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Fall 2016 On-road Emission Measurements in the Chicago Area: Comparison of two University of Denver Remote Sensing Datasets

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Fall 2016 On-road Emission Measurements in the Chicago Area: Comparison of two University of Denver Remote Sensing Datasets

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EXECUTIVE SUMMARY

The University of Denver has completed the ninth year of a multi-year remote sensing study in the Chicago area, with measurements made in Septembers of 1997 through 2000, 2002, 2004, 2006, 2014 and 2016. The remote sensor used in the 2016 study measured the ratios of CO, HC, NO, SO_2 and NH_3 to CO_2 in motor vehicle exhaust. Mass emissions per mass or volume of fuel are determined from these ratios and are the units used for the major results in this report. From these ratios, we can also calculate the percent concentrations of CO, CO_2, HC, NO, SO_2 and NH_3 in the exhaust that would be observed by a tailpipe probe, corrected for water and any excess air. The system used in this study was configured to determine the speed and acceleration of the vehicle, and was accompanied by a video system to record the license plate of the vehicle and, from this record, the vehicle's model year. Since fuel sulfur has been nearly eliminated in US fuels, SO_2 emissions have followed suit. Vehicle SO_2 measurements were collected but not calibrated and are not included in the discussion of the results.

As part of the ninth campaign the University collected the typical five days of measurements (E-106, September 12 - 16, 2016) at the on-ramp from Algonquin Rd. to eastbound I-290 in northwest Chicago then stayed for an additional three days of data collection (September 19 – 21, 2016) as part of a Coordinating Research Council initiated intercomparison with HEAT's EDAR remote exhaust sensor (CRC project number E-119a). The EDAR measurement results have never been made available for analysis by the University of Denver and therefore this report only compares the two data sets collected by the University of Denver for their representativeness. For the 2016 measurements, two databases were compiled for the E-106 campaign containing 20,431 records and the E-119a data set containing, 9,948 records for which the State of Illinois provided make and model year information. All of the records in both data sets contain valid measurements for at least CO and CO_2, and the vast majority of records also contain valid measurements for the other species. The database, as well as others compiled by the University of Denver, can be found at www.feat.biochem.du.edu.

For the purpose of this report we compared the two separate data sets to one another. The CO, HC, NO, NH_3 and NO_2 mean and standard errors of the mean emissions for the fleet measured in this study are listed with the E-106 data first and the E-119a data set in parenthesis. The results were 11.0 ± 0.4 gCO/kg (10.4 ± 0.7), 1.9 ± 0.1 gHC/kg (1.6 ± 0.1), 1.2 ± 0.05 gNO/kg (1.2 ± 0.2), 0.63 ± 0.01 gNH_3/kg (0.64 ± 0.06) and 0.1 ± 0.02 gNO_2/kg (0.11 ± 0.02 ppm) respectively. The uncertainties are all larger for the E-119a data set due to the fewer days of measurements. The mean model year of 2009.6 and a fleet age of 7.5 years old was observed for both data sets. Overall there are few statistical differences between the two data sets. The most significant difference was a slight change in driving mode between the two weeks. The mean speed, acceleration and vehicle specific power for the first week of measurements was 24.2 mph, 0.7 mph/sec and 7.9 kw/tonne respectively. During the following week all three values decreased with speed decreasing to 23.8 mph, acceleration dropping to 0.07 mph/sec and vehicle specific power decreasing to 6.7 kw/tonne. These small changes in driving mode are reflected in the emissions versus vehicle specific power analysis where the E-119a data set includes more measurements in the lower power bins when compared to the E-106 data set. It tends to reason that the presence of the EDAR system

downstream from our setup are behind the changes but that cannot be established with any certainty.

The comparison of the three day E-119a data set with the 5 day E-106 data set collected in Chicago during the fall of 2016 has resulted in the finding that the smaller data set is very representative of the larger data set. The fewer number of days contained in the E-119a data set does result in slightly larger uncertainties but that should be expected. What we can conclude is that fewer days of measurements at this location does not substantially change the results.

INTRODUCTION

Since the early 1970's, many heavily populated U.S. cities have violated the National Air Quality Standards (NAAQS) established by the Environmental Protection Agency (EPA) pursuant to the requirements of the federal Clean Air Act.[1, 2] Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas, and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). Ambient levels of particulate emissions can result either from direct emissions of particles or semi-volatile species or from secondary reactions between gaseous species, such as ammonia and nitrogen dioxide. As of 2010, on-road vehicles continued to be estimated as one of the larger sources for major atmospheric pollutants, contributing approximately 44% of the CO, 34% of the VOC's, 8% of the NH_3 and 34% of the NO_x to the national emission inventory.[3]

The use of the internal combustion engine (and its combustion of carbon-based fuels) as a primary means of transportation, makes it a significant contributor of species covered by the NAAQS. For a description of the internal combustion engine and causes of pollutants in the exhaust, see Heywood.[4] Properly operating modern vehicles with three-way catalysts are capable of partially (or completely) converting engine-out CO, HC and nitric oxide (NO) emissions to carbon dioxide (CO_2), water, and nitrogen. Control measures to decrease mobile source emissions in non-attainment areas include inspection and maintenance (I/M) programs, reformulated and oxygenated fuel mandates, and transportation control measures, but the effectiveness of these measures is difficult to quantify. Many areas remain in ozone non-attainment. The eight-hour ozone standards introduced by the EPA in 1997, tightened in 2008, with expected further tightening, mean that many new locations are likely to have difficulty meeting the standards in the future.[5]

In 1997, the University of Denver began conducting on-road tailpipe emission surveys at a site northwest of Chicago IL, in Arlington Heights to follow long term emission trends. Since 1997, measurements have also been collected in Los Angeles CA, Denver CO, Omaha NE, Phoenix AZ, Riverside CA, and Tulsa OK.[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. The data have been used by many researchers to study fleet emission trends.

This report briefly describes on-road emission measurements collected over ten days in the Chicago IL area in the fall of 2016, under CRC Contract No. E-106. The first five days, Monday September 12 to Friday September 16 were the standard E-106 measurements. An additional three days of measurements were made from Monday, September 19, to Wednesday, September 21 to support a CRC initiated data intercomparison with HEAT's EDAR remote sensor. The measurement results from the EDAR remote sensor have not been provided for a comparison so this report only details a comparison made between the two data sets collected by the University of Denver. All the data was collected generally between the hours of 9:00 and 18:30 on the on-ramp from Algonquin Rd. to southbound I-290/SH53. Heavy rain on Wednesday September 21

significantly reduced data collection on that day to only the hours of 10:25 to 12:00 and between the hours of 16:20 to 18:30.

MATERIALS AND METHODS

The FEAT remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust; it has been extensively discussed in the literature.[7-9] The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC and twin dispersive ultraviolet (UV) spectrometers (0.26 nm/diode resolution) for measuring oxides of nitrogen (NO and NO_2), SO_2 and NH_3. The source and detector units are positioned on opposite sides of a single lane road in a bi-static arrangement. Collinear beams of infrared (IR) and UV light are passed across the roadway into the IR detection unit then focused through a dichroic beam splitter, which separates the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC and reference.

The UV light is reflected from the surface of the dichroic beam splitter and focused onto the end of a quartz fiber bundle mounted to a coaxial connector on the side of the detector unit. The quartz fibers in the bundle are divided in half to carry the UV signal to two separate spectrometers. The first spectrometer's wavelength ranges from 227nm down to 198nm to measure the species of NO, SO_2 and NH_3. The absorbance from each respective UV spectrum of SO_2, NH_3, and NO is compared to a calibration spectrum using a classical least squares fitting routine in the same region to obtain the vehicle emissions. The second spectrometer measures only NO_2 by measuring an absorbance band at 438nm in the UV spectrum and comparing it to a calibration spectrum in the same region.[10] All species are sampled at 100Hz. Since the removal of sulfur from US gasoline and diesel fuel, SO_2 emissions have become negligibly small. While SO_2 measurements were collected as a part of this study, they will not be reported or discussed because the sensor was not calibrated for SO_2 emissions.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and depend on, among other things, the height of the vehicle's exhaust pipe, engine size, wind, and turbulence behind the vehicle. For these reasons, the remote sensor measures directly only ratios of CO, HC, NO, NH_3 or NO_2 to CO_2. The molar ratios of CO, HC, NO, NH_3 or NO_2 to CO_2, termed Q^{CO}, Q^{HC}, Q^{NO}, Q^{NH3} and Q^{NO2} respectively, are constant for a given exhaust plume; they are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as grams/kilogram of fuel (g/kg of fuel) or as molar %CO, %HC, %NO, %NH_3 and %NO_2 in the exhaust gas, corrected for water and excess air not used in combustion. The HC measurement is calibrated with propane, a C_3 hydrocarbon. Based on measurements using flame ionization detection (FID) of gasoline vehicle exhaust, the remote sensor is only half as sensitive to exhaust hydrocarbons on a per carbon atom basis as it is to propane on a per carbon atom basis as demonstrated by Singer et al.[11] To calculate mass emissions as described below, the %HC values reported are first multiplied by 2.0 as shown below to account for these "unseen" hydrocarbons, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the following equations.

$$\text{gm CO/gallon} = 5506 \cdot \%CO \,/\, (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1a)$$
$$\text{gm HC/gallon} = 2(8644 \cdot \%HC) \,/\, (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1b)$$
$$\text{gm NO/gallon} = 5900 \cdot \%NO \,/\, (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1c)$$
$$\text{gm NH}_3\text{/gallon} = 3343 \cdot \%NH_3 \,/\, (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1d)$$
$$\text{gm NO}_2\text{/gallon} = 9045 \cdot \%NO_2 \,/\, (15 + 0.285 \cdot \%CO + 2(2.87 \cdot \%HC)) \quad (1e)$$

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

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

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

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in 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.[11]

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

Quality assurance calibrations are performed twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant additional calibrations. The multi-species instrument used in this study requires three calibration cylinders. The first contains 6% CO, 6% CO_2, 0.6% propane and 0.3% NO; the second contains 0.1% NH_3 and 0.6% propane and the final cylinder contains 0.05% NO_2 and 15% CO_2. A puff of gas is released into the instrument's path, and the measured ratios from the instrument are compared to those certified by the cylinder manufacturer (Air Liquide). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and

instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are reported as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[12, 13] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to have it independently validated in an extensive blind study and instrument intercomparison. Tests involving a late-model low-emitting vehicle indicate a detection limit (3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations.[8] A list of criteria for determining data validity is shown in Appendix A.

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

RESULTS AND DISCUSSION

Figure 1 is a satellite image of the Algonquin Rd and I-290/SH53 interchange with approximate locations for the University of Denver FEAT remote sensor and the HEAT EDAR system along with DU's traffic control setup for the collection of the second data set. With the exception of the first 45 minutes of measurements collected on Monday September 19 the FEAT equipment was located 106 ft. before the EDAR equipment. FEAT was originally setup as close as possible to the EDAR reflective strip but was subsequently moved at HEAT's request to the location routinely used for the E-23 and E-106 measurements. Figures 2 and 3 are photographs of the equipment on the ramp taken looking east from the FEAT setup (Figure 2) and then looking west from the EDAR system (Figure 3).

