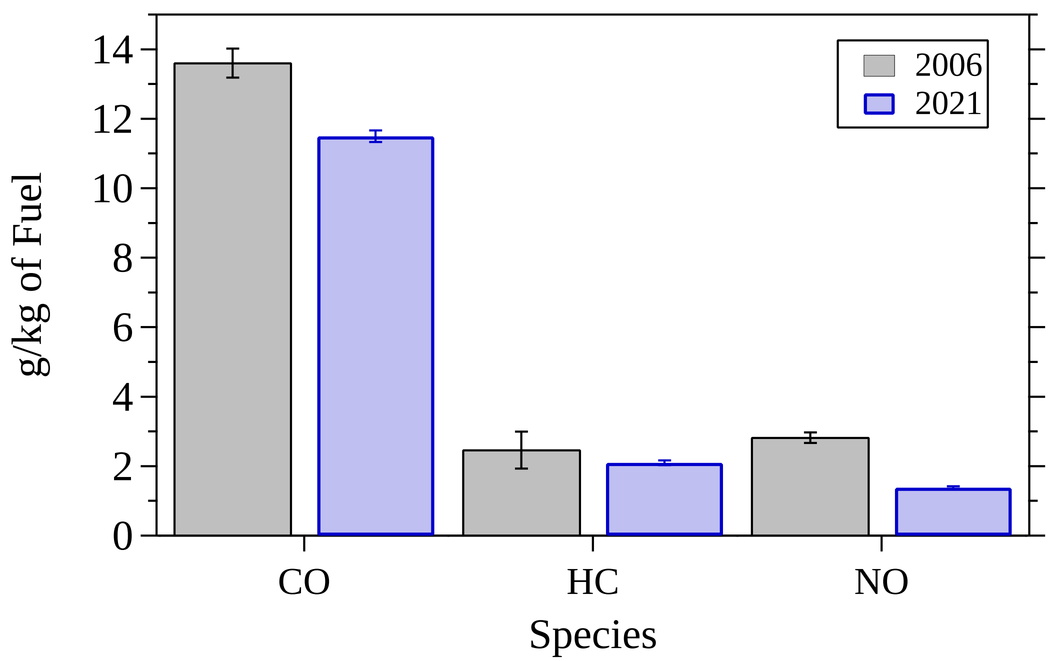

Figure E2. Mean fleet fuel specific emissions for carbon monoxide, hydrocarbons and nitric oxide for the 2006 and 2021 Phoenix data sets. The uncertainties are standard error of the mean calculated using the daily measurements.

An analysis of running loss emission from this fleet was conducted using our previously published method utilizing the high frequency data collected with each vehicle emission measurement. The method found that 0.4% of the measurements was suspected to have had a running loss emission problem and this fleet was approxiamately 2 years older than the entire fleet. The eleven vehicles with the higher running loss indexes (Bins 4 to 6) were significantly older with an average model year of 2005.7

INTRODUCTION

Since the early 1970's, many heavily populated U.S. cities have violated 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.

In 1997, the University of Denver began conducting on-road tailpipe emission surveys at a site northwest of Chicago IL, in Arlington Heights to follow long-term emission trends. Since 1997, measurements have also been collected in Los Angeles CA, Denver CO, Omaha NE, Phoenix AZ, Riverside CA, and Tulsa OK.[5] Following a protocol established by the Coordinating Research Council (CRC) as part of the E-23 program, the data collected have provided valuable information about the changes in fleet average on-road emission levels. The data have also been used by other researchers to study fleet emission trends and construct emission inventories.[6-9] All of the databases can be found at https://digitalcommons.du.edu/feat/.

The remote sensing instrumentation developed by the University of Denver is approaching 30 years old and is scheduled to be retired soon. As a result the Coordinating Research Council designed a program that coordinated on-road emission measurement comparison between the University of Denver's remote sensing instrument and the instrument of the two commercial operators, Hager Environmental & Atmospheric Technologies (HEAT) and Opus International. This report describes only the on-road emission measurements taken with the University of Denver's Fuel Efficiency Automobile Test (FEAT) in the Phoenix AZ area in the spring of 2021, under CRC Contract No. E-119-3. Measurements were made on five weekdays, from Monday, April 12, to Friday, April 16 between the hours of 7:00 and 17:00 on the uphill curved interchange ramp (1° slope) from eastbound U.S. 60 to northbound SH101 (see Figures 1 & 2).

