CRC Report No. E-119-3

Phoenix, Arizona 2021

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

March 2022

COORDINATING RESEARCH COUNCIL, INC.

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Hager Environmental & Atmospheric Technologies
HEAT

Remote Sensing of Automobiles Emissions in Arizona:

Spring 2021

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We would also like to thank ADEQ for providing us with the vehicle data after the survey was completed.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADOT – Arizona Department of Transportation

2D – Two Dimensional

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 – Nitrogen Oxide

NO_2 – Nitrogen Dioxide

NOx – Nitrogen Oxides

OREMS – On-road Emissions Measurement Standards

PDF - Probability Density Function

PM – Particulate Matter

RSD – Remote Sensing Data

s – Second

VIN – Vehicle Identification Number

EXECUTIVE SUMMARY

The Coordinating Research Council contracted Hager Environmental & Atmospheric Technologies (HEAT) to perform a study utilizing the Emissions Detection and Reporting (EDAR) system. The purpose of this study is to demonstrate HEAT's methodology and expertise in deploying the EDAR system and collecting the required data to meet the expectations of the CRC-E-119-3", Evaluation of Emissions Detection and Reporting (EDAR) Technology – Phase 2" project.

EDAR was installed on April 12-16, 2021, at the on-ramp from E 60 to N 101 exit 176B in West Tempe, a suburb of Phoenix, AZ, in a temporary deployment alongside the Fuel Efficiency Automobile Test (FEAT) device and the Opus device to make real time comparisons of on-road emissions measured from vehicles over a five-day period. EDAR collected 43,205 valid measurements which are analyzed in this report. Once the EDAR system was deployed on April 12, 2021, it ran continuously, 24 hours a day, for the entire five-day period.

We appreciate the opportunity once again to work collaboratively with the Coordinating Research Council (CRC) on this project and to provide accurate and reliable emissions measurements in order to contribute to the comparison between EDAR, the Opus device, and the FEAT device.

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.

HEAT conducted the Phoenix remote sensing study at the on-ramp from E 60 to N 101 exit 176B, using the EDAR system. The purpose of this study was to evaluate the effectiveness of remote sensing for accuracy and evaporative emissions as well as to measure on-road emissions over a five-day period alongside Opus and the University of Denver. The chosen dates were April 12 through April 16, 2021. Although the OPUS system and the University of Denver's system only ran for the hours starting in early morning and ending in the evening at 5:00 pm local time, the EDAR unit continuously took data for 24 hours for the entire 5-day period. To perform this study, HEAT obtained the proper permits and Letter of Authority from Arizona Department of Transportation (ADOT) for the deployment of EDAR on-road. The HEAT team utilized EDAR's temporary deployment setup which involves a specialized trailer equipped with a hydraulic arm that sits 16 feet above the lane and allows EDAR to be safely and easily deployed in an unobtrusive manner for true real-world vehicle emission results, as seen in Figure1.

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[1] https://www.dec.ny.gov/chemical/8394.html

Figure 1. Image of EDAR at the On-Ramp from E60 to N101 in Phoenix Showing Trailer Setup

The EDAR device measured CO, CO_2, NO, NO_2, PM, and HC from all vehicles, light duty and heavy duty, driving under the laser-based exhaust gas sensor as they gained speed to merge on the highly traveled northbound route. In addition to 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 a vehicle and plume as it drove underneath EDAR.

A total of 53,063 measurements were attempted and of those, 39,375 Arizona license plates were submitted to the Arizona DOT. All the records submitted had valid measurements for all the detected gases. Out of the attempted measures of 53,063, there were 43,205 valid measurements, which will be analyzed in this report.

Furthermore, this study provides an average of absolute emissions for each gas in moles/m, which can be converted to instantaneous g/mile depending on the molecular mass of a molecule. This does not represent regulatory testing.

Because EDAR can see the entire plume, these values represent the actual amount the vehicle left behind while under EDAR.

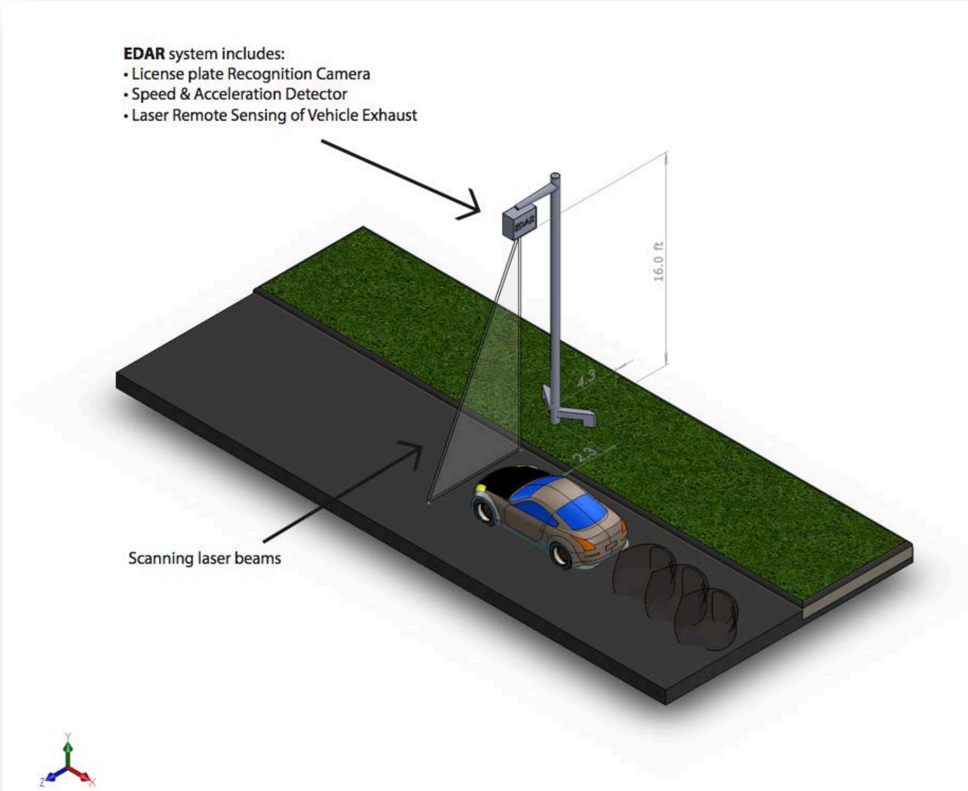
1. BACKGROUND

1.1. Equipment Description

EDAR is HEAT's proprietary on-road remote sensing technology. EDAR is an eye-safe laser-based technology capable of remotely detecting and measuring the infrared absorption of environmentally critical gases being emitted from virtually any moving vehicle regardless of the tailpipe location or fuel type Specifically, EDAR uses the DiAL method to measure the entire exhaust plume as the vehicle passes underneath the unit. Infrared lasers are scattered off a retroreflective tape installed transversely on the road surface and the back-scattered light is then collected by EDAR and focused onto the detector.

The EDAR system is an unmanned, automated vehicle emissions measurement system, which collects data on pollutants such as CO, CO_2, NO, NO_2 (NOx), Total HC, Speciated HC, and PM. The system is comprised of a gas sensor (EDAR), a vehicular speed/acceleration sensor, a license plate recognition (LPR) camera, a weather sensor, and a retroreflector. The all-in-one EDAR system is fully weatherproofed to protect it from environmental elements (heat, rain, snow, wind, etc.) The entire system is designed so it can be locked down to deter vandalism or theft. In addition, EDAR is located 16ft above the roadway and occupies a relatively small footprint, sitting on a single pole that is deployable roadside in either a temporary or permanent application. See Figure 2 below for configuration.

Figure 2. EDAR System Configuration



The EDAR system also gathers vehicle characteristic data necessary for analysis of the emissions results using additional capabilities. 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 measured vehicle along with a picture of its 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 exact 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 whether 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. By providing a measure of the ratio of exhaust gas temperature relative to ambient temperature, EDAR can be used to isolate cold-start vehicles, so they are not identified as false-positive high emitters.

Figure 3 demonstrates an example of the report produced by EDAR for every vehicle detected and evaluated. As displayed in Figure 3, EDAR captures a 2D image of the vehicle and plume for the four specified 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.

Figure 3. Example EDAR Report

1.2. Detector Accuracy

The EDAR system's measurements have higher accuracies than 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 according to the 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).

HEAT has participated in validation and correlation studies[2,3] for on-road emissions in both the United States and Europe. The integrity of HEAT's data has been validated by various blind studies[2,3] comparing the EDAR system to a Portable Emissions Measurement System (PEMS), chaser vans, calibrated gases, as well as other *in-situ* measurement devices. All studies have shown that the accuracy and sensitivity of EDAR are far above those of conventional remote sensing technologies.

In the United States, an independent blind validation study[2] was performed by the Colorado Department of Public Health and Environment (CDPHE), the United States EPA, and the Eastern Research Group (ERG) using an RSD audit truck equipped with calibrated gases. The results show a remarkably high correlation (R^2 of 0.99) could be attested for all gases with speeds ranging from 15mph to 60mph during the CDPHE and EPA blind validation study.