E-106 data was collected between Monday September 12 through Friday September 16, 2016 follow by three additional days of measurements for the intercomparison (CRC project number E-119a), Monday September 19 through a rain shortened Wednesday September 21, 2016. The digital images for both data sets were transcribed for license plate identification. Plates that appeared to be in state and readable were sent to the State of Illinois to be matched against the state's non-personal vehicle registration information. Tables 1 and 2 detail the data reduction
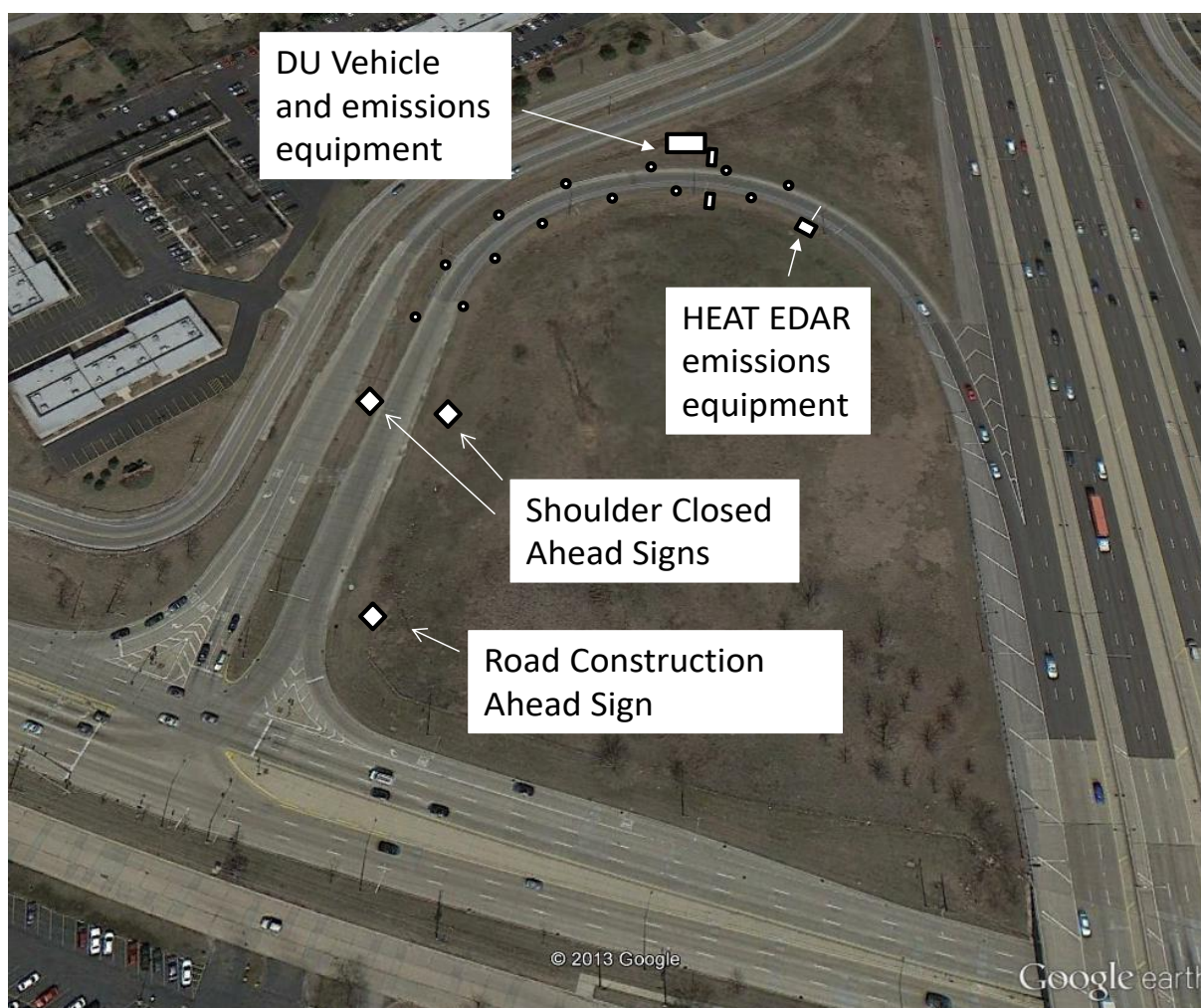
Figure 1. Satellite image of the on-ramp from Algonquin Road to eastbound I-290 in northwest Chicago, showing the approximate locations of the University of Denver (DU) and the HEAT EDAR remote sensor configurations. The FEAT light beam and the EDAR reflector strip are 106 ft. apart as measured on the outside of the ramp. The overlaid elements have been drawn to be visible and are not drawn to scale.

Table 1. E-106 Measurements Validity Summary.

	CO	HC	NO	NH$_3$	NO$_2$
Attempted Measurements	27,565				
Valid Measurements	24,421	24,408	24,419	24,386	24,134
Percent of Attempts	88.6%	88.5%	88.6%	88.5%	87.6%
Submitted Plates	20,651	20,643	20,649	20,623	20,440
Percent of Attempts	74.9%	74.9%	74.9%	74.8%	74.2%
Percent of Valid Measurements	84.6%	84.6%	84.6%	84.6%	84.7%
Matched Plates	20,431	20,423	20,429	20,403	20,221
Percent of Attempts	74.1%	74.1%	74.1%	74.0%	73.4%
Percent of Valid Measurements	83.7%	83.7%	83.7%	83.7%	83.8%
Percent of Submitted Plates	98.9%	98.9%	98.9%	98.9%	98.9%

Figure 2. A photograph looking east at the Algonquin Rd. monitoring site and 2016 remote sensing setup with HEAT's EDAR unit in the distance.

Table 2. E-119a Measurements Validity Summary.

	CO	HC	NO	NH$_3$	NO$_2$
Attempted Measurements	13,480				
Valid Measurements	11,738	11,724	11,738	11,727	11,641
Percent of Attempts	87.1%	87.0%	87.1%	87.0%	86.4%
Submitted Plates	10,039	10,031	10,039	10,028	9,967
Percent of Attempts	74.5%	74.4%	74.5%	74.4%	73.9%
Percent of Valid Measurements	85.5%	85.6%	85.5%	85.5%	85.6%
Matched Plates	9,948	9,940	9,948	9,937	9,877
Percent of Attempts	73.8%	73.7%	73.8%	73.7%	73.3%
Percent of Valid Measurements	84.8%	84.8%	84.8%	84.7%	84.8%
Percent of Submitted Plates	99.1%	99.1%	99.1%	99.1%	99.1%

Figure 3. A photograph looking west at the Algonquin Rd. monitoring site and 2016 remote sensing setup with the University of Denver's FEAT unit in the distance.

process for each data set.

The resulting databases contained 20,431 (E-106) and 9,948 (E-119a) records with make and model year information and valid measurements for at least CO and CO_2 respectively. Most of these records also contain valid measurements for HC, NO, NH_3 and NO_2. These databases and all of our previous databases compiled for CRC E-106 and CRC E-23-4 campaigns can be found at www.feat.biochem.du.edu.

The data reduction process of the measurements is summarized in Tables 1 and 2. The table details the steps beginning with the number of attempted measurements and ending with the number of records containing both valid emissions measurements and vehicle registration information. An attempted measurement is defined as a beam block followed by a half second of data collection. If the data collection period is interrupted by another beam block from a close following vehicle, the measurement attempt is aborted and a new attempt is made to measure the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement. The first significant data losses occur from invalid measurement attempts when the vehicle plume misses the sampling beam, is highly diluted or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit (See Appendix A). The second significant loss of data occurs during the plate reading process, when out-of-state vehicles and vehicles with unreadable plates (obscured,

rusted, missing, dealer, out of camera field of view) are omitted from the database. The data reduction rates are similar for both of the data sets collected.

Table 3 provides an analysis of the number of vehicles that were measured repeatedly and the number of times they were measured for the two data sets. There are 20,431 records for the E-106 data set and 9,948 records for the E-119a data set used in this analysis. The comparison shows that the extra two sampling days for the E-106 data increased the number of repeat vehicle measurements from 65.5% of the records for the three day E-119a data set to 55.7% for the five day E-106 data set. Subsequent percentage increases are also seen for the increasing multiple measurement categories as well. The E-106 data set is comprised of 14,893 unique vehicles of which 3,438 (23%) are also in the E-119a data set.

Table 3. Number of measurements of repeat vehicles.

Number of Times Measured	Number of E-106 Vehicles	Number of E-119a Vehicles
1	11,387 (55.7%)	6,515 (65.5%)
2	2,068 (20.2%)	1,298 (26.1%)
3	966 (14.2%)	253 (7.6%)
4	390 (7.6%)	17 (0.7%)
5	55 (1.3%)	2 (0.1%)
6	18 (0.5%)	
6+	9 (0.3%)	

Table 4 is a data summary, which includes a comparison of the 2016 E-106 database collected by the University of Denver at the I-290 and Algonquin Rd. site the previous week. Afternoon traffic levels in 2016 were similar to several of the previous year measurements, with a drop in traffic speeds and some stop-and-go driving brought about by congestion downstream on the freeway during the afternoon rush. The percentages reported are molar percent's and the fuel specific calculations assume there are 860 grams of carbon per kilogram of fuel. The only substantial difference between the two measurement sets is that the vehicle speed, acceleration and resulting vehicle specific power (VSP) measured during the second week were lower than those measured in the first week. This may be a result of the HEAT system being downstream of the FEAT equipment.

The mean HC values have been adjusted for comparison purposes to remove an artificial offset in the measurements. This offset, restricted to the HC channel, has been reported in previous CRC reports. The adjustment is calculated by computing the mode and means of the newest model year vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. The offset adjustment subtracts this value from all of the hydrocarbon data. For the 2016 Chicago data this process was carried out using all ten days of measurements. Since it is assumed that the cleanest vehicles emit little hydrocarbons, this approximation 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. The normalization value of 25ppm was applied uniformly to all of the HC measurements.

Table 3. Data summary.

