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

August 2022

COORDINATING RESEARCH COUNCIL, INC.

5755 NORTH POINT PARKWAY SUITE 265 • ALPHARETTA, GA 30022

CRC PROJECT E-119-3 – PROJECT
Fleet Evaluation Analysis

Draft Report

Prepared by:

Rob Klausmeier
de la Torre Klausmeier Consulting, Inc.

Niranjan Vescio
Opus Inspection

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1 INTRODUCTION

Between April 12-16, 2021, Opus Inspection participated in an evaluation of commercial remote sensing devices (RSD) sponsored by the Coordinating Research Council (CRC). Using its 5th generation RSDs, Opus made 33,434 valid emission measurements in Phoenix, Arizona, alongside the University of Denver and Hager Environmental and Atmospheric Technologies (HEAT). The Arizona Department of Environmental Quality was able to provide vehicle information such as vehicle type and model year for 24,310 of the measurements on Arizona-registered vehicles. This report summarizes the results of these measurements. It specifically provides a breakdown of the results of the remote sensing measurements by vehicle type, model year, I/M status and other parameters. Other RSD performance evaluation analyses are being undertaken by independent CRC analysts.

2 BACKGROUND

The CRC has contracted with the University of Denver (UofD) to evaluate the on-road emissions of motor vehicle fleets around the country using their Fuel Efficiency Automobile Test (FEAT) RSD for almost three decades. The CRC's objective in the April 2021 E-119 study was to compare other commercially available RSDs to the FEAT RSD device before making contracting decisions with either Opus and/or HEAT s for future CRC-sponsored remote sensing type work. The goal of the study was also to collect 20,000 common vehicle measurements across three commercial RSD instruments over a 5-day period at a site that could provide for other experiments.

CRC separately contracted with UofD, Opus and HEAT to perform the 5-days of collocated, on-road data collection, at a site where instrumented vehicles (for tailpipe exhaust and running loss evaporative emissions evaluation) could also be driven by the three RSDs in free traffic flow. The entire project team included the above-mentioned RSD contractors, along with Revecorp, CRC and its auto/oil stakeholders.

Opus was contracted in June 2019 and began study planning with the project team in Fall 2019. After considering several cities, the team settled on testing in Phoenix in the winter when ambient temperatures would be ideal for the evaporative emissions testing and experiments. Opus volunteered to select candidate Phoenix sites in December 2019 which provided for the required low speed with adequate load which is ideal for evaporative emissions detection, and traffic volume to gather 20,000 common all-valid records over 5 days. Data collection was postponed by an entire year due to the COVID-19 pandemic.

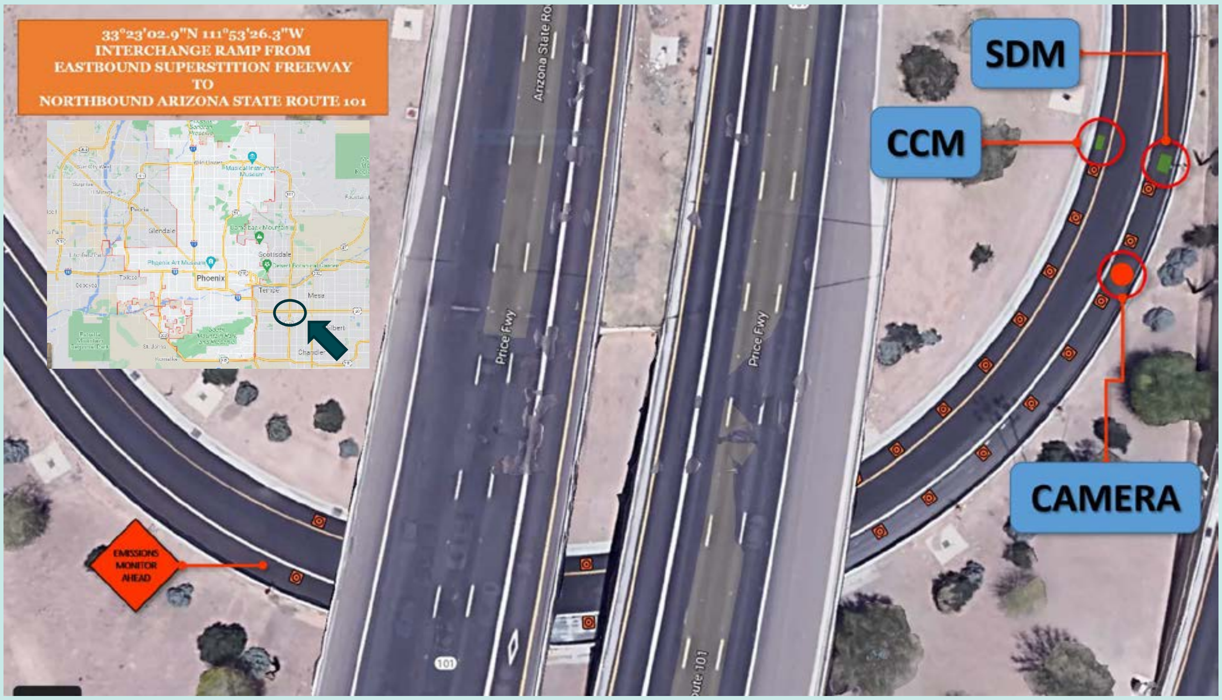
Evaluation of tailpipe emission measurement accuracy (using an electric vehicle dispensing known quantities of a dry exhaust gases and PEMS-equipped vehicles) and evaporative emissions detection and estimation (using butane as the evaporative hydrocarbon surrogate released from various chassis locations on the Mazda and F-150 test vehicles) was the inherent task of the CRC and their independent analyses contractors. A general fleet evaluation analysis and report was requested of each of the three RSD contractors.

The Arizona license plates of vehicles measured by the three CRC remote sensing vendors were delivered to the Arizona Department of Environmental Quality (ADEQ) on July 19, 2021 for plate matching with state vehicle registration records. Information for DMV-matched license plates was returned on November 24, 2021 and passed to CRC and Revecorp.

2.1 RSD Test Site

After reviewing several candidate sites, the team settled on the Opus-recommended connector from US 60 East to 101 North on the Tempe, AZ – Mesa, AZ border. The single lane site provided for 30 mph average speeds as vehicles emerged from the underpass and climbed the 2% incline to merge with 101 North traffic; ideal conditions for high valid emissions measurement capture, including the CRC's instrumented vehicles (**Figure 1**).

Figure 1: Unattended Model RSD5000 On-Road Deployment



3 Opus RSD Technology

The remote sensors Opus deployed in Phoenix at the 60 EB to 101 NB cloverleaf connector were its fifth-generation remote sensing devices (RSD). Model RSD5000s have been used for on-road screening in Opus' largest I/M programs (e.g., Colorado and Virginia) since the early 2010s, results of which are reported in annual reports to the state agencies.[1] Today's model RSD5000 systems are capable of measuring NO_2 and soon NH_3, in addition to the standard CO, HC, NO, PM (uVSmoke) and evaporative emissions. Systems with enhanced capability are built on the RSD5000+ platform and are designated RSD5300s.