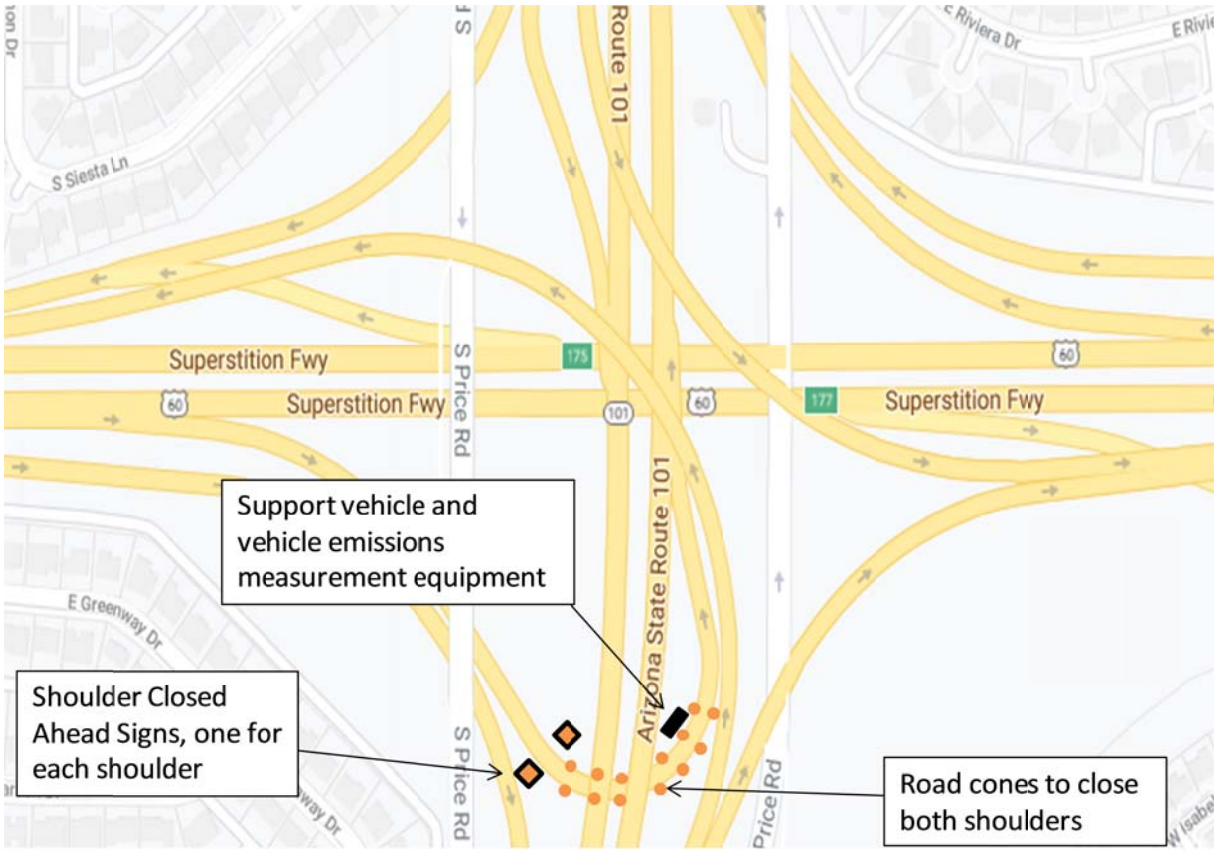

Figure 1. Area map of the on-ramp from eastbound U.S. 60 to northbound SH 101 in Phoenix AZ area, showing the approximate location of the FEAT remote sensor configuration and safety equipment.

FEAT 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.[10-12] 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

Figure 2. A photograph looking southwest at the interchange ramp from eastbound U.S. 60 to northbound SH 101 monitoring site and the remote sensing setup. The FEAT instrument is the closest to the camera in this picture follow by the HEAT and Opus instruments.

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.[13] 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.[14] 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.

$$\text{gm CO/gallon} = 5506 \bullet \%CO / (15 + 0.285 \bullet \%CO + 2(2.87 \bullet \%HC)) \quad (1a)$$
$$\text{gm HC/gallon} = 2(8644 \bullet \%HC) / (15 + 0.285 \bullet \%CO + 2(2.87 \bullet \%HC)) \quad (1b)$$
$$\text{gm NO/gallon} = 5900 \bullet \%NO / (15 + 0.285 \bullet \%CO + 2(2.87 \bullet \%HC)) \quad (1c)$$
$$\text{gm } NH_3\text{/gallon} = 3343 \bullet \%NH_3 / (15 + 0.285 \bullet \%CO + 2(2.87 \bullet \%HC)) \quad (1d)$$
$$\text{gm } NO_2\text{/gallon} = 9045 \bullet \%NO_2 / (15 + 0.285 \bullet \%CO + 2(2.87 \bullet \%HC)) \quad (1e)$$

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:

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

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.[14]

$$\text{gm CO/kg} = (28Q^{CO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3a)$$
$$\text{gm HC/kg} = (2(44Q^{HC}) / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3b)$$
$$\text{gm NO/kg} = (30Q^{NO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3c)$$
$$\text{gm NH}_3\text{/kg} = (17Q^{NH3} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3d)$$
$$\text{gm NO}_2\text{/kg} = (46Q^{NO2} / (1 + Q^{CO} + 6Q^{HC})) / 0.014 \quad (3e)$$

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.[15, 16] 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.[11] 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

Following the five days of data collection in April of 2021 in Phoenix, the digital images were transcribed for license plate identification. Plates that appeared to be in state and readable were sent to the State of Arizona to be matched against the State's non-personal vehicle registration information. Because of the design of this program the original on-road vehicle emission measurements included many measurements on vehicles connected with the evaluation program that were not a part of the public fleet. Therefore, after the plates were matched against the State records we have attempted, to the best of our abilities, to expunge the emission measurements of the program vehicles from the final database. The success of this process is not completely known and future users of this database should weigh the possibility that this database may not be an unbiased view of the Phoenix fleet at this site. With this caveat the resulting database that will be analyzed in this report contains 18,294 records with make and model year information and valid measurements for at least CO and CO_2. The majority of these records also contain valid measurements for HC, NO, NH_3 and NO_2.

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.

While data capture rates were much better than average (>93%) the plate match for this data set was particularly poor for unknown reasons. We are accustomed to the "Percent of Submitted Plates" to be returned in the mid to upper 90% levels. The 86% match rate resulted in more than a 1000 plates which were correctly transcribed being unmatched. This may or may not have been related to the significant time lag that occurred between the measurement dates and the match being returned as evidenced by the fact that the vast majority (>80%) of model year 2022

Table 1. Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	27,561				
Valid Measurements	26,495	26,425	26,488	26,436	25,854
Percent of Attempts	96.1%	95.9%	96.1%	95.9%	93.8%
Submitted Plates	21,270	21,219	21,238	21,202	20,832
Percent of Attempts	77.2%	77.0%	77.1%	76.9%	75.6%
Percent of Valid Measurements	80.3%	80.3%	80.2%	80.2%	80.6%
Matched Plates	18,294	18,276	18,288	18,261	17,984
Percent of Attempts	66.4%	66.3%	66.4%	66.3%	65.3%
Percent of Valid Measurements	69.0%	69.2%	69.0%	69.1%	69.6%
Percent of Submitted Plates	86.0%	86.1%	86.1%	86.1%	86.3%

vehicles that were returned in the match not being the vehicle that was measured. It is not known if the loss of these plates were a random process or whether this introduced an additional bias in the final data set.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly and the number of times they were measured. Of the 18,294 records used in this analysis, 12,588 (68.8%) were contributed by vehicles measured only once, and the remaining 5,706 (31.2%) records were from vehicles measured at least twice.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	12,588
2	1,517
3	498
4	193
5	62
6	8
7	2
>7	4

Table 3 provides the data summary for 2021 Phoenix measurements. 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

Table 3. Phoenix data summary.

Study Year	2021
Mean CO (%) (g/kg of fuel)	0.089 11.5
Median CO (%)	0.034
%Total CO from the 99th Percentile	28%
Mean HC (ppm)[a] (g/kg of fuel)[a] Offset (ppm)	52 2.1 20
Median HC (ppm)[a]	41
%Total HC from the 99th Percentile	19%
Mean NO (ppm) (g/kg of fuel)	98 1.38
Median NO (ppm)	6
%Total NO from the 99th Percentile	32%
Mean NH_3 (ppm) (g/kg of fuel)	39 0.31
Median NH_3 (ppm)	10
%Total NH_3 from the 99th Percentile	19%
Mean NO_2 (ppm) (g/kg of fuel)	2 0.04
Median NO_2 (ppm)	1
%Total NO_2 from the 99th Percentile	49%
Mean Model Year	2013.3
Mean Fleet Age[b]	8.3
Mean Speed (mph)	23.2
Mean Acceleration (mph/s)	0.9
Mean VSP (kw/tonne) Slope (degrees)	13.6 3.8°

[a]Indicates values that have been HC offset adjusted as described in text.
[b]Assumes new vehicle model year starts September 1.

