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EXECUTIVE SUMMARY

The University of Denver conducted a three-day remote sensing study in the Denver, CO area in the winter of 2013. The remote sensor used in this study is capable of measuring the ratios of CO, HC, and NO to CO_2 in motor vehicle exhaust. From these ratios, we calculate mass emissions per kg of fuel and the molar percent concentrations of CO, CO_2, HC and NO in motor vehicle exhaust which would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. The system used in this study was also 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.

Three days of fieldwork (December 12 and 13, 2013 and January 3, 2014) were conducted on the uphill exit ramp from northbound Interstate 25 to westbound US 6 Denver, CO. A database was compiled containing 19,242 records for which the State of Colorado provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 19,196 contained valid measurements for HC and NO as well. The database, as well as others compiled by the University of Denver, can be found at www.feat.biochem.du.edu.

The mean measurements for CO, HC, and NO were determined to be 0.1%, 45ppm, and 193ppm, (12.6 g/kg, 1.8 g/kg and 2.7 g/kg), respectively. These values have continued to decrease despite the fact that the 2008 recession caused an unexpected 2 year increase in the average age of the fleet. The fleet emissions measured in this study exhibit a gamma distribution, with the dirtiest 10% of the fleet responsible for 85%, 79%, and 77% of the CO, HC, and NO emissions, respectively.

The 2013 data continues to show a decreasing dependence on VSP and are once again lower than any of the previous data sets. CO, HC and now NO emissions are at low levels across the entire VSP range. Using VSP, the emissions of the vehicle fleet measured in 2013 were adjusted to match the vehicle driving patterns of the fleet measured in 1999. All of the emissions continue to trend downward even at higher loads. Mean emissions in the model year adjustments are now significantly higher than when the fleet was first sampled in 1999. Mean CO emissions are 26% higher, HC emissions are 44% higher and NO emissions are 46% higher. However, during the 15 years in the process the size of the remaining fleet has shrunk in size substantially and has likely increased the uncertainties in this calculation.

An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters, for instance 1.5% of the fleet emits 23% of the total CO and 14% of the total HC. The noise levels in the CO, HC and NO measurement channels were determined to be comparable to previous campaigns.

INTRODUCTION

Since the early 1970's many heavily populated cities in the United States have violated 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, 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 2010, on-road vehicles were estimated to still be one of the larger sources for the major atmospheric pollutants, contributing approximately 44% of the CO, 34% of the VOC's, 8% of the NH3 and 34% of the NOx to the national emission inventory.[3]

The use of the internal combustion engine and the combustion of carbon based fuels as one of our primary means of transportation of course accounts for it being 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 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, and with the new 8 hour ozone standards introduced by the EPA in 1997 and tightened again in 2008, many more locations violate the standard and likely will have some difficulty meeting the standards.[5]

Beginning in 1997 the University of Denver began conducting on-road tailpipe emission surveys at selected sites to follow long term emission trends. A site northwest of Chicago IL, in Arlington Heights, was the first to be established but over the years we have also collected measurements 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, 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 researchers to establish fleet emission trends.

Reflecting a desire to continue evaluating the historical and recent emissions trends several of the previous E-23 sites have been chosen for additional data collection. This report describes the on-road emission measurements taken in the Denver, CO area in the winter of 2013 and 2014, under CRC Contract No. E-106. Measurements were made on three weekdays, Thursday December 12, Friday December 13 and Friday January 3, 2014, October 4, between the hours of 9:00 and 16:00 on the uphill interchange ramp from northbound I-25 to westbound US6. Measurements have previously been collected at this exact location in since 1995 with E-23 measurements collected in 1999, 2000, 2001, 2003 and 2005 and 2007.

MATERIALS AND METHODS

The 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.[7-9] The instrument consists of a non-dispersive infrared (IR) component for detecting carbon monoxide, CO_2, and hydrocarbons, and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Collinear beams of 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 distributes the light across the four infrared detectors: CO, CO_2, HC and reference.

The UV light is reflected off the surface of the beam splitter and is focused into the end of a quartz fiber-optic cable, which transmits the light to an ultraviolet spectrometer. The UV unit is then capable of quantifying nitric oxide by measuring an absorbance band at 226.5 nm in the ultraviolet spectrum and comparing it to a calibration spectrum at the same wavelength.

The exhaust plume path length and the 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, wind, and turbulence behind the vehicle. For these reasons, the remote sensor can only directly measure ratios of CO, HC or NO to CO_2. The ratios of CO, HC, or NO to CO_2, termed Q, Q' and Q", respectively, are constant for a given exhaust plume; and, on their own, are useful parameters for describing a hydrocarbon combustion system. The remote sensor used in this study reports the %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen 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.[10] 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 conversion is directly from the measured ratios to g pollutant per kg of fuel. This conversion is achieved directly by first converting the pollutant ratio readings to the moles of pollutant per mole of carbon in the exhaust from the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 3HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q, 2Q', Q'')}{Q+1+6Q'} \quad (2)$$

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, assuming gasoline is stoichiometrically CH_2. Again, the HC/CO_2 ratio must use two times the reported HC (as above) because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading.[10]

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

Quality assurance calibrations are performed as dictated in the field by the atmospheric conditions and traffic volumes. A puff of gas containing certified amounts of CO, CO_2, propane and NO 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). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[11, 12] The NO channel used in this study has been extensively tested by the University of Denver. 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.[8] Appendix A gives a list of the criteria for valid/invalid data.

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 a pair of infrared beams passing across the road, 6 feet apart and approximately 2 feet above the surface. Vehicle speed is calculated 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 and reported in mph/s. Appendix B defines the database format used for the data set.

RESULTS AND DISCUSSION

Measurements were collected for three days on December 12 & 13, 2013 and January 3, 2014 at the interchange from northbound I-25 to westbound 6th Avenue in central Denver. A map of the measurement location is shown in Figure 1 and a photograph of the site in Figure 2. This interchange ramp has an uphill grade of 8% (4.6°) at the measurement location. Measurements were generally made between the hours of 9:00 and 16:00, the pictures were read for license plate identification. Plates, which appeared to be in state and readable, were sent to the State of Colorado to be matched against registration records. The resulting database contains 19,242 records with registration information and valid measurements for at least CO and CO_2. Most of these records also contained valid measurements for HC, NO, NH_3 and NO_2. The database and all previous databases compiled for CRC E-23 and E-106 campaigns can be found at www.feat.biochem.du.edu. The temperature and humidity record for the measurement days is included in Appendix C.

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, the 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 or electric/hybrid engine off operation), or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit (see Appendix A). The greatest loss of data in this process occurs during the plate reading process, when out-of- state vehicles and vehicles with unreadable plates (obscured, missing, dealer, out of camera field of view) are omitted from the database.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 19,242 records used in this fleet analysis, 16,020 (83%) were contributed by vehicles measured once, and the remaining 3,222 (17%) records were from vehicles measured at least twice. The Denver site has fewer repeat measurements because it is a high volume site requiring fewer measurement days and this year the days were widely spaced due to weather.