EDAR system accuracies as performed by Colorado, ERG and EPA study[3] are:

Gas	Accuracy
Carbon Monoxide (CO)	± 0.0075%
Nitric Oxide (NO)	± 20 ppm
Total Hydrocarbons (HC)	± 125 ppm

[2] https://www.heatremotesensing.com/_files/ugd/3ee5f0_d7b884c7fd6a4ab582287d3f589b36aa.pdf

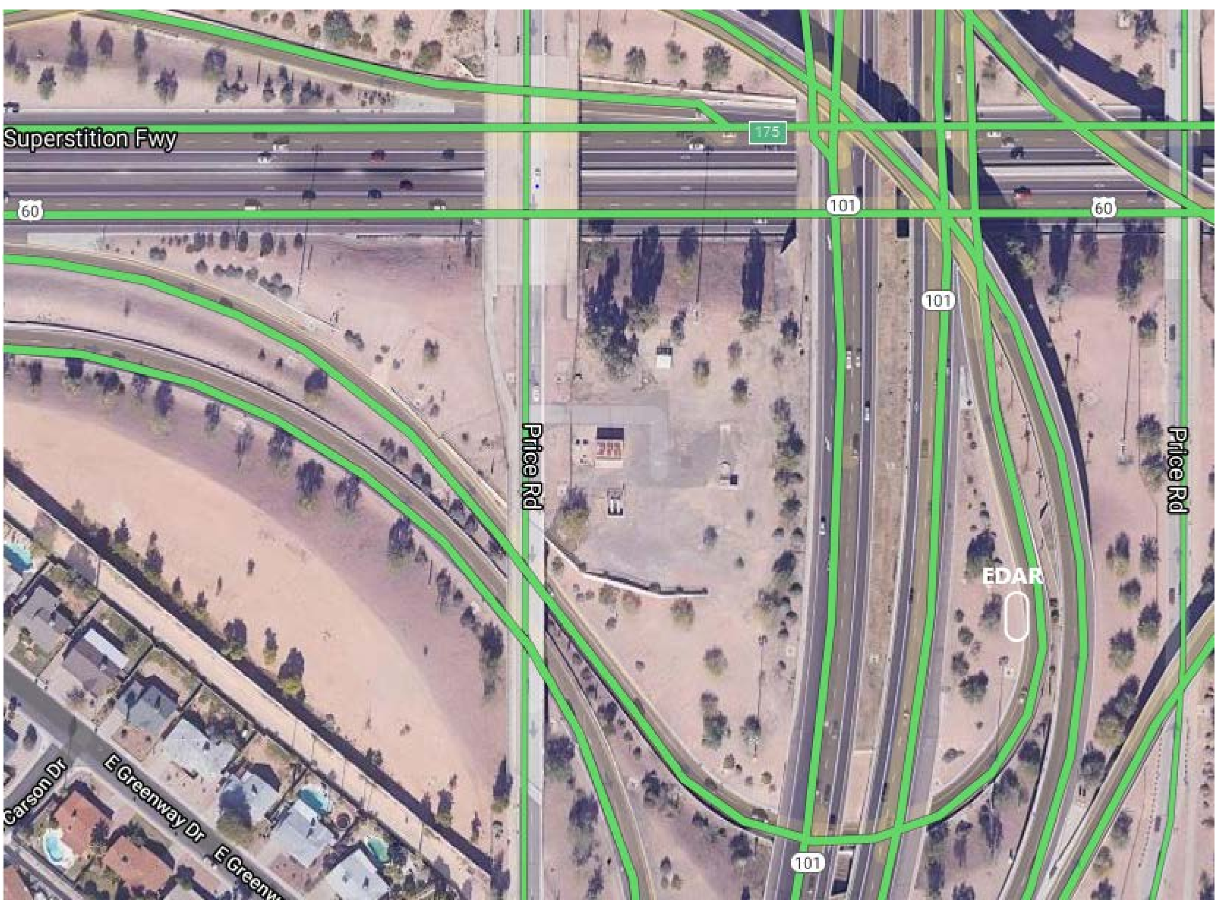
[3] https://www.sciencedirect.com/science/article/abs/pii/S0048969717318405?via%3Dihub

- The carbon monoxide (CO %) readings are within an absolute value of ±0.0075% of the Certified Gas Sample.
- The nitric oxide reading (ppm) are within an absolute value of ±20 ppm NO.
- The hydrocarbon readings are within an absolute value of ±125 ppm hexane.
- The EDAR system has been found to have no drift allowing for the unit to be set up to run continuously collecting accurate data without any need for calibration.
- The R-Squares of the linear regression between the EDAR unit's measurements and known concentrations of each gas at the various speeds were calculated. An "R Squared" of one means perfect fit and an "R Squared" of zero means no fit. The EDAR system's R-Squares show excellent correlation and high linearity for all gases:
    - Methane – 0.983
    - Propane – ranged 0.996 to 0.934
    - NO – 0.998
    - CO – 0.996

2. METHODS

The purpose of this study was to evaluate the EDAR system's ability to measure on-road emissions over a five-day period and make real-time comparisons to Denver University's Fuel Efficiency Automobile Test (FEAT) device and the OPUS system. The exact location was the on-ramp from E 60 to N 101 exit 176B in West Tempe, Arizona, as seen in Figure 4. Approximately 43,205 valid data points were collected over the five-day period. During this five-day timeframe, EDAR collected data from vehicles in a real-world operating environment, which included the detection of CO, CO_2, NO, NO_2, HC, and PM in addition to speed, acceleration, license plate, and ambient conditions. Once the testing was completed, the data was processed, and the applicable data was returned by the ADEQ. The data collected by EDAR will be coordinated with the measurements taken by the FEAT device and Opus for analysis and reporting.

Figure 4. EDAR Location at Transition – from E 60 to N 101 exit 176B

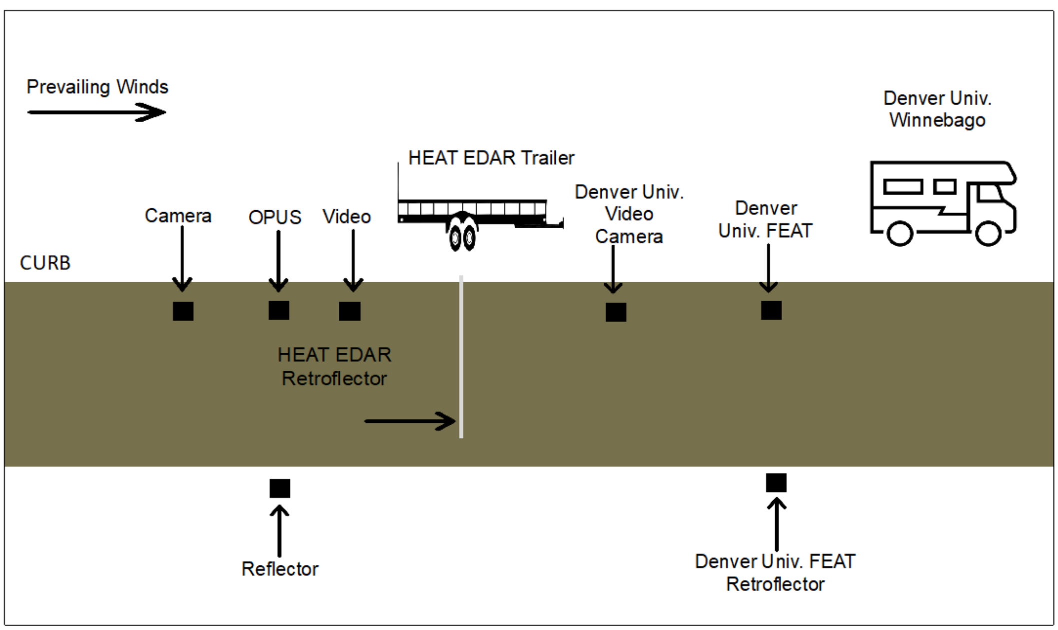


2.1. The Setup

EDAR has a simple unmanned setup that does not require any calibration once deployed. All the EDAR system components (EDAR, license plate camera, rangefinder, and weather sensor) are installed onto the HEAT deployment trailer arm which is raised to 16ft above the lane before the retroreflective strip (retroreflector) is adhered to the pavement. After the retroreflector has been installed, EDAR is powered on and aligned.

For this study, EDAR was powered with electricity provided by ADOT and was connected to a wireless hotspot for internet connectivity. Due to EDAR's specially designed deployment trailer, setup and alignment processes are simple and are completed in approximately one hour. EDAR was taken down after collecting, for five days, the appropriate data to achieve the required 20,000 valid data points. For the purpose of this study, as seen in Figure 5, HEAT set up the EDAR system approximately 20 feet on either side between the Opus and the FEAT systems.

Figure 5 : Configuration of the HEAT, OPUS and FEAT



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 capturing 2D images of passing vehicles and their respective emissions plumes. One axis on the image depicts the length across the road, while the other axis depicts the passage of time. The 2D 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 emissions plume showing the quantity of pollutants detected per unit area or optical mass in moles/m^2.

