CRC Report No. E-123

ON-ROAD REMOTE SENSING OF AUTOMOBILE EMISSIONS IN THE DENVER AREA: WINTER 2020

July 2020

COORDINATING RESEARCH COUNCIL, INC.
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On-Road Remote Sensing of Automobile Emissions in the Denver Area: Winter 2020

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July 2020

Prepared for:

Coordinating Research Council, Inc.
5755 North Point Parkway, Suite 265
Alpharetta, Georgia 30022
Contract No. E-123

EXECUTIVE SUMMARY

The University of Denver conducted four days of remote sensing in the Denver, Colorado area in January and February of 2020. 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. Since fuel sulfur has been nearly eliminated in U.S. fuels SO_2 emissions have followed suit and while vehicle SO_2 measurements are collected they were not calibrated and the measurements are not included in the discussion of the results.

Measurements were made on four weekdays, Thursday January 16, Wednesday January 22, Friday January 24, and Friday February 21, 2020, between the hours of 9:00 and 17:00 on the interchange ramp from northbound I-25 to westbound US6. Since this is a winter measurement program only days with mild temperatures were used to collect measurements (high temperatures generally >50° F) and as such the sampling does not always occur on consecutive days. This is the same location previously used for the Denver measurements in the winters of 1999-2001, 2003, 2005, 2007, 2013, 2015 and 2017. However, between the 2013 and 2015 measurements this ramp was completely redesigned. Previously it was a tightly curved uphill (4.6°) interchange ramp with average speeds around 20 mph. The redesigned interchange reduced both the curvature and the steepness (1°) of the ramp increasing average speeds to above 30 mph, decreasing loads and increasing the fraction of observed high speed decelerations.

A database was compiled for the 2020 Denver data containing 19,909 records for which the State of Colorado 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 www.feat.biochem.du.edu.

Table ES1 compares the fuel specific mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured in this study with the previous measurements in the winter of 2017/2018. The uncertainties reported are standard error of the means determined using the daily means. The 2020 Denver measurements show reductions for all of the species measured when compared with the 2017 values and the fleet age decreased 0.4 model years for the first time since measurements resumed in 2013. Fuel specific emission factors decreased for CO (41%), HC (16%), NO (23%), NH_3 (8%), NO_2 (12%) and NO_x (22%). However, only the differences for CO, NO and NO_x are statistically significant at the 95% confidence interval.

Figure ES1 shows the mean fuel specific emissions for CO (○, left axis), HC (▲, right axis) and NO (□, right axis) versus measurement year for all the data sets collected at the Denver site

Table ES1. Fleet Mean Emissions for Previous Two Measurement Years.

Year	Mean grams/kg of Fuel					
	CO	HC	NO[a]	NH_3	NO_2	NO_x[b]
2020	4.7 ± 0.5	2.2 ± 0.4	1.36 ± 0.07	0.34 ± 0.01	0.1 ± 0.01	2.2 ± 0.1
2017/18	8.0 ± 0.2	2.6 ± 0.2	1.77 ± 0.05	0.37 ± 0.01	0.11 ± 0.02	2.8 ± 0.1

[a] grams of NO
[b] grams of NO_2

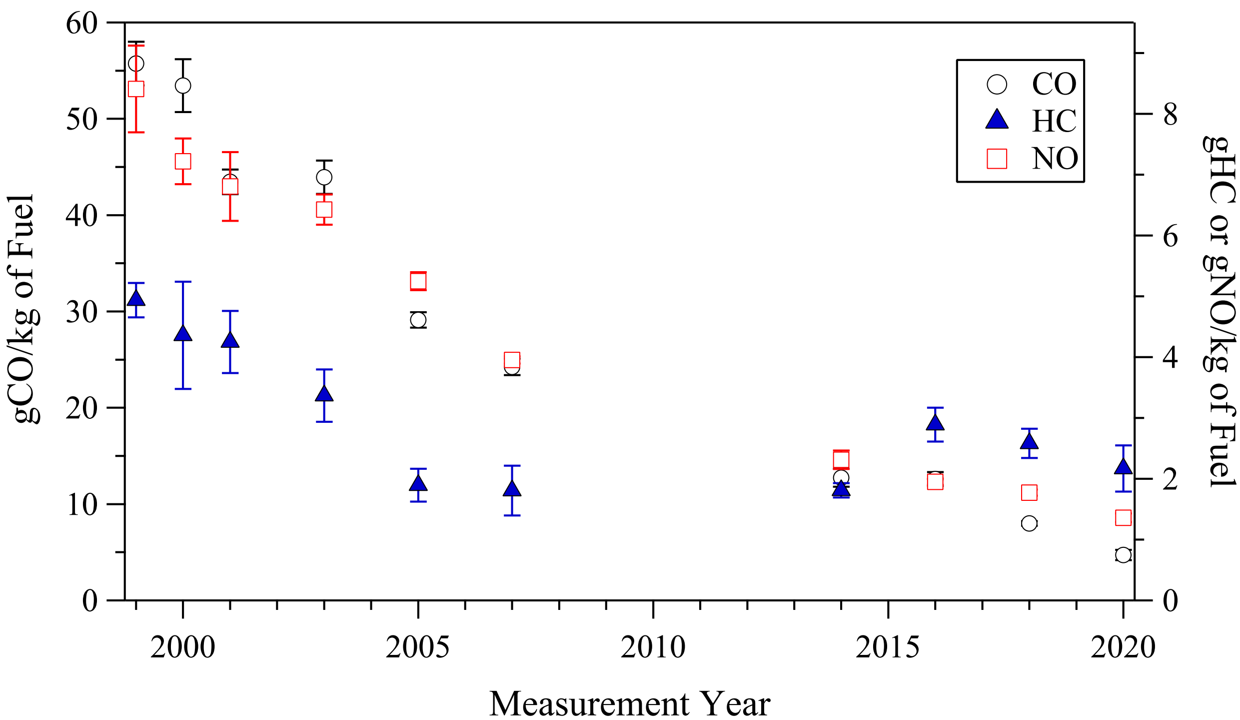

Figure ES1. Denver 6th Avenue historical fuel specific fleet mean emissions for CO (○, left axis), HC (▲ , right axis) and NO (□, right axis) by measurement year. Uncertainties are standard errors of the mean calculated using the daily measurements. The fuel specific HC means have been adjusted as described in the report.

using the E-23 protocols. Uncertainties are standard errors of the mean calculated using the daily means. Since 1999 the fuel specific CO emissions have decreased by 92%, HC by 56% and NO by 84%. The rates of decreases for all of the species has slowed since the measurements were collected in 2013 and mean fuel specific HC emissions increased after 2013 when the interchange ramp was reconstructed.

The average age of the Denver fleet at this location had remained constant at 9.2 years old since 2013. In this data set the observed fleet age dropped 0.4 model years to 8.8. This is still significantly older (~1.5 years) than the fleet observed prior to the 2008-2009 recession but undoubtedly a reflection of the strong Colorado economy. Fleet mean emissions remain dominated by a small fraction of the fleet that is high emitting. In the 2020 data set the highest emitting 1% of the measurements (99th percentile) are responsible for 57%, 26%, 30%, 17 % and 41% of the overall fleet CO, HC, NO, NH_3 and NO_2 emissions, respectively.

The history of NH_3 emission measurements at the Denver 6th Avenue site include measurements collected in a separate summer campaign of 2005 and winter CRC measurements in 2013, 2015, 2017 and 2020. Overall, we have observed a 24% reduction in the mean emissions since 2005 (0.45 ± 0.09 to 0.34 ± 0.01) or a 23% reduction since measurements resumed in 2013. The peak NH_3 emissions continue to extend into older models with the 2020 measurements following the 2017 observations that push the peak NH_3 emissions to beyond 20 year old vehicles. However, the increased uncertainty, due to fewer measurements in the older model year vehicles, makes an exact assignment difficult but illustrates the fact that catalytic converters in modern gasoline vehicles continue to show outstanding durability. The NH_3 fleet reduction rates continues to be less than half (24%) of that observed for tailpipe NO emissions which at the Denver site have decreased 62% (3.7 gNO/kg in the summer of 2005 to 1.4 gNO/kg) over the same time period. The large uncertainties in the 2005 measurements shown in Figure ES2 stem from the small overall sample size (3,680 total measurements).

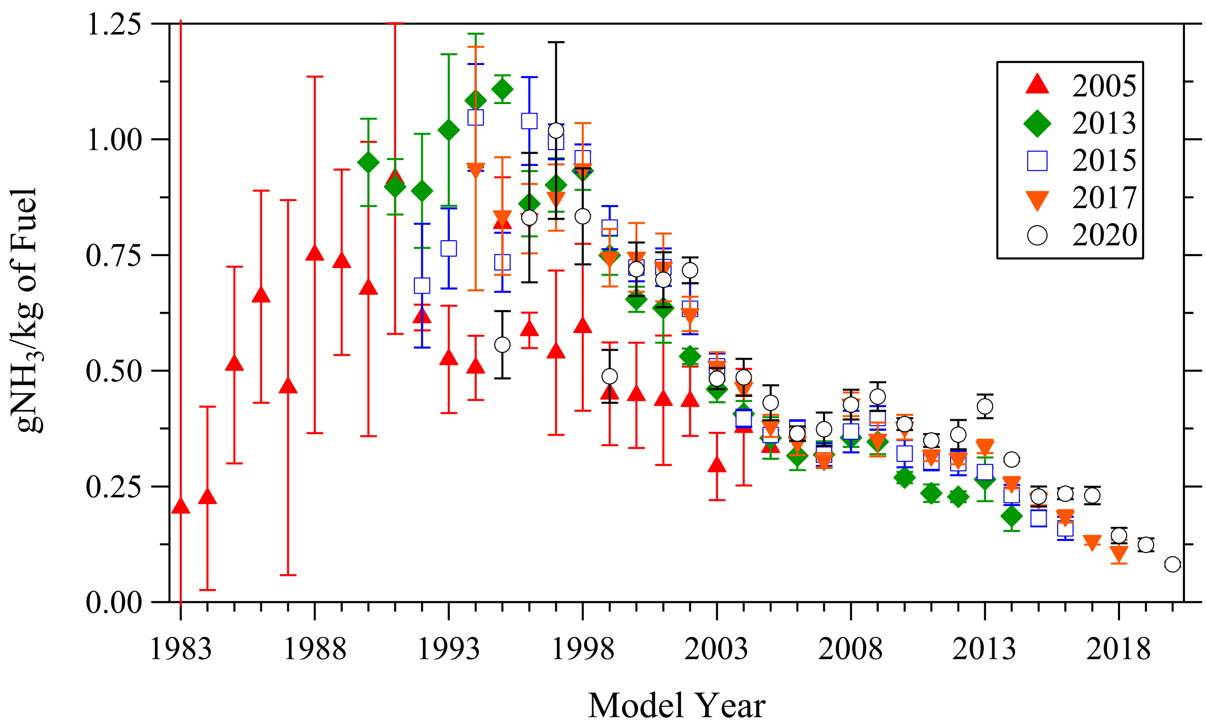

Figure ES2. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the four measurement data sets collected at the Denver site. Uncertainties are standard errors of the mean determined using the daily measurements.

The total fixed nitrogen in g/kg of fuel for the Denver 2020 measurements are shown in Figure ES3 (◆, right axis) with the molar percent composition distributed between NH_3 (●, left axis) and the NO_x (▲, left axis) component versus model year for non-diesel vehicles. The total fixed

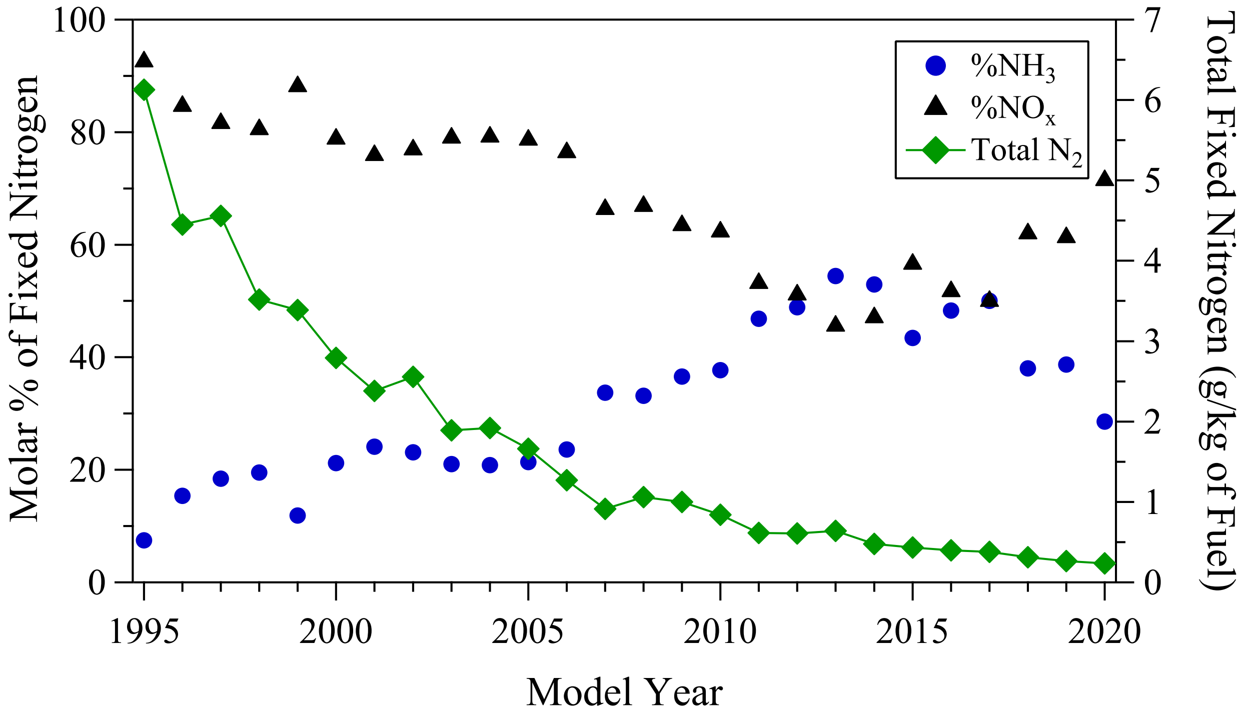

Figure ES3. Total fixed nitrogen in g/kg of fuel (◆, right axis) with the molar percent composition distributed between the NH_3 (●, left axis) and NO_x (▲, left axis) component versus model year for non-diesel vehicles.

nitrogen calculation neglects any unmeasured nitrous oxide (N_2O) and nitrous acid (HONO) that may account for a few percent of the total. Total fixed nitrogen emissions have been on a steep decline since the mid-nineties in the gasoline 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 until the 2017 measurements, but appears to have leveled out soon after the introduction of Tier 2 vehicles and starting around the 2016 models is now declining. It is not known what 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.