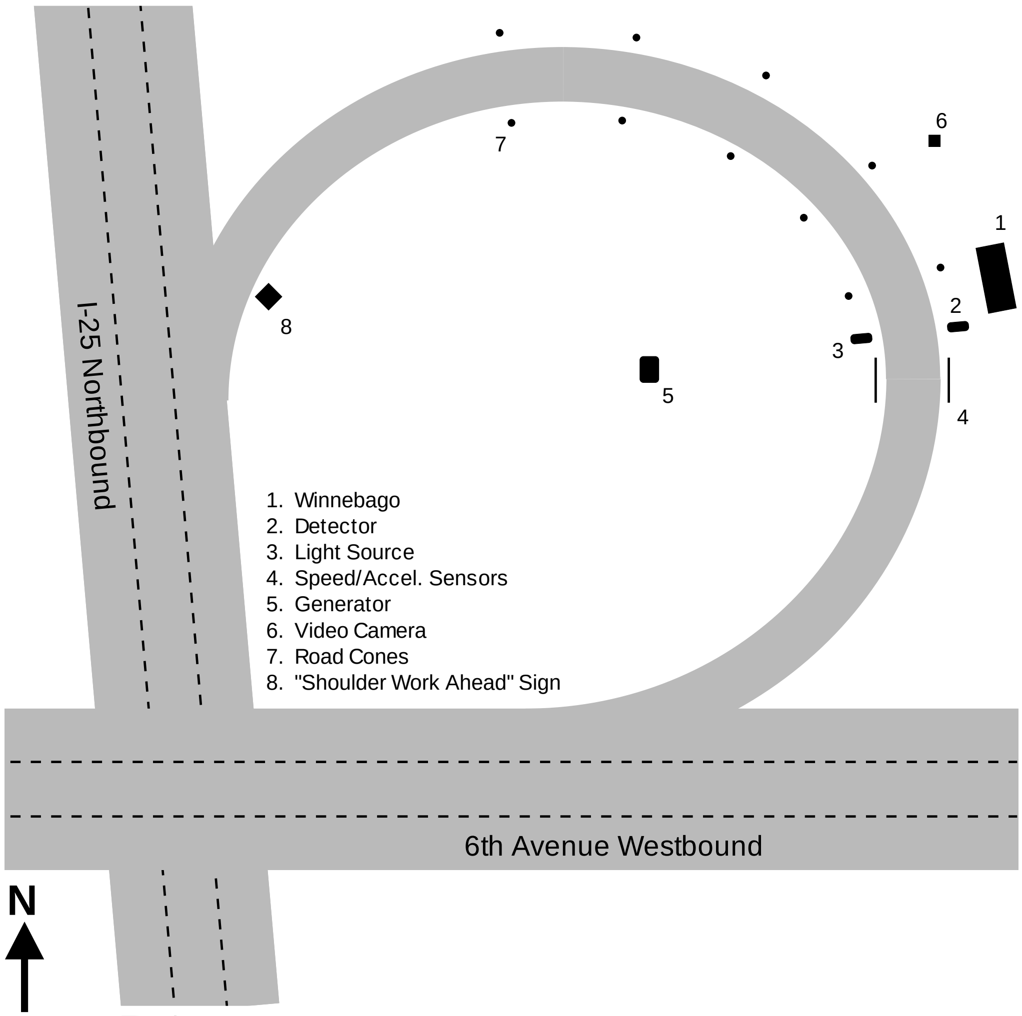

Figure 1. Area map of the interchange from I-25 northbound to 6th Avenue westbound in central Denver, showing remote sensor configuration and safety equipment.

Table 3 is the data summary; included is the summary of the previous remote sensing databases collected by the University of Denver at this site for the E-23 project. The 1999, 2000, 2001, 2003, 2005 and 2007 measurements were collected as part of this multi-year CRC study. The average HC values here have been adjusted for comparison purposes only 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 vehicles and assuming these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. The offset is then subtracted from all of the hydrocarbon data. Since we assume the cleanest vehicles to emit little hydrocarbons, such an adjustment will only err 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

Figure 2. Picture of the 6th Avenue measurement site looking northwest.

Table 1. Validity Summary.

	CO	HC	NO	NH_3	NO_2
Attempted Measurements	25,881				
Valid Measurements	25,148	25,100	25,114	24,845	23,843
Percent of Attempts	97.2%	97.0%	97.0%	96.0%	92.1%
Submitted Plates	19,883	19,864	19,854	19,659	18,859
Percent of Attempts	76.8%	76.8%	76.7%	76.0%	72.9%
Percent of Valid Measurements	79.1%	79.1%	79.1%	79.1%	79.1%
Matched Plates	19,242	19,224	19,214	19,022	18,252
Percent of Attempts	74.3%	74.3%	74.2%	73.5%	70.5%
Percent of Valid Measurements	76.5%	76.6%	76.5%	76.6%	76.6%
Percent of Submitted Plates	96.8%	96.8%	96.8%	96.8%	96.8%

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	16,020
2	1,315
3	179
4	7
5	1
>5	3

same site. The data for this year did not have a measurable offset and therefore no adjustments have been made to this year's HC data.

The inverse relationship between vehicle emissions and model year has been observed at a number of locations around the world, and Figure 3 shows that the fleet in the Denver area, during all seven years of measurement, is not an exception. The Denver gNO/kg emissions finally appear to level off after the 1989 model year in the newest data set though those years have only a small number of measurements. As seen at the other E-23 sites, the Denver data show that vehicle deterioration is slowing even for tailpipe NO emissions. This is especially noticeable since model year 2004 when the Tier II vehicles began to be introduced into the fleet.

Plotting vehicle emissions by model year, with each model year divided into emission quintiles results in the plots shown in Figures 4 - 6. Very revealing is the fact that, for all three major pollutants, the cleanest 60% of the measurements, regardless of model year, make an essentially negligible contribution to the total emissions. This observation was first reported by Ashbaugh, *et al*.[12] These plots also show that even though older model years have higher average emissions, the numerical superiority of newer models dominate the fraction of emissions. Figures 3 and 5 highlight the decreasing HC emission levels where approximately 80% of the measurements now have HC emission readings that are zero ± instrument noise. The accumulations of negative emissions in the first two quintiles are the result of ever decreasing emission levels. Our instrument is designed such that when measuring true zero emission plumes (a ratio of zero), half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to dive toward zero emissions, the negative emission readings will continue to grow toward half of the measurements. The results shown here continue to demonstrate that broken emissions control equipment has a greater impact on fleet emissions than vehicle age.

The middle graph in Figures 4 – 6 shows the fleet fractions by model year for the 2013 Denver database. The impact of the recent reduction in light-duty vehicle sales due to the economic recession is clearly evident in the fleet model year fraction beginning in 2009 and continuing through 2011. The previous recession that occurred in 2001 is not noticeable in this data set though we have previously reported that data collected in the California cities of San Jose and Fresno clearly showed its effects.[13] Nationwide new vehicle sales, as reported by the National Automobile Dealers Association, for 2009 were the lowest per capita since World War II.[14, 15] For the 2013 Denver measurements the

Table 3. Data Summary.