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.

In general the mean emission values and fleet age observed at this location are similar to other sites sampled in the past year. For example a similarly aged fleet (7.9 years old) measured seven months previously in Chicago, IL had fuel specific emission means of 10.9, 2.8, 0.9, 0.57 and 0.12 grams/kg of fuel for CO, HC, NO, NH_3 and NO_2 respectively.[17] These means are very similar to those observed at this location in Phoenix.

The inverse relationship between vehicle emissions and model year is shown in Figure 3 for the 2021 Phoenix data. The fuel specific CO emissions are plotted in the top panel, the HC emissions in the middle panel and the NO emissions in the bottom panel. The HC data have been offset adjusted as previously described and the uncertainties plotted are standard error of the mean determined from the daily samples. As observed in previous measurements at other locations with the introduction of Tier II vehicles in 2009 fuel specific emissions for all three species are low and vary little even with age. With the phase-in of Tier III vehicles beginning with the 2017 model year, there appears to be some additional reductions in CO and NO emissions though small on an absolute basis. Despite increases in uncertainties due to fewer measurements NO emissions show the largest increases in emissions for the model year 2008 and older vehicles with smaller increases observed in the CO and HC emissions.

The 2021 Phoenix fleet vehicle fuel specific emissions by model year, were divided into quintiles and plotted using the format originally presented by Ashbaugh et al.[18] 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 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 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 only ~2.4% of the measurements and the contribution to the total emissions ranges between 7.2% (HC) to 22.4% (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. For CO and HC only the last two quintiles contribute 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.

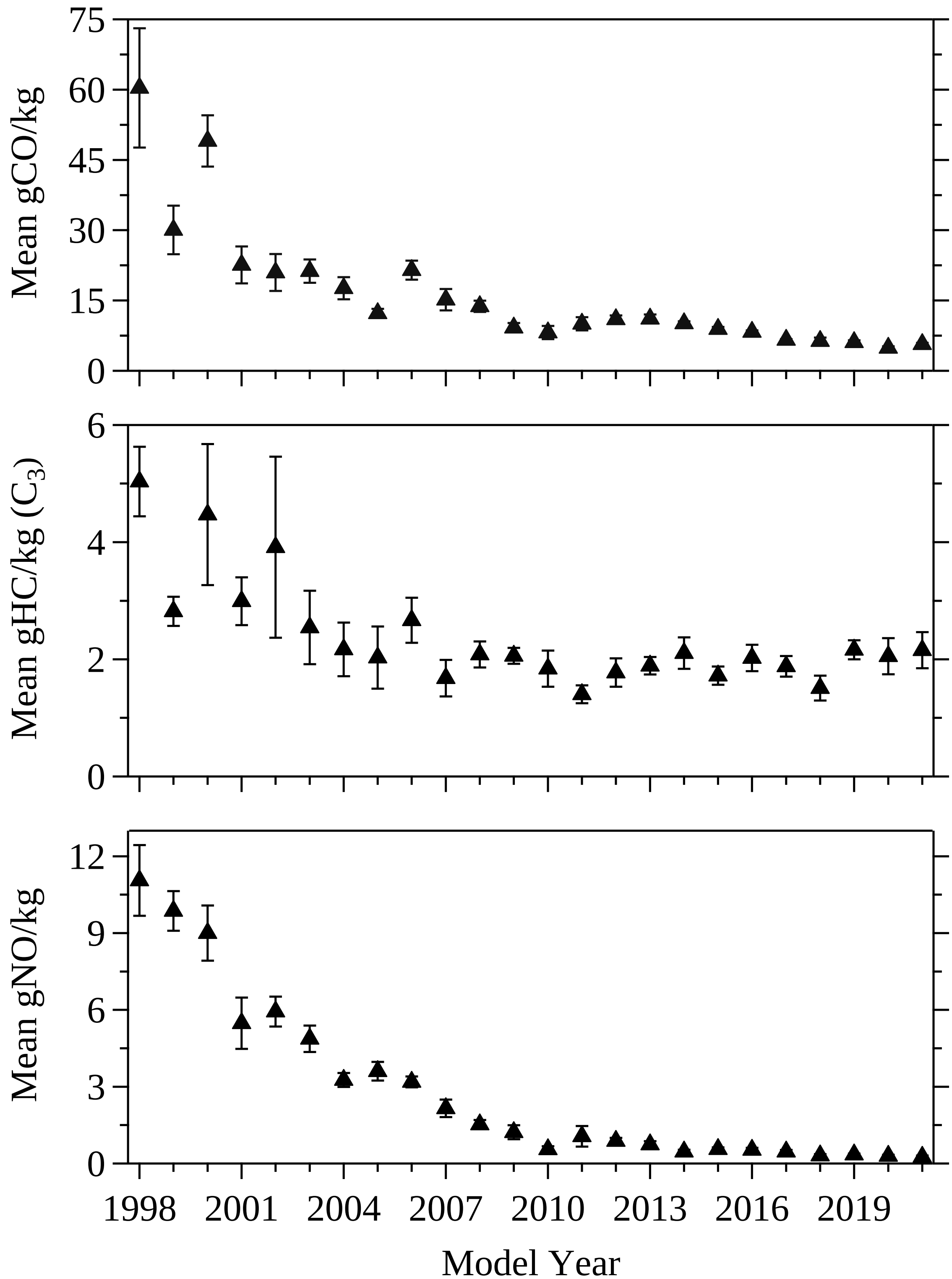

Figure 3. Phoenix fuel specific mean vehicle emissions plotted as a function of model year. HC data have been offset adjusted as described in the text. Uncertainties are standard error of the mean calculated using the daily samples.