Study Year Program	2016 E-106	2016 E-119a
Number of Records	20,431	9,948
Mean CO (%) (g/kg of fuel)	0.086 (11.0)	0.084 (10.7)
Median CO (%)	0.024	0.021
Percent of Total CO from the 99th Percentile	27.6%	30.3%
Mean HC (ppm)[a] (g/kg of fuel)[a] Offset (ppm)	48 (1.9) 25	42 (1.6) 25
Median HC (ppm)[a]	24	15
Percent of Total HC from the 99th Percentile	23.8%	30.8%
Mean NO (ppm) (g/kg of fuel)	83 (1.2)	86 (1.2)
Median NO (ppm)	2	6
Percent of Total NO from the 99th Percentile	30.2%	31.3%
Mean NH_3 (ppm) (g/kg of fuel)	79 (0.63)	80 (0.64)
Median NH_3 (ppm)	37	39
Percent of Total NH_3 from the 99th Percentile	10.6%	10.1%
Mean NO_2 (ppm) (g/kg of fuel)	5 (0.1)	5 (0.1)
Median NO_2 (ppm)	2	2
Percent of Total NO_2 from the 99th Percentile	37.3%	35.4%
Mean Model Year	2009.6	2009.6
Mean Fleet Age[b]	7.5	7.5
Mean Speed (mph)	24.2	23.8
Mean Acceleration (mph/s)	0.7	0.07
Mean VSP (kw/tonne) Slope (degrees)[d]	7.9 1.0°	6.7 1.0°

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

The inverse relationship between vehicle emissions and model year is shown in Figure 4 for the two sets data collected. E-106 data is comprised measurements from 5 days, and E-119a data is representative of 3 days' worth of measurements. The HC data have been offset adjusted as previously described. For all emissions displayed (CO, HC and NO) the newer model year vehicles remain unchanged from one week to the next. Both data sets suffer from a lack of measurements when vehicle age begins to reach 20 years (~1996). Congruent with previously published data[14], high emitting vehicles can introduce large variations in mean emissions and will not be evenly distributed in the smaller sample of vehicles comprising each of these data points.

As shown in previous E-106 data sets the fuel specific CO and HC emissions show little if any deterioration in mean emission levels in the first twelve to fifteen model years. Fuel specific NO emissions also show little if any mean emission deterioration but only through the first eight or nine model years. Since the introduction of Tier II vehicles (phase in began with the 2004 models and was completed by the 2009 model year) fuel specific NO emissions have been steadily reduced and the emissions versus model year plots look more and more like the CO and HC plots.

As originally presented by Ashbaugh et al., vehicle emissions by model year, with each model year divided into emission quintiles, were plotted for the two data sets collected in Chicago in 2016.[15] This resulted in pairwise plots for fuel specific CO, HC and NO emissions shown in Figures 5 - 10. The bars in the top graphs of each figure represent the mean emissions for each quintile. The middle graphs give the fraction of the fleet for each model year. The bottom graphs, which are a product of the first two graphs, display the contribution to the mean emissions by quintiles and model year. Model years older than 1996 and not graphed account for ~0.7% of the measurements and contribute between 6.3% (HC) and 7.7% (CO) of the emissions for E-106 data and 7.1% (HC) and 8.2% (CO) for E-119a data set. The bottom graphs illustrate that at least the first three quintiles of the measurements, regardless of model year make an essentially negligible contribution to the total emissions. Negative emissions are largely accumulated in the first two quintiles, a result of ever decreasing emission levels with newer model year vehicles. The instrument is designed such that when measuring a zero emission plume, half of the readings will be negative and half will be positive. As new vehicle emissions progress toward zero, the fleet parallels this with the negative readings continuing to grow toward half of all the measurements.