Study Year	1999	2000	2001	2003	2005	2007	2013
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)
Median CO (%)	0.09	0.11	0.06	0.08	0.05	0.05	0.02
Percent of Total CO from Dirtiest 10% of the Data	66.3	65.3	73.2	68.9	71.0	73.0	85.2
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
Median HC (ppm)[a]	75	50	80	40	20	30	31
Percent of Total HC from Dirtiest 10% of the Data	66.0	77.6	77.2	74.8	81.4	92.3	79
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)
Median NO (ppm)	240	165	133	113	76	40	17
Percent of Total NO from Dirtiest 10% of the Data	44.6	48.4	51.7	53.5	58.0	63.1	76.9
Mean Model Year	1992.4	1993.4	1994.6	1996.4	1998.1	2000	2005.2
Mean Fleet Age[b]	6.9	6.9	6.7	6.9	7.2	7.3	9.2
Mean Speed (mph)	20.6	21.9	22.3	20.2	23.5	22.5	22.9
Mean Acceleration (mph/s)	0.21	0.08	-0.77	0.12	-0.47	0.07	0.01
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°

[a]Indicates values that have been HC offset adjusted as described in text.

[b]Assumes new vehicle model year starts September 1.

2009 fleet fraction is 36% lower than the 2008 models. This reduction is similar to reductions seen at the West LA and Tulsa measurement sites.

The direct result is that the average age of the Denver fleet has increased between 2007 and 2013. Table 3 summarized the mean fleet ages for all of the previous data sets collected at the Denver site. The vehicle age has been estimated assuming that a vehicle model year starts in September. This sites many data sets shows how dramatic the change in fleet age that has occurred since the 2007 data was collected. The 2013 fleet is on average 2 model years older than has ever been observed at this Denver location. It will be interesting going forward to see how the direction and magnitude of future vehicle sales and retirement will impact this trend in fleet average age.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez[16], which takes the form

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

where SP is the vehicle specific power (VSP) 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. Using this equation, VSP was calculated for all measurements in the database. The emissions data were binned according to VSP, and illustrated in Figure 7. The solid line in the figure provides the number of measurements in each bin for the 2007 data. The 2007 data show the least dependence on VSP of any of the previous data sets. All of the species are remarkably flat across the VSP range with only slight rises at the VSP levels that in past years showed larger increases. These observations are probably the result of a number of factors that influence vehicle emissions. This could possibly include the continued improvement in emissions systems durability and lower national tailpipe standards through the 50-state certification program.

Using VSP, it is possible to eliminate some of the remaining influence of load and of driving behavior from the mean vehicle emissions for the 1999, 2000, 2001, 2003, 2005, 2007 and 2013 databases. Table 4 shows the mean emissions from vehicles in the 1999, 2000, 2001, 2003, 2005, 2007 and 2013 with specific powers between -5 and 20 kW/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire databases, as shown in Table 3. This correction is accomplished by applying the mean vehicle emissions for each specific power bin in Figure 7 for each measurement year, to the vehicle distribution by specific power, for each bin from 1999. A sample calculation, for the specific power adjusted mean NO emissions in Chicago in 1998, is shown in Appendix D. The uncertainty values in the table are standard errors of the means determined from the daily averages. Table 4 shows the mean VSP adjusted emissions during the six years have been steadily decreasing since the 1999 data set. The current measurements are the lowest to date, most likely due to the robust emissions durability of the newer model year vehicles entering the Denver fleet.

Table 4. Vehicle specific power adjusted fleet emissions (-5 to 20 kW/tonne only) with standard error of the means calculated using daily averages.

	1999 measured (adjusted)	2000 measured (adjusted)	2001 measured (adjusted)	2003 measured (adjusted)	2005 measured (adjusted)	2007 Measured (adjusted)	2013 Measured (adjusted)
Mean gCO/kg	52.4 ± 2.1 (52.4 ± 2.1)	51.2 ± 2.8 (51.0 ± 2.8)	41.8 ± 0.8 (42.2 ± 0.9)	42.0 ± 1.9 (42.2 ± 1.9)	28.3 ± 0.7 (31.1 ± 0.7)	22.9 ± 0.6 (22.6 ± 0.5)	12.0 ± 0.9 (12.3 ± 0.9)
Mean gHC/kg[a]	5.0 ± 0.2 (4.9 ± 0.2)	6.8 ± 0.9 (4.3 ± 0.9)	2.0 ± 0.6 (3.6 ± 0.5)	4.2 ± 0.4 (3.4 ± 0.4)	2.3 ± 0.3 (1.7 ± 0.3)	1.9 ± 0.5 (1.9 ± 0.5)	3.8 ± 0.1 (2.0 ± 0.1)
Mean gNO/kg	8.1 ± 0.7 (8.1 ± 0.7)	7.0 ± 0.4 (7.0 ± 0.4)	6.6 ± 0.5 (7.3 ± 0.6)	6.2 ± 0.2 (6.1 ± 0.2)	5.0 ± 0.1 (5.1 ± 0.1)	3.6 ± 0.1 (3.6 ± 0.1)	2.4 ± 0.1 (2.5 ± 0.1)

[a]HC emissions are offset adjusted for all years.

