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ON-ROAD REMOTE SENSING OF AUTOMOBILE EMISSIONS IN THE ROLLING MEADOWS AREA: FALL 2016

January 2018

COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

Hager Environmental & Atmospheric Technologies
HEAT

Remote Sensing of Automobiles Emissions in Rolling Meadows: Fall 2016

Dr. J. Stewart Hager

Hager Environment &
Atmospheric Technologies
539 Milwaukee Way
Knoxville, TN 37932

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Prepared for:

Coordinating Research Council, Inc.
5755 North Point Parkway, Suite 265
Alpharetta, Georgia 30022

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We would also like to thank the Illinois Secretary of State, Freedom of Information Act Office, and Illinois EPA for providing us with the vehicle data after the survey was completed from the license plates collected while on road in Rolling Meadows, Illinois.

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LIST OF ACRONYMS AND ABBREVIATIONS

BAR – California Bureau of Automotive Repair
CO – Carbon Monoxide
CO_2 – Carbon Dioxide
CRC – Coordinating Research Council
DIAL – Differential Absorption LiDAR
EDAR – Emissions Detection And Reporting
FEAT – Fuel Efficiency Automobile Test Device
HC – Hydrocarbons
HEAT – Hager Environmental & Atmospheric Technologies
NO – Nitric Oxide
OREMS – On-road Emissions Measurement Standards
PDF - Probability Density Function
2D – Two Dimensional
VIN – Vehicle Identification Number
s - second

EXECUTIVE SUMMARY

Hager Environmental & Atmospheric Technologies (HEAT) conducted a remote sensing study using its proprietary Emissions Detecting and Reporting (EDAR) on-road remote sensing system in the Rolling Meadows area during the fall of 2016. For the past decade, the University of Denver has completed this specific remote sensing study at this location. This was HEAT's first time deploying alongside the University of Denver for this study.

This study involved setting up EDAR on September 19 - 21, 2016, at the on-ramp from Algonquin Rd. to eastbound I-290 in northwest Chicago in the suburb of Rolling Meadows, IL. The EDAR device measured CO, CO_2, NO, and HC from vehicles driving under the laser-based exhaust gas sensor as they gained speed to merge on to the highly traveled I-290. In addition to the gas data, the EDAR system collected the following information: license plate, speed, acceleration, wind speed, temperature, humidity, a scene image, and a 2D infrared image of the vehicle as it drove underneath EDAR. A total of 16,852 measurements were attempted and of those 13,985 Illinois license plates were submitted to the Secretary of State of Illinois. All the records submitted had valid measurements for all the detected gases. Out of the attempted measures of 16,852, there were 15,255 valid measurements, which accounted for a 91% valid hit rate. The data reduction process is summarized in Table 1.

This document also includes error analysis with a report of standard errors. The captured valid CO2 measurements, show the fleet as a whole mean (and standard errors of the mean) tailpipe emissions for CO, NO and HC, to be 759 ± 0.28 ppm, 85 ± 0.11 ppm and 42 ± 0.13 ppm respectively.

Furthermore, this study provides an average of absolute emissions for each gas in moles/m, which can be converted to instantaneous mg/mile depending on the molecular mass of the molecule. This does not represent regulatory testing. Due to the fact EDAR can see the entire plume, these values represent the actual amount the vehicle left behind while under EDAR and exhibit a decreasing general trend for vehicles of newer model years.

Introduction

Maintaining the National Ambient Air Quality Standards established by the Environmental Protection Agency (EPA) has been challenging for many of the heavily populated U.S. cities. Motor vehicles are thought to be one of the largest sources of many air pollutants in urban areas.[1] Real-world emissions measurements are needed to characterize these pollutants. It is of paramount importance to precisely measure vehicle exhaust emissions in general so government bodies can make sound policy decisions. In addition, interest in the remote sensing of vehicle exhaust emissions as an alternative and/or supplement to traditional dynamometer-based measurements has increased due to the desire to monitor real world impacts.

Hager Environmental & Atmospheric Technologies (HEAT) has developed the remote sensing Emissions Detection and Reporting device called EDAR. HEAT conducted the Rolling Meadows remote sensing study at the on-ramp from Algonquin Road to I-290, using its EDAR device. This site was first chosen in 1997 for a 5-year study by the University of Denver. Subsequent studies were performed by University of Denver in 2004, 2006, 2014 and 2016. HEAT was contracted by the Coordinating Research Council (CRC) to measure on-road emissions over a three-day period. The chosen dates were September 19-21 with hours starting in the early mornings and ending in the late evening in order to cover rush hours for both morning and evening. To perform this study, HEAT obtained the proper permits and Letter of Authority from the City of Rolling Meadows for the deployment of EDAR on-road. The purpose of this study is to examine the effectiveness of remote sensing.

In addition, the calculation of absolute emission rates (grams/mi) are possible with the EDAR system because of the geometry of the remote sensing set up (*See section 1.2 for a more detailed equipment description*). EDAR scatters laser light off of a reflector placed on the road surface; therefore, it is always looking down onto the plume. This allows EDAR to remotely detect the entire plume at one time. One can use the total optical mass of each measurement across the plume to calculate absolute values, the mole or gram per distance emission rates are calculated directly.

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[1] http://www.dec.ny.gov/chemical/8577.html

1. BACKGROUND

1.1. Company Profile

Hager Environmental & Atmospheric Technologies, LLC (HEAT), is a Woman-Owned, NASA spin off[2] business founded in 2009 with headquarters in Knoxville, Tennessee. HEAT's founder, Dr. Stewart Hager, developed the Emissions Detection and Reporting (EDAR) device which is an eye-safe, laser-based technology capable of remotely detecting and measuring the infrared absorption of environmentally critical gases (such as CO, CO_2, NO, NO_2, HC and $PM_{2.5}$) coming out of a moving vehicle.

EDAR was successfully introduced to the North American emissions measurement industry at the I/M Solutions Conference in Salt Lake City, Utah, in April 2014. EDAR is operational and has been successfully deployed commercially in Connecticut, Arizona, Tennessee and the United Kingdom. Since that time, HEAT has been rehired by Connecticut and Arizona for testing in 2016 as well as contracted with Scotland for a large-scale pilot. In addition, HEAT recently won their first large-scale clean screen program in Nashville, TN.

EDAR is a laser-based technology with one footprint for both heavy and light duty vehicles. The basic geometry of EDAR allows for the detection of the plume no matter where the tailpipe is located. Another unique characteristic EDAR possesses is the application of the DiAL (Differential Absorption LiDAR) method to detect and quantify gases such as but not limited to CO, CO_2 HC, NO, NO_2 and $PM_{2.5}$. This laser based system does not require calibration therefore it is unmanned. The EDAR device is an emissions camera that is capable of reading emissions from vehicles on multilane highways and can measure the exhaust temperature from vehicles as well as create a 2-D image of the plume in real time.

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[2] https://spinoff.nasa.gov/Spinoff2017/t_4.html

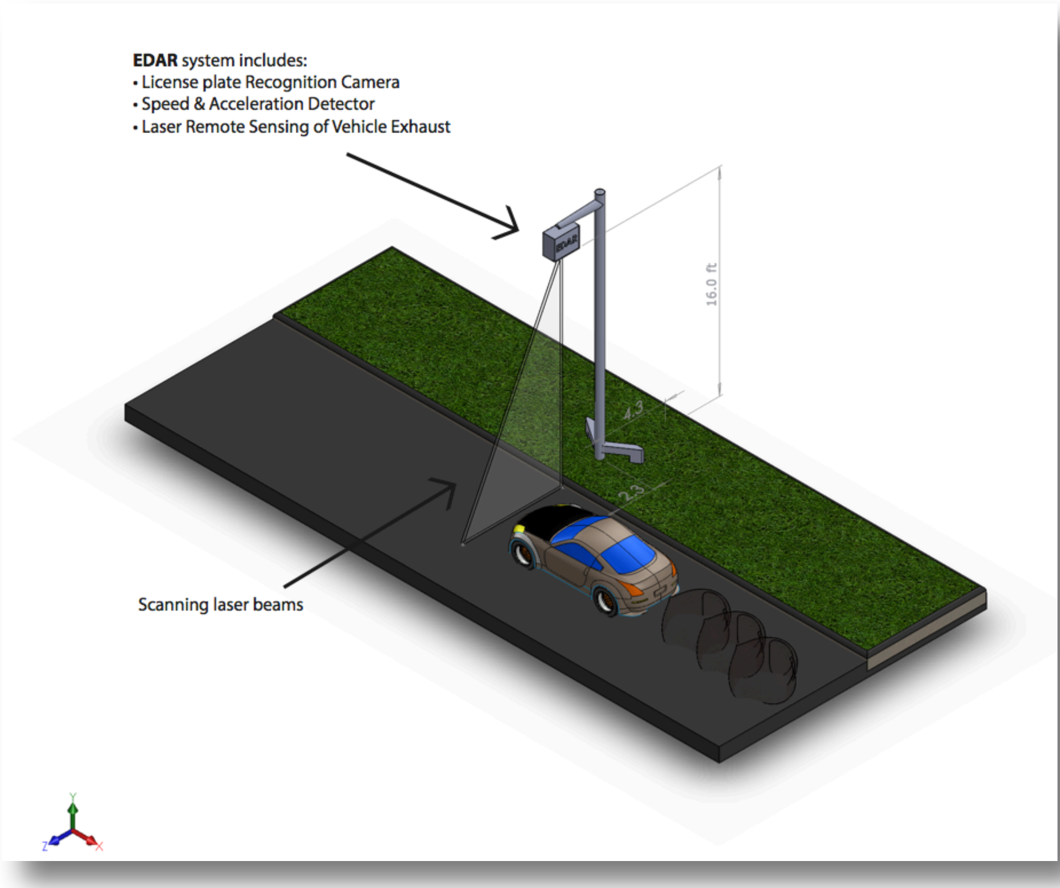
1.2. Equipment Description

The Rolling Meadows study was performed using HEATs EDAR (Emission Detection And Reporting) system, which is an unmanned, automated vehicle emissions measurement system. The entire system is comprised of an eye-safe, laser-based infrared gas sensor, a vehicular speed/acceleration sensor, and a license plate reader.

EDAR measures the infrared absorption of environmental critical gases (such as CO, CO_2, NO, NO_2, HC and $PM_{2.5}$) coming out of virtually any moving vehicle: specifically, pollutants emitted by in-use vehicles. It also measures the entire exhaust plume as the vehicle passes allowing for the determination of the mass emission rates of the vehicle. Infrared laser light is scattered off a reflector placed on the road surface and then the back-scattered light is collected by EDAR.