The fleet fraction reductions in the 2009 model year vehicles is a response to the economic recessions and is illuminated in the middle plots, and this reduction is present in both measurement data sets. The 2011 model year vehicles resume pre-2009 model year fleet fraction growth until model year 2015, where model years 2016 and 2017 are still underrepresented as they have not been fully incorporated into the fleet. Independent of which week the fleet was measured, the mean fleet age of 7.5 years old remains unchanged for the data set collected in 2014. However, in the early part of the 21rst century the fleet age at this location was around 6 years old and like other E-106 sites sampled shows that the on-road age of the vehicle fleet was negatively impacted by the last recession and has not fully recovered.
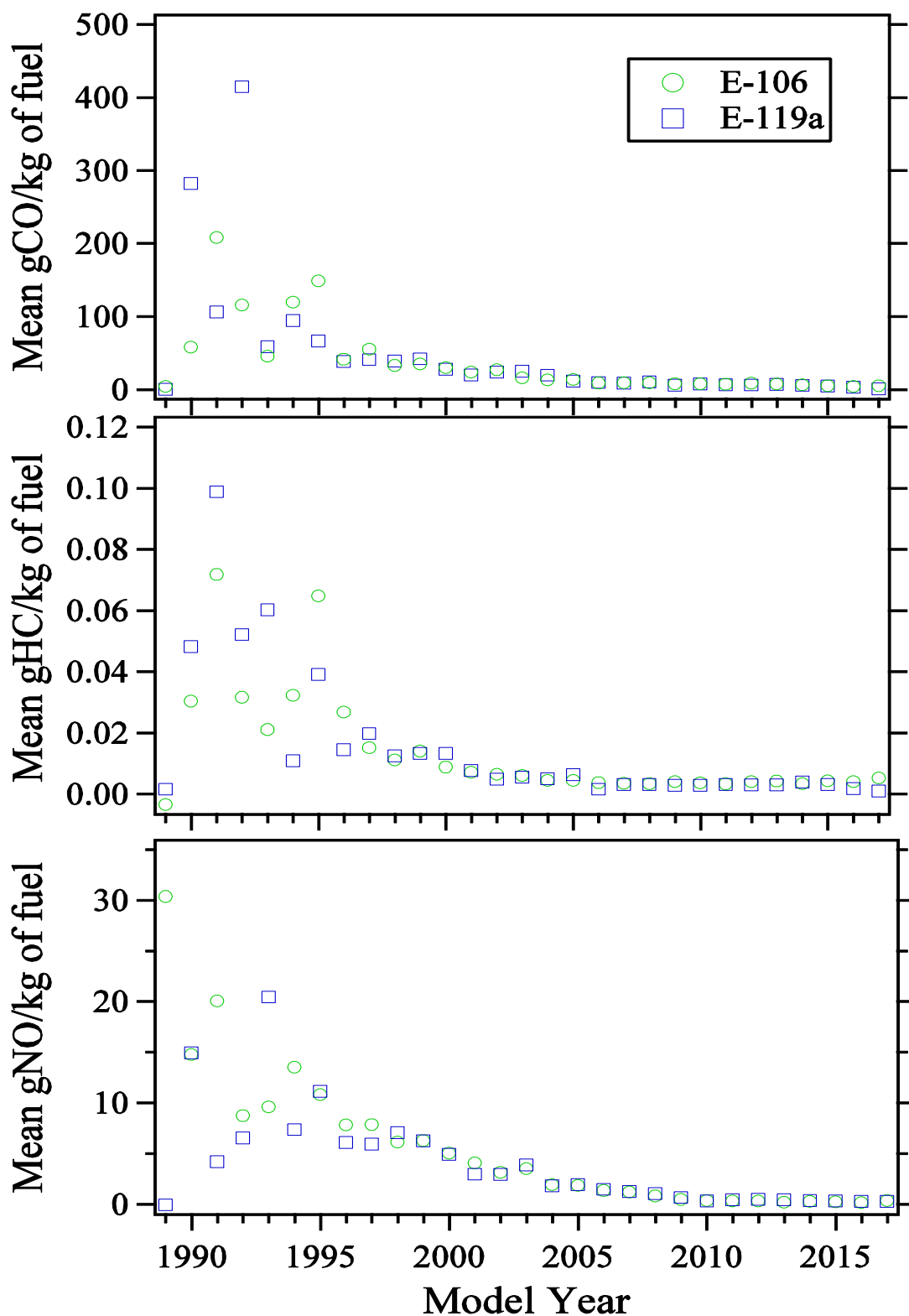
Figure 4. Fuel specific mean vehicle emissions plotted as a function of model year. HC data have been offset adjusted as described in the text. Green circles represent E-106 vehicle measurements and blue squares represent the E-119a vehicle measurements.
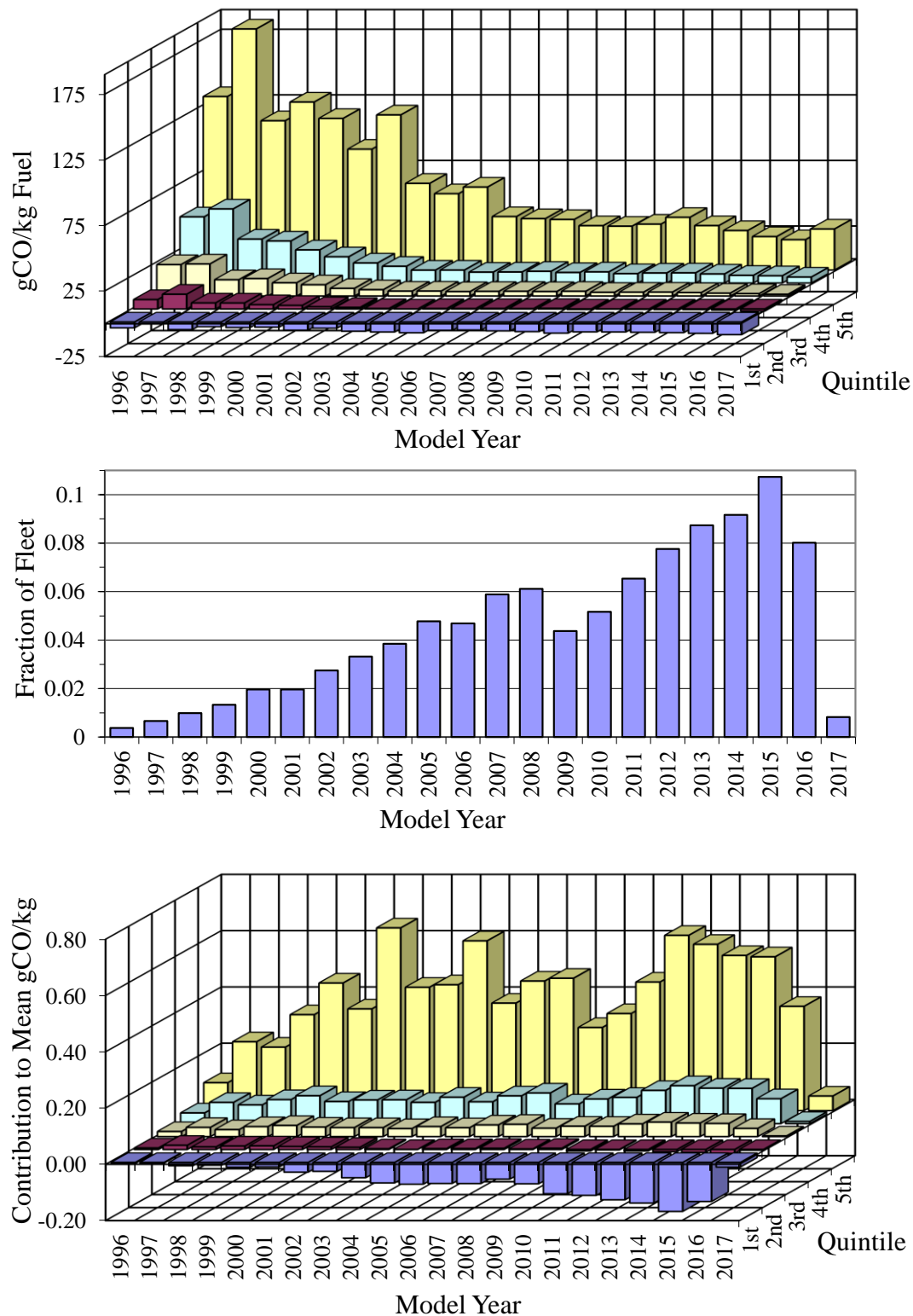
