OREGON REMOTE SENSING EMISSIONS STUDY

[An I/M Program & Fleet Evaluation Analysis]

Prepared for:

State of Oregon
Department of
Environmental
Quality
DEQ

Final Report

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OPUS INSPECTION

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Terms and Glossary

ASM	Acceleration Simulation Mode
ALPR	Automatic License Plate Reader
BAR	California Bureau of Automotive Repair
CCM	Corner Cube Mirror
CDPHE	Colorado Department of Public Health and Environment
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COVERS	Colorado On-road Vehicle Emissions Remote Sensing System
CRC	Coordinating Research Council
DEQ	Oregon Department of Environmental Quality
DTC	Diagnostic Trouble Code
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
FFF	Failing readiness and MIL, with catalyst DTCs
FFP	Failing readiness and MIL
FNP	Failing readiness, no MIL
FPP	Failing readiness, MIL
FID	Flame Ionization Detector
g/kg	Grams of Pollutant Per Kilogram
g/mi	Grams of fuel Per Mile
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbons
IR	Infrared
I/M	Vehicle Emissions Inspection and Maintenance
I/M area fleet	Describes all the vehicles registered in the I/M area, regardless of whether they are subject to biennial testing.
I/M fleet/tested vehicles	Specific to only vehicles registered in the I/M area that are subject to biennial inspection. The term *I/M fleet* would not include heavy-duty diesels or any other vehicle exempt by Oregon Rule such as vehicles less than five years old. Note that Oregon tests hybrids and other light-duty vehicles more than four years old.
kg/mi	Kilograms of fuel per mile
kW/t	Kilowatts per metric ton
LDV	Light-Duty Vehicle
HDV	Heavy-Duty Vehicle
M	Mean
MDV	Medium Duty Vehicle
MIL	Malfunction Indicator Light
MOVES	Motor Vehicle Emission Simulator
MPG	Miles Per Gallon
NMHC	Non-Methane Hydrocarbons
NO	Nitric Oxide

NO_2	Nitrogen Dioxide
NOV	Notice of Violation
NO_X	Oxides of Nitrogen
O_3	Ozone
OBD	On-Board Diagnostics
OBD-II	On-Board Diagnostics-II
OCR	Optical Character Recognition
ORE	On-Road Emissions
Oregon VIP	Oregon Vehicle Emissions Testing/Inspection Program
OREMS	On-Road Emissions Measurement System
ORHE	On-Road High Emitter
ORLL	On-Road Liquid Leaker
PEMS	Portable Emissions Measurement System
PFF	Passing readiness, failing MIL, with catalyst DTCs
PFP	Passing readiness, failing MIL, no catalyst DTCs
PM	Particulate Matter
PNP	Passing readiness, null MIL, no catalyst DTCs
PPM	Parts Per Million
RSD	Remote Sensing Device
S/A	Speed/Acceleration
SCU	System Control Unit
SDM	Source/Detector Module
TPD	Tons Per Day
TSI	Two-Speed Idle
US	United States
UV	Ultraviolet
VDEQ	Virginia Department of Environmental Quality
VIP	Vehicle Emissions Testing/Inspection Program
VIN	Vehicle Identification Number
VIR	Vehicle Inspection Report
VIS	Vehicle Inspection Station
VMT	Vehicle Miles Traveled
VSP	Vehicle Specific Power

1. Executive Summary

> *Both the Portland and Medford-metro areas have experienced unhealthy levels of ozone in recent years. Emissions from cars and trucks are responsible for the majority of the pollution that produces this ozone. To address the leading cause of pollution, Oregon operates a biennial vehicle emissions testing program* (i.e., vehicle inspection program; VIP) *in the Portland and Medford areas. Vehicles registered within the two testing boundaries must pass an emissions test in order to be re-registered with the Oregon Department of Transportation, Driver and Motor Vehicle Services.*[1]

The Oregon Department of Environmental Quality (DEQ) commissioned the Remote Sensing Emissions Study to evaluate the performance of Oregon's vehicle emissions testing/inspection program (Oregon VIP) using a US EPA-recognized method[2] that compares the real-world emissions of tested vehicles to untested vehicles as measured by remote (emissions) sensing devices (RSD).

Technical results are presented in Section 1.2:*Technical summary of findings*. A narrative summary of findings is offered in Section 1.1, below.

1.1 Narrative summary of findings

The Oregon Remote Sensing Emissions Study performed by Opus Inspection team members in summer 2022 for the Oregon DEQ found:

- Definitive evidence of a well-functioning Oregon VIP with far lower overall emissions rates from Oregon VIP tested vehicles[3] than Oregon untested vehicles; and
- Emissions reductions in Oregon VIP tested vehicles, as compared to similar-age untested vehicles, are far greater than the US EPA model credits to the Oregon VIP.

Vehicle emissions testing programs, like the Oregon VIP, direct vehicles with noncompliant emissions above their in-use limits to undergo practical, cost-effective emission-lowering maintenance/repair to return emissions to compliant levels. When repairs are impractical or cost-prohibitive the outcome is often retirement of the dirty vehicle or its sale/export out of the testing area and replacement with a cleaner vehicle (*fleet turnover*). The Oregon Remote Sensing Emission Study found significantly ***lower*** numbers of ***high emitters*** (with emissions far above compliant levels) within Oregon tested vehicles as compared to untested Oregon vehicles, Washington vehicles,[4] and vehicles from other states measured in the study.

The much lower rate of onboard diagnostic system (OBD) Check Engine Light illumination the DEQ independently observed in tested vs untested vehicles indicates that the Oregon VIP is evoking the desired timely OBD response in owners of tested vehicles. The benefits of proper

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[1] Oregon DEQ; https://www.oregon.gov/deq/Vehicle-Inspection/Pages/About-the-program.aspx

[2] "Reference Method", USEPA Guidance on Us of Remote Sensing for Evaluation of I/M Program Performance, Page 10; https://nepis.epa.gov/Exe/ZyPdf.cgi?Dockey=P1002J6C.pdf

[3] The Oregon VIP exempts the first 4 model years. In 2022, at the time of the study, Portland was testing 2018 back to the fixed 1975 model year. Medford was testing a rolling 20 model year range starting with 2018 (2018-1999).

[4] Washington Department of Ecology; https://ecology.wa.gov/Air-Climate/Air-quality/Vehicle-emissions/Emissions-check-ends#:~:text=Why%20did%20Washington%20end%20the,the%20program%20began%20in%201982

maintenance and repair were also evident in the many older model tested vehicles that exhibited low emissions; that is, emissions levels comparable to very new vehicle models.

The net effect of timely and proper maintenance, fewer high emitters, and fleet turnover to cleaner models is a shifted fleet emissions distribution. The study found that the Oregon VIP has shifted the tested fleet even further towards a **cleaner** distribution than a US EPA benchmark centralized emissions testing program in Arizona.

Using observation rates of vehicle model years to approximate their relative *vehicle miles traveled* (VMT), the study estimated less than half the ozone producing vehicular emissions within the testing area are from tested Oregon vehicles registered inside the testing area boundaries (Category 1, as seen in Section 8.6, Table 10: Percentage of total emissions in I/M Area by registration status). More than half the ozone producing vehicular emissions are from all other vehicles, including untested inside-registered Oregon vehicles, untested outside-registered Oregon vehicles, and vehicles from other states (Categories 2 through 7, Table 10). The untested Oregon vehicles registered outside the testing area alone contribute more than a quarter of the ozone producing vehicular emissions within the testing area (Categories 3 and 4, Table 10), and Washington vehicles contribute about 5%. All out-of-state vehicles combined contribute 18% of the ozone producing vehicular emissions inside the testing area.

The Oregon Remote Emissions Study effectively characterized the real-world emissions rates of Oregon vehicles and others operating inside the Oregon VIP boundaries. The Oregon VIP was found to be very effective at maintaining a low-emitting tested motor vehicle fleet. However, based on study estimates of VMT and emissions rates of vehicles operating inside the testing area boundaries, the study found vehicles operating inside the boundaries that are not subject to Oregon VIP (including inside-untested, outside-untested, and out-of-state) contributed over half of all I/M area light-duty vehicle emissions even though they collectively accounted for less than half of the VMT inside the boundaries. In order words, while the Oregon VIP is very effective at maintaining low emissions from vehicles it impacts, the vehicles it does not impact are higher polluting and responsible for more than half the vehicular pollution inside the Oregon VIP boundaries. Better VMT numbers for more accurate apportionment of real-world vehicle emissions inside the boundary can confirm these findings and inform future strategies to mitigate this principal source of light-duty vehicular emissions inside the Oregon VIP boundary.

1.2 Technical summary of results

Using our latest remote sensing device (RSD) technology, the Opus team surveyed on-road vehicle emissions in Oregon in the summer of 2022. Opus team members collected 85,920 valid emission measurements of Oregon and out-of-state vehicles in multiple locations across Oregon. Test sites were located inside and outside Oregon’s inspection and maintenance (I/M) program (Oregon VIP) boundaries to facilitate various comparisons. A total of 76,091 valid measurements included a legible license plate; 47,946 (63%) of which were unique Oregon vehicles. Vehicle information was retrieved from Oregon Driver and Motor Services using Oregon license plates and the Washington State Department of Licensing for Washington license plates. Following are the key conclusions from our analysis of RSD emissions from the survey:

- Nitrogen oxide (NO) and carbon monoxide (CO) emissions and (to a lesser extent) hydrocarbon (HC) emissions of Oregon-registered vehicles were highly skewed. For example, the dirtiest 10% contributed 58% and 78% of (O_3 precursors) HC and NO emissions as measured by RSD; the cleanest 50% only 0.2% and 0.8%, respectively.

  - I/M programs, by directing failing vehicles to undergo emissions-reducing maintenance/repair or retire, effectively skew fleet emissions distribution. The Oregon fleet is even more skewed than Arizona's where 2021-2022 measurements indicate 10% of vehicles contribute 53% and 70% of HC and NO.[5]
  - Using model year observation rates to approximate their relative vehicle miles traveled (VMT), it was estimated 2005 and older vehicles accounted for only 15% of VMT but contributed 70% of on-road HC, 43% of CO, and 64% of NO.
- Emissions from vehicles registered in Oregon's I/M area in aggregate, are 44%, 10%, and 45% lower than CO, HC, and NO emissions from vehicles registered outside the I/M area, respectively. CO and NO differences were significant at the 95% confidence level. While overall HC differences are small and not statistically significant, the effect of I/M on the 2005 and older model years is clearly evident in the inverted traces (Figure 25).
- Differences based on measurements made at I/M area sites alone and adjusted for inside vs outside fleet age differences, can be compared to other centralized and decentralized I/M programs and US EPA MOVES model projections. In this case, vehicles registered in Oregon's I/M area are 29%, 30%, and 29% lower than CO, HC, and NO emissions from vehicles registered outside the I/M area, respectively.
  - These 2022 differences are equal to or larger than comparable I/M site-only, age-adjusted differences for the Colorado (2018: 8%,16%, 22%) and Arizona (2021: 14%, 34%, 26%) centralized I/M programs and the Virginia decentralized I/M program (2021: 25%, 31%, 31%); Table 9.
  - These real-world differences are much higher than simulated mobile source emissions model (MOVES3) estimates of 16% for CO, 7%-8% for HC, and 8% to 13% for NO.
  - Oregon DEQ's OBD testing results indicate the I/M program strongly affects *malfunction indicator light* (MIL) response (2.5% MIL-On rate for I/M area vehicles versus a 16.5% for no I/M), corroborating the lower emissions of vehicle registered in the I/M area.
  - Gross emitter rates were also significantly higher at 3.1% for non-I/M vehicles versus 1.4% for I/M vehicles.
- RSD results also reinforce the benefits of proper maintenance, showing that older vehicle models when properly maintained can have low emissions. For example, up to the 90% percentile there's little difference between HC and NO emissions for 2006 to 2010 vehicles registered in the I/M area and 2019+ groups (Section 8.7).
- Examining RSD observations at I/M-area sites also allow us to estimate the contribution of vehicles registered outside Oregon's I/M area to I/M area light-duty vehicular emissions:
  - Vehicles that are operated in the I/M area but are not subject to testing (Categories 2 through 7, Table 10) contribute 51% to 57% of the emissions observed in the I/M area yet account for a disproportionately lower 48% (100%-Column 1, Table 10) of the vehicle miles traveled. Oregon vehicles registered outside but operating in the I/M area (Categories 3 and 4, Table 10) contribute more than a quarter of the I/M area emissions.
  - Vehicles registered in Washington contribute 4% to 6% of the I/M area emissions, and 2.2% of them were gross emitters based on RSD.

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[5] Arizona's is often a US EPA benchmark I/M program due its long centralized IM240 history.

2. Introduction

Opus Inspection (Opus) was contracted by Oregon Department of Environmental Quality (DEQ) under contract DEQ# 038-22 to collect on-road emissions measurements of light duty vehicles inside and outside the two inspection and maintenance (I/M) program areas of Portland and Medford. The latest Opus remote sensing device (RSD) technology was used to complete a US EPA Reference Method[6] evaluation of I/M program performance.

Opus team members used our fifth-generation remote sensing device (RSD 5000) to survey CO, HC, and NO emissions from vehicles in Oregon. The survey was conducted between June 13, 2022, and July 14, 2022. The battery powered RSD5000 was capable of unattended operation, but monitored onsite by an operator who also aligned, calibrated, and conducted periodic gas audits to ensure data integrity. The RSD5000 and associated equipment complied with all applicable Quality Control and Engineering Practices set forth by the US EPA[7] and were certified to California Bureau of Automotive Repair (BAR), Colorado On-road Vehicle Emissions Remote Sensing (COVERS), and/or equivalent specifications.

The goal of the survey was to provide meaningful insights into vehicle emissions in Oregon. The principal focus was on matching and comparing RSD results with vehicles inside and outside Oregon's I/M test area. Another major focus was on the emission impact of commuters, using registration data as the basis for a commuter designation. The Opus analysis included emission rate comparisons grouped by the following model years:

- 1995 and older (pre OBD-II)
- 1996 to 2000
- 2001 to 2005
- 2006 to 2010
- 2011 to 2018
- 2019 and newer (exempt from I/M at the time of data collection)[8].

This report summarizes the survey results. It was prepared by de la Torre Klausmeier Consulting, Inc. (dKC) and Opus Inspection.

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[6] Guidance on Use of Remote Sensing for Evaluation of I/M Program Performance, EPA420-B-04-010, Office of Transportation and Air Quality, USEPA July 2004; https://nepis.epa.gov/Exe/ZyPdf.cgi?Dockey=P1002J6C.pdf

[7] Ibid.

[8] Oregon exempts the first four new model year vehicles.

3. Remote Sensing Device (RSD) Requirements

The scope of work required the collection of exhaust emission samples from vehicles both inside and outside of DEQ's I/M testing boundaries. At a minimum, the testing equipment was required to have the functionality to capture all elements listed below.

Gases:

- The tailpipe gaseous emissions (carbon monoxide, hydrocarbons, nitrogen oxides, and/or carbon dioxide) of a tested vehicle will be captured at a level within 15% of the known concentration emitting from the vehicles in 90% of the samples.

Speed measurement:

- The speed of a tested vehicle will be captured within one mile per hour, to an accuracy of 90%, or higher, for each testing session.

Acceleration measurement:

- The rate of acceleration of a tested vehicle will be captured within 0.5 mile per hour per second, to an accuracy of 90%, or higher, for each testing session.

Load measurement:

- The load measurement calculations will be the industry standard, Vehicle Specific Power (VSP). This method will be consistent with EPA Guidance, and BAR and COVERS remote sensing device specification.

License plate imaging:

- For each testing session, an image of the tested vehicle's license plate will be captured at a quality and resolution allowing for an accurate matching of the license plate number to Oregon's registration database, allowing for identifying the Vehicle Identification Number of the tested vehicle, and to an accuracy of 90% of vehicles recorded in a daily session.

Chronographs and synchronization:

- All times associated with an individual test on a tested vehicle will be within five seconds of Coordinated Universal Time (UTC) and, when interdependent with other captured times, within 1/100 of a second of those other times, as well as within five seconds of UTC. All times will be expressed in the time local to the testing site which should be Pacific Standard Time (PST) for the purposes of this study.

The following sections describe how these requirements have been fulfilled for Oregon.

4. Opus RSD Technology

The remote sensor Opus deployed in Oregon was our fifth-generation remote sensing device (RSD). Model RSD5000s have been used for on-road screening in the largest Opus I/M programs (such as Colorado and Virginia) since the early 2010s, results of which are reported in annual reports to the state agencies.[9] Today's model RSD5000 systems are capable of measuring NO_2 and soon NH_3, in addition to the standard CO, HC, NO, PM (uV Smoke), and evaporative emissions. Systems with such enhanced capability are built on the RSD5000+ platform and are designated RSD5300s.

RSD5000+ instruments consist of a nondispersive infrared (NDIR) component for detecting CO, CO_2, HC, and IR Smoke and a dispersive ultraviolet (UV) spectrometer for measuring nitrogen oxide (NO) and uV Smoke. The source and detector elements are adjacent in a single module, referred to as a source/detector module (SDM). For light-duty US I/M programs, the SDM 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 1).

The Opus RSD5009 RSD was deployed as an unattended system and captured CO, HC, NO, PM, and evaporative emissions.

Collinear beams of infrared (IR) and ultraviolet (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. 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 samples are always discarded due to electronic noise, and a maximum of 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 and uV Smoke-opacity. The spectrometer measures the distinct 227nm peak of NO by comparing to a calibration spectrum in the same region.

The Opus uV Smoke channel's light extinction is measured in a region near 250nm, 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.[10] The uV Smoke is ratioed to the sum of CO, CO_2 and HC (which represents fuel consumed) and can be multiplied by an appropriate light extinction factor to estimate grams of black carbon particulate (soot) per kilogram of fuel consumed.[11]

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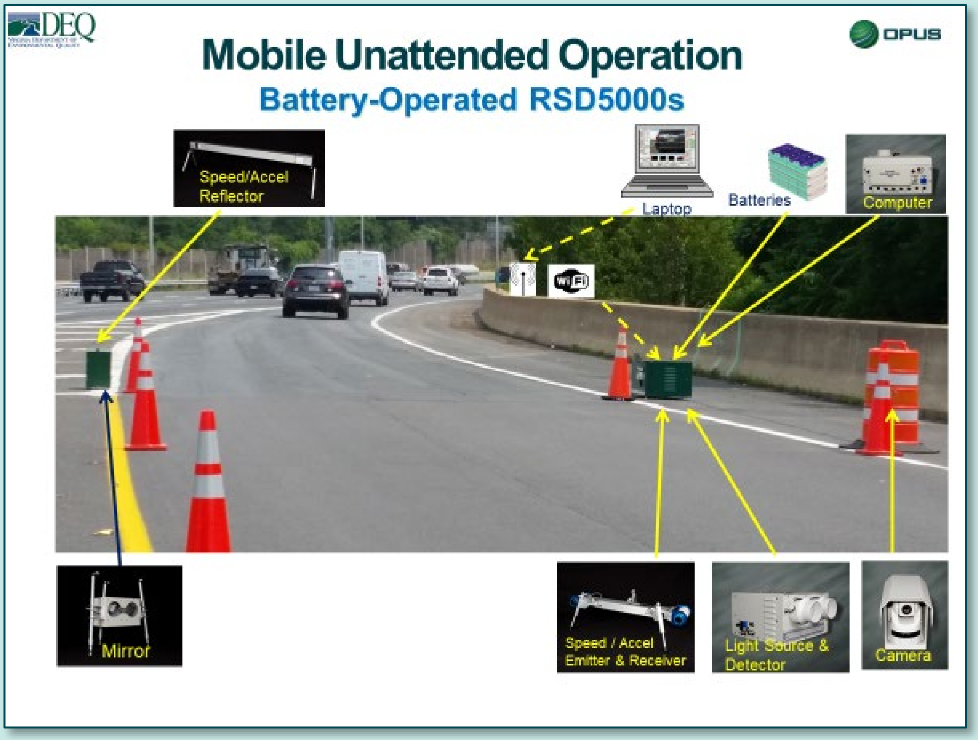
[9] These reports are not published on the internet but are available upon request.

[10] "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

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

Figure 1: Unattended RSD5300 on-road deployment



Mobile Unattended Operation

Battery-Operated RSD5000s

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 that 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	Rear license plate images	Oregon 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.

Calibration was performed with a sealed gas cell 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 were released into the instrument's path, and the measured ratios from the instruments were then compared to those certified by the cylinder manufacturer (Airgas). These audits accounted 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 was used to calibrate and audit the instrument, all hydrocarbon measurements reported by the remote sensor were reported as hexane equivalents in the database.