The 5300 instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, HC, and IR Smoke and a dispersive ultraviolet (UV) spectrometer for measuring oxides of nitrogen (NO, NO_2), and uV Smoke. The source and detector elements are adjacent in a single module, referred to as a Source/Detector module (SDM), which for light duty US programs, is packaged together with the roadside computer and cell modem, known as the system control unit (SCU), in a large green box fitted with lithium batteries for up to 16 hours of semi-unattended operation (**Figure 2**).

Figure 2: Unattended RSD5000 On-Road Deployment

Opus' two RSD5300 SDMs were deployed separately as manned systems (one at 12" and the other at 18-23", respectively) to capture butane released from different chassis locations. These RSD5300 were capable of measuring CO, HC, NO, NO_2, PM and evaporative emissions. Batteries were unnecessary since ADOT provided power to all three contractors (**Figure 3**).

[1] These reports are not published on the internet but are available upon request.

Figure 3: Two Manned RSD5000 Deployments at Different Heights

Collinear beams of infrared (IR) and (UV) light are directed by an infrared diode and deuterium lamp, respectively, from within the source side of the SDM, across the roadway (parallel to the pavement) to the Corner Cube Mirror module (CCM) which returns the light to the detector side of the SDM. A blue LED is added behind the collimating mirror of the 5300s to boost light in the NO_2 spectral region. Upon their return to the detector module, the collinear IR/UV light beams are focused through a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed through bandpass filters for CO, HC, CO_2 and IR-reference mounted on a spinning wheel and onto a single IR detector. The filter wheel modulates sampling, providing 100 distinct, averaged samples in the standard 0.5 second measurement. The first three are always discarded due to electronic noise, and a maximum 97 can be included in calculations.

The UV light is reflected off the surface of the dichroic mirror and is focused onto the end of a quartz fiber bundle that is mounted to a coaxial connector on the side of the detector unit. The quartz fiber bundle carries the UV signal to an Ocean Optics spectrometer for measurement of NO (NO_2 in 5300s) and uVSmoke-opacity. The spectrometer measures the distinct 227nm peak of NO, by comparing to a calibration spectrum in the same region.[4]

Opus' uVSmoke channel's light extinction is measured in a region near 249nm, not affected by gases, more sensitive to fine particulates, and centered on the accumulation mode which contains most of the particle mass emitted by modern diesels.[2] The uVSmoke is ratioed to the sum of CO, CO_2 and HC (which represents fuel consumed) and can be multiplied by an

[2] "Ultrafine Particle: How should they be defined and measured (cheaply)"; Kittleson, Dr. David; Center for Diesel Research, University of Minnesota, 26th CRC Real World Emissions Workshop, Hyatt Regency, Newport CA, March 13-16, 2016; http://www.nanoparticles.ch/archive/2015_Kittelson_PR.pdf

appropriate light extinction factor to estimate grams of black carbon particulate (i.e., soot) per kilogram of fuel consumed.[3]

Opus' LDV remote sensors use a digital camera to capture a freeze-frame image of the rear license plate of each vehicle measured. The emissions information, as well as a time and date stamp, is 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.

Opus remote sensors measure the speed and acceleration (S/A) of vehicles driving past the remote sensor. The typical S/A system for light duty vehicles consists of a pair of low-power infrared emitters and detectors which generate a pair of infrared beams crossing the road, five feet apart and approximately two inches above the surface. Vehicle speed is calculated from the time the front tire blocks the first and then the second beam. To measure vehicle acceleration, a second speed is determined from the time the second axle tire blocks the first and the second beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated. **Table 1** summarizes the information that was collected.

Table 1: Opus Inspection RSD5000 data collection summary

Item	Measurement Collected	Additional Notes
Fuel Specific Carbon Monoxide	Molar CO/CO_2 ratio	IR spectral region
Fuel Specific Total Hydrocarbons	Molar HC/CO_2 ratio	IR spectral region
Fuel Specific Opacity	Smoke Factor (light extinction)	UV spectral region
Fuel Specific Nitric Oxide	Molar NO/CO_2 ratio	UV spectral region
Speed	Vehicle speed (miles/hour)	+1 mph 5 – 100 mph
Acceleration	Vehicle acceleration (mph/sec)	+ 0.5 mph/second (5 – 100 mph)
Plate Images	Front license plate images	AZ Plates, and immediate neighboring states identified

Details of Opus remote sensing calculations are provided in Appendix A, page A-1, "Remote Sensing Device Trial for Monitoring Heavy-Duty Vehicle Emissions"; report prepared by Opus (Envirotest) for the Metro Vancouver Regional Council, March 2003. http://www.metrovancouver.org/services/air-quality/AirQualityPublications/2013_RSD_HDV_Study.pdf

Vehicle plates were read by an Open ALPR brand Optical Character Recognition (OCR) system, followed by manual transcription of the unread plates.

[3] uVSmoke Factor; https://www.esp-global.com/downloads/RSDSmokeMeasurement.pdf. RSD5300 uVSmoke = RSD4000*10.

Calibration is performed with a sealed gas cell that is moved in and out of the beam path within the SDM. Immediately following calibration and periodically thereafter, calibration verification audits (CVA) were performed using mixtures containing CO, HC, NO and CO_2. Several puffs of gas are released into the instrument's path, and the measured ratios from the instruments are then compared to those certified by the cylinder manufacturer (Air Gas). These audits account for day-to-day variations in instrument sensitivity, variations in ambient CO_2 levels caused by local sources, atmospheric pressure, and instrument path length. Although propane is used to calibrate and audit the instrument, all hydrocarbon measurements reported by the remote sensor are reported as hexane equivalents in the database.

4 Opus RSD Setup

The US 60 East to 101 North site provided for the complete set-up of all three instruments; Opus' RSD5000s, HEAT's EDAR and the University of Denver's FEAT. Exact placement of the three RSDs was agreed to on Sunday, April 11th. HEAT set-up in the middle position overnight, when road-closure was permitted. Opus and UofD set-up starting 7am on Monday, April 12^{h}. Opus initially set-up approximately 9 feet upstream from HEAT's on-road reflective strip and UofD approximately 9 feet downstream (**Error! Reference source not found.**). Opus and the University of Denver took down their instruments each night, while HEAT left their EDAR erected. Opus setup one RSD at 12 inches; the standard height to capture trailing light duty vehicle exhaust. The setup of the second RSD varied from 18-23 inches to test its detection of butane released from varying points on the vehicles' chassis.

4.1 Extenuating Circumstances

Opus experienced extreme conditions on Monday, April 12th, the first day of testing at the CRC site. Opus set-up its two RSD5300s starting 9 feet ahead of HEAT's reflector strip (Figure 4).

Figure 4: Initial Distance from HEAT Reflector Strip (April 12, 2021) – 9 feet

Axles of heavy vehicles with rigid suspensions passing over the 1.5" inch strip would fall back to the pavement, vibrating the road and moving Opus' optical alignment. This caused optical alignment alarms on Opus RSDs, indicating signal levels had shifted beyond an acceptable threshold and forcing recalibration and audit of Opus' system. This alignment alarm is a quality control measure standard on Opus RSDs. Opus made numerous unsuccessful attempts to stabilize our RSDs, including weighing-down the high RSD and vibration-dampening both RSDs (**Figure 5**) using yoga mats.