In the Denver truck fleet (weight classes 2 & higher) NO emission reductions on a percentage basis have occurred faster in the non-diesel trucks than in the diesel portion though the magnitude of reduction is larger for the diesel fleet. Since 2003 the non-diesel truck fleet has seen an 82% reduction in fuel specific NO emissions (6.5 to 1.2 gNO/kg of Fuel) and the diesel truck fleet a 64% reduction (23.1 to 8.3 gNO/kg of Fuel). The differences between the two fleets revolves around the introduction of Tier 2 vehicles in 2009 where we observed a significantly larger reduction in NO emissions in the non-diesel truck fleet (63% reduction) than seen in the diesel trucks (25%) between 2005 and 2013. Since 2013, on a percentage basis, NO and NO_x emission reductions have been similar in both fleets with reductions around 50%, however, the diesel truck fleet has yet to catch up to the emission levels observed in the non-diesel trucks and are factors of 2 to 3 times higher than the same model year non-diesel trucks.

INTRODUCTION

Since the early 1970's many heavily populated cities in the United States have been unable to comply with the National Air Quality Standards (NAAQS) that have been 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. 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 (NO_2). As of 2015, on-road vehicles were estimated to be one of the larger sources for major atmospheric pollutants, contributing approximately 39% of the CO, 14% of the volatile organic carbons, 3% of the ammonia (NH_3) and 36% of the NO_x to the national emission inventory.[3]

The use of the internal combustion engine and the combustion of carbon based fuels as one of the primary means of transportation makes it a significant source 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, hydrocarbons (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 include inspection and maintenance (I/M) programs, reformulated and oxygenated fuel mandates, and transportation control measures, but the effectiveness of these measures are difficult to quantify. Many areas remain in non-attainment for ozone. The further reduction of the federal eight-hour ozone standards (first introduced by the EPA in 1997 and subsequently lowered in 2008 (75ppb) and again in 2015 (70ppb)) means that many new locations are likely to have difficulty meeting the standards in the future.[5]

Beginning in 1997 the University of Denver began conducting on-road tailpipe emission surveys at selected sites in the U.S. to follow long term vehicle emission trends. A site northwest of Chicago IL, in Arlington Heights, was the first but over the years measurements have also been collected in Los Angeles CA, Denver CO, Omaha, NE, Phoenix AZ, Riverside CA, and Tulsa OK.[6] 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 and the data have been used by many additional researchers to establish fleet emission trends and inventories.[7-13]

Reflecting a desire to continue evaluating the historical and recent emissions trends, several of the previous E-23 sites were chosen for additional data collection. As part of the E-106 program two additional measurement campaigns were conducted in Denver, CO in the winter of 2013 and 2015. CRC E-123 continues these measurements and this report describes the on-road emission measurements collected in Denver, CO in the winter of 2020. Measurements were made on four separate weekdays between the hours of 9:00 and 17:00 on the interchange ramp from northbound I-25 to westbound US6.

Measurements were previously collected at this location beginning in 1995; however, those collected for the E-23 program started in 1999 and were followed in 2000, 2001, 2003 and 2005 and 2007. The E-106 and E-123 measurements have been collected every other year since 2013, however, between the 2013 and 2015 measurements the ramp was redesigned altering the driving mode. Previously it was a tightly curved uphill (4.6°) interchange ramp with average speeds around 21 mph. The redesigned interchange reduced both the curvature and the steepness (1°) of the ramp allowing average speeds to increase above 30 mph and loads to decrease.

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, and has previously been described in the literature.[14-16] The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC, and twin dispersive ultraviolet (UV) spectrometers for measuring oxides of nitrogen (NO and NO_2), SO_2 and NH_3 (0.26 nm/diode resolution). The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Collinear beams of infrared (IR) and UV light are passed across the roadway into the IR detection unit, and are then focused through a dichroic beam splitter, which serves to separate 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 mirror and is focused onto the end of a quartz fiber bundle that is mounted to a coaxial connector on the side of the detector unit. The quartz fiber bundle is divided in half to carry the UV signal to two separate spectrometers. The first spectrometer was adapted to expand its UV range down to 200nm in order to measure the peaks from SO_2 and NH_3 and continue to measure the 227nm peak from NO. 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 in order 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.[17] Since the removal of sulfur from gasoline and diesel fuel in the U.S. SO_2 emissions have become negligibly small and as such, 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 are dependent upon, 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 only directly measures ratios of CO, HC, NO, NH_3 or NO_2 to CO_2. The molar ratios of CO, HC, NO, NH_3 or NO_2 to CO_2, termed Q^{CO}, Q^{HC}, Q^{NO}, Q^{NH3} and Q^{NO2} respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions 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. But 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.[18] To calculate mass emissions as described below, the %HC values reported first have to be multiplied by 2.0 to account for these “unseen” hydrocarbons as shown below, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the equations shown below.

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

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 close to 100% NO in the case of gasoline fueled vehicles.

Another useful relationship is the conversion from percent emissions to grams pollutant per kilogram (g/kg) of fuel. This is directly 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 fuel (this translates to 860 gC/kg of 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.[18]

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

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. For the multi-species instrument three calibration cylinders are needed. The first contains CO, CO_2, propane and NO, the second contains NH_3 and propane and the final cylinder contains NO_2 and CO_2. A puff of gas is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Air Liquide and PraxAir). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are reported as propane equivalents.

Double blind 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.[19, 20] The NO channel used in this study has been extensively tested by the University of Denver, but has not been subjected to an extensive double blind study and instrument inter-comparison to have it independently validated. 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.[15] Comparison of fleet average emission by model year versus IM240 fleet average emissions by model year show correlations between 0.75 and 0.98 for data from Denver, Phoenix and Chicago.[21] Appendix A gives a list of criteria for determining data validity.

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, as well as a time and date stamp, is 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 0.1mph) 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. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated (reported to 0.001 mph/sec). Appendix B defines the database format used for the data set.

RESULTS AND DISCUSSION

Measurements were made on four weekdays, Thursday January 16, Wednesday January 22, Friday January 24, and Friday February 21, 2020, between the hours of 9:00 and 16:00 on the interchange ramp from northbound I-25 to westbound US6. Since this is a winter measurement program only days with mild temperatures were chosen to collect measurements (high temperatures >~50° F) and as such the sampling does not always occur on consecutive days. A satellite image of the measurement location is shown in Figure 1 and a photograph of the setup from the 2015 campaign is shown in Figure 2. Appendix C gives temperature and humidity data

Figure 1. A satellite picture of the Denver interchange ramp from Northbound I-25 to Westbound US6 (labeled W 6th Avenue Fwy. in this image). The large black arrow marks the approximate sampling location.

for the study dates.

The digital video images of the license plates were subsequently transcribed for license plate identification. Colorado license plates were transcribed and submitted to the state for matching against registration records for all non-personal vehicle information. The resulting 2020 database contains 19,909 records with make and model year information and valid measurements for at least CO and CO_2. Most of these records also contain valid measurements for HC, NO, NH_3 and NO_2. This database and all previous databases compiled for the CRC E-23 and E-106 campaigns can be found at www.feat.biochem.du.edu.

Figure 2. The Denver US6 monitoring site looking west toward the mountains.

The validity of the attempted measurements is summarized in Table 1. The table describes the data reduction process 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 closely following vehicle, that measurement attempt is aborted and an attempt is made at measuring the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement. Invalid measurement attempts arise when the vehicle plume is highly diluted or absent (elevated, electric/hybrid engine off operation or rapid deceleration from foot off the throttle), or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit (see Appendix A). For the Denver site this represents the largest loss of measurements as the higher speeds at the redesigned ramp allow vehicles the opportunity to coast through the measurement beam. Additional data losses occur during the plate reading process, when out-of-state vehicles, vehicles with unreadable plates (obscured, missing, dealer, out of camera field of view) are omitted from the database.

Table 1. Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	31,742				
Valid Measurements	25,435	25,415	25,434	25,404	24,686
Percent of Attempts	80.1%	80.1%	80.1%	80.0%	77.8%
Submitted Plates	20,585	20,575	20,584	20,562	19,982
Percent of Attempts	64.9%	64.8%	64.8%	64.8%	63.0%
Percent of Valid Measurements	80.9%	81.0%	80.9%	80.9%	80.9%
Matched Plates	19,909	19,900	19,908	19,886	19,322
Percent of Attempts	62.7%	62.7%	62.7%	62.6%	60.9%
Percent of Valid Measurements	78.3%	78.3%	78.3%	78.3%	78.3%
Percent of Submitted Plates	96.7%	96.7%	96.7%	96.7%	96.7%

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 19,909 records used in this fleet analysis, 15,931 (80%) were contributed by vehicles measured only once, and the remaining 3,978 (20%) records were from vehicles measured at least twice. The combination of high traffic volumes and fewer consecutive days of sampling at this site increases the number of unique vehicle measurements.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	15,931
2	1,396
3	279
4	80
5	4
>5	1

Table 3 summarizes the data for the current and all of the previous winter CRC remote sensing campaigns conducted at this site. The measurements that were collected in the years following reconstruction of the exit ramp at the 6th Avenue site are delineated in the table by the double lines separating the columns labeled 2013 and 2015. The average HC values have been adjusted for this comparison to remove an artificial offset in the measurements. This offset, restricted to the HC channel, has been reported in earlier CRC E-23-4 reports. Calculation of the offset is accomplished by computing the mode and means of the newest model year and vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons and that the median of these group's emissions distribution should be very close to zero, using the lowest of either of these values as the offset. The offset adjustment is subtracted or added to the individual hydrocarbon measurements. This normalizes each data set to a similar emissions zero point since it is assumed that the cleanest vehicles emit few hydrocarbons. Such an approximation will err only slightly

Table 3. Winter Campaign Data Summary.

Study Year	1999	2000	2001	2003	2005	2007	2013	2015	2017	2020
Mean CO (%) (g/kg of fuel)	0.45 (56)	0.43 (54)	0.34 (43)	0.35 (44)	0.23 (29)	0.19 (24)	0.10 (12.6)	0.10 (12.6)	0.06 (8.0)	0.04 (4.7)
Median CO (%)	0.09	0.11	0.06	0.08	0.05	0.05	0.02	0.03	0	-0.02
99^{th} Percentile Contribution	15.4	16.4	19.6	19.2	23.1	25.7	33.6	32.5	47.2	57.2
Mean HC (ppm)[a] (g/kg of fuel)[a] Offset (ppm)	125 (5.0) 5	115 (4.6) 60	112 (4.6) -50	88 (3.4) 20	50 (1.9) 10	46 (1.8) 0	45 (1.8) 45	77 (2.9) 11	65 (2.6) 26	55 (2.2) 25
Median HC (ppm)[a]	75	50	80	40	20	30	31	42	31	28
99^{th} Percentile Contribution	22.7	25.7	29.0	30.8	42.3	33.1	26.5	30.4	29.2	26.1
Mean NO (ppm) (g/kg of fuel)	600 (8.4)	511 (7.2)	483 (6.8)	456 (6.5)	371 (5.3)	278 (4.0)	193 (2.7)	138 (2.0)	125 (1.8)	96 (1.4)
Median NO (ppm)	240	165	133	113	76	40	17	8	10	10
99^{th} Percentile Contribution	7.4	8.6	9.4	9.8	11.0	12.6	17.6	23.3	25.6	30.0
Mean NH_3 (ppm) (g/kg of fuel)	NA	NA	NA	NA	NA	NA	55 (0.44)	53 (0.42)	46 (0.37)	43 (0.34)
Median NH_3 (ppm)	NA	NA	NA	NA	NA	NA	16	15	13	14
99^{th} Percentile Contribution	NA	NA	NA	NA	NA	NA	15.0	15.8	16.7	17.4
Mean NO_2 (ppm) (g/kg of fuel)	NA	NA	NA	NA	NA	NA	11 (0.24)	6 (0.14)	5 (0.11)	4 (0.10)
Median NO_2 (ppm)	NA	NA	NA	NA	NA	NA	4	2	2	2
99^{th} Percentile Contribution	NA	NA	NA	NA	NA	NA	44.8	43.1	41.1	41.3
Mean Model Year	1992.4	1993.4	1994.6	1996.4	1998.1	2000	2005.2	2007.2	2009.2	2011.6
Mean Fleet Age[b]	6.9	6.9	6.7	6.9	7.2	7.3	9.2	9.2	9.2	8.8
Mean Speed (mph)	20.6	21.9	22.3	20.2	23.5	22.5	22.9	32.8	32.5	32.1
Mean Acceleration (mph/s)	0.21	0.08	-0.77	0.12	-0.47	0.07	0.01	-1.0	0.33	-0.02
Mean VSP (kw/tonne) Slope (degrees)	9.9 4.6°	10.1 4.6°	5.9 4.6°	10.7 4.6°	8.1 4.6°	10.4 4.6°	10.4 4.6°	-1.4 1.0°	8.9 1.0°	6.2 1.0°

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

values as the offset. The offset adjustment is subtracted or added to the individual hydrocarbon measurements. This normalizes each data set to a similar emissions zero point since it is assumed that the cleanest vehicles emit few hydrocarbons. Such an approximation will err only slightly towards clean because the true offset will be a value somewhat less than the average of the cleanest model year and make. This adjustment facilitates comparisons with the other E-23 sites and/or different collection years for the same site. The offset adjustments have been performed where indicated in the analyses in this report and a detailed example of how it is calculated is included in Appendix D.