5. Opus RSD Setup

5.1 RSD sites

DEQ provided links to ODOT traffic volumes at highway on-ramps and interchanges. Opus team members used that information to select the most productive candidate sites that would yield valid exhaust measurements under load. We then proposed a schedule of test days at the highest volume accessible sites inside and outside the Portland and Medford I/M areas, as seen in Table 2.

DEQ personnel approved the test schedule, which included eliminating sites 4 and 11, and then aided the Opus team in securing permits from each of the independent jurisdictions.

Table 2: Candidate RSD sites

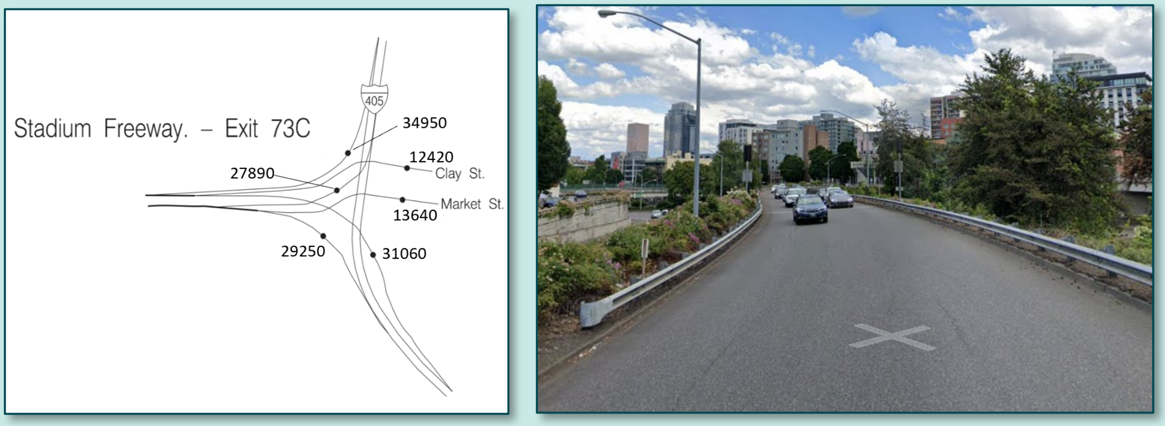
#	Description	Map	Type	ODOT Volume	Proposed Test Days
	Inside Portland	Portland			
1	SW Clay EB to 26 WB – Sunset	US 26 I-84 I-84 I-84	2-lane metered/flat	12420	2
2a	I5 SB to 84 EB		uphill connector	19420	2
2b	84 WB to I5 NB		uphill connector	~23000	2
3	NE Glisan to 84 EB		uphill after tunnel	8800	1
4	~~NE Glisan EB (before NE 136th Ave)~~		~~flat, before crosswalk~~	~~?~~	-
	Outside Portland	Portland			
5	I5 SB (from Vancouver) to 99 EB	I-5	cloverleaf uphill	17960	2
10	Empire Blvd to US97 SB in Bend	US 97	downhill, early @ ramp	10080	1
~~11~~	~~SE Dayton Bypass (223) to 99W NB~~		~~flat, catch @ merge~~	~~?~~	~~-~~
	Eugene	Eugene/Salem			
6a	I5 SB to 105/126 EB	I-5	cloverleaf uphill	9590	2
6b	I5 NB to 105/126 WB	I-5	cloverleaf uphill	5480	1
	Outside Medford	Medford			
7a	199 to I-5 South	I-5	straight uphill	8390	2
7b	199 to I-5 North	I-5	cloverleaf uphill	3450	1

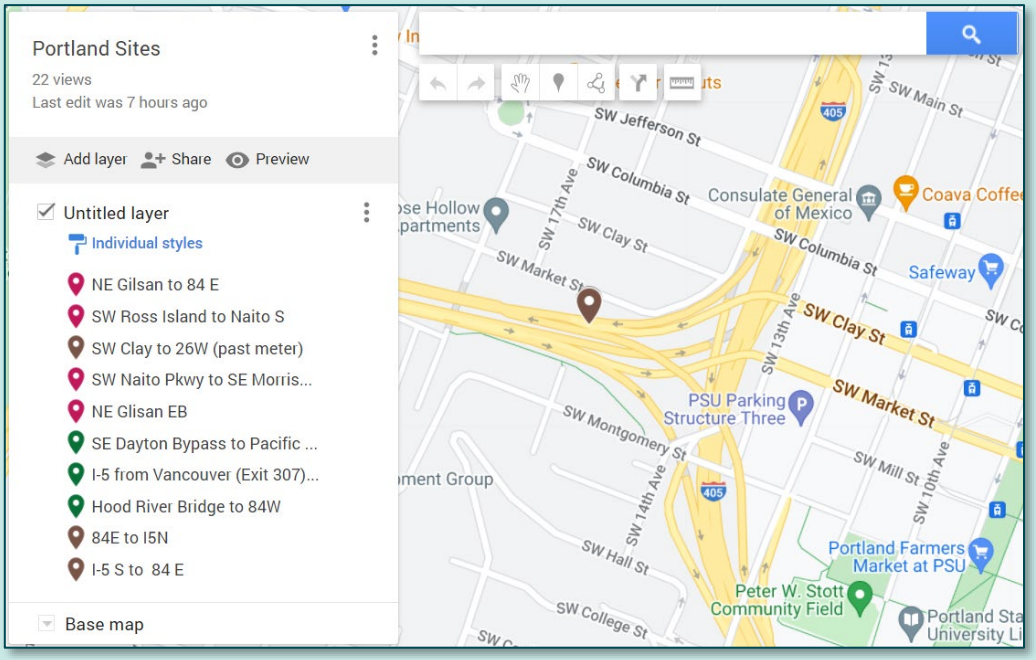
	Inside Medford	Medford			
8a	East Pine Street to I-5 NB	I-5	downhill, early @ ramp	6710	1
8b	East Pine Street to I-5 SB	I-5	downhill, early @ ramp	4820	1
9	62WB (Crater lake) to I5 SB	I-5	downhill, @ merge	8080	2

Descriptions of the sites are presented in the figures below.

5.1.1 Inside Portland I/M Area

Figure 2: Site 1 SW Clay EB to 26 WB—Sunset [Meter timed 2-lane to 1; volume = 12,420]





Portland Sites
22 views
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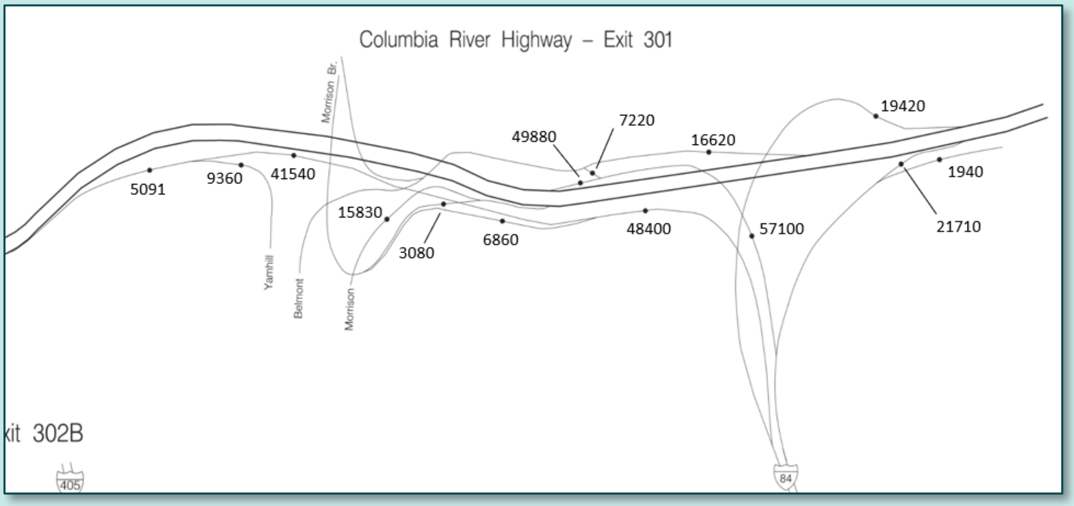
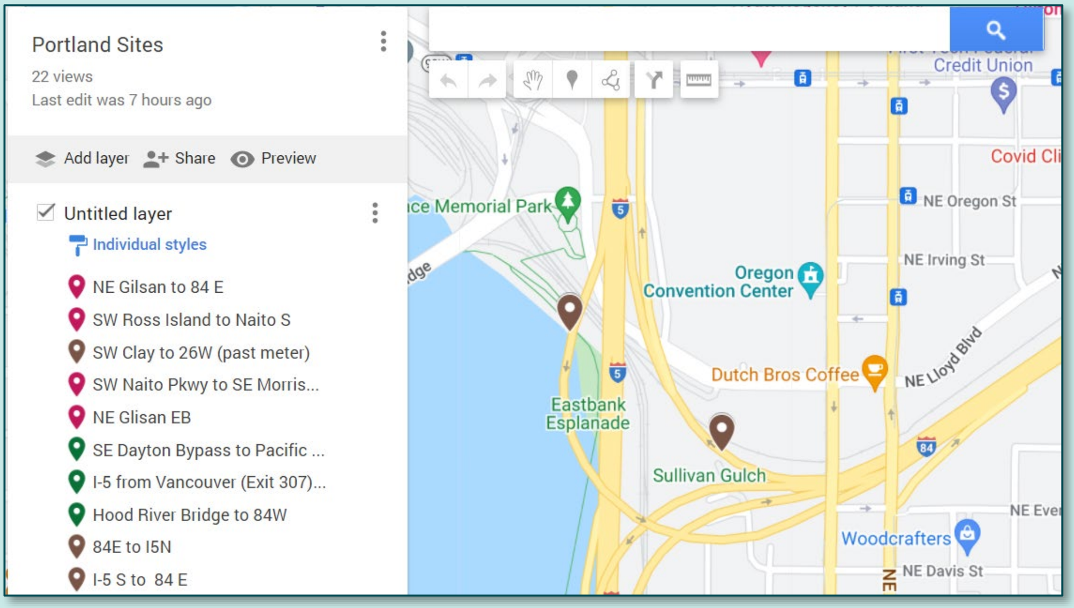
- NE Gilsan to 84 E
- SW Ross Island to Naito S
- SW Clay to 26W (past meter)
- SW Naito Pkwy to SE Morris...
- NE Glisan EB
- SE Dayton Bypass to Pacific ...
- I-5 from Vancouver (Exit 307)...
- Hood River Bridge to 84W
- 84E to I5N
- I-5 S to 84 E

Figure 3: Site 2 Two Sites @ I5 (Columbia River Highway) and I84 Interchange





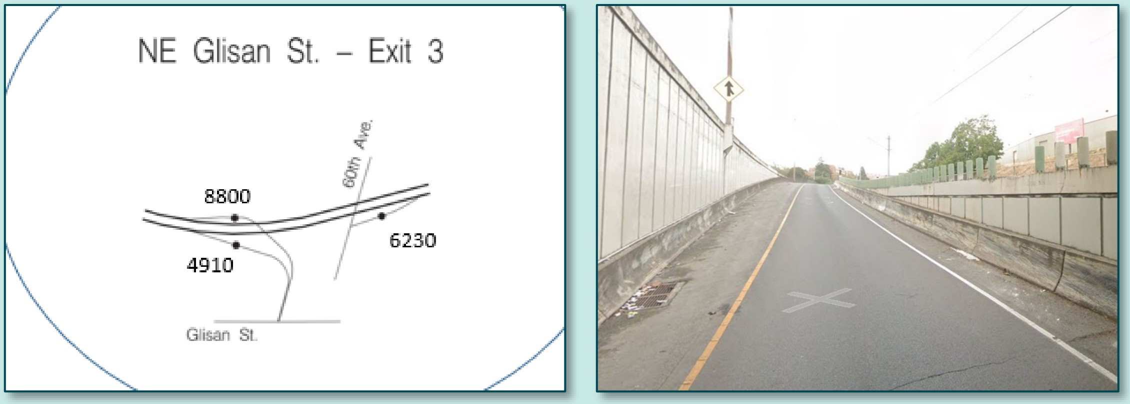
Site 2a: I5 SB to 84 EB – [uphill connector; volume 19,420]

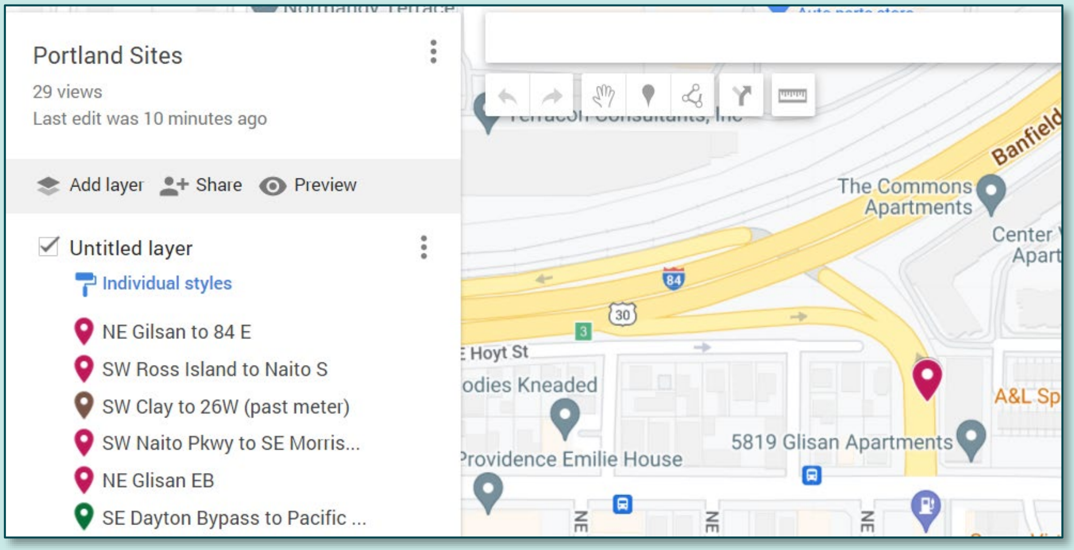
Site 2b: 84 WB to I5 NB [uphill connector; volume = ~23,000]


US-30


US-30

Figure 4: Site 3 NE Glisan to 84 EB—[Uphill after tunnel; Volume = 8,800]




Portland Sites

29 views

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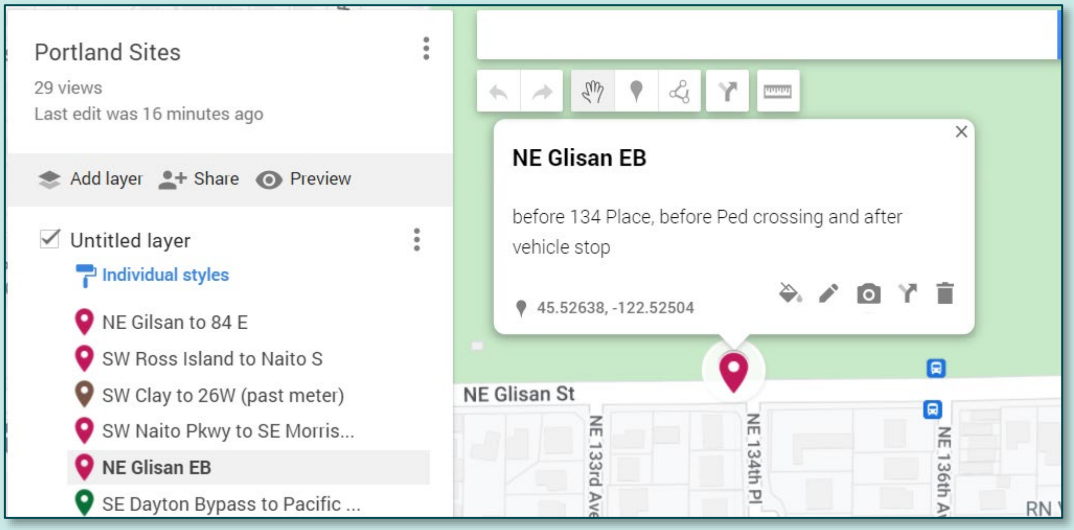
Individual styles

- NE Gilsan to 84 E
- SW Ross Island to Naito S
- SW Clay to 26W (past meter)
- SW Naito Pkwy to SE Morris...
- NE Glisan EB
- SE Dayton Bypass to Pacific ...

Figure 5: Site 4 NE Glisan EB (before NE 136th Ave)—[flat, before crosswalk—Volume = 9480]



Portland Sites

29 views

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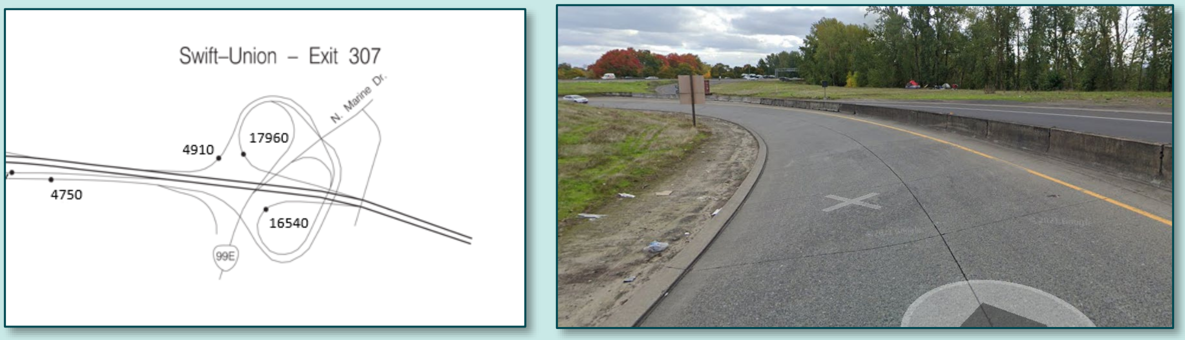
NE Glisan EB

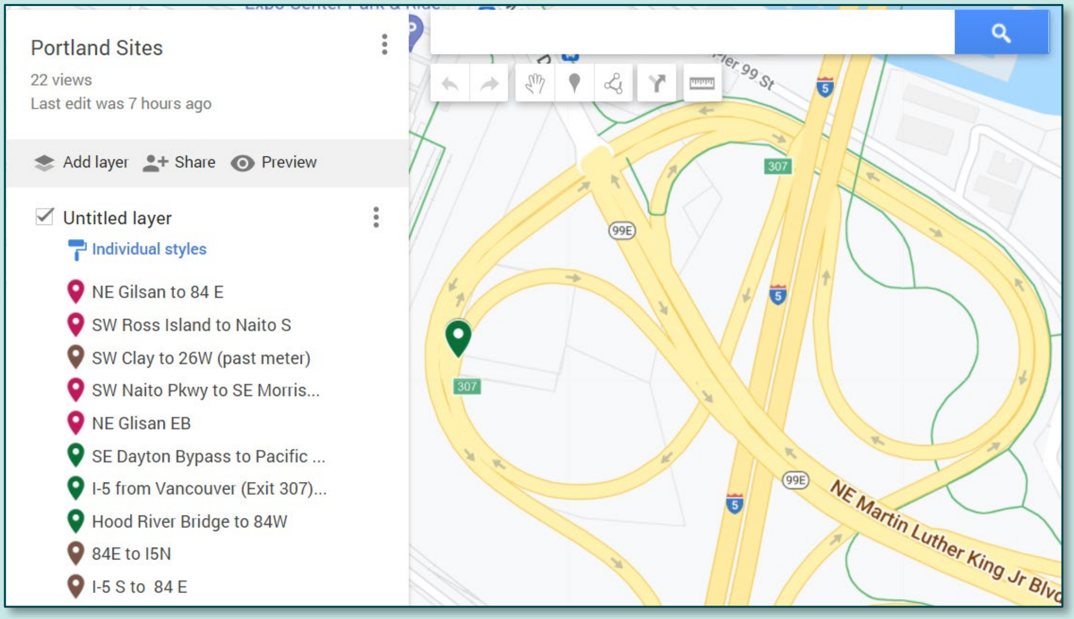
before 134 Place, before Ped crossing and after vehicle stop

45.52638, -122.52504

5.1.2 Outside Portland I/M Area

Figure 6: Site 5 I5 SB (from Vancouver) to 99 EB—[cloverleaf uphill; volume = 17,960]