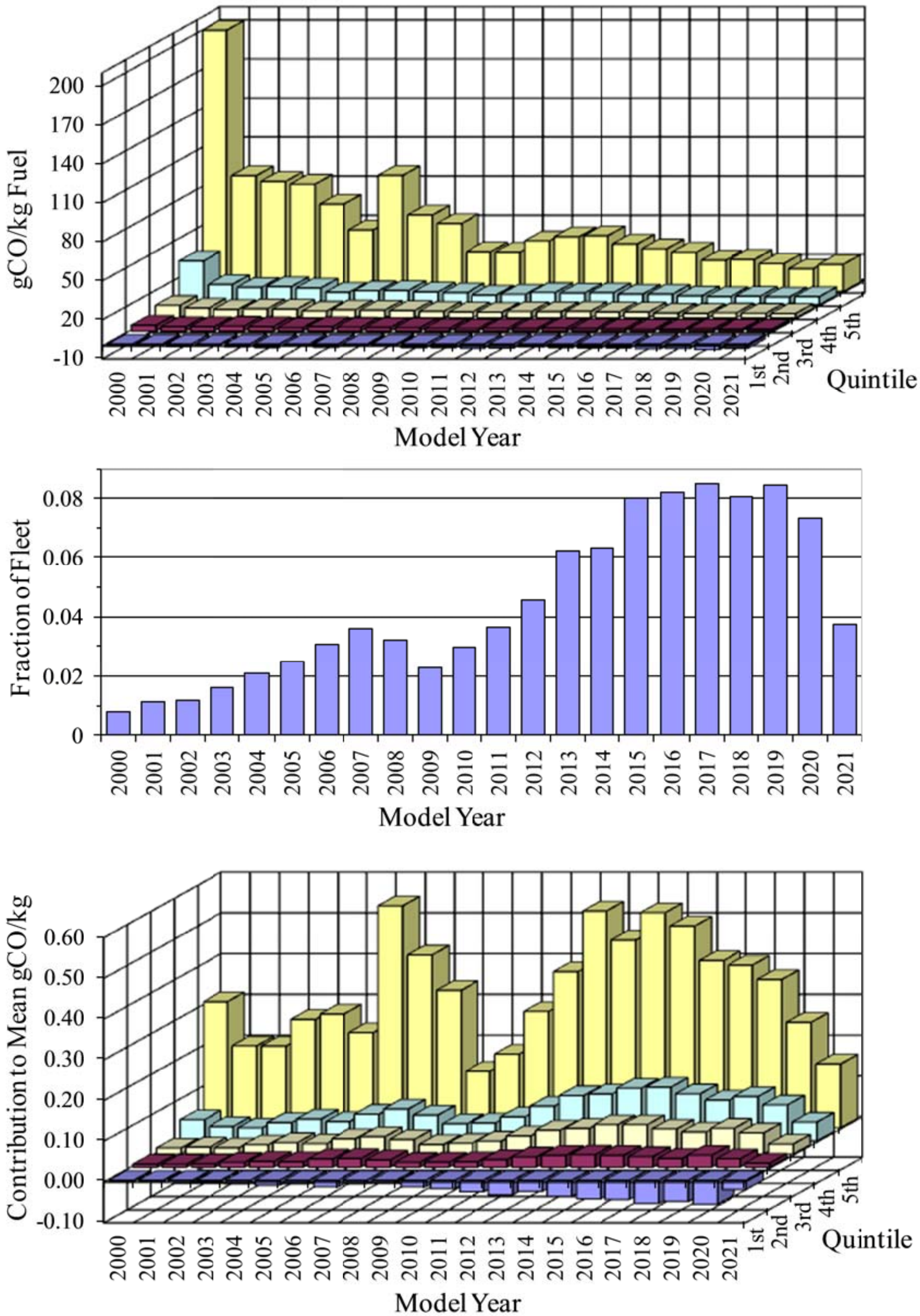

Figure 4. 2021 Phoenix CO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional CO emissions by model year and quintile (bottom).