The 2020 Denver measurements show reductions for all of the species measured when compared with the 2017 values. Fuel specific emission factors (g/kg of fuel) decreased for CO (41%), HC (16%), NO (23%), NH_3 (8%), NO_2 (12%) and NO_x (22%). Only the differences for CO, NO and NO_x are statistically significant at the 95% confidence interval. The percent of emissions contributed by the highest emitting 1% of the fleet (the 99th percentile) increased for all of the species except HC.

An inverse relationship between vehicle emissions and model year is shown in Figure 3 for the nine periods sampled during the winters of 1999 – 2001, 2003, 2005, 2007, 2013, 2015, 2017 and 2020. The HC data have been offset adjusted here for comparison. There is a noticeable increase in the mean HC emissions for all the model years beginning with the 2015 measurements after reconstruction of the ramp. The new design increased the number of vehicles measured during rapid deceleration events (foot off the gas motoring as well as braking). CO and NO mean emissions by model year are not significantly affected by this change in driving mode and the dominate feature for these two species is the gradual increases in fleet average emissions, year over year, beginning in the early 2000 model years. Note that the uncertainty levels rises quickly in the mean emission levels for the oldest model years in all of the data sets due to the decreasing sample sizes. For example in the 2020 for the 1994 model year vehicles, the last model year plotted there are only 43. All three species graphed in Figure 3 show an ever increasing number of model years with emission levels that do not change from the initial model year average. NO emissions are the first to show increases but the Tier 2 (2009 - 2016) and now Tier 3 certified vehicles (2017 & newer) have significantly reduced fleet average NO emissions deterioration.

Following the data analysis and presentation format originally shown by Ashbaugh et al.,[22] the vehicle emissions data by model year from the 2020 study were divided into quintiles and plotted. The results are shown in Figures 4 - 6. The bars in the top plot represent the mean emissions for each model year's quintile, but do not account for the number of vehicles in each model year. The middle graph shows the fleet fraction by model year for the newest 22 model years showing the impacts the last recession had on car sales between 2009 and 2010 and the recovery that has followed. Model years older than 1999 and not graphed account for 2.9% of the measurements and contribute between 10.4% (HC) and 26.4% (CO) of the total emissions. The bottom graph for each species is the combination of the top and middle figures. These figures illustrate that at least the lowest emitting 60% of the on-road fleet, regardless of model year, make an essentially negligible contribution to the overall fleet mean emissions. The top and

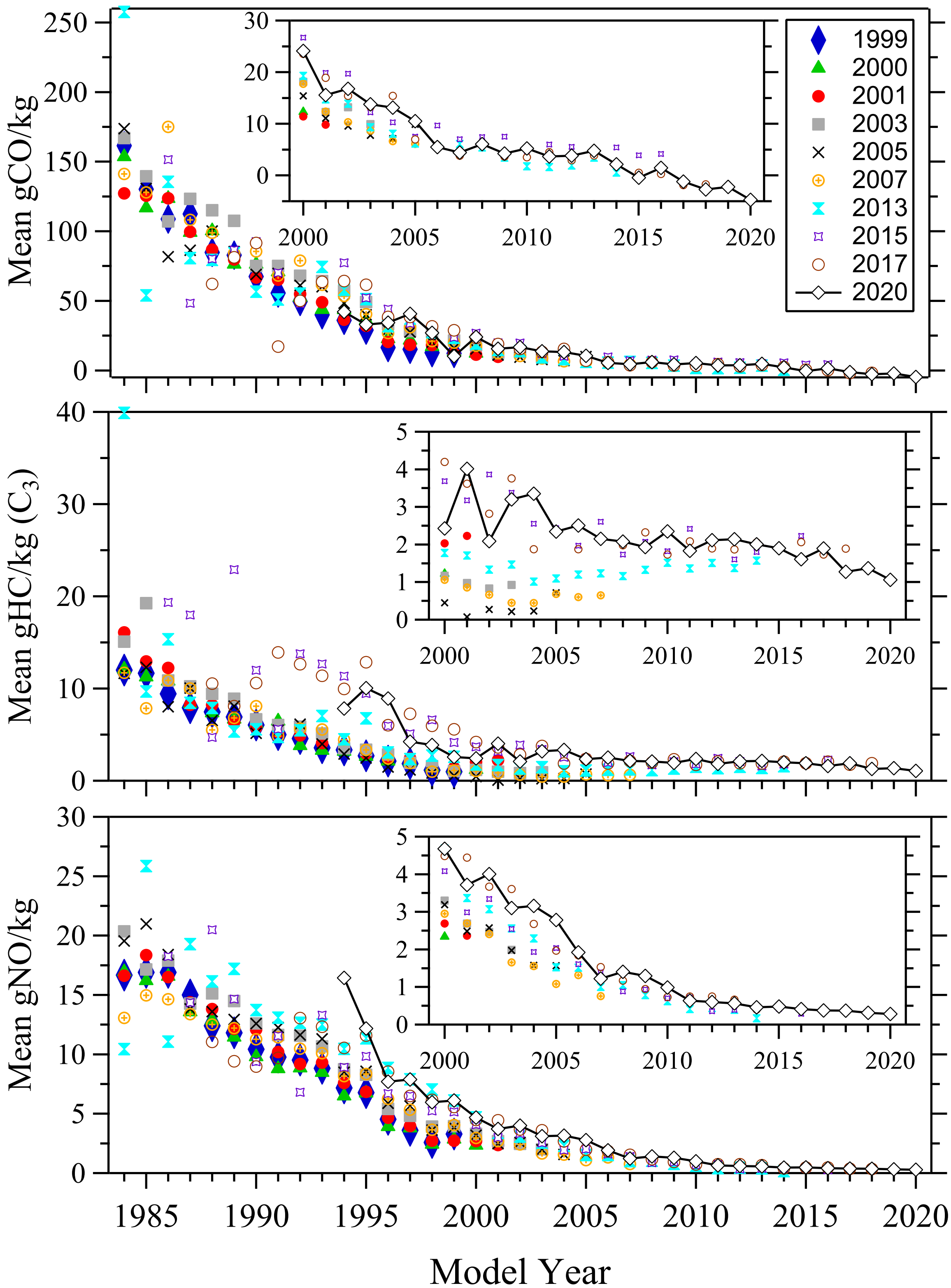

Figure 3. Mean fuel specific vehicle emissions plotted as a function of model year for all the collected Denver data sets. HC data have been offset adjusted as described in the text. Insets expand model years 2000 to 2020 for each species.

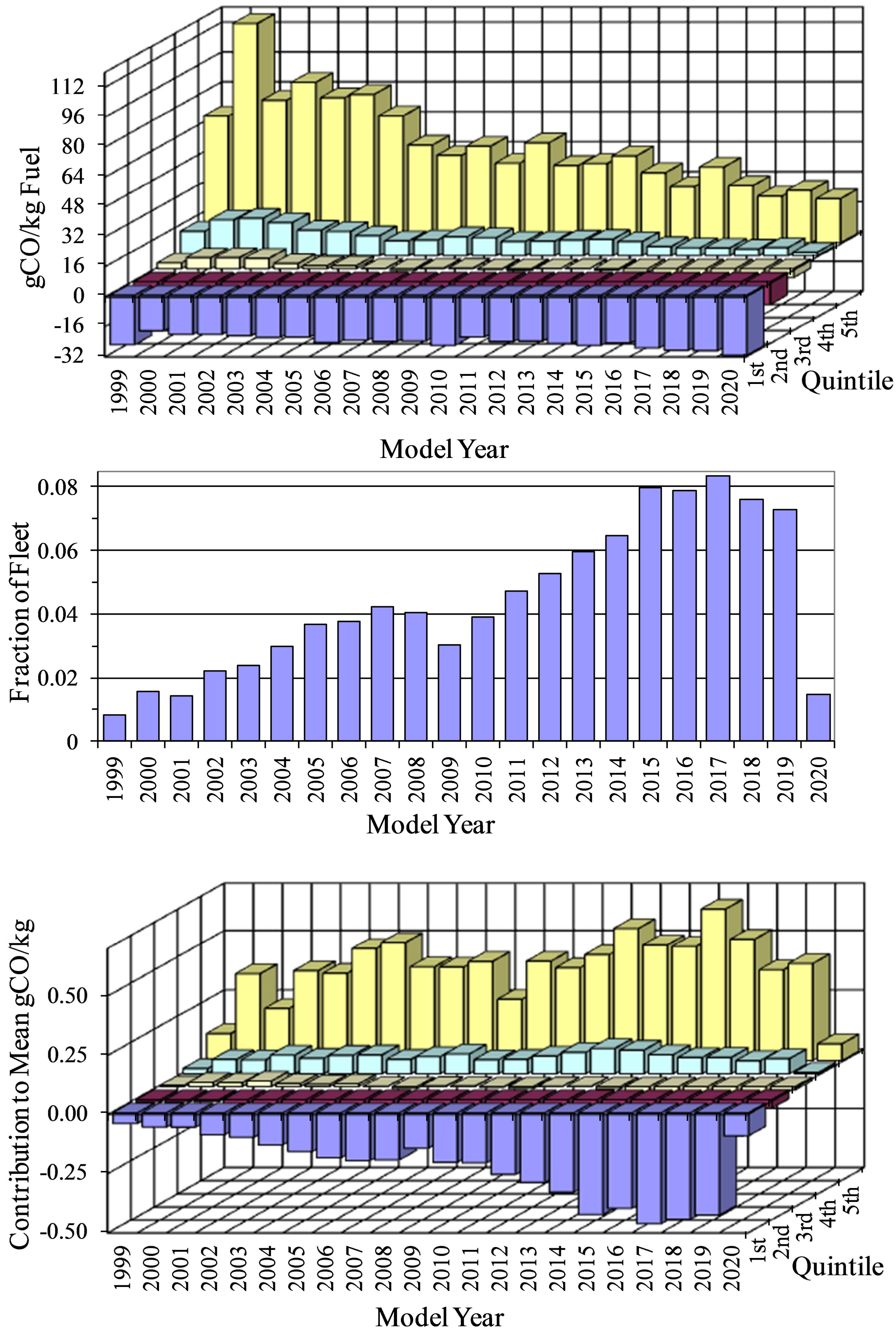

Figure 4. Mean gCO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gCO/kg of fuel emissions by model year and quintile (bottom).