The all-in-one EDAR system is fully weatherproofed to protect it from environmental elements (heat, rain, snow, wind, etc.). In addition, EDAR occupies a relatively small footprint, sitting on a single pole that is deployable roadside in either a temporary or permanent application. See Figure 1.

Figure 1. Example of EDAR Roadside Implementation



The gas sensor emits a sheet of invisible laser light from above that can unambiguously measure specified molecules emitted from any vehicle that breaks the beam. The lasers are configured for the pollutants CO_2, CO, NO, and HC. Due to the fact that the gas sensor looks down from above and can "see" a whole lane of traffic, EDAR can detect an entire exhaust plume as it exits the vehicle as well as any indication of interfering plumes (*see* *section 2.2* *for further explanation on interfering plumes*.) Seeing the whole plume is advantageous since it allows for consistently high signal to noise ratio (SNR) and measurements such as absolute amounts which allows for determination of emissions rates in mass per unit travelled (grams/mile), which can be used to calculate the quantity of emissions produced. Furthermore, in the case of strong crosswinds, where absolute amounts are not possible directly, HEAT will use the stoichiometric calculation because EDAR's geometry allows for the measurement of the thickest optical mass of the plume. In other words, EDAR always measures the thickest part of the plume so its results are consistent from vehicle to vehicle. In addition, EDAR is able to take infrared images of the vehicles passing below the sensor, allowing the vehicle's shape to be determined whether it is a heavy truck, car, motorcycle or a vehicle pulling a trailer. The position of the tailpipe can also be determined by the CO_2 plume's position with respect to the image of the vehicle. This allows for the identification of any pollution hot spots such as evaporative HC emissions leaks on the vehicle. Furthermore, vehicle speed and acceleration rates during the measurement that could negatively impact the measurements are detected, thus facilitating a precise and controlled data collection. It is also important to note EDAR uses DiAL (Differential Absorption LiDAR). The DiAL method continuously subtracts the background which includes fog, dust, dirt, ambient light, instrument variations and humidity. In addition, the principle that underlies the DiAL method is the reason the EDAR system does not require calibration. EDAR also calculates the temperature of the exhaust using spectroscopic techniques and by using temperature insensitive absorption features. Therefore, EDAR's measurements are not affected by temperature, fog, dust, dirt, ambient light, instrument variations or humidity. Remote sensing technologies in general cannot operate in rain or snowy conditions.

The EDAR system also gathers vehicle characteristic data necessary for analysis of the emissions results. These include:

- A laser-based rangefinder system for vehicle detection as well as speed and acceleration measurements. The rangefinder detects the vehicles from above in the same manner as the gas sensor.

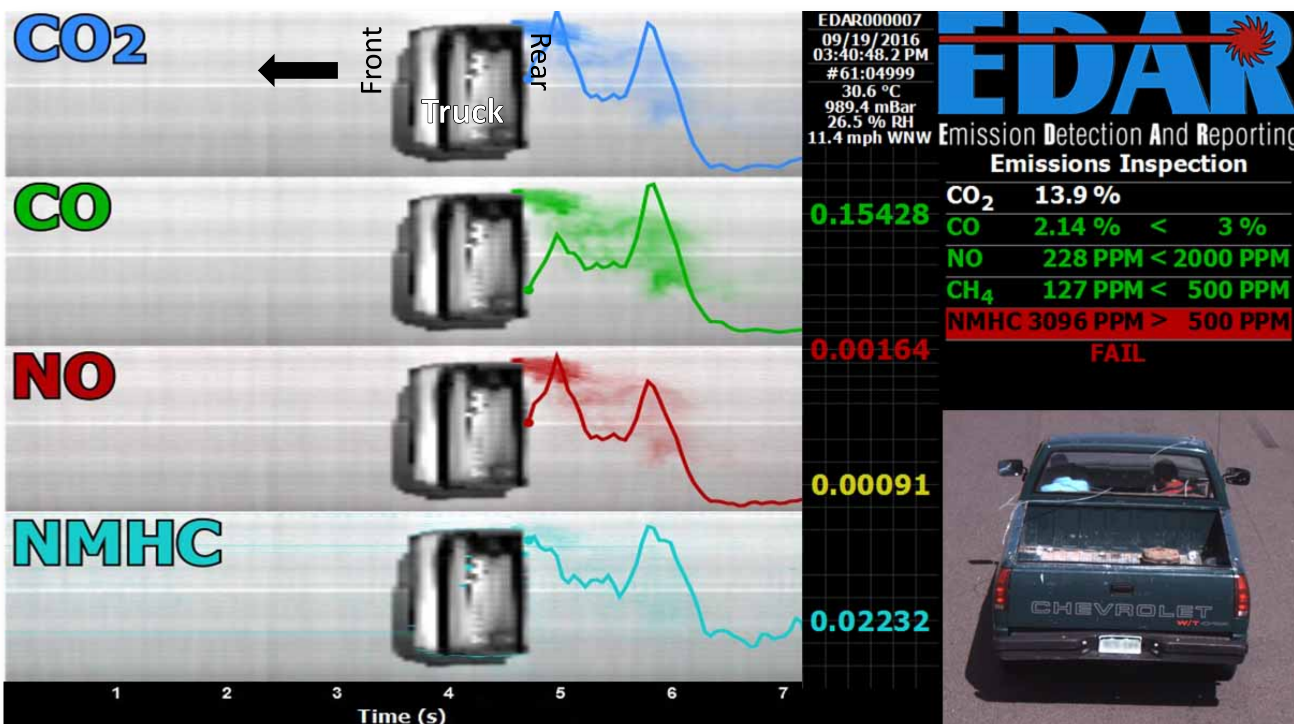
- A system to measure current weather conditions, including ambient temperature, barometric pressure, relative humidity, and wind speed and direction.

- A license plate reader that identifies the plate of each vehicle when its emissions are measured along with a picture of each license plate. The reader automatically transcribes the license plate number for further analysis.

Furthermore, for each vehicle, EDAR finds the exhaust plume at the location where it exits the tailpipe of the vehicle at the moment the plume becomes visible. This gives a reasonable measure of the temperature of the exiting exhaust gases. The temperature of the exhaust gases relative to the ambient temperature is an indication of if the vehicle is in a warmed-up condition, that is, not in cold start. If the vehicle was in cold start, it may have high emissions appearing to indicate the vehicle has an emissions problem. However, by providing a measure of the ratio of exhaust gas temperature relative to ambient temperature, the EDAR unit can be used to identify these vehicles so they are not identified as false positive high emitters as opposed to the screen out vehicles in cold start condition from the true high emitters.

Figure 2 demonstrates an example of the report that is produced by EDAR for every vehicle detected and evaluated. As displayed in Figure 2, EDAR captures a 2D image of the vehicle and plume for the four gases as well as the license plate, date, time, speed, acceleration, temperature, barometric pressure, humidity, wind speed, a pass or fail indication, and an actual image of the vehicle itself. The curve represents the amount in each scan.

Figure 2. Example EDAR Report



1.3. Detector Accuracy

EDAR measurements are well within the range of the certified gas sample accuracy and the detector accuracy standards of the California Bureau of Automotive Repair (BAR) On-Road Emissions Measurement Standards (OREMS).

Minimum accuracies per California BAR are:

- The carbon monoxide (CO%) reading will be within ± 10% of the Certified Gas Sample, or an absolute value of ± 0.25% CO (whichever is greater), for a gas range less than or equal to 3.00% CO. The CO% reading will be within ± 15% of the Certified Gas Sample for a gas range greater than 3.00% CO.

- The hydrocarbon reading (recorded in ppm propane) will be within ± 15% of the Certified Gas Sample, or an absolute value of ± 250 ppm propane, (whichever is greater).

- The nitric oxide reading (ppm) will be within ± 15% of the Certified Gas Sample, or an absolute value of ± 250 ppm NO, (whichever is greater).

1.4. Sources of Data and Data Collected

The EDAR unit pollutant measurements (HC, CO, CO_2 and NO) and license plate captures were the two main sources of data used for this report. The information below demonstrates the format of the data collected in this report.

1.5. Information Collected

- HEAT units operated: EDAR 7
- Date
- Time
- License plate image
- HC, CO, CO_2, and NO measurements
- Speed
- Acceleration
- Temperature of the vehicle

1.6. Data Collection Statistics

- Unit
- Site
- Date
- Start time
- End
- Hourly temperature
- Hourly humidity

1.7. Vehicle Registration Data

The license plate data collected by the HEAT license plate recognition camera system was submitted to the Illinois Secretary of State so that vehicle VIN and other vehicle data could be provided for analysis. The information provided includes:

- License plate
- Vehicle Identification Number (VIN)
- Model year
- Make
- Body style
- EPA vehicle type

2. METHODS

The purpose of this study was to evaluate the EDAR system's ability to measure on-road emissions over a three-day period at the on-ramp from Algonquin Rd to I-290 in Rolling Meadows, IL, a suburb of Chicago. The on-ramp set up can be seen in Figure 3. Approximately 15,255 valid data points were collected over the 3-day time frame; September 19-21, 2016. During this 3-day period EDAR collected on-road emissions data from vehicles in their natural operating environment detecting CO_2, CO, HC, and NO. The data collected was correlated with license plate data.

EDAR has a simple unmanned set up that does not require any calibration once deployed. EDAR uses the same principles as satellite Differential Absorption LiDAR or DiAL and once the device is setup does not need to be calibrated. During the initial deployment process, traffic was temporarily diverted from the lane that has been designated for testing to mount the system, its components, and to adhere the retroreflective tape to the pavement. Due to EDAR's specially designed deployment trailer, this set up and alignment process is simple and easily set up daily then EDAR is left to run unattended.

Once all of the components were mounted and in place, EDAR is powered on by a pack of batteries that are incorporated as a part of the EDAR trailer. EDAR is then powered on and connected to an Internet connection to allow HEAT's engineers to monitor EDAR remotely.

EDAR was mounted and taken down daily for the three consecutive days, collecting the appropriate data to achieve the goal of collecting 15,000 valid data points all while being monitored remotely.

2.1. The Setup

EDAR has a specially designed portable system for temporary setups that can be towed by any light duty truck to the deployment site. The trailer was positioned off the shoulder of the road for minimum interference to traffic flow and to maximize safety as shown in Figure 4. The trailer has been over engineered for safety and reliability and was secured using scissor screw jacks for extra stability once the trailer was positioned into the desired location. There is an automated system in which the mast and arm are controlled by hydraulics, so both can be raised or stowed by the push of a button. In addition to the automated mounting arm system, EDAR can position itself through a tip tilt device for easy alignment. Once EDAR is in place, the retroreflective tape was adhered to the roadway and is protected by small ½ inch high ramps. A license plate camera is positioned at the rear of the trailer and is triggered by the blocking of the laser beams as the vehicle travels underneath EDAR. A weather sensor gives wind speed and direction in addition to temperature, pressure and relative humidity.

