Roadside Optical Vehicle Emissions Reporter III

[A Survey of On-Road Light and Heavy-Duty Vehicle Emissions]

Prepared for:

Final Report

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Disclaimer

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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
CARB	California Air Resources Board
CASA	Clean Air Strategic Alliance
CAAQS	Canada Ambient Air Quality Standards
DPF	Diesel Particulate Filter
dKC	de la Torre Klausmeier Consulting
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
g/kg	Grams of pollutant per kilogram of fuel burned
g/km	Grams of pollutant per kilometer traveled
g/mi	Grams of pollutant per mile traveled
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbons
ICCT	International Council on Clean Transportation
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	Term specific only to vehicles registered in the I/M area that are subject to biennial inspection. The term I/M fleet would not include the heavy-duty diesel or gasoline vehicles exempted based on weight, model year, hybrids, etc.
kg/mi	Kilograms of pollutant per mile traveled
kg/km	Kilograms of pollutant per kilometer traveled

kW/t	Kilowatts per metric ton
LDV	Light Duty Vehicle
LDGV	Light Duty Gasoline Vehicle
HDV	Heavy Duty Vehicle
HDDV	Heavy Duty Diesel Vehicle
M	Mean
MDV	Medium Duty Vehicle
MIL	Malfunction Indicator Light
MOVES	Motor Vehicle Emission Simulator
MPG	Miles per gallon
nm	Nanometer
NMHC	Non-Methane Hydrocarbons
NO	Nitric oxide
NO_2	Nitrogen dioxide
NOV	Notice of Violation
NO_X	Oxides of nitrogen (NO + NO_2)
OBD	On-Board Diagnostics
OBD-II	On-Board Diagnostics-II
OCR	Optical Character Recognition
ORE	On-Road Emissions
OREMS	On-Road Emissions Measurement System
ORHE	On-Road High Emitter
ORLL	On-Road Liquid Leaker
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
PPP	Passing readiness, passing MIL, no catalyst DTCs
ROVER	Roadside Optical Vehicle Emissions Reporter
RSD	Remote Sensing Device
S/A	Speed/Acceleration
SCR	Selective Catalytic Reduction
SCU	System Control Unit
SDM	Source/Detector Module
SFU	Simon Fraser University
TSI	Two-Speed Idle
US	United States

UV	Ultraviolet
VDEQ	Virginia Department of Environmental Quality
VIP	Vehicle Inspection Program
VIN	Vehicle Identification Number
VIR	Vehicle Inspection Report
VIS	Vehicle Inspection Station
VMT	Vehicles Miles Traveled
VSP	Vehicle Specific Power

1. Executive Summary

Roadside Optical Vehicle Emissions Reporter (ROVER) III emerged as an outcome of a 2015 to 2017 CASA project that examined non-point sources for emissions reduction opportunities from the transportation sector.[1,2] Based on the 2014 Air Pollutant Emissions Inventory, the on-road transportation sector was projected to be:

- A large source of nitrogen oxides[3] (NO_x, particularly from heavy-duty diesel vehicles, followed by light duty gasoline trucks);
- A source of hydrocarbons (HC, particularly from light-duty gasoline trucks); and
- A source of particulate matter ($PM_{2.5}$, particularly from heavy-duty diesel vehicles).

Remote sensing device (RSD) surveys of light duty vehicle (LDV) emissions worldwide have consistently found on-road distributions to be *skewed*, meaning a disproportionately small percentage of (malfunctioning or broken and often older) vehicles are responsible for most fleet emissions, and that distributions grow more skewed over time with the adoption of modern, cleaner vehicles that stay cleaner longer. ROVER I and II observed this effect of *natural fleet turnover* when ROVER I (1998) found 7% of LDVs contributed 54% of carbon monoxide (CO) emissions and ROVER II (2006) found 5% contributed 60% of CO.[4]

Vehicle emissions inspection programs, like the Oregon vehicle inspection program (VIP), direct vehicles with noncompliant emissions above their in-use limits to undergo practical, cost-effective emission-lowering maintenance and repair to return emissions to compliant levels. When repairs are impractical or cost-prohibitive the outcome is often retirement, sale, or export of the dirty vehicle out of the testing area and replacement with a cleaner vehicle (*enforced fleet turnover*). The net effect of timely and proper maintenance is fewer high emitters (which refer to vehicles with emissions multiple times the in-use limits of vehicle emission inspection programs) and accelerated turnover to cleaner models, all of which further *skews* fleet emissions distribution.

Light-Duty Vehicles

ROVER III (2020 to 2022)—which characterized emissions of the predominantly gasoline-powered (>95%) LDV fleet in Calgary, Red Deer, Edmonton, Grande Prairie, and Fort McMurray—did not find CO had further skewed as observed elsewhere in modern inspected vehicle fleets, but did find HC had skewed significantly since ROVER II, and to a lesser extent NO. In comparison to Oregon vehicles measured with similar RSD technology in 2022,

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[1] ROVER III Project, Background; https://www.casahome.org/current-initiatives/roadside-optical-vehicle-emissions-reporter-iii-project-team-53/

[2] Recommendations to Reduce Non-Point Source Air Emissions in Alberta; Clean Air Strategic Alliance, 2018; Report - https://drive.google.com/file/d/1M5Aq9AZA_QO0vEVFO44sR77vz8mo6EsX/view?pli=1

[3] Nitrogen oxides (NO_x) are mixture of gases that are comprised of nitrogen and oxygen. The two most prevalent in motor vehicle exhaust are nitric oxide (NO) and nitrogen dioxide (NO_2). Gasoline internal combustion emits very little NO_x as NO_2 (Carslaw, p.7), hence NO_2 from LDGVs was not measured and NO alone is reported. In contrast, diesels can emit 10-50% of their NOx and NO_2 depending on operating mode and engine load, so both NO and NO_2 were measured from HDVs and reported as a combined NOx.

[4] ROVER I only measured carbon monoxide (CO). ROVER II measured CO, HC, and NO. ROVER III measured CO, HC, NO and NO_2 (the latter from heavy duty vehicles only, which are largely diesel-powered).

Alberta's model year 2003 and newer LDGVs, which represent 97% of all light duty vehicle kilometers travelled (VKT), had significantly higher emissions than both Oregon's OBD-inspected and uninspected 2003 and newer vehicles, particularly for HC and to a lesser extent NO. Alberta model year 2003 and newer vehicles also had a much larger percentage of overall high emitters than Oregon's. In fact, more than half (55%) of 2003 and newer on-road HC measurements exceeded the federal standards for new and imported vehicles and engines in Canada, used herein as a benchmark only,[5] while more than a third of NO (37%) and much less than a quarter of CO (17%) measurements exceeded these emission benchmarks.

By using remote sensing model year observation rates to approximate model year VKT and applying their measured grams/km emissions rates, ROVER III estimated that 2013 and newer vehicles—which are within the Tier 2 useful life of 10-years[6] and are expected to meet standards—harboured more than half of all the LDGV HC emissions in excess of the emission benchmark (*excess emissions*). Collectively, the three findings; 1) that Alberta LDGV HC and NO emissions are significantly higher than Oregon inspected and uninspected LDGVs, 2) have a significantly larger fraction of high emitters, and 3) vehicles less than 10-years old harbour significant excess HC and NO emissions, are indicators of emissions control system deterioration and/or malfunctions, and lack of timely maintenance and/or *check engine light* response.

A breakdown by city found HC and NO grams/km emissions rates of vehicles measured at Calgary sites to be significantly higher than Edmonton sites and a breakdown by vehicle type confirmed the CASA non-point source report's identification of light-duty gasoline trucks (particularly pickups) as a large contributor of HC and NO emissions and a non-point source opportunity for HC and NO reductions. ROVER III emissions rates multiplied by better VKT figures by vehicle type would provide a more accurate apportionment of on-road LDV emissions and confirm ROVER III findings that light duty gasoline vehicles (particularly pickup trucks) are an important source of HC emissions and NO emissions.

A public awareness campaign promoting timely response to OBD *check engine lights*, particularly for 2013 and newer vehicles that may still be under warranty, in conjunction with an advisory RSD high emitter screening program for all LDGVs, could be effective in reducing emissions from the highest emitters, particularly for HC since emissions are so skewed.[7]

Heavy-Duty Vehicles

ROVER III (2022) also characterized heavy duty vehicle (HDV) emissions of the predominantly diesel-powered fleet at six vehicle inspection stations (VIP) across Alberta—Coutts, Airdrie, Leduc, Whitecourt, Atmore, and Demmitt. In comparison to LDGVs distributions, distributions of the primary heavy duty diesel vehicle (HDDV) emissions of concern, particulate matter (PM) and nitrogen oxides (NO_x, $NO + NO_2$), were far less skewed and even larger fractions of the HDDV

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[5] Refer to section 7.1.2 for a discussion on how to interpret comparisons of *Real-world RSD measurements to laboratory certification-test measurements*.

[6] Canada Vehicle Regulations: https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/amendments-vehicle-engine-emission-regulations-questions.html

[7] Rapid Detection of High-Emitting Vehicles by On-road Remote Sensing Technology Improves Air Quality; Science Advances; Huang et. al., 2 Feb 2022: Rapid detection of high-emitting vehicles by on-road remote sensing technology improves urban air quality | Science Advances

fleet emitted in excess of NO_x (62%) and PM (72%) emission benchmarks.[8,9] Excess emissions on-road are certainly not uncommon, but have remained an issue for HDDVs ever since the late 1990s HDDV defeat device scandal led to the largest ever fine for US Clean Air Act violations.[10] Much like the mid-2010s light duty diesel vehicle scandal, existence of on-road emissions far in excess of certification levels (such as 10 or more times) were confirmed to have been detected in RSD surveys.[11,12,13] More recently, high excess emissions were confirmed in pullover roadside inspections to be malfunctions or tampering of advanced HDDV emissions control systems, like Selective Catalytical Reduction (SCR) and Diesel Particulate Filters (DPF).[14,15]

Most of the Alberta-registered HDDVs measured in ROVER III (83%) were 2010 and newer models, expected to have the latest emissions control systems. ROVER III found that these Alberta HDDVs not only emitted NO_x (in particular) and PM[8] (to a lesser extent) at levels significantly above their emission benchmarks,[9]but also significantly above comparable California-registered HDDVs measured a year earlier with similar RSD technology and under similar operating conditions. About 30% of the Alberta HDV NOx measurements appear to be at least 10 times the NOx emission benchmark (Figure 56).

The California Air Resources Board (CARB) has made a major investment using public funds to both modernize and retrofit HDVs to reduce their emissions. CARB's existing heavy-duty inspection programs also rely on random field inspections by CARB staff members and annual self-inspections by truck owners to test for smoke opacity levels. Because those programs do not ensure that vehicle owners are regularly inspecting and repairing their vehicles' broken emissions controls, under Senate Bill 210(3), starting in 2024 HDVs will be subject to the country's first of its kind periodic OBD inspection program with on-road enforcement using RSDs and CARB's plume capture systems.[16]

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[8] Opus devices measure a more useful ultraviolet smoke opacity than the green light smoke opacity of traditional opacimeters. Opus uV smoke was converted, with assumptions about diesel particulate distribution, to the units of federal certification standards. Refer to Section 4 for an explanation of Opus uV smoke measurement and Section 7.2.2 for its conversion to comparable units.

[9] Refer to *Real-world RSD measurements versus laboratory certification-test measurements; Sec. 7.1.2*

[10] US Environmental Protection Agency; https://www.epa.gov/archive/epapages/newsroom_archive/newsreleases/93e9e651adeed6b7852566a60069ad2e.html

[11] Technologies for the Convenient Monitoring and Enforcement of Heavy-Duty Vehicle Exhaust Emissions; Niranjan Vescio; I/M Solution Training Forum, May 8, 2013

[12] In-Use Compliance Surveillance Using Remote Sensing Technology; Niranjan Vescio; I/M Solutions Training Forum, May 3, 2016

[13] Did One Company Spot Volkswagen's Diesel Deception Six Years before Anyone Else?; David Plank, Jalopnik, October 19, 2015: https://jalopnik.com/did-one-company-spot-volkswagens-diesel-deception-six-y-1737309474

[14] Measurements of Cheating with SCR Catalyts on Heavy Duty Vehicles, Ministry of Environment and Food of Denmark, Environment Project NO. 2021, June 2018: Rapport (mst.dk)

[15] Opus HDDV Screening: https://www.opus.global/vehicle-inspection/remote-sensing/remote-sensing-applications/hddv-screening/

[16] California ODB HDVIP; Workgroup Discussions Paper: Heavy-Duty Vehicle Inspection and Maintenance; 2019: https://ww2.arb.ca.gov/sites/default/files/classic//msprog/hdim/meetings/20190716_hdim_workgroup_discussion_paper.pdf

Multiple RSD measurements are used to lower uncertainty and increase confidence for on-road screening enforcement of high emitting vehicles.[17] ROVER III examined 2010 and newer HDDVs that received four or more RSD tests during the study for a more robust estimate of the percentage that were consistently emitting at high levels. Most of those measured four or more times had low average NO_x emissions, indicating the SCR systems were working correctly. However, about 30% are suspected of having malfunctioning or tampered control systems because their NO_x was higher on average and even achieved very high levels at the low engine load operating conditions at vehicle inspection stations. Trends in PM were not as clear in these repeat measurements.

ROVER III also examined emissions by vehicle inspection station and truck type. The lowest average NO_x emissions were observed at the Atmore site, the highest at Demmitt, but their vehicle numbers were by far the lowest of the six VIS. Average NO_x was significantly lower at the Coutts and Leduc stations than at the Airdrie and Whitecourt stations. Average model year for observations at the Coutts and Leduc stations was slightly higher (younger fleet) than average model year at the Airdrie and Whitecourt stations, which could explain some of the differences. Truck type also varied by location. Coutts had the youngest average fleet and the highest percentage of tractor trailers (97%), which were much lower emitting than dump trucks (see Figure 6), the latter numbering the highest (24%) at Airdrie which also had the oldest average fleet.

In summary, ROVER III found HDDVs broadly emitting NO_x and PM[8] at levels well above emission benchmarks[9] and comparable periodically inspected California HDDVs. High excess NOx emissions among 2010 and newer HDDVs, further supported by repeat high observations, indicates 30% of these modern HDDVs could be malfunctioning or tampered. ROVER III characterized HDVs at vehicle inspection stations when staffed and operating rather than on-road; therefore, observation rates may not accurately reflect their relative kilometers traveled. The use of better VKT estimates for the comparatively high-emitting dump trucks within the Calgary (Airdrie) to Edmonton (Leduc) corridor would confirm their suspected large NOx and PM contribution to the three southern Alberta air zones.[18]

The absence of emissions inspections and prohibitions on tampering in Alberta[19] may be contributing to a large amount of excess NO_x and PM HDDV emissions. The deterrent and enforcement effect of inspection programs in California may be partly contributing to their much lower HDDV emissions, as was reported for the earlier Vancouver ACOR inspection program (Appendix G). Short of the required enabling periodic inspection legislation, RSD screening at vehicle inspection stations can identify the highest emitters for advisory notice of suspected malfunctions and/or tampering during the secondary inspections conducted at those stations.