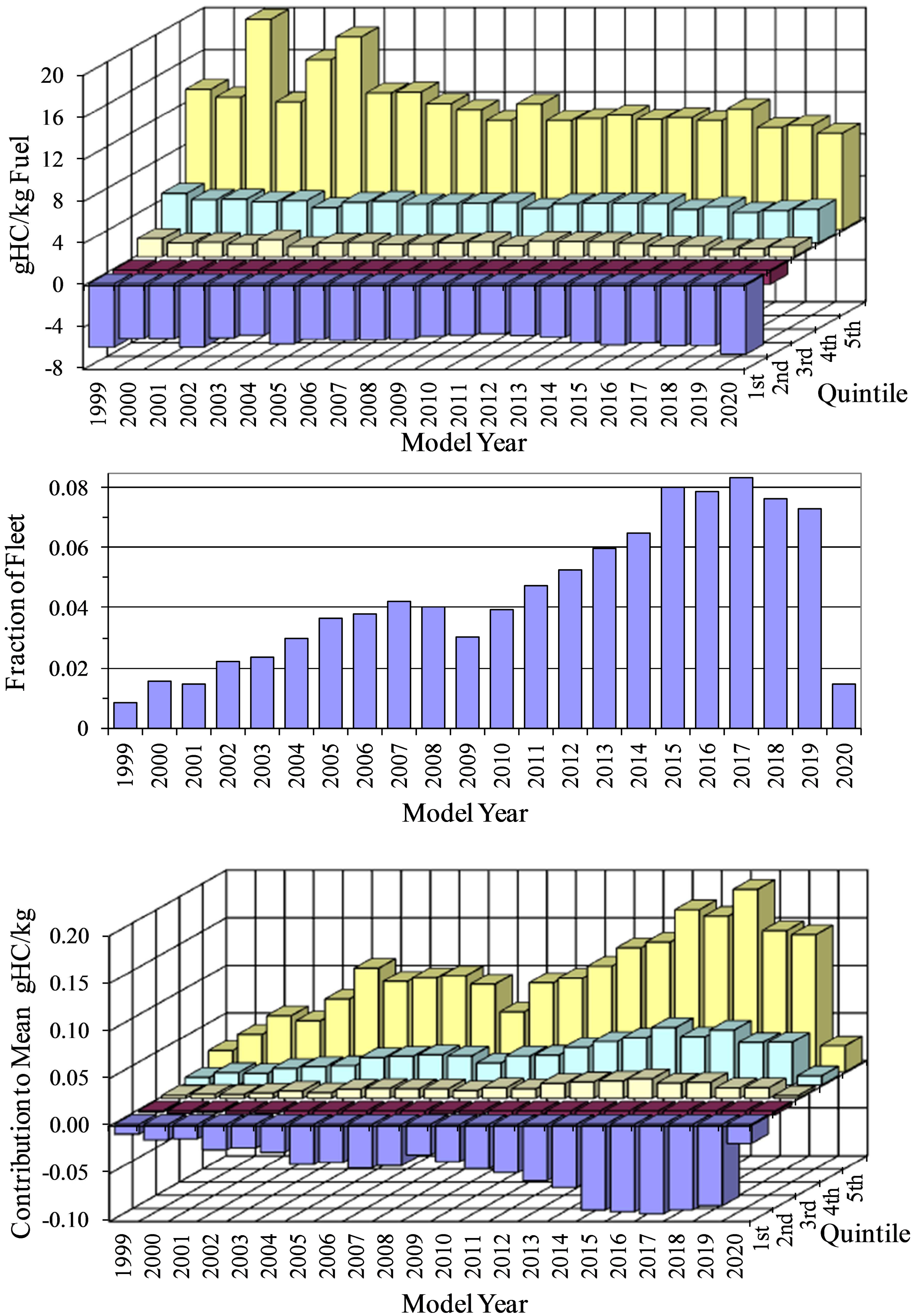

Figure 5. Mean gHC/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gHC/kg of fuel emissions by model year and quintile (bottom).

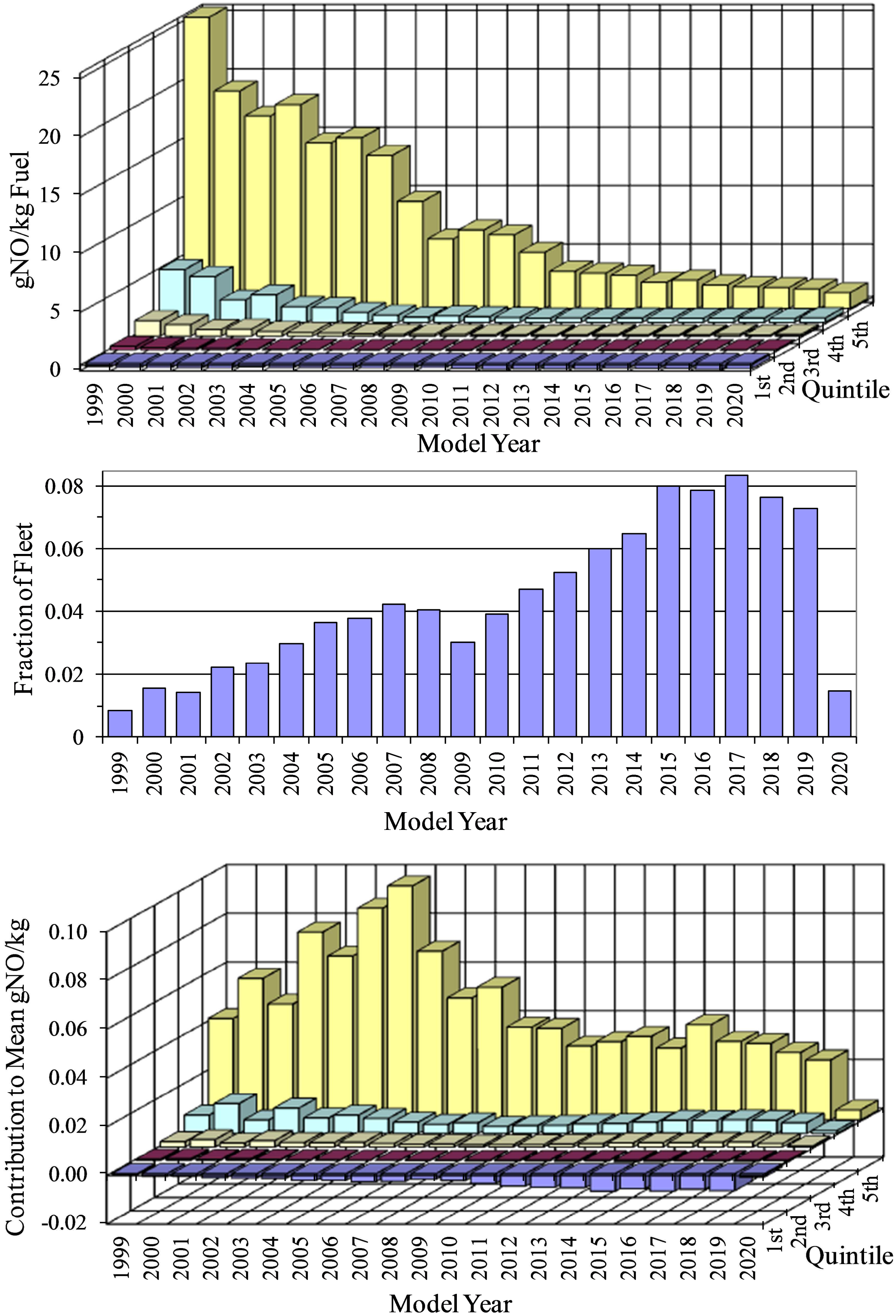

Figure 6. Mean gNO/kg of fuel emissions by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean gNO/kg of fuel emissions by model year and quintile (bottom).

bottom graph for the NO emissions is perhaps the most striking. As previously mentioned, the introduction of Tier 2 vehicles in 2009 and Tier 3 in 2017 has essentially eliminated NO emission increases due to age. This has resulted in prior model years now responsible for the majority of fleet NO emissions (see top graph in Figure 6). The emission levels of the highest emitting Tier 1 vehicles in the top quintile have expanded the y-axis so that the contribution of all the model years in the first four quintiles appears insignificant (see bottom graph in Figure 6). Selective catalytic reduction systems were introduced starting with 2009 diesel vehicles and reduce emission levels in the fifth quintile. These impacts will be discussed further later.

The accumulations of negative emissions in the first two quintiles are the result of continuously decreasing emission levels. Our instrument is designed such that when measuring true zero emission plumes (a ratio of zero), approximately half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to trend toward zero emissions, the negative emission readings will continue to grow toward half of the measurements. This is evident for approximately the first 10 model years for CO (bottom panel, Figure 4) where the negative height of the first quintile is generally equal to the positive height of the last quintile.

The middle graph in Figures 4 – 6 shows the fleet fractions by model year for the 2020 Denver database. The impact of the reduction in light-duty vehicle sales during the 2008 recession is still a prominent feature of the 2020 data.[23] In both Denver and Los Angeles the 2008 recession increased average fleet ages by 2 full model years. Table 3 shows that the average age of the Denver fleet observed at this ramp remained constant at 9.2 years since 2013 until the collection of this data set where fleet age decreased 0.4 model years to 8.8. This has increased the number of measurements contributed by the first 11 model years (2020 - 2010) to 67% (62% for the 2017/18 measurements) though this is still significantly below the 79% of the measurements observed for the 2006/2007 (~7.3 year old fleet) fleet.

As emissions of CO and HC have been drastically reduced over the past two decades, generally all those that contribute to the means are found in the last quintile (as shown in the bottom graphs of Figures 4 -6). For CO these contributions to the fleet mean emissions are generally evenly distributed across the first twenty model years (refer to bottom graph Figure 4). For HC the contributions by model year to the fleet mean in the last quintile follows the pattern of the fleet fractions. NO is the exception. The large reductions in NO emissions in the Tier 2 and now Tier 3 vehicles combined with lower vehicle sales when they were introduced into the fleet has shifted the bulk of the contributions to the NO mean to 2008 and older models (see the bottom graph of Figure 6). In addition, the small numbers of diesel powered vehicles in this fleet also contribute to the last quintile for NO.

While NH_3 is not a regulated pollutant it is a necessary precursor for the production of ammonium nitrate and sulfates which are often a significant component of secondary aerosols and $PM_{2.5}$ found in urban areas.[24] Ammonia is most often associated with farming and livestock operations but it can also be produced by 3-way catalyst equipped gasoline and natural gas vehicles.[25] The production of exhaust NH_3 emissions is contingent upon the vehicle's ability to produce NO in the presence of a catalytic convertor that has enough hydrogen available to reduce the NO to NH_3. The absence of either of these species precludes the formation of exhaust NH_3. Dynamometer studies have shown that the hydrogen stores can be increased when acceleration events are preceded by a deceleration event though not necessarily back to back.[26] Previous on-road ammonia emissions have been reported by Baum *et al.* for a Los Angeles site in 1999, by Burgard *et al.* in 2005 from gasoline-powered vehicles for this Denver site, our E-106 site in Tulsa and by Kean et al in 1999 and 2006 from the Caldecott tunnel near Oakland.[27-30] The University of Denver collected NH_3 measurements at three California, (San Jose, Fresno and West LA) sites in 2008 and from a Van Nuys, California site in 2010.[31, 32] In addition air borne measurements of ammonia were collected in 2010 over the South Coast Air Basin as part of the CalNex campaign.[11] Most recently we have reported on ammonia emissions collected in 2013 from West LA, Tulsa and this Denver site.[33]

With the collection of the 2020 data set there are now 5 Denver data sets (2005, 2013, 2015, 2017 and 2020) that can be used to look at the changes in NH_3 emissions. The 2005 data were collected in a non-CRC measurement campaign during the summer while the remaining data sets were collected during the winter. Figure 7 compares gNH_3/kg of fuel emissions collected at the Denver site for all five measurement campaigns by model year. The uncertainties plotted are standard errors of the mean determined using the daily means (see Appendix E). The 2005 data set has considerably more measurement uncertainty owing to its significantly smaller size (~3,700 total measurements). With each data set collected we find that the newest model year vehicles continue to have lower NH_3 emissions.

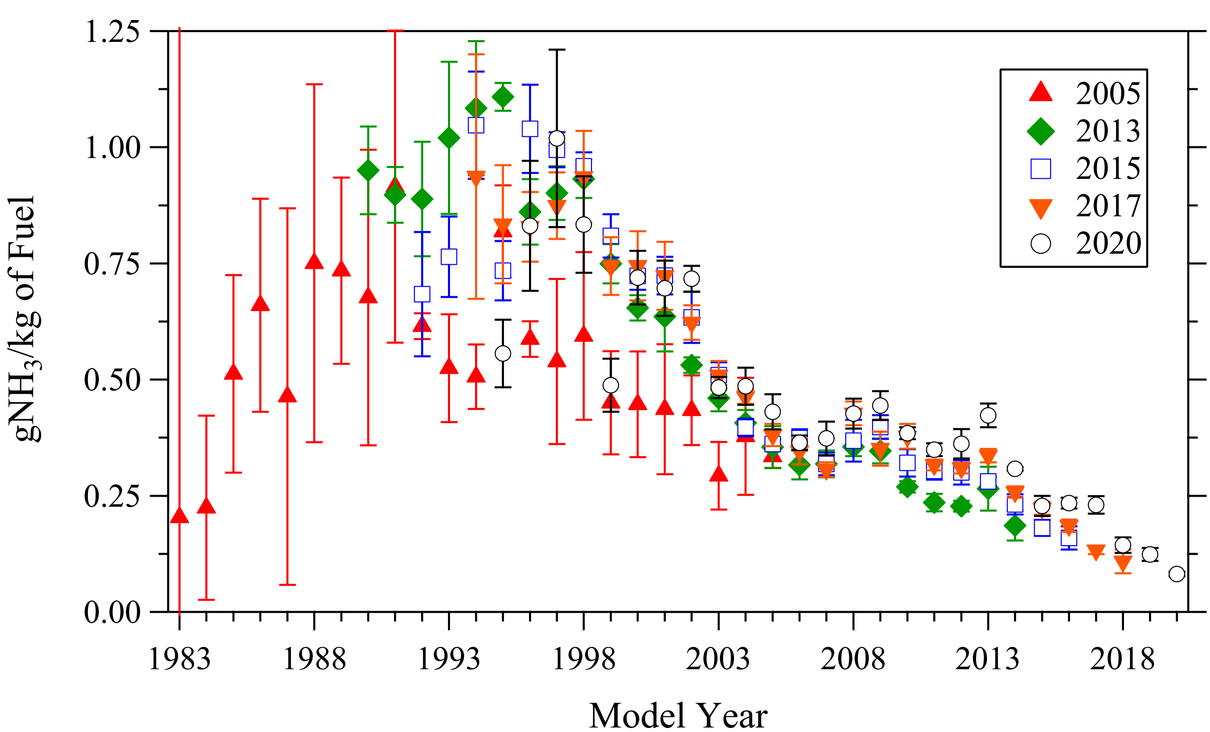

Figure 7. Mean gNH_3/kg of fuel emissions plotted against vehicle model year for the five measurement data sets collected at the Denver site with uncertainties plotted as standard errors of the mean determined using the daily means.