Figure 5: Attempts to stabilize and dampen RSD5300s affected by HEAT's on-reflective strip (April 12, 2021)

Opus moved further away (18-23ft) from the HEAT set-up starting Tuesday afternoon (April 13) and on subsequent days, but still experienced above average alignment alarms, causing recalibrations and audits. An example of a unladen truck passing over the HEAT reflector, falling back to the pavement and causing vibration was captured on video. A slow-motion and normal speed video can be found in the following DropBox folder: **https://www.dropbox.com/sh/3wejb29sehtr9d3/AABJwfRZVMkSciGZKOzu3lZCa?dl=0**.

HEAT claims to have observed our dispensed audit gas within its measurement beam. Opus dispenses gas outside the SDM, which is on the road shoulder. Opus' audit gas is at concentrations present in dirty vehicles and is dispensed at volumes observed from modern vehicles, but only for a fraction of a second. Therefore, it is not in volumes emitted by vehicles during a complete drive-by. Furthermore, audit gas is only dispensed when no other vehicle has passed for at least 3 seconds (allowing the air to clear) and there will be no oncoming vehicles for at least 1.5 seconds so it does not interfere with the 1 second audit sequence.

If a vehicle travels ~60 feet at 40 mph, the average speed at the site, the vehicle measurement HEAT claims our audit gas is interfering with is still 113 feet from their sensor at the time of our audit gas release. Even if the audit gas dispensed at the shoulder entered their beam, it should have diluted to near background level by the time that next vehicle arrived. At that point, their system, like ours, should be able to effectively characterize and correct for any lingering background.

4.2 Concentrations from Measured Ratios

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor only directly measures ratios of CO, HC, NO, and NO_2 to CO_2. The molar ratios of CO, HC, NO, and NO_2 to CO_2, termed Q^{CO}, Q^{HC}, Q^{NO}, and Q^{NO2} respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system.

The measured emissions are ratios of pollutant to CO_2. The submitted dataset includes the ratios and also reports the calculated grams pollutant / kilogram of fuel burned for the petrol vehicles tested in Phoenix. The default concentrations calculated using standard stoichiometric petrol combustion chemistry (%CO, ppmHC, ppmNO, and ppmNO_2 in the exhaust gas, corrected for water and excess air not used in combustion), are inaccurate and meaningless for diesel vehicles. These concentrations appear watermarked on the bottom of the vehicle images and should be ignored. This conversion is achieved directly by first converting the pollutant ratio readings to moles of pollutant per mole of carbon in the exhaust using the following equation:

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

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.

Ratios
gm CO/kg = $(28Q^{CO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014$
gm HC/kg = $(2(44Q^{HC}) / (1 + Q^{CO} + 6Q^{HC})) / 0.014$
gm NO/kg = $(30Q^{NO} / (1 + Q^{CO} + 6Q^{HC})) / 0.014$
gm NO_2/kg = $(46Q^{NO2} / (1 + Q^{CO} + 6Q^{HC})) / 0.014$

The on-road clean screening program for the Colorado Department of Public and Environment (CDPHE) and the high emitter screening program for the Virginia Department of Environment (VDEQ) have shown that the Opus' remote sensing methods identify and excuse clean LDVs with 97-99% of the inspected fleet's excess repairable emissions retained, and high emitting vehicles with 1-3% false failures.[4] Comparison of fleet average emissions by model year versus IM240 fleet average emissions by model year show correlations between 0.93 and 0.98 for data from Denver, collected by the RapidScreen program.[5] Finally, measurements with Opus RSD5000s agree well with corresponding emissions measured with PEMS.[6]

4 2018 Virginia On-Road Emissions Program Annual Report; prepared by Opus Inspection for Virginia Department of Environment Quality, June 2019.

5 2009 Colorado Remote Sensing Program Annual Report; page 44, report prepared by Opus for the CDPHE, July 2010.

6 Real-driving emissions from diesel passenger cars measured by remote sensing and as compared with PEMS and chassis dynamometer measurements - CONOX Task 2 report; Sjodin, et. al.; May 2018 https://www.ivl.se/download/18.2aa26978160972788071cd79/1529407789751/real-driving-emissions-from-diesel-passengers-cars-measured-by-remote-sensing-and-as-compared-with-pems-and-chassis-dynamometer-measurements-conox-task-2-r.pdf

5 SUMMARY STATISTICS

A summary of the RSD emissions data collected by Opus is presented below.

Observations by Vehicle Type and Model Year

Table 2 provides a breakdown of the observations by model year and vehicle type.

Table 2: Observations by Vehicle Type and Model Year

Model Year	Car	Truck	Grand Total
1981	2		2
1985	2	2	4
1986	4	1	5
1987	1	2	3
1988	10	3	13
1989	2	3	5
1990	1	1	2
1991	2	4	6
1992	2	9	11
1993	1	6	7
1994	15	22	37
1995	12	18	30
1996	13	26	39
1997	32	48	80
1998	68	40	108
1999	50	101	151
2000	67	120	187
2001	110	177	287
2002	101	192	293
2003	125	246	371
2004	182	331	513
2005	210	405	615

2006	329	453	782
2007	390	502	892
2008	333	404	737
2009	345	259	604
2010	625	322	947
2011	502	407	909
2012	713	485	1,198
2013	961	597	1,558
2014	862	708	1,570
2015	1,101	943	2,044
2016	1,050	1,049	2,099
2017	1,022	1,217	2,239
2018	782	1,221	2,003
2019	776	1,280	2,056
2020	642	1,222	1,864
2021	15	24	39
Grand Total	**11,460**	**12,850**	**24,310**

Observations by I/M Status

Test data were matched with the most recent inspection/maintenance (I/M) results from Arizona's I/M database. Data were grouped into the following categories:

- Compliance – I/M test expiration date was after RSD observation date.
- Not Tested/Expired – Vehicle not tested or I/M expiration was before RSD observation date.
- Exempt – Vehicle exempt from I/M requirements.

Table 3 presents the number observations broken down by model year and I/M status. The number of observations in this dataset was slightly lower than the overall dataset, because some observations could not be matched with I/M Status.

Table 3: Observations by Model year and I/M Test				
Model Year	I/M Status			
	Compliance	Not Tested/Expired	Exempt	Grand Total
1981		2		2
1985	1	3		4
1986	5			5
1987	2	1		3
1988	8	5		13
1989	5			5
1990	2			2
1991	5	1		6
1992	10	1		11
1993	7			7
1994	29	8		37
1995	23	7		30
1996	31	8		39
1997	60	20		80
1998	101	7		108
1999	125	26		151
2000	145	42		187
2001	242	45		287
2002	256	37		293
2003	329	42		371
2004	434	79		513
2005	558	57		615
2006	704	78		782
2007	822	70		892
2008	658	79		737
2009	565	39		604
2010	898	56		954

2011	842	67		909
2012	1103	95		1198
2013	1487	70		1557
2014	1455	113		1568
2015	1862	179		2041
2016	1591	503		2094
2017	33	6	2165	2204
2018	8		1983	1991
2019	10		2036	2046
2020			1708	1708
2021			39	39
Grand Total	14416	1746	7931	24093

Observations by State

Table 4 presents the number of valid observations broken down by state as indicated on the vehicle's plate. Vehicles from all 50 states were observed. Information such as year, make, and vehicle type also could not be identified for out of state vehicles. Because of this, we cannot make valid comparisons of emissions by state.