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[17] MBTA Bus Fleet Emissions Screening Using Remote Sensing Technology; https://trid.trb.org/view/757580

[18] CAAQS, Alberta air zone reports and regional actions plans; Canadian Ambient Air Quality Standards | Alberta.ca

[19] Heavy-Duty Emissions Control Tampering in Canada; International Center for Clean Transportation; March 2022; Heavy-duty emissions control tampering in Canada (theicct.org)

2. Introduction

The Clean Air Strategic Alliance (CASA) contracted Opus Inspection Inc. (Opus) under Agreement No. 01-2019 to use remote sensing device (RSD) technology to measure real-world emissions from in-use heavy-duty vehicles (HDV) and light-duty vehicles (LDV) across Alberta. The goal of the ROVER III project is to characterize in-use on-road emissions from the transportation sector (particularly diesel vehicles), compare vehicle classes across Alberta, and inform CASA of actions for transportation emissions management to help achieve the Canadian Ambient Air Quality Standards (CAAQS) in Alberta.[20]

CASA was established in Alberta in 1994 to help manage air quality. CASA is a multi-stakeholder partnership composed of representatives selected by industry, government, and non-government organizations.

The Opus team and CASA began project planning in 2019 and met with stakeholders from the five target cities of Fort McMurray, Grande Prairie, Edmonton, Red Deer, and Calgary to select on-road sites where both LDVs and HDVs could be tested. The planned spring 2020 deployment had to be postponed due to the pandemic. In its place, Opus team members conducted a brief four-day demonstration in October 2020 of Opus unattended light duty vehicle RSD technology in Edmonton, collecting a few thousand real-world LDV measurements over three days at available on-road sites and repeatedly measuring select vehicles during a one-day experiment at an on-campus site at the University of Alberta.

The demonstration served to introduce CASA and its academic partners to RSD technology and was instrumental in the decision to identify alternate sites where larger volumes of HDVs could be exclusively sampled. As a result, six HDV vehicle inspection stations were identified in 2021 for the HDV characterization in 2022.

Opus staff members led by Niranjan Vescio and Jimmy Guckian collected LDV emissions data in 2020-2022[21] and HDV emissions data in summer 2022 using respectively configured RSD technology. RSDs were deployed at street level to capture LDV exhaust emissions as well as the exhaust of HDVs with low exhaust pipes. Towers were used to elevate the *emissions analyser* to capture exhaust emissions from HDVs with high exhaust pipes.

This report presents results of RSD tests on both LDVs (passenger cars and light-duty trucks) and HDVs (tractor trailers and delivery/dump trucks). Using our fifth generation RSDs, Opus team members made:

- 49,747 valid emissions measurements on light-duty vehicles; 41,724 of which were matched with Service Alberta vehicle information via licence plates.
- 6,338 valid measurements on heavy-duty vehicles; 2,928 of which were matched with Service Alberta vehicle information via licence plates. Delivery and dump truck license plates could not be captured and matched to the Service Alberta registry but were identified as *delivery and dump* for general analysis purposes.

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[20] ROVER III Project, CASA; https://www.casahome.org/current-initiatives/roadside-optical-vehicle-emissions-reporter-iii-project-team-53/

[21] Most LDV data was collected in summer 2021; 5.1% in October 2020 in Edmonton and 10.6% in July 2022 in Ft. McMurray.

3. RSD Test Sites

Opus team members selected nine (9) roadside LDV sites in the five Alberta cities of Fort McMurray, Grande Prairie, Edmonton, Red Deer, and Calgary to conduct the 2020-2022 LDV testing. LDV sites were single-lane sections of highway on-ramps or highway connectors where an exhaust emissions measurement of each passing vehicle could be attempted under some acceleration.

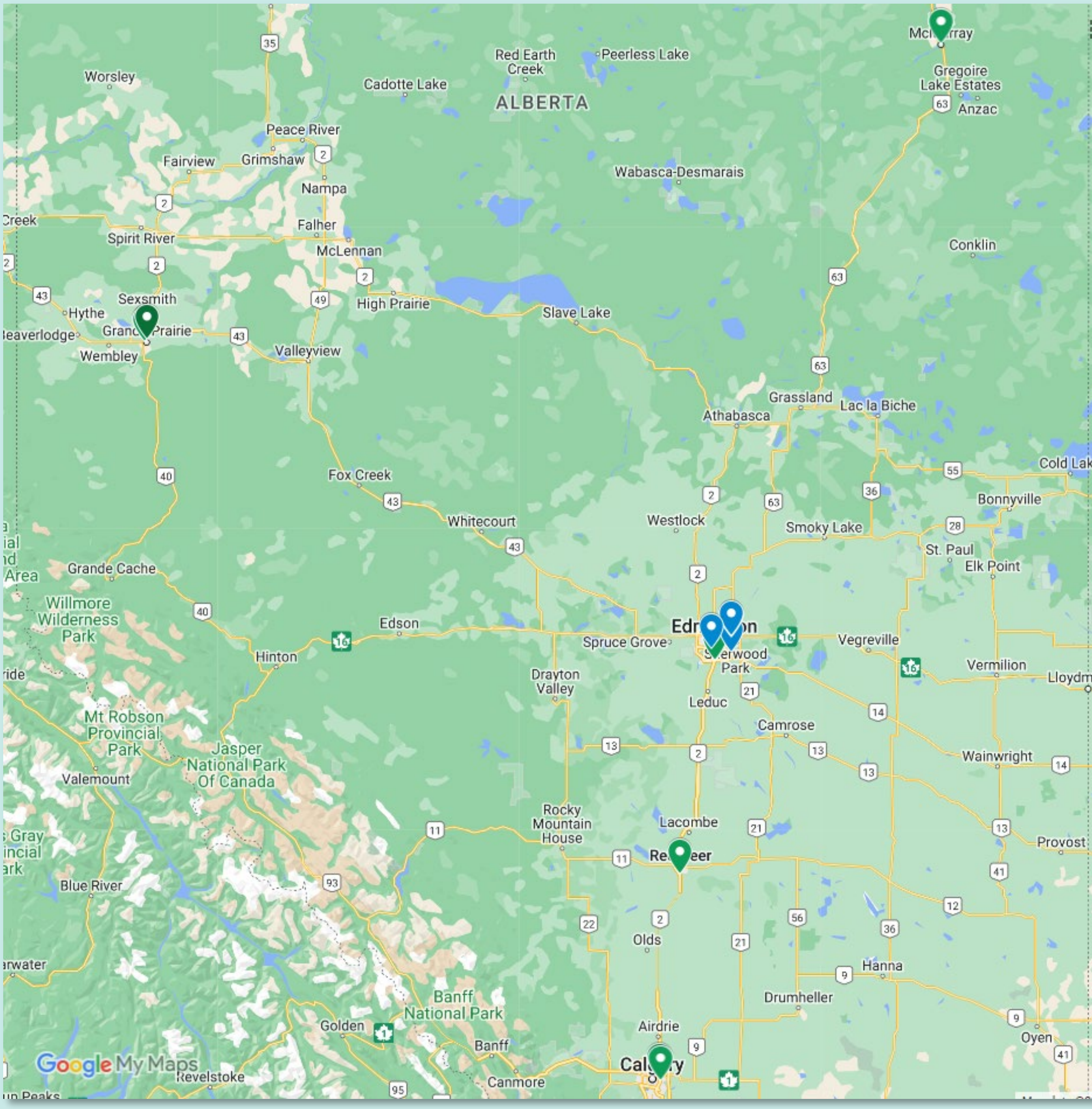
Subsequent to the 2020 pilot, six vehicle inspection stations (VIS) were selected by CASA to conduct the 2022 HDV testing. HDV sites were on the VIS inspection lane, just after weight-in-motion measurement as vehicles accelerated to merge onto the highway. A few vehicles that used a by-pass lane at some VISs were not measured and not counted.

Table 1 lists all testing sites and includes hyperlinks to their location in Google Maps. On the following pages, Figure 1 provides a map of light-duty testing site locations and Figure 2 shows a map of heavy-duty testing sites.

Table 1: Vehicle emissions testing sites used in the Alberta project					
Light duty vehicle sites (city on-road locations)					
Site #	***Start***	***End***	***City***	***Description***	***Coordinates/Google Map Link***
FM1	8/23/2021	8/23/2021	Ft. McMurray	AB-63 Frontage Road Southbound (SB)	56°43'38.6"N 111°23'17.0"W
FM2	7/10/2022	7/11/2022	Ft. McMurray	Entrance Ramp from Base Plant Rd to AB-63 Northbound (NB)	56°58'19.7"N 111°29'12.3"W
ED1	8/25/2021	8/26/2021	Edmonton	NB 2 to Anthony Henday (216) WB	53°26'09.3"N 113°30'14.7"W
ED2		8/26/2021	Edmonton	EB Anthony Henday (216) to NB 2	53°26'07.6"N 113°29'17.3"W
ED6	10/05/2020	10/05/2020	Edmonton	Interchange Ramp from AB-216 SB to Whitemud Drive EB	53°28'56.6"N 113°20'41.3"W
ED8	10/06/2020	10/06/2020	Edmonton	Anthony Henday NB to Yellowhead Hwy WB	53°33'59.0"N 113°20'34.8"W
ED9	10/08/2020	10/08/2020	Edmonton	WB Yellowhead Hwy to NB Anthony Henday Dr.	53°34'16.0"N 113°20'35.2"W
AU1	10/07/2020	10/07/2020	Edmonton	University of Alberta Study Site	53°30'07.9"N 113°32'07.8"W
GP1	8/28/2021	8/28/2021	Grande Prairie	108 Street SB Turning Lane to 100 Avenue WB	55°10'14.9"N 118°49'17.9"W
GP1	8/28/2021	8/28/2021	Grande Prairie	100 Avenue EB Turning Lane to 108 Street SB	55°10'12.9"N 118°49'14.4"W
RD1	8/30/2021	8/30/2021	Red Deer	ON-RAMP FROM Taylor/19 ST. to NB2 (QEII)	52°14'05.9"N 113°49'24.8"W
CG1	8/31/2021	8/31/2021	Calgary	Memorial Dr. East to Deerfoot Trail South	51°02'50.8"N 114°01'04.9"W
CG2	9/1/2021	9/1/2021	Calgary	Deerfoot Trail South to 17 Avenue West	51°02'17.1"N 114°00'13.3"W

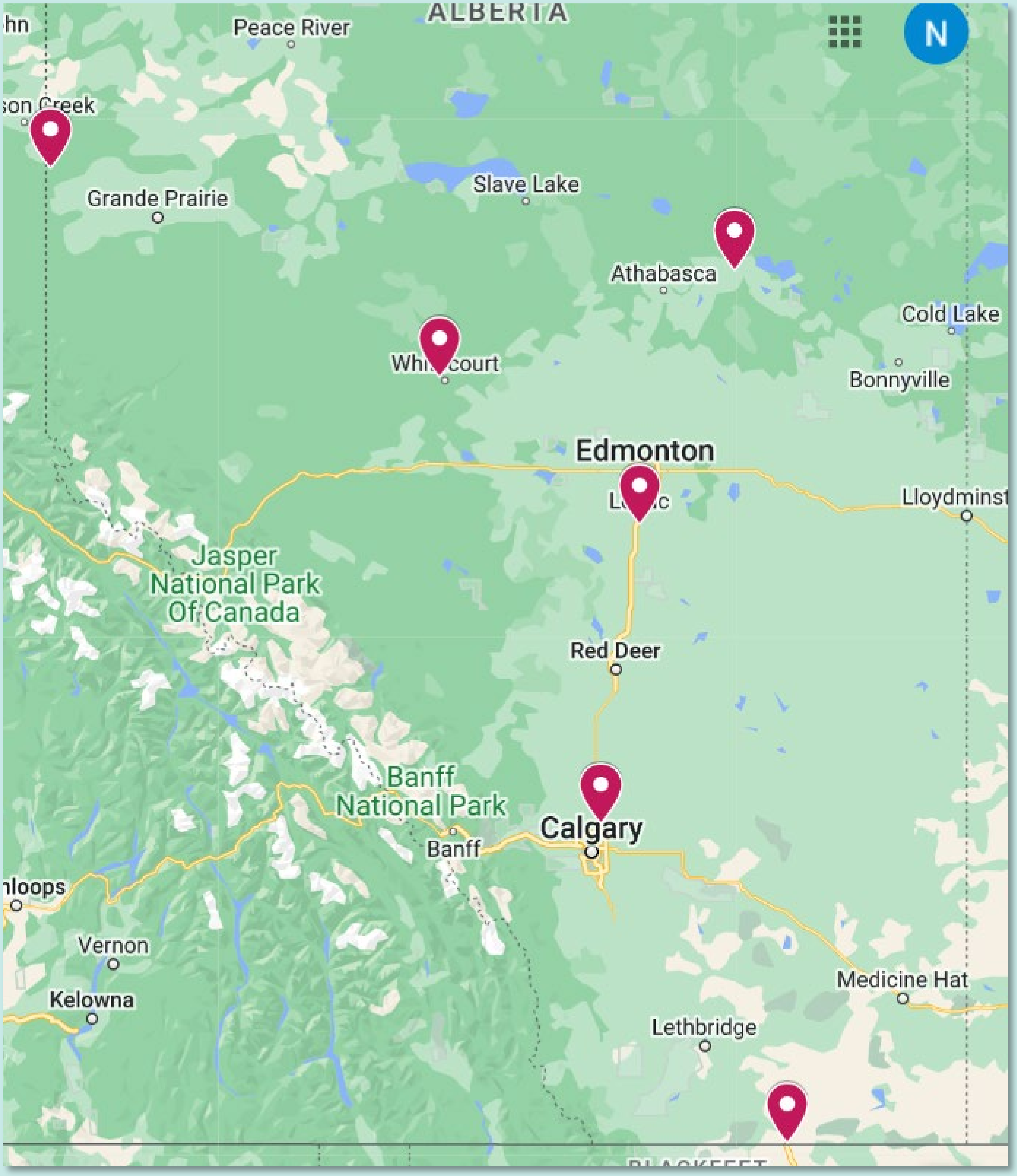
Heavy duty vehicle sites (highway vehicle inspection stations after weigh-in-motion scales)					
Site #	***Start***	***End***	***City***	***Description***	***Google Map Link***
WHTCRT	6/27/2022	6/30/2022	Whitecourt	Route 43 Northbound	https://goo.gl/maps/mSBmZQnRb3xq6XyC7
LEDC	7/3/2022	7/8/2022	Leduc	Highway 2; Southbound	https://goo.gl/maps/ab5BequZKzb4uBNKA
ATM	7/12/2022	7/14/2022	Atmore	Route 43 Northbound	https://goo.gl/maps/HQ7nTYXv5P7Z4DdZ8
DEM	7/16/2022	7/18/2022	Demmitt	Route 43	https://goo.gl/maps/sEc9QwET8LDJV8Lw5
AIRDRIE	8/5/2022	8/10/2022	Airdrie	Highway 2; Northbound	https://goo.gl/maps/etHXo8u3XEpP2tBi6
CTS	8/12/2022	8/16/2022	Coutts	Highway 4; Southbound	https://goo.gl/maps/C7ZY9t9t21Q42JC59

Figure 1: Map of LDV sites



[Alberta LDV Site Map - Google My Maps](#) Hyperlink Blue = Demo Sites; Green = Test Sites

Figure 2: Map of HDV sites—Vehicle inspection stations (VIS)



[Alberta VIS Site Map - Google My Maps]() Hyperlink

4. Opus RSD Technology

Opus technicians deployed our fifth-generation remote sensing devices (RSD) in Alberta. 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.[22] Today's model RSD5000 systems are capable of measuring NO_2 in addition to standard CO, HC, NO, PM (uV Smoke), and evaporative emissions. Systems with enhanced capability are built on the RSD5000+ platform and are designated as RSD5300s. All 5000 instruments consist 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 3).