Because NH_3 emissions are sensitive to vehicle age it often helps to plot the data against vehicle age as opposed to model year. Figure 8 compares the four Denver data sets in this way where year 0 vehicles are 2020, 2018, 2016, 2014 and 2006 models for the 2020, 2017, 2015, 2013 and 2005 data sets, respectively. The uncertainties plotted are standard error of the mean calculated from distributing the daily means for each year's data (see Appendix E). Most noticeable in the 2005 data set is the characteristic shape with NH_3 emissions increasing with model year until the vehicles reach an age where the catalytic converters lose their ability to reduce NO emissions and then the emissions start decreasing to levels approaching zero.

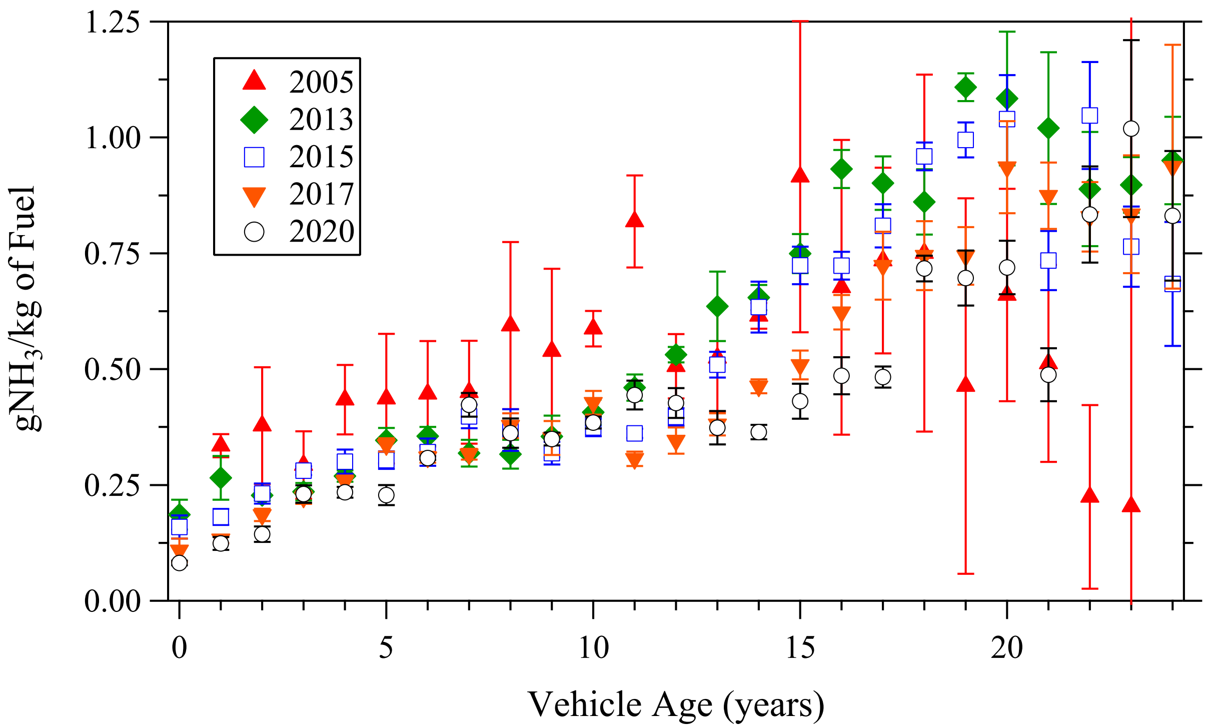

Figure 8. Mean gNH3/kg emissions plotted against vehicle age for the 2020, 2017, 2015, 2013 and 2005 measurements at the Denver site. The uncertainties plotted are the standard error of the mean determined using the daily means.

The differences between the 5 data sets are more obvious when NH_3 emissions are plotted as a function of vehicle age instead of model year as shown in Figure 8. For the same age vehicles, which are manufactured to significantly different standards, substantial emissions reductions relative to 2005 measurement campaign have occurred for the first 10 years. In addition there is a lower rate of increase in NH_3 emissions as a function of vehicle age, seen initially with the 2013 data set, which is still a feature of the 2020 data. While the rate of increase has slowed it appears that the average vehicle age at which NH_3 emissions peak and then begin to decrease keeps getting older as previously mentioned. The period of increasing NH_3 emissions has grown considerably since 2005, though it is debatable as to the exact point in the 2005 data that the emissions peak. The 2005 data increases for approximately 10 years (1996 model year was the introduction of Tier 1 vehicles) and certainly starts to decline before the 15 year old vehicles

(1991 models). The 2013 data set rises for approximately 17 years (1997 models) and then declines. This is consistent with several other data sets collected since 2008.[32] The 2015 data set appears to not peak until approximately 19 year old vehicles; though there is increased uncertainty about assigning the exact point because the small sample sizes of these older model years complicates that determination. As previously seen for the 2017 Denver data set the 2020 data also does not show any significant decline in emissions from a peak through the first 24 model years. Certainly declining fuel sulfur levels have improved the longevity of catalytic converters which is a factor in these NH_3 emission trends.

The total fixed nitrogen in g/kg of fuel for the Denver 2020 measurements is shown in Figure 9 (◆, right axis) with the molar percent composition distributed between NH_3 (●, left axis) and the NO_x (▲, left axis) component versus model year for non-diesel vehicles. The total fixed nitrogen calculation neglects any unmeasured nitrous oxide (N_2O) and nitrous acid (HONO) that may account for a few percent of the total. Total fixed nitrogen emissions have been on a steep decline since the mid-nineties in the gasoline fleet and are continuing to show decreases in the newest model years in this data as well. The percent of fixed nitrogen made up of NH_3 had been on the rise until the 2017 measurements but appears to have leveled out soon after the introduction of Tier 2 vehicles and starting around the 2016 model year vehicles it has now declined. The start of this decline in the percent of fixed nitrogen as NH_3 was also observed in the 2017 Tulsa, OK measurements but at that time there were not enough vehicle model years to establish the decline with any certainty. 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.

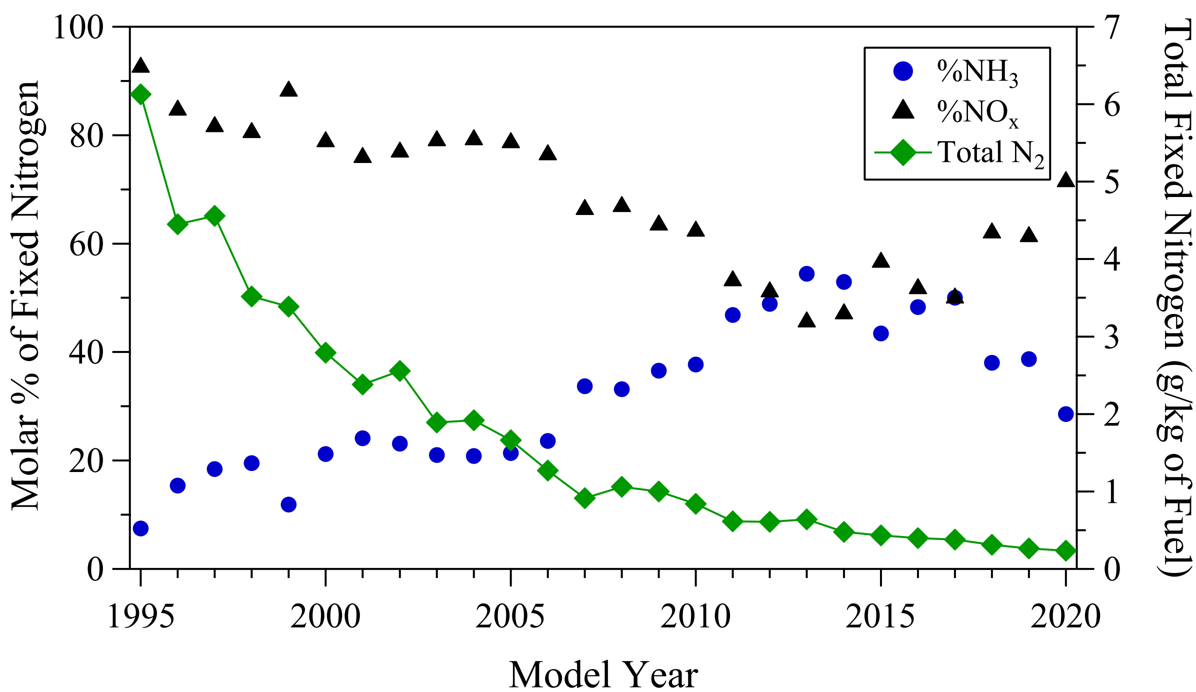

Figure 9. Total fixed nitrogen in g/kg of fuel (◆, right axis) with the molar percent composition distributed between the NH_3 (●, left axis) and NO_x (▲, left axis) component versus model year for the Denver 2020 non-diesel vehicles.

The history of NH_3 emission measurements at the Denver 6th Avenue site include measurements collected in a separate summer campaign of 2005 and winter CRC measurements in 2013, 2015, 2017 and 2020. Table 4 lists the fuel specific NH_3 emissions and the standard error of the mean uncertainties for these five campaigns. Overall, we have observed a 24% reduction in the mean emissions since 2005 and a 23% reduction since measurements resumed in 2013. This compares to a 32% reduction in NH_3 emissions observed in Tulsa, OK since 2005 and an identical 23% emissions reduction since 2013.[34]

Table 4. Mean Fuel Specific Ammonia Emissions with Standard Error of the Mean Uncertainties for the Five Denver Measurement Campaigns.

Measurement Year	Mean gNH_3/kg of Fuel
2005	0.45 ± 0.09
2013	0.44 ± 0.02
2015	0.42 ± 0.01
2017	0.37 ± 0.008
2020	0.34 ± 0.009

Over this same time period fleet NO emissions in Denver have decreased by 62% (3.7 gNO/kg in the summer of 2005 to 1.4 gNO/kg in 2020). Further research is necessary to understand why NO emissions have decreased dramatically more during this fourteen year period than NH_3 since they have a common origination point in engine out NO emissions. However, we have observed these same differences in emission reductions rates in Tulsa, OK where we have measurements collected over a similar time frame. Fuel changes might be a contributing factor, as fuel sulfur levels have decreased significantly during this period, but laboratory research on the fuel effects of NH_3 emissions is contradictory, due in part to the small number of vehicles tested.[25, 35] Driving mode and catalyst age are two additional factors discussed in the literature that impact NH_3 emissions and might be involved.[26, 35] Also as previously mentioned NH_3 emissions are not regulated while NO emissions are and one can speculate that engine operating conditions that minimize tailpipe NO emissions will be emphasized by the manufacturer.

An equation for determining the instantaneous power of an on-road vehicle by Jimenez takes the form

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

where VSP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees), v is vehicle speed in mph, and a is vehicle acceleration in mph/s.[36] Derived from dynamometer studies, and 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. Using equation 4, VSP was calculated for all measurements in each of the five years' databases. This equation, in common with all dynamometer studies, does not include any load effects arising from road curvature. The emissions data were binned according to vehicle specific power, and graphed in Figure 10. Each of the specific power bins contains at least 97 measurements, except for the 25 VSP bin in 2005 which only contains 57 measurements, and the HC data have been offset adjusted for this comparison. The uncertainty bars included in the plot are standard error of the mean calculated using the daily means (see Appendix E). The solid line in the bottom graph is the frequency count distribution of vehicles in the 2020 dataset sorted by specific power bin.

Within each vehicle specific power bin there have been significant year over year reductions in mean fuel specific emissions of all the species between the 1999 and 2020 datasets. The redesigned ramp effects can also be seen in the increase in the range of positive and negative VSP values observed. The increases are the result of the increased speeds and the potential for significant decelerations they afford when congestion on the road occurs ahead. In addition to the emissions reductions all of the species show a decreasing dependency on VSP where the emissions trend has slowly flattened out since the early campaigns. HC emissions still show increasing emissions with decelerations though in the Denver data that dependence seems to flatten out at the largest VSP bins. Keep in mind that the lack of an influence of VSP for CO and NO are for fuel specific emissions and likely is not the case for distance specific emissions as the fuel economy changes by at least a factor of 3 or more across the range of VSP's plotted.