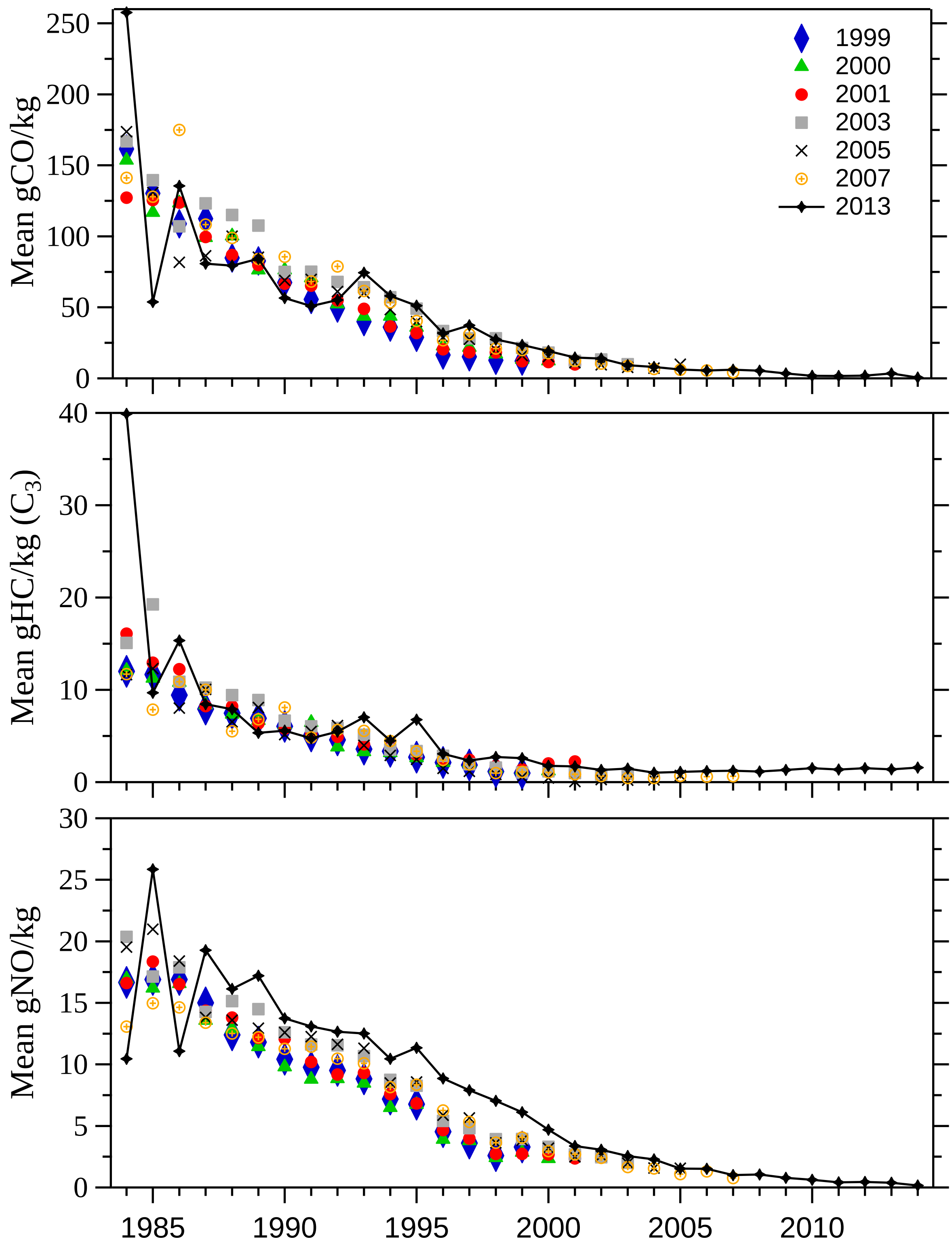

Figure 3. Mean fuel specific vehicle emissions as a function of model year for each Denver data set. HC data have been offset adjusted as described in the text

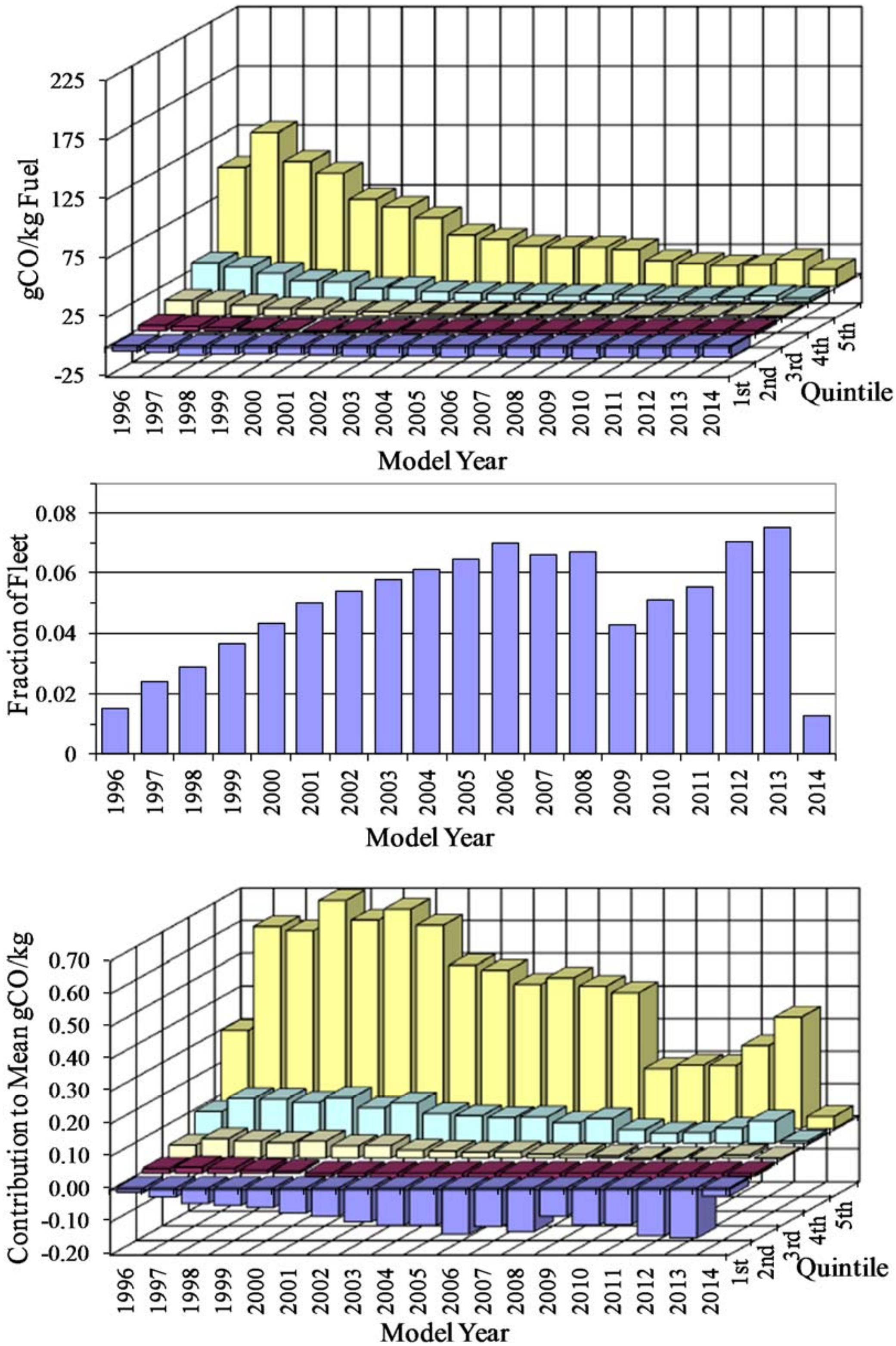

Figure 4. 2013 fuel specific CO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional CO emissions by model year and quintile (bottom).