Figure 3. EDAR Location on Entrance Ramp from W. Algonquin Rd. and I-290

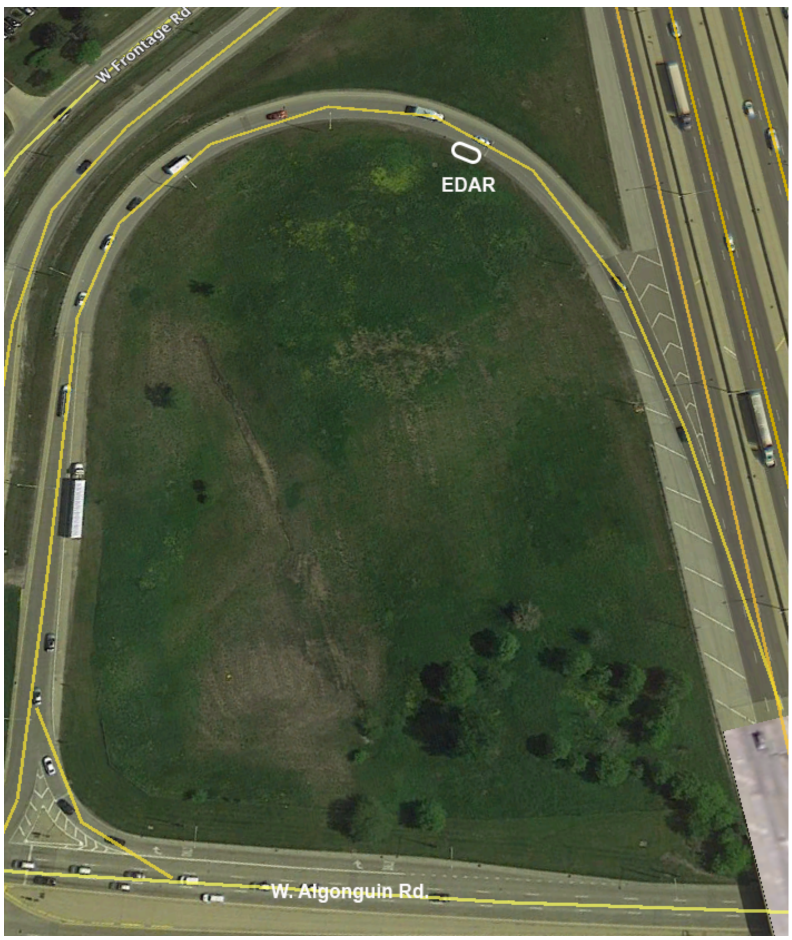


Figure 4. Image of EDAR at the Ramp in Rolling Meadows Showing Trailer Setup

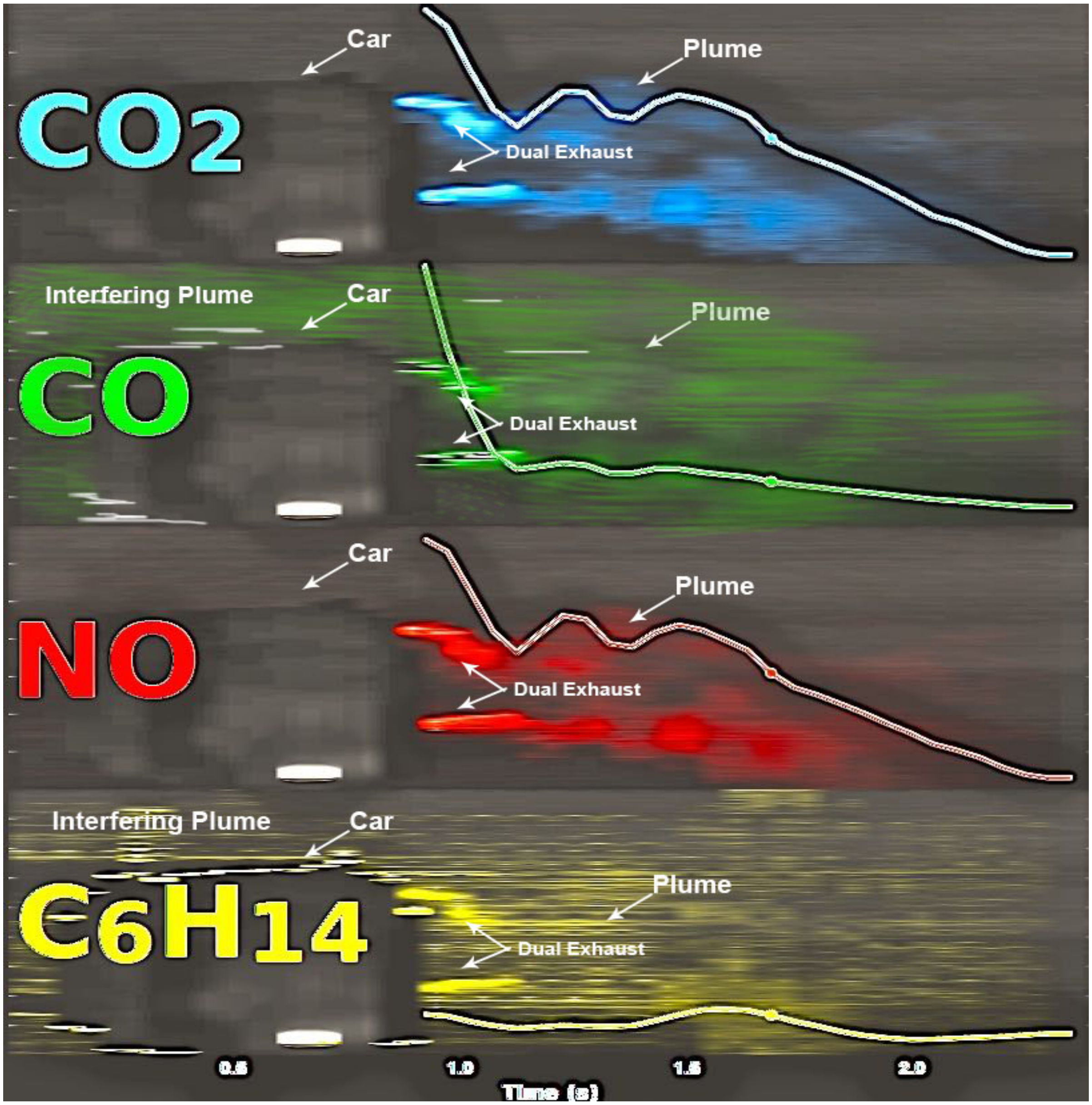
2.2. Screening of Exhaust Plumes

Since EDAR measures the exhaust plume with a sheet of laser light scanning the roadway, EDAR is capable of imaging two-dimensional images of passing vehicles and their respective emission plumes. One axis of the image depicts the length across the road, while the other axis depicts the passage of time. The image shows the shape of the vehicle, its lane position and the position of its tailpipe. In addition, EDAR forms an active image of a vehicle's emission plume showing the quantity of pollutant detected per unit area or optical mass in moles/m^2.

The active image, as described above and shown in Figure 5, shows the position of the plume for each pollutant as well as the dispersion rate of the plume. The gas record is considered valid if there is one scan where the average measurement of CO_2 in the scan exceeds 0.004 moles/m^2. Furthermore, the linear correlation coefficient or Pearson's correlation criteria (r) is applied between the CO_2 measurements and the CO, NO and HC measurements. If the correlation factor is relatively high along with elevated amounts of pollutants, the measurement is considered valid. This signifies that there are no interfering plumes. Interfering plumes usually have different ratios of pollutant to CO_2 (See **Appendix. A**), therefore the linear correlation coefficient drops in value. The highest linear correlation coefficient is 1.0, whereas values near zero indicate no correlation and negative 1.0 indicates complete negative correlation. When gas readings are near zero for CO, NO and HC, then correlation values are ignored, because of the lack of presence of those gases. EDAR's algorithm identifies the distinct presence of an interfering plume thus removing it from the valid data set.

In addition, the visual 2D representation of the exhaust plumes shows interfering plumes from either neighboring lanes or previous vehicles. When a prior in-lane vehicle is a high emitter, it is common for the subsequent vehicle to be "engulfed" by the large plume. On the other hand, when a plume enters from a neighboring lane, it is common for it to be distinct from the plume exiting the tailpipe of the target vehicle, which makes it easy to discern neighboring plumes, as shown in Figure 5. Each plume image is rescaled according to the highest readings. The vehicle in Figure 5 CO_2 plume is much larger than the residual CO_2 in the interfering plume and therefore the interfering plume's CO_2 is not visible in the picture. This is not the case for CO whose residual plume is on the same scale as the current vehicles CO plume.

Figure 5. Example of Dual Exhaust Vehicle Driving through the Plume of a Preceding High Emitter



2.3. Monitored Remotely

HEAT's EDAR units are monitored remotely from Knoxville. Annunciators are set up so that HEAT's engineers are alerted to anomalies or changes that do not meet the standard parameter criteria. Examples would include an alert if the system was knocked out of alignment, if it experienced a loss of power, or if there were connectivity issues.

3. RESULTS AND DISCUSSIONS

After three days of data collection in September of 2016, the license plate readings were provided to the state of Illinois to be matched to the state's vehicle registration information. The information from the state did not include any personal driver or registration information that was released to HEAT, only relevant vehicle data was released to HEAT for the purpose of the analysis. The State of Illinois was able to match 9,830 records that included duplicates with make and model year of scanned vehicles, of those 9,027 were unique plates. The data reduction process of the measurements is summarized in Table 1. The table details the steps beginning with the number of attempted measurements and ending with the number of records containing both valid emissions measurements and vehicle registration information. Valid measurements are filtered by the amount of CO_2 measured and the ratios of other gases with respect to CO_2. Measurements that do not fall under the prescribed criteria are considered as invalid and are excluded from further analysis. As a whole, the measurements resulted in a 91% validity rate. This is outlined in Table 4.

During this study, there were two instances that affected the total amount of attempted measures. The first instance occurred on September 19, which was the first day of testing, between the hours of 8:00am and 11:00am where the EDAR equipment was unintentionally displaced by the adjacent researchers. EDAR was quickly placed back online by 11:00am. The second instance occurred on the last day of testing, September 21. There was a significant amount of intermittent rain episodes throughout the day.