Portland Sites

22 views

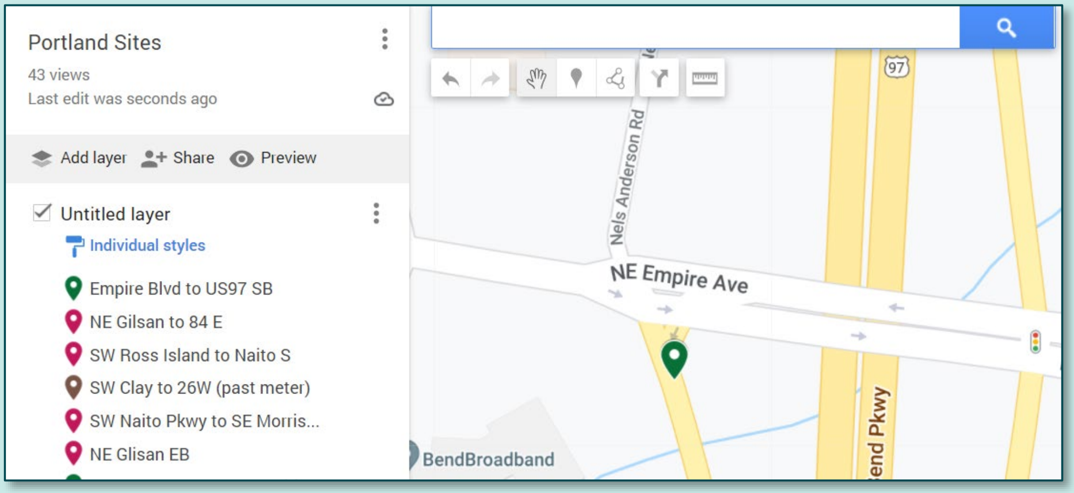
Last edit was 7 hours ago

☑ Untitled layer

Individual styles

- NE Gilsan to 84 E
- SW Ross Island to Naito S
- SW Clay to 26W (past meter)
- SW Naito Pkwy to SE Morris...
- NE Glisan EB
- SE Dayton Bypass to Pacific ...
- I-5 from Vancouver (Exit 307)...
- Hood River Bridge to 84W
- 84E to I5N
- I-5 S to 84 E

Figure 7: Site 10 Empire Blvd to US97 SB in Bend—[downhill, catch early; volume = 10,080]


Portland Sites

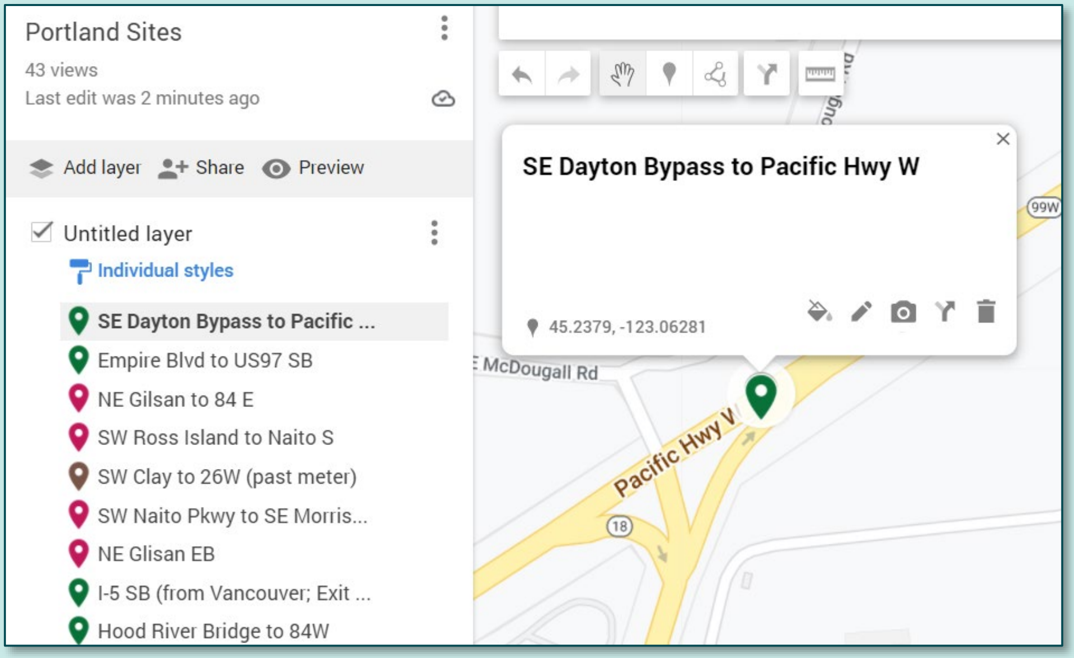
43 views

Last edit was seconds ago

Untitled layer

- Empire Blvd to US97 SB
- NE Gilsan to 84 E
- SW Ross Island to Naito S
- SW Clay to 26W (past meter)
- SW Naito Pkwy to SE Morris...
- NE Glisan EB

Figure 8: Site 11 SE Dayton Bypass (223) to 99W NB – [flat @ merge; volume = 8700]



Portland Sites

43 views

Last edit was 2 minutes ago

☑ Untitled layer

Individual styles

- SE Dayton Bypass to Pacific ...
- Empire Blvd to US97 SB
- NE Gilsan to 84 E
- SW Ross Island to Naito S
- SW Clay to 26W (past meter)
- SW Naito Pkwy to SE Morris...
- NE Glisan EB
- I-5 SB (from Vancouver; Exit ...
- Hood River Bridge to 84W

SE Dayton Bypass to Pacific Hwy W

45.2379, -123.06281

5.1.3 Eugene (Non-I/M Area)

Figure 9: Site 6a: I5 SB to 105/126 EB—Q Street [Cloverleaf uphill; volume = 9,590]

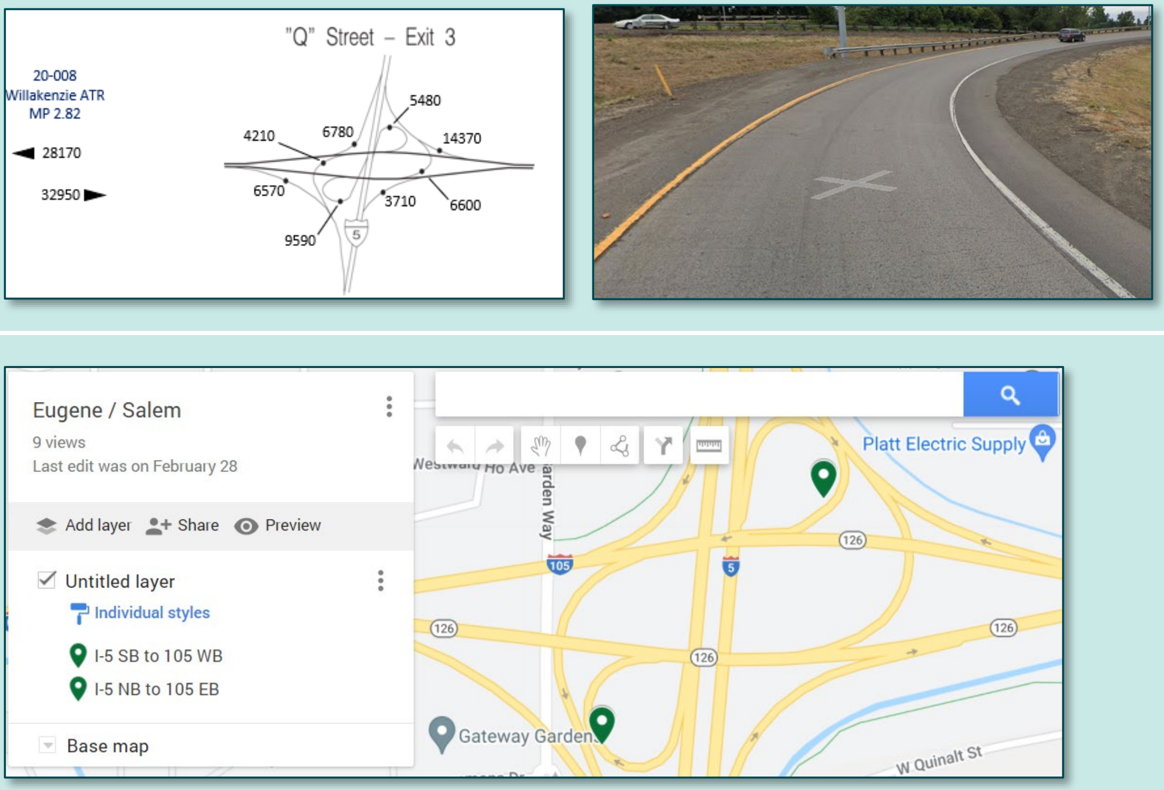
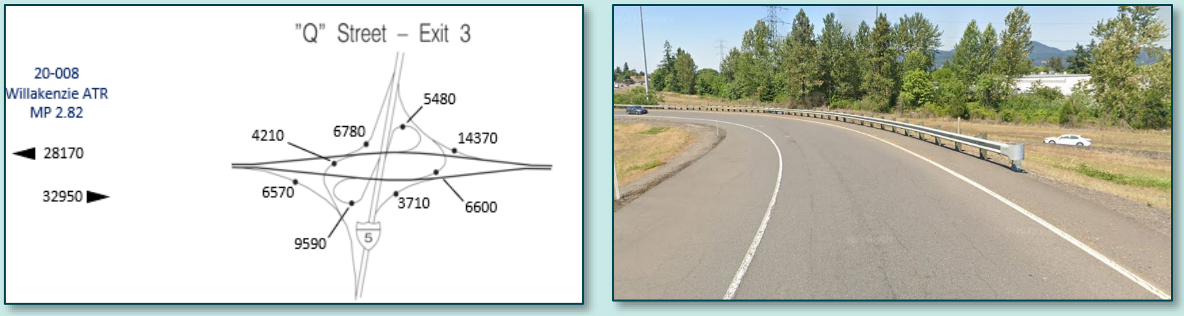
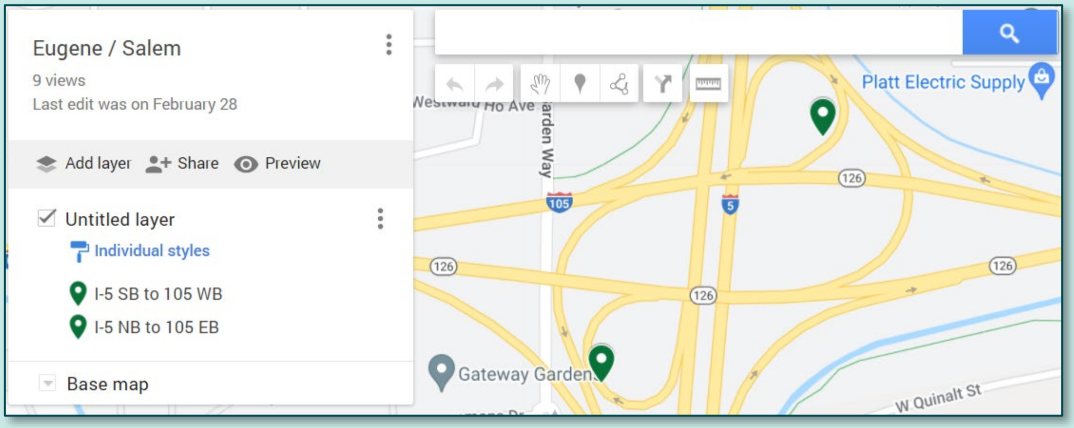


Figure 10: Site 6b: I5 NB to 105/126 WB—Q Street [Cloverleaf uphill; volume = 5,480]





5.1.4 Outside Medford I/M Area

Figure 11: Site 7a 199 to I-5 South—Grants Pass [straight uphill; volume = 8,390]

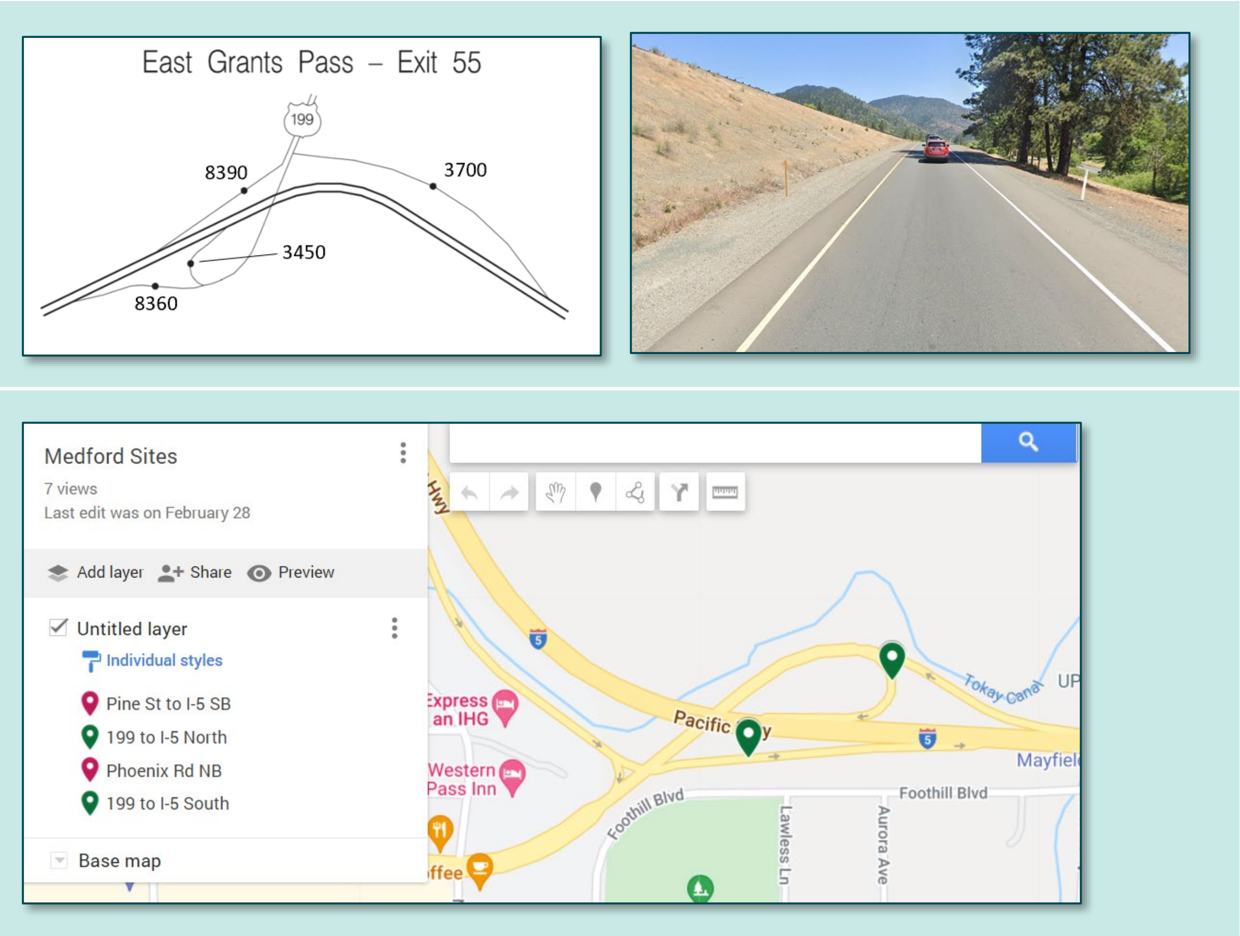
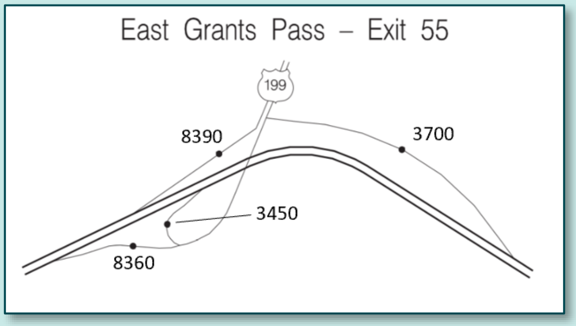
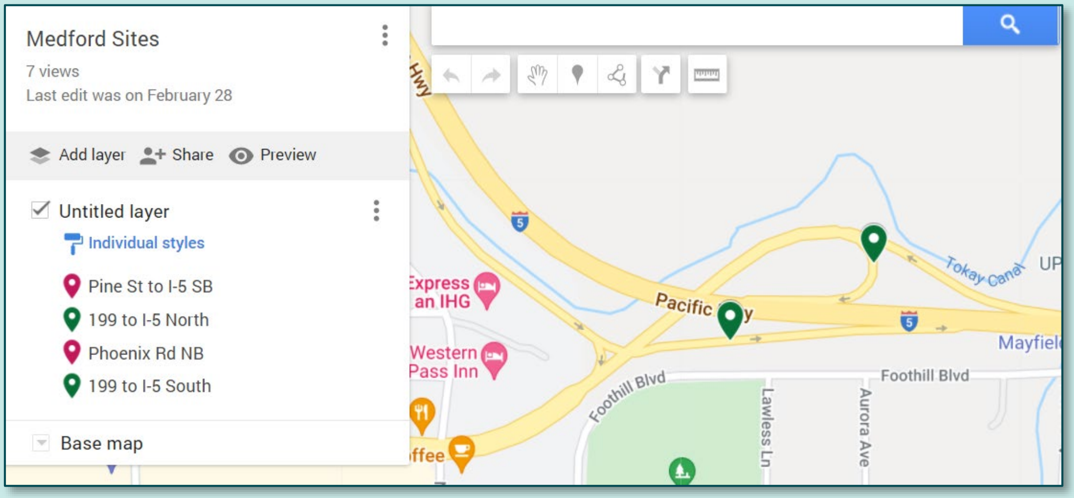


Figure 12: Site 7b 199 to I-5 North—Grants Pass [cloverleaf uphill; volume = 3,450]





5.1.5 Inside Medford I/M Area

Figure 13: Site 8a East Pine Street to I-5 NB—Central Point [downhill, early between trees, volume = 6710]