Figure 5. 2016 fuel specific CO emissions for the E-106 data set by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean CO emissions by model year and quintile (bottom).
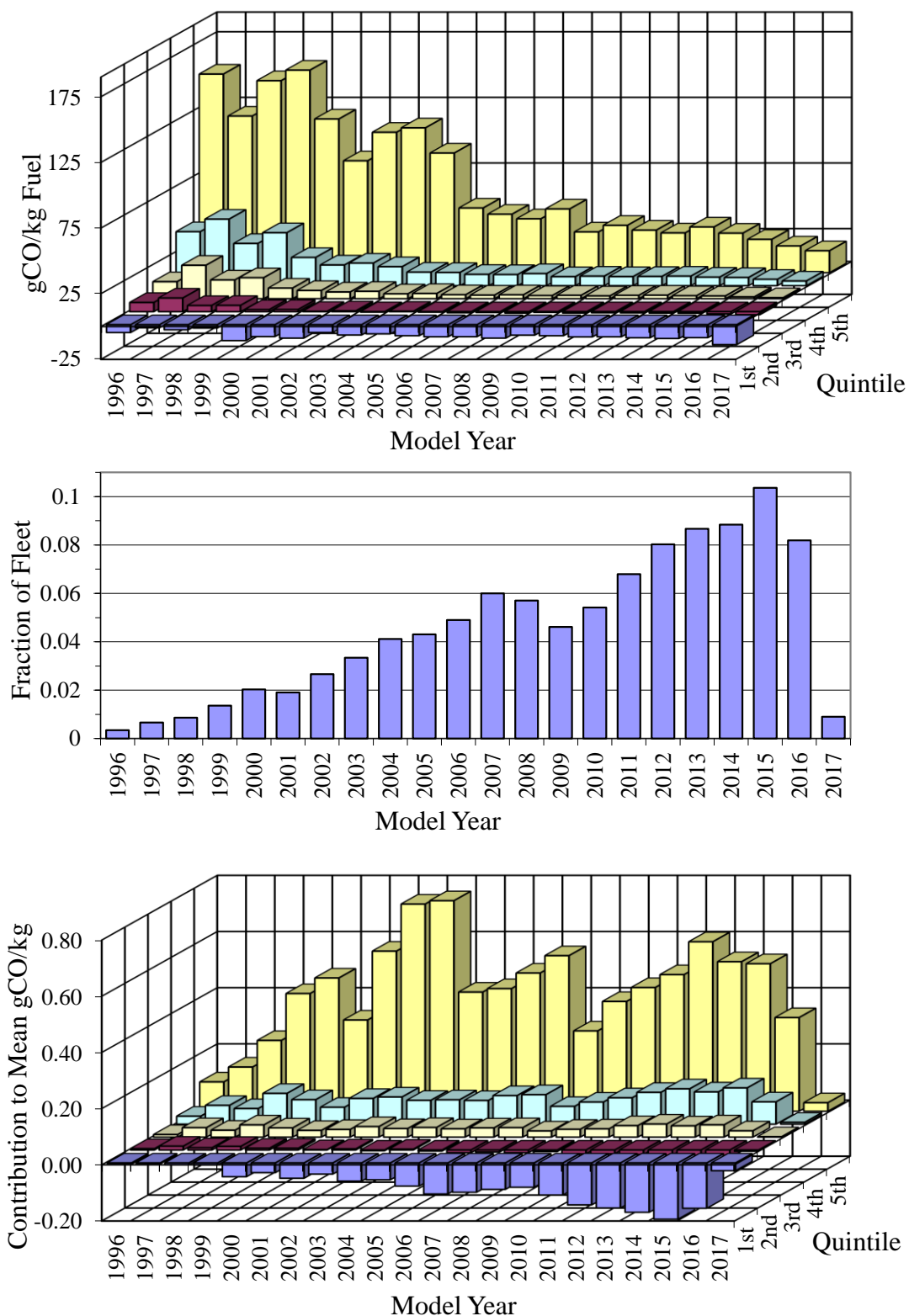
Figure 6. 2016 fuel specific CO emissions for the E-119a data set by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean CO emissions by model year and quintile (bottom).
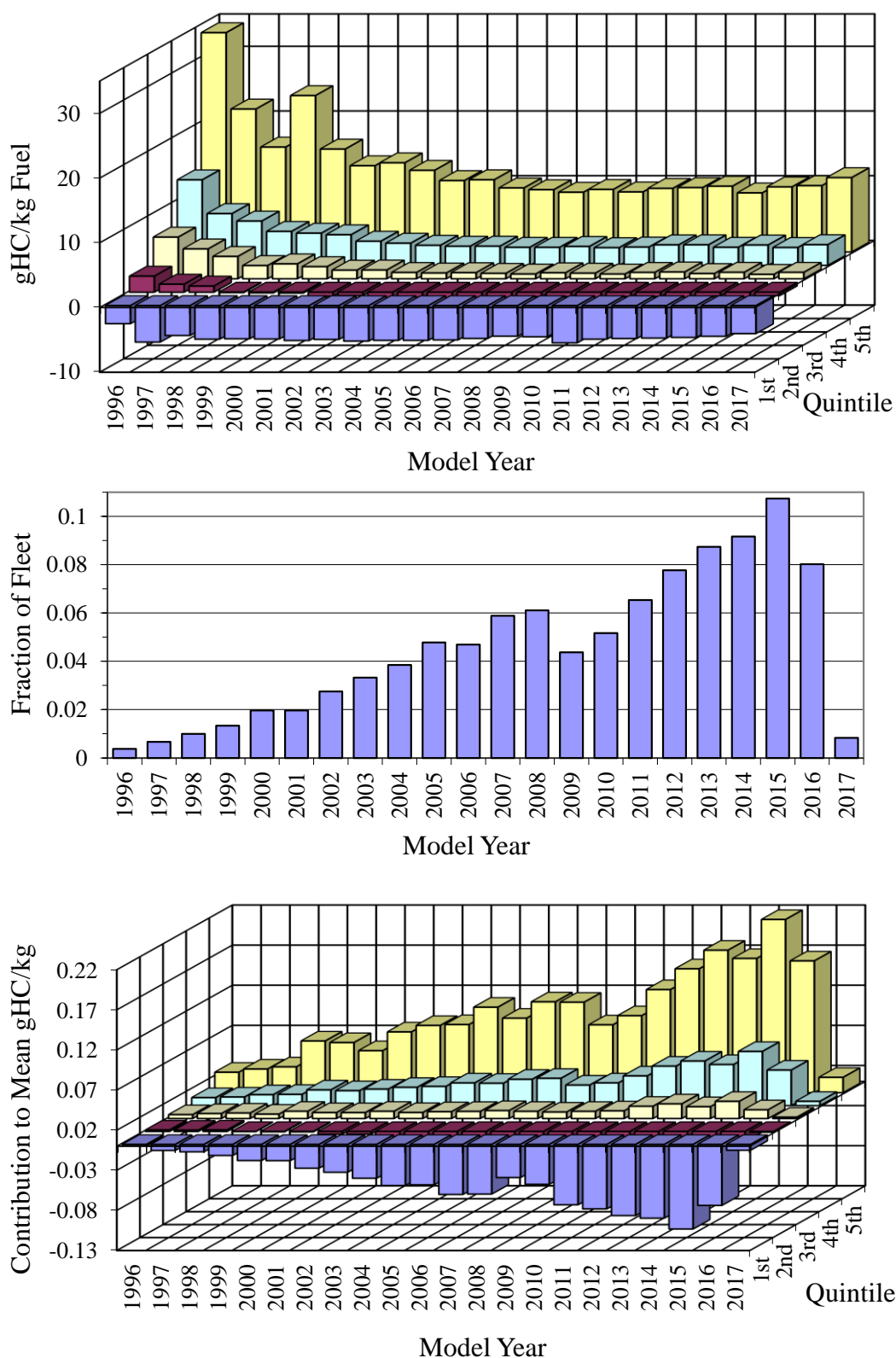
Figure 7. 2016 fuel specific HC emissions for the E-106 data set by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean HC emissions by model year and quintile (bottom).
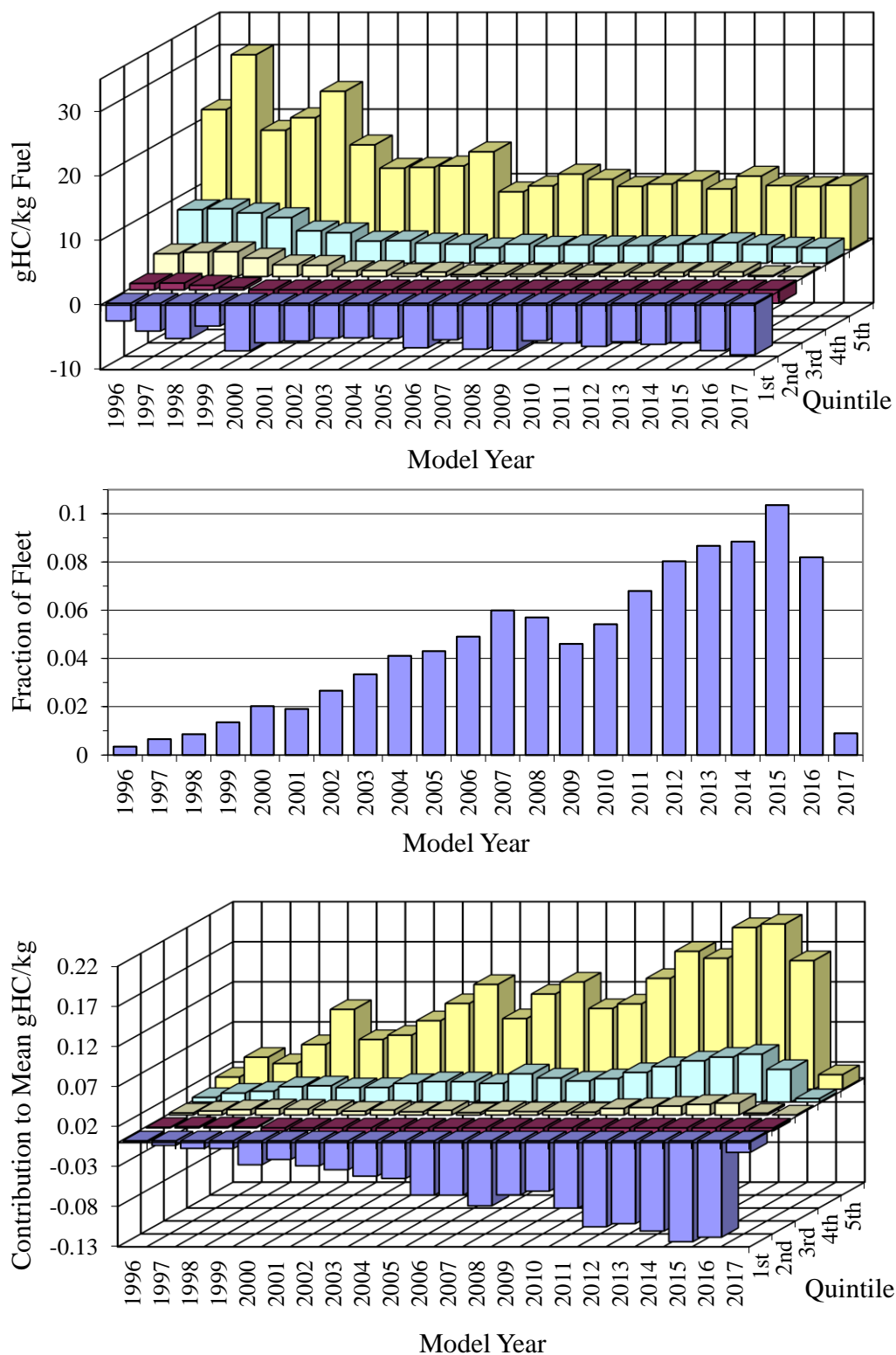
Figure 8. 2016 fuel specific HC emissions for the E-119a data set by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean HC emissions by model year and quintile (bottom).
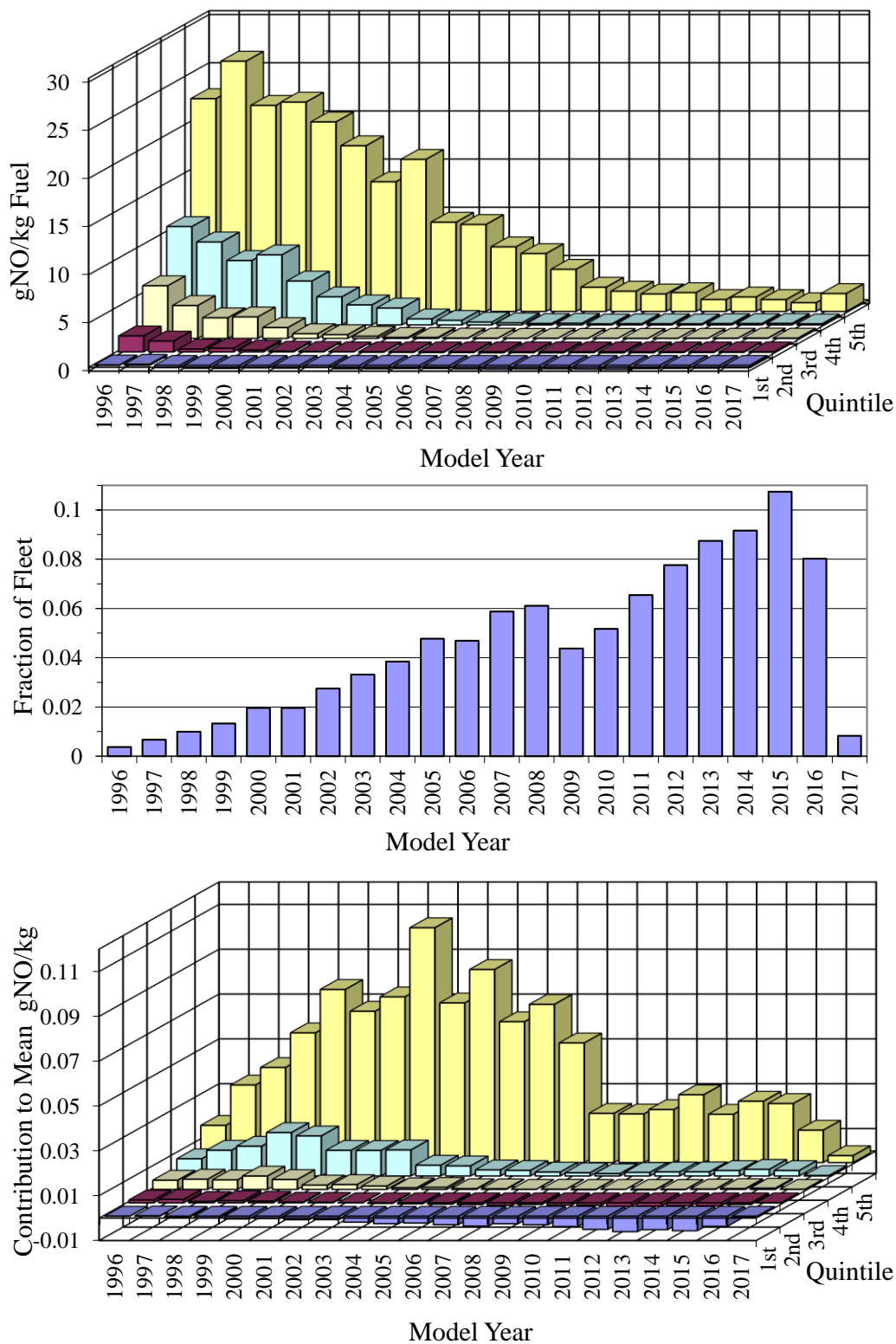
Figure 9. 2016 fuel specific NO emissions for the E-106 data set by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean NO emissions by model year and quintile (bottom).
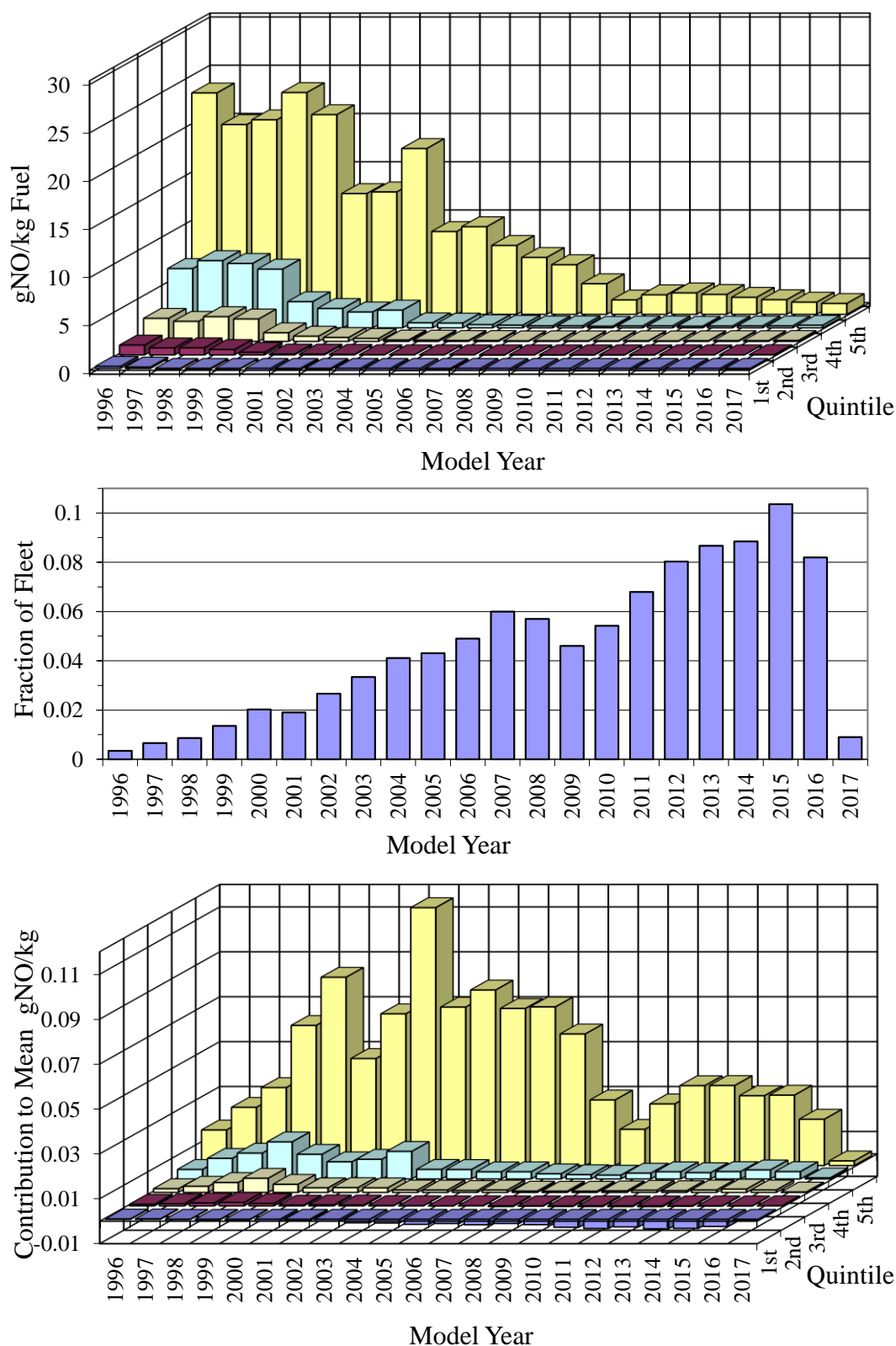
Figure 10. 2016 fuel specific NO emissions for the E-119a data set by model year and quintile (top), fleet distribution (middle) and their product showing the contribution to the mean NO emissions by model year and quintile (bottom).