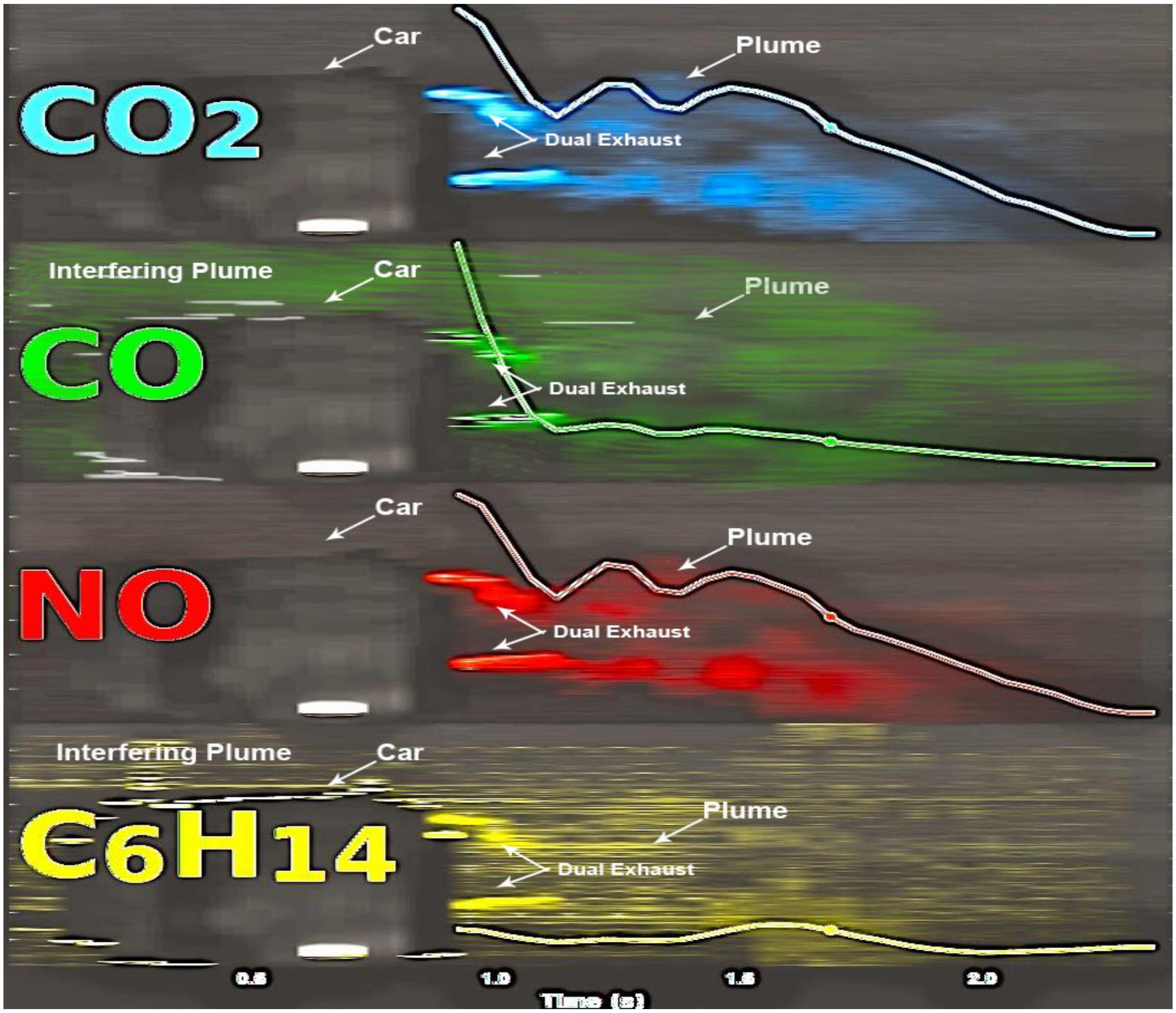
The active image, as described above and shown in Figure 6, shows the position of the plume for each pollutant as well as the dispersion rate of the plume. The gas record is considered valid if there is one scan where the average measurement of CO_2 exceeds 0.004 moles/m^2. The linear correlation coefficient, 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, signifying that there are no interfering plumes. Interfering plumes usually have different ratios of pollutant to CO_2 (See **Appendix A**); thus, the linear correlation coefficient drops in value.[4]

The visual 2D representation of the exhaust plumes shows interfering plumes from either neighboring lanes or preceding (prior-in-lane) 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 6. Each plume image is re-scaled according to the highest readings. In Figure 6, the vehicle's CO_2 plume is much larger than the residual CO_2 in the interfering plume and therefore the interfering plume's CO_2

[4] The highest linear correlation coefficient is 1.0, where 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, the 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.

is not visible in the picture. This is not the case for CO whose residual plume is on the same scale as the current vehicle's CO plume.

Figure 6. 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. Annunciators are set up so that HEAT's engineers are notified in real-time of anomalies or changes that do not meet the standard parameters' criteria. Examples would include an alert if the system moved out of alignment, if it experienced a loss of power, or if there were connectivity issues.

3. RESULTS AND DISCUSSIONS

After five days of data collection in April of 2021, the license plate readings were provided to the state of Arizona to be matched to the State's vehicle registration information. The information released to HEAT from the State did not include any personal driver or registration information, and only contained vehicle data relevant to the analysis. The State of Arizona was able to match 30,393 records that included duplicates with make and model years of scanned vehicles. Of those, 21,093 were unique plates. The data reduction process of the measurements is summarized in Table 1.

Table 1 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 were filtered by the amount of CO_2 measured and the ratios of other gases with respect to CO_2. Measurements that did not fall under the prescribed criteria were considered invalid and were excluded from further analysis.

Table 1 - Validity Summary

EDAR Units	1
Sites	1
Data Collection Days	5
Attempted Vehicles Measured	53,063
Valid Vehicles Measured	43,205
Out of State Plates	4,653
Valid Measurements after Removing Interfering Plumes Submitted to State	39,375
Records Matched to AZ Registration	30,393
Unique Arizona Vehicles Identified	21,093
Unique Arizona Vehicles Identified Once	15,924
Unique Arizona Vehicles Identified Twice	2,787
Unique Arizona Vehicles Identified Three Times	1,420
Unique Arizona Vehicles Identified Four or More Times	962

As a whole, the measurements resulted in an 81.4% validity rate, as outlined in Table 2. The 81.4% validity rate is much below EDAR's 90% normal validity rate at that location due to curious motorists slowing down and reducing speed to take a look as they passed by the elaborate setup of equipment display on the on-ramp, which affected EDAR's data validity rates. (See Figure 1 in Section 1).

Table 2 - Daily Measurements

EDAR	Date	Location	City	County	Attempted Measures	Valid Emissions Reads	Valid %
9	4/12/2021		Tempe	Maricopa	10,851	8,094	74.6%
9	4/13/2021	On-ramp from	Tempe	Maricopa	9,245	7,291	78.9%
9	4/14/2021	E 60 to N 101 Exit 176B	Tempe	Maricopa	12,598	10,941	86.8%
9	4/15/2021		Tempe	Maricopa	12,820	10,419	81.3%
9	4/16/2021		Tempe	Maricopa	7,549	6,460	85.6%
				Totals	53,063	43,205	81.4%

Table 3 below shows the numbers of unique and multi-read vehicles measured.

Table 3 - Number of Measurements of Unique and Multi-Read Vehicles

Number of Times Measured	Number of Vehicles
1	15,924
2	2,787
3	1,420
≥4	926

Table 4 below shows the Temperature and Humidity measurements for the five-day period.

Table 4 - Temperature and Humidity

2021										
Time (CDT)	**12-Apr**		**13- Apr**		**14-Apr**		**15-Apr**		**16-Apr**	
	T(°F)	**RH (%)**	**T (°F)**	**RH (%)**	**T (°F)**	**RH (%)**	**T (°F)**	**RH (%)**	**T (°F)**	**RH (%)**
0	80.5	18.7	60	23	79.2	20.0	79.1	18.5	74.4	14.1
200	76.8	23.5	59	23	73.7	22.9	76.1	19.9	71.2	17.4
400	74.0	24.3	57	23	72.1	24.6	72.1	22.0	67.7	21.9
600	70.9	30.0	68.3	29.3	65.8	30.6	65.6	27.6	66.8	18.4
800	80.4	23.4	75.4	22.4	73.7	23.8	70.8	25.7	75.4	12.8
1000	85.5	17.8	84.0	18.6	79.1	21.3	75.4	21.4	81.8	10.8
1200	90.9	14.0	87.7	15.4	84.1	17.4	83.0	13.4	83.1	10.4
1400	93.5	12.1	94.9	12.4	90.7	14.5	87.9	11.0	86.1	8.8
1600	97.9	11.4	93.2	12.0	90.8	11.8	88.4	10.5	90.0	7.5
1800	95.5	11.6	91.0	15.1	86.4	12.4	82.5	10.3		
2000	88.0	14.8	84.8	17.0	83.3	18.9	79.1	11.2		
2200	84.0	18.0	79.9	18.8	80.0	19.6	76.7	12.5		
2400	79.9	24.7	79.3	19.9	79.5	18.4	74.6	14.1		

3.1. Phoenix Average Emissions by Model Year

The sampled fleet population distribution and average emissions concentrations by model year for Tempe, AZ, are shown in Figures 7 through 12 below. The older the model year, the more likelihood of higher emissions and greater variation in emissions in general, due to the degradation of the emissions mitigation system as vehicles age, and the fact that older vehicles were subject to different, less stringent standards when manufactured. HEAT's data confirms this by showing considerable variation in the older model years' averages.