Table 1 - Validity Summary

EDAR Units	1
Sites	1
Data Collection Days	3
Attempted Vehicles Measured	16,852
Valid Vehicles Measured	15,255
Out of State Plates	1,270
Valid Measurements after Removing Interfering Plumes Submitted to State	13,985
Records Matched to IL Registrations	9,830
Unique Illinois Vehicles Identified	9,027
Unique Illinois Vehicles Identified Once	6,154
Unique Illinois Vehicles Identified Twice	1,309
Unique Illinois Vehicles Identified Three Times	319
Unique Illinois Vehicles Identified Four or More Times	22

Table 2 - Number of Measurements of Repeat Vehicles

Number of Times Measured	Number of Vehicles
1	6,154
2	1,309
3	319
≥4	22

Table 3 - Temperature and Humidity

Time (CDT)	2016 19-Sep T (°F)	19-Sep RH (%)	20-Sep T (°F)	20-Sep RH (%)	21-Sep T (°F)	21-Sep RH (%)
700	63.8	60.5	66.9	85.0	66.9	77.1
800	70.0	62.0	72.0	84.0	66.0	78.7
900	75.9	60.0	75.9	81.0	66.9	70.5
1000	80.1	61.0	78.1	80.0	70.0	68.0
1100	82.0	57.8	80.1	76.4	72.5	71.0
1200	84.9	43.2	81.1	64.0	73.4	78.0
1300	86.1	41.0	82.2	52.0	72.9	86.0
1400	87.2	38.0	81.0	48.0	71.1	89.0
1500	87.3	35.0	81.0	37.0	68.0	73.0
1600	84.0	28.0	80.1	32.0	73.0	76.0
1700	82.5	27.5	79.0	31.0	72.0	72.0
1800	82.0	27.0	75.0	27.3	72.0	74.0

Table 4 - Daily Measurements

EDAR	Date	Location	City	County	Attempted Measures	Valid Emissions Read	Valid %
7	9/19/16	On ramp from Algonquin Road to I-290	Rolling Meadows	Cook	6,427	6,041	94%
7	9/20/16		Rolling Meadows	Cook	6,193	5,501	89%
7	9/21/16		Rolling Meadows	Cook	4,232	3,713	88%
				Totals	16,852	15,255	91%

3.1. Rolling Meadows Average Emissions by Model Year

The sampled fleet population distribution and average emissions concentrations by model year for Rolling Meadows, IL, a suburb of Chicago, are shown in Figures 6 to 8. The older the model year, the more likely there will be higher emissions and greater variation in those emissions in general due to older vehicles being subject to different, less stringent standards when manufactured. HEAT's data confirms this by showing considerable variation in the older model year averages.

The model years 2011 thru 2016, which constitute 45% of the vehicles measured in the graphs below, show average emissions that are fairly consistent. Furthermore, large variation of model years older than 15 years could be due to lack of samples. The number of samples for each year is shown in Figure 9.