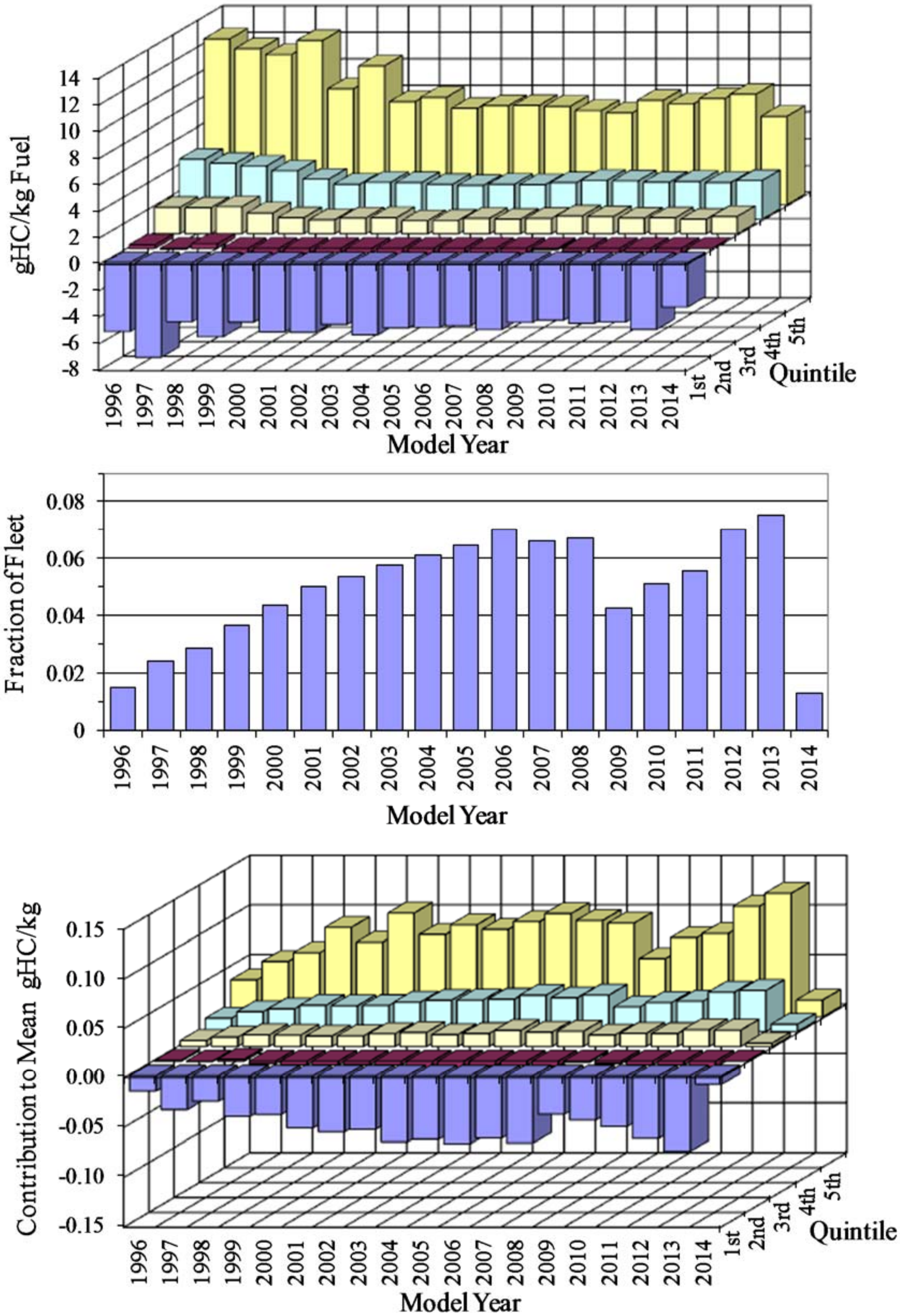

Figure 5. 2013 fuel specific HC emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional HC emissions by model year and quintile (bottom).

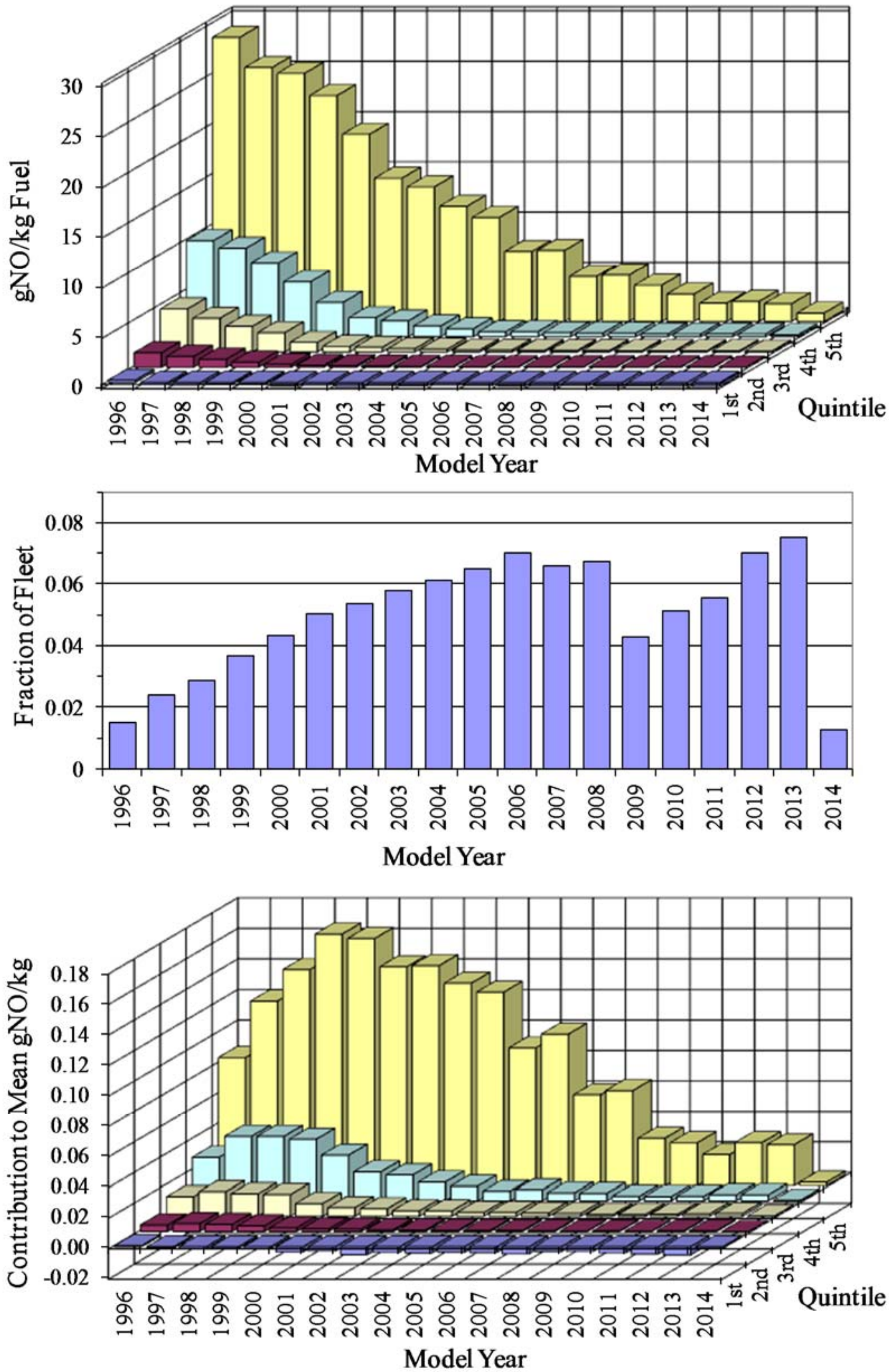

Figure 6. 2013 fuel specific NO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional NO emissions by model year and quintile (bottom).