Two unattended RSD5000s were deployed separately to collect low-exhaust LDV emissions measurements in ROVER III between 2020-2022 and two attended 5300s (one at road level and one on towers) were used together to collect HDV emissions measurements (Figure 4) during summer 2022.

Nitrogen oxides (NO_x) are mixture of gases that are comprised of nitrogen and oxygen. The two most prevalent in motor vehicle exhaust are nitric oxide (NO) and nitrogen dioxide (NO_2). Gasoline vehicles emit a consistently very low, and often undetectable amount of their NO_x in the form of NO_2, therefore ROVER III measured the CO, HC, and NO emissions from light duty vehicles (which were 95% gasoline) and the CO, HC, NO and NO_2 emissions from heavy duty vehicles (which were 97% diesel).[23] **NO alone is reported for LDVs and NO_x (NO + NO_2) for HDVs**.

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

[23] "Remote Sensing of NO_2 exhaust emissions from road vehicles", a report to the City of London Corporation and London Borough of Ealing; Davi Carslaw, King's College, Glyn Rhys-Tyler, Newcastle University, July 2013; https://uk-air.defra.gov.uk/assets/documents/reports/cat05/1307161149_130715_DefraRemoteSensingReport_Final.pdf

Figure 3: Unattended RSD5000s on-road deployment to measure LDVs

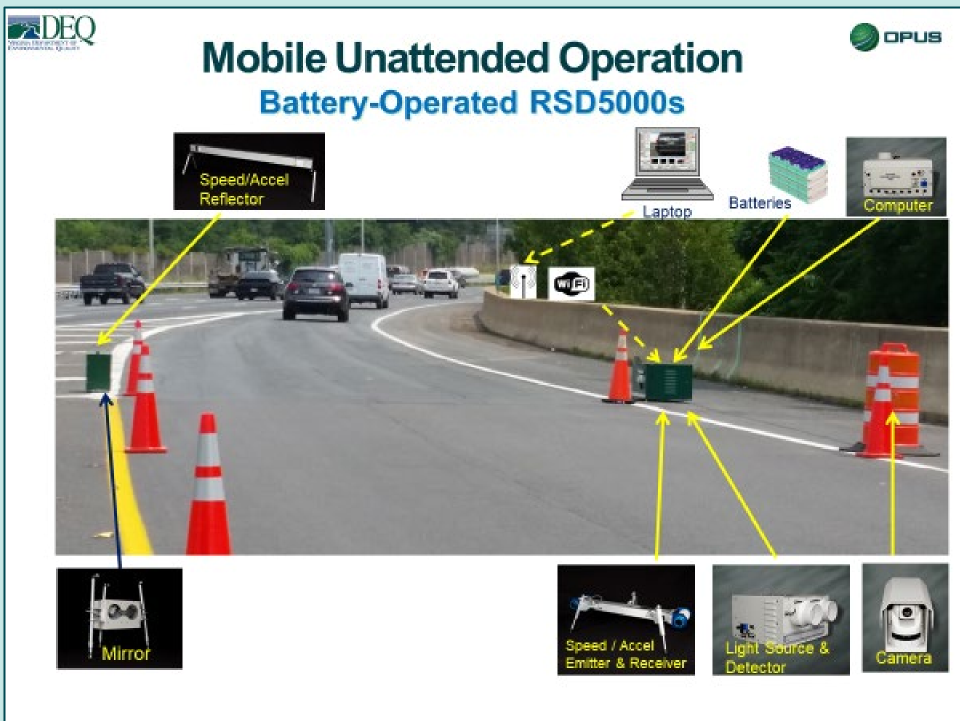
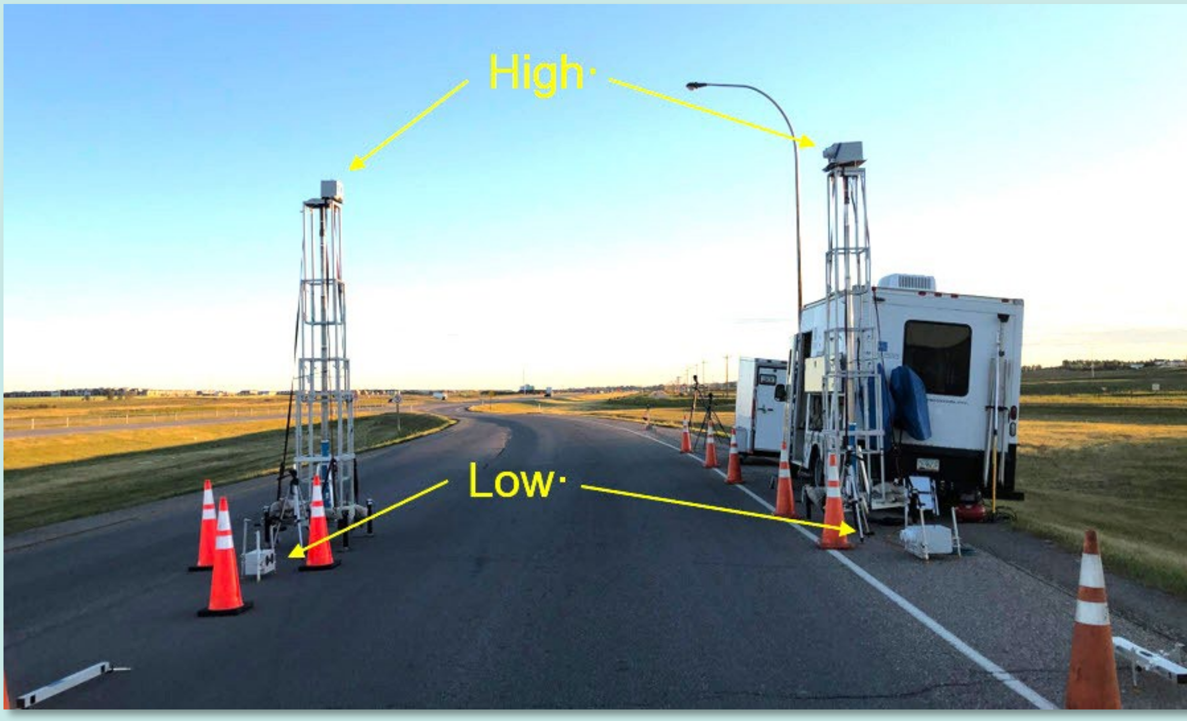


Figure 4: Two attended RSD53000s deployed at different heights to measure HDVs



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 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 carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (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 fibre bundle that is mounted to a coaxial connector on the side of the detector unit. The quartz fibre bundle carries the UV signal to an Ocean Optics spectrometer for measurement of NO, NO_2 and uV Smoke-opacity. The spectrometer measures NO's ultraviolet absorbance at its distinct 227nm peak and NO_2's absorbance at many peaks around 470nm. The Opus uV Smoke 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 that contains most of the particle mass emitted by modern diesels.[24] The uV Smoke is ratioed to the sum of CO,

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[24] "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

CO_2, and HC (which represents fuel consumed) and can be multiplied by an appropriate light extinction factor (such as for black carbon/soot) to estimate grams per kilogram of fuel consumed.[25]

> *The reader is cautioned not to interpret uV Smoke results in this report as directly representing Particulate Matter (PM) mass. The Opus uV Smoke measurement is an optical measurement of 249nm ultraviolet light extinction, similar to the ~550nm green light extinction measurement of traditional opacimeters but enhanced by relating it to the amount of fuel burned. $PM_{2.5}$ and PM_{10} are gravimetric measurements captured by extracting exhaust onto filters or other media that are then weighed to determine particulate mass. For diesel emissions (by assuming a black carbon particle distribution) the Opus uV Smoke measurements can be converted to grams particulate per kilogram of fuel. Individually, Opus uV Smoke measurements are best used to screen and identify individual vehicles as low or high emitters[26] and collectively for fleets, for comparative qualitative trends analysis rather than as absolute measures of PM mass.*

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 bar-mounted 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.

The low RSD at VIS stations used the bar-mounted emitters to measure speed and acceleration. A radar system was placed ten metres upstream of the high RSD to measure speed and acceleration as the HDV crossed through the towers. Table 2 summarizes the information that was collected.

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

[26] Comparison of Remote Sensing Devices (RSD) with Gravimetric Measurements of Light-Duty Gasoline PM Emissions; Tao Huai, California Air Resources Board, 17th CRC On-Road Vehicle Emissions Workshop, Mar 26-28, 2007 San Diego, CA

Table 2: 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
Fuel Specific Nitrogen Dioxide	Molar NO_2/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	AB Plates, and multiple other provinces identified
Details of Opus remote sensing calculations are provided in Appendix A, page A-1 of the "Remote Sensing Device Trial for Monitoring Heavy-Duty Vehicle Emissions"; report prepared by Opus (Envirotest) for the Metro Vancouver Regional Council, March 2013. http://www.metrovancouver.org/services/air-quality/AirQualityPublications/2013_RSD_HDV_Study.pdf		

Calibration was 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 two gas mixtures: one containing CO, HC, NO, and CO_2, and one containing NO_2 and CO_2, each in a nitrogen balance.[27] 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 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 sensors were reported as hexane equivalents in the database.

4.1 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,

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[27] Audits with both mixtures were conducted for HDV measurements.

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 and evaluating the efficiency of a hydrocarbon combustion system.

Therefore, the native measurement of RSDs are ratios of pollutant to CO_2. They were only historically converted to concentrations simply for ease of interpretation by technicians most familiar with handheld tailpipe emissions analyzers. The submitted dataset includes the native ratios and the default calculated gasoline concentrations. In addition to the default concentrations, the native ratios can be converted to grams/kg of consumed fuel (g/kg), and grams per kilometer (g/km) for light duty gasoline vehicles and grams per brake horsepower-hr (g/bhp-hr) for heavy duty diesel vehicles.

The following paragraphs explain the conversion of our native ratios to gasoline concentrations. Other conversions are reported in Appendix A of the Metro Vancouver report cited at the bottom of Table 2.

The default gasoline concentrations are calculated using standard stoichiometric gasoline combustion chemistry (%CO, ppmHC, ppmNO) in the exhaust gas, corrected for water and excess air not used in combustion), and are inaccurate for diesel vehicles which typically operate at much higher lambdas (air to fuel proportions) than gasoline vehicles.[28] The submitted dataset includes these ratios and default gasoline concentrations, but also the more appropriate converted [grams pollutant/kilogram of fuel burned] for the gasoline vehicles and the [grams per brake horse-power hour] for diesel vehicles. Finally, the default concentrations that appear watermarked on the bottom of the vehicle images should be ignored for diesel vehicles.

This default conversion to gasoline vehicle concentrations 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:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{Pollutant}}{\text{CO} + \text{CO2} + 6\text{HC}} = \frac{\text{Pollutant/CO2}}{(\text{CO/CO2}) + 1 + 6(\text{HC/CO2})} = \frac{\text{QCO, 2QHC, QNO}}{\text{QCO} + 1 + 6\text{QHC}}$$

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 FID reading.

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[28] CarThrottle.com; https://www.carthrottle.com/post/engineering-explained-gasoline-vs-diesel-engines/

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 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 one to three percent false failures.[29] 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.[30] Finally, measurements with Opus RSD5000s agree well with corresponding emissions measured with PEMS.[31]

4.2 Vehicle identification and data processing

The RSDs used in ROVER III captured emissions readings, vehicle speed and acceleration, and identifying pictures of vehicles passing through the RSD light beams. During LDV testing RSD cameras were trained on the rear license plates and during HDV testing on the more appropriate front (tractor) license plates. 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 information 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 5 shows an example of a TagEdit™ screen. This combined license plate editing method is superior to 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.

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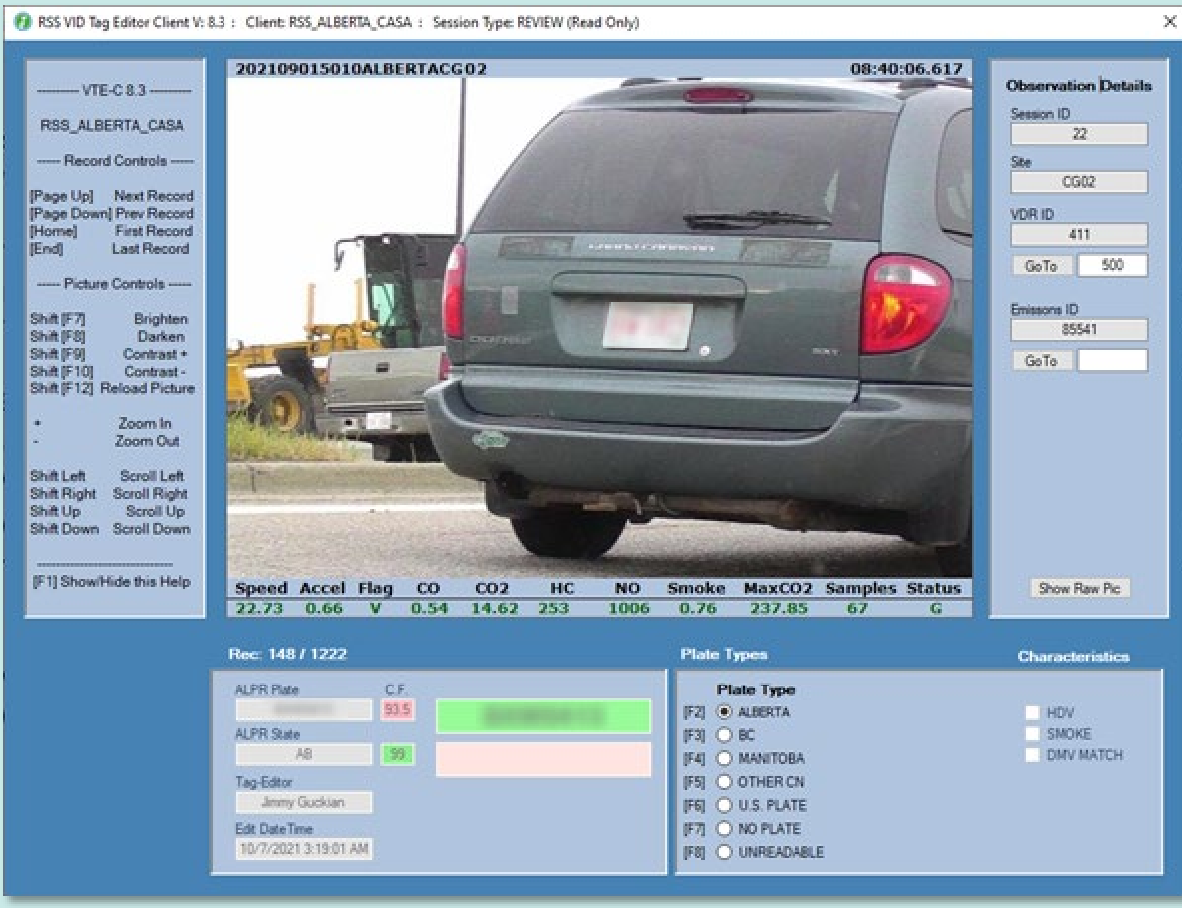
[29] 2018 Virginia On-Road Emissions Program Annual Report; prepared by Opus Inspection for Virginia Department of Environment Quality, June 2019.