Table 4: Observations by Plate State

State	Count		State	Count		State	Count		State	Count		State	Count
AZ	29,388		UT	99		IN	44		ID	22		SD	14
CA	841		MN	84		OK	41		MD	22		SC	11
TX	581		OR	73		NJ	39		MT	22		NH	10
CO	251		OH	72		NY	33		AL	21		KY	8
IL	204		WI	63		MO	32		AR	21		MS	8
NM	196		TN	54		KS	30		NC	21		DE	4
FL	194		MI	53		CT	29		VA	21		HI	3
WA	191		IA	46		LA	29		AK	19		RI	3
NV	154		GA	45		ND	27		MA	19		WV	3
			PA	45		NE	24		WY	18		DC	2
UNKNOWN	1,310											ME	2

6 EMISSIONS TRENDS

Following is an analysis of emissions trends for vehicles observed in the CRC survey. The pollutants that are analyzed are carbon monoxide (CO), hydrocarbons (HC as hexane), and nitrogen oxide (NO).

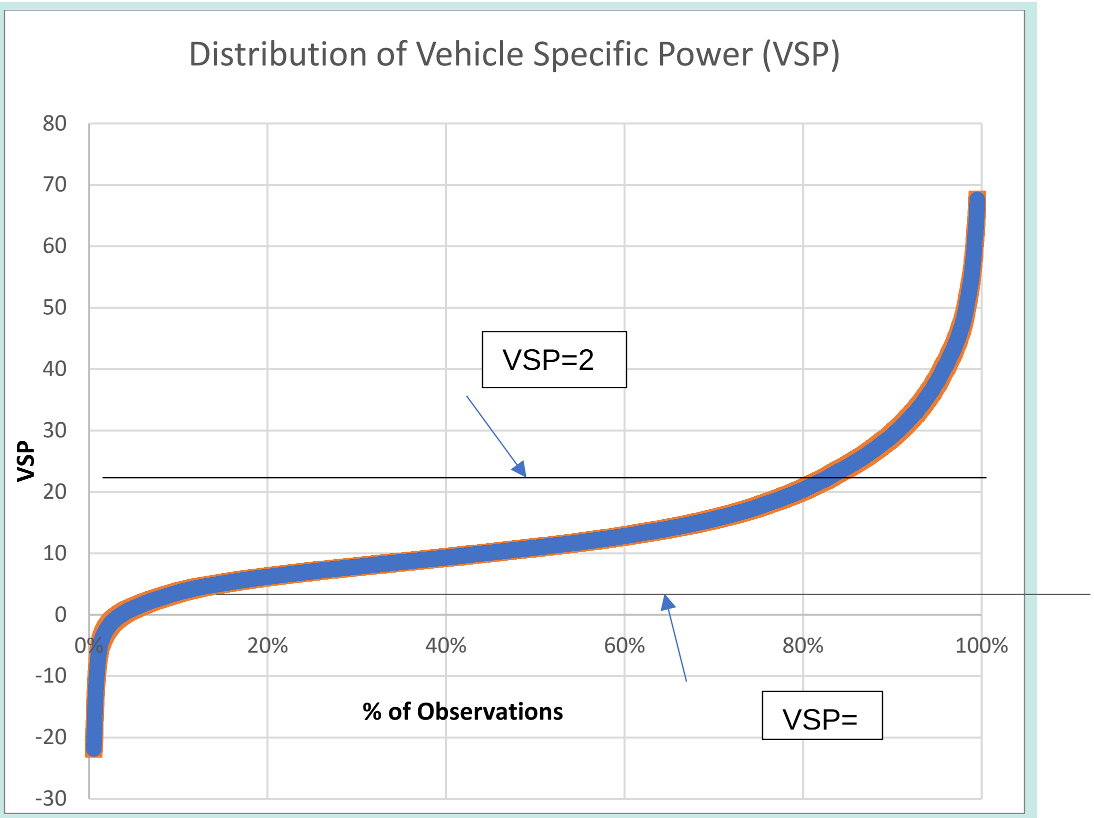
6.1 Impact of Vehicle Specific Power on Emissions

Opus used the speed/acceleration and site grade data to determine Vehicle Specific Power (VSP). VSP attempts to characterize the power requirements of the vehicle based upon speed, acceleration and slope at the site. VSP is defined by the following equation:

VSP (KW/ton) = 4.364*sin (Grade in Deg/57.3)*Speed + 0.22*Speed*Accel + 0.0657*Speed + 0.000027*Speed*Speed*Speed

Figure 6 shows the distribution of VSP. Median VSP was 10.9; average VSP was 13.8. During the Federal Test Procedure (FTP), vehicles have a range of VSP between 3 and 22.

Figure 6: Distribution of Vehicle Specific Power (VSP)

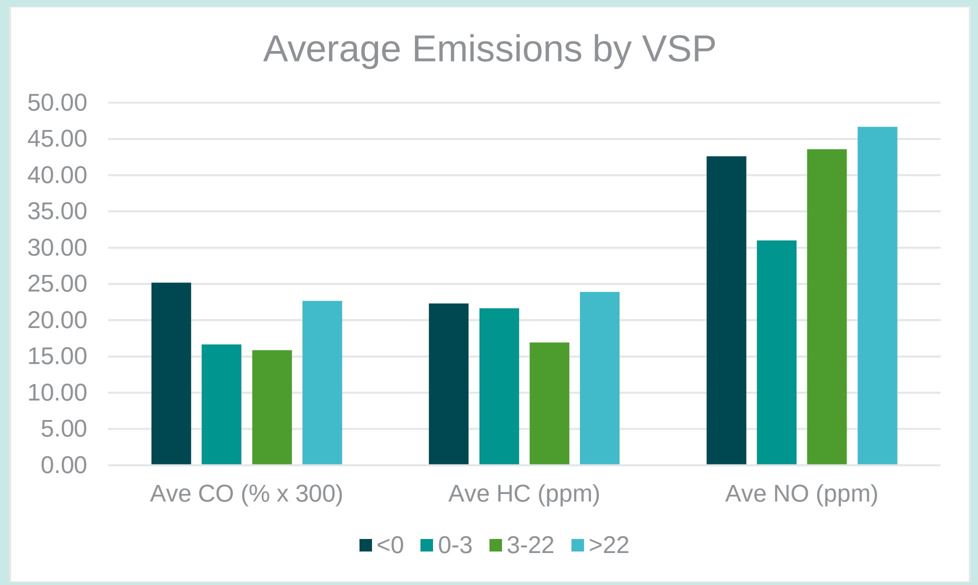


Opus grouped RSD emissions into four VSP groups:

1) VSP less than zero (4% of sample),
2) VSP between 0 and 3 (5% of sample),
3) VSP between 3 and 22 (74% of sample), and
4) VSP greater than 22 (18% of sample).

Figure 7 shows average CO, HC and NO RSD emissions by VSP group. HC, CO and NO emissions for all pollutants were greater when VSP was less than zero. This is likely because CO_2 volumes during deceleration are dynamic and fall rapidly, briefly raising the ratios of the pollutants to CO_2.[7] For CO and HC, the VSP 3-22 group had the lowest emissions. For NO, the VSP 0-3 group had the lowest emissions. All measurements, regardless of VSP, are used in the subsequent analysis.

Figure 7: Average Emissions by VSP



[7] See section "Concentrations from Measured Ratios" for more details.

6.2 Trends by Model Year and Vehicle Type

Figure 8 through **Figure 10** present average CO, HC, and NO emissions by vehicle type and model year. As expected, newer vehicles have lower emission rates than older vehicles. CO and HC emission concentrations are similar for cars and trucks. The older trucks have higher NO emissions than the cars.