Light and medium-duty diesel vehicles generally only represent a few percent of the overall fleet and are overwhelmingly trucks. However, they are still an important source of NO_x emissions. In the 2020 Denver fleet light and medium-duty diesel vehicles accounted for 3% of the measurements (95% were classified as trucks) and 19% of the NO_x emissions. Table 5 shows how the 2020 truck measurements are distributed by weight class and fuel type. The overwhelming majority of diesel vehicles are pickup trucks (weight class 2) and larger while the non-diesel vehicles are dominated by the more car like sport utility vehicles (weight class 1) that have become so popular in the last decade.

Table 5. 2020 Denver Truck Measurements and Fleet Percentages by Weight Class and Fuel Type

Weight Class	Non-Diesel Trucks	Fleet Percent	Diesel Trucks	Fleet Percent
1	8000	40.2%	5	0.03%
2	5567	28.0%	319	1.6%
3	95	0.5%	138	0.7%
4	40	0.2	17	0.1%
5	8	0.04%	39	0.2%
6	2	0.01%	44	0.2%
7	0		1	0.01%
8	0		20	0.1%

To compare the historical NO and NO_x emission trends of the truck fleet we are going to compare the diesel and non-diesel trucks whose VIN decoded weight classifications were larger than class 1. Table 6 compiles the statistics for all of the Denver measurements for NO and NO_x emissions collected since 2003 except for the 2007 measurement campaign. It has been excluded

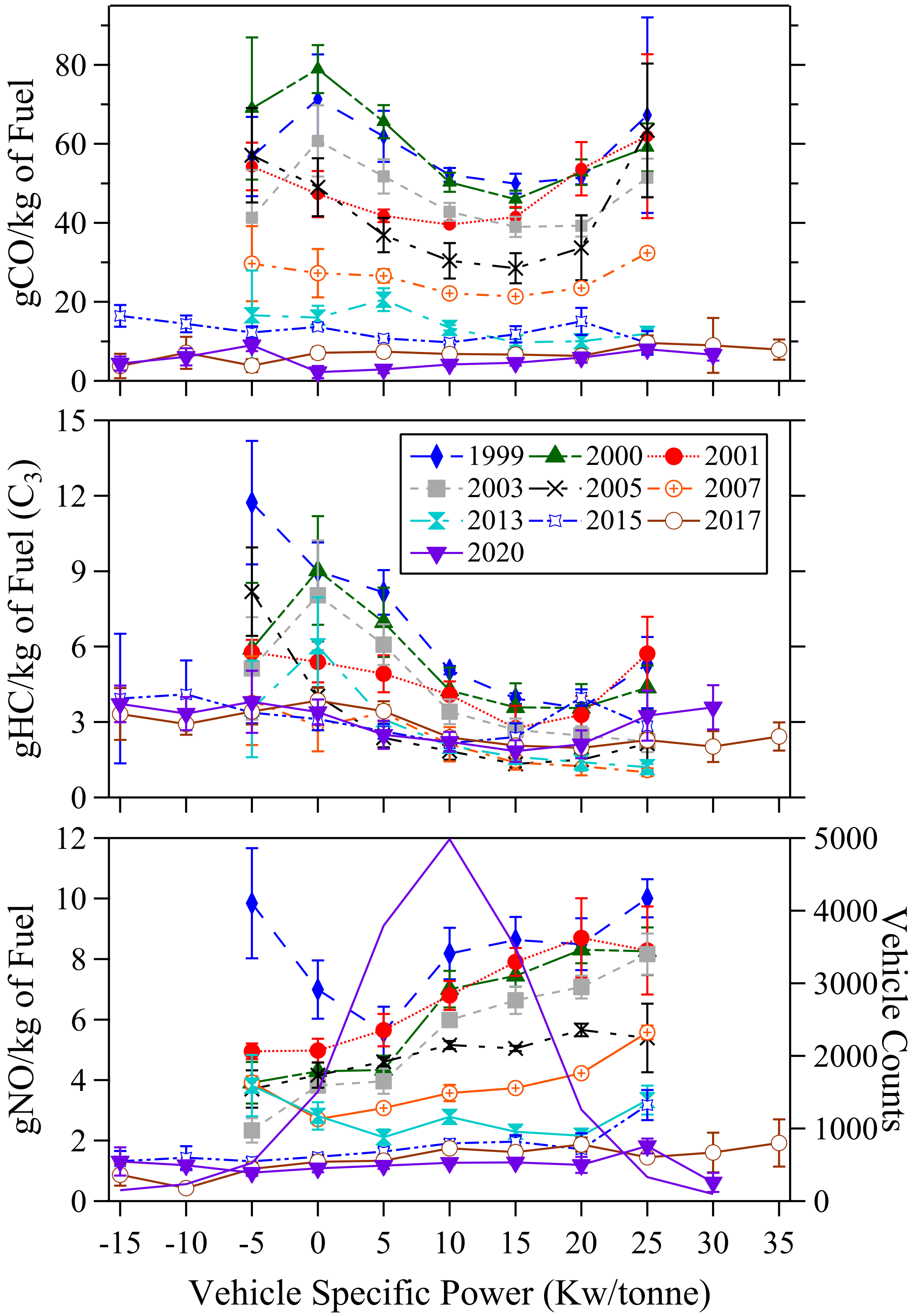

Figure 10. Vehicle emissions as a function of vehicle specific power for all of the Denver data sets. Uncertainties plotted are standard errors of the mean calculated using the daily samples. The solid line without markers in the bottom graph is the vehicle count profile for the 2020 data.

Table 6. Denver Non-Diesel and Diesel Truck (wt. class > 1) Fuel Specific NO and NO_x emissions with Standard Error of the Mean Uncertainties, Mean Model Year and Fleet Percent.

Year	Non-Diesel Trucks				Diesel Trucks			
	gNO/kg of Fuel[a]	gNO_x/kg of Fuel[b]	Mean Model Year	Fleet Percent	gNO/kg of Fuel[a]	gNO_x/kg of Fuel[b]	Mean Model Year	Fleet Percent
2003	6.5 ± 0.2		1997.8	18.4%	23.1 ± 0.5		1998.6	2.3%
2005	5.3 ± 0.3		1999.4	18.2%	21.9 ± 0.8		2000.6	2.5%
2013	2.4 ± 0.2	3.8 ± 0.3	2006.0	20.8%	17.3 ± 0.2	29.1 ± 0.7	2005.7	2.7%
2015	1.5 ± 0.1	2.3 ± 0.1	2007.8	25.1%	14.9 ± 0.4	24.7 ± 0.8	2007.7	3.0%
2017	1.5 ± 0.1	2.3 ± 0.1	2009.6	28.9%	12.1 ± 0.6	20.0 ± 1.0	2009.7	3.3%
2020	1.2 ± 0.1	1.9 ± 0.2	2012.0	28.7%	8.3 ± 0.5	13.9 ± 0.9	2012.5	2.9%

[a]grams of NO
[b]grams of NO_2

from this analysis because it was not VIN decoded which is necessary for determining the vehicle class (car or truck) and weight category. Also we have included NO in this comparison because NO_2 measurements, necessary for reporting NO_x emissions, were not collected in Denver until the 2013 measurements. Fuel specific NO emissions are in grams of NO and fuel specific NO_x emissions are in grams of NO_2 and the uncertainties are the standard error of the mean determined from the daily measurements. Since 2003 the non-diesel truck fleet has seen an 82% reduction in fuel specific NO emissions and the diesel truck fleet a 64% reduction. A larger reduction in NO emissions occurred within the non-diesel truck fleet (63% reduction) than is seen from in the diesel truck fleet (25%) between 2005 and 2013. This coincided with the introduction of Tier 2 vehicles in 2009. Since 2013, on a percentage basis, NO and NO_x emission reductions have been similar in both fleets with reductions around 50%, however, the diesel truck fleet has yet to catch up to the emission levels observed in the non-diesel trucks.

Figure 11 compares the fuel specific NO_x emissions by model year for the 2020 Denver non-diesel and diesel trucks in weight classes 2 and higher. The uncertainties plotted are standard error of the mean determined from the daily measurements for each model year. The larger uncertainties in the diesel fleet emissions are a direct result of the smaller number of measurements. The non-diesel fleet has significantly lower NO_x emissions prior to the 2014 model year which is reflected in larger emission reductions prior to 2013 shown in Table 6. Light-duty Tier 2 vehicles were phased in beginning with the 2004 model year vehicles and were required to be fully phased in by the 2009 model year. Medium-duty diesel vehicle emission certifications are not as simple since their emission standards are regulated according to engine manufacture year and their introduction was subject to a banking and credit trading system.[37, 38] The current NO_x emission standards for medium and heavy-duty diesel engines applies to engines manufactured in 2010 and following. A general rule of thumb is that chassis model year is one year older than the vehicle's engine, so 2010 certified engines are most often found in 2011 model year vehicles. However, the introduction of the lowest emitting NO_x engines into the fleet was not absolute as the credit system and the Navistar lawsuit spread out the adoption of those engines into the fleet to between 2011 and 2017 when all the credits expired. This

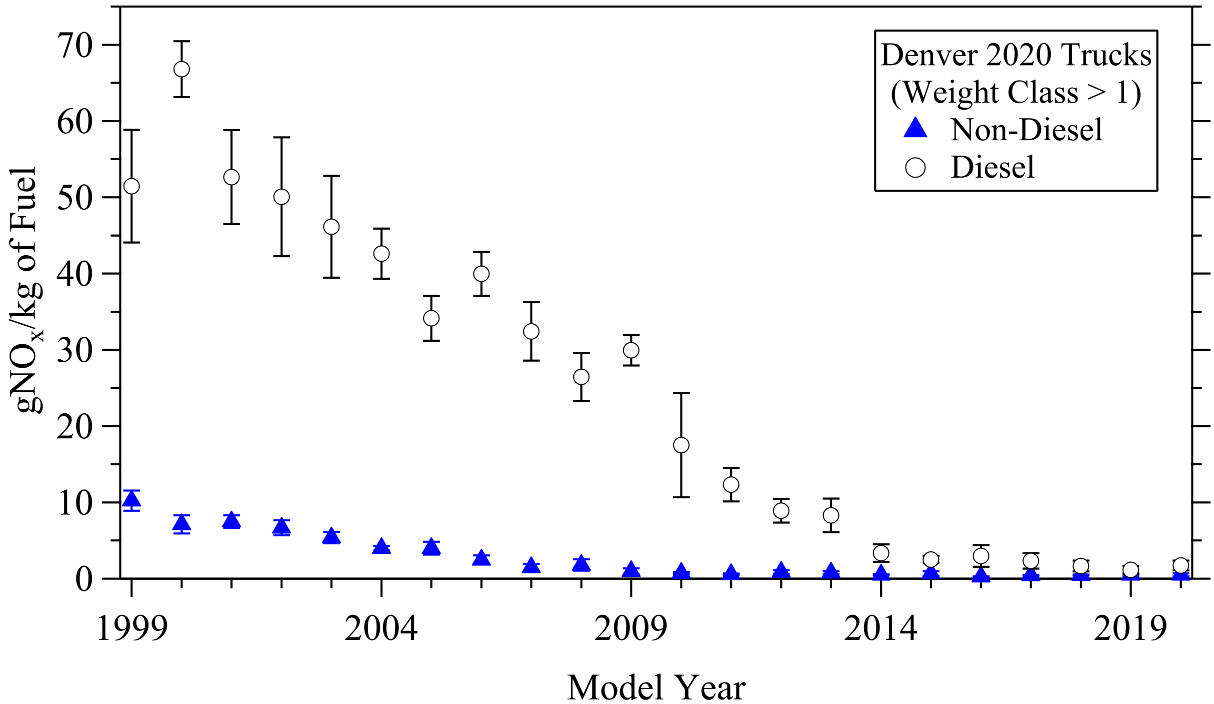

Figure 11. Fuel specific NO_x emissions by model year for the Denver 2020 non-diesel and diesel trucks in weight classes larger than 1. Uncertainties are standard error of the mean calculated using the daily means for each model year.

undoubtedly contributes to the large lag in NO_x emission reductions observed for the diesel trucks shown in Figure 11. The newest model year diesel trucks (2017 & newer) have NO_x emissions that are still approximately a factor of 2 to 3 times higher than the non-diesel trucks.

Figure 12 shows fuel specific NO_x emissions versus model year for the Denver diesel truck fleet (weight classes 2- 8) over the last three measurement campaigns. The uncertainties are standard error of the mean calculated using the daily means for each model year. The NO_x emission trend observed in the 2020 Denver fleet in Figure 11 shows little emissions deterioration within the uncertainties when compared to the 2015 measurements. All three measurement years tell a consistent story of large reductions in NO_x emissions in the light and medium-duty diesel truck fleet.