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

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

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. This equation is derived from dynamometer studies and is necessarily an approximation. The first term represents the work required to climb the gradient, the second term is the *f = ma* work to accelerate the vehicle, the third is an estimated friction term, and the fourth term represents aerodynamic resistance. This equation was used to calculate vehicle specific power for all measurements in each of the eight years' databases. This equation, like all dynamometer studies, does not include any load effects arising from road curvature. The emissions data, binned according to vehicle specific power for both data sets, are graphed in Figure 11. All of the specific power bins contain more than 100 measurements except the -10 bin for the E-106 data (37 measurements) and the 25 bin for the E-119a data (51 measurements) and the HC data have been offset adjusted. The green line with circles represent average emission measurements made during the E-106 data collection and the dashed blue line with squares represents the E-119a measurements. The solid green and dashed blue lines correspond to the right y-axis, presenting the number of vehicles that comprise the VSP data point for E-106 and E-119a measurements respectively. The uncertainties plotted are standard errors of the mean determined from the daily means.

There is a slight increase in measurements in the lower VSP values for the E-119a data set with the 5 VSP bin being the majority as opposed to the 10 VSP bin in E-106 data set. This may be related to the fact that during the E-119a data collection there was additional equipment on the on-ramp downstream of FEAT. This included a slightly raised reflective strip that was taped to the roadway for HEAT's EDAR measurements. Despite the slight difference in driving mode there is little to no differences in the fuel specific emissions versus VSP for CO and NO. In addition both species lack any strong VSP dependence on emissions. Fuel specific HC emissions for the two data sets have nearly identical shapes but the second week of measurements for the E-119a data are slightly lower across all VSP bins with a couple of bins having overlapping uncertainties. At the low VSP bins HC emissions increase as a result of increased deceleration events. Fuel management systems can generally stop air flow faster than fuel flow and this leads to tiny amounts of hydrocarbons being emitted from the engine in the absence of enough air to oxidize it on the catalyst.

Fuel specific NH_3 measurements, shown in Figure 12, show the E-106 and E-119a data sets with green circles and blue squares respectively plotted against model year. The uncertainties included are the standard error of the mean calculated from the daily means. The two data sets are statistically equal for model years newer than 1997. Again, the increase in the variability in emissions that is associated with declining number of measurements is evident after this point. Figure 13 uses the data in shown in Figure 12 and graphs mean fuel specific ammonia emissions for E-119a versus E-106 measurements for each model year newer than 1996. The uncertainties are standard errors of the means calculated from the daily means. The solid line is the best fit line
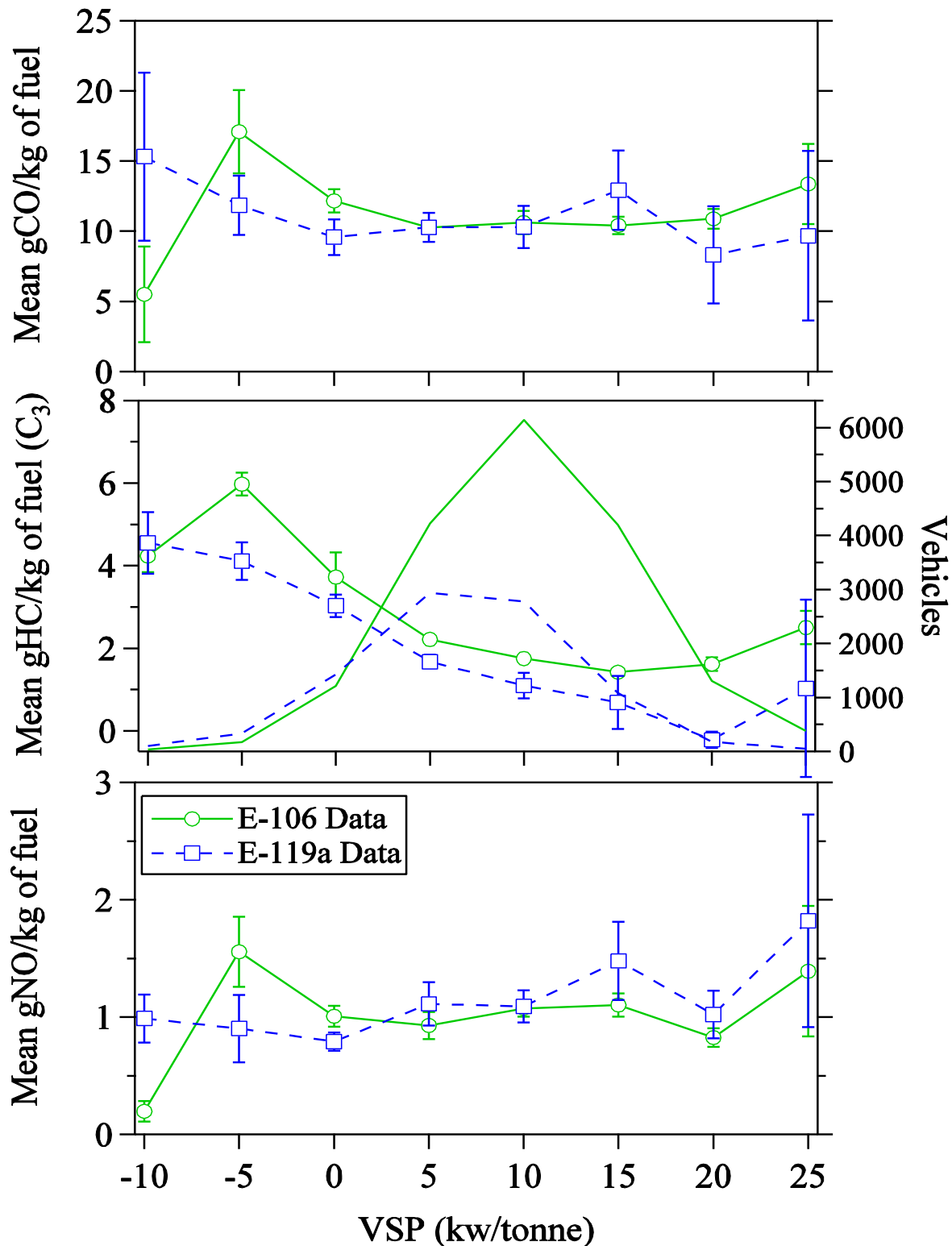
Figure 11. Vehicle emissions as a function of vehicle specific power for both Chicago data sets (E-106 data represented by green circles and E-119a data with blue squares). The lines without markers are the vehicle count profile for the 2015 data sets for E-106 (solid green line) and E-119a (dotted blue line). Uncertainties are standard errors of the mean calculated from the daily values.
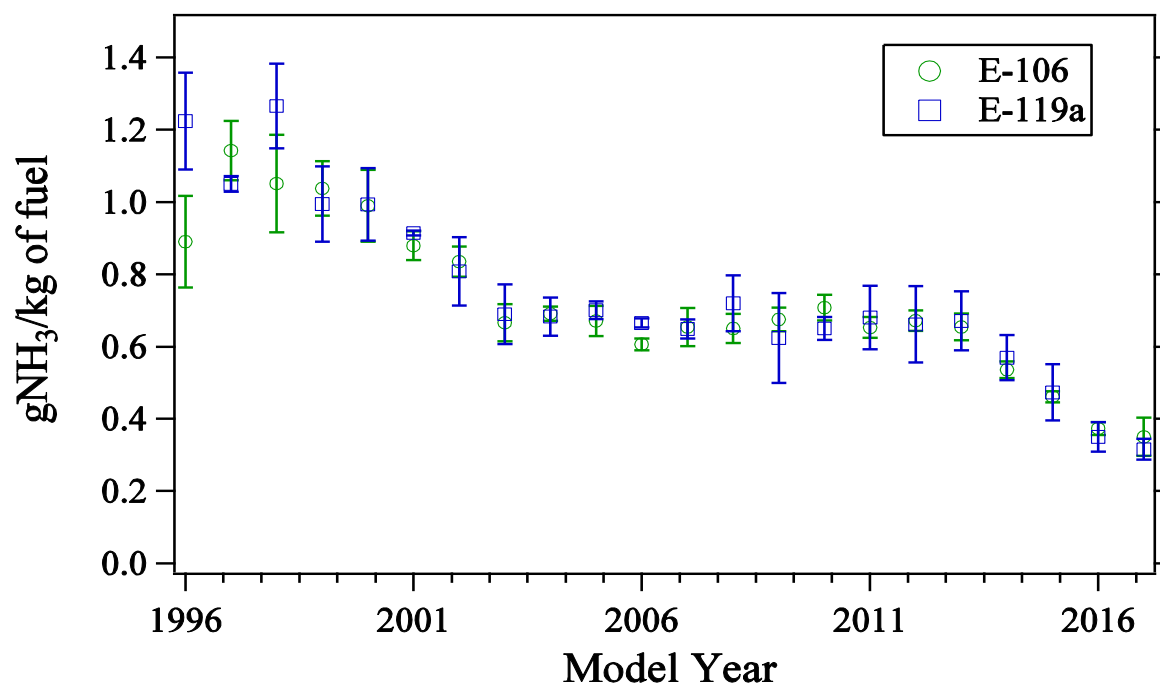
Figure 12. Comparison of gNH3/kg of fuel emissions by model year for the 2016 Chicago E-106 and E-119a data sets. The uncertainties are standard errors of the mean calculated from the daily measurements.
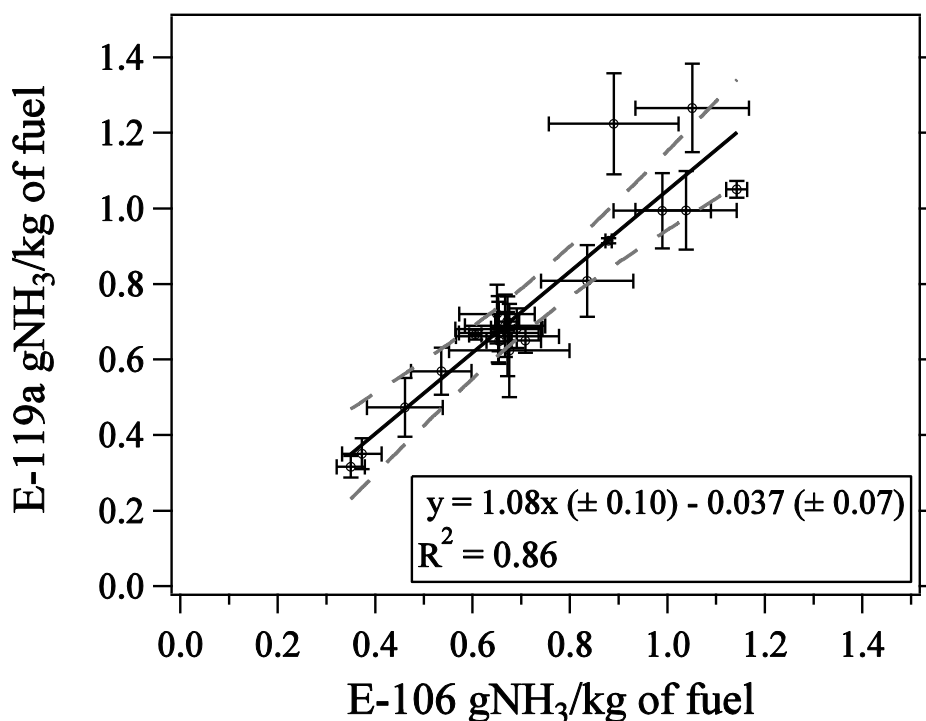
Figure 13. E-119a data set gNH3/kg of fuel by model year plotted against the E-106 data set gNH3/kg of fuel emissions also grouped by model year. The uncertainties plotted are the standard errors of the mean calculated from the daily means for each model year. The result for the least squares best-fit line is in the legend and the dashed lines represent the 95% confidence intervals for the fit.

for all data points with a slope of 1.07, with the dashed line representing the 95% confidence intervals for the least squares fit. The R^2 of 0.86 and a slope near 1 again indicates that model year averages from the E-119a data set and E-106 data set are in good agreement with each other. Older model years are characterized by the data points with the larger uncertainties that begin to deviate from the best fit line. Newer model years are largely represented by the cluster of data points directly on the best fit line.