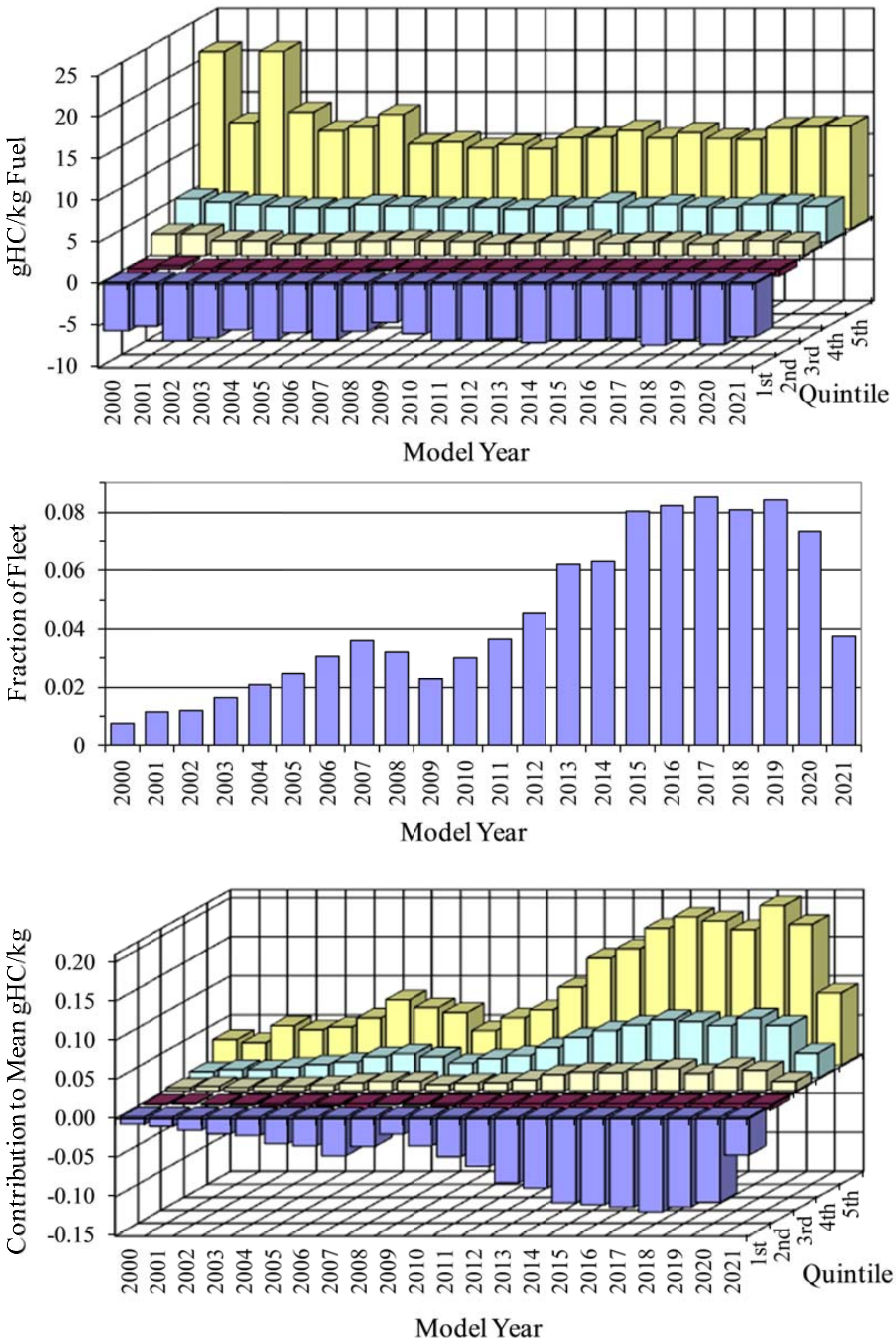

Figure 5. 2021 Phoenix HC emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional HC emissions by model year and quintile (bottom).

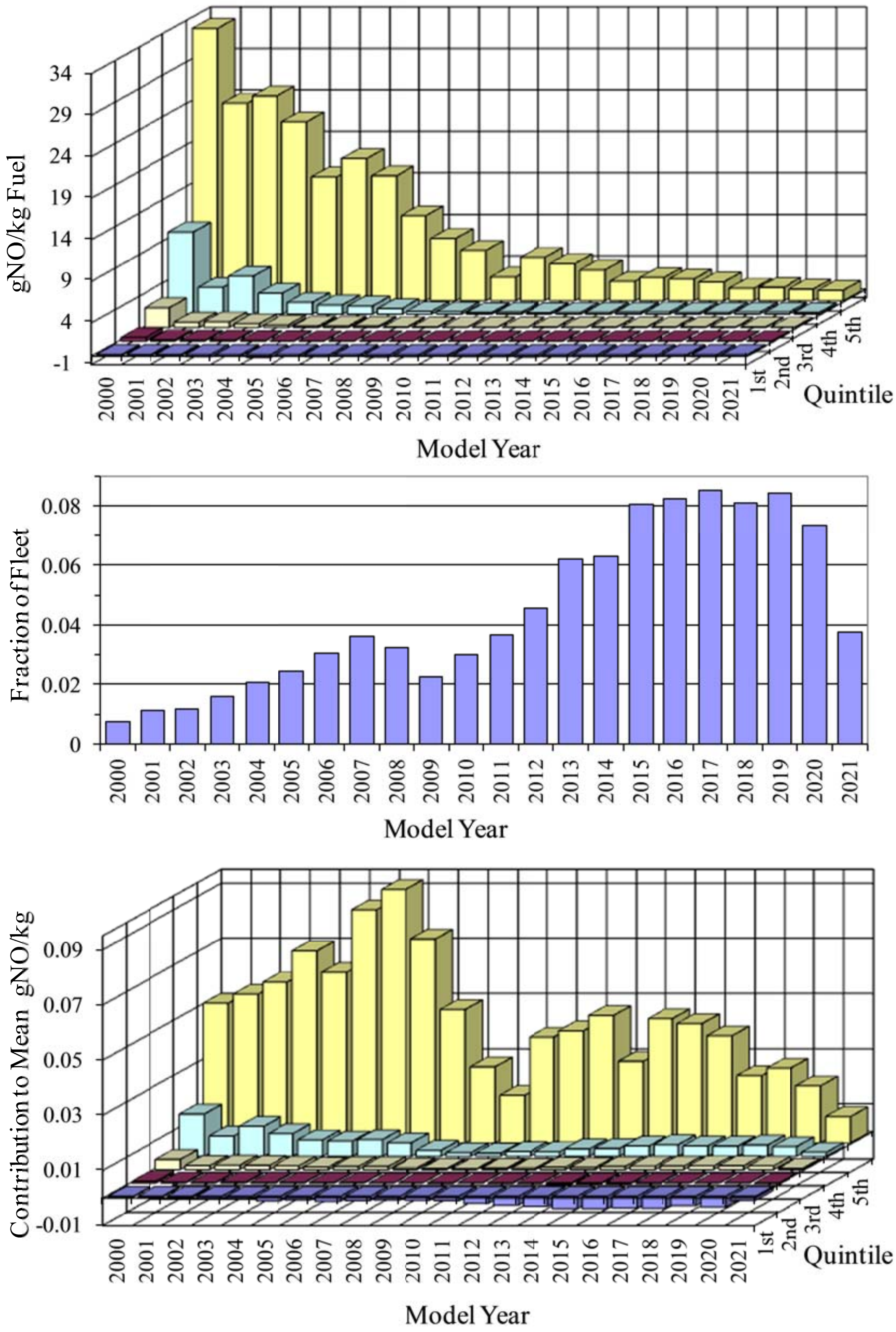

Figure 6. 2021 Phoenix NO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional NO emissions by model year and quintile (bottom).

Previously only the 2008 economic recession had exerted a negative influence on the fleet age in the vehicle fleets observed at the various sites the University of Denver has sampled. The impact of that 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. However, as previously seen in the 2020 Chicago measurements the pandemic and its assorted supply chain issues appears to have also significantly reduced the fleet of 1 and 2 year old vehicles (2020 - 2021 model year) in Phoenix. If we use the fleet fraction averages for the 2015 to 2019 model year vehicles for comparison the 2020 models are reduced by ~11% and the 2021 models are reduced by almost 55%.

An equation for determining the instantaneous power demand of an on-road vehicle published by Jimenez[19], takes the form

$$VSP = 4.39 \bullet \sin(slope) \bullet v + 0.22 \bullet v \bullet a + 0.0954 \bullet v + 0.0000272 \bullet v^3 \quad (4)$$

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 with CO emissions plotted in the top panel, HC emissions in the middle panel and NO emissions in the bottom panel. All of the specific power bins for 2021 contain at least 93 measurements and the HC data have been offset adjusted. The uncertainty bars included in the plot are standard errors of the mean calculated from the daily averages. These uncertainties were generated for these gamma distributed data sets by applying the central limit theorem.[20] Each day's average emission for a given VSP bin was assumed an independent measurement of the average emissions at that VSP. Normal statistics were then applied to these daily averages. In general we observe similar fuel specific emissions across the VSP emissions range plotted with increases for decelerations seen in the HC and slight increases for CO and NO at the higher VSP bins. However, the small number of measurements in the bins at each end of the plot significantly increases the uncertainty, not only in the binned means but the trend as well.