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.[39] Such plots were constructed for all of the measured species (not shown). 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 11.8, 2.9, 0.2, 0.04 and 0.2 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 16.7 gCO/kg of fuel (0.1%), 4.1 gHC/kg of fuel (94 ppm), 0.28 gNO/kg of fuel (23 ppm), 0.06 gNH_3/kg of fuel (8 ppm) and 0.3 gNO_2/kg of fuel (14 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,

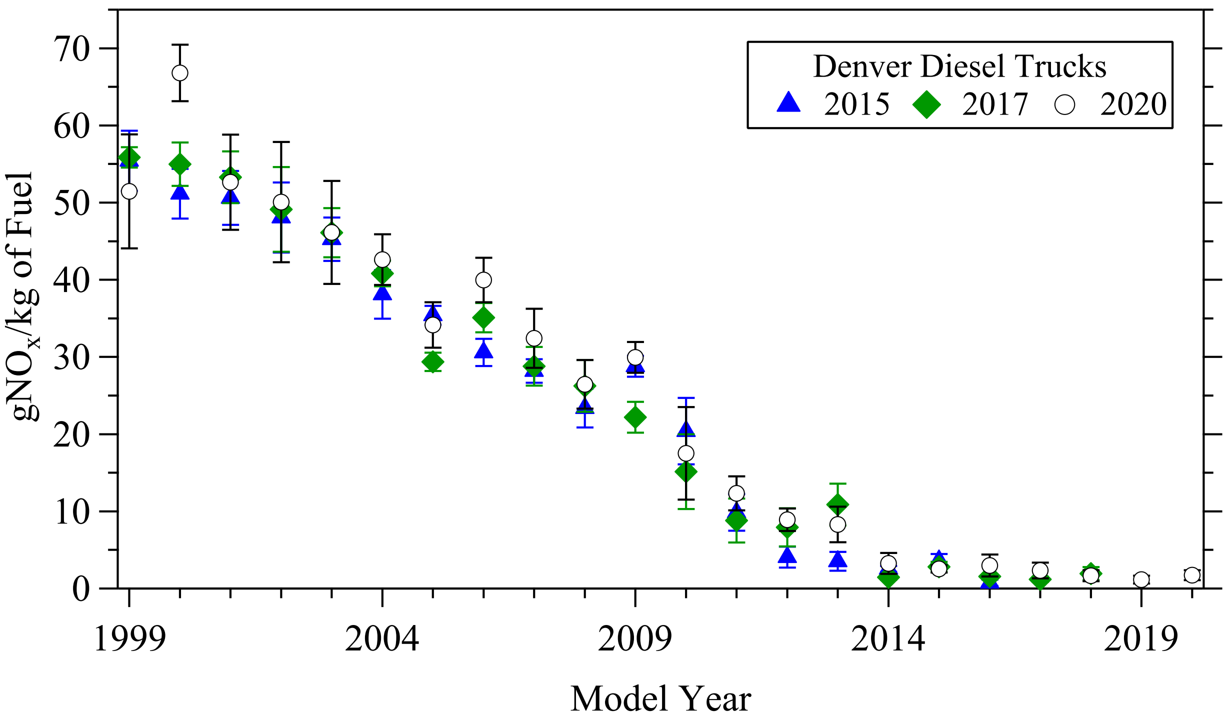

Figure 12. Fuel specific NO_x emissions by model year for the Denver 2015, 2017 and 2020 diesel trucks in weight classes larger than 1. Uncertainties are standard error of the mean calculated using the daily means for each model year.

with an average of 100 measurements, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages of a hundred measurements reduce to 1.7 gCO/kg of fuel, 0.4 gHC/kg of fuel, 0.03 gNO/kg of fuel, 0.006 gNH_3/kg of fuel and 0.03 gNO_2/kg of fuel, respectively.

CONCLUSIONS

The University of Denver carried out four days of remote sensing in the Denver, Colorado area in January and February of 2020. Measurements were made on four weekdays, Thursday January 16, Wednesday January 22, Friday January 24, and Friday February 21, 2020 on the interchange ramp from northbound I-25 to westbound US6. This is the same location previously used for measurements in the winter of 1999-2001, 2003, 2005, 2007, 2013, 2015, 2017 and 2020. A database was compiled containing 19,909 records for which the State of Colorado 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 2020 mean CO, HC, NO, NH_3 and NO_2 emissions for the fleet measured in this study were 4.7 ± 0.5 g/kg of fuel (0.04%), 2.2 ± 0.4 g/kg of fuel (55 ppm), 1.36 ± 0.07 g/kg of fuel (96 ppm), 0.34 ± 0.01 g/kg of fuel (43 ppm) and 0.1 ± 0.01 g/kg of fuel (4 ppm) respectively. The 2020 Denver measurements show reductions for all of the species measured when compared with the 2017 values. Fuel specific emission factors (g/kg of fuel) decreased for CO (41%), HC

(16%), NO (23%), NH_3 (8%), NO_2 (12%) and NO_x (22%). Only the differences for CO, NO and NO_x are statistically significant at the 95% confidence interval.

For the first time since before 2013 the average age of the Denver fleet at this location show a reduction of 0.4 model years to 8.8 years old (2011.6 average model year). This is still significantly older (~1.5 years) than observed prior to the 2008-2009 recession but undoubtedly a reflection of the Colorado economy. Fleet mean emissions remain dominated by a few high emitting vehicles. For the 2020 data set the highest emitting 1% of the measurements (99^{th} percentile) are responsible for 57%, 26%, 30%, 17 % and 41% of the overall fleet CO, HC, NO, NH_3 and NO_2 emissions, respectively.

The history of NH_3 emission measurements at the Denver 6th Avenue site include measurements collected in a separate summer campaign of 2005 and winter CRC measurements in 2013, 2015, 2017 and 2020. Overall, we have observed a 24% reduction in the mean emissions since 2005 (0.45 ± 0.09 to 0.34 ± 0.01) or a 23% reduction since measurements resumed in 2013. The peak NH_3 emissions continue to extend into older models with the 2020 measurements following the 2017 observations that push the peak NH_3 emissions to beyond 20 year old vehicles. However, the increased uncertainty, due to fewer measurements in the older model year vehicles, makes an exact assignment difficult but illustrates the fact that catalytic converters in modern gasoline vehicles continue to show outstanding durability.

The NH_3 fleet reduction rates continues to be less than half (24%) of that observed for tailpipe NO emissions which at the Denver site have decreased 62% (3.7 gNO/kg in the summer of 2005 to 1.4 gNO/kg) over the same time period. Total fixed nitrogen emissions have been on a steep decline since the mid-nineties in the gasoline 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 until the 2017 measurements, but appears to have leveled out soon after the introduction of Tier 2 vehicles and starting around the 2016 models is now declining. 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.

NO emission reductions have been found to have occurred faster on a percentage basis in the non-diesel Denver truck fleet than in the diesel portion of the fleet. NO and NO_x emission reductions in the diesel truck fleet lag significantly behind the non-diesel fleet and despite the large magnitude reductions in diesel NO_x emissions the most recent model year diesel vehicles still have mean NO_x emissions that are factors of 2 to 3 times higher than the same model year non-diesel trucks.

ACKNOWLEDGEMENTS

The successful outcome of this project would not be possible without the assistance of Rob Dawson of the Colorado Department of Public Health and Environment and Mrs. Annette Bishop for plate transcription. Comments from the various reviewers of this report were also invaluable and appreciated.

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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 exhaust. The restart number appears in the database.
2) Vehicle which drives completely through during the 0.4 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 heavy-duty diesel trucks, bicycles.
2) Too much 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) Too much 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) Too much 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 $\pm$50ppm.
9) Reported NH_3 < -80ppm or > 7000ppm. NH3 "invalid".
10) Excessive error on NO_2/CO_2 slope, equivalent to $\pm$20% for NO_2 > 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 Denver_20.dbf database.

The Denver_20.dbf is a Microsoft FoxPro database file, and can be opened by any version of MS FoxPro. The file can be read by a number of other database management programs as well, and is available on our website at www.feat.biochem.du.edu. The following is an explanation of the data fields found in this database:

License	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.
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”.
NO_flag	Indicates a valid nitric oxide 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”.
CO2_max	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.
Year	Model year.

Make Manufacturer of the vehicle.

Model Oklahoma model designation.

Body Oklahoma designated body style

Fuel Fuel type: ‘G’ gasoline, ‘D’ diesel, ‘Z’ hybrid.

County County name of registrant.

Legal_Zip Registrant’s zip code.

County_num Colorado county number where vehicle is registered.

Exp_date Date that current vehicle registration expires.

Im_status I/M status: E – exempt, P, C

Im_test Previous I/M test date.

IM_next Due date for next I/M inspection.

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 Percent hydrocarbon concentration 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 calculated using the equation provided in the report. Kw/metric tonne

V_class Vin decoded vehicle type classification.

V_cylinder Vin decoded number of engine cylinders

V_disp Vin decoded engine displacement in liters

V_engine Vin decoded engine type/model information

V_wtclass Vin decoded weight class designation

V_model Vin decoded model information

V_year Vin decoded model year.

V_fuel Vin decoded fuel (G, D, F (flex), N)

V_type Vin decoded Passenger (P) or Truck (T) type

V_make Vin decoded make.

Wt_class Numeric weight class extracted from V_wtclass

APPENDIX C: Temperature and Humidity Data

Denver 1999 Temperature Data							
1/14 Time	1/14 °F	1/15 Time	1/15 °F	1/18 Time	1/18 °F	2/1 Time	2/1 °F
14:16	57	9:25	47	8:30	40	8:00	26
15:50	56	9:45	48	9:30	45	8:33	30
		10:24	58	10:20	50	9:11	33
		11:08	58	10:50	55	9:29	33
		11:25	58	11:30	50	10:00	40
				12:00	46	10;25	46
						11:07	54
						11:56	55

Denver 1999/2000 Temperature and Humidity Data											
12/30 Time	12/30 °F	12/30 %RH	1/11 Time	1/11 °F	1/11 %RH	1/13 Time	1/13 °F	1/13 %RH	1/14 Time	1/14 °F	1/14 %RH
11:23	48	38	9:33	54	38	8:43	35	61	7:53	32	69
12:03	51	32	10:3	54	32	9:43	35	61	8:42	35	65
13:06	54	29	11:5	55	28	10:4	35	62	9:53	43	50
14:02	55	28	12:3	52	30	11:0	36	61	11:1	51	36
15:14	64	26	13:3	49	37	12:0	39	59			
16:00	57	26	14:3	50	39	13:0	41	56			
16:54	52	27	15:5	49	41	14:1	42	52			
			16:0	48	41	15:0	45	48			

Denver 2001 Temperature and Humidity Data								
1/5 Time	1/5 °F	1/5 %RH	1/6 Time	1/6 °F	1/6 %RH	1/8 Time	1/8 °F	1/8 %RH
7:42	33	60	7:12	41	44	7:50	27	38
8:57	37	59	8:13	42	46	10:18	43	28
9:45	43	51	10:12	50	38	11:19	46	24
11:49	59	28	11:30	51	38	12:27	51	21
13:05	64	24	12:30	52	37	13:27	53	<20
14:10	66	20	13:33	61	21	14:27	54	<20
			14:43	61	<20	15:27	53	<20
			15:47	61	25			

Denver 2002/2003 Temperature and Humidity Data											
12/31 Time	12/31 °F	12/31 %RH	1/7 Time	1/7 °F	1/7 %RH	1/8 Time	1/8 °F	1/8 %RH	1/31 Time	1/31 °F	1/31 %RH
9:45	34	31	9:05	43	38	9:27	48	32			
10:45	39	30	10:09	48	36	10:40	57	26	10:15	55	37
11:19	43	29	11:09	54	30	11:16	61	25	11:15	64	31
11:38	41	29	12:12	59	25	12:16	68	17	12:03	63	26
12:38	50	26	12:39	61	21	13:17	70	14	12:15	64	24
13:16	50	26	13:09	64	18	14:19	73	11	13:15	64	24
14:16	52	26	14:09	66	15	15:25	68	15			
15:16	52	26	15:09	68	15	15:50	66	15			
16:00	48	27	16:02	66	15						

Denver 2005 Temperature and Humidity Data								
1/8 Time	1/8 °F	1/8 %RH	1/10 Time	1/10 °F	1/10 %RH	1/11 Time	1/11 °F	1/11 %RH
12:06	52	34	8:44	41	51	8:00	37	77
13:22	54	33	9:11	36	65	9:01	39	77
14:06	55	33	10:11	37	64	10:03	37	76
15:06	54	34	11:11	45	57	11:01	41	70
16:06	50	36	12:11	45	53	12:25	46	56
			13:11	45	57	13:19	54	56
			14:16	48	50	14:19	39	72
			15:11	46	54	15:19	39	71
			16:12	45	57	16:19	39	74
			16:46	45	60	16:45	37	75

Denver 2007 Temperature and Humidity Data								
1/10 Time	1/10 °F	1/10 %RH	1/25 Time	1/25 °F	1/25 %RH	2/27 Time	2/27 °F	2/27 %RH
8:56	45	26	8:46	36	48	7:56	34	52
9:45	48	23	9:45	39	45	8:55	39	43
10:46	52	26	10:45	41	49	10:55	45	35
11:45	54	24	11:45	45	42	11:45	46	37
12:58	55	23	12:48	46	44	12:48	46	34
13:46	61	19	13:46	46	37	13:55	50	32
14:45	63	12	14:52	50	32	14:45	46	50
15:45	63	11	15:45	50	32	15:45	46	50
16:46	59	10	16:45	46	37	16:45	45	51

Denver 2013 / 2014 Temperature and Humidity Data								
12/12 Time	12/12 °F	12/12 %RH	12/13 Time	12/13 °F	12/13 %RH	1/3 Time	1/3 °F	1/3 %RH
8:55	30	43	8:47	41	30	8:53	54	20
9:47	39	36	9:47	45	26	9:47	55	21
10:47	45	31	10:45	46	23	10:55	57	18
11:47	46	30	11:47	48	21	11:55	59	16
12:50	52	20	12:45	50	19	12:47	59	17
13:47	54	17	13:50	46	30	13:50	59	16
14:47	50	28	14:45	45	31			
15:47	46	33	15:45	43	34	15:50	59	16
16:47	45	34	16:50	37	46	16:50	55	18