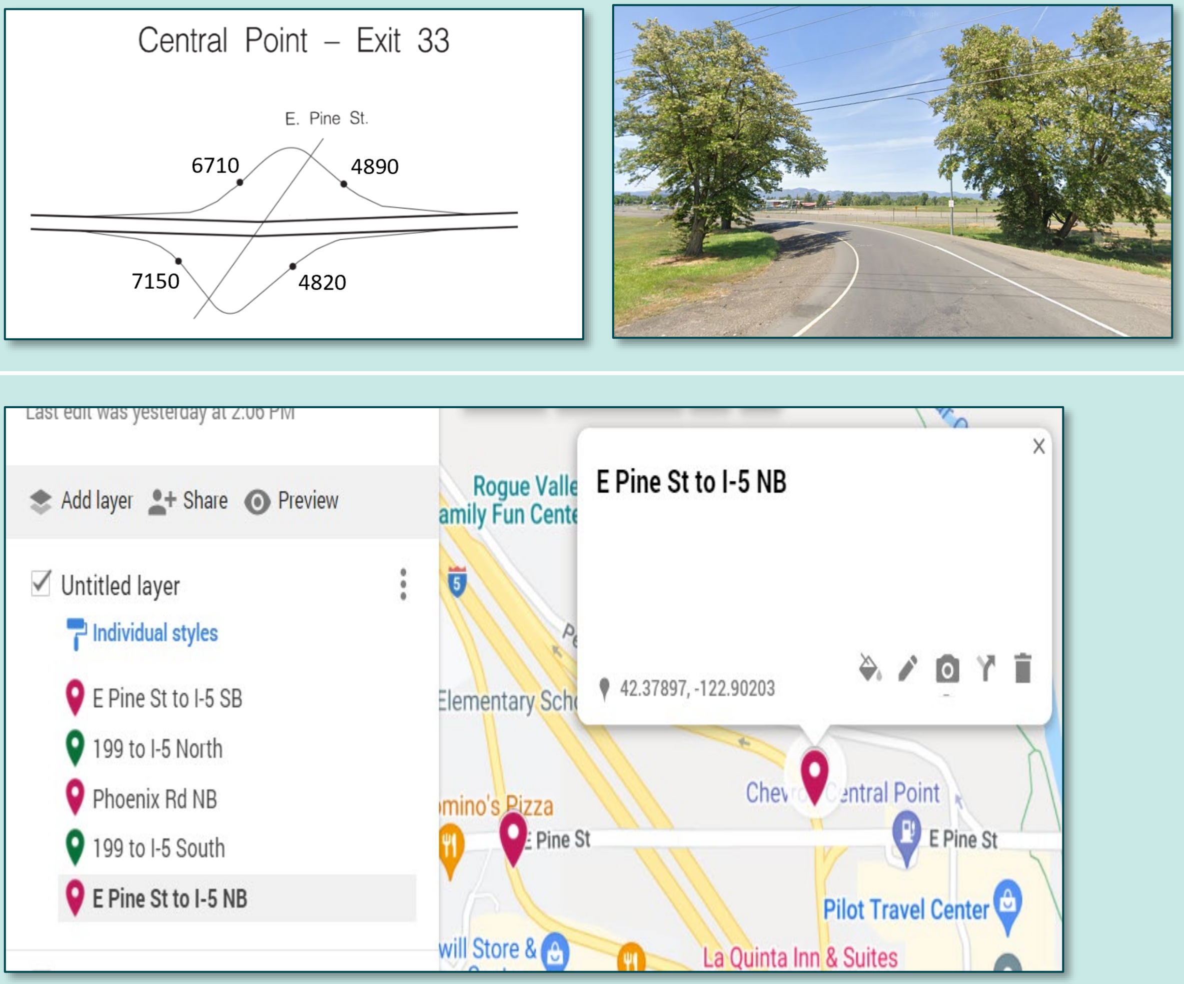
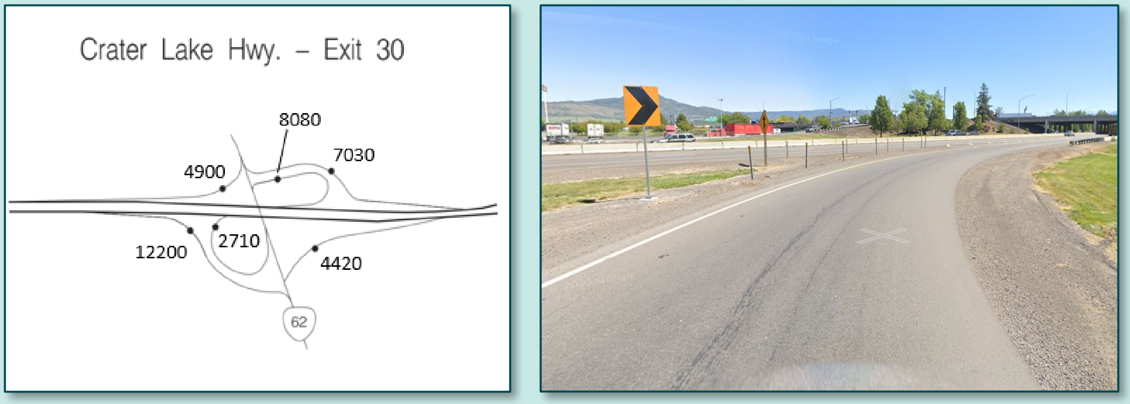
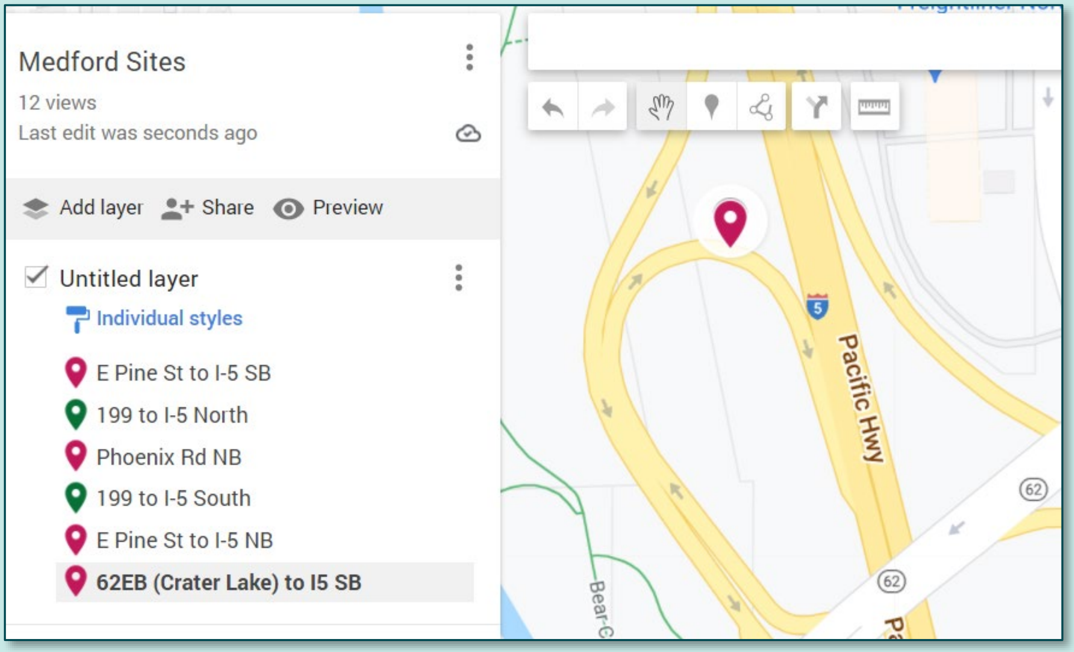


Figure 14: Site 8b East Pine Street to I-5 SB—Central Point [downhill, early, volume = 4,820]

Figure 15: Site 9 62WB (Crater Lake) to I5 SB—[downhill, @ merge, volume = 8,080]




Medford Sites

12 views

Last edit was seconds ago

☑ Untitled layer

Individual styles

- E Pine St to I-5 SB
- 199 to I-5 North
- Phoenix Rd NB
- 199 to I-5 South
- E Pine St to I-5 NB
- 62EB (Crater Lake) to I5 SB

5.2 Determining 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 reports the calculated grams pollutant/kilogram of fuel burned for the petrol vehicles tested in Oregon. 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 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:

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

Next, moles of pollutant are converted to grams by multiplying by molecular weight (such as 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 flame ionization detector (FID) reading.

Table 3: 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 Health and Environment (CDPHE) and the high emitter screening program for the Virginia Department of Environment (VDEQ) have shown that Opus remote sensing methods identify and excuse:

- Clean LDVs with 97% to 99% of the inspected fleet's excess repairable emissions retained; and
- High emitting vehicles with 1% to 3% false failures.[12]

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[12] 2018 Virginia On-Road Emissions Program Annual Report; prepared by Opus Inspection for Virginia Department of Environment Quality, June 2019.

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.[13] Finally, measurements with Opus RSD5000s agree well with portable emissions measurement systems (PEMS).[14]

5.3 Vehicle identification and data processing

The RSD5000 captured emissions readings, vehicle speed and acceleration, and rear pictures of vehicles passing through the RSD light beams. At the end of each data collection session, emissions readings and digital images were transferred to a removable media disk for upload to a dedicated and secure cloud database and server.

Upon upload, Open ALPR Optical Character Recognition (OCR) software automatically recognized and transcribed the license plate into the emissions record. Opus **TagEdit**™ software was then used to manually review OCR entries and transcribe the vehicle license plates not read by the OCR.

Figure 16 shows an example of a TagEdit screen. This combined license plate editing method is superior to the sole use of an automatic license plate reader for the reasons listed below.

- All video images associated with valid emissions data get processed. The highest possible vehicle capture rate is ensured.
- Out-of-state vehicles and other plate types can be designated accordingly. Relying on OCRs to perform this function can leave many vehicle emissions records unaddressed.
- Vehicles with special plates are also processed. This is especially important in areas where many unique special license plates are issued as the failure to process all plate types can create a statistically skewed database that could be misinterpreted by the public as *targeting* certain vehicle classes.

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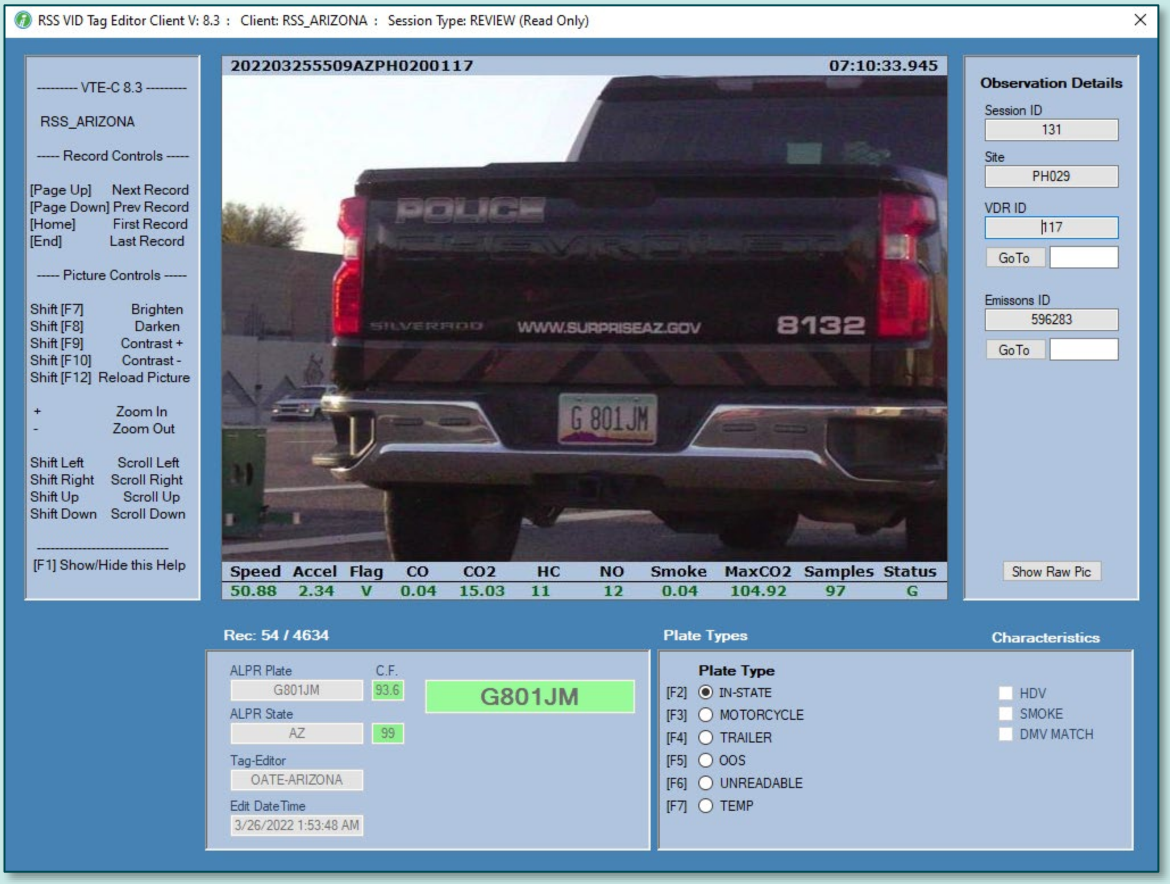
[13] 2009 Colorado Remote Sensing Program Annual Report; page 44, report prepared by Opus for the CDPHE, July 2010.

[14] 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

Figure 16: Arizona TagEdit™ Screen



RSS VID Tag Editor Client V: 8.3 : Client: RSS_ARIZONA : Session Type: REVIEW (Read Only)

-------- VTE-C 8.3 --------

RSS_ARIZONA

----- Record Controls -----

[Page Up]	Next Record
[Page Down]	Prev Record
[Home]	First Record
[End]	Last Record

----- Picture Controls -----

Shift [F7]	Brighten
Shift [F8]	Darken
Shift [F9]	Contrast +
Shift [F10]	Contrast -
Shift [F12]	Reload Picture
+	Zoom In
-	Zoom Out
Shift Left	Scroll Left
Shift Right	Scroll Right
Shift Up	Scroll Up
Shift Down	Scroll Down

[F1] Show/Hide this Help

202203255509AZPH0200117 07:10:33.945

Speed	Accel	Flag	CO	CO2	HC	NO	Smoke	MaxCO2	Samples	Status
50.88	2.34	V	0.04	15.03	11	12	0.04	104.92	97	G

Observation Details

Session ID: 131

Site: PH029

VDR ID: 117

Emissons ID: 596283

Rec: 54 / 4634

ALPR Plate: G801JM C.F.: 93.6

G801JM

ALPR State: AZ 99

Tag-Editor: OATE-ARIZONA

Edit DateTime: 3/26/2022 1:53:48 AM

Plate Types

Plate Type

[F2] ● IN-STATE
[F3] ○ MOTORCYCLE
[F4] ○ TRAILER
[F5] ○ OOS
[F6] ○ UNREADABLE
[F7] ○ TEMP

Characteristics

☐ HDV
☐ SMOKE
☐ DMV MATCH

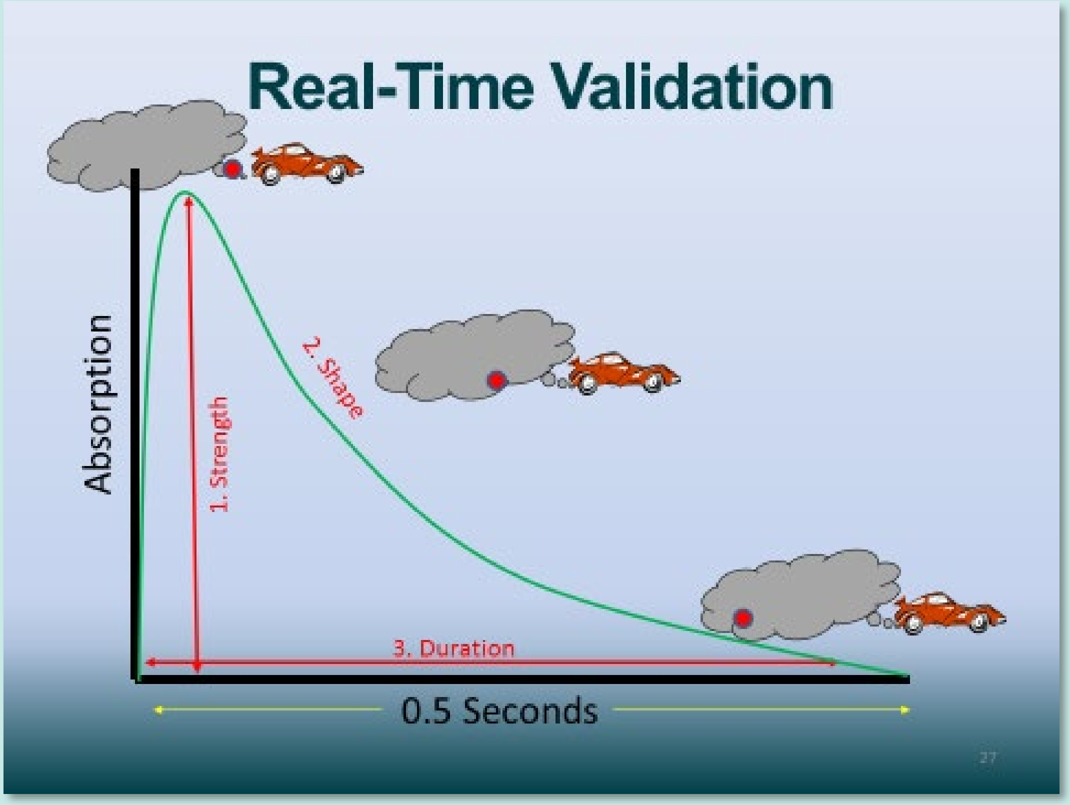
A special cloud-based data management system was developed for the Oregon RSD study that allowed nightly upload of the data collection session(s) and overnight OCR, followed by manual license plate entry. License plates provided to the DEQ were used to recover VINs and vehicle information (data matching) upon completion of this data processing exercise.

5.4 Emissions data quality assurance

The RSD5000 takes up to 97 aggregate readings of each vehicle's exhaust to determine the tailpipe emissions. Real-time RSD software then evaluates whether a *valid* measurement of that vehicle's trailing exhaust plume was achieved. The evaluation criteria for validity include how much of the vehicle exhaust plume intersected with the IR and UV light beams (*strength*), the length of time the plume was measured (*duration*), whether the plume measurements were consistent with normal plume dissipation (*shape*), and the conditions of the background prior to the emissions measurement (Figure 17).

Only valid measurements that passed the real-time filters were marked with "V," advanced to post-collection quality screening, and included in data analysis (Task 8; See Section 6.1).

Figure 17: Real-time measurement validation



Real-Time Validation

5.4.1 Daily setup and calibration

Every scheduled workday, the RSD operator drove to a predetermined and ODOT-permitted site. The operator's first duty was to provide and maintain a safe work area for themselves and passing motorists. The next step was to set-up the SDM and allow the electronic components within to warm up for a minimum of 15 minutes. Following an approximate 30-minute setup and alignment of the other components, the SDM and CCM were aligned and readied for calibration with an internal gas cell. The cell was rocked in and out of the RSD's IR and UV light path multiple times to generate stable and consistent results that could then be used to establish a field calibration. A calibration verification (puff) audit (CVA) immediately followed the cell calibration and was intended to confirm the remote sensor's accuracy and the calibration's validity.

The CVA involves dispensing a known mixture of the gaseous pollutants (CO, HC, NO, and CO_2 in an N_2 balance) repeatedly into the external optical path of the RSD during gaps in traffic. Three consecutive measurements of puffed gas within accuracy tolerances constitute a passing CVA. If the CVA fails, the RSD setup, alignment, and calibration may need to be improved to achieve a passing audit. A cell calibration capped by a passing CVA permits the operator to enter and commence vehicle emissions testing.

5.4.2 Periodic equipment audits

After an initial calibration and CVA, the RSD operator is required to perform CVAs periodically over the course of the day to verify and optimize the RSD's calibration and accuracy. All calibrations and audits are marked in the database with a "C" and "A," respectively. These periodic CVAs must pass a predetermined pass/fail tolerance, just like the initial post-calibration CVA, before the RSD allows the operator to continue testing vehicles. If the periodic CVA fails, the operator is required to realign and recalibrate the system until it passes the audit process. Only valid data captured under an Audit = "G" status was used in data analysis.

6. Operations and Data Collection

Opus Inspection was contracted by Oregon Department of Environmental Quality to collect on-road emissions measurements of light duty vehicles inside and outside the two I/M areas of Portland and Medford using the latest Opus remote sensing device (RSD) technology for a comparison evaluation of I/M program performance.

Opus team members delivered turnkey services that started in February 2022 with study planning (Task 1) to select areas for focusing inside and outside on-road testing. Opus personnel then selected sites in those areas that would yield a proportional volume of inside and outside on-road data (Task 2) and worked with the Oregon DEQ to secure site permits from the respective Oregon Department of Transportation (ODOT) authorities (Task 3).

6.1 Oregon RSD study task schedule

A data collection schedule (Table 4) was developed to achieve the contractual objective of collecting data during the driest months of June and July 2022 (Task 4). Opus team members collected on-road vehicle emissions measurements using the battery-operated RSD5409 over 25 days from June 13, 2022, to July 14, 2022.

Table 4: Oregon RSD Study Task Schedule

Tasks	Start	Finish
Planning (Task 1)	Contract Execution	3/18/2022
Site Selection (Task 2)	3/21/2022	4/15/2022
Site Permitting (Task 3)	4/18/2022	5/20/2022
Site Scheduling (Task 4)	5/23/2022	6/3/2022
Data Collection (Task 5)	6/6/2022	7/22/2022
Data Processing (Task 6)	7/25/2022	11/25/2022
Data Matching (Task 7)	8/22/2022	12/9/2022
Data Analysis/Draft Report (Task 8)	9/19/2022	1/20/2023
Final Report (Task 9)	10/17/2022	3/31/2023

6.2 Oregon RSD data collection

Opus team members made 123,899 raw measurement attempts (RawCnt) which yielded 85,920 all-valid measurements (70%), including valid measurements of emissions (CO, HC, and NO), speed and acceleration with a passing CVA audit period (Table 5).