The 2021 Phoenix measurements is the ninth U.S. site to have the University of Denver collect light-duty fleet NH_3 measurements. The 2021 fuel specific mean emissions reported in Table 3 (0.31 ± 0.01) represents the lowest fuel specific NH_3 means observed to date and is approximately a ~9% reduction from the means observed in 2019 and 2020 in Tulsa OK and Denver CO. Figure 8 is a graph of gNH_3/kg of fuel emissions by model year for the Phoenix data set. The uncertainties are standard error of the mean calculated using the daily means.

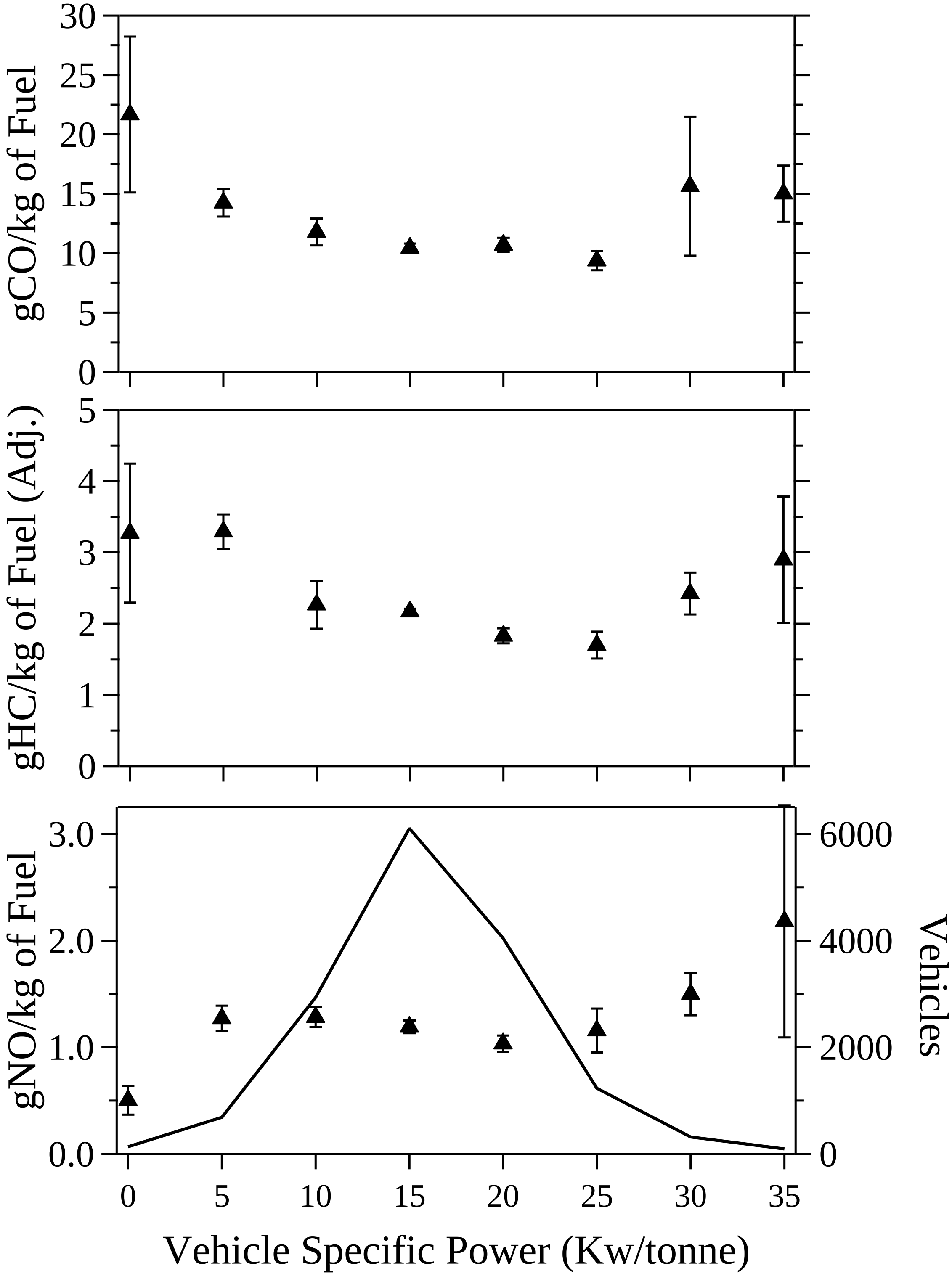

Figure 7. Vehicle emissions as a function of vehicle specific power the 2021 Phoenix data. The uncertainties are plotted as the standard errors of the mean calculated from daily samples. The solid line without markers is the vehicle count profile (right y-axis) for the data set.