[30] 2009 Colorado Remote Sensing Program Annual Report; page 44, report prepared by Opus for the CDPHE, July 2010.

[31] 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

- 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.

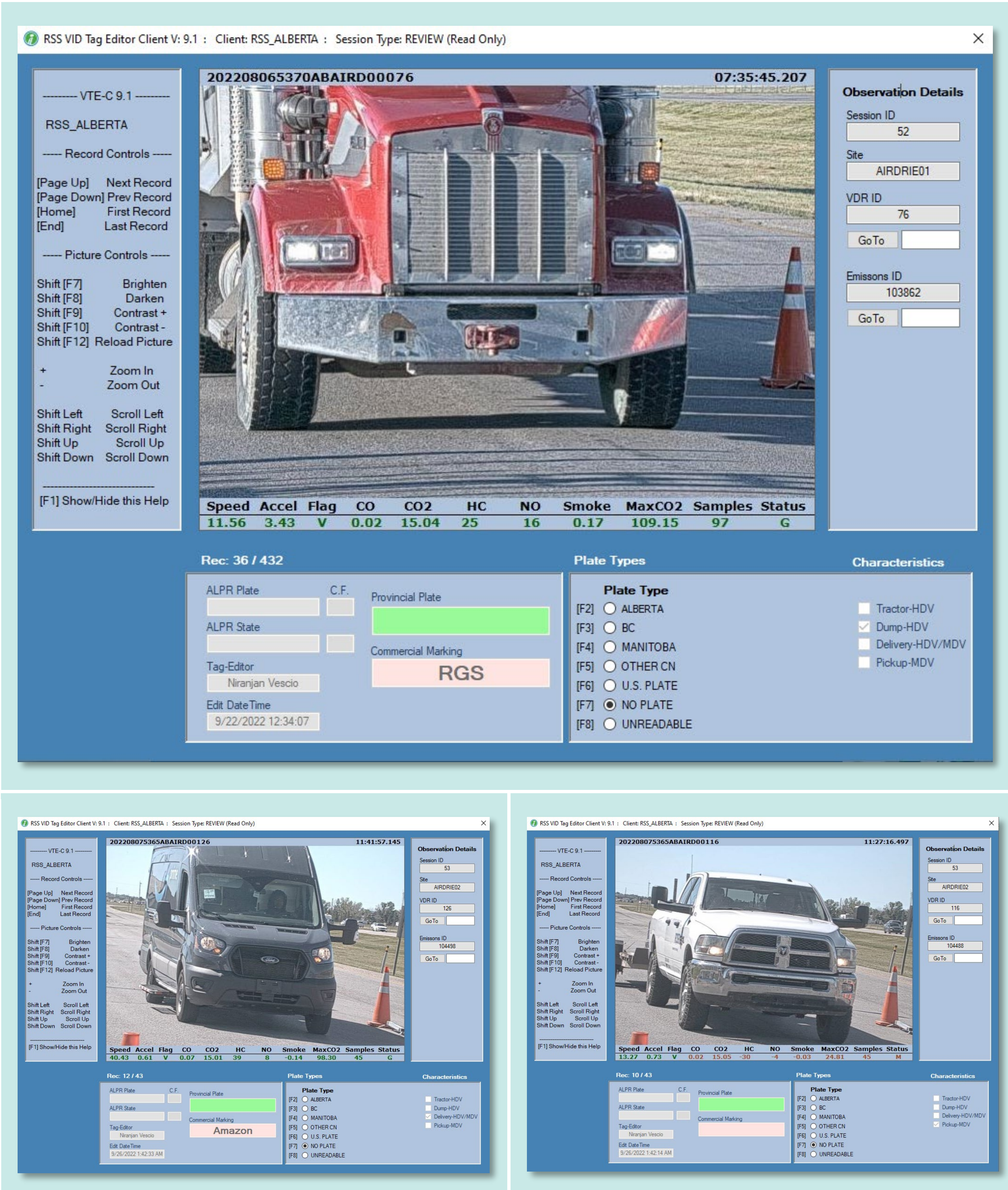
Figure 5: Alberta LDV TagEdit™ screen



A special cloud-based **data management system** was developed for the ROVER III study that allowed nightly upload of the data collection session(s) and overnight OCR, followed by manual license plate entry. License plates provided to Service Alberta via CASA were used to recover VINs and vehicle information (Data Matching) upon completion of this data processing exercise.

License plates of HDVs were also first read by the Open ALPR brand OCR, followed by manual transcription of the misread or unread plates. Cameras associated with the two attended HDV RSDs were trained to read the front plates of the most common HDVs, such as tractor trailers. Because other HDVs, such as delivery trucks and dump trucks, often did not carry front plates, Opus engineers adapted our TagEdit™ software to allow measurements of HDVs without front license plates to at least be grouped (Tractor-HDV, Dump-HDV, Delivery-HDV/MDV, and Pickup MDV) and identified by a Commercial Marking (RGS = Red, Grey, Silver) other than the license plate as seen in Figure 6. This allowed those otherwise valid measurements to be included in special general analyses rather than going unused due to lack of identifying vehicle information.

Figure 6: Alberta HDV TagEdit™ screens

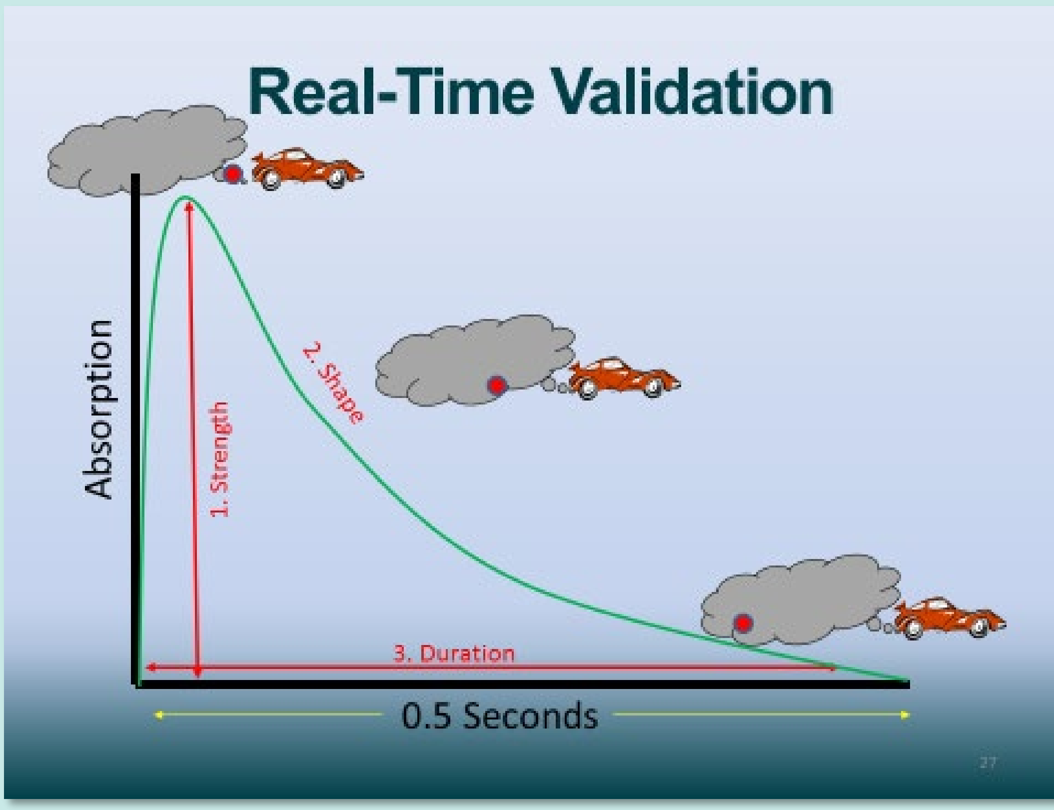


4.3 Emissions data quality assurance

Series 5000 RSDs take 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 emissions 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 7).[32]

Only valid measurements of emissions captured within the period of a passing audit were advanced to post-collection quality screening and included in data analysis.

Figure 7: Real-time measurement validation



[32] The Opus validation criteria were developed and improved over decades to support low and high emitter screening applications, and therefore, are more stringent that necessary for general fleet evaluations. They are considered proprietary and not published.

4.3.1 Daily setup and calibration

Each scheduled workday with clement weather, the RSD operators drove to a predetermined and permitted site. Their first duty was to provide and maintain a safe work area for themselves and passing motorists. The next step was to setup the SDM and allow the electronic components within to warm up for a minimum of 15 minutes.

Following an approximate 45-minute setup and alignment of the other unattended 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 repeatedly dispensing known mixtures of the gaseous pollutants (CO, HC, NO, and CO_2 in an N_2 balance; and additionally, NO_2 and CO_2 in a N_2 balance for HDV measurements) into the external optical path of the RSD during gaps in traffic. Three consecutive measurements of puffed gas within accuracy tolerances constitutes 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.

4.3.2 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.

5. Operations and Data Collection

Opus Inspection was contracted by the Clean Air Strategic Alliance (CASA) of Alberta to collect on-road emissions measurements of light-duty vehicles (LDV) and heavy-duty vehicles (HDV) across the province using the latest Opus remote sensing device (RSD) technology. The objective of this ROVER III motor vehicle fleet emissions characterization project was to inform actions and/or next steps for transportation emissions management to help achieve the Canadian Ambient Air Quality Standards (CAAQS) in Alberta.

5.1 ROVER III operations (project tasks)

ROVER III was to be completed in a series of tasks following contract execution in July 2019.

Tasks

1. **Planning:** Planning for the coordinated execution of the full schedule of services.
2. **Site selection:** Opus training for CASA/Opus selection and review of test sites.
3. **Site permitting/site scheduling:** Coordinating **and** securing of permits for Opus/CASA approved sites. Scheduling of testing across sites; planning for weather contingencies.
4. **Launch:** Deployment of all test equipment, data management system, and operations staff members to Alberta. Special medical permissions were required to enter the country during the pandemic.
5. **Data collection:** Operating RSD(s) at scheduled sites to collect ample measurements over a minimum of 25 test-days.
6. **Data processing/quality review:** Performing Optical Character Recognition (OCR) of license plates, manual review, data quality assurance, and license plate export for matching.
7. **Data matching:** Coordinating retrieval and merging of vehicle information retrieved from Service Alberta with emissions data.
8. **Data analysis and report preparation:** Analysing data consistent with interests of CASA and stakeholders. Delivering a draft report and a final report after incorporating client/stakeholder feedback and comments.

Opus team members delivered turnkey services that started in 2019 with study planning (Task 1) to select areas to focus on-road testing activities. An initially proposed Fall 2019 deployment was delayed due to equipment unavailability. Then the planned spring 2020 deployment had to be postponed due to the onset of the pandemic. To test plans for LDV and HDV characterization at the same on-road sites, Opus personnel conducted a four-day demonstration in Edmonton with unattended RSDs in October 2020.

The October 2020 demonstration served to introduce CASA and its academic partners to RSD technology and was instrumental in the decision to identify alternate sites where larger volumes of HDVs could be exclusively sampled. As a result, the LDV and HDV fleet characterizations were split, and six vehicle inspection stations (VIS) were identified for a dedicated HDV characterization in 2022.

5.2 ROVER III data collection

Initial planning between summer 2019 and spring 2020 consisted of devising plans to test both LDVs and HDVs at the same on-road sites in the five cities of Fort McMurray, Grande Prairie, Edmonton, Red Deer, and Calgary (Task 1). Sites were selected by Opus, CASA, and representatives from each city (Task 2). Permits were secured for just Edmonton sites (ED6, ED8, ED9; Table 1) to salvage a LDV demonstration in October 2020 after the COVID pandemic forced a delay of larger scale ROVER III testing. Following the demonstration, Opus team members selected new LDV-only sites that would accommodate the unattended LDV RSDs and secured permits through Alberta Transportation (Task 3). Working with Alberta Transportation, CASA and the project co-chairs later identified six vehicle inspection stations where HDV testing could be conducted.

The Opus LDV testing team was deployed on August 19, 2021, from Tucson, Arizona (Task 4). The team completed LDV data collection between August 23, 2021, and September 1, 2021 (Task 5). The Opus HDV testing team deployed on June 22, 2022, and completed HDV data collection between June 27, 2022, and August 16, 2022.

Opus team members made a total of 49,747 valid measurements of LDV emissions (CO, HC, NO, and smoke), including 2,525 during the October 2020 demonstration in Edmonton and 5,271 in Ft. McMurray in July 2022. A total of 41,724 measurements were matched with Service Alberta vehicle information via licence plate. Opus personnel made 6,338 valid HDV measurements (CO, HC, NO, NO_2, and smoke); 2,928 of which were matched with Service Alberta vehicle information via licence plate. Table 4 summarizes data collection by site, date, and data collection session.