Table 5: Oregon RSD Study data collection results

	SessionsID	Date	SiteCode	City	Description	Latitude	Longitude	RawCnt	SA_Valid	Gas_Valid	Gas_SA_CVA_Valid	Total	% of Total
INSIDE PORTLAND	1	6/13/2022	OR_001	PORTLAND	SW CLAY EB TO 26WB SUNSET	45.51519	-122.6911	5,054	4,995	4,154	4,109	35,732	42%
	2	6/14/2022	OR_001	PORTLAND	SW CLAY EB TO 26WB SUNSET	45.51519	-122.6911	5,476	5,317	4,431	4,337		
	3	6/15/2022	OR-002A	PORTLAND	I-5 TO 84 EB RAMP	45.527	-122.666	9,817	9,544	6,403	6,253		
	4	6/16/2022	OR-002A	PORTLAND	I-5 TO 84 EB RAMP	45.527	-122.666	8,635	8,102	5,560	5,220		
	5	6/17/2022	OR-002A	PORTLAND	I-5 TO 84 EB RAMP	45.527	-122.666	4,294	4,146	3,243	3,145		
	6	6/20/2022	OR-002B	PORTLAND	84 WB TO I-5 NB	45.52564	-122.6634	5,577	5,044	3,953	3,605		
	7	6/21/2022	OR-003	PORTLAND	NE GILSAN TO 84 EB ON RAMP	45.5276	-122.6064	2,699	2,537	2,089	2,002		
	8	6/22/2022	OR-002B	PORTLAND	84 WB TO I-5 NB	45.52564	-122.6634	10,604	10,093	7,347	7,061		
OUTSIDE PORTLAND	9	6/23/2022	OR-005	PORTLAND	I-5 SB (FROM VANCOUVER) TO99 EB	45.60487	-122.6839	5,173	4,974	4,153	4,012	29,785	35%
	10	6/24/2022	OR-005	PORTLAND	I-5 SB (FROM VANCOUVER) TO99 EB	45.60487	-122.6839	5,198	4,995	4,140	4,004		
	11	6/25/2022	OR-011	DAYTON	SE DAYTON BYPASS TO 99W NB	45.23822	-123.0621	5,041	4,913	3,792	3,704		
	12	6/27/2022	OR-010	BEND	EMPIRE BLVD TO US 97 SB IN BEND	44.0065	-121.0628	5,690	5,539	4,238	4,126		
	13	6/28/2022	OR-010	BEND	EMPIRE BLVD TO US 97 SB IN BEND	44.0065	-121.0628	4,088	3,800	3,024	2,821		
	14	6/29/2022	OR-006A	EUGENE	I-5 SB TO 105/126 EB	44.06421	-123.0509	3,816	3,762	3,274	3,229		
	15	6/30/2022	OR-006A	EUGENE	I-5 SB TO 105/126 EB	44.06421	-123.0509	5,715	5,571	4,504	4,409		
	16	7/1/2022	OR-006B	EUGENE	I-5 NB TO 105/126 WB	44.06421	-123.0473	3,133	2,842	2,642	2,419		
	17	7/2/2022	OR-006B	EUGENE	I-5 NB TO 105/126 WB	44.06421	-123.0473	1,456	1,263	1,208	1,061		
OUTSIDE MEDFORD	18	7/5/2022	OR-007A	MEDFORD	199 TO I-5 SOUTH	42.43776	-123.293	5,696	5,326	4,758	4,474	12,249	14%
	19	7/6/2022	OR-007A	MEDFORD	199 TO I-5 SOUTH	42.43776	-123.293	5,984	5,558	4,808	4,489		
	20	7/7/2022	OR-007B	MEDFORD	199 TO I-5 NORTH	42.43824	-123.2161	2,112	1,984	1,578	1,491		
	21	7/8/2022	OR-007B	MEDFORD	199 TO I-5 NORTH	42.43824	-123.2161	2,163	2,119	1,818	1,795		
INSIDE MEDFORD	22	7/11/2022	OR-008A	MEDFORD	EAST PINE ST TO I-5 NB	42.37956	-122.9035	2,362	1,841	1,337	1,063	8,154	9%
	23	7/12/2022	OR-008B	MEDFORD	EAST PINE ST TO I-5 SB	42.37783	-122.9049	4,535	4,481	3,342	3,311		
	24	7/13/2022	OR-009	MEDFORD	62 WB (CRATER LAKE) TO I-5 SB	42.3517	-122.8773	4,898	4,718	1,925	1,858		
	25	7/14/2022	OR-009	MEDFORD	62 WB (CRATER LAKE) TO I-5 SB	42.3517	-122.8773	4,683	4,291	2,108	1,922		
						Totals		123,899	117,755	89,829	85,920		100%

A total of 76,091 all-valid measurements included a legible license that could be transcribed into the emissions record. Following data processing, (as described in section 5.3 of this report), license plates for all valid measurements were sent to the DEQ for retrieval of relevant vehicle information from the vehicle registration database (data matching, Task 7). A total of 55,322 were matched to Oregon registrations and 47,946 (63%) were unique measurements of Oregon vehicles. A merged dataset of [emissions measurements + vehicle information] was compiled and sent to de la Torre Klausmeier Consulting (dKC) for data analysis (Task 8) and draft report (Task 9) preparation.

Result of analyses are presented in the sections of this report that follow.

7. Summary Statistics

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

Table 6 provides a breakdown of the observations by registration status. Registration status was broken down into the categories shown on Table 6. Oregon vehicles were broken down into the four categories listed in the table.

Overall, 32% of the observations were from testable vehicles registered in Oregon's I/M areas. Testable means that the vehicle model years and types are tested in the I/M program area.

Table 6: Observations by registration status

Vehicle Registration Category	Total	%
1. OR In I/M ZIP[15]—Testable (Vehicle model years and types are tested)	24,509	32%
2. OR In I/M ZIP—Not Testable	7,724	10%
3. OR Outside I/M ZIP—Testable	18,162	24%
4. OR Outside I/M ZIP—Not Testable (Includes Oregon vehicles that could not be matched to vehicle registration data)	10,516	14%
5. Washington	5,511	7%
6. California	3,408	4%
7. Other out-of-state	6,261	8%
Grand Total	**76,091**	**100%**

As seen in Table 7, results were further broken down by location of RSD Site (Inside I/M or Outside I/M); 52% of the observations at I/M area sites were testable vehicles subject to I/M requirements. Figure 18 shows a breakdown of observations in the I/M area.

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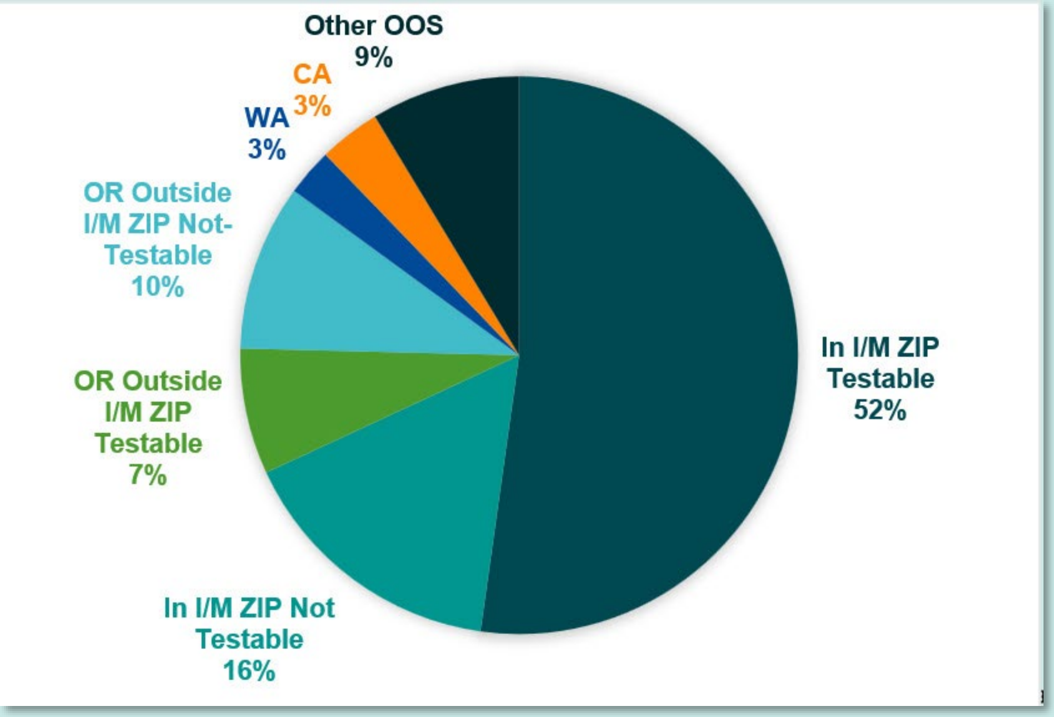
[15] Vehicle is registered in the zip-code that requires I/M compliance.

Table 7: Observations by registration status and site location

Vehicle Reg Category	Inside I/M Site		Outside I/M Site	
	Number	Percentage	Number	Percentage
1. In I/M ZIP Testable	20794	52%	3715	10%
2. In I/M ZIP Not Testable	6322	16%	1402	4%
3. OR Outside I/M ZIP Testable	2903	7%	15259	42%
4. OR Outside I/M ZIP Not Testable (Includes Oregon vehicles that could not be matched to vehicle registration data)	3845	10%	6671	18%
5. WA	1095	3%	4416	12%
6. CA	1417	4%	1991	5%
7. Other OOS	3446	9%	2815	8%
Grand Total	**39822**	**100%**	**36269**	**100%**

Figure 18: Breakdown of observations at sites in I/M Area



Observations inside the I/M area were further broken down by model year group (Table 8).

- A majority (72% to 87%) of the observations of 2018 and older models at I/M area sites were I/M testable vehicles registered in the I/M area. Overall, 86% of 2018 and older models at I/M area sites were I/M testable vehicles registered in the I/M area.
- 11% to 15% of the observations of 2018 and older models at I/M area sites were testable vehicles registered outside the I/M area.

Table 8: Observations by registration status and model year—Sites In I/M Area

Model Years	1. In I/M ZIP Testable	2. In I/M ZIP Not Testable	3. OR Outside I/M ZIP Testable	4. OR Outside I/M ZIP Not-Testable	In I/M Total
1995-	252	33	53	12	350
1996-2000	788	20	136	7	951
2001-2005	2453	105	376	28	2962
2006-2010	4115	102	634	22	4873
2011-2018	13186	217	1704	47	15154
2019+		5845		799	6644
Grand Total	**20794**	**6322**	**2903**	**3845**	**39822**
Model Years	**1. In I/M ZIP Testable**	**2. In I/M ZIP Not Testable**	**3. OR Outside I/M ZIP Testable**	**4. OR Outside I/M ZIP Not Testable**	**In I/M Total**
1995-	72%	9%	15%	3%	100%
1996-2000	83%	2%	14%	1%	100%
2001-2005	83%	4%	13%	1%	100%
2006-2010	84%	2%	13%	0%	100%
2011-2018	87%	1%	11%	0%	100%
2019+	0%	88%	0%	12%	100%
Grand Total	**52%**	**16%**	**7%**	**10%**	**100%**

8. Emissions Trends

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

8.1 Impact of vehicle specific power on emissions

Opus team members 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:

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

During the Federal Test Procedure (FTP), VSP varies between 3 and 22.

dKC grouped RSD emissions into four VSP groups:

1. VSP less than zero (3% of sample),
2. VSP between 0 and 3 (5% of sample),
3. VSP between 3 and 22 (73% of sample), and
4. VSP greater than 22 (18% of sample).

Figure 19 shows average CO, HC, and NO RSD emissions by VSP group. All observations of Oregon vehicles were used in these calculations. There's no clear trend in emissions by VSP. 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.[16] For CO and NO, the VSP 0 to 3 group had the lowest emissions. For HC, the VSP 3 to 22 group had the lowest emissions. All valid measurements, regardless of VSP, are used in the subsequent analysis.

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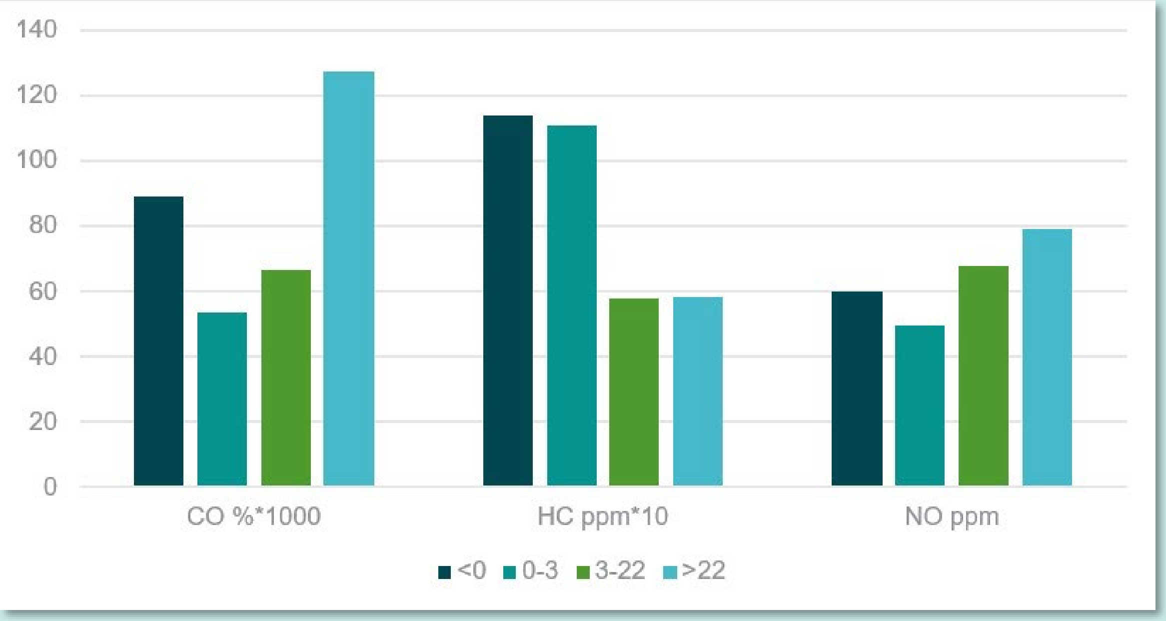
[16] See section "Concentrations from Measured Ratios" for more details.

Figure 19: Average emissions by VSP



8.2 Emissions by I/M status

Data were grouped into the following categories:

- I/M—Oregon vehicles registered in an area requiring I/M compliance.
- No I/M—Oregon vehicles registered in an Oregon area not requiring I/M compliance.

> *The US EPA RSD-based Reference Method I/M program evaluation is designed to measure the full effect of an I/M program on a vehicle fleet, by comparing the emissions of a fleet subject to I/M with estimated fleet emissions if no I/M program were in place.*[17]
>
> *The difference in total fleet emissions between the I/M program area and the untested reference area represents the emission reductions benefit of the I/M program.*[18]

Figure 20 compares average CO, HC, and NO emissions for all Oregon vehicles registered inside and outside Oregon's I/M area. This includes testable and non-testable vehicles. Error bars show the 95% confidence limit. In aggregate, average emissions of I/M area vehicles were lower than average emissions of non-I/M area vehicles by the percentages listed below.

- CO: 44% reduction

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[17] Guidance on Use of Remote Sensing for Evaluation of I/M Program Performance, EPA420-B-04-010, Office of Transportation and Air Quality, USEPA July 2004; https://nepis.epa.gov/Exe/ZyPdf.cgi?Dockey=P1002J6C.pdf

[18] Guidance on Biennial Performance Evaluation Requirements for Enhanced vehicle Inspection and Maintenance (I/M) Programs, EPA-420-B-20-040, Office of Transportation and Air Quality, USEPA June 2020; https://nepis.epa.gov/Exe/ZyPDF.cgi/P100YQX8.PDF?Dockey=P100YQX8.PDF

- HC: 10% reduction
- NO: 45% reduction

The CO and NO reductions were significant at the 95% confidence level.

Based on US EPA's emissions model MOVES3 for Clackamas and Multnomah Counties, Oregon VIP reduces emissions from similar-age vehicles by the following percentages:

- CO: 16% reduction
- HC: 7 to 8% reduction
- NO: 8 to 13% reduction

The average model year for vehicles registered in the I/M area was 2013 vs 2012 for vehicles registered in no I/M areas; MOVES assumes there's no shift in vehicle age from I/M. This partially accounts for the greater I/M benefits shown by remote sensing devices than by MOVES.[19]

Reductions were also examined for measurements made at I/M sites alone. The makes possible direct comparisons to similar reference method evaluations conducted for the centralized Arizona and Colorado I/M programs and the decentralized Virginia I/M program.[20] Comparisons are presented in Table 9.

Table 9: Oregon VIP reductions compared to Colorado, Virginia, and Arizona I/M programs

RSD Data Collection			**RSD Reference Method Evaluations (Tested vs Un-Tested by IM Program & Year of Study)**							
~Valids by Registration Area			I/M Program (Eval Yr)	% Reductions (Un-Adjusted)				% Reductions (Age-Adjusted)		
I/M Area	non-I/M Area	%ofTotal	Reference Method	CO	HC	NO		CO	HC	NO
39,822	36,269	48%	Oregon (22) - All	44%	10%	45%				
27,116	6,748	20%	**Oregon (22) - I/M Sites**	**37%**	**43%**	**42%**		**29%**	**30%**	**29%**
3,200,000	280,000	8%	**VA (21) - I/M Sites**	**24%**	**33%**	**39%**		**25%**	**31%**	**31%**
2,300,000	210,000	8%	VA (20) - I/M Sites	43%	33%	42%		43%	32%	35%
2,900,000	310,000	10%	VA (19) - I/M Sites	38%	46%	56%		30%	31%	39%
1,700,000	200,000	11%	VA (18) - I/M Sites	33%	44%	48%		23%	30%	28%
			CO (21) - I/M Sites	17%	31%	38%				
2,500,000	150,000	6%	CO (20) - I/M Sites	21%	32%	38%				
3,200,000	210,000	6%	CO (19) - I/M Sites	18%	32%	34%				
4,300,000	270,000	6%	CO (18) - I/M Sites	**18%**	**30%**	**33%**		**8%**	**16%**	**22%**
105,014	8,742	8%	AZ (21) - I/M Sites	26%	48%	46%		**14%**	**34%**	**26%**

On an age-adjusted basis, the Oregon VIP achieves reductions equal to or greater than the Colorado, Virginia, and Arizona I/M programs.

Most vehicles tested in Oregon's I/M program receive OBD inspections. DEQ performed surveys of OBD faults for vehicles inside and outside Oregon's I/M program area. Following are malfunction indicator light (MIL) illumination rates based on these surveys:

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[19] Another limitation of MOVES is that it assumes no impact on diesel fueled vehicles.

[20] In AZ and CO, RSD measurements were made entirely at sites within the I/M area. In Virginia, as stipulated by contract, ~5% of the collection effort was at sites outside the I/M area (in Richmond versus the Northern VA I/M counties).

- No I/M (Springfield): 16.5% MIL-On rate
- I/M (results from clean air station): 2.5% MIL-On rate

The emission reductions observed in the RSD comparisons make sense given the impact Oregon’s I/M program has on MIL-On rates.

Figure 20: Average emissions—Vehicles registered inside and outside of Oregon’s I/M area

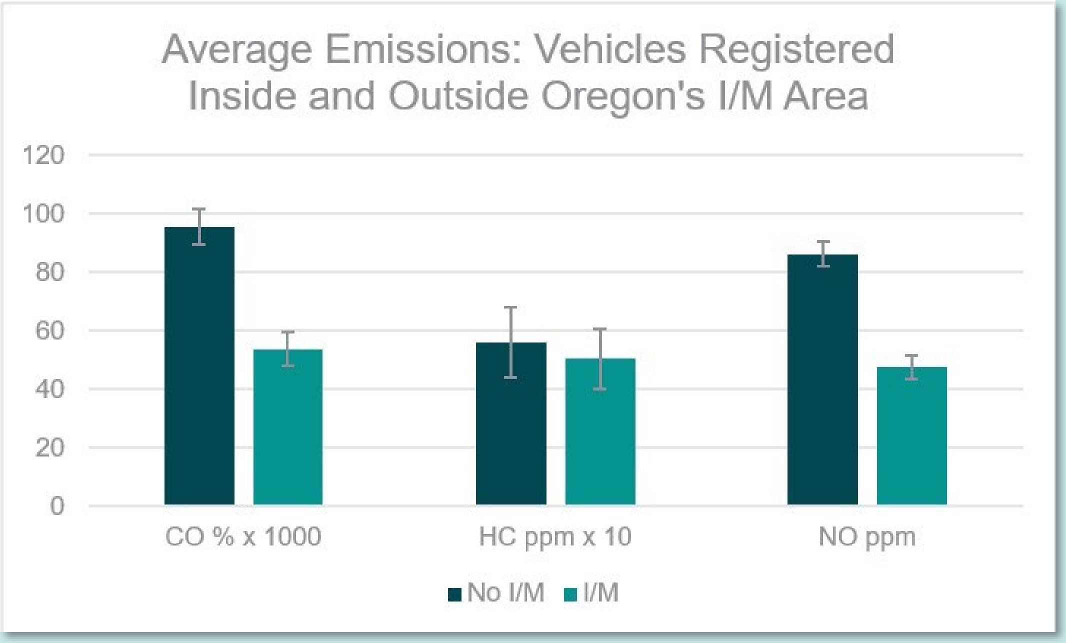


Figure 21, Figure 22, and Figure 23 show average CO, HC, and NO emissions by registered area. CO emissions were significantly lower for observations of vehicles registered in Oregon’s I/M area than for all the other groups. All the groups except for vehicles with California plates had significantly higher NO emissions than vehicles registered in Oregon’s I/M area. HC trends are inconsistent.