Figure 6. Rolling Meadows Average CO Emissions

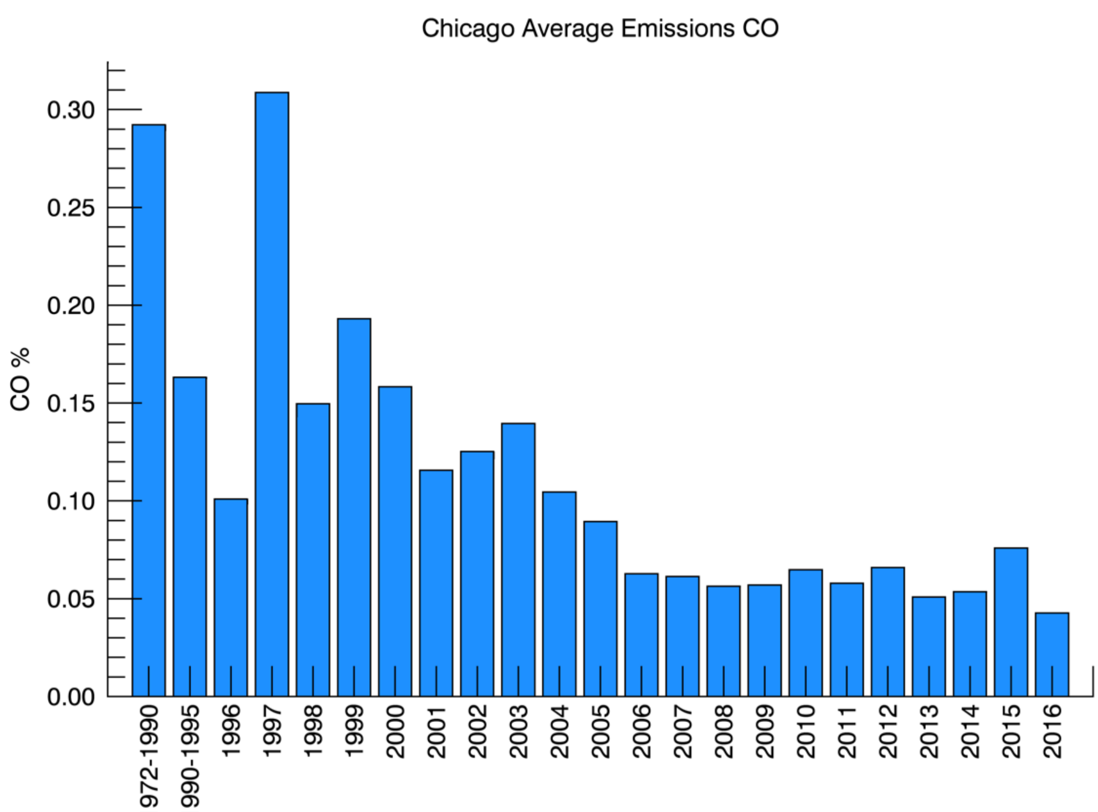


Figure 7. Rolling Meadows Average NO Emissions

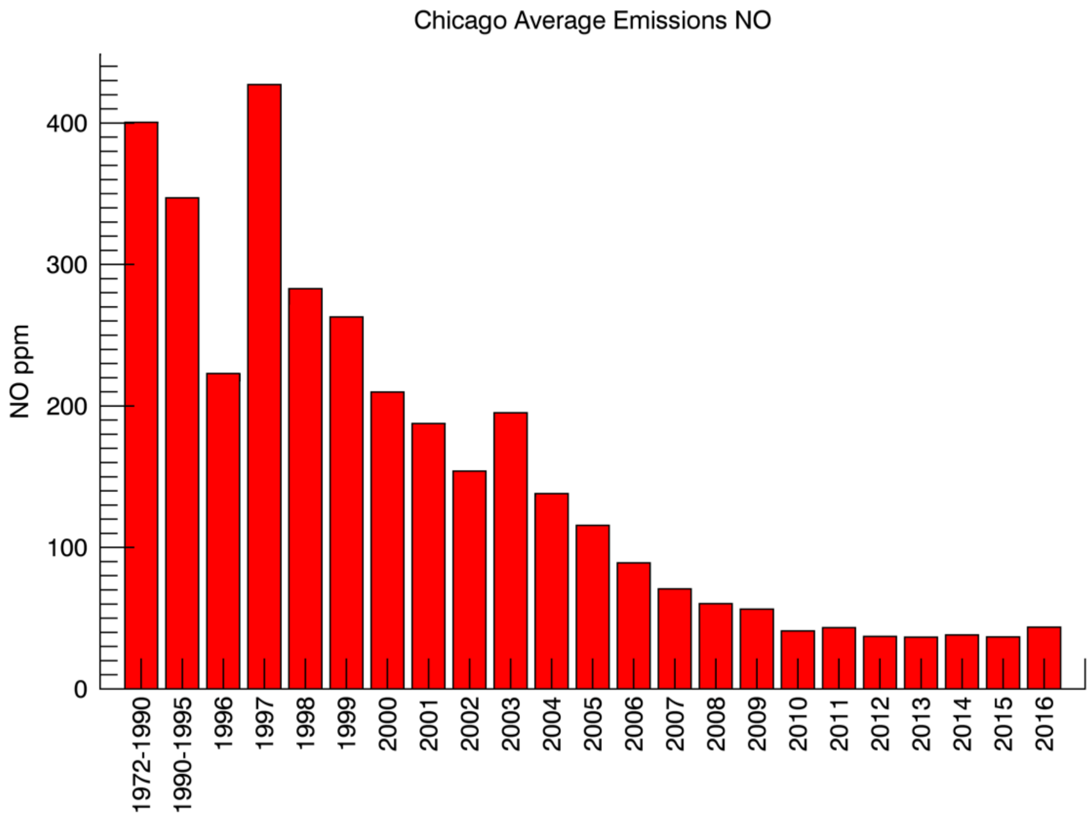


Figure 8. Rolling Meadows Average HC Emissions

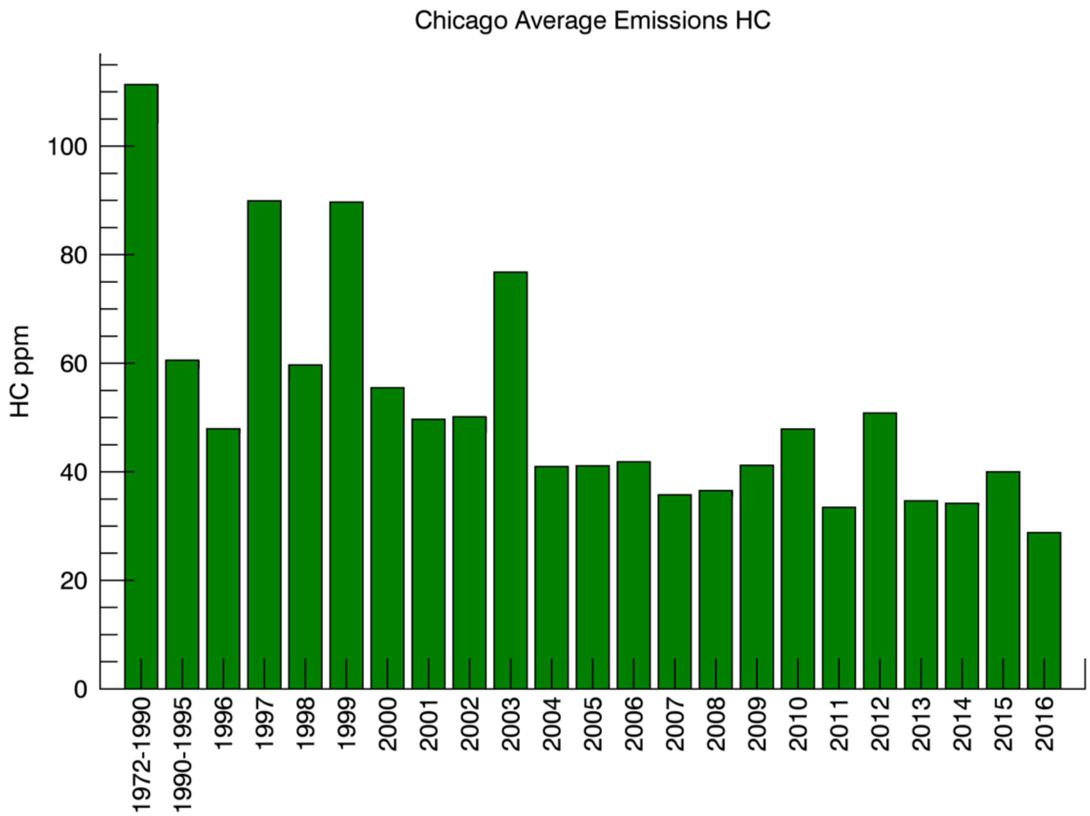
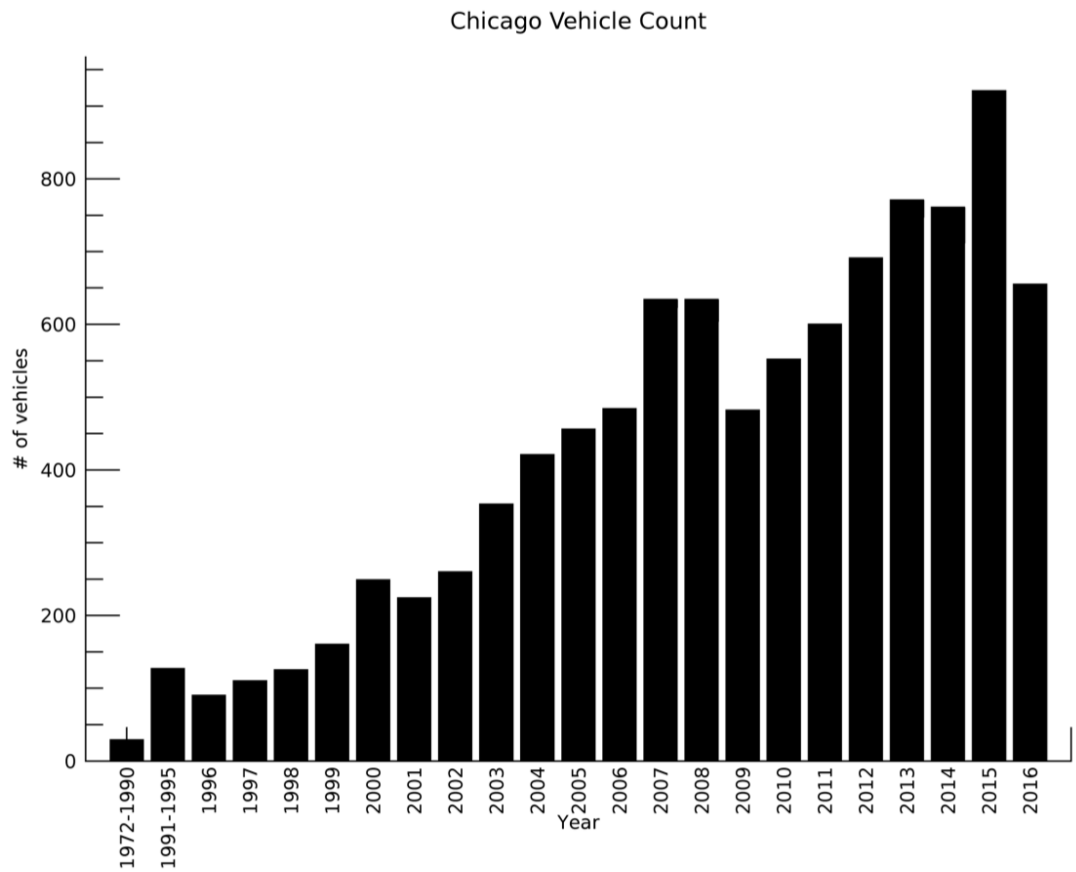


Figure 9. Rolling Meadows Vehicle Distribution for Passenger Cars and Trucks



3.2. Noise Analysis

The accuracy measurements of the EDAR system are well within the range of the certified gas sample accuracy and the detector accuracy standards of the California Bureau of Automotive Repair (BAR) On-Road Emissions Measurement Standards (OREMS).

In past remote sensing studies, the negative values are also considered an indication of the accuracy or noise in the instrument.[3,4] Despite the heavy traffic on the ramp and ample evidence of interfering plumes, (see Appendix 6.1) a noise analysis is performed on the negative data.

Exponential distribution is adequate to describe the distribution of the negative values in all gases. A Laplace Probability Density Function (PDF) is the simplest PDF for an exponential distribution with only 2 parameters. Since the mean is considered to be zero only one parameter is actually needed.

The Laplace distribution PDF is $\frac{1}{2b}\,exp(-\frac{|x-\mu|}{b})$, where μ is the location parameter and *b* is scaling parameter. Our locations are zero, so if we take the *ln* of the negative side of the distribution and then fit to a straight line we can retrieve the scaling parameter *b* from the slope of the fit.

Figures 10 to 12 show the straight-line fits for NO, CO, and HC. The straight-line fit inset of the *ln* of the number of vehicles have been normalized. For NO, HC and CO the fit parameter b is then the reciprocal of the slope or 0.00079, 0.000907 and 0.00201 respectively. The variance of a Laplace PDF is $2b^2$ and therefore the standard deviation $\sqrt{2}b$. The standard deviation for NO, HC and CO are therefore 0.0011% or 11ppm, 0.0013% or 13ppm, and 0.0028% or 28ppm, respectively.

The average measured emissions for CO, NO and HC were 759 ppm, 85 ppm and 42 ppm. As expected, CO exhibits larger range of values. For CO, the positive side of the slope is much shallower than the negative part. On the other hand, NO and HC exhibit larger slopes with respect to their mean values.

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3 Jimenez, J.L.; Koplow, M.D.; Nelson, D.D.; Zahniser, M.S.; Schmidt, S.E.; J. Air & Waste Manage. Assoc. 1999, 49, 463.

4 Pokharel, S. S.; Bishop, G. A.; Stedman, D. H., On-road remote sensing of automobile emissions in the Phoenix area: Year 2; Coordinating Research Council, Inc: Alpharetta, 2000.

Figure 10. Noise Study: NO Measurement

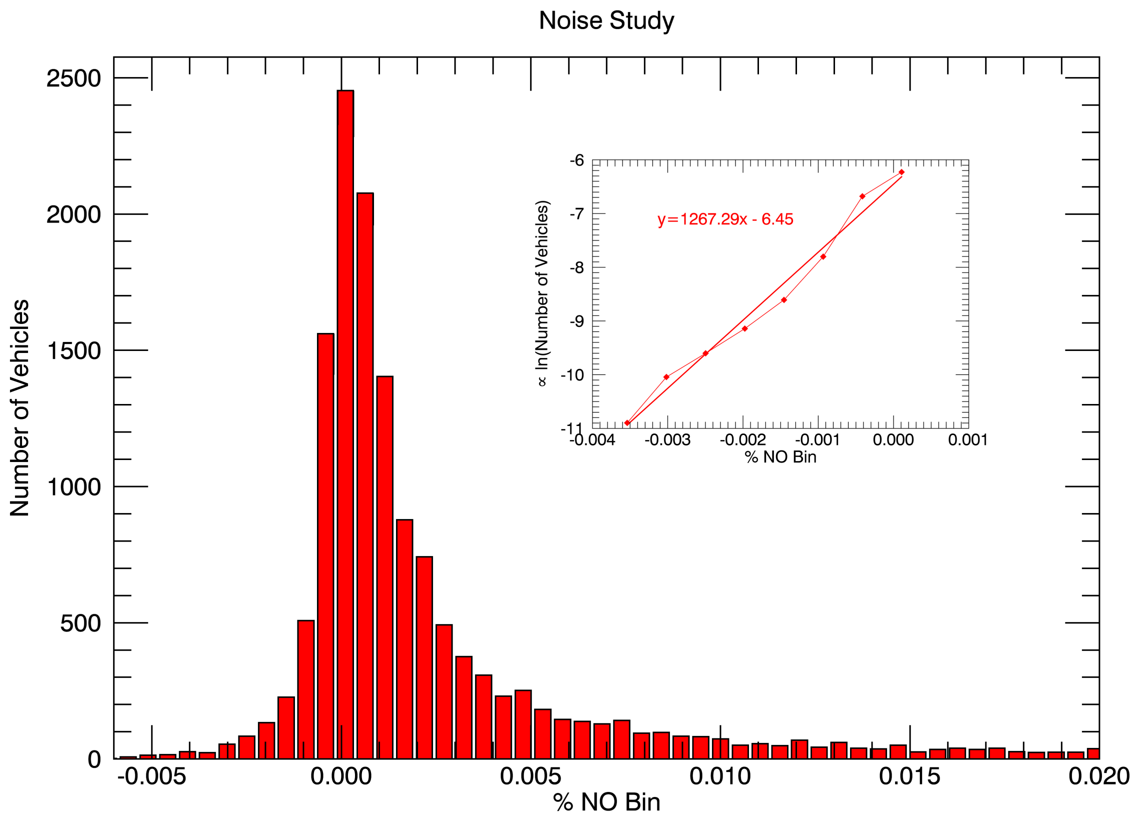


Figure 10 shows the histogram of NO measurements. Inset is the fit of the ln of the number of vehicles that has a normalized distribution. The fit parameter b is then the reciprocal of the slope or 0.00079.