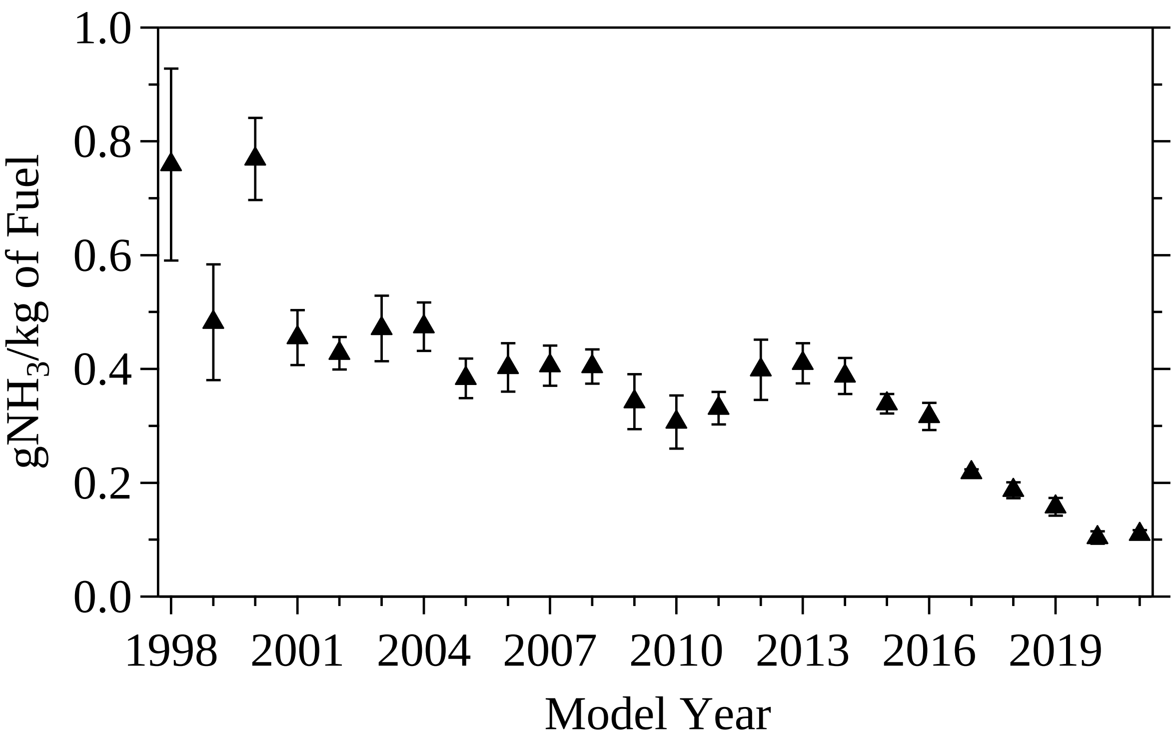

Figure 8. gNH_3/kg of fuel emissions by model year for the 2021 Phoenix data. The uncertainties are standard error of the mean calculated using the daily measurements.

We continue to see lower ammonia emissions from the newest model year vehicles that work to lower the emission means though in this data set there is no difference seen between the one and two year old vehicles. Emissions deterioration in 3 to 9-year-old vehicles continues to limit some of the overall reductions.

The Phoenix AZ area was one of the original Coordinating Research Council's E-23 light-duty vehicle emissions measurement sites with measurements collected in 1998, 1999, 2000, 2002, 2004 and 2006 at a location near the Sky Harbor Airport.[21] When measurements were paused after the 2006 measurements and the end of the E-23 program, the ramp used for the measurements in Phoenix was eliminated by new road construction and a new site was not pursued when measurements were resumed in 2013 as part of the E-106 program. Figure 9 is a bar chart that compares the mean fuel specific emissions for CO, HC and NO between the 2006 and 2021 measurements. The uncertainties are standard error of the mean determined using the daily samples. CO and HC emissions have decreased modestly, approximately 15% each, though the uncertainty in the 2006 HC measurements makes it likely that the HC difference is not statistically significant. NO emissions show the largest reductions having declined by more than 50%. Looking back in time at the fuel specific emissions by model year shown in Figure 3, highlights the small decreases in the CO and HC vehicle emissions observed since 2006. While the introduction of Tier II vehicles in 2009 dramatically lowered light-duty vehicle NO emissions and accounts for the large decreases seen in the mean emissions since 2006.

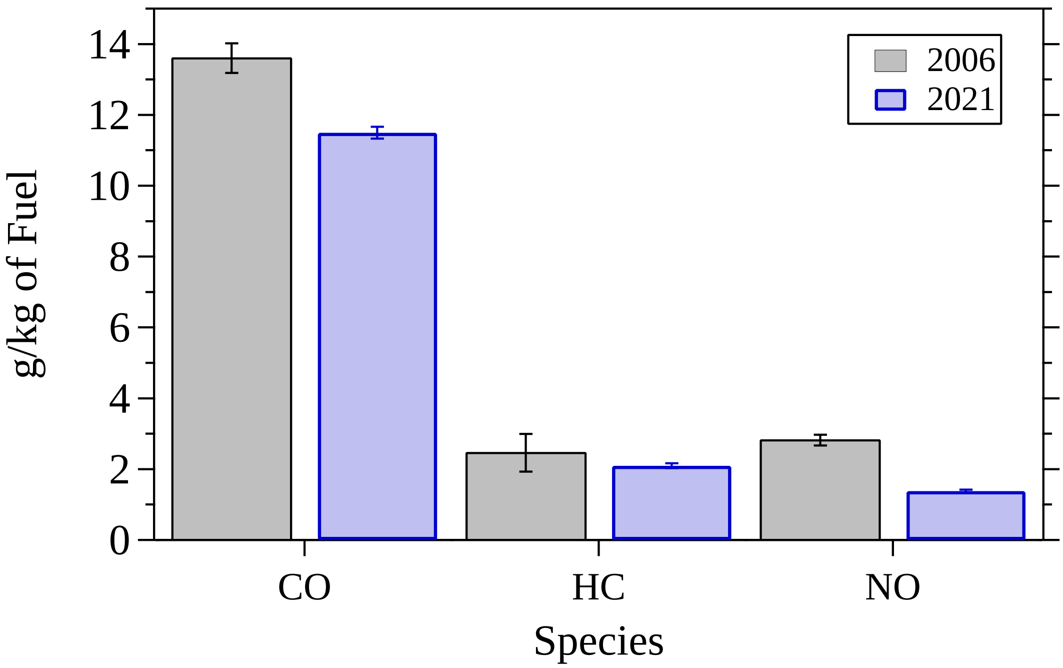

Figure 9. Mean fleet fuel specific emissions for carbon monoxide, hydrocarbons and nitric oxide for the 2006 and 2021 Phoenix data sets. The uncertainties are standard error of the mean calculated using the daily measurements.

As part of the 2021 Phoenix campaign the FEAT system was configured to collect and save the high frequency data from each attempted vehicle measurement. This data can then be post-processed to look for vehicles suspected of having elevated running loss emissions. In vehicles with HC emissions only originating from the tailpipe we expect to find those emissions well correlated with the co-emitted CO_2 emissions. In the event that there are additional sources of HC emissions from the vehicle those plumes can disrupt that correlation. Using our published method the high frequency data for each vehicle with a matching license plate in the Phoenix data set was used to locate and categorize any disruption in the expected linear correlation between tailpipe HC and CO_2 emissions and rank them using a Running Loss Index (RLI).[22]

The RLI's calculated for the newest model year vehicle at the site, where we assume few if any running loss emissions will be present, are used to establish the RLI_{Noise} value for the instrument at this location. For this campaign this RLI_{Noise} value was found to be 31. Using the RLI_{Noise} value the measured RLI values are binned according to the number of standard deviations the measurement exceeds the instrument noise. Vehicle whose measured RLI value exceeds 3 standard deviations above the instrument noise value are suspected of having some type of running loss emission. As the number of standard deviations increase so does the probability of the vehicle having running loss emissions.