Figure 21: Average CO by registered area

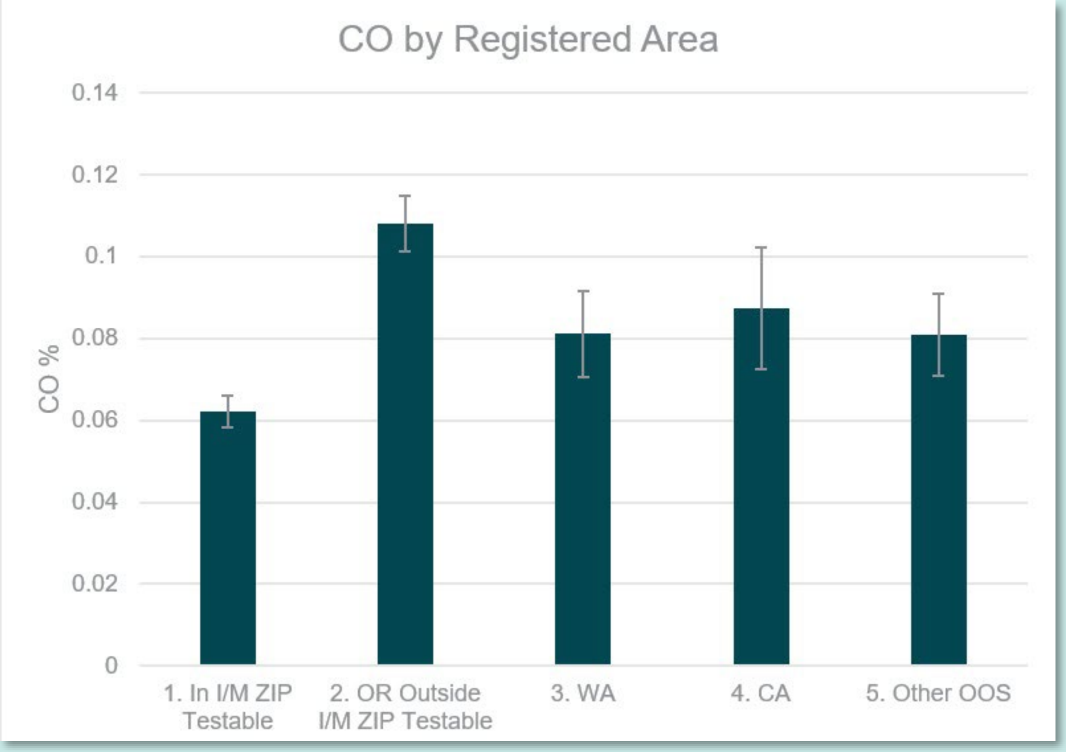


Figure 22: Average HC by registered area

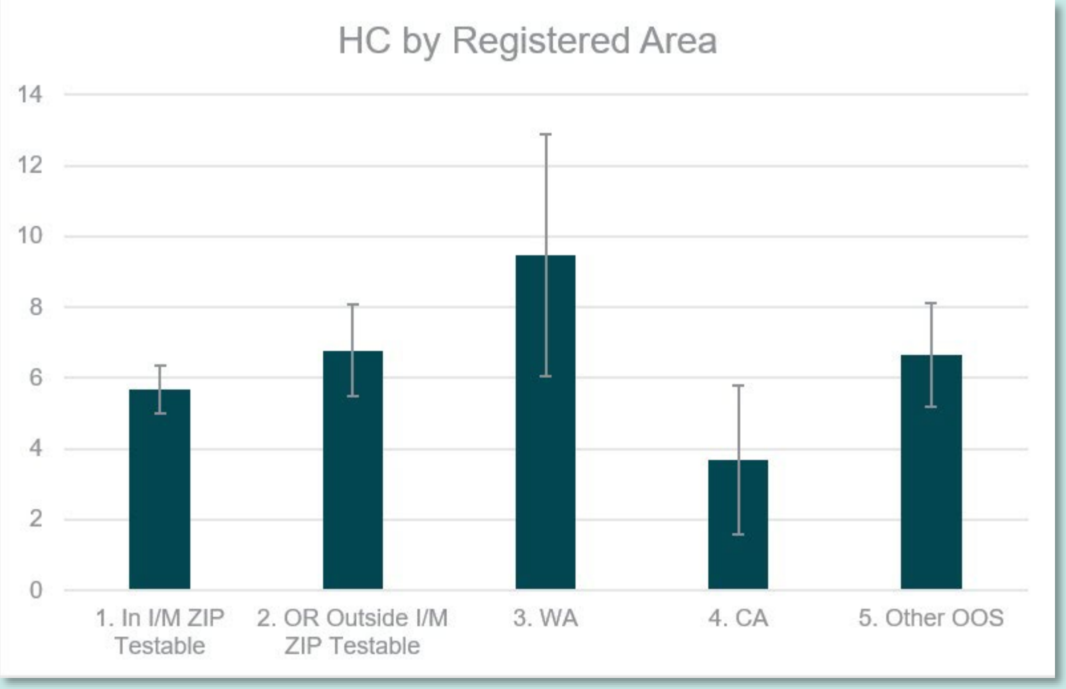


Figure 23: Average NO by registered area

The following figures show CO (Figure 24), HC (Figure 25), and NO (Figure 26 and Figure 27) emissions by model year for two groups, I/M and No I/M. CO and NO emissions are much lower for vehicles that were required to undergo I/M tests, largely remain lower and widen for the older model years that experience higher I/M-directed emissions lowering maintenance and/or repair. The impact on HC was less pronounced, which is consistent with the lower overall emission reductions observed for HC emissions. While the no I/M vehicles appear to have slightly lower everage emissions (~2ppm) than I/M through model year 2007, emissions levels invert after model year 2005, consistent with higher I/M-directed maintenance/repair. This is noteworthy, since 2005 and older vehicles account for only 15% of overall VMT but contribute the majority (70%) of overall HC emissions.

Note on the following figures that 2019 and newer have extremely low emissions. Oregon's policy of exempting the newest four model years does not impact the effectiveness of Oregon's I/M program.

Figure 24: Average CO emissions by I/M status

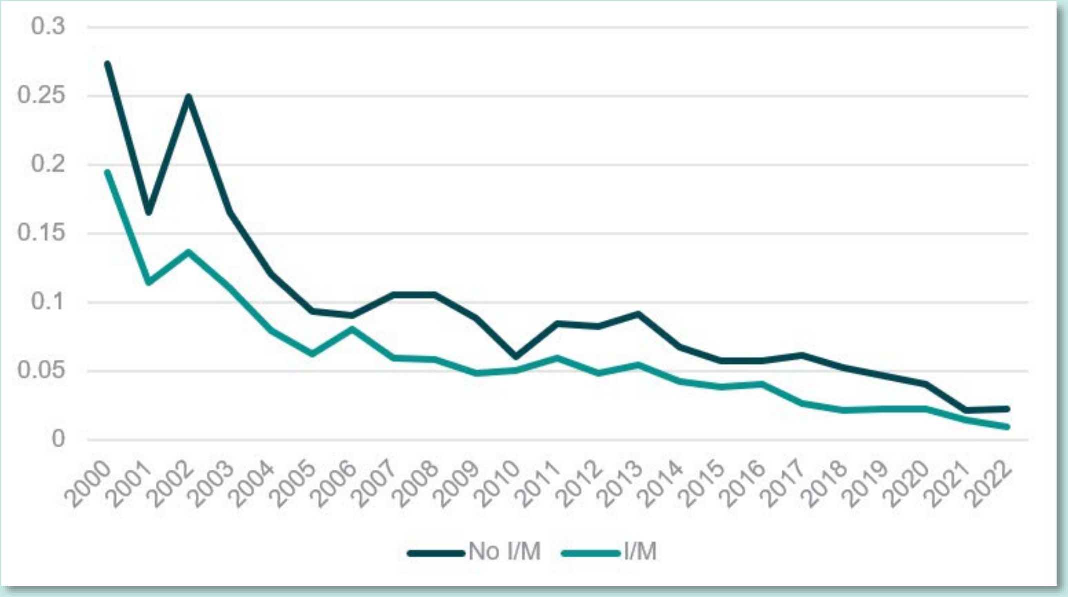


Figure 25: Average HC emissions by I/M status

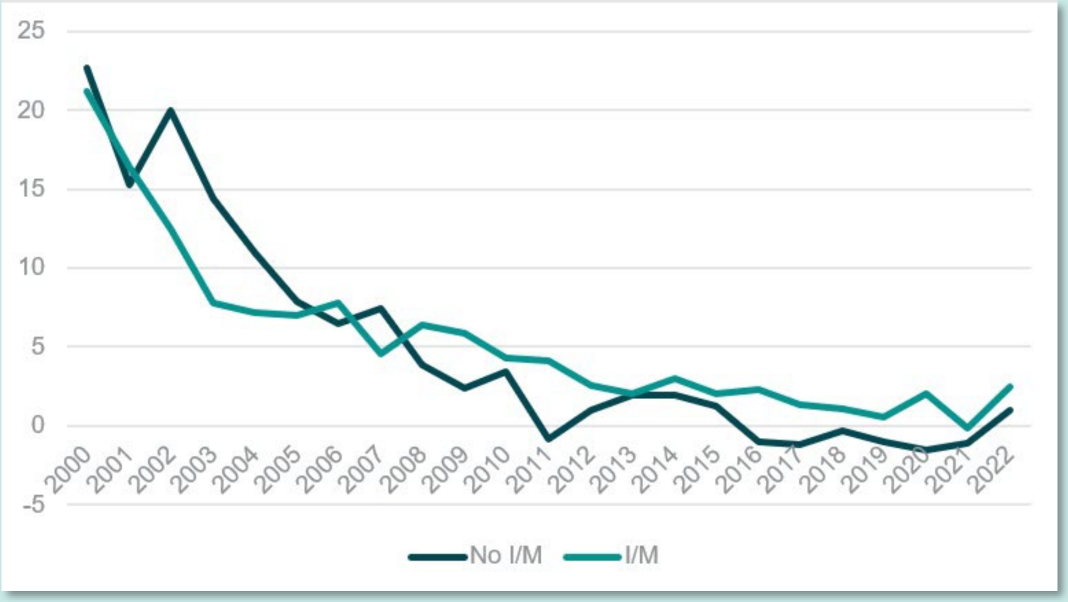


Figure 26: Average NO emissions by I/M status (2000+)

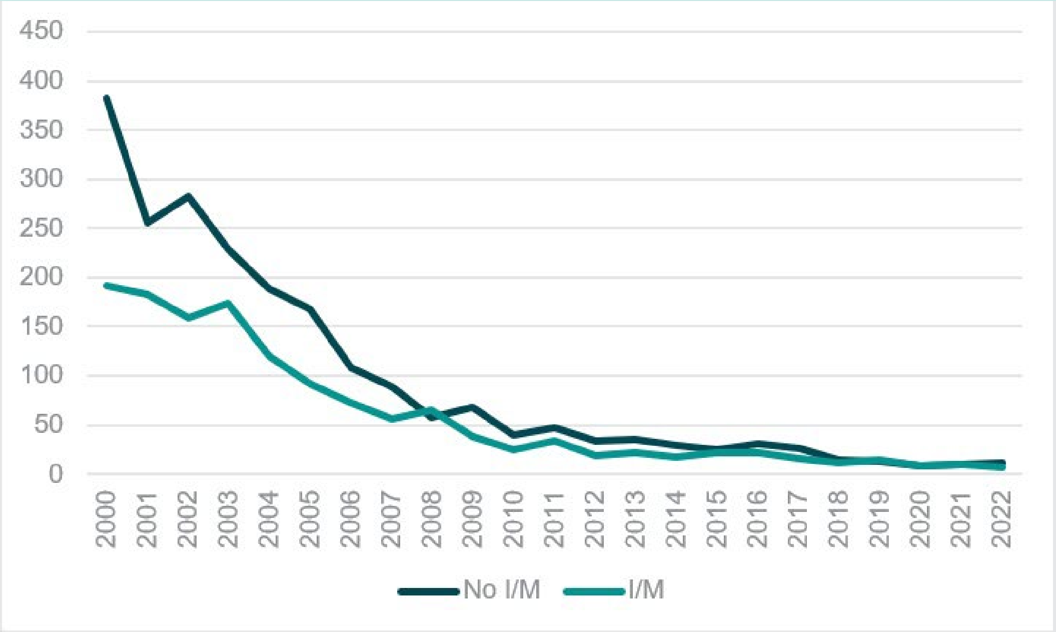
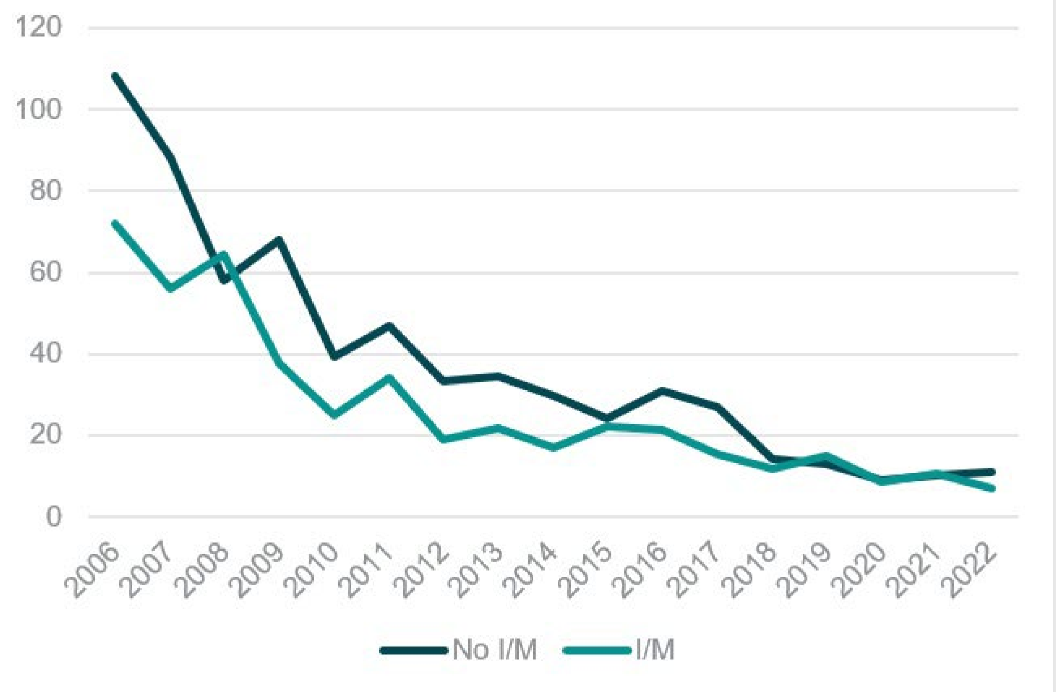


Figure 27: Average NO emissions by I/M status (2006+)



8.3 Analysis of Gross Polluters

dKC used Maryland's RSD cutpoints of 1.5% CO, 220 ppm HC, and 1650 ppm NO to identify gross polluters. Figure 28 shows the percent of vehicles that exceeded these cutpoints broken down by I/M status. The gross polluter rate was more than twice as high for the group of vehicles that were not required to be tested.

Figure 29 shows the percent of gross polluters by vehicle registration status. Testable vehicles registered in the I/M area had much lower percentages of gross polluters than testable vehicles registered outside the I/M area in Oregon. Vehicle registered in Washington, California, and other states also had higher percentages of gross polluters than Oregon's I/M group.

Figure 28: Percent gross polluter vs. I/M status

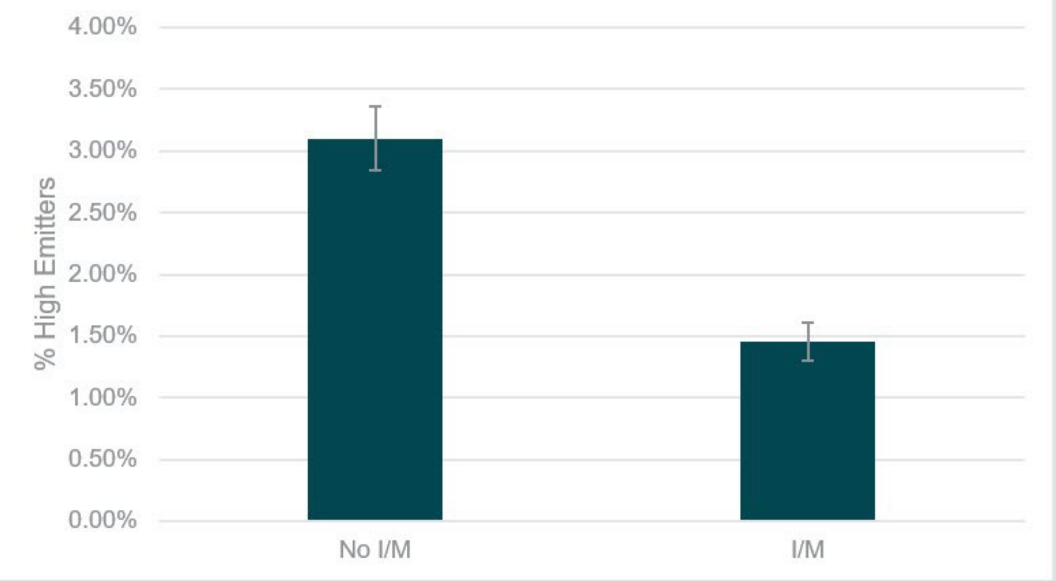
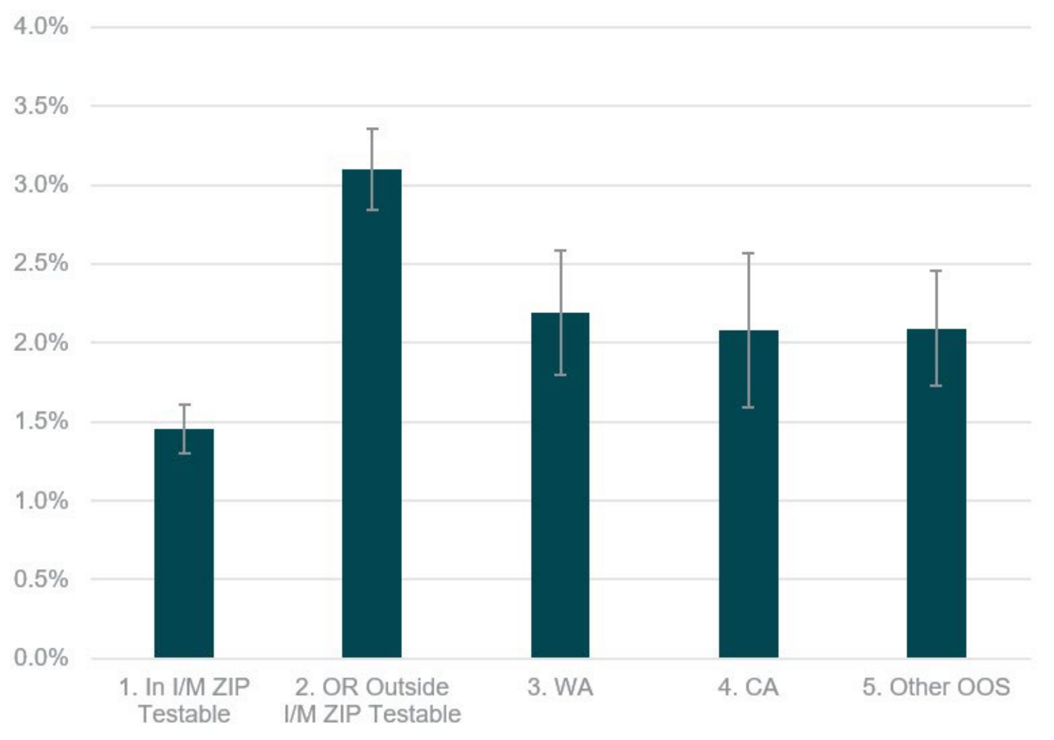


Figure 29: Percent gross polluter vs. vehicle registration status



8.4 Comparison with Washington Vehicles

Washington provided vehicle information for most of the plates observed in the Oregon RSD survey. Figure 30, Figure 31, and Figure 32 compare emissions by model year group for vehicles registered in Washington with vehicles registered inside Oregon's I/M area. CO and NO emissions were consistently lower for vehicles registered in Oregon's I/M area than for vehicles registered in Washington. HC trends were inconsistent.