Figure 11. Noise Study: HC Measurement

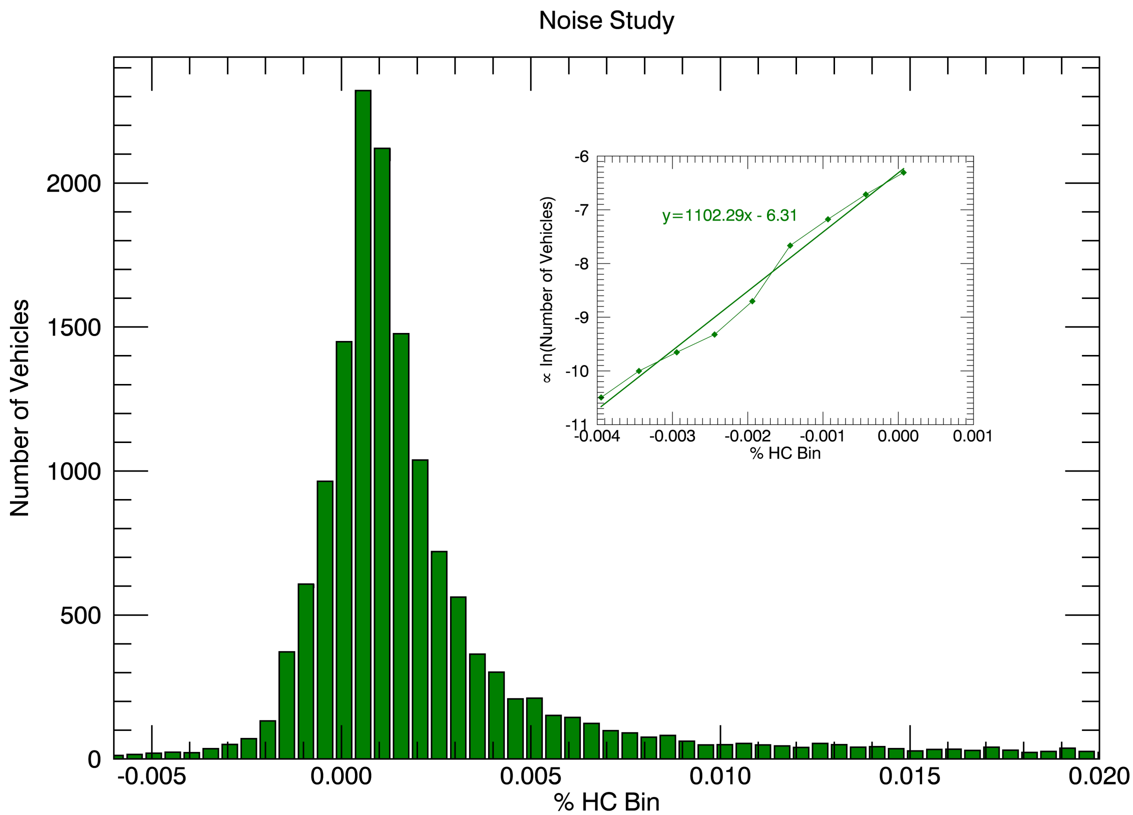


Figure 11 shows the histogram of HC measurements. Inset is the fit of the ln of the number of vehicles that has a normalized distribution. The fit parameter b is then the reciprocal of the slope or 0.000907.

Figure 12. Noise Study: CO Measurements

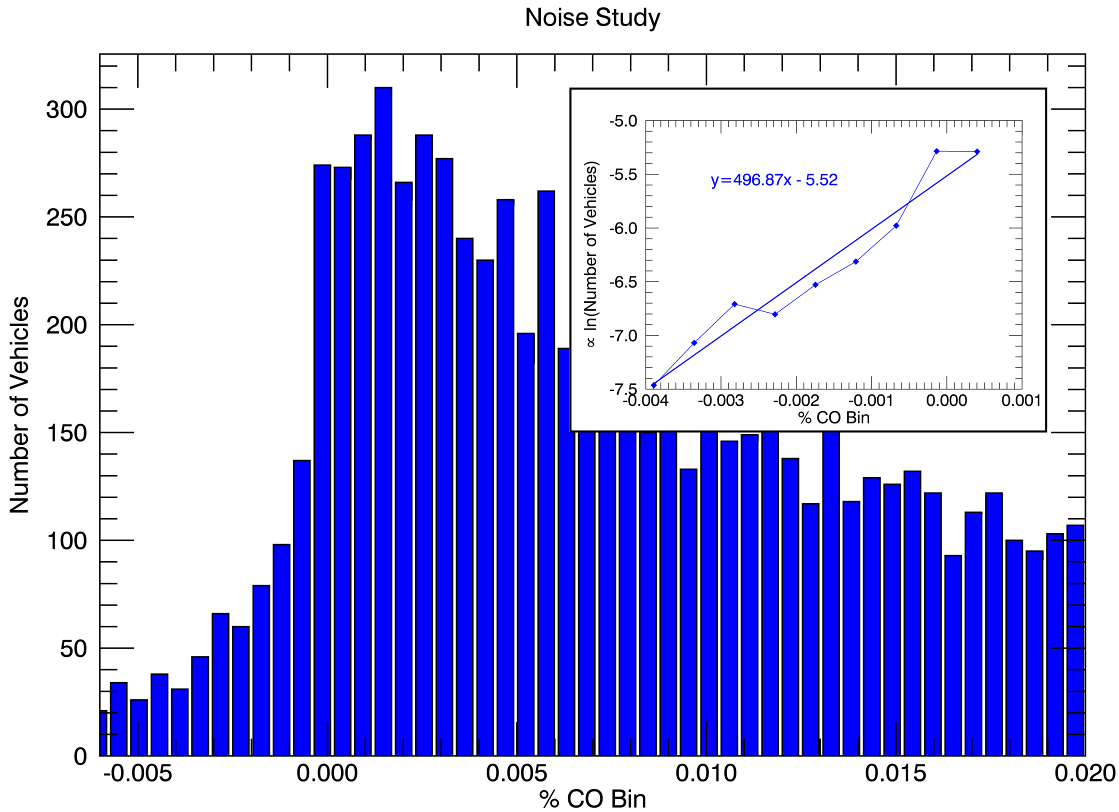


Figure 12 shows the histogram of CO measurements. Inset is the fit of the ln of the number of vehicles that has a normalized distribution. The fit parameter b is then the reciprocal of the slope or 0.00201.

3.3. Measurements of Multi-Read Vehicles

Multiple measurements of the same vehicle are analyzed in Figures 13-15. The plots show the mean emission and standard error of the mean for vehicles measured at least three times. The vehicles are sorted with respect to the mean emissions. Most vehicles are low emitting vehicles showing little variability. This confirms the practicality of using remote sensing for clean screening. In general, the observed variability increases as the mean emissions increase.

Figure 13. Sorted Multi-Read Vehicles: CO

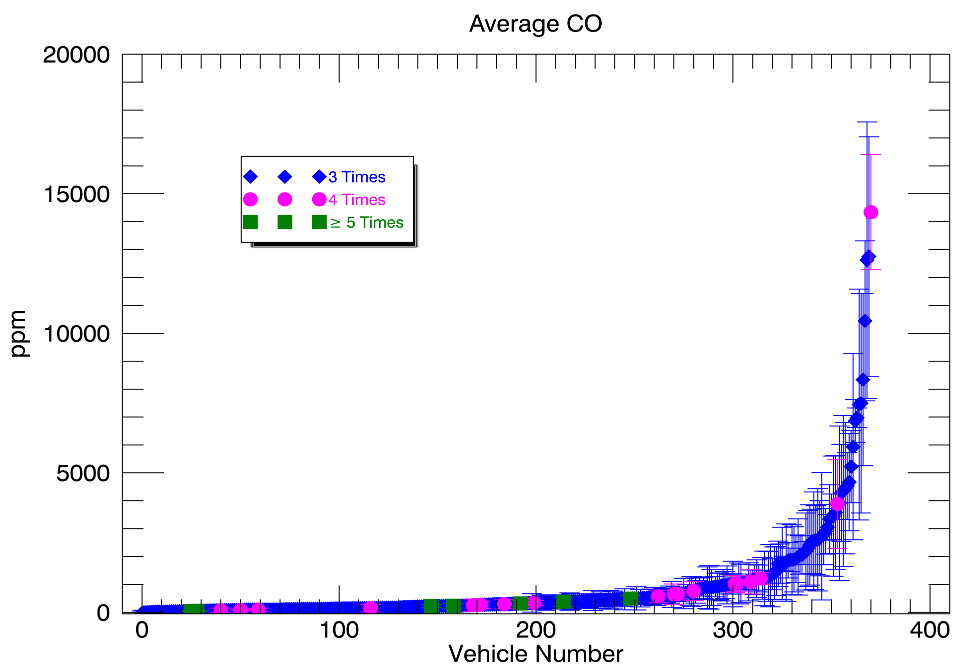


Figure 14. Sorted Multi-Read Vehicles: NO

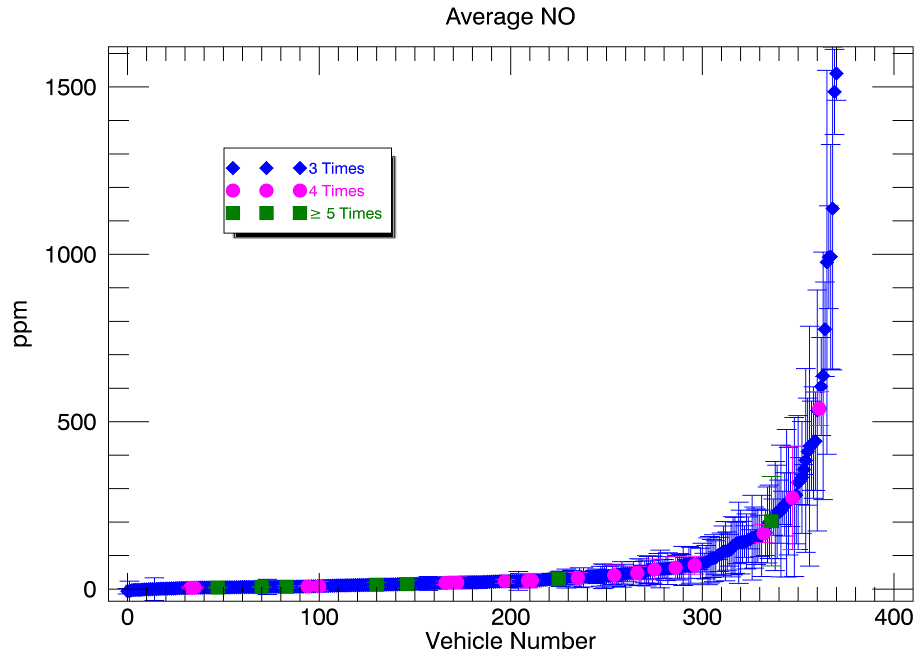
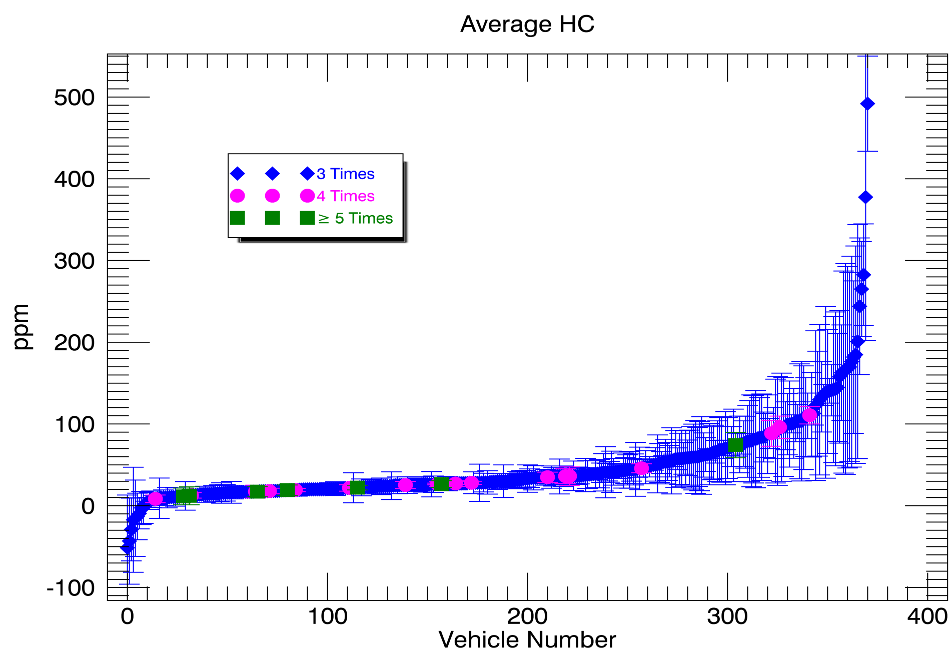


Figure 15. Sorted Multi-Read Vehicles: HC



3.4. Absolute Amounts

The calculation of absolute emission amounts is possible with the EDAR system because of the unique geometry of the remote sensing set up as mentioned in section 1. EDAR scatters laser light off of the road surface; therefore, it is always looking down onto the plume. This allows EDAR to remotely detect the entire plume at one time. One can use the optical mass or optical density of each measurement across the plume to calculate absolute values, mole or gram per meter, kilometer or mile.