Table 4 provides a break-out of the distribution by bin for the 18,294 RLI measurements. For this eight year old fleet there were 80 measurements from the 18,294 (0.4%) total measurements found to have an RLI_bin value greater than or equal to 3 and are suspected running loss emitters. Average model year for the 80 measurements was 2011.13 or about 2 years older than the fleet average and two vehicles a 2015 Chevrolet Pickup and a 2002 Ford Explorer were identified twice with all 4 measurements having an RLI_bin value of 3. The eleven measurements with an RLI_bin value of 4 and larger have a mean model year of 2005.7 or significantly older than the fleet in general.

Table 4. RLI Measurement Results for the 2021 Phoenix Data Set.

RLI Bin	Measurements (%) Mean RLI (ppm·cm)
≤ 0	14,252 (77.91%) 26.8
1	3,285 (17.95%) 44.8
2	677 (3.70%) 64.4
3	69 (0.38%) 108.2
4	6 (0.03%) 189.0
5	3 (0.02%) 302.1
6	2 (0.01%) 578.8
Totals	18,294 31.9

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.[23] Such plots were constructed for all 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 3.4, 3.9, 0.106, 0.018 and 0.19 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 4.9 gCO/kg of fuel

(0.04%), 5.5 gHC/kg (128 ppm), 0.15 gNO/kg (12 ppm), 0.025 gNH_3/kg (3 ppm) and 0.27 gNO_2/kg (12 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 0.5 gCO/kg of fuel, 0.55 gHC/kg, 0.015 gNO/kg, 0.0025 gNH_3/kg and 0.03 gNO_2/kg, respectively. These values are in the low range of the recent campaigns for average noise.

CONCLUSIONS

The University of Denver carried out five days of remote sensing in the Phoenix, AZ area in April of 2021. Measurements were collected Monday, April 12, to Friday, April 16, between the hours of 7:00 and 17:00 on the uphill interchange ramp from EB U.S. 60 to NB SH 101. A database was compiled containing 18,294 records for which the State of Arizona 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 11.5 ± 0.2 g/kg of fuel (0.09%), 2.1 ± 0.1 g/kg of fuel (52 ppm), 1.38 ± 0.04 g/kg of fuel (98 ppm), 0.31 ± 0.01 g/kg of fuel (39 ppm) and 0.04 ± 0.01 g/kg of fuel (2 ppm) respectively. The 2021 Phoenix measurements showed reductions for CO (-15%), HC (-15%) and NO (-52%) when compared with the 2006 values collected at a different location. NO emissions show a significantly larger reduction than the other two species do to the higher NO emission levels present in the fleet prior to the introduction of Tier II vehicles in 2009. 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 28%, 19%, 32%, 19% and 49% of the overall fleet CO, HC, NO, NH_3 and NO_2 emissions, respectively.

An analysis of running loss emission from this fleet was conducted using our previously published method utilizing the high frequency data collected with each vehicle emission measurement. The method found that 0.4% of the measurements was suspected to have had a running loss emission problem and this fleet was approxiamately 2 years older than the entire fleet. The eleven vehicles with the higher running loss indexes (Bins 4 to 6) were significantly older with an average model year of 2005.7

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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 NH_3/CO_2 slope, equivalent to +50ppm.
9) Reported NH_3 < -80ppm or > 7000ppm. NH_3 "invalid".
10) Excess error on NO_2/CO_2 slope, equivalent to +20% for NO2 > 200ppm, 40ppm for NO_2 < 200ppm
11) Reported NO_2 < -500ppm or > 7000ppm. NO_2 "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 AZ_2021.dbf database.

The AZ_2021.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, Excel, Access or Filemaker Pro, regardless of platform. The following is an explanation of the data fields found in this database:

License	Arizona 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.
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.
Percent_co2	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”.
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	The highest absolute concentration of CO_2 measured; indicates plume strength.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”.
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.
Csv_name	File name for the high frequency data file.
Vin	Vehicle identification number.
Make	Manufacturer of the vehicle.
Year	Model year of the vehicle.
Style	Vehicle style information.
Model	Model information.
Fuel	Fuel type.
IM_type	Arizona IM test type.
Last_test	Date of last Arizona IM test.
Next_test	Date of next Arizona IM test.
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.
Hc_slope	Slope of HC/CO_2 from high frequency data.
Hc_slperr	Uncertainty of linear fit of HC/CO_2.
Rli_meas	Measured Running Loss Index.
Hc_ppm	HC in ppm for valid HC measurements. Set to zero for invalid HC measurement.
Rli_0	Running loss index noise limit.
Trans_rli0	Rli_0 value after being transformed into a normal distribution.
Trans_rlim	Rli_meas value after being transformed into a normal distribution.
Std_delta	Trans_rlim minus Trans_rli0. The standard deviation separation.
Rli_bin	Rounded number of standard deviation between Trans_rlim and Trans_rli0.

APPENDIX C: Temperature and Humidity Data from Sky Harbor Airport.

2021										
Time (CDT)	April 12		April 13		April 14		April 15		April 16	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0651	68	27	67	26	66	29	65	27	62	21
0751	73	25	70	23	68	27	68	22	65	16
0851	78	21	73	23	73	23	71	19	70	14
0951	81	19	78	19	77	19	74	19	74	11
1051	85	14	79	20	79	17	77	13	77	10
1151	85	14	82	16	80	16	76	14	79	10
1251	89	12	85	14	84	15	76	12	81	9
1351	88	11	86	13	85	13	80	12	79	9
1451	89	12	88	12	85	12	81	12	81	7
1551	91	12	88	11	86	11	82	10	83	7
1651	90	11	89	12	85	13	81	9	82	7
1751	90	11	87	14	83	11	80	8	81	7

APPENDIX D: Field Calibration Record.

2021						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
4/12	8:30	1.84	1.84	1.45	1.10	1.17
4/12	10:25	1.32	1.34	0.97	1.08	0.80
4/12	13:00	1.21	1.25	0.98	1.04	0.82
4/13	8:20	1.67	1.67	1.36	1.11	1.30
4/13	10:00	1.37	1.39	1.11	1.08	1.04
4/13	12:00	1.26	1.29	1.04	1.09	0.91
4/14	8:15	1.71	1.67	1.37	1.11	1.30
4/14	10:00	1.37	1.37	1.07	1.09	1.08
4/14	12:00	1.32	1.33	1.08	1.05	0.98
4/15	8:11	1.79	1.75	1.44	1.07	1.51
4/15	9:47	1.55	1.55	1.28	1.05	1.24
4/15	12:00	1.55	1.55	1.28	1.05	1.24
4/16	7:15	1.83	1.78	1.49	1.12	1.55
4/16	9:05	1.54	1.52	1.24	1.08	1.28
4/16	11:00	1.47	1.47	1.24	1.10	1.10