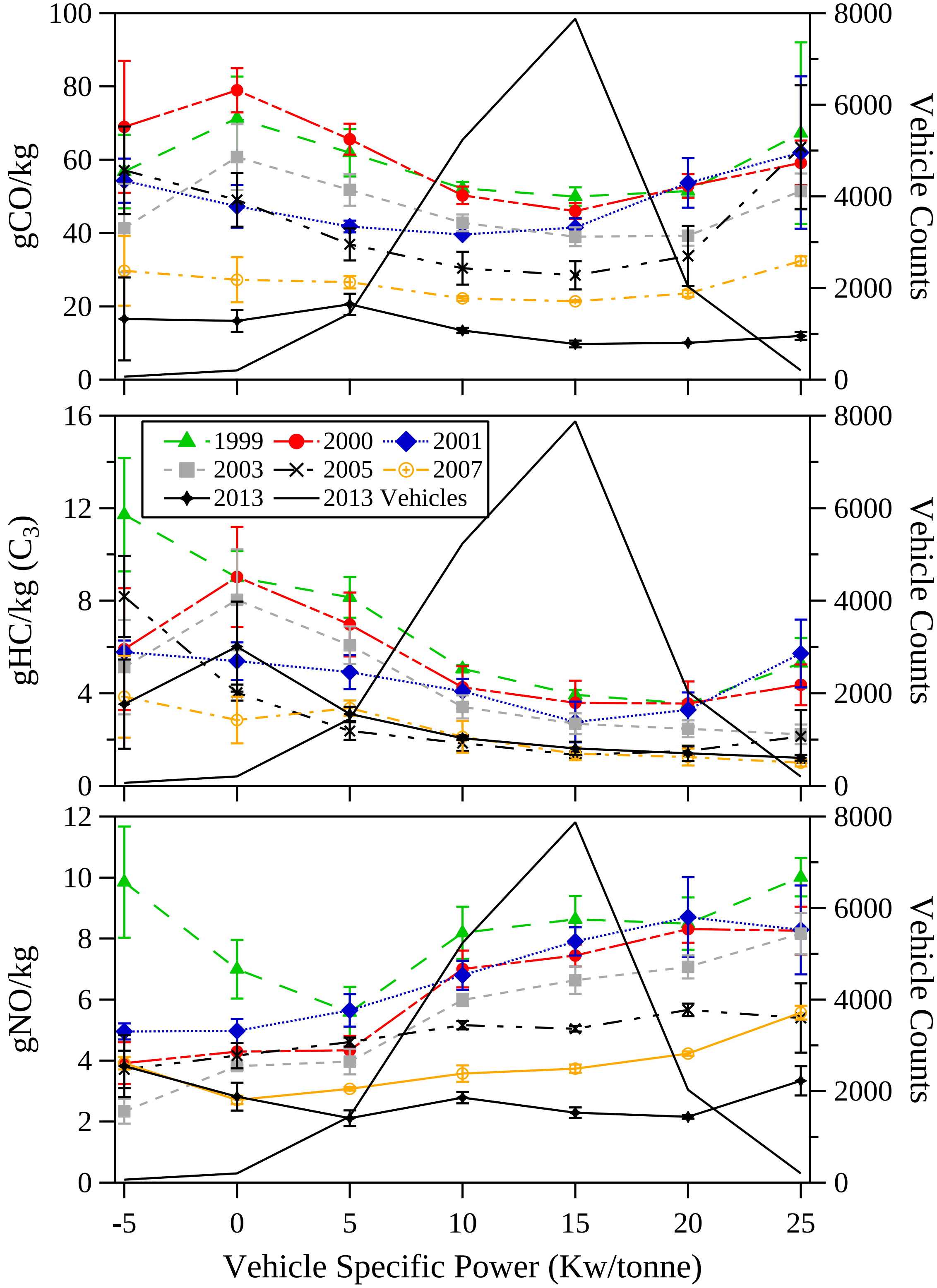

Figure 7. Vehicle emissions are plotted as a function of vehicle specific power for the entire Denver E-23 data sets. Error bars are standard errors of the mean calculated from daily samples. The solid line without markers is the vehicle count profile for the 2013 data set.

A correction similar to the VSP adjustment can be applied to a fleet of specific model year vehicles to look at model year deterioration, provided we use as a baseline only model years measured in the 1999 study. This restriction reduces the number of vehicles in the calculation for each subsequent year and that fleet size is listed at the bottom of the table. Table 5 shows the mean emissions for all vehicles from model years 1984 to 1999, as measured in 1999, 2000, 2001, 2003, 2005, 2007 and 2013. Applying the vehicle distribution by model year from 1999 to the mean emissions by model year from each of the other three years of measurement yields the model year adjusted fleet emissions. What deterioration that is occurring in this fleet is small with only the CO emissions showing an increase that is outside the error limits given. The HC and now the NO emissions have flattened out and do not show a statistically significant deterioration effect. An expanded sample calculation, for the model year adjusted mean NO emissions in Chicago in 1998, is shown in Appendix E.

Table 5. Model year adjusted fleet emissions (MY 1984-1999 only). Errors are standard error of the means calculated using the daily means.

	1999 measured (adjusted)	2000 measured (adjusted)	2001 measured (adjusted)	2003 measured (adjusted)	2005 measured (adjusted)	2007 Measured (adjusted)	2013 Measured (adjusted)
Mean gCO/kg	45.8 ± 1.5 (45.8 ± 1.5)	45.9 ± 2.2 (50.8 ± 2.5)	41.0 ± 1.6 (48.2 ± 1.9)	51.9 ± 1.9 (62.5 ± 2.3)	41.5 ± 0.5 (54.0 ± 0.6)	43.6 ± 1.4 (59.7 ± 1.9)	40.1 ± 2.6 (57.7 ± 1.9)
Mean gHC/kg[a]	4.3 ± 0.2 (4.1 ± 0.2)	6.3 ± 0.9 (4.2 ± 1.0)	1.8 ± 0.5 (4.6 ± 0.6)	4.9 ± 0.5 (5.1 ± 0.6)	3.2 ± 0.2 (4.0 ± 0.3)	3.2 ± 0.5 (4.5 ± 0.7)	3.9 ± 0.4 (5.9 ± 0.9)
Mean gNO/kg	7.9 ± 0.6 (7.9 ± 0.6)	6.9 ± 0.4 (7.5 ± 0.4)	7.2 ± 0.6 (8.2 ± 0.7)	8.0 ± 0.3 (9.4 ± 0.4)	7.7 ± 0.1 (9.5 ± 0.1)	7.0 ± 0.1 (8.7 ± 0.1)	8.9 ± 0.3 (11.5 ± 0.2)
Number of Vehicles	24,588	21,138	16,678	13,716	10,132	8,227	3,012

[a]HC emissions are offset adjusted for all years.

Vehicle deterioration can also be illustrated by Figure 8, which shows the mean emissions of the 1984 to 2007 model year fleet as a function of vehicle age. The first point for each model year was measured in 1999, the second in 2000, the third in 2001, the fourth in 2003 the fifth in 2005 the sixth in 2007 and the seventh in 2013. Vehicle age is determined by the difference between the year of measurement and the vehicle model year. The number of pre-1990 models is dropping rapidly in the 2013 data set and increases the uncertainties in those models mean emission values which accounts for some of the large emission changes. Since the Denver measurements are taken half way into a new vehicle model year, each studies newest model year is assumed to be zero year's old. What is most striking is how the first four to six years of age the mean CO and HC show very small amounts if any emissions deterioration. With the current data set, NO emissions are starting to appear to flatten out in the first 5 years of age.