Table 4: Data collection by site, date, and data collection session

Light Duty Vehicles

2020 Technology Demonstration

Sessions	Site #	Database Site Code	SDM ID#	Date	City	Site Description	Coordinates	Valid Data	Matched Data
5	ED6	ED006	5377	10/05/2020	EDMONTON	INTERCHANGE RAMP FROM AB-216 SB TO WHITEMUD DRIVE EB	53.4824, -113.3448	46	39
6	ED8	ED008	5377	10/06/2020		ANTHONY HENDAY NB TO YELLOWTAIL HWY WB	53.5664, -113.343	27	20
9								1,105	597
7	AU1	AU001	5377	10/07/2020		UNIVERSITY OFALBERTA STUDY SITE	53.5022, -113.5355	233	115
8	ED9	ED009	5377	10/08/2020		WB YELLOWHEAD HWY TO NB ANTHONY HENDAY DR	53.5711, -113.3431	1,114	734
	Test Sites:	**4**	**Test Days:**	**4**			**Total 2020 Valid Measurements:**	**2,525**	**1,505**

2021 Light Duty Vehicle Testing (On-Road Sites)

Sessions	Site #	Database Site Code	SDM ID#	Date	City	Site Description	Coordinates	Valid Data	Matched Data
11	FM1	FM0001	5072	08/23/2021	FORT MCMURRAY	AB-63 FRONTAGE ROAD SB	56.72739, -111.3881	756	664
12								2,059	1,795
10		FM001A	5010				56.72808, -111.3889	1,213	1,040
45	FM1	FTMAC01HI	5370	07/10/2022		SETUP ON AB-63 FRONTAGE ROAD SB	56.72736, -111.3882	461	410
44	FM2	FTMAC02LO	5370			SETUP ON AB-63 FRONTAGE ROAD SB	56.72736, -111.3882	201	136
41	FM2	FTMAC02LO	5365	07/11/2022		SETUP ON AB-63 FRONTAGE ROAD SB	56.72736, -111.3882	334	205
43	FM1	FTMAC01HI	5370			SETUP ON AB-63 FRONTAGE ROAD SB	56.72736, -111.3882	4,275	3,815
14	ED1	ED01	5010	08/25/2021	EDMONTON	NB AB-2 TO WB ANTHONY HENDAY	53.43631, -113.502	5,249	4,587
13			5072					1,242	987
16	ED1	ED01	5010	08/26/2021		NB AB-2 TO WB ANTHONY HENDAY	53.43631, -113.502	6,220	5,469
15	ED2	ED02	5072			EB ANTHONY HENDAY TO NB AB-2	53.4362, -113.4897	5,559	4,922
17	GP1	GP01	5010	08/28/2021	GRANDE PRAIRIE	108 ST SB TO 100 AVE WB	55.1708, -118.8215	1,906	1,457
18	GP2	GP02	5072			100 AVE EB TO 108 ST SB	55.17024, -118.8207	828	650
19	RD1	RD01	5072	08/30/2021	RED DEER	ENTRANCE RAMP FROM TAYLOR (19) ST TO AB-2 NB	52.23523, -113.8247	4,461	3,655
20			5010					4,115	3,501
21	CD1	CG01	5010	08/31/2021	CALGARY	MEMORIAL DRIVE EB TO DEERFOOT TRAIL (AB-2) SB	51.0475, -114.0181	6,790	5,879
22	CD2	CG02	5010	09/01/2021		AB-2 NB TO 17 AVE WB	51.03722, -114.0038	1,553	1,047
	Test Sites:	**9**	**Test Days:**	**9**			**Total 2021 & 2022 Valid Measurements:**	**47,222**	**40,219**
							Total LDV Valid Measurements:	**49,747**	**41,724**

Heavy Duty Vehicles

2022 Heavy Duty Vehicle Testing (Vehicle Inspection Stations)

Sessions	Site #	Database Site Code	SDM ID#	Date	City	Site Description	Coordinates	Valid Data	Matched Data
23	Whitecourt	WHTCRT01	5370	06/27/2022	WHITECOURT	WHITECOURT VIS W/B	54.17529, -115.7534	194	130
25		WHTCRTHIWB	5370	06/28/2022		WHITECOURT VIS W/B	54.17529, -115.7534	400	265
24		WHTCRTLOWB	5365	06/28/2022		WHITE COURT VIS WB LOW STACK	54.17529, -115.7534	21	1
27		WHTCRTHIWB	5370	06/30/2022		WHITECOURT VIS W/B	54.17529, -115.7534	314	199
26		WHTCRTLOWB	5365	06/30/2022		WHITE COURT VIS WB LOW STACK	54.17529, -115.7534	32	3
32	Leduc	LEDCHISB	5370	07/03/2022	LEDUC	LEDUC VIS SOUTHBOUND	53.2311, -113.5727	56	37
31		LEDCHISB	5365	07/03/2022		LEDUC VIS SOUTHBOUND	53.2311, -113.5727	4	4
28		LEDCHISB	5365	07/04/2022		LEDUC VIS SOUTHBOUND	53.2311, -113.5727	233	140
29		LEDCLOSB	5370	07/04/2022		LEDUC VIS LOW SOUTHBOUND	53.2311, -113.5673	211	78
30		LEDCLOSB	5370	07/06/2022		LEDUC VIS LOW SOUTHBOUND	53.2311, -113.5673	270	91
33		LEDCHISB	5365	07/06/2022		LEDUC VIS SOUTHBOUND	53.2311, -113.5727	69	48
35		LEDCLOSB	5370	07/07/2022		LEDUC VIS LOW SOUTHBOUND	53.2311, -113.5673	250	92
34		LEDCHISB	5365	07/07/2022		LEDUC VIS SOUTHBOUND	53.2311, -113.5727	71	52
36		LEDCLOSB	5365	07/08/2022		LEDUC VIS LOW SOUTHBOUND	53.2311, -113.5673	62	4
37		LEDCHISB	5370	07/08/2022		LEDUC VIS SOUTHBOUND	53.2311, -113.5727	52	32
42	Atmore	ATMHINB	5370	07/12/2022	ATMORE	NORTHBOUND LANE AT ATMORE VIS - HIGH STACK	54.85387, -112.5453	17	6
40		ATMLONB	5365	07/12/2022		ATMORE VIS NORTHBOUND USING 5365 (LOW STACK)	54.85379, -112.5452	9	6
39		ATMHINB2	5370	07/13/2022		ATMORE VIS NORTHBOUND USING 5365 AT 2ND SITE	54.85397, -112.5453	39	30
38		ATMHINB2	5365	07/14/2022		ATMORE VIS NORTHBOUND USING 5365 AT 2ND SITE	54.85397, -112.5453	40	29
47	Demmitt	DEM01	5370	07/16/2022	DEMMITT	LOW-STACK DEMMITT 43 WB	55.47356, -119.9645	3	1
46		DEM01	5365	07/16/2022		LOW-STACK DEMMITT 43 WB	55.47356, -119.9645	8	1
48		DEM01	5365	07/17/2022		LOW-STACK DEMMITT 43 WB	55.47356, -119.9645	10	0
49		DEM01	5365	07/18/2022		LOW-STACK DEMMITT 43 WB	55.47356, -119.9645	68	49
50	Airdrie	AIRDRIE03	5370	08/05/2022	AIRDRIE	LOW-STACK W/70 NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	27	1
51		AIRDRIE02	5365	08/05/2022		LOW-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	12	0
52		AIRDRIE01	5370	08/06/2022		HIGH-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	431	175
61		AIRDRIE02	5365	08/06/2022		LOW-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	41	4
54		AIRDRIE01	5370	08/07/2022		HIGH-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	146	105
53		AIRDRIE02	5365	08/07/2022		LOW-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	43	7
55		AIRDRIE01	5370	08/08/2022		HIGH-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	536	245
56		AIRDRIE02	5365	08/08/2022		LOW-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	232	74
57		AIRDRIE01	5370	08/09/2022		HIGH-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	519	244
58		AIRDRIE02	5365	08/09/2022		LOW-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	288	65
59		AIRDRIE01	5370	08/10/2022		HIGH-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	571	242
60		AIRDRIE02	5365	08/10/2022		LOW-STACK NB QUEEN ELIZABETH HWY 2	51.23305, -114.0005	219	58
66	Coutts	CTSLOSB	5365	08/12/2022	COUTTS	COUTTS VIS SOUTHBOUND LOW STACK	49.00547, -111.9755	36	8
67		CTSHISB01	5370	08/12/2022		COUTTS VIS SOUTHBOUND	49.00547, -111.9755	105	52
64		CTSHISB01	5370	08/13/2022		COUTTS VIS SOUTHBOUND	49.00547, -111.9755	100	55
65		CTSLOSB	5365	08/13/2022		COUTTS VIS SOUTHBOUND LOW STACK	49.00547, -111.9755	52	26
63		CTSHISB01	5370	08/14/2022		COUTTS VIS SOUTHBOUND	49.00547, -111.9755	127	69
62		CTSLOSB	5365	08/14/2022		COUTTS VIS SOUTHBOUND LOW STACK	49.00547, -111.9755	39	20
69		CTSHISB01	5370	08/15/2022		COUTTS VIS SOUTHBOUND	49.00547, -111.9755	166	97
68		CTSLOSB	5365	08/15/2022		COUTTS VIS SOUTHBOUND LOW STACK	49.00547, -111.9755	31	10
70		CTSHISB01	5370	08/16/2022		COUTTS VIS SOUTHBOUND	49.00547, -111.9755	113	47
71		CTSLOSB	5365	08/16/2022		COUTTS VIS SOUTHBOUND LOW STACK	49.00547, -111.9755	71	26
	Test Sites:	**6**	**Test Days:**	**25**			**Total Valid Measurements:**	**6,338**	**2,928**

The 2020-2022 LDV measurements were collected in each of five Alberta cities (see Figure 8 through Figure 13). Unattended RSDs were deployed before the morning rush and removed after the evening rush. Up to two RSDs were deployed simultaneously at sites within close proximity, monitored remotely and periodically audited by operators.

Figure 8: LDV testing deployment in Edmonton (1 of 2)

Figure 9: LDV testing deployment in Edmonton (2 of 2)

Figure 10: LDV testing deployment in Fort McMurray

Figure 11: LDV testing deployment in Grande Prairie

Figure 12: LDV testing deployment in Calgary

Figure 13: LDV testing deployment in Red Deer

The 2022 HDV measurements were made with two attended RSDs to capture vehicles with both low- and high-exhaust. Testing was conducted only when vehicle inspection stations (VIS) were operating and staffed by Sheriff Highway Patrol (usually 6:00 a.m. until 4:00 p.m.). VIS sites were scheduled when at least three consecutive full days of VIS operation could be coordinated with each of the six Sheriff districts.

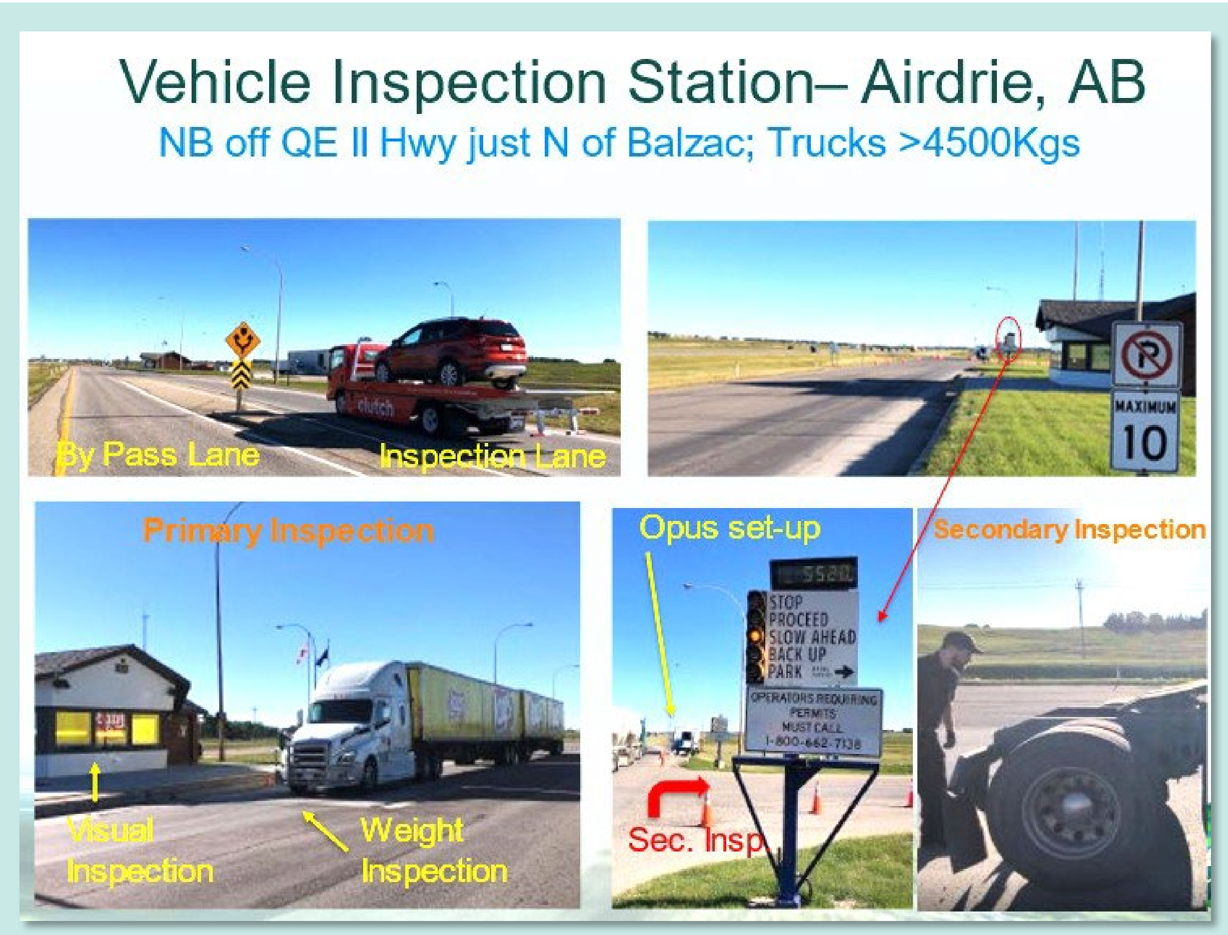
Opus team members were able to set up our safety zone and towers at each VIS once and remove the equipment at the end of testing at that site. RSD equipment was removed each night and secured in the van for safety. Each test day started with an approximate one-hour deployment of the two RSDs, often before the HDV inspections began.

HDVs were directed to enter the off-highway VIS sites when the flashing lights were illuminated (Figure 14).

Figure 14: Heavy-duty vehicle emissions testing at vehicle inspection stations (1 of 2)

At the Airdrie vehicle inspection station, HDVs taking the offramp could use the bypass lane if pre-approved (Figure 15). Most used the inspection lane, paused before the visual inspection booth before passing over the weigh-in-motion scales slowly (primary inspection), and then proceeded passed our RSDs at speed varying from 10kph to 35kph. Vehicle(s) detained for secondary inspection were sometimes sent over the scales and through our RSDs again. The by-pass lane at Leduc was closed and vehicles were coned into a single lane. The other VISs did not have by-pass lanes.

Figure 15: Heavy-duty vehicle emissions testing at vehicle inspection stations (2 of 2)



Speed and acceleration measurement can be challenging for traditional S/A bars with multi-axled HDVs, so the high RSD was integrated with a radar system (Figure 16). Each RSD attempted to capture speed and acceleration just prior to the emissions measurement. There were fewer valid measurements of HDV speed and acceleration than of emissions.

Figure 16: ROVER III speed/acceleration measurement at vehicle inspection stations

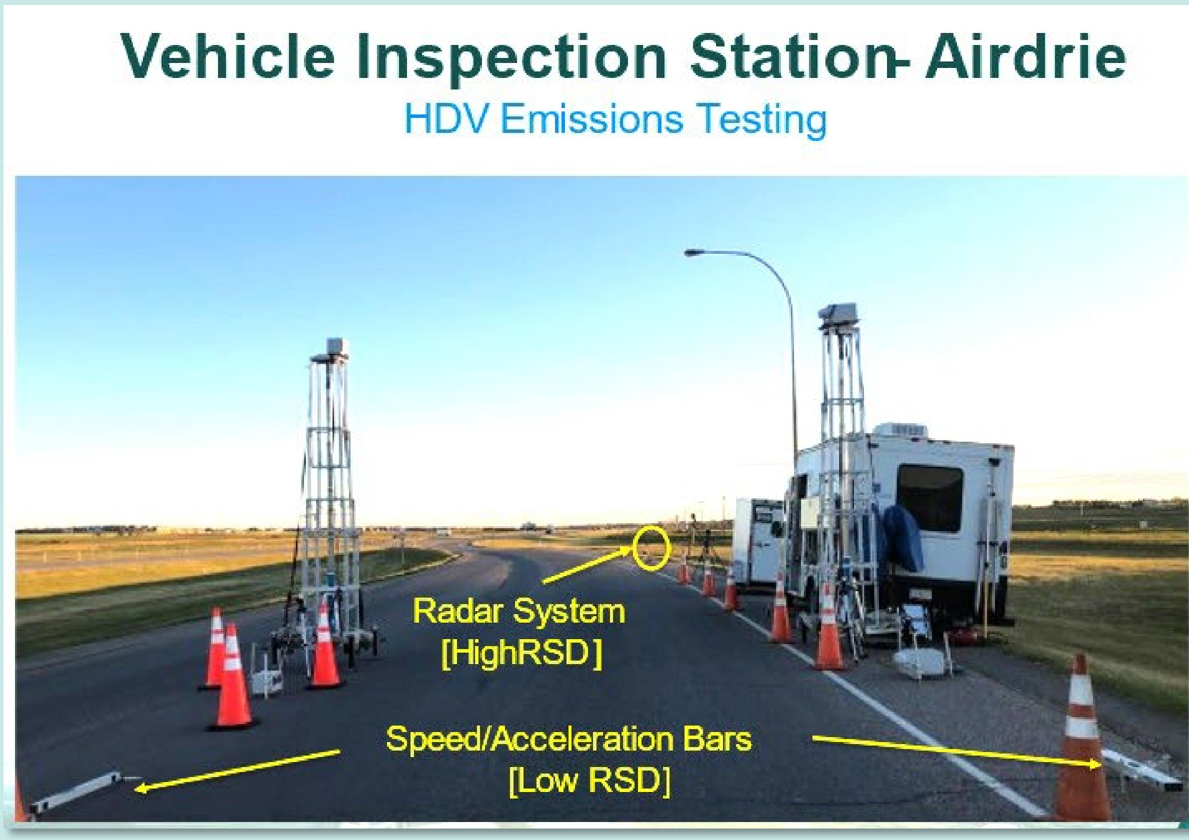


Figure 17 to Figure 21 show HDV testing at the other five (5) vehicle inspection stations.