Repeat vehicles measured three or more times during each week of data collection are shown in Figure 14. Mean fuel specific emissions data for CO, HC and NO are shown in black, blue and green respectively with the standard error of the mean uncertainties shown calculated from each vehicles individual measurements. Because the number of high emitting vehicles has dropped over the last few decades only a few vehicles in each panel dictate the axis ranges. The uncertainties scale with the variability within each vehicles individual measurements. A number of the highest emitting vehicles in the first week show up also in the second week.

In the manner described in the Phoenix, Year 2 report[17], instrument noise was measured by looking at the slope of the negative portion of emissions distribution using a log plot. Such plots were constructed for all the measured pollutants for both 2016 data sets. Linear regression gave best fit lines whose slopes correspond to the inverse of the Laplace factor, which gives an estimate of the noise present in the measurements of each species. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a complete description of the noise. For the E-106 data set the Laplace factors for the g/kg measurements were 5.1, 2.9, 0.34, 0.03 and 0.15 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 7.2 gCO/kg (0.06%), 4.1 gHC/kg (98 ppm), 0.5 gNO/kg (68 ppm), 0.04 gNH_3/kg (5 ppm) and 0.2 gNO_2/kg (11 ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2 respectively. Noise levels were similar for the 3 days of the E-119a data set with the Laplace factors for the g/kg measurements being 4.7, 2.9, 0.28, 0.04 and 0.14 for CO, HC, NO, NH_3 and NO_2 respectively. These values indicate standard deviations of 6.6 gCO/kg (0.05%), 4.1 gHC/kg (99 ppm), 0.4 gNO/kg (54 ppm), 0.06 gNH_3/kg (5 ppm) and 0.2 gNO_2/kg (11 ppm) for individual measurements of CO, HC, NO, NH_3 and NO_2 respectively. Compared to previous campaigns the CO and HC noise levels are improved and the NO and NH_3 noise is a little higher. However, NH_3 in particular is difficult to completely judge by this method as there are very few NH_3 measurements that are near zero.

In terms of uncertainty in average values reported within this report, the numbers are reduced by a factor of the square root of the number of measurements. For example, with an average of 100 measurements, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages for the E-106 data means reduce to 0.7 gCO/kg, 0.4 gHC/kg, 0.05 gNO/kg, 0.004 gNH_3/kg and 0.02 gNO_2/kg and for the E-119a data set 0.7 gCO/kg, 0.4 gHC/kg, 0.04 gNO/kg, 0.006 gNH_3/kg and 0.02 gNO_2/kg respectively.
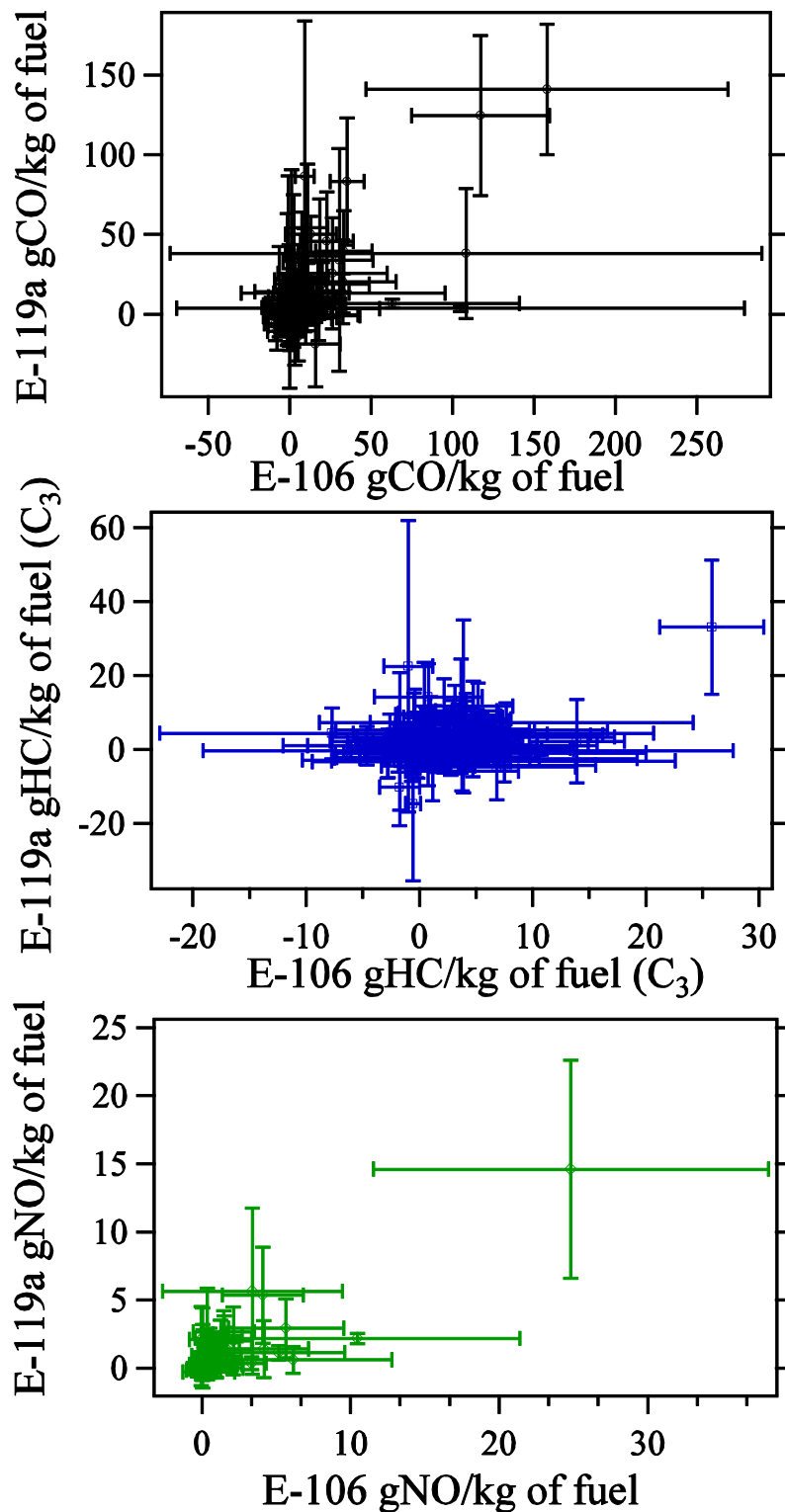
Figure 14. Repeat vehicle (measured at least 3 times in each data set) mean fuel specific emissions comparison plots for CO (top), HC (middle) and NO (bottom). Mean vehicle emissions for the E-106 data set are plotted on the x-axis and the mean emissions for the same vehicle from the E-119a data set are plotted on the y-axis. Standard errors of the mean are the uncertainties shown.

ACKNOWLEDGEMENTS

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

Not measured:

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

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

Invalid :

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX B: Explanation of the ILL_E119a16.dbf database.

The ILL_E119a16.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, Excel, Access or Filemaker Pro, regardless of platform. The following is an explanation of the data fields found in this database:

License   Illinois 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_so2   Sulfur dioxide concentration, in percent.

So2_err   Standard error of the sulfur dioxide measurement.

PercentNH3   Ammonia concentration, in percent.

NH3_err   Standard error of the ammonia measurement.

PercentNO2   Nitrogen dioxide concentration, in percent.

NO2_err   Standard error of the nitrogen dioxide measurement.

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; indicates the strength of the observed plume.

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.

Exp_month   Indicates the month the current registration expires.

Exp_year   Indicates the year the current registration expires.

Year   Model year of the vehicle.

Make   Manufacturer of the vehicle.

Body_style   Type of vehicle.

Vin   Vehicle identification number.

Owner_code   Illinois DMV ownership codes (1 – individual, 2 – multiple individuals same last name, 3 – multiple individuals different last names, 4 – corporate owner, 5 – combined corporate and individual, 6 – multiple corporate ownership, 7 – local government, 8 – state government and 9 – Federal government).

Make_abrv   Abbreviated manufacturer.

City_state   Vehicle's registered city and state.

Zipcode   Vehicle's registered zip code.

Co_gkg   Fuel specific CO emissions, in g/kg of fuel.

Hc_gkg   Fuel specific HC emissions, in g/kg of fuel.

No_gkg   Fuel specific NO emissions, in g/kg of fuel.

Nh3_gkg   Fuel specific NH_3 emissions, in g/kg of fuel.

No2_gkg   Fuel specific NO_2 emissions, in g/kg of fuel.

Nox_gkg   Fuel specific NO_x emissions, in g/kg of fuel.

Hc_offset   Offset used to calculate gHC/kg of fuel.

Hcgkg_off   Fuel specific HC emissions using offset, in g/kg of fuel.

Vsp   Calculated VSP.

APPENDIX C: Temperature and Humidity Data from Chicago O'Hare Int. Airport.

Time (CDT)	1997									
	Sept. 15		Sept. 16		Sept. 17		Sept. 18		Sept. 19	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	64	100	68	87	68	81	64	78	71	84
0800	69	78	71	84	69	70	71	68	-	-
0900	73	68	75	73	71	61	75	57	77	76
1000	75	68	78	71	75	46	77	46	78	73
1100	78	61	80	66	77	39	78	44	80	73
1200	80	57	84	60	78	38	82	36	82	69
1300	80	57	82	62	80	32	82	36	80	73
1400	80	57	84	60	80	29	82	36	77	76
1500	80	62	84	58	80	29	82	32	73	87
1600	78	66	82	58	80	27	80	32	71	93
1700	75	73	82	58	78	32	78	38	71	100
1800	73	78	80	68	78	38	77	39	71	93

Time (CDT)	1998							
	Sept. 21		Sept. 22		Sept. 23		Sept. 24	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	57	66	57	80	51	68	53	89
0800	59	62	62	72	55	54	55	83
0900	60	59	62	72	59	51	57	77
1000	64	51	64	67	60	49	59	72
1100	64	55	66	56	62	42	60	77
1200	64	55	62	67	64	39	64	72
1300	66	48	62	67	64	39	64	72
1400	64	60	64	60	64	36	66	67
1500	64	62	64	51	66	34	64	72
1600	64	62	62	60	66	36	64	72
1700	62	67	62	55	62	51	64	78
1800	62	67	59	53	55	61	62	83

1999								
Time (CDT)	Sept. 20		Sept. 21		Sept. 22		Sept. 23	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	54	87	48	89	46	80	54	65
0800	55	80	49	80	54	56	58	56
0900	57	75	53	74	59	43	62	51
1000	60	62	57	67	63	37	70	42
1100	62	56	57	64	66	34	74	36
1200	62	52	59	58	66	33	77	31
1300	60	53	60	58	71	33	78	31
1400	60	50	59	56	72	32	79	31
1500	63	43	60	53	72	33	80	31
1600	62	43	59	58	72	33	78	36
1700	59	51	57	62	71	35	77	37
1800	58	60	55	69	67	40	75	40