In this study, only two percent (2%) of the vehicles identified were diesel. Therefore, the large variability in NO_2 is due to the small amount of NO_2 coming from gasoline vehicles. In addition, the NOx plot in Figure 10 shows little difference from the NO plot in Figure 8 due to the low amount of NO_2 emitted by gasoline vehicles.

Figure 7. Phoenix Average CO Emissions

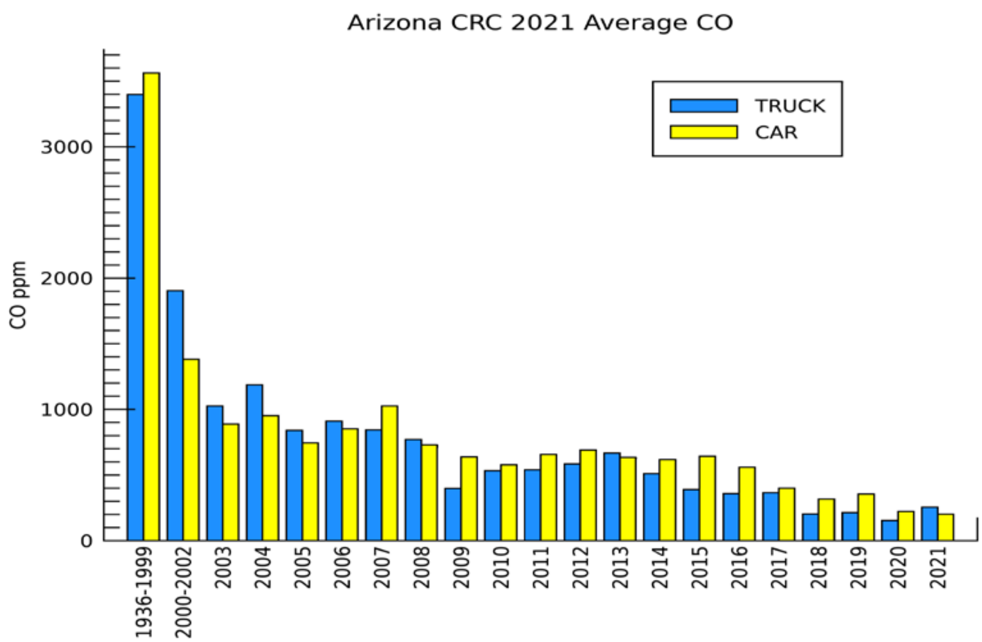


Figure 8. Phoenix Average NO Emissions

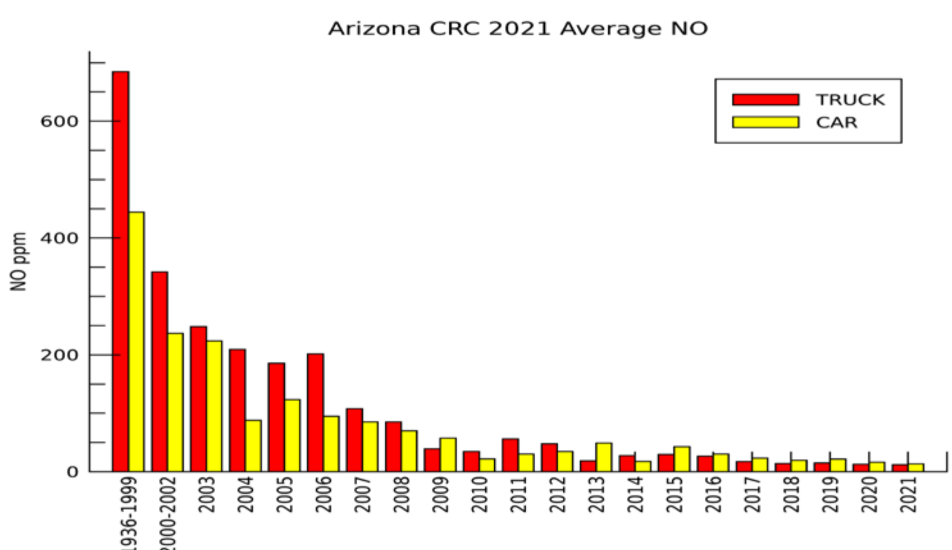


Figure 9. Phoenix Average NO_2 Emissions

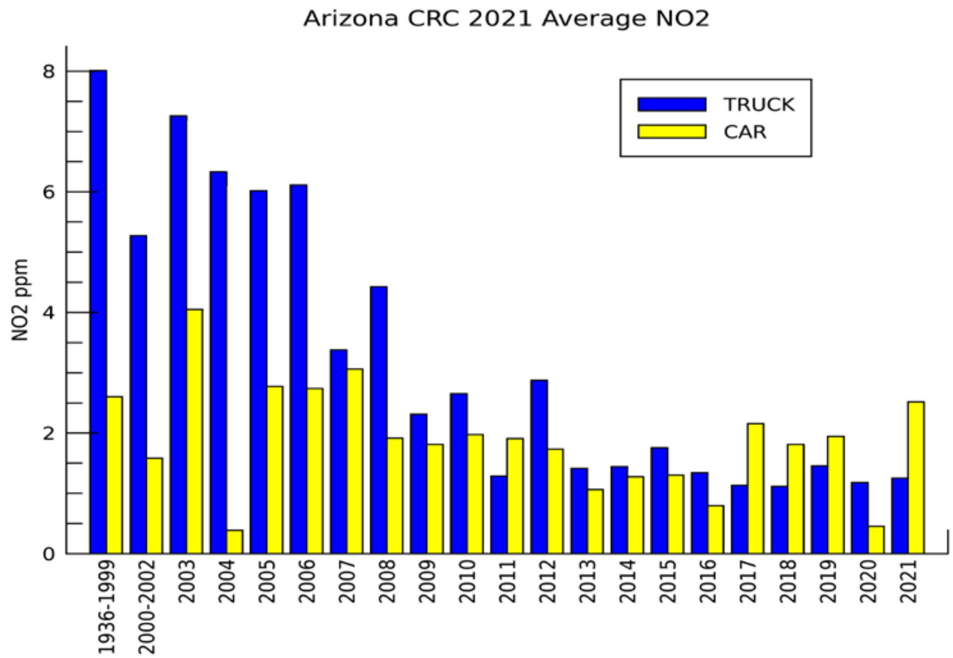


Figure 10. Phoenix Average NO_x Emissions

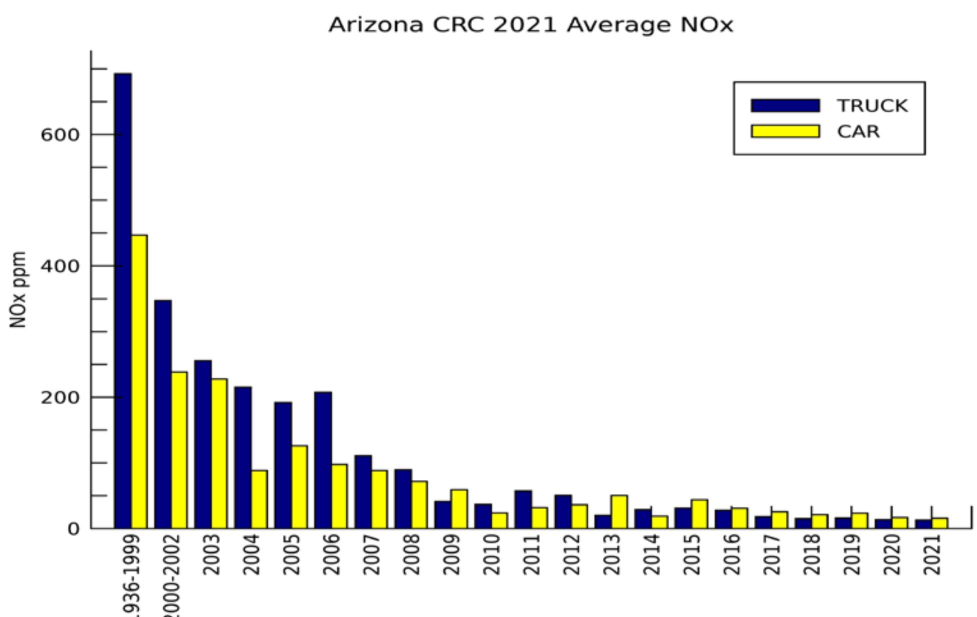
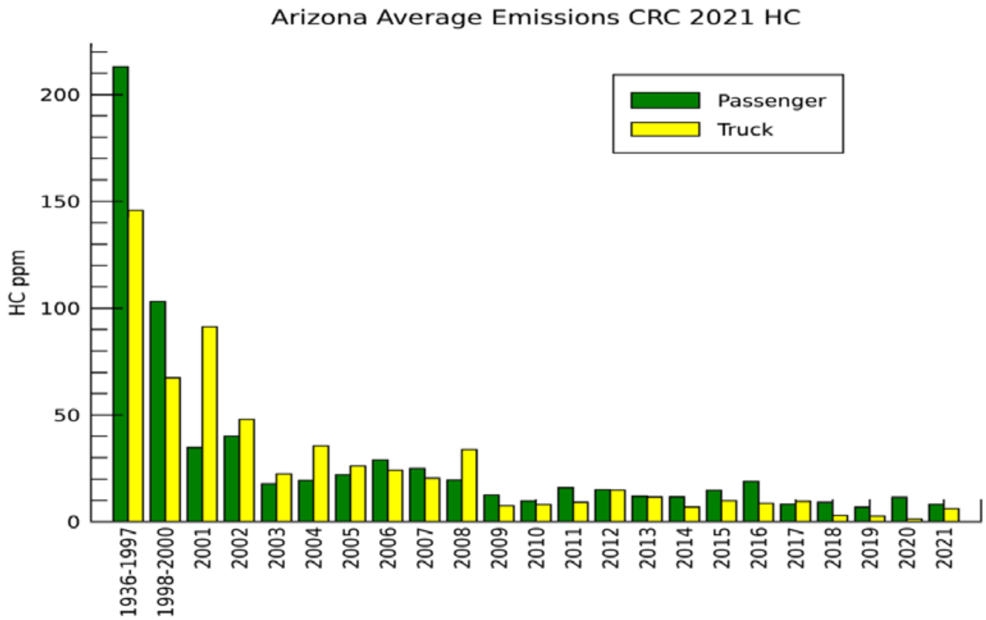
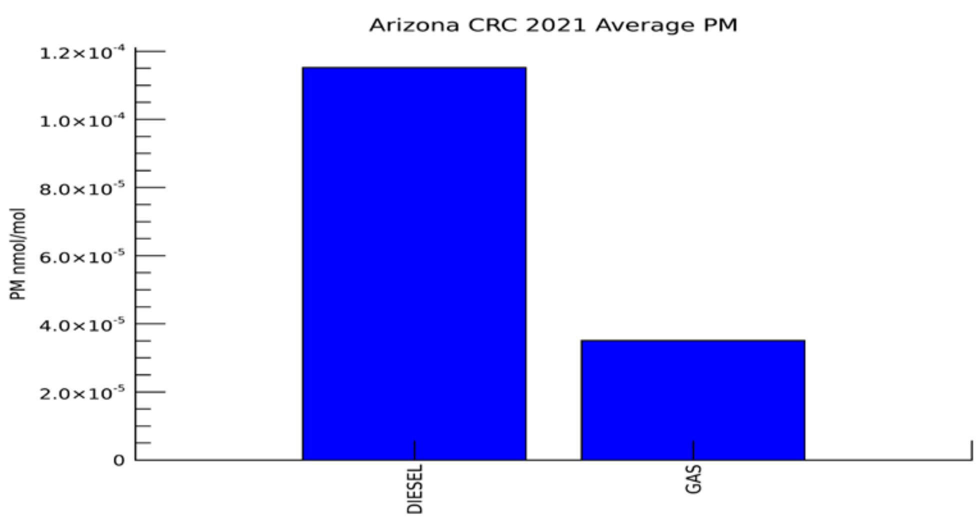


Figure 11. Phoenix Average HC Emissions



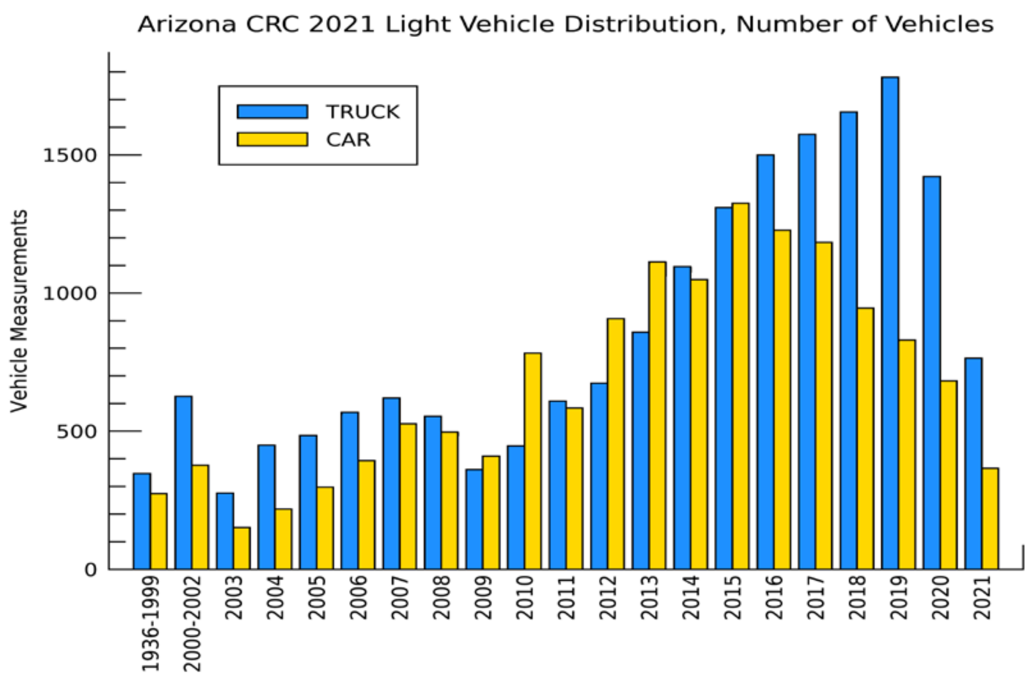
The year-by-year particulate matter (PM) data was not very informative due to the small sample of diesel vehicles. Therefore, an overall analysis compares diesel to gasoline vehicles average PM that is shown in Figure 12.

Figure 12. Phoenix Average PM Emissions



Model years 2009 through 2021, which constitute 73% of the vehicles measured in the graphs below, show average emissions that are fairly consistent. Large variations of averages in vehicles older than 15 years could be due to low sampling. The number of samples for each year for identified cars and trucks are shown in Figure 13.

Figure 13. Phoenix Vehicle Distribution for Passenger Cars and Light duty Trucks



3.2. Measurements of Multi-Read Vehicles

Multiple measurements of the same vehicle are analyzed in Figures 14-16. The plots show the mean emissions 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 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 14. Sorted Multi-Read Vehicles: CO