Figure 17: Vehicle inspection station—Whitecourt

Figure 18: Vehicle inspection station—Leduc

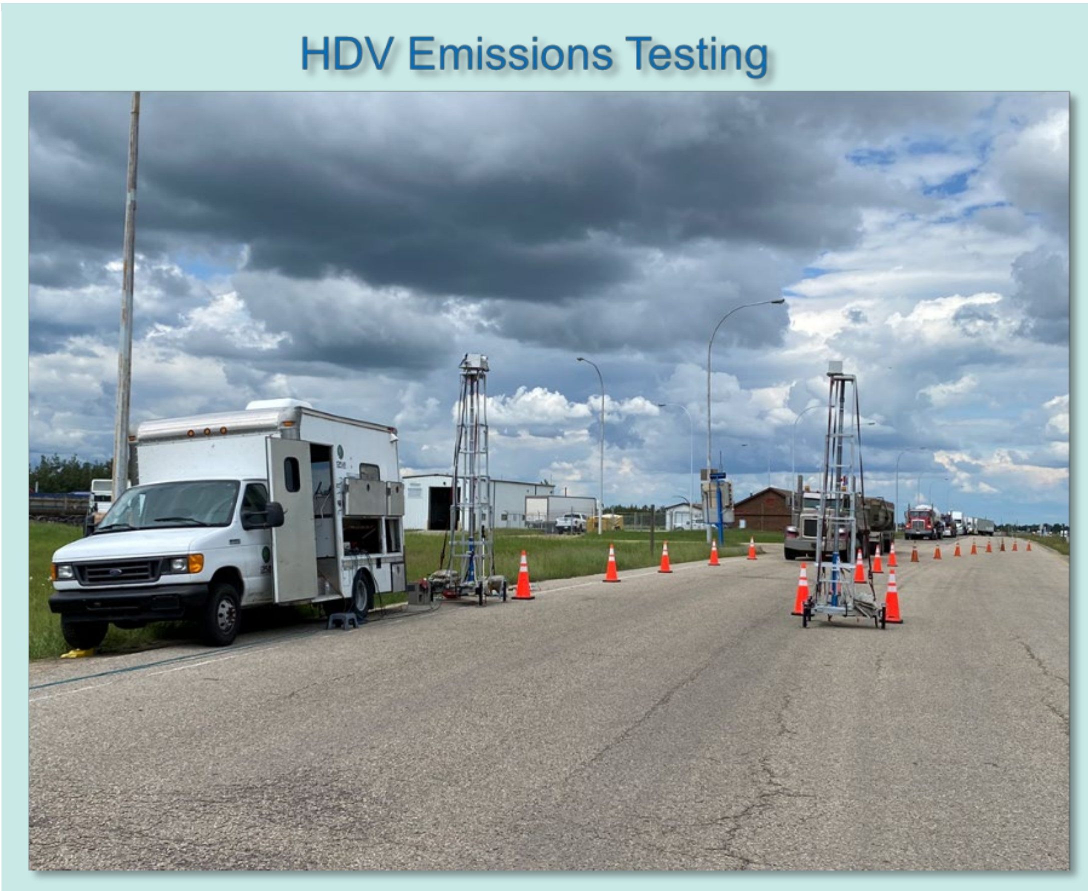


Figure 19: Vehicle inspection station—Atmore

Figure 20: Vehicle inspection station—Coutts

Figure 21: Vehicle inspection station—Demmitt

LDV and HDV data were processed (Task 6) after each data collection campaign. License plates for all valid measurements were sent to CASA for retrieval of relevant vehicle information from Service Alberta (data matching; Task 7). Upon return of the vehicle information, 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 preparation.

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

6. Summary Statistics

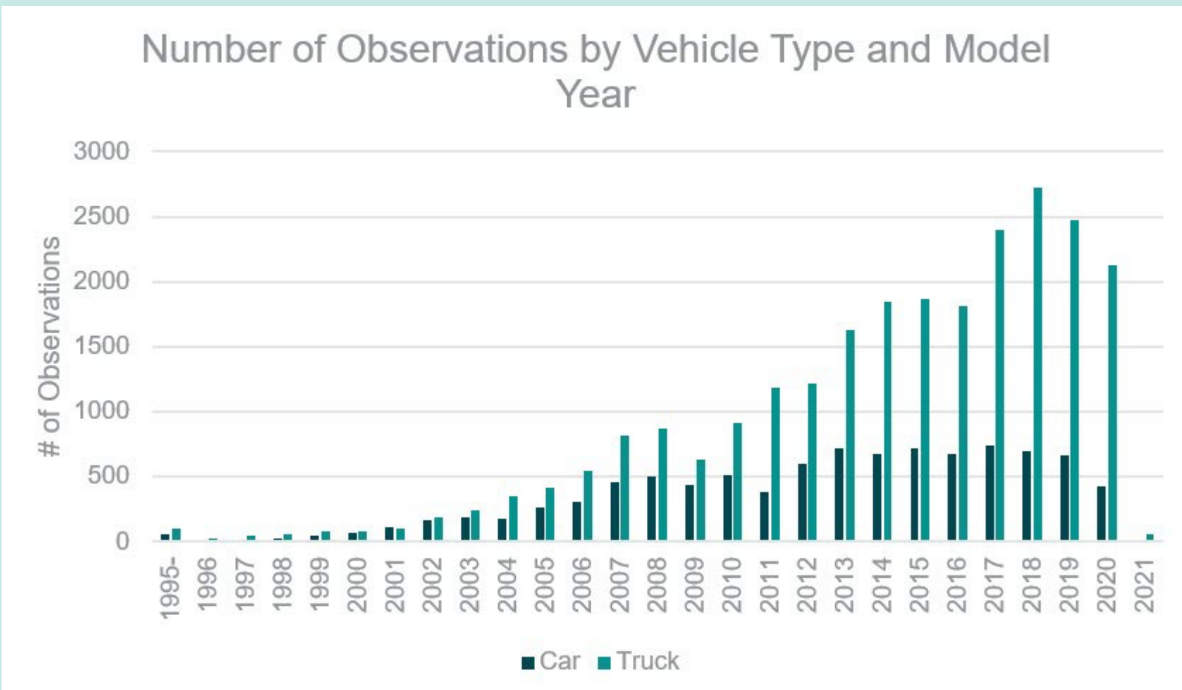
A summary of the RSD emissions data collected by Opus team members is presented below.

6.1 Remote sensing tests on light-duty vehicles

6.1.1 Observations by LDV type and model year

Figure 22 provides a breakdown of the observations by model year and vehicle type; 67% of the observations were on light trucks (SUVs, pickups, and vans). All observations were matched with registration data and have valid emissions and speed/acceleration readings.

Figure 22: Number of observations by LDV type and model year



6.1.2 Observations by LDV fuel type

Based on fuel type in the dataset, 94.9% of the vehicles were powered by gasoline or gasoline blends; 5.1% of the vehicles were diesel fueled.

6.1.3 Observations by province

Based on the registered postal code, 99.4% of the light-duty vehicles observed in this study were registered in Alberta. This was an artifact of the plate matching process. Opus team members investigated using the second digit of the postal code to identify specific registered locations but found multiple locations for some of the digits.

6.2 Remote sensing tests on heavy-duty vehicles

6.2.1 Observations by HDV type and model year

There were two datasets with RSD tests on heavy-duty vehicles:

1. All valid observations of heavy-duty vehicles.
2. Subset of (1); observations of heavy-duty vehicles matched with vehicle information provided by Service Alberta (for Alberta HDVs only).

Table 5 provides a breakdown of the number of different truck types observed. Truck type determinations were made by the Opus field team and license plate editors. Table 6 provides observations by Province as indicated by Opus team members' observation of the plate. Figure 23 provides observations by model year based on plate matches with the Service Alberta dataset. Note that more than 99% of the tests that could be matched with Service Alberta data were classified as tractor trailers.

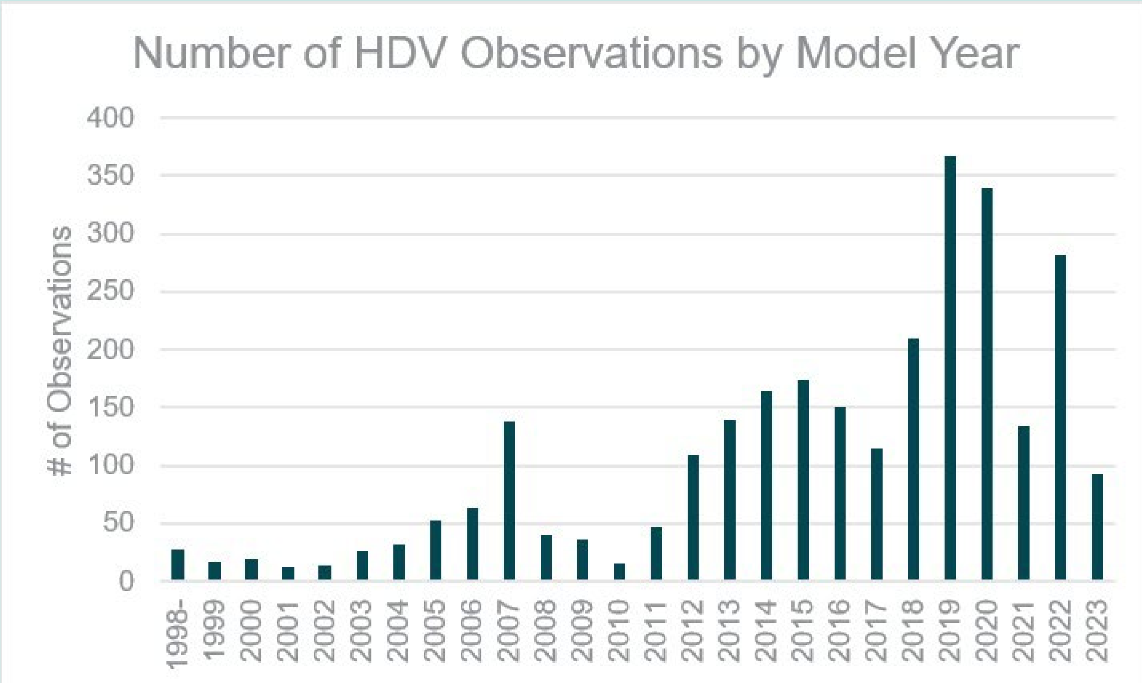
Table 5: RSD Observations by Truck (HDV) Type

Truck Type	Number	Percentage
Delivery—HDV/MDV	411	7%
Dump—HDV	848	14%
Pickup—MDV	411	7%
Tractor Trailer—HDV	4,605	73%

Table 6: RSD HDV Observations by Province

Province	Number	Percentage
Alberta	3067	83%
British Columbia	216	6%
Manitoba	193	5%
Ontario	80	2%
Saskatchewan	68	2%
Other	57	2%

Figure 23: Number of HDV observations by model year



As expected, the vast majority of HDVs observed at the VIS stations were Alberta-registered tractors, weighted principally by their high-volumes at Airdrie and Leduc.

7. Emissions Trends

Following is an analysis of emissions trends for vehicles observed in the Alberta survey. The pollutants that are analyzed are carbon monoxide (CO), hydrocarbons (HC as hexane), nitrogen oxide (NO), and for heavy-duty vehicles UV Smoke (particulate matter—PM) and nitrogen dioxide (NO_2).

> *Nitrogen oxides (NO_x) are mixtures of gases that are comprised of nitrogen and oxygen. The two most prevalent in motor vehicle exhaust are nitric oxide (NO) and nitrogen dioxide (NO_2). Gasoline internal combustion engines emit very little NO_x as NO_2 (Carslaw, p.7), hence NO_2 from LDGVs was not measured and NO alone is reported. In contrast, diesel engines can emit 10 to 50% of their NOx as NO_2 depending on operating mode and engine load, so both NO and NO_2 were measured from HDVs and reported as NOx.*

7.1 Light-duty vehicle emissions

Following is an analysis of remote sensing device (RSD) readings on light-duty vehicles. Because there were so few observations of diesel fueled light-duty vehicles (<5%), the analysis is limited to gasoline powered vehicles. The next section (7.2) analyzes emissions from diesel fueled heavy-duty vehicles.

7.1.1 Impact of vehicle specific power on LDV emissions

Opus team members used the speed/acceleration and site grade data to determine *vehicle specific power* (VSP).[33] 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

Because emissions can vary by VSP, Opus team members grouped RSD emissions into four VSP groups:

1. VSP less than zero (1% of sample),
2. VSP between 0 and 3 (3% of sample),
3. VSP between 3 and 22 (79% of sample), and
4. VSP greater than 22 (16% of sample).

Figure 24 shows the distribution of VSP:

- Median VSP was 15.5
- Average VSP was 16.1

[33] Vehicle-Specific Power; Wikipedia; https://en.wikipedia.org/wiki/Vehicle-specific_power

During the US Federal Test Procedure (FTP), vehicles have a range of VSP between 3 and 22. Operating conditions outside this range are generally termed *off-cycle emissions*; that is, emissions that occur at engine speed/load points not covered by the FTP certification test. Only RSD measurements captured within this range are used in identification of high emitters on-road, therefore, only measurements within the range were used in the high emitter analysis.