Another use of the on-road remote sensing data is to predict the abundance of vehicles that are high emitting for more than one pollutant measured. One can look at the high CO emitters and calculate what percent of these are also high HC emitters, for example. This

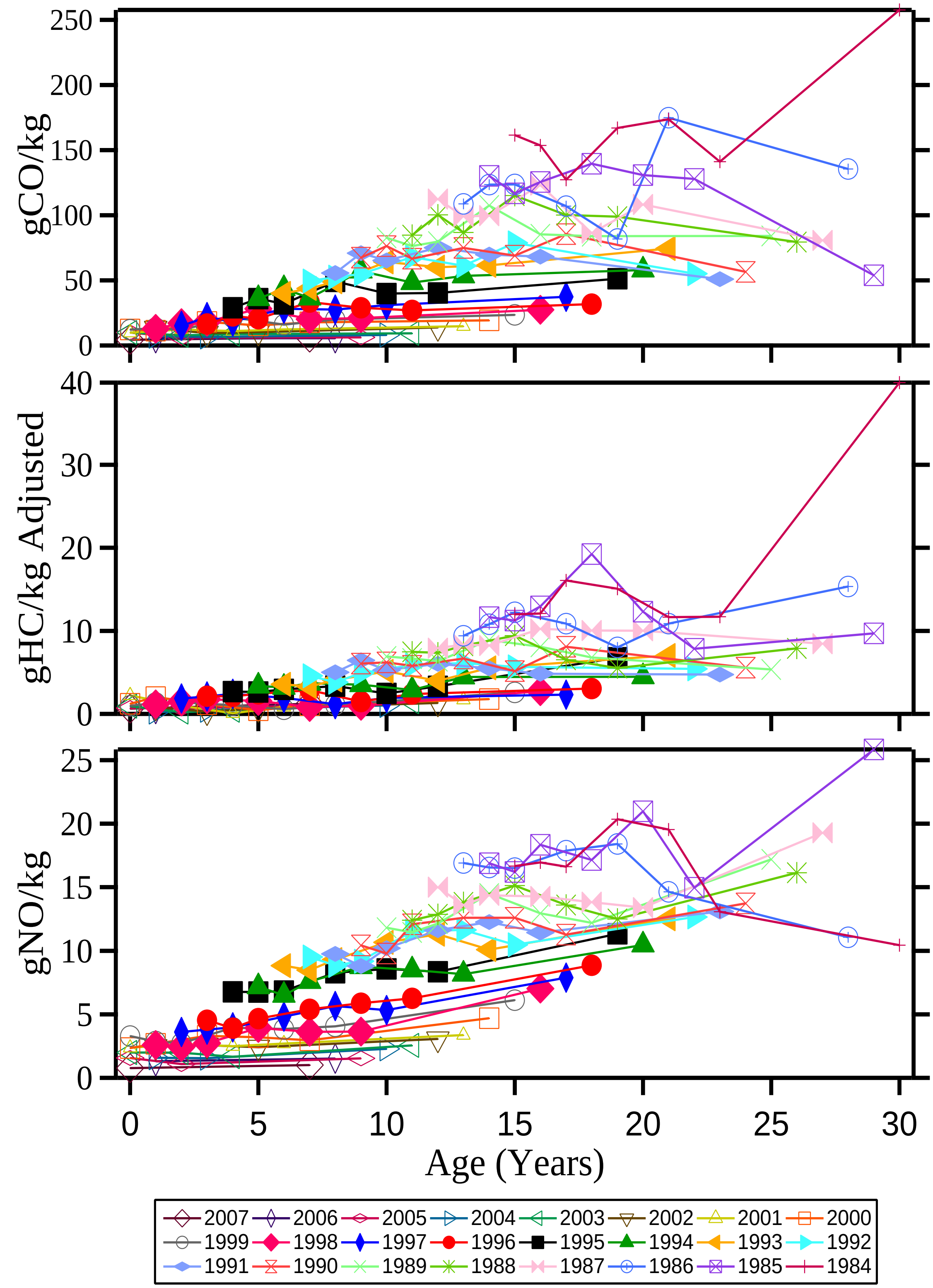

Figure 8. Mean fuel specific vehicle emissions as a function of age, shown by model year. Included are data collected from the site in 1999, 2000, 2001, 2003, 2005, 2007 and 2013.

type of analysis would allow a calculation of HC emission benefits resulting from fixing all high CO emitters. To this extent, we have analyzed our data to determine what percent of the top decile of emitters of one pollutant are also in the top decile for another.

These data are in Table 6; included in the analysis are only those vehicles that have valid readings for all three pollutants. The column heading is the pollutant whose top decile is being analyzed, and the values indicate what percentage of the data are high emitters only for the pollutants in the column and row headings. Where the column and row headings are the same, the values indicate the percentage that is high emitting in only that pollutant. The "All" row gives the percentage of the data that are high emitting in all three pollutants. Thus 1.5% of the measurements are in the top decile for both HC and CO but not for NO; 1.5% are high emitting for CO and NO but not for HC; 5.8% are only high CO emitters.

Table 6. Percent of all measurements that are high emitting.

Top 10% Decile	CO	HC	NO
CO	5.8%	1.5%	1.5%
HC	1.5%	6.2%	1.1%
NO	1.5%	1.1%	6.1%
All		1.2%	

The preceding analysis gives the percent of vehicle overlap but does not directly give emissions overlap. In order to assess the emissions overlap one must convert the Table 6 values to percent of emissions. Table 7 shows that identification of all measurements that are high emitting for CO would identify an overall 23% of HC and 9% of NO. More efficiently, identification of the 1.5% high CO and HC vehicles accounts for 14% of the total CO and 23% of the total on-road HC from these data.

Table 7. Percent of total emissions from high emitting vehicles.

Top 10% Decile	CO	HC	NO
CO	38%	23.1%	9.3%
HC	14.2%	43.7%	8.7%
NO	10.6%	9.8%	46.2%
All	14.4%	11.8%	10.3%

Most vehicles are low emitting and show little emissions variability when measured more than once. Vehicles that have one high reading often have other readings that vary widely.[17] This effect has also been observed from multiple FTP and IM240 tests. The evidence from pullover studies in California is that even one high reading identifies vehicles that have a >90% probability of failing an alternative I/M test if performed immediately. These vehicles also have a high probability of showing evidence of tampered or defective emission control equipment.[11] Because of this variability in the emissions of broken cars, the emissions distribution obtained from any snapshot of fleet emissions (remote sensing or annual I/M testing) is bound to be more skewed than were one able to monitor the emissions of all vehicles at all times. This phenomenon does not affect the means measured by these snapshots but it does imply that the overlap and high emitter fractions in the tables above would show less skewness were one able to fully characterize all vehicles and their variability.

In the manner described in the Phoenix, Year 2 report[18], instrument noise was measured by looking at the slope of the negative portion of the log plots. Such plots were constructed for the three pollutants. Linear regression gave best fit lines whose slopes correspond to the inverse of the Laplace factor, which describes the noise present in the measurements. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. The Laplace factors were 4.8, 3.5, and 0.3 for CO, HC and NO, respectively. These values indicate standard deviations of 6.8 g/kg (0.05%), 4.9 g/kg (116 ppm) and 0.4 g/kg (33 ppm) for individual measurements of CO, HC and NO, respectively. These levels are consistent with the low noise level as discussed in a previous Phoenix report.[15] 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 averages of 100 measurements, which is the low limit for number of measurements per bin, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages reduce to 0.7 g/kg, 0.5 g/kg, and 0.04 g/kg, respectively.