Figure 8: CO Emissions by Vehicle Type and Model Year

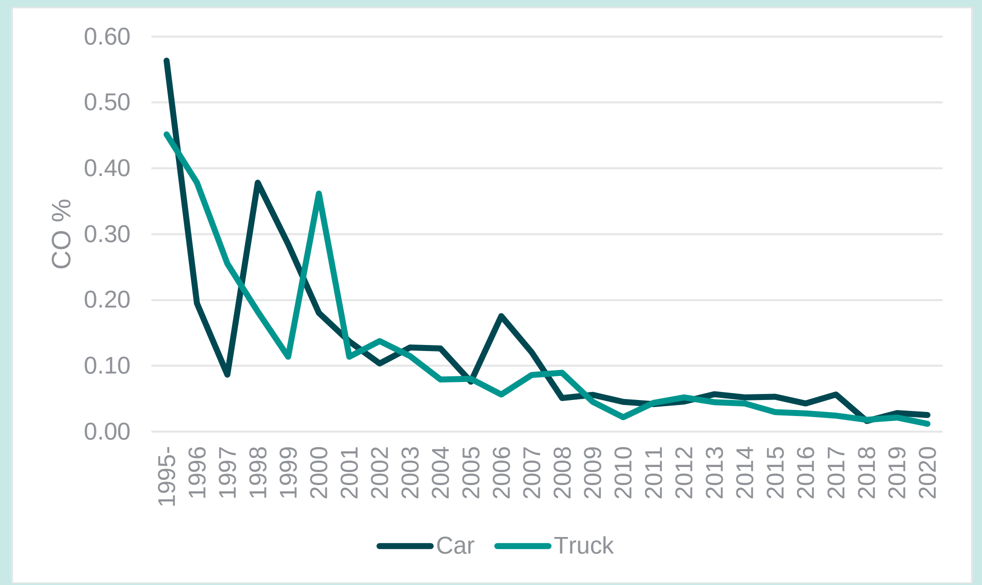


Figure 9: HC Emissions by Vehicle Type and Model Year

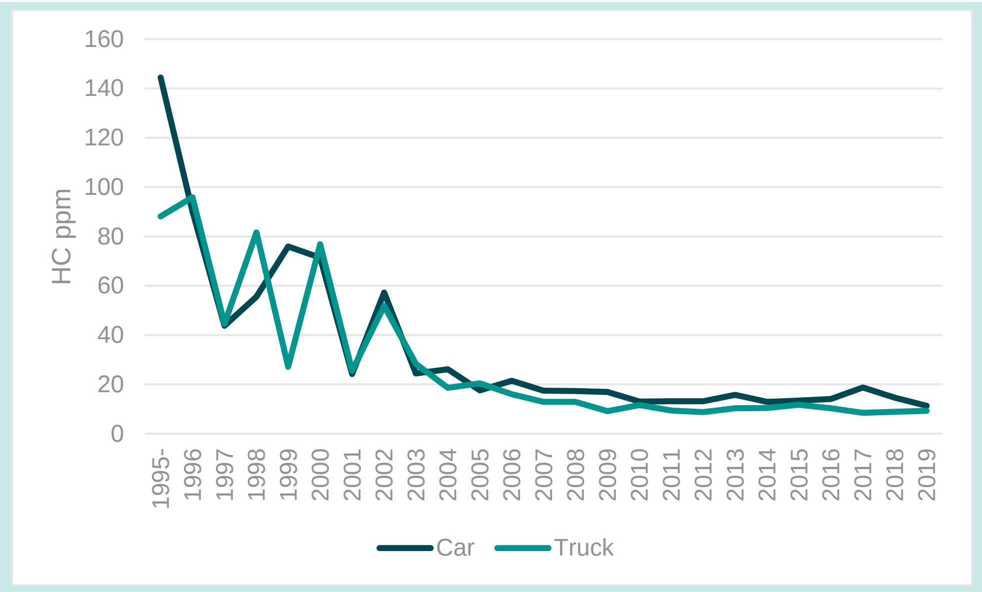
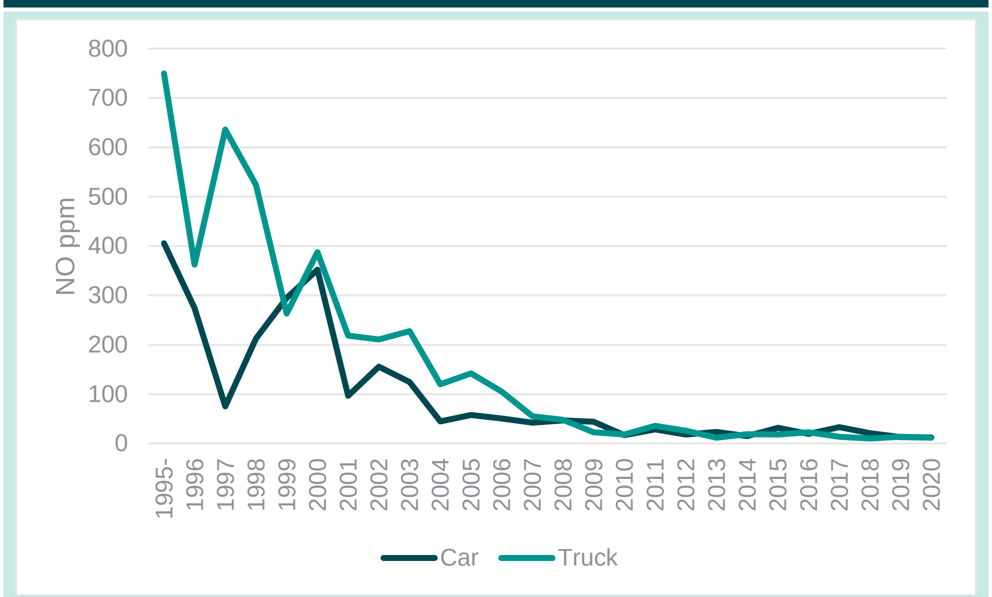