Figure 24: Distribution of Vehicle Specific Power (VSP)—Observations of Light-Duty Vehicles

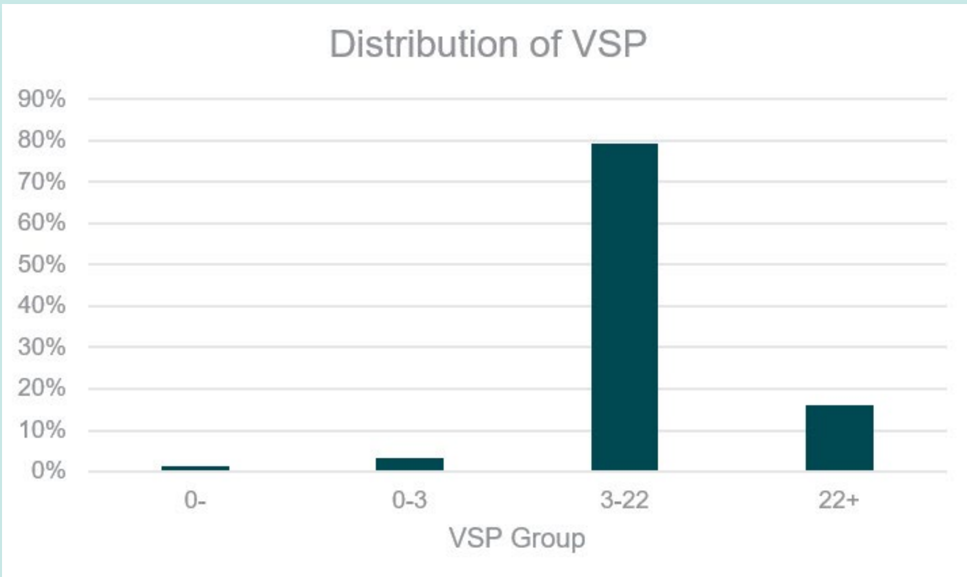
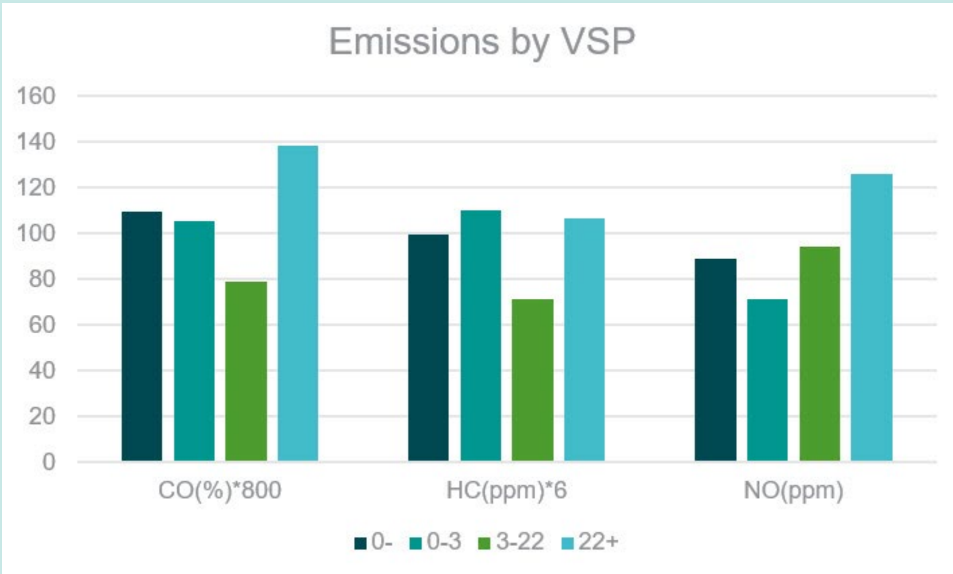


Figure 25 shows average CO, HC, and NO RSD emissions by VSP group. As expected, HC, CO, and NO emissions concentrations were controlled within the FTP range of VSP and were generally greater when VSP was less than zero (due to some incomplete combustion combined with lower exhaust volumes) or greater than 22 (due to off-cycle emissions). For CO and HC, the VSP 3 to 22 group had the lowest emissions. As expected for NO, the VSP 0 to 3 group had the lowest emissions since NO production increases with power. Regardless of VSP, all valid observations are used in the general fleet emissions analyses (other than high emitter).

Figure 25: Average emissions by VSP – Observations of Light-Duty Vehicles



7.1.2 Comparison of LDV emissions with emission benchmarks

Opus analysts converted the RSD emissions readings into grams per kilometer (g/km). This conversion was performed so that emission readings could be compared to the federal standards for new and imported vehicles in Canada. The Canadian vehicle standards, **used as benchmarks only and herein referred to as emission benchmarks**, are presented in Appendix D.

Canada uses the same federal vehicle emissions standards as the United States. Analysts used the US EPA Composite fuel economy to convert the native RSD concentrations in g/kg fuel to g/km. Figure 26 to Figure 28 compare CO, HC, and NO readings with the emission benchmarks. The emission benchmarks for 2003 and older models were based on the US EPA standard for the predominant vehicle types. The emission benchmarks for 2004 to 2006 models were based on the Tier 2 US EPA standards weighted by the Tier 2 phase in schedule. Emission benchmarks for 2007 and newer models are based on the US EPA Tier 2 standards.

> *Real-world RSD measurements versus laboratory new vehicle certification-test measurements.* *New vehicles are certified to federal emissions standards and expected to maintain emissions below those standards for a defined useful life; for example, 10 years or 100,000 for Tier 2 standards.*[34] *However, it is not uncommon for the real-world emissions during everyday driving to be higher than emissions under the controlled laboratory conditions of standardized new vehicle certification test cycles. Differences are generally recognized to be vehicle maintenance condition, road type and gradient, vehicle load, traffic conditions*

[34] § 86.1805-04 Useful life; https://www.law.cornell.edu/cfr/text/40/86.1805-04

and weather, to name a few.[35] Egregious real-world exceedances of certification levels by the newest vehicles (such as 10 to 40 times higher in the case of Euro 5 VW light duty diesels) have historically been associated with outright cheating of certification tests,[36] hence the introduction of real-world in-use compliance testing regimes.[37] RSD experience has shown that emissions generally remain less than two to three times the standards during their early years of useful life and increase as vehicles age to multiple times the standard as control systems age, malfunction, or break. The direct comparison of real-world RSD emissions to federal laboratory new vehicle certification standards herein is meant to serve as a ***benchmark****, rather than a definitive indication of noncompliance. The further comparison to Oregon inspected LDVs and California HDVs serves as another* ***point of reference*** *to judge degree of exceedance, malfunction, or tampering of Alberta vehicles. Remote sensing device measurements are widely recognized as having identified real-world exceedances due to manufacturer cheating or owner tampering and are accepted as an important external data source for in-service compliance testing.[38]*

The data on these figures were limited to 2003 and newer models, which accounted for 97% of the observations. These model years had relatively uniform Canadian emission standards for passenger cars and light trucks. The percentages of observations listed below were higher than the appropriate emission standard in g/km.

- CO: Approximate Standard 1.4 g/km—17% of the observations exceeded standard.
- HC: Approximate Standard 0.04 g/km—55% of the observations exceeded standard.
- NO: Approximate Standard 0.05 g/km—37% of the observations exceeded standard.

Appendix F contains decile charts for light-duty vehicles by age group (<1997, 1998-2005, 2006-2012, >2013.

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35 Car Emissions Testing Facts; https://www.caremissionstestingfacts.eu/difference-between-lab-tests-real-world-emissions/

36 Learn about Volkswagen Violations, Timeline of Key Milestones, USEPA; https://www.epa.gov/vw/learn-about-volkswagen-violations

37 CARB In-Use Compliance Testing; https://ww2.arb.ca.gov/overview-use-compliance-testing

38 EPA Did Not Identify Volkswagen Emissions Cheating; Enhanced Controls Now Provide Reasonable Assurance of Fraud Detection; Office of Inspector General, May 15, 2018, Report No.18-P-0181, page 21; file:///C:/Users/Niranjan.Vescio/Documents/IM%20Solutions%202022/OIG-may%202018-%20EPA%20Did%20not%20Identify%20Volkswagen.pdf

Figure 26: Distribution of CO emissions—2003 and newer LDV models

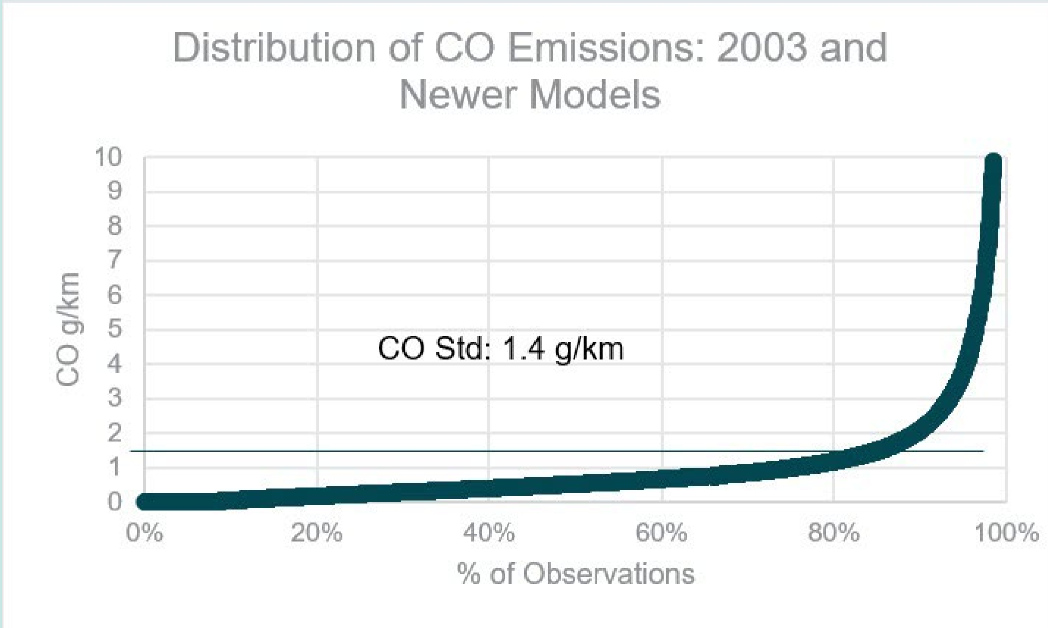


Figure 27: Distribution of HC emissions—2003 and newer LDV models

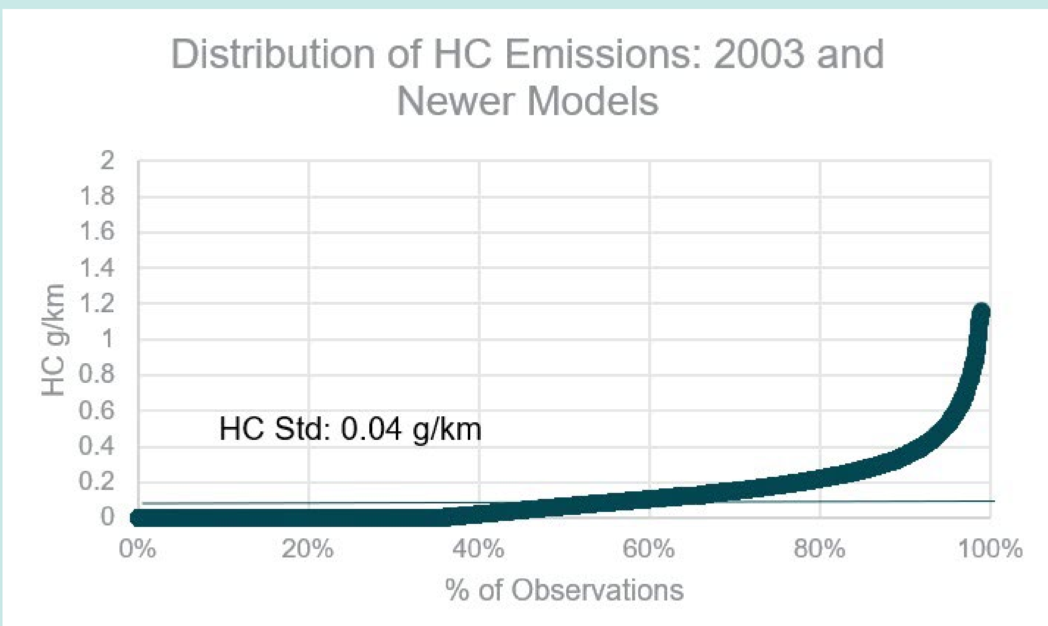
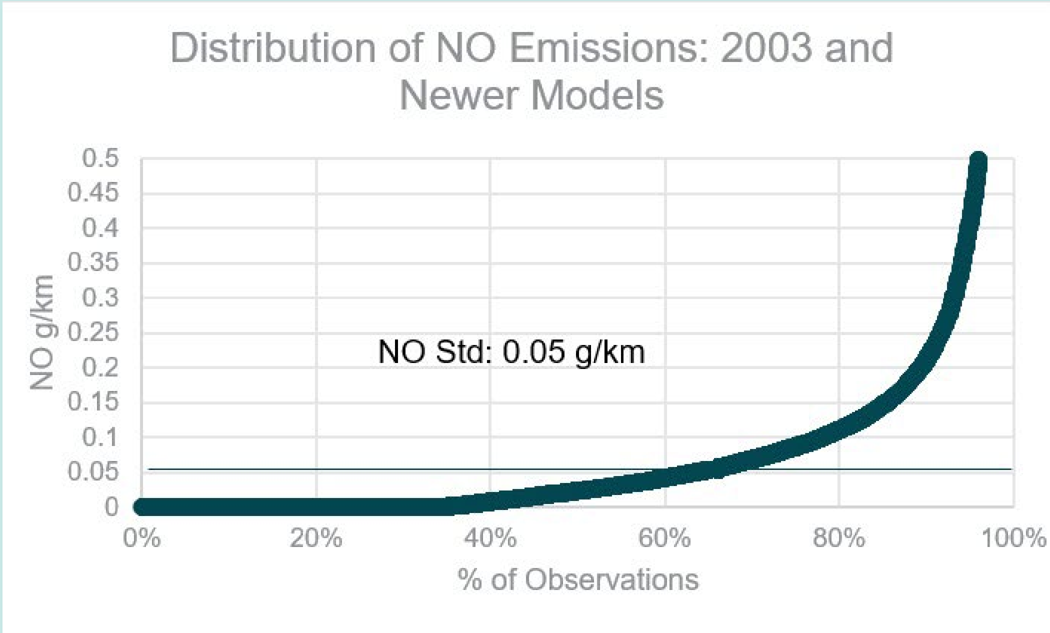


Figure 28: Distribution of NO emissions—2003 and newer LDV models



7.1.3 Average LDV emissions by model year

RSD observations were grouped into model year categories, as seen in Table 7.