Denver 2015/2016 Temperature and Humidity Data												
Time	12/9		12/10		1/13		1/27		1/28		1/29	
	°F	%RH	°F	%RH	°F	%RH	°F	%RH	°F	%RH	°F	%RH
8:53	53	26	50	24	35	48	38	46	37	50	45	37
9:53	57	22	54	19	42	41	43	40	44	41	47	31
10:53	58	22	54	22	44	41	50	32	47	37	49	28
11:53	58	23	57	21	49	31	48	34	51	29	51	24
12:53	59	19	59	20	50	29	49	33	54	24	52	22
13:53	63	17	61	15	48	34	49	35	56	22	54	18
14:53	61	19	65	15	51	28	50	36	56	24	55	16
15:53	58	23	60	19	47	36	49	35	55	28	54	17
16:53	57	23	56	22	43	45	44	45	53	28	48	27

Denver 2017/2018 Temperature and Humidity Data										
Time	12/15		12/19		12/20		1/9		1/18	
	°F	%RH	°F	%RH	°F	%RH	°F	%RH	°F	%RH
8:53	42	27	38	48	48	23	48	46	37	33
9:53	47	24	46	32	55	19	54	40	52	13
10:53	51	21	48	33	59	16	57	36	55	12
11:53	55	16	50	29	61	14	60	41	59	9
12:53	58	14	49	32	63	13	64	26	61	10
13:53	60	13	50	30	63	13	65	26	63	10
14:53	60	14	50	29	64	12	65	26	64	9
15:53	57	21	51	29	60	16	63	28	63	10
16:53	51	21	41	41	55	18	56	34	59	11

Denver 2020 Temperature and Humidity Data								
Time	1/16		1/22		1/24		2/21	
	°F	%RH	°F	%RH	°F	%RH	°F	%RH
8:53	30	41	44	35	42	35	32	33
9:53	33	36	46	31	46	30	38	31
10:53	36	34	47	29	49	26	43	25
11:53	41	28	49	26	51	24	47	24
12:53	42	27	51	23	53	22	51	11
13:53	38	36	52	23	53	21	50	18
14:53	42	28	50	26	56	19	47	25
15:53	37	37	47	23	53	21	50	22
16:53	35	42	47	24	48	27	48	27

APPENDIX D: Methodology to Normalize Mean gHC/kg of fuel Emissions

The hydrocarbon channel on FEAT has the lowest signal to noise ratio of all the measurement channels in large part because the absorption signals are the smallest (millivolt levels). FEAT 3002 uses one detector for the target gas absorption and a second detector for the background IR intensity (reference). These channels are ratioed to each other to correct for changes in background IR intensities that are not the result of gas absorption. The detector responses are not perfectly twinned and for the low signal HC channel this lack of perfect intensity correction can result in small systematic artifacts, which can be a positive or negative offset of the emissions distribution, being introduced into the measurement. In addition the region of the infrared spectrum that is used for HC absorption measurements is overlapped by an absorption band for liquid water. Normally this is not an issue as fully warmed up vehicles emit little if any liquid water at the tailpipe. However, there are times when low temperatures and high dew points cause water vapor to condense at the tailpipe and create an additional absorption artifact in the measurements that are not related to HC emissions. In these cases the normalization value calculated will be larger because it includes an additional adjustment for the liquid water emissions.

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 and that their emissions distribution should have a median value very near zero, using the lowest of either of these values as the offset. The offset value is then added (for negative offsets) or subtracted from all of the hydrocarbon measurements adjusting the zero point of the emissions distribution. Since it is assumed that the newest vehicles are the lowest emitting this approximation will slightly over correct because the true offset will be a value somewhat less than the average of the cleanest model year and make.

As an example of the process the calculation is demonstrated using data collected in Chicago in 2014 and shown in Table D1. The Chicago 2014 measurement included a correction for both of the previously discussed issues as the first three days of measurements were with normal temperatures and low humidity while the last three days experienced the exact opposite. FEAT ratios are first reported as percent emissions and the normalization calculations are performed using these percent values. Below are the data tables used for estimating the HC normalization value for the 2014 Chicago measurements.

For the Monday through Wednesday time slot Honda's vehicles had the lowest average HC emissions with a mean %HC of 0.0013. In Table S2 the mode calculation has two values that are very close to each other 0.001 and 0.0015. It was decided to average those two values and the HC normalization value for the first time period used was 0.00125% which is approximately 0.5 gHC/kg of fuel.

For the Thursday through Saturday time period Honda vehicles again had the lowest HC emission. The average of 2009 – 2014 Honda vehicles is 0.003% which is the same as the mode shown in Table S2. This is approximately 1.25 gHC/kg of fuel.

2014 Chicago Mode Calculations
For model year 2009 and newer vehicles

Table D1. HC Normalization Mode Calculation.

Monday – Wednesday		Thursday - Saturday	
%HC	Counts	%HC	Counts
-0.0015	129	-0.0015	73
-0.001	147	-0.001	59
-0.0005	138	-0.0005	75
0	125	0	67
0.0005	126	0.0005	79
0.001	152	0.001	69
0.0015	155	0.0015	75
0.002	143	0.002	85
0.0025	104	0.0025	51
0.003	131	0.003	94
0.0035	129	0.0035	68
0.004	120	0.004	77
0.0045	115	0.0045	80
0.005	124	0.005	88

This method will successfully normalize the fleet HC means but may over or under correct smaller sub-fleets.

APPENDIX E: How standard errors of the mean for our reported uncertainties are estimated

Vehicle emissions from US vehicle fleets are not normally distributed, thus the assigning of uncertainties on fleet emission means involves a process that many readers may not be familiar with. Standard statistical methods that were developed for normally distributed populations, when used on a skewed distribution, result in uncertainties that are unrealistically too small due to the large number of samples. The Central Limit Theorem in general indicates that the means of multiple samples, randomly collected, from a larger parent population will be normally distributed, irrespective of the parent populations underlying distribution. Since multiple days of emission measurements are almost always collected at each site, these daily measurements are used as our randomly collected multiple samples from the larger population and the reported uncertainties are based on their distribution. Next the means, standard deviations and standard errors of the mean for this group of daily measurements is calculated. Next an error percentage is calculated from the ratio of the standard error of the mean for the daily measurements divided by the daily measurement mean. The fleet weighted means for all of the emission measurements are reported and the standard error of the fleet mean is calculated by multiplying the error percentage obtained previously against the fleet mean. An example of this process is provided below for the 2017 Denver gCO/kg of fuel and gNO/kg of fuel measurements. While this example is for a fleet mean this technique is also used when reporting uncertainties for other statistics such as individual model years, specific fuel or technology types, and VSP. For example each model year will have its daily means averaged and then its standard error of the mean for the daily average computed and that percent uncertainty (Daily STD Error MY/Daily MY average) will be applied to that entire model year's mean emissions.

Denver 2017

Date	Mean gCO/kg of fuel	Counts	Mean gNO/kg of fuel	Counts
12/15/17	8.72	4300	1.80	4299
12/19/17	7.48	5430	1.92	5429
12/20/17	8.37	5027	1.77	5027
1/9/17	7.48	4910	1.60	4908
1/18/17	8.17	2599	1.75	2598
Average for Daily Mean	8.04		1.77	
Standard Error for the daily means	0.25		0.05	
Weighted Fleet Mean	8.00		1.77	
Standard Error calculated for the fleet means	0.24		0.05	
As reported	8.0 ± 0.2		1.77 ± 0.05	

APPENDIX F: Field Calibration Record.

1999				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
1/15	8:30	1.54	1.73	1.53
1/15	10:15	1.31	1.50	1.35
1/15	12:30	0.96	1.1	0.78
1/16	8:00	1.27	1.3	0.72
1/18	7:15	1.56	1.6	1.9
2/1	7:45	1.76	2.0	1.66
2/1	12:15	1.20	1.32	1.25

1999 / 2000				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
12/30	11:20	1.27	1.2	1.67
1/11	9:30	1.14	1.12	1.25
1/13	8:30	1.76	1.74	1.64
1/13	10:55	1.23	1.09	1.34
1/14	7:50	2.45	2.5	3.1
1/14	10:00	1.40	1.40	1.61

2001				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
1/5	7:30	1.96	2.2	3.1
1/5	11:45	1.13	1.05	1.32
1/6	7:00	1.57	1.42	1.84
1/6	11:30	1.41	1.35	1.66
1/8	7:05	1.67	1.6	2.32
1/8	11:30	1.18	1.1	1.6

2002 / 2003				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
12/31	11:14	1.33	1.44	2.22
12/31	13:09	1.258	1.204	1.733
1/7	10:00	1.342	1.204	1.443
1/7	12:35	0.974	0.939	1.084
1/7	15:12	1.157	1.158	1.277
1/8	9:15	1.237	1.191	1.834
1/8	11:10	0.97	1.096	1.493
1/31	10:00	1.124	1.084	1.567
1/31	12:00	0.912	0.932	1.257

2005				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
1/8	8:30	2.6	1.8	4.45
1/8	11:30	1.14	0.96	1.56
1/10	8:30	2.03	1.17	1.43
1/10	12:30	1.44	1.17	1.43
1/11	7:50	1.72	1.45	3.13
1/11	11:10	1.47	1.27	2.65

2007				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
1/10	9:00	1.67	1.51	2.27
1/10	10:10	1.49	1.69	1.76
1/10	12:40	1.16	1.10	1.26
1/25	8:25	2.14	1.87	2.27
1/25	9:20	1.45	1.26	1.35
1/25	12:15	1.35	1.25	1.34
2/27	8:30	1.55	1.47	1.69
2/27	9:35	1.37	1.34	1.35
2/27	11:25	1.19	1.18	1.19

2013 / 2014 Denver						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
12/12	9:15	1.83	1.85	2.12	1.14	1.06
12/12	11:00	1.49	1.55	1.76	1.11	0.83
12/12	13:00	1.41	1.47	1.68	1.14	0.66
12/13	8:45	2.67	2.78	3.06	1.56	1.37
12/13	9:45	2.07	2.16	2.28	1.19	0.93
12/13	11:00	1.71	1.81	1.88	1.19	0.97
12/13	13:00	1.38	1.47	1.57	1.21	0.90
1/3	8:45	1.73	1.83	1.87	1.35	1.06
1/3	10:10	1.18	1.23	1.30	1.35	0.69

2015 / 2016 Denver						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
12/9	11:00	1.32	1.54	1.46	1.10	1.25
12/9	13:10	1.27	1.47	1.49	1.12	1.19
12/10	9:50	1.28	1.44	1.08	1.03	1.28
12/10	12:20	1.14	1.29	1	1.06	1.02
1/13	10:15	1.43	1.63	1.70	1.08	1.67
1/13	12:30	1.27	1.47	1.56	1.13	1.25
1/27	9:40	1.72	1.85	1.93	1.06	2.33
1/27	11:45	1.43	1.57	1.60	1.09	1.33
1/27	13:45	1.29	1.45	1.44	1.09	1.27
1/28	9:30	1.72	1.96	1.81	1.07	1.99
1/28	11:50	1.39	1.52	1.56	1.06	1.33
1/28	13:45	1.24	1.43	1.35	0.89	1.18
1/29	9:22	1.48	1.64	1.51	1.09	1.50
1/29	11:41	1.28	1.43	1.34	1.07	1.23

2017 / 2018 Denver						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
12/15	9:50	1.48	1.62	1.55	1.12	1.33
12/15	11:30	1.33	1.47	1.45	1.11	1.41
12/15	13:30	1.21	1.35	1.37	1.14	1.22
12/19	9:20	1.94	2.10	1.96	1.07	1.73
12/19	10:50	1.72	1.87	1.89	1.11	1.77
12/19	12:30	1.50	1.60	1.65	1.12	1.53
12/20	9:00	1.98	2.20	1.99	1.12	1.82
12/20	10:20	1.33	1.51	1.46	1.13	1.42
12/20	12:00	1.15	1.31	1.28	1.14	1.06
1/9	9:25	2.08	2.40	2.16	1.08	2.26
1/9	11:00	1.35	1.60	1.47	1.09	1.33
1/9	12:40	1.26	1.40	1.37	1.09	1.14
1/18	10:15	1.52	1.66	1.60	1.11	1.43
1/18	11:45	1.29	1.44	1.39	1.12	1.30

2020 Denver						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
1/16	10:45	1.67	1.73	1.68	1.13	1.95
1/16	13:30	1.57	1.65	1.62	0.96	1.73
1/22	9:45	1.47	1.58	1.42	1.10	1.62
1/22	11:05	1.33	1.44	1.31	1.15	1.44
1/22	13:50	1.31	1.41	1.31	1.17	1.44
1/24	10:00	1.40	1.57	1.39	1.14	1.61
1/24	11:20	1.30	1.42	1.28	1.15	1.47
1/24	13:30	1.20	1.37	1.25	1.16	1.32
2/21	10:10	1.45	1.58	1.45	1.20	1.51
2/21	12:30	1.25	1.34	1.28	1.17	1.19