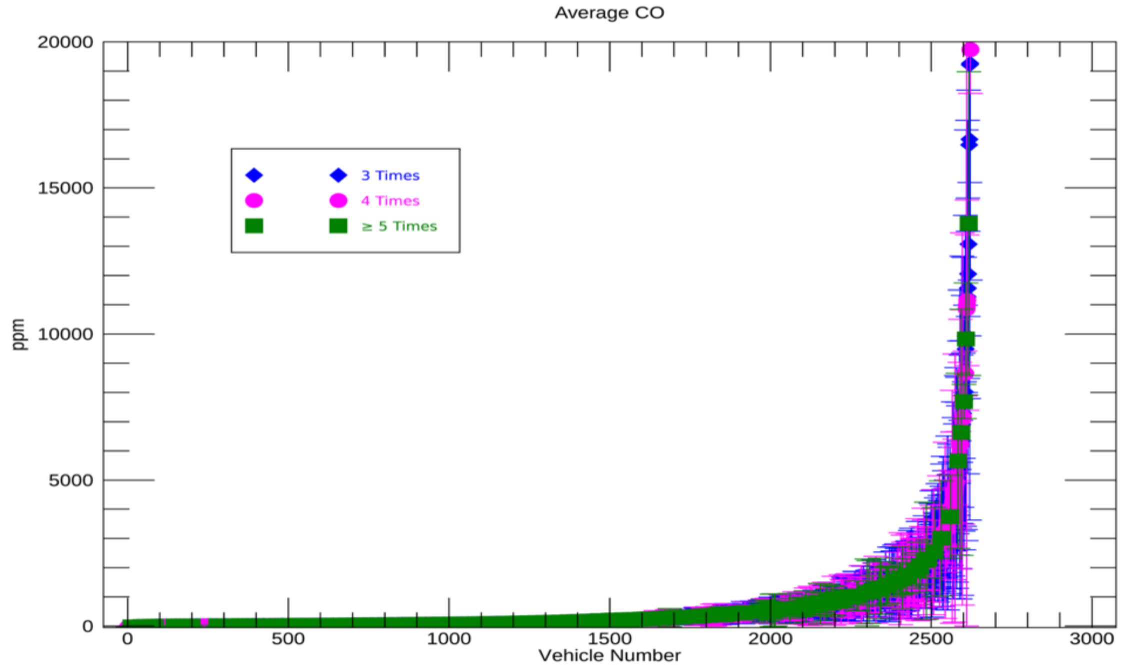


Figure 15. Sorted Multi-Read Vehicles: NO

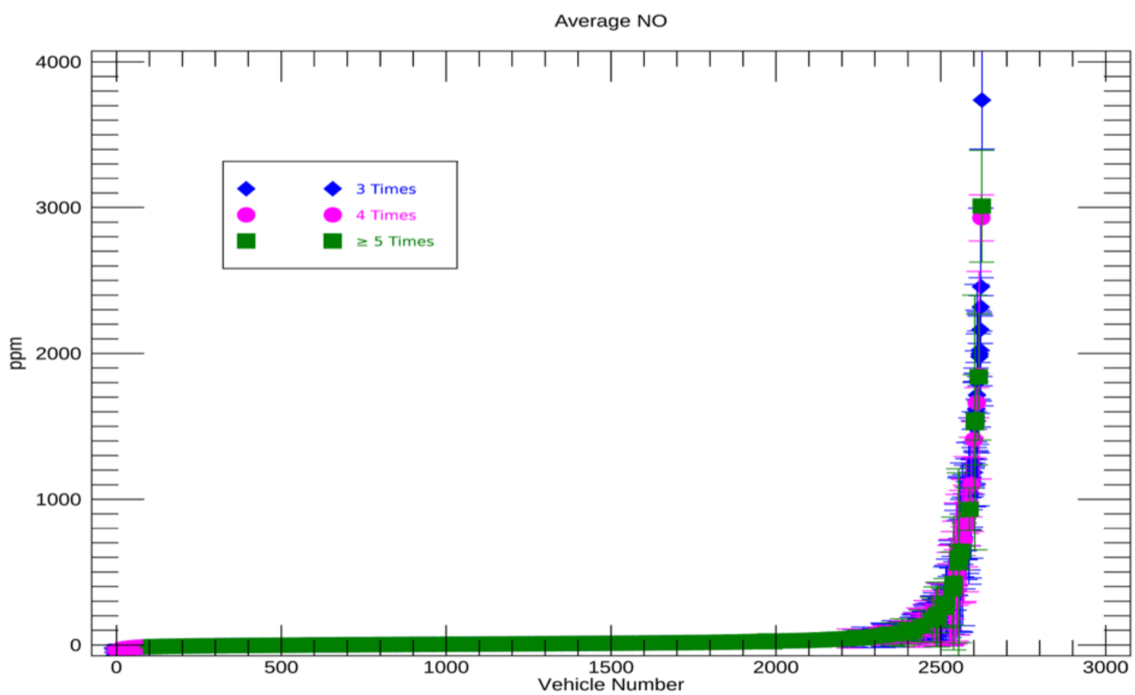
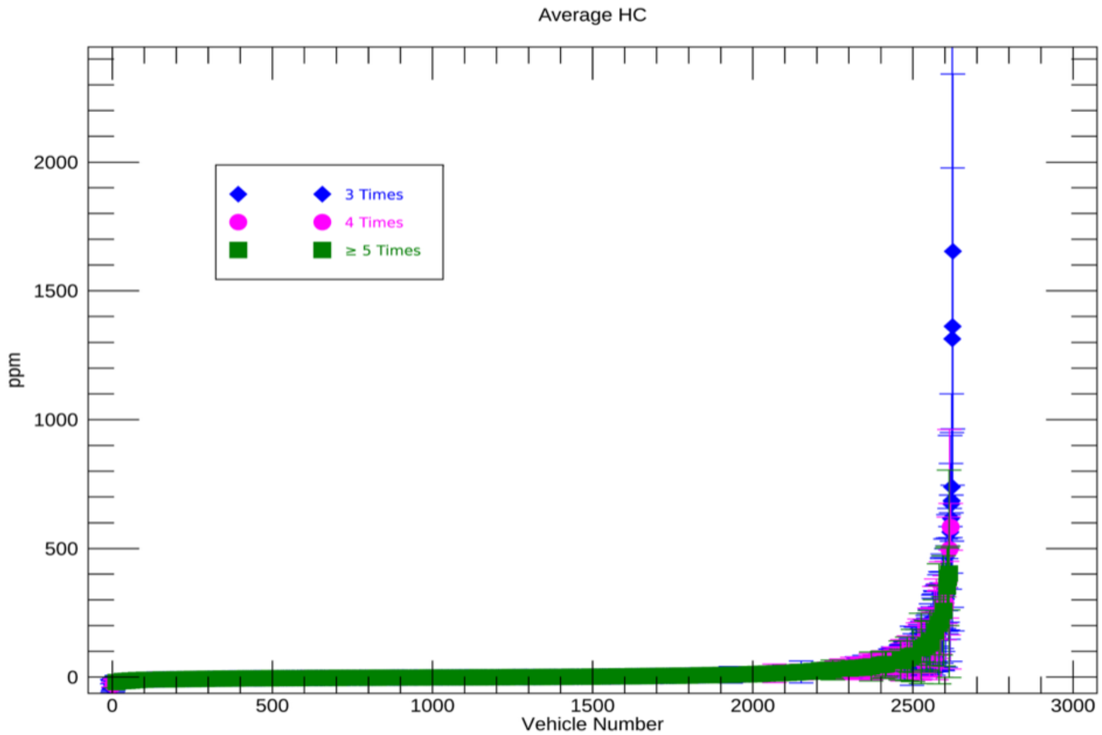


Figure 16. Sorted Multi-Read Vehicles: HC



3.3. Absolute Amounts

The calculation of absolute emission amounts is possible with the EDAR system because of the unique geometry of the remote sensing setup as mentioned in Section 1. EDAR scatters laser light off the road's surface; and 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 to calculate tailpipe percentages. When using this equation, only three ratios are measured, resulting in one of the species' percentages being meaningless.

The CO_2 percentage is derived from the other three and has no meaning except as a denominator.[5] EDAR measures each gas independently from the others, making EDAR's CO_2 measurement, reported in gram/mile, meaningful.

Figures 17 through 22 show the average instantaneous absolute amounts of CO_2, CO, HC, NO, NO_2, and NOx against the model years. The direct measurement of CO_2 can be used for greenhouse gas computations. In Europe, manufacturers' CO_2 g/km ratings for vehicles can be used to scale the pollutants coming from the vehicles by manufacturers' CO_2 g/km/Instantaneous g/km. The EPA gives an average value of 411 g/mi for gasoline vehicles. The average CO_2 for all the records was used to scale g/mi of CO_2 to 411 g/mi to give a realistic value. Otherwise, the values would be much higher than typical averages over excepted drive cycle tests due to the vehicles being under load, which is not always the case in a drive cycle.

The CO_2 averages are lower in the earlier model years. The is due to the higher CO and HC in those years. The CO_2 for trucks starts to become larger than cars from 2010 forward. This is most likely due to a larger average engine size truck.

[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.