Figure 10: NOx Emissions by Vehicle Type and Model Year

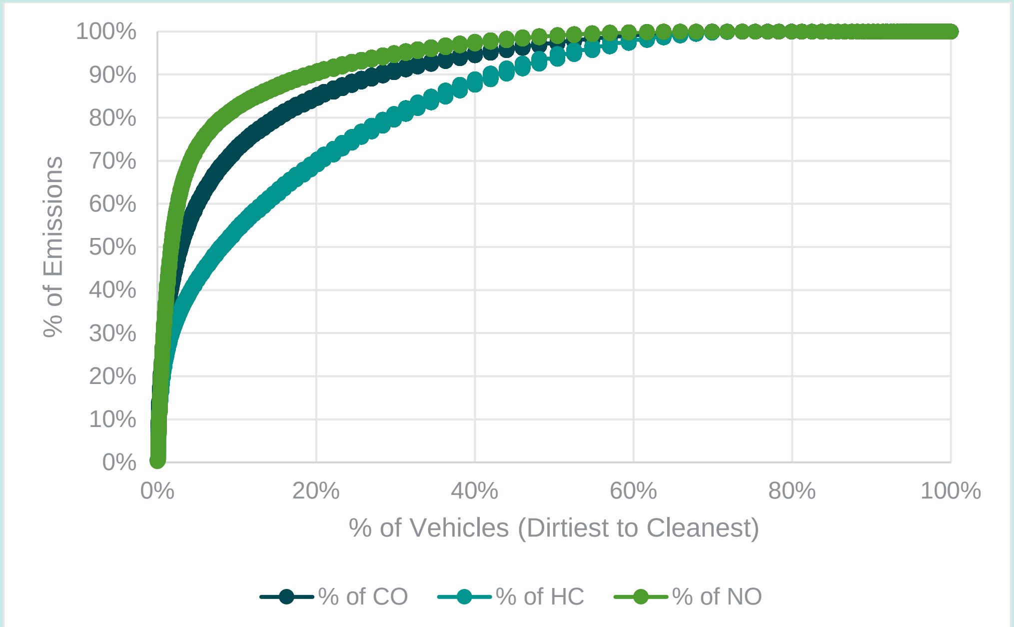


6.3 Distribution of Emissions

CO, HC, and NOx emissions were plotted from highest to lowest value, and the distribution of total emissions as a percent of observations was determined. The goal was to determine how much the dirtiest vehicles contribute to total emissions. The distribution is shown on **Figure 11**.

Emissions are highly skewed. The dirtiest 10% account for 73%, 54%, and 82% of the CO, HC and NO emissions. The dirtiest 20% account for 85%, 69%, and 90% of the CO, HC and NO emissions. Conversely, the cleanest 50% account for 3%, 6%, and 1% of the CO, HC and NO emissions.

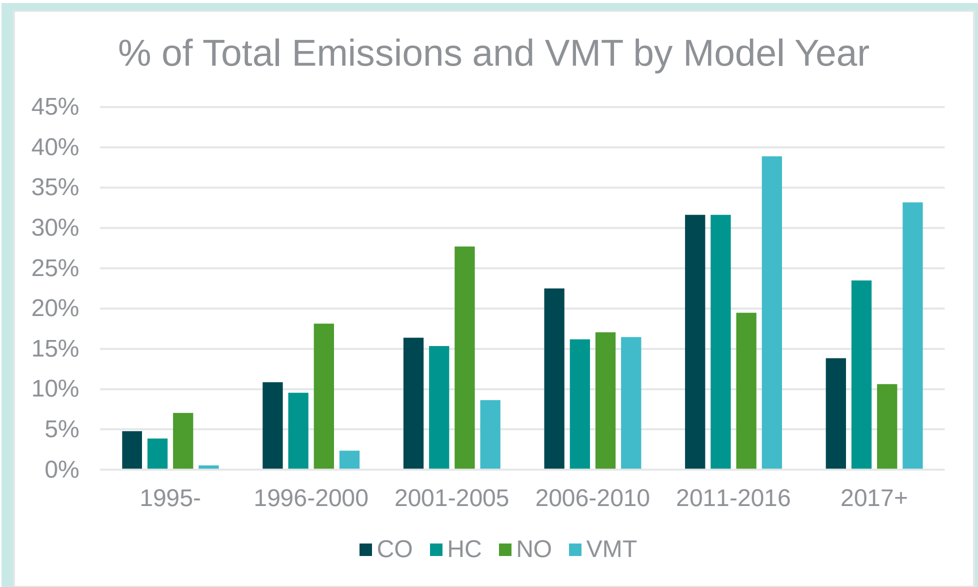
Figure 11: Distribution of CO, HC, and NO



6.4 Contribution to Total Emissions by Model Year

Figure 12 shows the approximate contributions of vehicle miles traveled (VMT) and emissions from each age group. Other studies have shown that the frequency with which vehicles of different ages are seen approximates their VMT. Vehicle models 2005 & older contributed only 11% of VMT but accounted for 29% of on-road HC, 32% of CO and 53% of NO.

Figure 12: Contribution to Total Emissions by Model Year



6.5 Emissions by I/M Status

As mentioned earlier, data were grouped into the following categories:

- Compliance – I/M test expiration date was after RSD observation date.
- Not Tested/Expired– Vehicle not tested or I/M expiration was before RSD observation date.
- Exempt – Vehicle exempt from I/M requirements.

Table 5 presents average emissions by model year group for the above I/M status groups. Exempt vehicles are the youngest being confined to 2017 and newer models. Accordingly, emissions for the exempt category are the lowest of the three I/M status groups.

Based on the results shown on Table 5, dKC calculated the weighted average emission reductions for vehicles subject to I/M as follows:

- CO – 28% reduction
- HC – 29% reduction
- NO – 42% reduction

Figure 13 to **Figure 15** show CO, HC, and NO emissions for two groups, Compliance and Not Tested/Expired. Emissions are lower for vehicles that were in compliance with I/M requirements. Clearly, Arizona's I/M program is reducing emissions.

Table 5: Average Emissions by I/M Status				
Average Percent CO				
Yr Group	**I/M Compliance Status**			
	Compliance	**Not Tested/Expired**	**Exempt**	**Grand Total**
1995-	0.42	0.76		0.50
1996-2000	0.21	0.45		0.25
2001-2005	0.10	0.13		0.10
2006-2010	0.07	0.09		0.07
2011-2016	0.04	0.05		0.04
2017+			0.02	0.02
Grand Total	0.07	0.11	0.02	0.05
Average HC -- Hexane (ppm)				
Yr Group	**I/M Compliance Status**			
	Compliance	**Not Tested/Expired**	**Exempt**	**Grand Total**
1995-	103	145		112
1996-2000	55	91		62
2001-2005	23	56		27
2006-2010	15	17		15
2011-2016	12	13		12
2017+			11	11
Grand Total	16	27	11	15
Average NO (ppm)				
Yr Group	**I/M Compliance Status**			
	Compliance	**Not Tested/Expired**	**Exempt**	**Grand Total**
1995-	619	539		601
1996-2000	289	578		341
2001-2005	129	227		142
2006-2010	44	70		46
2011-2016	20	39		22
2017+			14	14
Grand Total	**53**	**112**	**14**	**44**