2000								
Time (CDT)	Sept. 11		Sept. 12		Sept. 13		Sept. 14	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0800	76	85	63	76	62	60	64	96
0900	79	79	65	70	66	50	63	93
1000	82	71	67	59	69	47	60	96
1100	84	66	68	53	71	44	65	81
1200	87	61	69	45	74	41	68	63
1300	77	73	71	41	76	39	70	53
1400	74	78	71	47	77	36	73	38
1500	66	95	70	46	78	36	72	38
1600	67	95	70	47	79	34	72	44
1700	68	89	68	47	77	36	71	42
1800	69	84	66	49	73	48	67	47
1900	69	87	64	52	64	70	64	52

	2002									
	Sept. 16		Sept. 17		Sept. 18		Sept. 19		Sept. 20	
Time (CDT)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	57	90	60	84	62	100	73	96	71	94
0800	63	70	66	72	64	93	74	94	70	100
0900	67	55	71	63	68	87	75	94	70	100
1000	69	55	74	60	70	76	76	91	70	100
1100	70	53	75	52	72	73	77	90	71	96
1200	72	50	77	50	72	79	76	97	70	90
1300	73	44	76	52	75	79	79	88	69	87
1400	75	40	79	47	78	74	79	82	69	90
1500	75	42	79	42	79	74	78	85	69	87
1600	76	39	77	45	79	74	78	79	69	87
1700	74	41	74	52	78	74	79	77	69	84
1800	67	57	73	57	77	79	77	79	67	87

	2004							
	Sept. 20		Sept. 21		Sept. 22		Sept. 23	
Time (CDT)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0800	63	54	67	61	69	57	70	61
0900	67	47	72	46	73	50	75	50
1000	71	42	75	37	76	43	79	44
1100	72	41	77	35	78	37	80	39
1200	74	38	80	34	78	37	81	38
1300	76	33	80	34	80	35	83	37
1400	77	28	81	32	80	35	84	35
1500	78	29	82	28	78	40	84	32
1600	77	30	81	30	80	38	84	33
1700	75	39	80	33	76	43	82	34
1800	71	49	70	55	68	63	78	39
1900	67	59	67	59	70	57	76	42

	2006							
Time (CDT)	Sept. 12		Sept. 13		Sept. 14		Sept. 15	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0751	67	93	60	93	64	70	65	87
0851	68	93	60	93	66	70	69	76
0951	68	90	61	93	68	68	72	66
1051	68	97	61	90	71	61	72	59
1151	68	97	62	84	71	64	77	52
1251	70	90	62	87	71	64	75	52
1351	70	87	63	84	71	61	77	50
1451	71	84	62	87	72	57	78	47
1551	68	93	63	81	71	61	74	60
1651	66	90	63	81	69	66	73	64
1751	65	90	63	81	67	68	71	68
1851	65	90	62	81	65	75	69	76

	2014											
Time (CDT)	Sept. 8		Sept. 9		Sept. 10		Sept. 11		Sept. 12		Sept. 13	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0851	70	51	70	66	71	90	50	66	52	61	47	74
0951	72	46	71	66	73	90	51	69	52	64	49	69
1051	74	43	75	60	73	90	51	69	54	59	51	61
1151	75	40	77	54	74	82	52	64	54	67	53	59
1251	76	43	79	52	78	71	52	64	52	83	54	57
1351	76	42	77	60	79	67	53	62	51	90	57	51
1451	76	43	78	58	78	64	53	64	49	93	56	53
1551	75	46	78	58	77	64	52	66	48	89	56	53
1651	74	48	77	62	76	64	51	66	47	89	57	51
1751	72	50	75	66	68	81	51	69	46	93	54	59
1851	70	51	76	62	63	78	51	69	46	89	52	64

2016										
Time (CDT)	Sept. 12		Sept. 13		Sept. 14		Sept. 15		Sept. 16	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0851	71	55	74	64	71	59	70	68	72	71
0951	73	50	76	62	72	51	72	62	77	67
1051	75	48	78	62	73	52	74	56	80	62
1151	76	47	80	58	73	52	76	50	79	65
1251	77	45	81	53	73	52	77	48	79	69
1351	78	40	82	51	73	50	77	50	82	61
1451	78	40	84	51	73	48	76	54	81	63
1551	78	42	82	47	72	50	75	58	81	63
1651	77	45	80	54	71	53	73	59	80	60
1751	73	52	75	71	69	61	71	66	79	60
1851	70	59	73	76	67	68	70	68	78	62

2016						
Time (CDT)	Sept. 19		Sept. 20		Sept. 21	
	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0851	76	50	76	50	70	87
0951	80	44	78	40	72	79
1051	82	40	80	35	73	79
1151	85	35	81	30	73	74
1251	86	29	82	27	68	90
1351	87	28	81	28	68	90
1451	87	26	81	27	70	79
1551	86	26	80	28	72	71
1651	84	29	79	28	73	74
1751	82	33	75	33	72	73
1851	79	36	72	40	68	81

APPENDIX D: Calculation of Vehicle Specific Power Adjusted Vehicle Emissions

1997 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	236	225	53200
	0	224	1609	360090
	5	307	4985	1531000
	10	431	6146	2648020
	15	548	2624	1438060
	20	590	456	269180
			16045	6299550
		Mean NO (ppm)		**393**

1998 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	233	137	31951
	0	239	784	187394
	5	265	3613	956613
	10	385	6685	2576433
	15	475	6012	2856195
	20	483	2392	1156320
			19623	7764906
		Mean NO (ppm)		**396**

1998 (Adjusted)	VSP Bin	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	-5	233	225	52474
	0	239	1609	384588
	5	265	4985	1319877
	10	385	6146	2368700
	15	475	2624	1246616
	20	483	456	220436
			16045	5592691
		Mean NO (ppm)		**349**

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

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

APPENDIX E: Calculation of Model Year Adjusted Fleet Emissions

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

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

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

APPENDIX F: Field Calibration Record.

1997				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/15	9:35	1.42	1.35	1.07
9/15	14:30	1.26	1.18	0.94
9/16	9:20	1.33	1.25	1.02
9/16	12:40	1.12	1.08	0.86
9/17	8:10	1.39	1.27	1.11
9/17	11:55	1.19	1.12	0.97
9/18	8:15	1.49	1.41	1.20
9/18	12:30	1.15	1.10	0.86
9/19	11:00	1.24	1.16	0.95

1998				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/21	8:15	1.38	1.26	1.21
9/21	13:00	1.31	1.17	1.15
9/22	7:40	1.48	1.36	1.46
9/22	11:40	1.26	1.15	1.27
9/23	8:00	1.64	1.52	1.26
9/23	10:45	1.32	1.25	1.13
9/24	9:00	1.46	1.33	1.41
9/24	12:30	1.30	1.19	1.12

1999				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/20	9:50	1.32	1.05	1.21
9/20	14:30	1.25	0.99	1.15
9/21	8:15	1.45	1.19	1.46
9/21	10:30	1.33	1.07	1.27
9/22	8:30	1.47	1.13	1.32
9/22	11:10	1.22	1.01	1.201
9/23	8:15	1.46	1.16	1.41
9/23	10:30	1.25	0.97	1.12

2000				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/11	8:50	1.22	0.94	1.22
9/11	11:20	1.12	0.87	1.10
9/11	18:05	1.28	0.98	1.35
9/12	8:35	1.29	0.99	1.49
9/13	8:10	1.41	1.11	1.38
9/13	10:35	1.18	0.94	1.13
9/14	8:25	1.36	1.03	1.49
9/14	10:25	1.35	1.07	1.49
9/14	12:35	1.19	0.93	1.25

2002				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/16	11:10	1.35	1.07	1.59
9/17	9:35	1.52	1.19	1.82
9/17	12:00	1.35	1.07	1.46
9/18	9:00	1.51	1.19	1.67
9/18	12:45	1.36	1.07	1.44
9/19	9:20	1.59	1.31	1.60
9/19	12:35	1.39	1.16	1.40
9/20	12:30	1.31	1.17	1.68

2004				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/20	9:00	1.66	1.45	1.47
9/20	11:15	1.37	1.14	1.26
9/21	8:45	1.58	1.32	1.35
9/21	11:10	1.31	1.11	1.19
9/22	8:00	1.77	1.50	1.58
9/22	10:00	1.39	1.19	1.23
9/23	8:00	2.24	1.66	1.87
9/23	10:00	1.43	1.22	1.27

2006				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/12	9:05	1.69	1.41	1.52
9/13	10:00	1.58	1.30	1.51
9/13	11;50	1.75	1.38	1.48
9/13	13:50	1.48	1.20	1.19
9/14	8:00	1.59	1.30	1.41
9/14	11:00	1.43	1.19	1.22
9/15	8:00	2.32	1.91	2.35
9/15	9:30	1.69	1.42	1.56
9/15	11:15	1.46	1.22	1.31

2014						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
9/8	10:00	1.58	1.44	1.44	0.99	0.72
9/8	12:30	1.34	1.23	1.33	0.99	0.6
9/9	9:25	1.62	1.46	1.58	0.96	0.72
9/9	11:30	1.41	1.30	1.37	0.96	0.67
9/10	13:45	1.34	1.24	1.35	0.91	0.69
9/11	9:15	1.83	1.66	1.79	0.98	1.03
9/11	12:20	1.75	1.59	1.73	1.0	0.97
9/11	16:15	1.83	1.63	1.77	0.98	1.04
9/12	9:20	1.85	1.65	1.78	1.02	1.09
9/12	12:15	1.76	1.57	1.68	1.03	0.98
9/13	9:25	1.90	1.70	1.82	0.99	1.13
9/13	12:00	1.75	1.55	1.67	1.03	0.92
9/13	14:35	1.66	1.49	1.62	1.04	0.99

2016						
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	NH_3 Cal Factor	NO_2 Cal Factor
9/12	10:00	1.52	1.42	1.36	0.97	1.32
9/12	13:00	1.4	1.3	1.3	1.0	1.0
9/13	09:20	1.53	1.40	1.44	1.0	1.20
9/13	12:00	1.39	1.27	1.35	1.0	0.91
9/14	09:06	1.72	1.61	1.61	0.95	1.30
9/14	11:22	1.52	1.42	1.44	0.98	1.07
9/14	13:53	1.54	1.45	1.46	1.01	1.08
9/15	9:05	1.78	1.63	1.66	0.97	1.4
9/15	13:15	1.56	1.44	1.48	1.01	1.12
9/16	9:00	1.70	1.60	1.61	0.95	1.23
9/16	11:15	1.48	1.41	1.43	0.96	1.06
9/19	9:30	1.68	1.62	1.55	0.94	1.23
9/19	11:10	1.42	1.34	1.24	0.98	1.10
9/20	9:20	1.62	1.54	1.51	0.94	1.10
9/20	12:10	1.45	1.41	1.39	1.03	1.07
9/21	10:10	1.66	1.57	1.54	0.86	1.37
9/21	16:10	1.67	1.53	1.58	0.89	1.34