Figure 17. Absolute Amounts CO_2

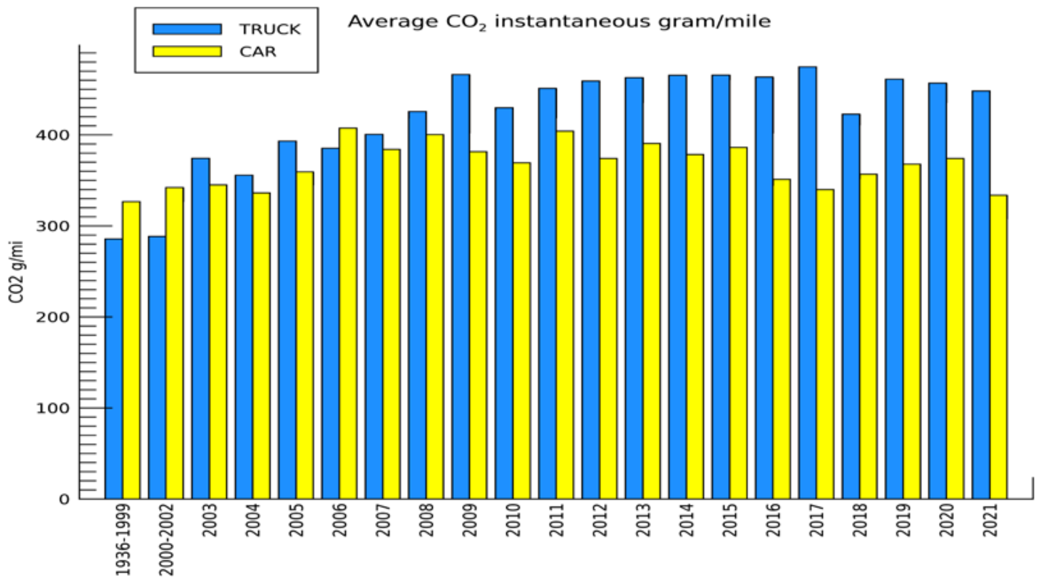


Figure 18. Absolute Amounts CO

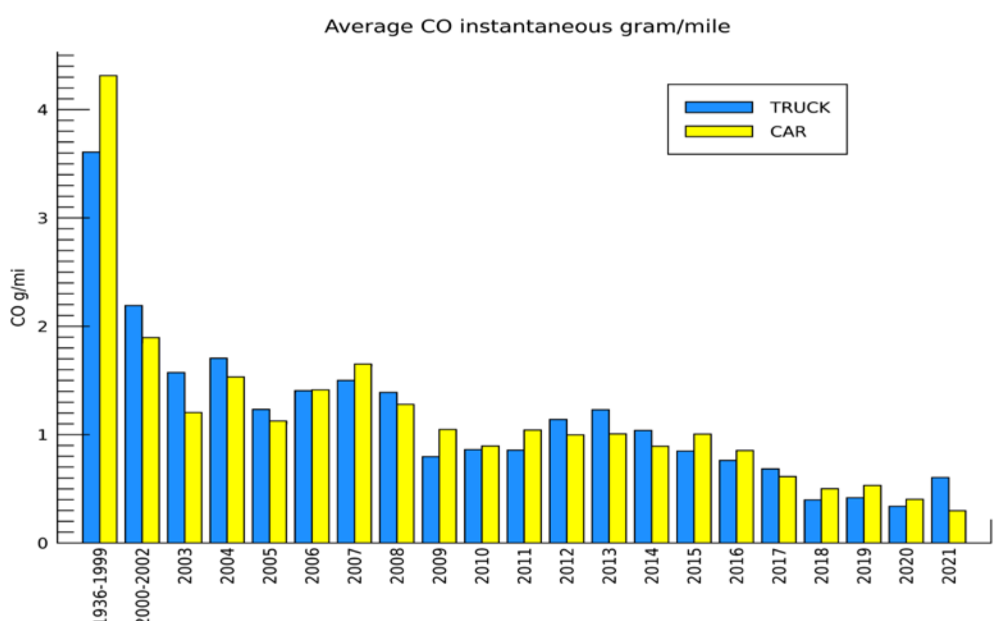


Figure 19. Absolute Amounts NO

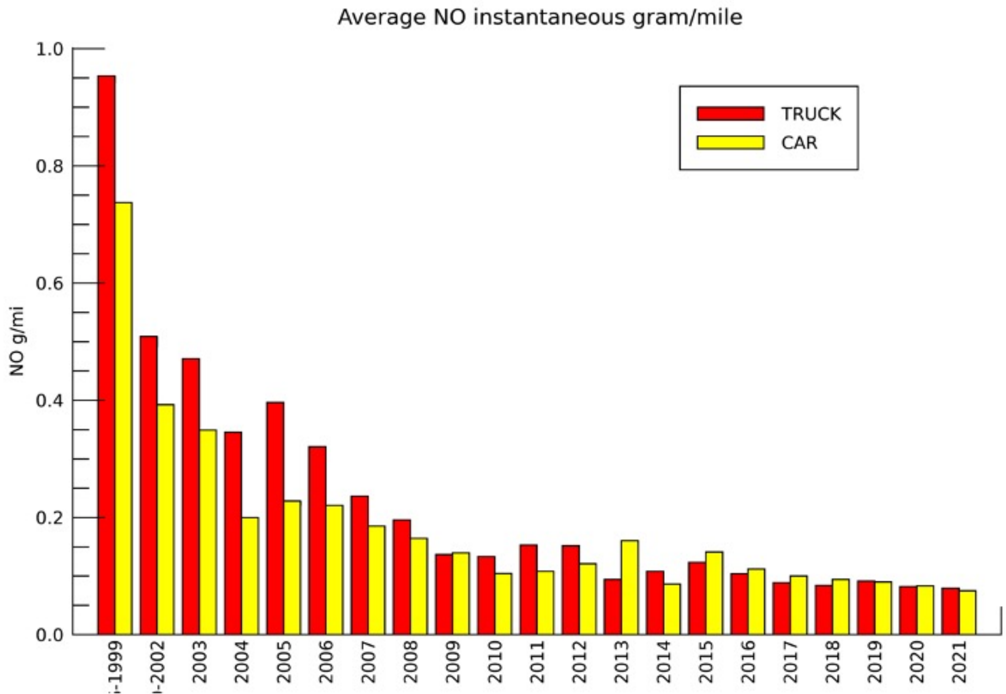


Figure 20. Absolute Amounts HC

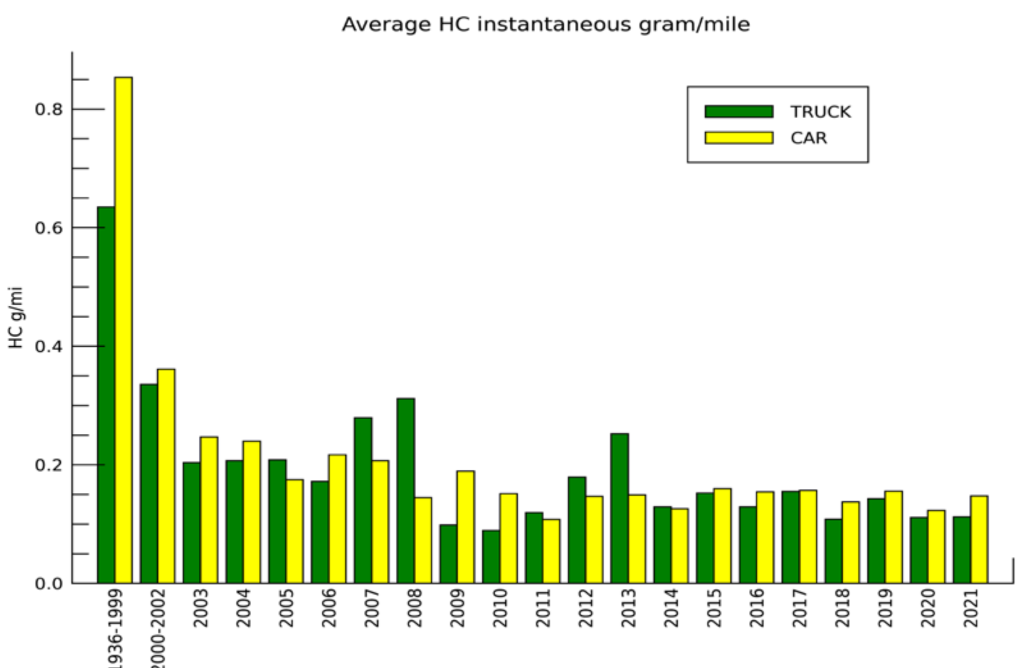


Figure 21. Absolute Amounts NO_2

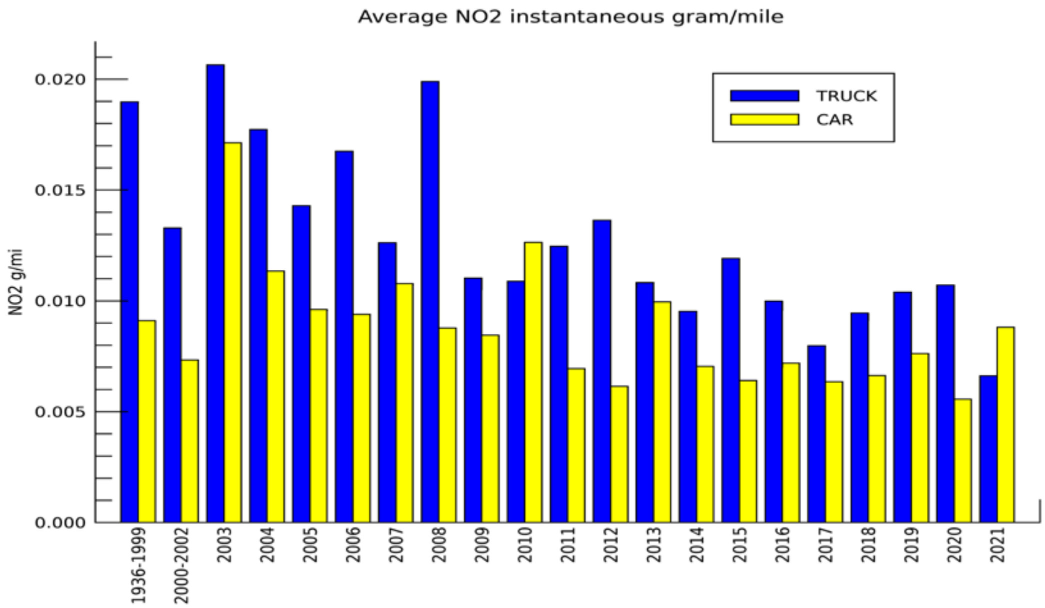
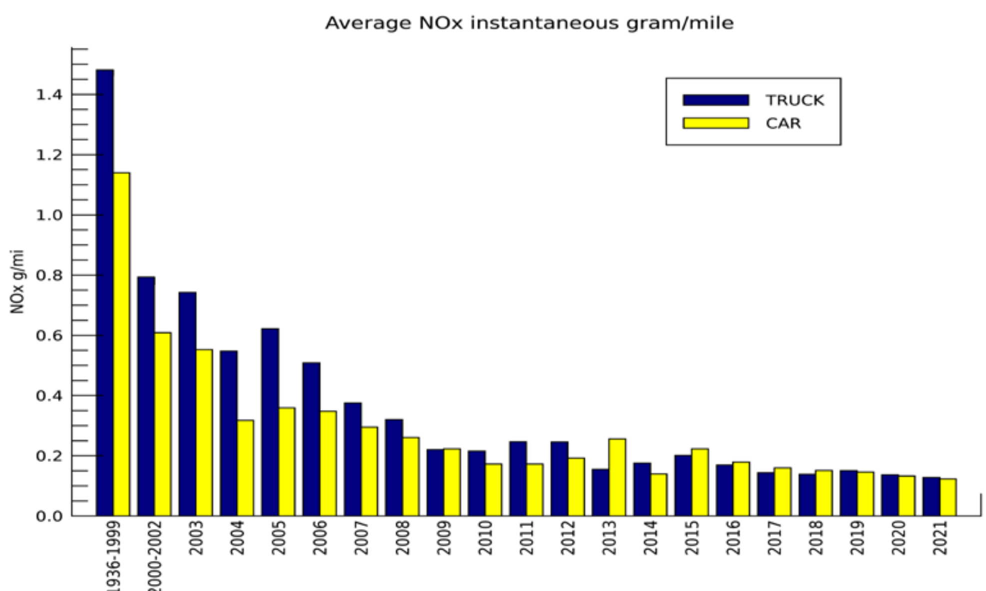