Figure 13: Average CO Emissions by I/M Status

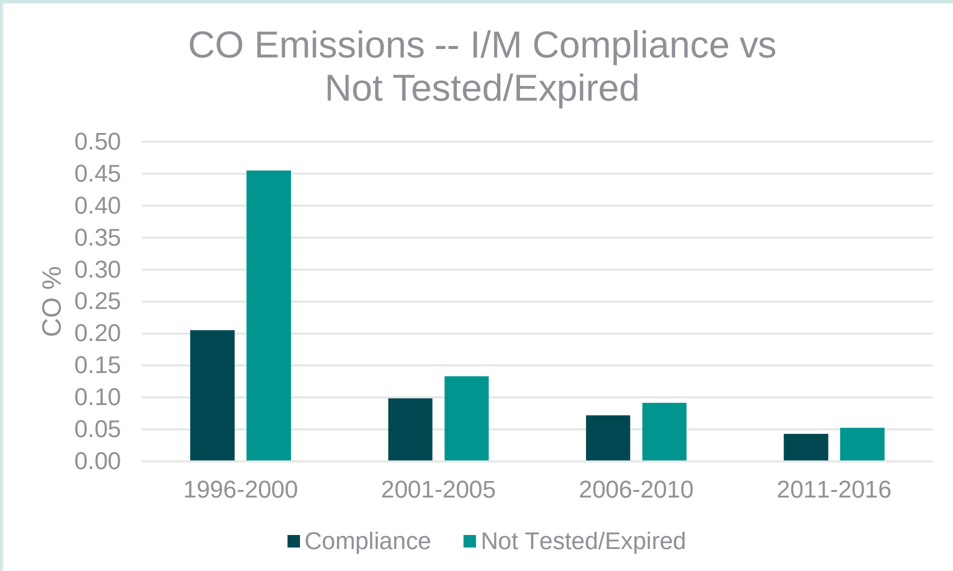


Figure 14: Average HC Emissions by I/M Status

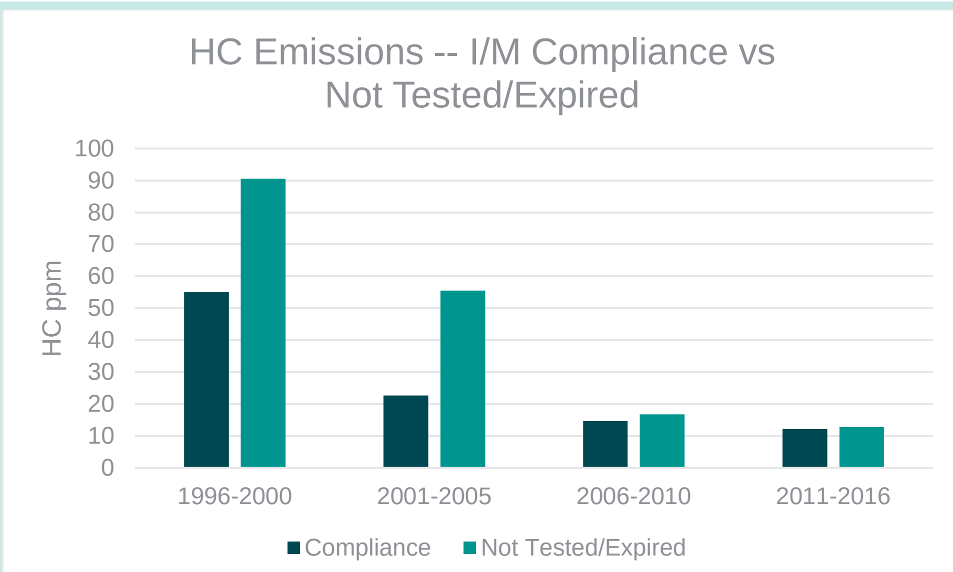
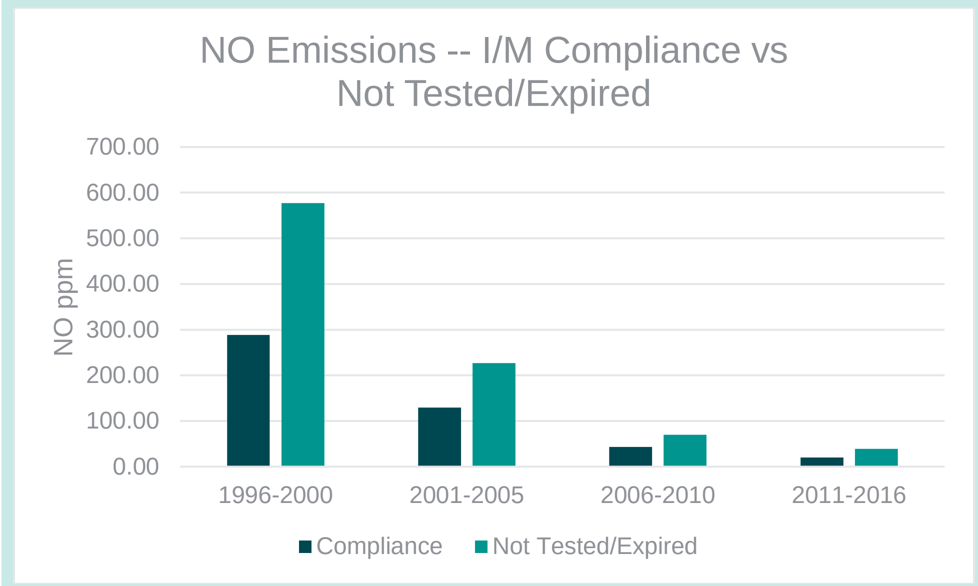


Figure 15: Average NO Emissions by I/M Status



6.6 Emission Deciles by Model Year

Emission measurements by model year group were divided into ten groups or deciles each containing an equal number of ordered measurements. **Figure 16** to **Figure 18** present the resultant decile charts by model year group for the population that was in compliance with I/M requirements or was exempt from I/M requirements. The 1, 2 … 9 values correspond to the 10%, 20% … 90% ranked emission measurements.

The charts demonstrate that older model vehicles can have low emissions. For example, older model year groups 1996-2000 and 2001-2005 have very low-emitting emitting vehicles, similar to the newer model year groups, within their lowest three deciles. There's also little difference between HC and NO emissions across the deciles for the 2006-2010 group and the 2011-2016 and 2017+ groups. The 2001-2005 group has similar HC and NO emissions up to about the 60th percentile.