CONCLUSION

The University of Denver successfully completed the seventh year of a multi-year remote sensing study in Denver. Three days of fieldwork (December 12, 13, 2013 and January 3, 2014) were conducted on the uphill exit ramp from northbound Interstate 25 to westbound US 6 Denver, CO. A database was compiled containing 19,242 records for which the State of Colorado provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 19,196 contained valid measurements for HC and NO as well. Of these measurements, 16,020 (83%) were of vehicles measured only once. The rest were of vehicles measured at least twice.

The mean measurements for CO, HC, and NO were determined to be 12.6 gCO/kg, 1.8 gHC/kg, and 2.7 gNO/kg, respectively with an average model year of 2005.2. This mean model year showed an unexpected 2 year increase in the average age of the Denver fleet as a result of the 2008 recession yet mean emissions decreased despite this fact. The fleet emissions observed in this study exhibited a typical skewed distribution, with the dirtiest 10% of the fleet contributing 85%, 79%, and 77% of the CO, HC, and NO emissions, respectively. An analysis of emissions as a function of model year showed a typical inverse relationship. Newer model year vehicles have shown their ability to maintain low CO and HC emissions levels for many years after their entry into the fleet and this database shows for the first time that they now are adding NO emissions.

The 2013 data continues to show a decreasing dependence on VSP and are once again lower than any of the previous data sets. CO, HC and now NO emissions are at low levels across the entire VSP range. Using VSP, the emissions of the vehicle fleet measured in

2013 were adjusted to match the vehicle driving patterns of the fleet measured in 1999. All of the emissions continue to trend downward even at higher loads. Mean emissions in the model year adjustments are now significantly higher than when the fleet was first sampled in 1999. Mean CO emissions are 26% higher, HC emissions are 44% higher and NO emissions are 46% higher. However, during the 15 years in the process the size of the remaining fleet has shrunk in size substantially and has likely increased the uncertainties in this calculation.

An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters, for instance 1.5% of the fleet emits 23% of the total CO and 14% of the total HC. The noise levels in the CO, HC and NO measurement channels were determined to be comparable to previous campaigns.[15]

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

Not measured:

1) vehicle 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 data base.

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 >160ppmm CO_2 or >400 ppmm CO. (0.2 %CO_2 or 0.5% CO in an 8 cm cell. This is equivalent to the units used for CO_2 max.) Often HD 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".

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.

A restart is an occurrence of a beam block within the 0.5 s exhaust data acquisition time. Data analysis is restarted using the clean air data collected in advance of the first blocking event. High clearance pickups typically generate one restart.

APPENDIX B: Explanation of the Den_2013.dbf database.

The Den_2013.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 CD-ROM or from www.feat.biochem.du.edu. The following is an explanation of the data fields found in this database:

License	Colorado 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”.
So2_flag	Indicates a valid sulfur dioxide measurement by a “V”, Invalid by an “X”.
Nh3_flag	Indicates a valid ammonia measurement by a “V”, Invalid by an “X”.
No2_flag	Indicates a valid Nitrogen dioxide measurement by a “V”, Invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.
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.

Veh_type	Dmv plate type classification.
Vin	Vehicle identification number.
Year	Model year of the vehicle.
Make	Manufacturer of the vehicle.
Model	Model name of the vehicle.
Veh_body	Dmv classified body style of the vehicle.
Legl_city	City the vehicle resides in.
Legal_zip	Zip code the vehicle resides in.
County	County code where vehicle resides.
Exp_date	Date that current vehicle registration expires.
Em_flag	I/M flag: 'Y', 'N', 'X'.
Fuel	Fuel type: 'G' indicates gasoline, 'D' indicates diesel.
Em_date	I/M test date.
Next_test	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	Hydrocarbon concentrations after offset adjustment (2013 database only).
Hcgkg_off	Grams of HC per kilogram of fuel using 860 gC/kg of fuel and using the HC_offset value for this calculation (2013 database only).
VSP	Vehicles specific power calculating using the equation provided in the report.
V_model	VIN decoded model information.
V_body	VIN decoded body information.
V_type	VIN decoded vehicle type information.
V_engine	VIN decoded engine size in liters.
V_wtclass	VIN decoded weight class.
V_gvw	VIN decoded gross vehicle weight.

V_fuel VIN decoded fuel type.

V_trans VIN decoded transmission type.

V_xdrive Vin decoded all-wheel drive capability

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
		9:25	47	8:30	40	8:00	26
		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
14:16	57					11:07	54
15:50	56					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
			9:33	54	38	8:43	35	61	7:53	32	69
11:23	48	38	10:33	54	32	9:43	35	61	8:42	35	65
12:03	51	32	11:50	55	28	10:42	35	62	9:53	43	50
13:06	54	29	12:33	52	30	11:02	36	61	11:15	51	36
14:02	55	28	13:37	49	37	12:01	39	59			
15:14	64	26	14:37	50	39	13:09	41	56			
16:00	57	26	15:51	49	41	14:11	42	52			
16:54	52	27	16:07	48	41	15:09	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
			8:44	41	51	8:00	37	77
			9:11	36	65	9:01	39	77
			10:11	37	64	10:03	37	76
			11:11	45	57	11:01	41	70
12:06	52	34	12:11	45	53	12:25	46	56
13:22	54	33	13:11	45	57	13:19	54	56
14:06	55	33	14:16	48	50	14:19	39	72
15:06	54	34	15:11	46	54	15:19	39	71
16:06	50	36	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

APPENDIX D: Sample Calculation of Vehicle Specific Power Adjusted Vehicle Emissions using data from Chicago 1997 and 1998.

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

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

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

APPENDIX E: Sample Calculation of Model Year Adjusted Fleet Emissions using data from Chicago 1997 and 1998

1997 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	690	398	274620
	84	720	223	160560
	85	680	340	231200
	86	670	513	343710
	87	690	588	405720
	88	650	734	477100
	89	610	963	587430
	90	540	962	519480
	91	500	1133	566500
	92	450	1294	582300
	93	460	1533	705180
	94	370	1883	696710
	95	340	2400	816000
	96	230	2275	523250
	97	150	2509	376350
			17748	7266110
			Mean NO (ppm)	**409**
1998 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	740	371	274540
	84	741	191	141531
	85	746	331	246926
	86	724	472	341728
	87	775	557	431675
	88	754	835	629590
	89	687	1036	711732
	90	687	1136	780432
	91	611	1266	773526
	92	538	1541	829058
	93	543	1816	986088
	94	418	2154	900372
	95	343	2679	918897
	96	220	2620	576400
	97	177	3166	560382
			20171	9102877
			Mean NO (ppm)	**451**
1998 (Adjusted)	Model Year	‘98 Mean NO (ppm)	‘97 No. of Meas.	Total Emissions
	83	740	398	294520
	84	741	223	165243
	85	746	340	253640
	86	724	513	371412
	87	775	588	455700
	88	754	734	553436
	89	687	963	661581
	90	687	962	660894
	91	611	1133	692263
	92	538	1294	696172
	93	543	1533	832419
	94	418	1883	787094
	95	343	2400	823200
	96	220	2275	500500
	97	177	2509	444093
			17748	8192167
			Mean NO (ppm)	**462**

APPENDIX F: Field Calibration 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