Figure 22. Absolute Amounts NO_x



4. CONCLUSIONS

The five-day study conducted has generated valuable insights into the intricacies of vehicle emissions in the state of Arizona. After analyzing the Arizona plates matched data, the following findings are observed.

- The average emissions of CO, NO, NO_2, PM and HC for the model years 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, NO_2 and HC were 600 ppm, 64 ppm, 2 ppm and 17 ppm, respectively. 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 directly calculate the average absolute emissions in moles/m of pollutants. These absolute values also exhibit similar trends such as a decrease of emissions for newer model-years.

- Assuming trucks would have a larger average engine size than cars, the absolute values for CO_2 for late-model vehicles clearly demonstrate dependency upon engine size. The high CO and HC emissions in the earlier model vehicles resulted in a decrease in the amount of CO_2, because there are only so many carbon atoms in the fuel.

5. LIST OF REFERENCES

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6. APPENDIX

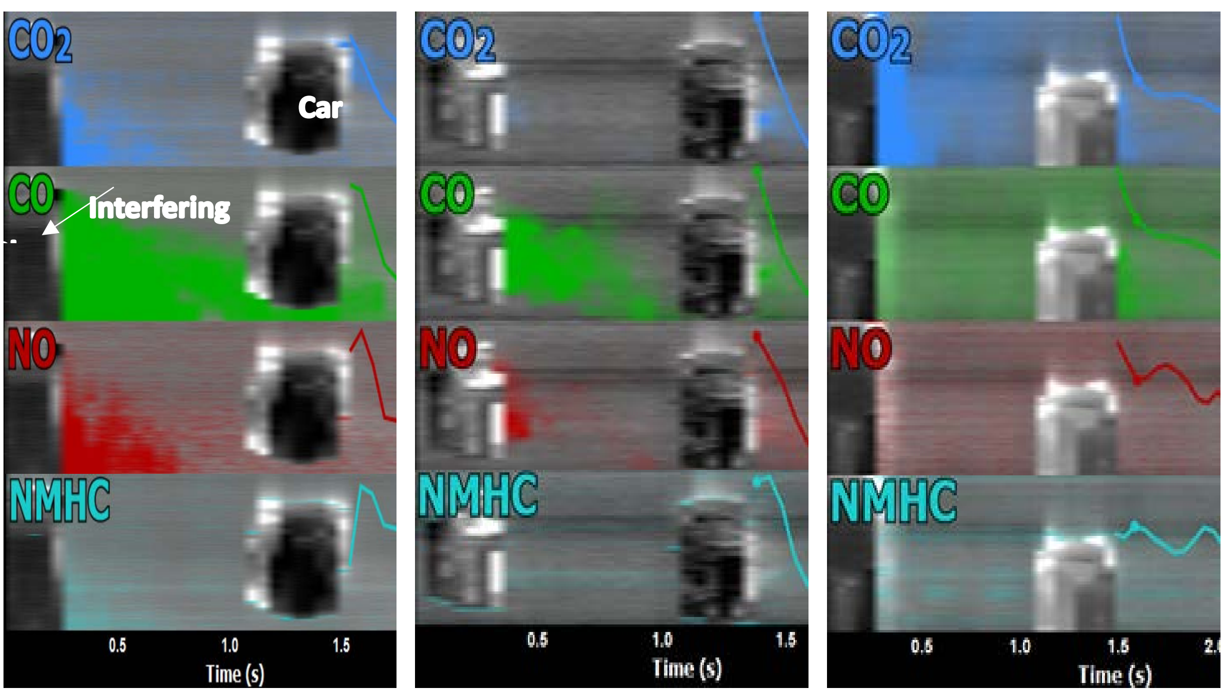
6.1 Appendix A. EDAR images showing interfering plumes of cars on-road

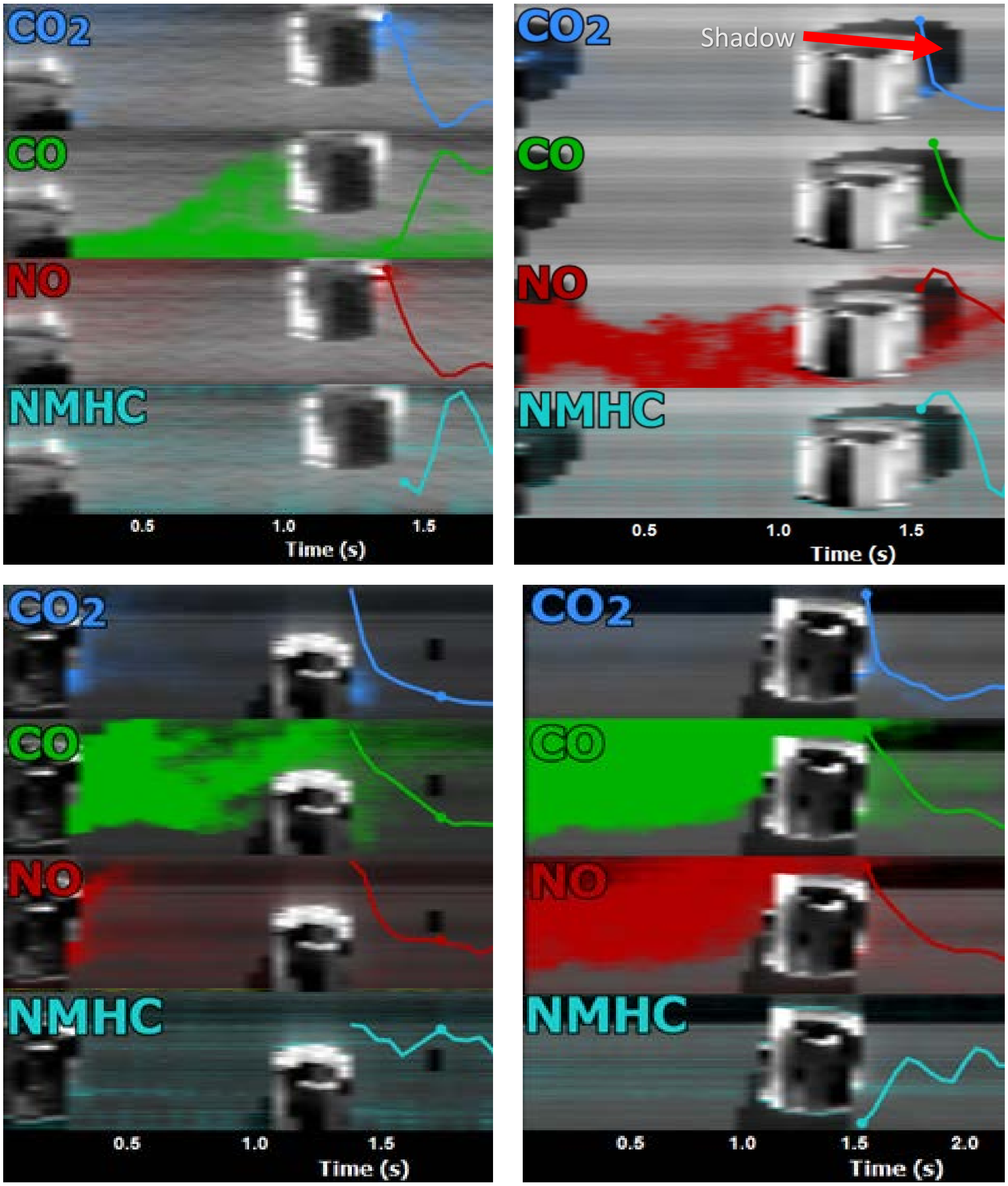
Interfering plumes can pose problems in remote sensing of exhaust emissions. In the present Phoenix study, interference due to neighboring lanes is not at issue since EDAR was mounted on a one-lane ramp. The main cause of interfering plumes in this study was high polluting vehicles.

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, as seen in the second pane on page 34.

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)