Figure 30: Comparison of CO emissions—Washington vs Oregon I/M

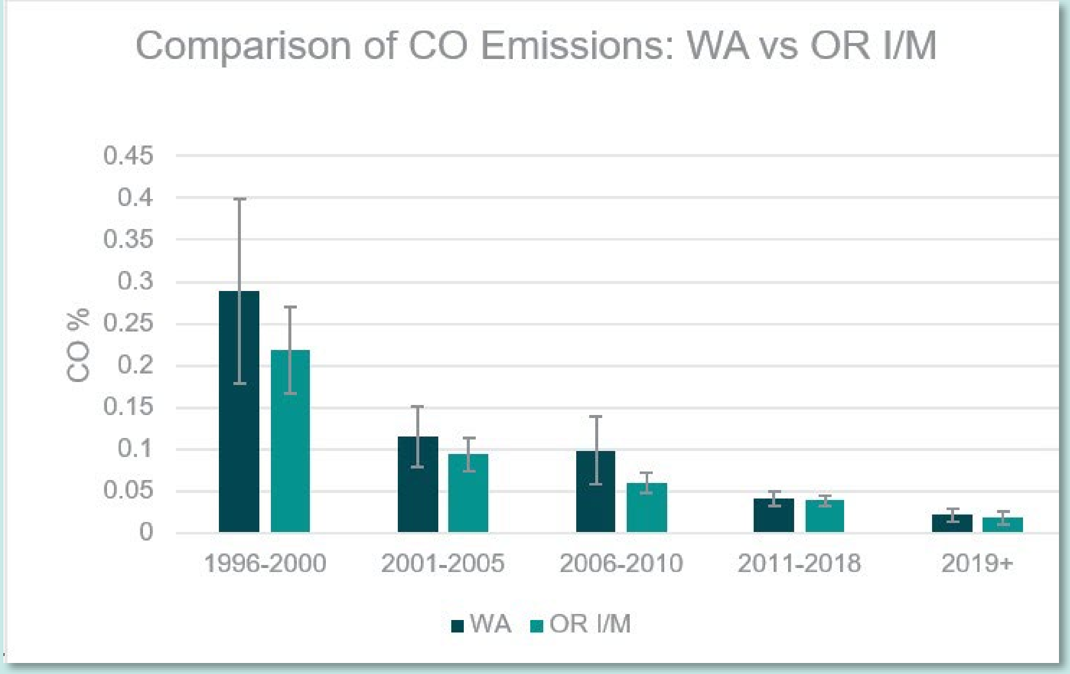


Figure 31: Comparison of HC emissions—Washington vs Oregon I/M

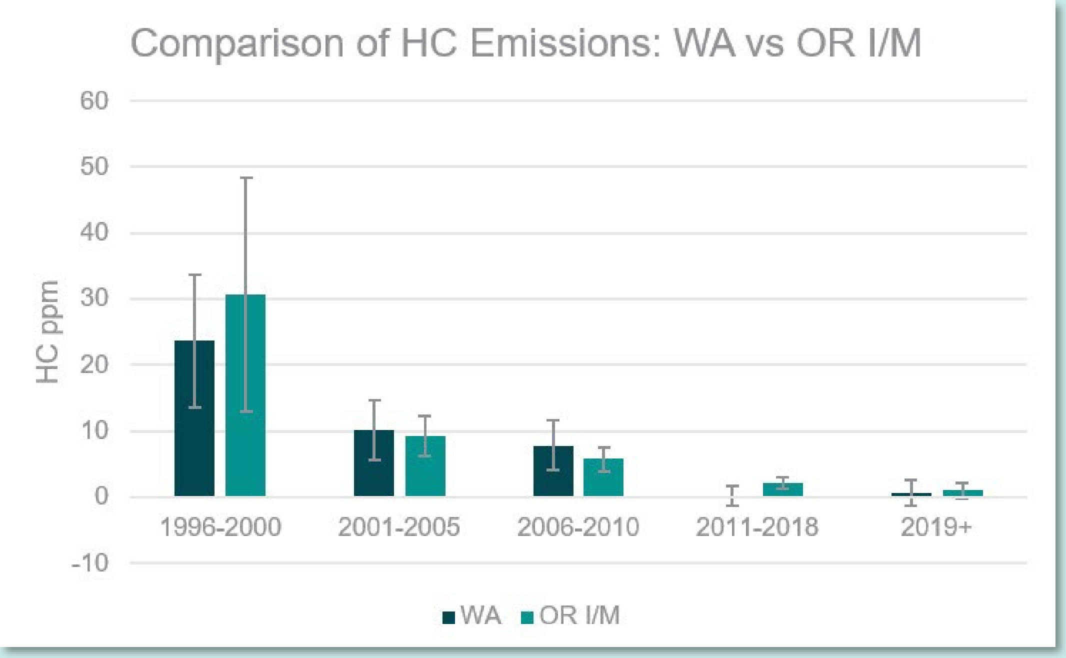
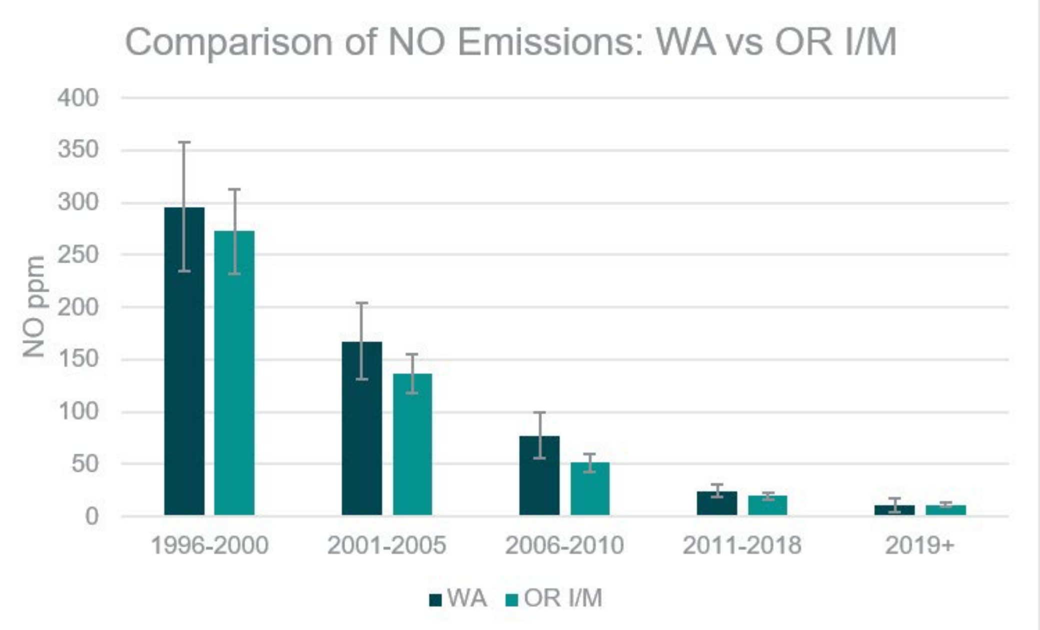
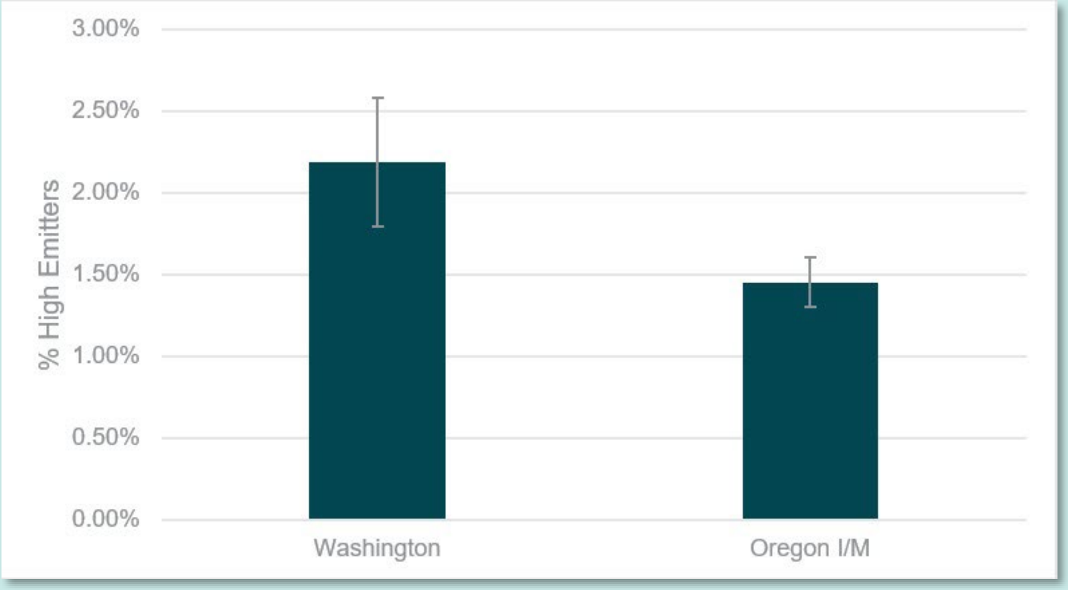


Figure 32: Comparison of NO emissions—Washington vs Oregon I/M



Gross polluter rates are compared on Figure 33. The rates for vehicles registered in Oregon's I/M program area are significantly lower than the rates for Washington vehicles.

Figure 33: Gross polluter rates—Washington vs Oregon I/M



8.5 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 34.

Emissions are highly skewed:

- Oregon's dirtiest 10% account for 77%, **58%**, and **78%** of the CO, HC, and NO emissions.
- Oregon's dirtiest 20% account for 88%, 77%, and 89% of the CO, HC, and NO emissions.
- Conversely, the cleanest 50% account for 1.2%, 0.2%, and 0.8% of the CO, HC, and NO emissions.

By directing the highest emitters to repair or retirement, vehicle I/M programs drive excess emissions into ever fewer vehicles, effectively skewing distributions. Skewness of the Oregon HC and NO distributions exceed that of Arizona where 2020 through 2021 RSD measurements found 10% of vehicles contribute 53% and 70% of NO emissions:[21]

- AZ's dirtiest 10% account for 78%, **53%**, and **70%** of the CO, HC, and NO emissions.
- AZ's dirtiest 20% account for 89%, **74%**, and **84%** of the CO, HC, and NO emissions.

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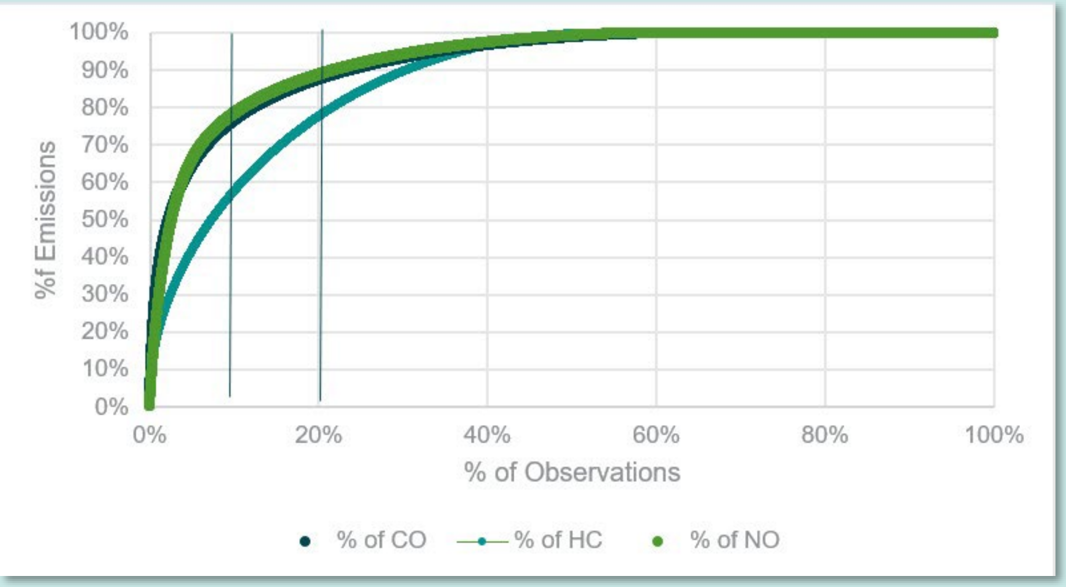
[21] The Arizona I/M program, because of its early history and continued use of centralized IM240, has long been an USEPA benchmark; Guidance on Use of Remote Sensing for Evaluation of I/M Program Performance, USEPA, EPA420-B-02-001, July 2002.

Figure 34: Distribution of CO, HC, and NO



8.6 Contribution to total emissions by model year and vehicle registration

Figure 35 shows the approximate contributions of vehicle miles traveled (VMT) and emissions from each age group. The frequency with which vehicles of different ages are seen approximates their VMT. In each model year group, the first three bars show the percent of CO, HC, and NO emissions; the last bar shows percent of VMT. All the groups up to the 2019+ group contribute significantly to total emissions. For example, the 2011 to 2018 group contributes approximately the same amounts of emissions as the older groups. The three groups of vehicle models 2005 and older contributed only 15% of VMT but accounted for 70% of on-road HC, 43% of CO, and 64% of NO.

Figure 35: Contribution to total emissions by model year

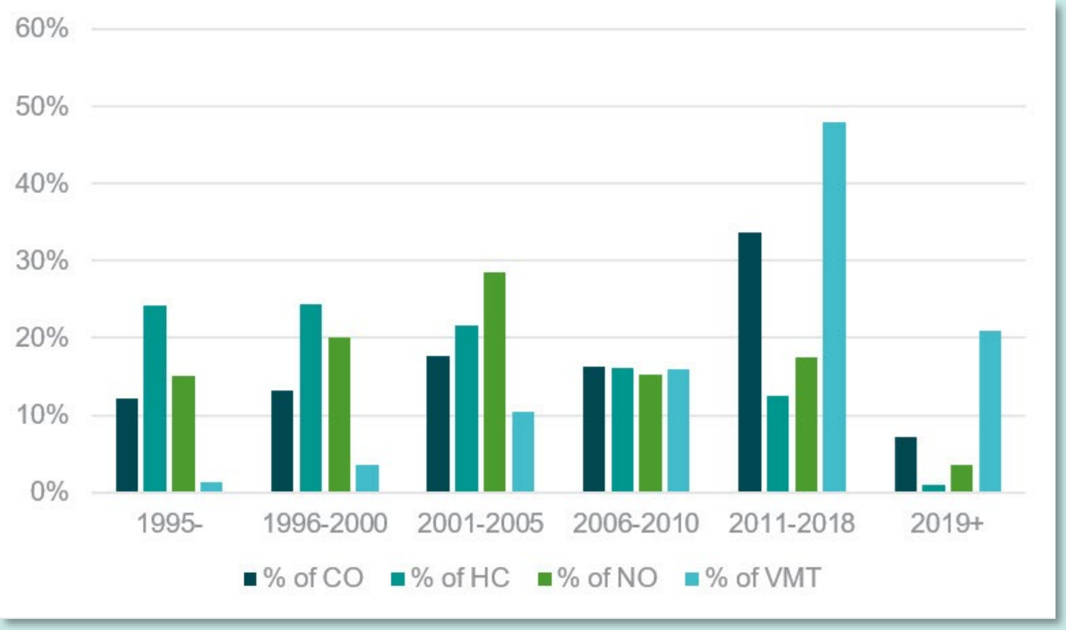


Table 10 shows total emissions in the I/M area by vehicle registration status. About half (43% to 49%) of the total emissions are from vehicles that are required to pass I/M and are testable.

Table 10: Percentage of total emissions in I/M Area by registration status

Vehicle Registration Category	% of CO	% of HC	% of NO
1. In I/M ZIP Testable	49%	43%	44%
2. In I/M ZIP Not Testable	6%	8%	12%
3. Oregon Outside I/M ZIP Testable	11%	11%	11%
4. Oregon Outside I/M ZIP Not Testable	16%	17%	17%
5. Washington	5%	6%	4%
6. California	3%	3%	2%
7. Other Out-of-state	10%	12%	9%
Total	**100%**	**100%**	**100%**

Table 11 shows total emissions from 2018 and older Oregon models in the I/M area by vehicle registration status. Out of state (OOS) and unmatched Oregon vehicles are not included in the totals.

- 67% to 77% of the total emissions from 2018 and older models are from vehicles that are required to pass I/M and are testable. This means that testable vehicles registered in Oregon's I/M area account for a majority of emissions observed in the I/M area. Therefore, Oregon's I/M program targets the predominant emission source. Note that 86% of the 2018 and older models observed in the I/M area were registered in the I/M area. Because the I/M program reduces vehicle emissions, vehicles registered in the I/M area account for less of the total emissions than their registration numbers would suggest.
- 16% to 18% of the total emissions from 2018 and older models are from testable vehicles registered outside the I/M area.

Table 11: Percentage of Total Emissions in I/M Area by Registration Status, 2018 and Older Oregon Models

Vehicle Registration Category	% of CO	% of HC	% of NO
1. In I/M ZIP Testable	77%	72%	67%
2. In I/M ZIP Not Testable	4%	9%	13%
3. OR Outside I/M ZIP Testable	17%	18%	16%

4. OR Outside I/M ZIP Not-Testable	1%	1%	3%
Total: 2018 and Older Models	**100%**	**100%**	**100%**

8.7 Emission deciles by model year group

Emission measurements by model year group were divided into ten groups or deciles each containing an equal number of ordered measurements. Figure 36, Figure 37, and Figure 38 present the resultant decile charts by model year group for the population that were in compliance with I/M requirements or were exempt from I/M requirements. The 1, 2 … 10 values correspond to the average emissions for each decile. Another way of interpreting deciles is that they represent the 5%, 15% … 95% values.

The charts demonstrate that older model vehicles can have low emissions[22]. For example, the 1996 to 2005 group has very low-emitting vehicles, similar to the newer model year groups, within their lowest six deciles. There's little difference between HC and NO emissions for the 2006 to 2010, 2011 to 2018, and 2019+ groups up to Decile 9.

Figure 39 and Figure 40 show HC and NO deciles for 1996 to 2005 model year vehicles broken down by I/M Status: I/M or No I/M. Starting at Decile 6, the no I/M group has higher emissions than the I/M group. Also, emissions from 1996 to 2005 vehicles registered in the I/M program area do not start to significantly increase until after decile 8, while emissions from vehicles registered outside the I/M area start to increase after decile 6. Note that the vehicles on Figure 39 and Figure 40 are 16 to 26 years old. Some even have collector's plates. Clearly, Oregon's I/M program significantly reduces vehicle emissions by encouraging good maintenance.

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[22] Some of readings are negative. Negative readings are a common occurrence in remote sensing when measuring vehicles emitting at near-zero levels due to the inherent variability in the analytical method. Generally, a near-zero emissions level will be measured near equally as a slightly negative and slightly positive value.