The stoichiometric equation is not used in the reporting of absolute amounts. The stoichiometric equation uses ratios of pollutant to CO_2 in order to calculate tailpipe percentages. When using the stoichiometric equation, only three ratios are measured (CO/CO_2, NO/CO_2 and $NMHC/CO_2$) and therefore one of the species percentages must be meaningless. CO_2 is chosen because it is the only non-pollutant and the pollutants are the main goal. The percent CO_2 is derived from the other three gases and has no meaning except as a denominator.[5] EDAR measures each gas independently therefore EDAR's CO_2 measurement is meaningful and can be reported as CO_2 gram/mile.

In Figures 16-19 the average instantaneous absolute amount of CO_2, CO, NO and NMHC is shown against model year. The direct measurement of CO_2 can be used for greenhouse gas computations. In fact, Europe manufacturer's ratings for CO_2 g/km can be used to scale the pollutants coming from the vehicles by calculating, $\left(\frac{Manutacturer's\ CO2\ \frac{g}{km}}{Instantaneous\ CO2\ g/km}\right) * (Instanteous\ pollutant\ g/km)$.

In this study, the absolute amounts demonstrate that CO_2 averages are fairly consistent throughout the model years. The instantaneous values are higher than typical averages over accepted drive cycle testing due to the vehicles being under load. The average gram/mile for new personal vehicles is 359 g/mi according to the EPA website.[6]

In addition, the relative values of absolute amounts are similar to the stoichiometric average tailpipe concentration plots, because the stoichiometric

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[5] D. A. Burgard, G. A. Bishop, R.S. Stadtmull, T. R. Dalton, and D. H. Stedman, *Spectroscopy Applied to On-Road Mobile Source Emissions*, Applied Spectroscopy, 60, 5, 2006, pp 135-148

[6] https://www.epa.gov/fuel-economy-trends/highlights-co2-and-fuel-economy-trends

equation uses ratios and the CO_2 is fairly constant. The results show that CO, NO, and HC absolute amounts decrease as the fleet gets younger and newer models are introduced. This is the classical profile similar to the tailpipe percentages shown in this report.

Figure 16. Absolute Amounts CO_2

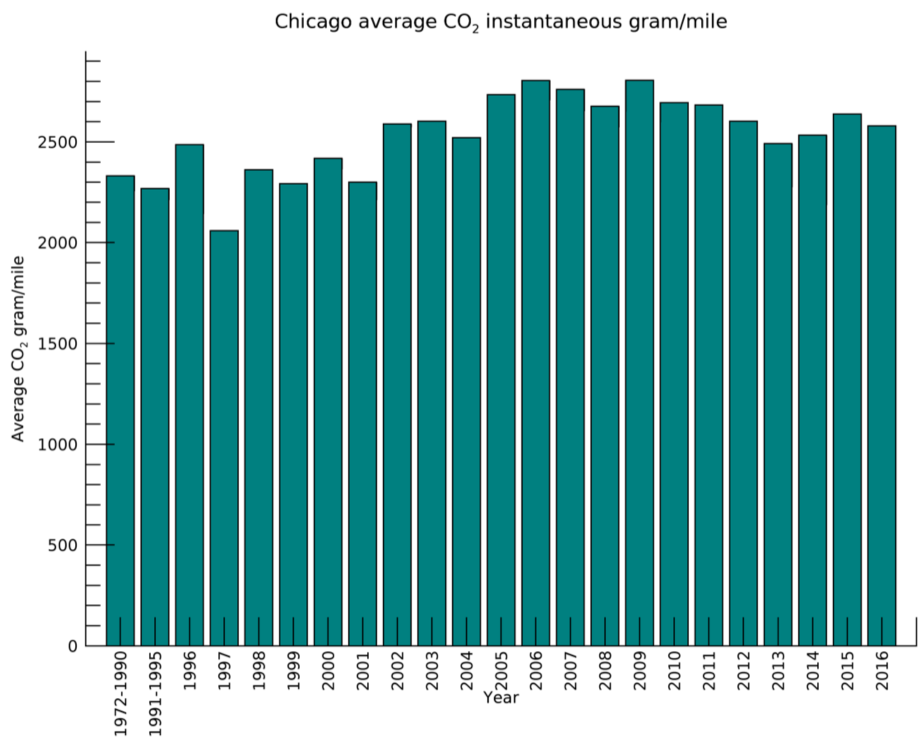


Figure 17. Absolute Amounts CO

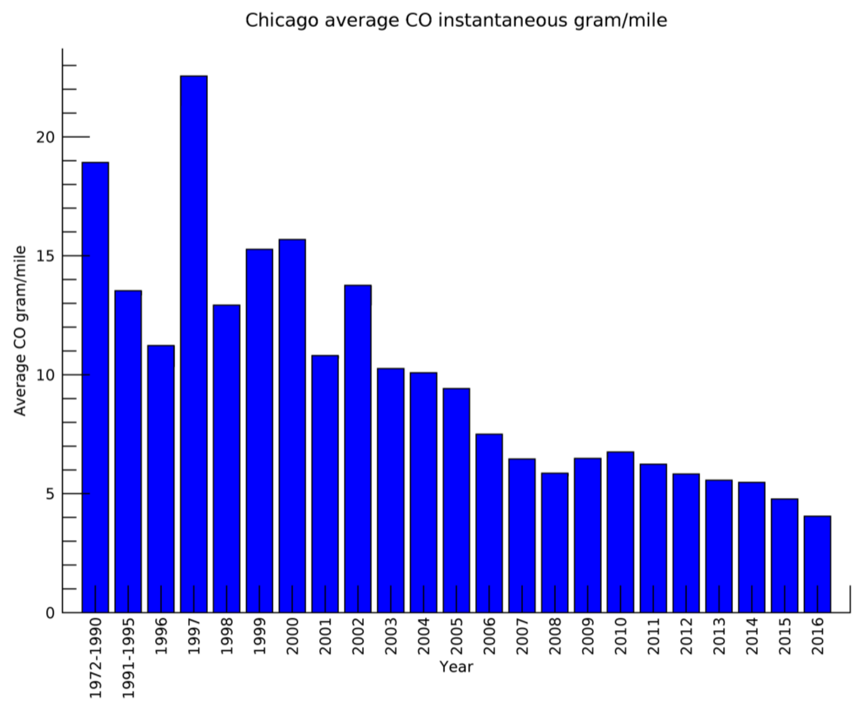


Figure 18. Absolute Amounts NO

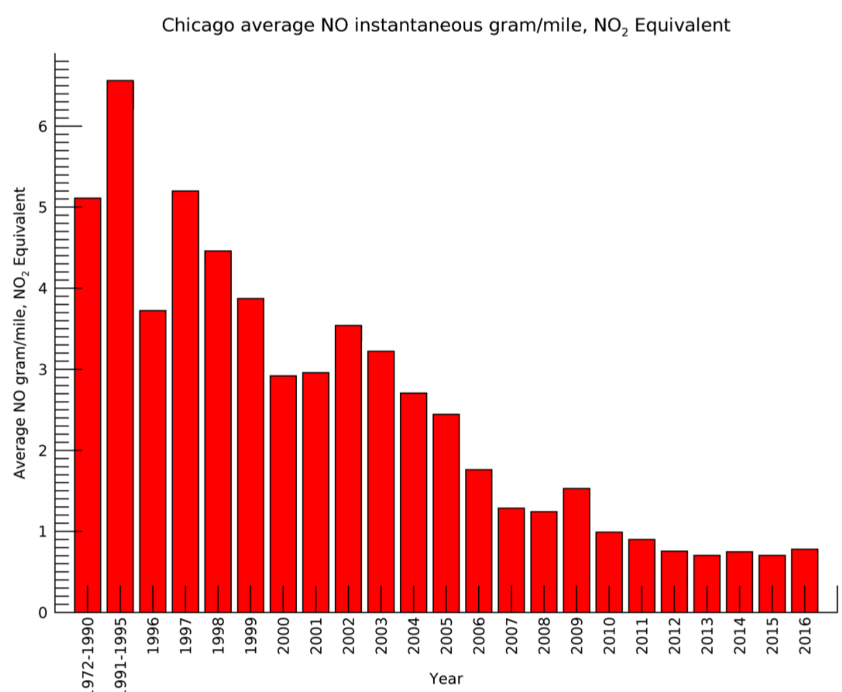
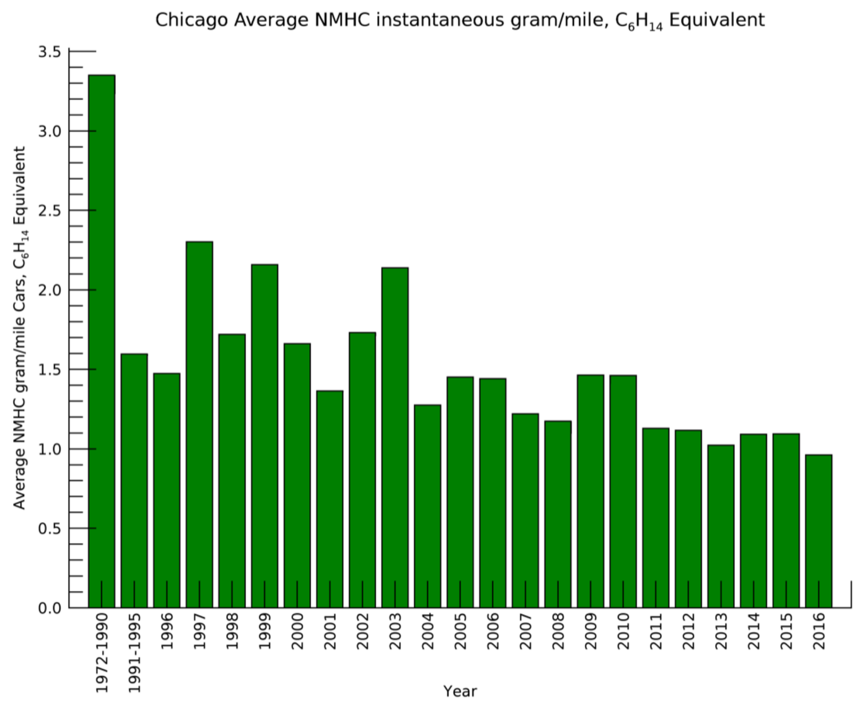


Figure 19. Absolute Amounts HC



4. CONCLUSIONS

The three-day study conducted has generated valuable insights into the intricacies of vehicle emissions for the state of Illinois. After analyzing the Illinois plate matched data, the following findings can be observed.