Figure 16: CO Emission Deciles

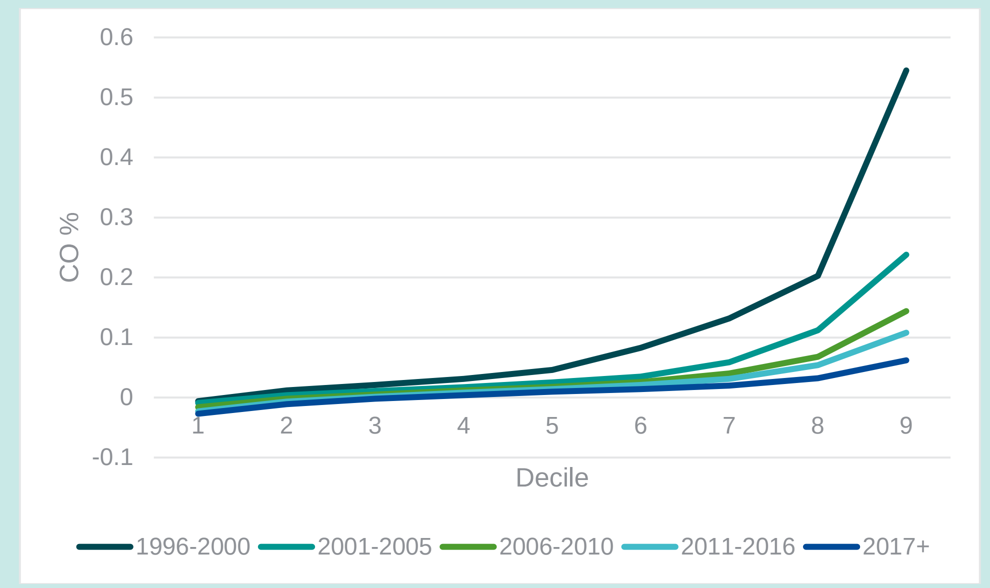


Figure 17: HC Emission Deciles

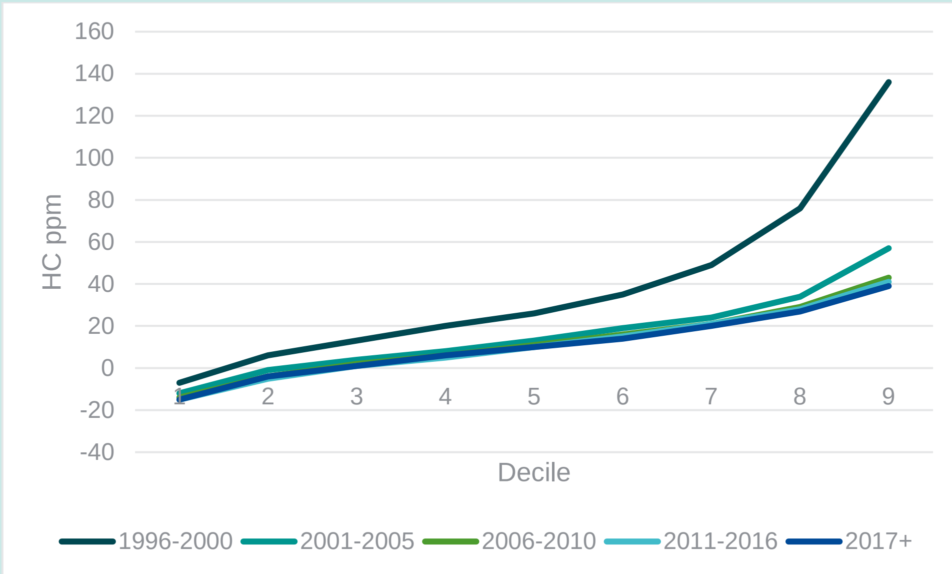
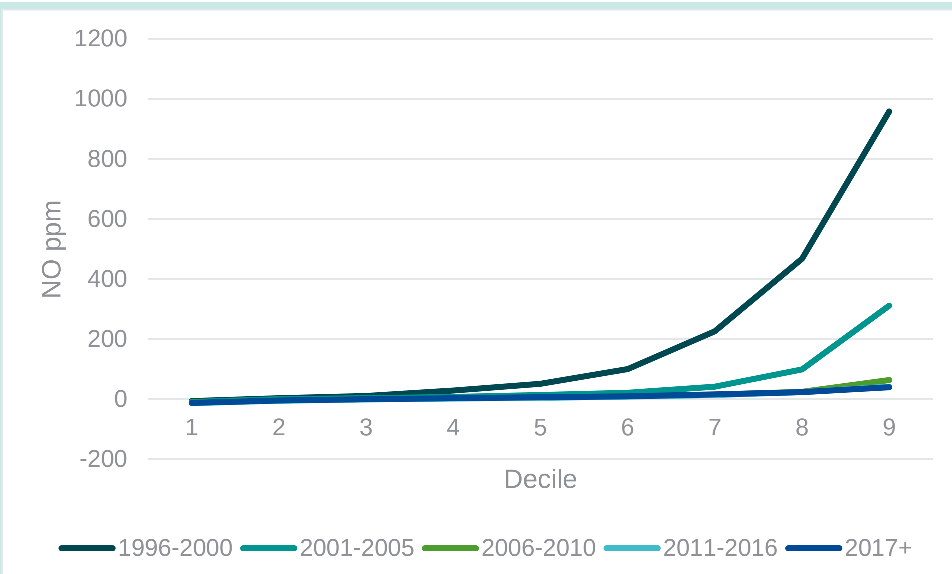


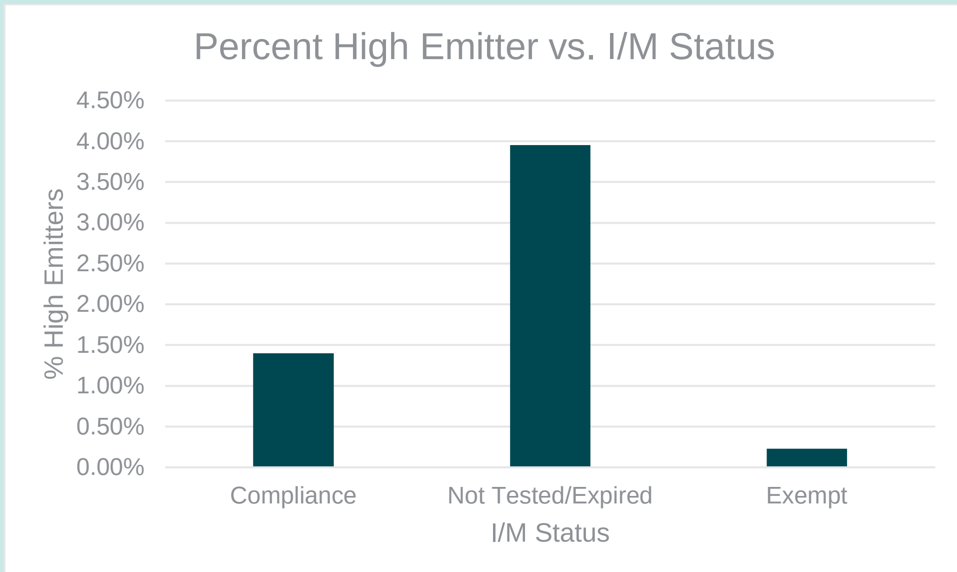
Figure 18: NO Emission Deciles



6.7 Analysis of High Emitters

dKC used Maryland's RSD cutpoints of 1.5% CO, 220 ppm HC and 1650 ppm NO to identify high emitters. **Figure 19** shows the percent of vehicles that exceeded these cutpoints by I/M status. The high emitter rate was 3 times higher for the group of vehicles that were not tested or had expired I/M tests.

Figure 19: Percent High Emitter vs. I/M Status



7 CONCLUSIONS

The goal of CRC E-119 was an intercomparison of the University of Denver's FEAT RSD to Opus' RSD5000 and HEAT's EDAR. Analyses of their exhaust- and evaporative-emissions measurement accuracy were conducted by CRC analysts based on known samples released by instrumented vehicles. Although vehicles from all 50 states were measured, this report used the 24,310 all-valid measurements of registration-matched Arizona vehicles to conduct a basic fleet emissions evaluation and a reference evaluation of the I/M program (i.e., comparing inspected/compliant to not inspected/expired vehicles).

US 60 to 101 North at the Mesa-Tempe border in greater Phoenix proved to be an effective site for fleet characterization, yielding over 34,000 valid exhaust measurements over 5-days, despite the extenuating circumstances causing considerable Opus RSD downtime. Median VSP was 11 Kw/t. 96% of the measurements were captured at VSPs greater than zero and 74% were between the 3-22 Kw/t range typically used for high emitter identification. Key conclusions from our analysis are listed below:

- Emissions of I/M compliant vehicles were increasingly lower than those of non-compliant vehicles as vehicles aged.
- Slightly more than half the Arizona-registered vehicles measured were trucks (i.e., including SUVs) versus cars. CO and HC emissions were similar for cars vs. trucks across all model years, while truck NO emissions increasingly exceeded those of cars before model year 2007.
- NO emissions and to a lesser extent CO and HC emissions of AZ-registered vehicles were highly skewed. The dirtiest 10% contributed 82% of NO emissions; the cleanest 50% contribute only 1% of the NOx emissions.
- RSD results indicate that older vehicle models can have low emissions. For example, for vehicles complying with I/M requirements, there's little difference between HC and NO emissions for the 2006-2010 group and the 2011-2016 and 2017+ groups.