Figure 36: CO emission deciles, I/M vehicles

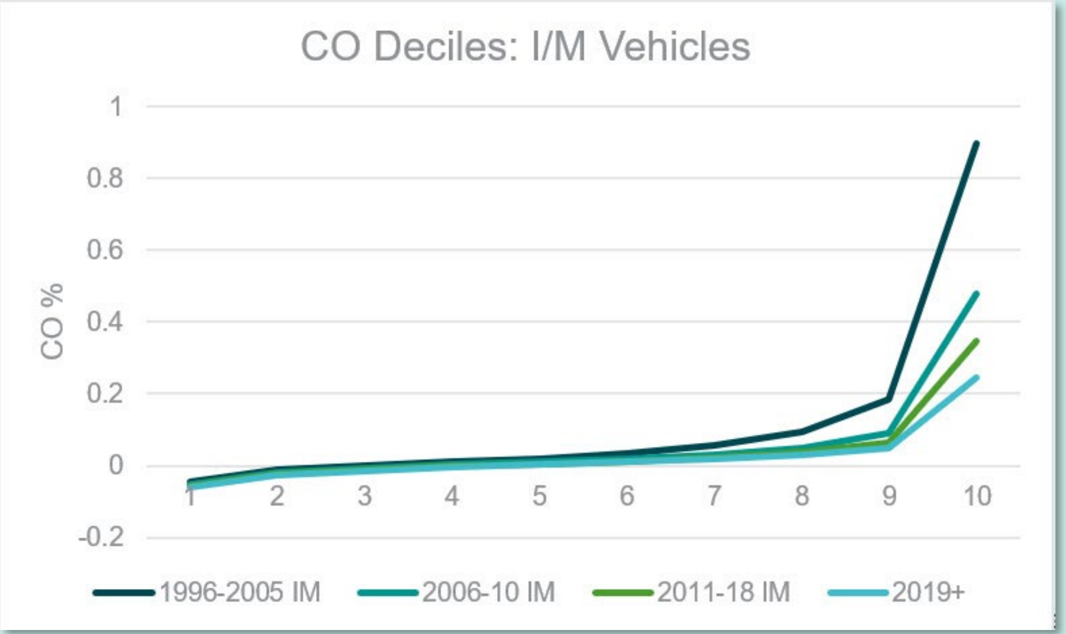


Figure 37: HC emission deciles, I/M vehicles

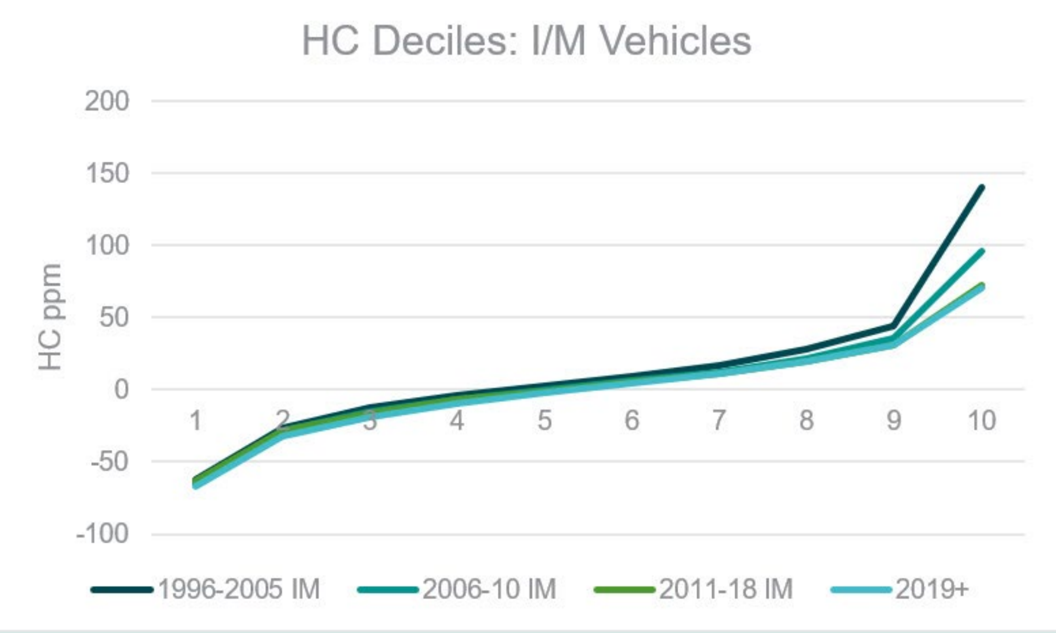


Figure 38: NO emission deciles, I/M vehicles

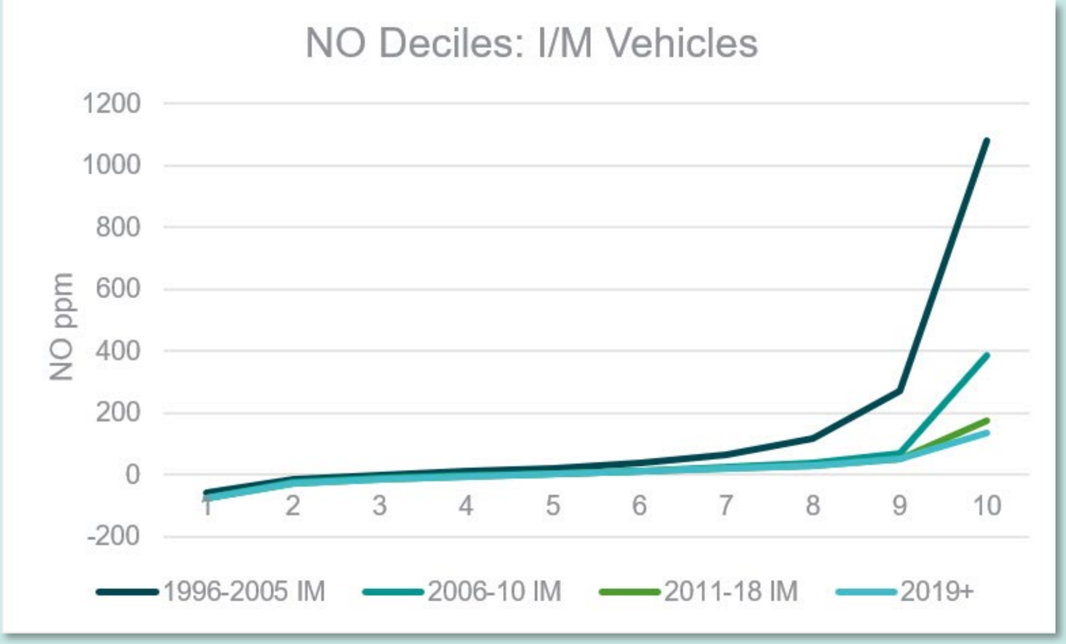


Figure 39: HC emission deciles—I/M vs No I/M—1996-2005 models

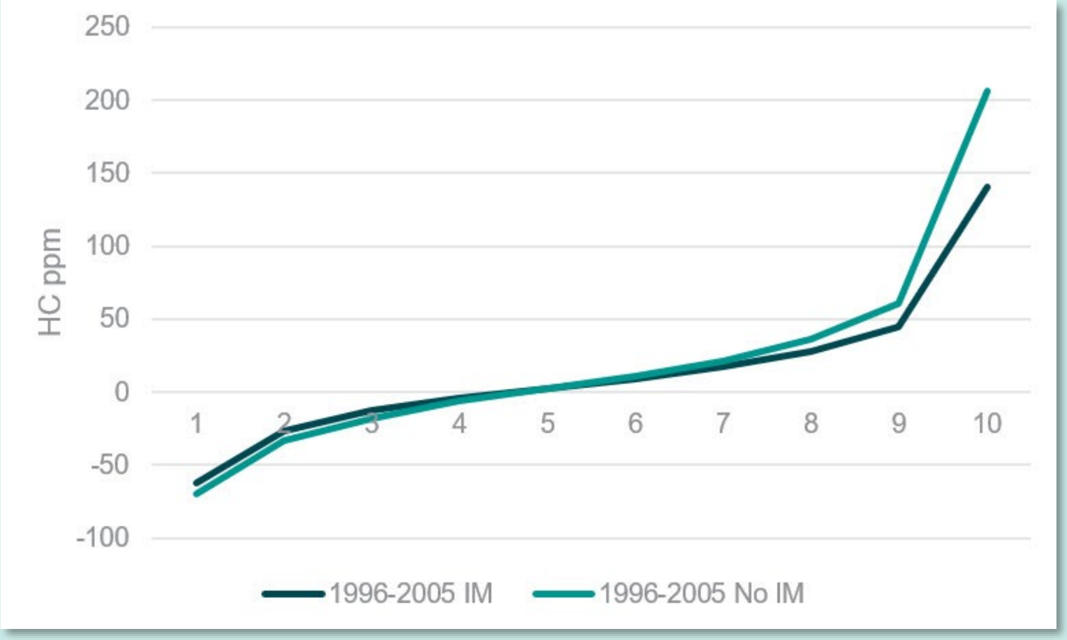
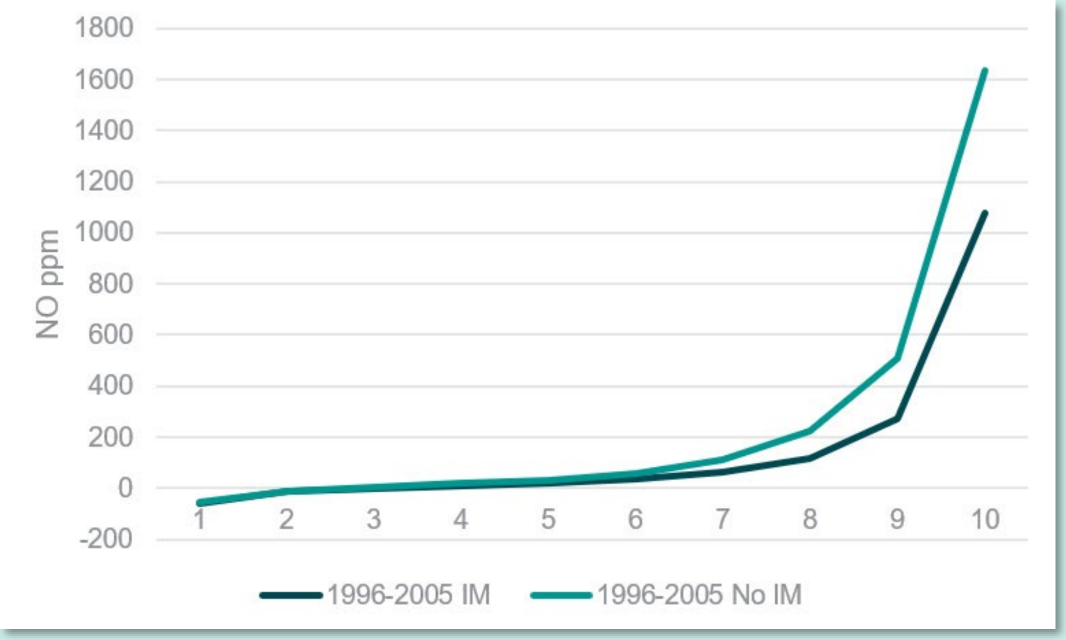


Figure 40: NO emission deciles—I/M vs No I/M—1996-2005 models



9. Conclusions

The primary goal of the Oregon remote emissions study was to compare emissions of vehicles inside and outside Oregon's I/M test area, a US EPA reference method evaluation of overall I/M program performance providing meaningful insights into vehicle emissions in Oregon. Key conclusions from our analysis are listed below:

- NO and CO emissions and to a lesser extent HC emissions of Oregon-registered vehicles were highly skewed, an effect of I/M programs. The dirtiest 10% contributed 58% and 78% of HC and NO emissions in Oregon as compared to 53% and 70% in the benchmark Arizona I/M program.[23] Oregon's cleanest 50% contribute only 0.2% and 0.8% of the HC and NO emissions.
- In aggregate, emissions from vehicles registered inside Oregon's I/M area are lower than emissions from vehicles registered outside the I/M area, and significant at the 95% confidence level for CO and NO. While small and statistically insignificant for HC overall, the impact of I/M-directed maintenance/repair is evident in the 2005 and older vehicles which contribute over 70% of all HC emissions.
  - CO emissions: 44% lower
  - HC emissions: 10% lower
  - NO emissions: 45% lower
- Based on measurements at I/M sites and adjusted for age, differences between Oregon I/M-area vehicles and no I/M-area vehicles are equal to or greater than differences observed in other centralized and decentralized I/M programs evaluated by Opus in a similar manner.

Table 12: Differences between Oregon I/M-area vehicles and others

	OR (2022)	VA (2021)	CO (2018)	AZ (2021)
CO emissions	29%	25%	8%	14%
HC emissions	30%	31%	16%	34%
NO emissions	29%	31%	22%	26%

- The differences in I/M vs no I/M emissions exceed vehicle emissions model (MOVES) estimates of 16% for CO, 7 to 8% for HC and 8 to 13% for NO. Corroborating DEQ surveys confirm the emission reductions by indicating the I/M program strongly affects Malfunction Indicator Light (MIL) response; 2.5% MIL-On rate for I/M area vehicles versus a 16.5% for no I/M.
- The percent of I/M vehicles that were gross polluters based on RSD was less than half the percent of no I/M vehicles that were gross polluters. These differences were significant at the 95% level.
  - 1.4% of the vehicles registered in the I/M area exceeded RSD thresholds of 1.5% CO, 220 ppm HC, and 1650 ppm NOx.

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[23] The Arizona I/M program, because of its early history and continued use of centralized IM240, has long been an USEPA benchmark; Guidance on Use of Remote Sensing for Evaluation of I/M Program Performance, USEPA, EPA420-B-02-001, July 2002.

  - 3.1% of the Oregon vehicles registered outside the I/M area exceeded RSD thresholds of 1.5% CO, 220 ppm HC, and 1650 ppm NOx.
- RSD results indicate that well maintained older vehicle models can have low emissions. For example, up to the 90% percentile, there's little difference between HC and NO emissions for 2006 to 2010 vehicles that are registered in the I/M area and 2019+ vehicles.
- RSD observations at I/M area sites alone allow us to estimate the contribution of outside-registered vehicles to Oregon's I/M area emissions:
  - Vehicles registered in Washington contribute 4% to 6% of the I/M area emissions (Category 5, Table 10), and 2.2% of them were gross emitters based on RSD.
  - Vehicles that are registered outside the I/M area (including Oregon and out-of-state) contribute a bit less than half (43% to 49%) of the emissions observed in the I/M area (Categories 3 through 9, Table 10). More than a quarter of the emissions in the I/M area are from Oregon vehicles registered outside the I/M area alone (Categories 3 and 4, Table 10).
  - Together, vehicles not subject to Oregon VIP observed operating inside the Oregon VIP boundaries contribute more than half (51 to 57%) of the light-duty vehicle emissions inside the Oregon VIP boundaries (Categories 2 through 7, Table 10).

10. Appendix—Repeatability of RSD measurements

dKC identified vehicles that received five or more valid RSD tests. We then plotted the average, minimum, and maximum value for each vehicle, and sorted from lowest to highest average value. These plots are shown below (Figure 41, Figure 42, and Figure 43). Generally, there is little spread between the minimum and maximum values for the clean vehicles, but high emitters have a large spread. HC emissions appear to be much more variable than CO and NO emissions.

Figure 41: CO—Multiple observations

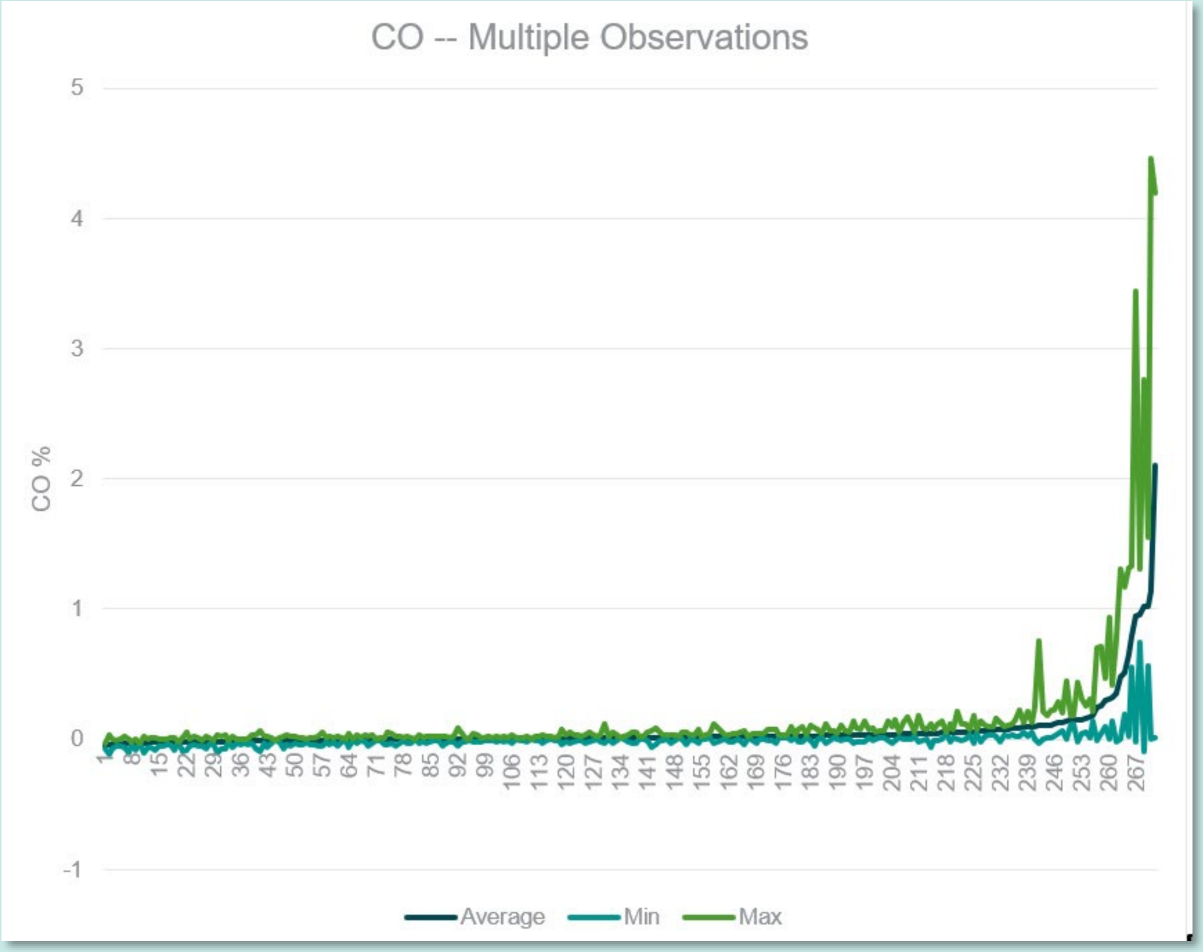

Figure 42: HC—Multiple observations

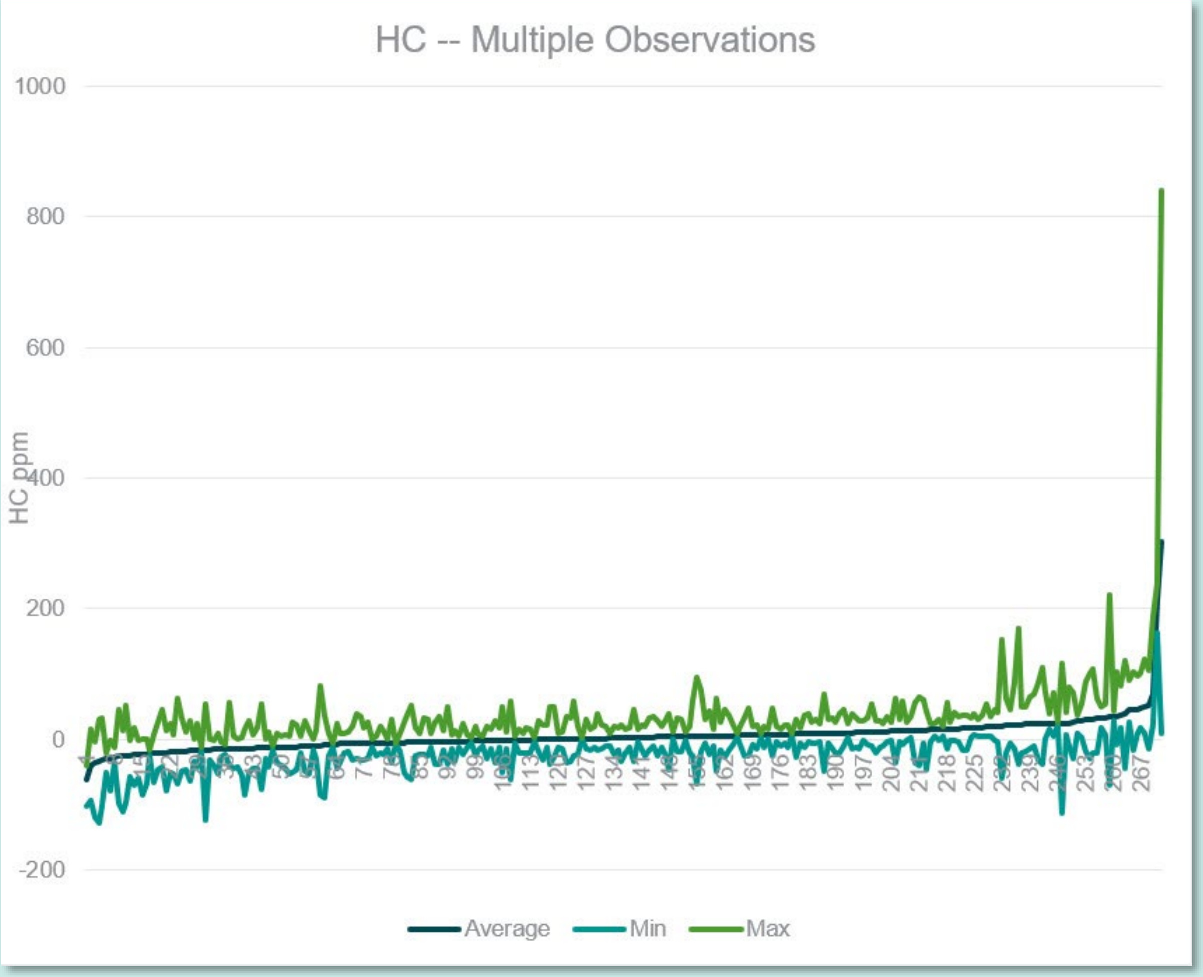

Figure 43: NO—Multiple observations