- The average emissions of CO, NO and HC for the model year of the vehicles were determined from the measured ratios. As expected, the average emissions decrease for vehicles of newer model years.

- The measured average emissions for CO, NO and HC were 759ppm, 85 ppm and 42 ppm. As expected, CO exhibits larger values due to the very nature of the fuel combustion in the engines.

- Due to its unique geometry, EDAR's data can be used to calculate directly the average absolute emissions in *moles/m* of pollutants. These absolute values also exhibit similar trends such as a decrease of emissions with newer model-year.

- The noise in the individual measurements arising due to the negative values is analyzed by considering the negative portion of the slope of the data, yielding Laplace parameters. The Laplace PDF spread parameter is used to calculate the standard error. Therefore, the standard deviations for NO, HC and CO are therefore 0.0011% or 11ppm, 0.0013% or 13ppm, and 0.0028% or 28ppm, respectively.

- The absolute values (g/mile) for CO, NO and HC, clearly demonstrates the decrease in emissions as the newer classes of vehicles enter the fleet. In addition, EDAR's capability of measuring absolute amounts of CO2 helps in estimating greenhouse gases.

5. LIST OF REFERENCES

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6. APPENDIX

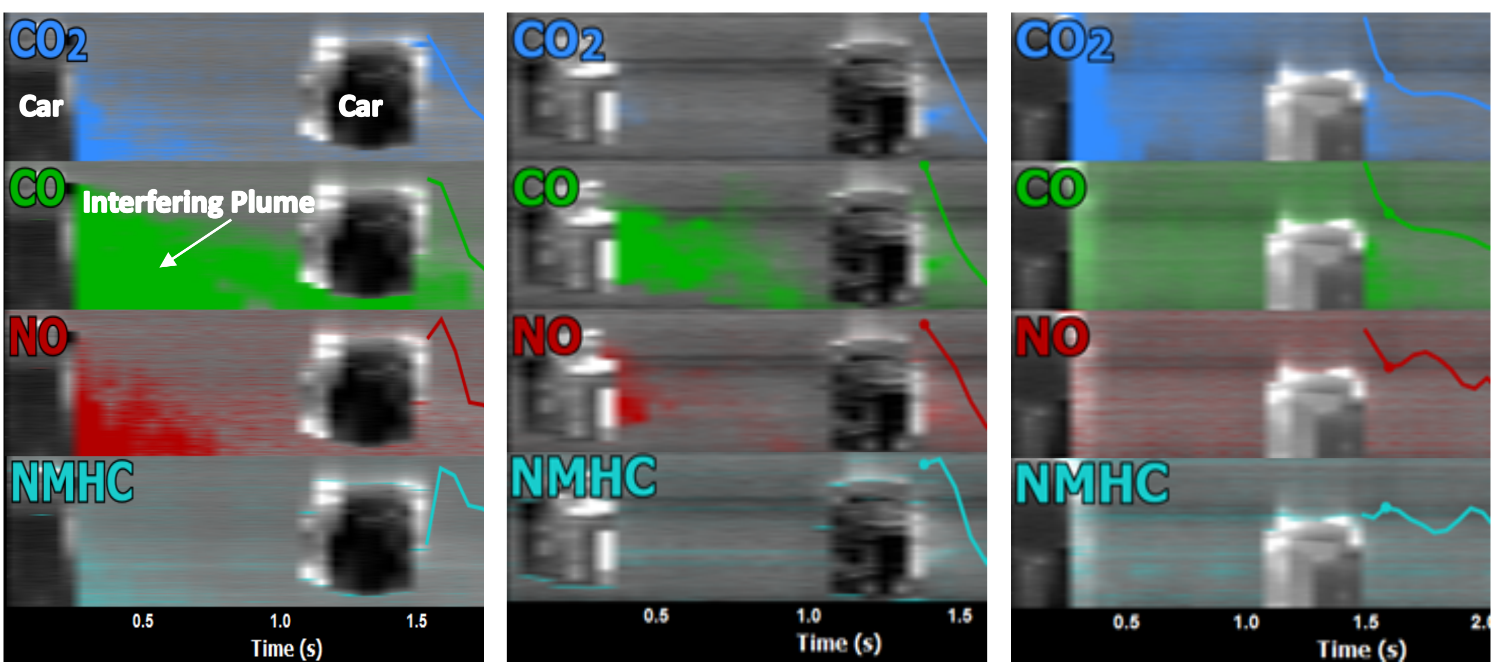
6.1. Appendix A. EDAR images showing interfering plumes of cars on road

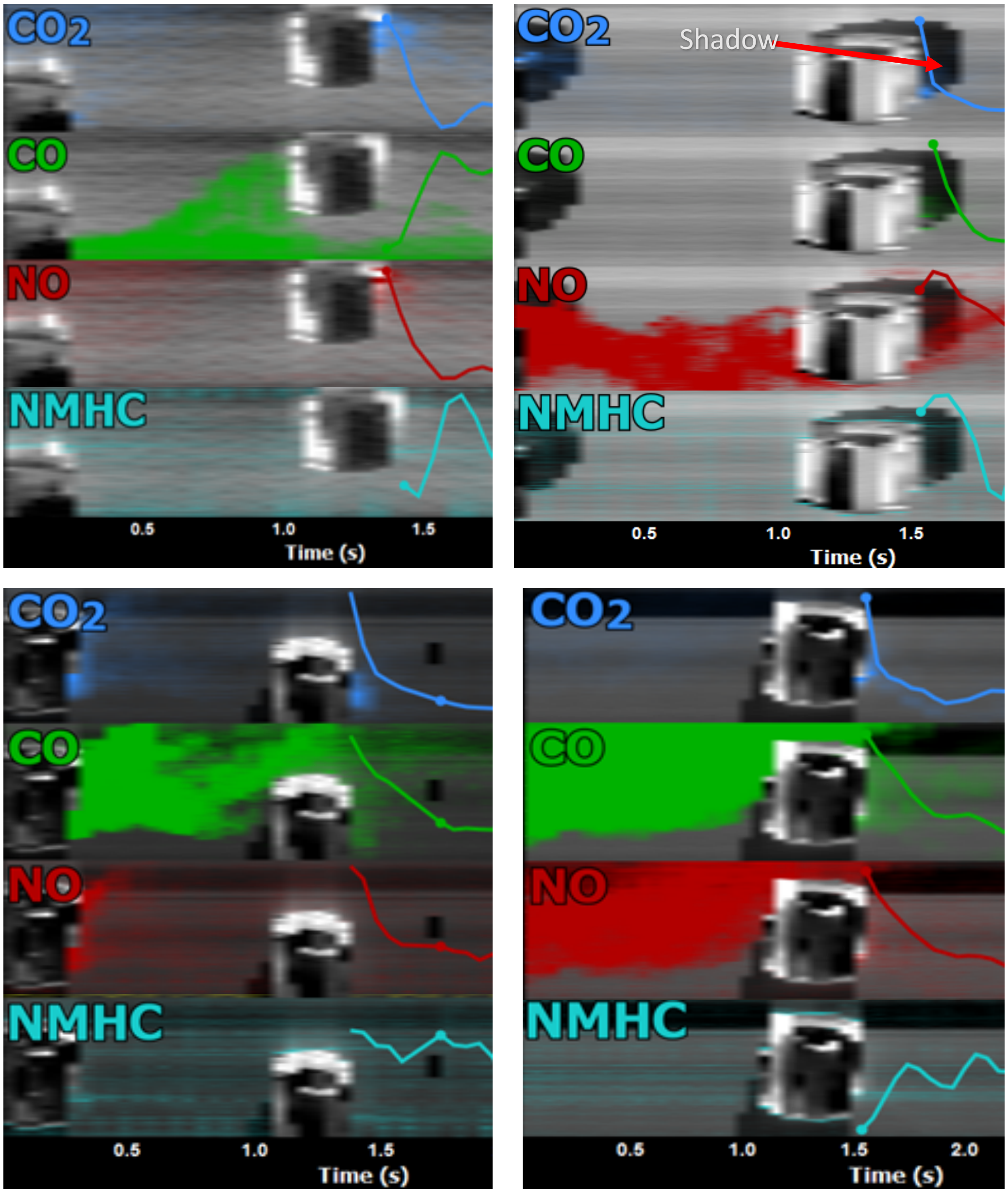
Interfering plumes can pose problems in remote sensing of exhaust emissions. In the present Rolling Meadows, Illinois study, interference due to neighboring lanes is not the case since EDAR was mounted on a one lane ramp. The main cause of interfering plumes in this study was due to high polluting vehicles.

The presence of interfering plumes can be readily seen from the EDAR images shown below. The black and white infrared image of the vehicle is shown with the exhaust plumes in color. Depending on the temperature of the outside of the vehicle the black and white image may show a hot hood and tires which would be white. A cold roof would be dark unless the sun's infrared radiation scatters off the vehicle. When the sun is at certain angles more details can be seen in the car along with a shadow like the second pane on page 39.

Each vertical block of images is the depiction of one specific vehicle. There are five different vehicle examples below showing the instance of interfering plumes.

Figure A.1: EDAR Images Showing the Effects of Interfering Plumes




CO2
CO
NO
NMHC
0.5
1.0
1.5
Time (s)
CO2
Shadow
CO
NO
NMHC
0.5
1.0
1.5
Time (s)
CO2
CO
NO
NMHC
0.5
1.0
1.5
Time (s)
CO2
CO
NO
NMHC
0.5
1.0
1.5
2.0
Time (s)