Table 7: RSD observations—LDV model year categories

Model years	Group description	Category
1997 and older	Vehicles without Onboard Diagnostic (OBD) systems	Primarily Tier 0. Outside useful life
1998 to 2002	Primarily transitional low emission vehicles	Outside useful life
2003 to 2012	Primarily Tier 2	Outside useful life
2013 and newer	Tier 2/3	Inside useful life

As required by federal legislation, vehicles are supposed to be designed to meet vehicle emission standards when new and for their useful life, which is defined as 10 years and/or 100,000 miles (161,000 km).[39]

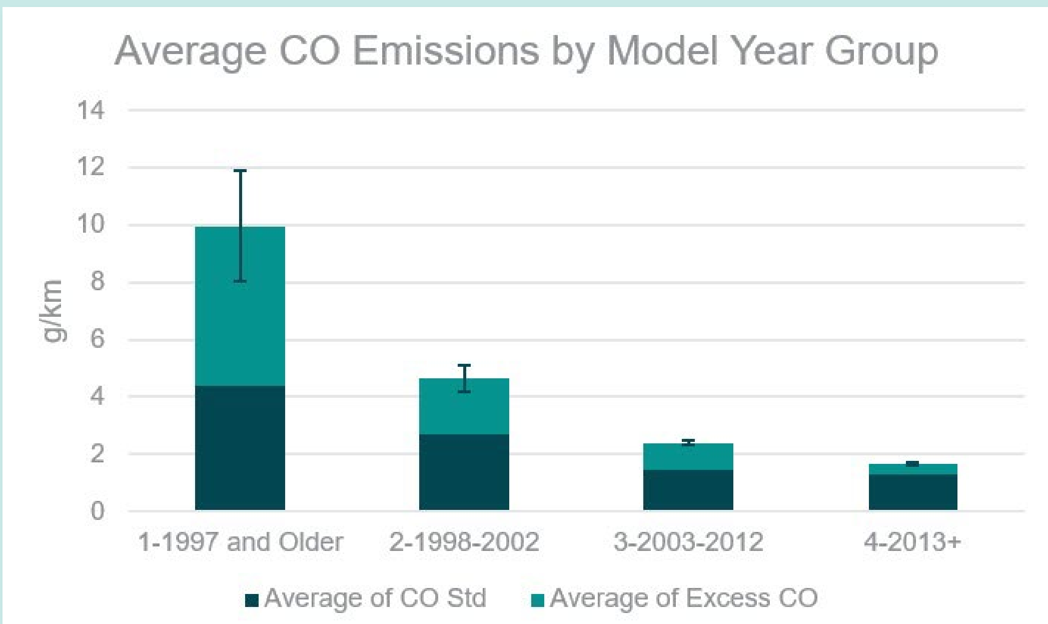
Figure 29 to Figure 32 present average emissions in g/mile for vehicles in the above categories. Average emissions are broken down into two components:

- Average emission standard. (The assumed vehicle emissions standards by model year are included in Appendix D.)
- Average excess emissions—emissions in excess of emission standard.

Unless indicated otherwise, all the averages shown in this report are straight averages of all the observations in the specific group.

For CO emissions, the newest model year group largely meets the standard as shown by the small excess emissions. **For HC and NO, excess emissions account for more than half the total emissions for all four groups.**

Figure 29: Average CO emissions by LDV model year group



[39] Tier 2 standards have a limit of 150,000 miles (241,000 km).

Figure 30: Average HC emissions by LDV model year group

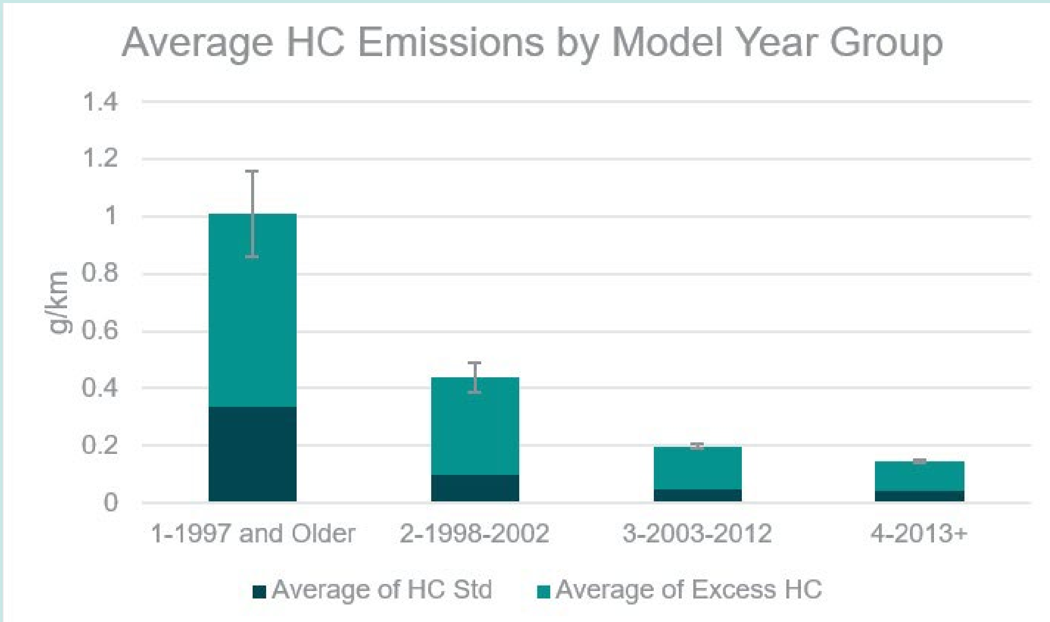


Figure 31: Average NO emissions by LDV model year group

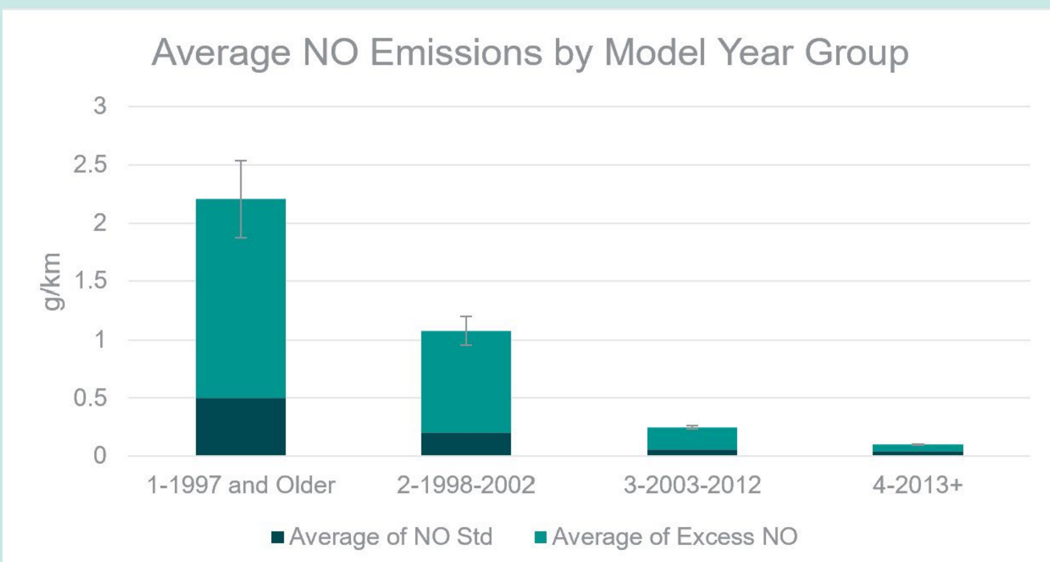
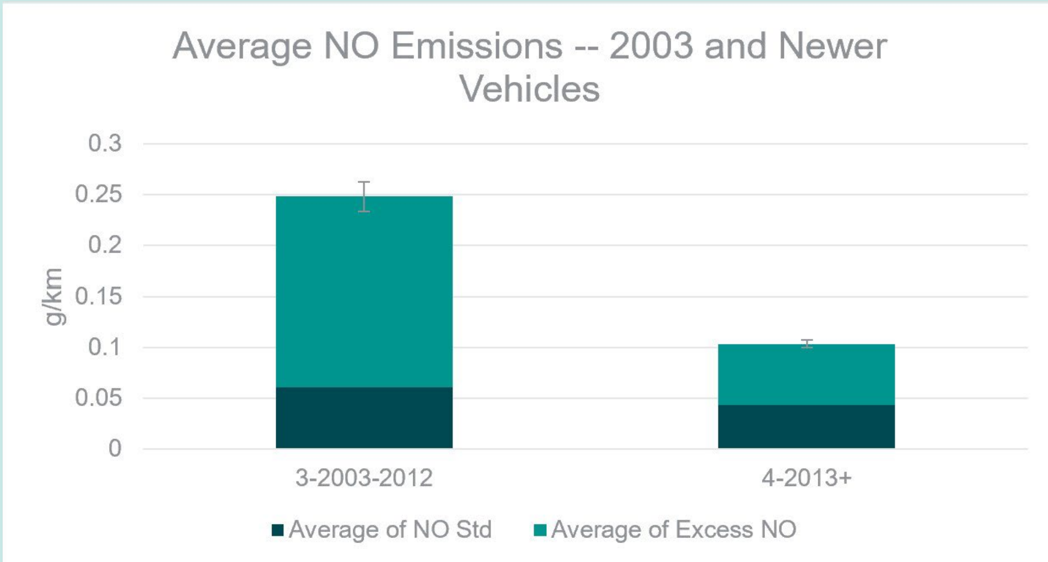


Figure 32: Average NO emissions—LDV model year 2003 and newer

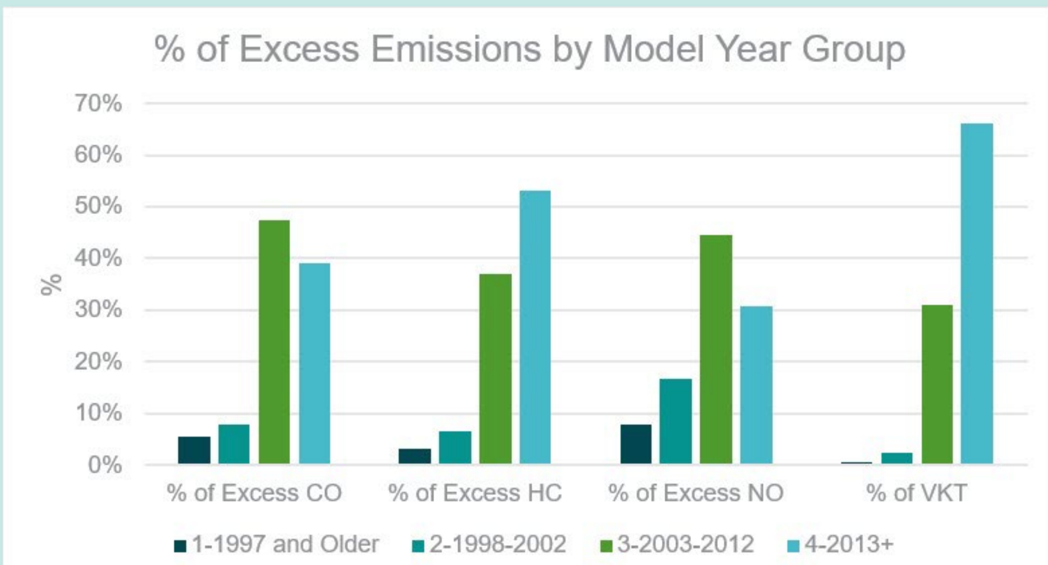


7.1.4 Contribution to total excess emissions by LDV model year

Figure 33 shows the approximate contributions of vehicle kilometres travelled (VKT) and excess emissions from each age group. As mentioned earlier, excess emissions are defined as emissions in excess of the emission standard. The frequency with which vehicles of different ages were seen was used to approximate their relative VKT. Even though average excess CO and NO emissions are lower for the 2003 to 2012 and the 2013 and newer model year groups, they account for a majority of the excess CO and NO emissions because they account for 97% of the VKT. **The 2013 and newer group alone accounts for 53% of the excess HC emissions.**

A public awareness campaign focusing on OBD malfunction indicator lights (MILs) in conjunction with an advisory RSD screening program might be effective in reducing emissions from the small percentage of vehicles that are high emitters. Many vehicles in the 2013 and newer group are likely to still be covered by the emissions warranty.

Figure 33: Contribution of total emissions by LDV model year group



7.1.5 Comparisons of LDV emissions with Oregon

The Oregon Department of Environmental Quality contracted the Opus team to collect measurements across the state in June 2022. Emissions from light-duty gasoline powered vehicles in Alberta were compared with similar vehicles in the state of Oregon. Alberta vehicles have never been subject to periodic emissions inspection. Oregon has had voluntary vehicle emissions inspection in Portland since 1975 and mandatory periodic emissions inspection in Portland and Medford since 1986. Oregon vehicles were divided into two groups:

- Those registered in Oregon's inspection/maintenance (I/M) program area; and
- Those registered outside Oregon's I/M area.

In Figure 34 through Figure 38, we show comparisons of CO, HC, and NO emission concentrations by model year group. Figure 39, Figure 40, and Figure 41 compare the percent of the population that are classified as high emitters using the cutpoints of 1.5% CO, 220 ppm HC, and 1650 ppm NO. A vehicle was classified as a high emitter if it exceeded any of these cutpoints. Generally, emissions and the percent of high emitters in Alberta were higher than in the two Oregon areas. The differences are statistically significant, albeit smaller, for 2013 and later model year vehicles than for 2003 to 2012 (middle-age) vehicles that typically contribute the most excess emissions due to their VKT. The results for each pollutant are presented on two charts because the emissions for the 2003 and newer groups are much lower than emissions for the 2002 and older groups. Average emissions for observations of vehicles registered in Oregon's I/M area were much lower than average emissions of Alberta's fleet, primarily because the I/M program forces the repair of vehicles with high emissions.

Figure 34: Comparison of LDV CO emissions—Alberta vs Oregon I/M and no-I/M, 2002 and older models

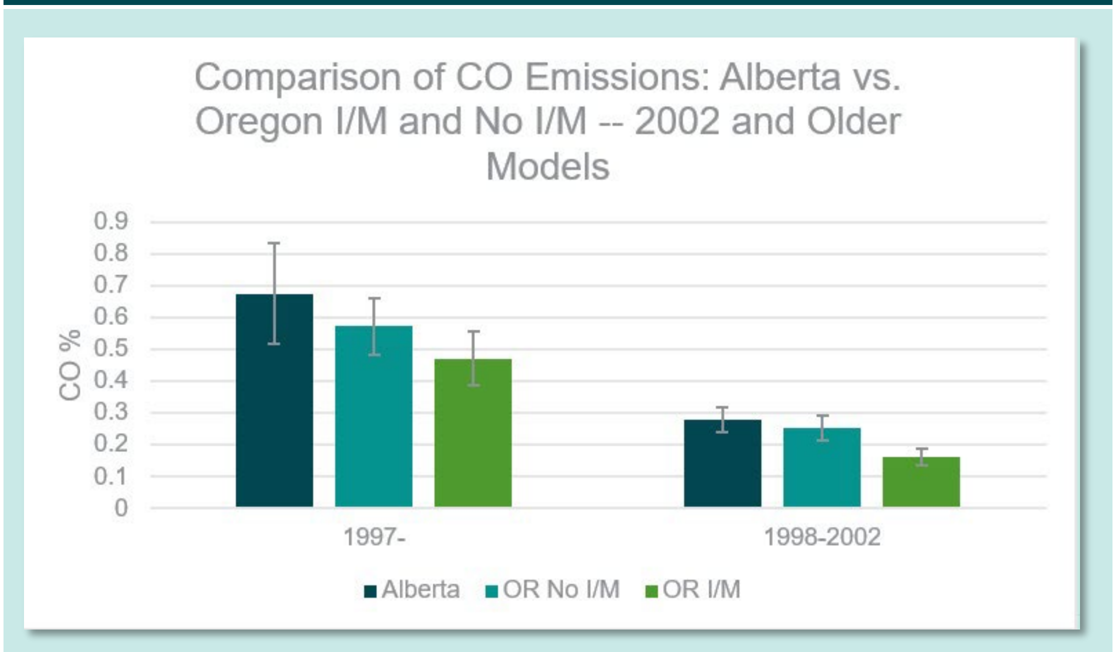


Figure 35: Comparison of LDV CO emissions—Alberta vs Oregon I/M and no-I/M, 2003 and newer models

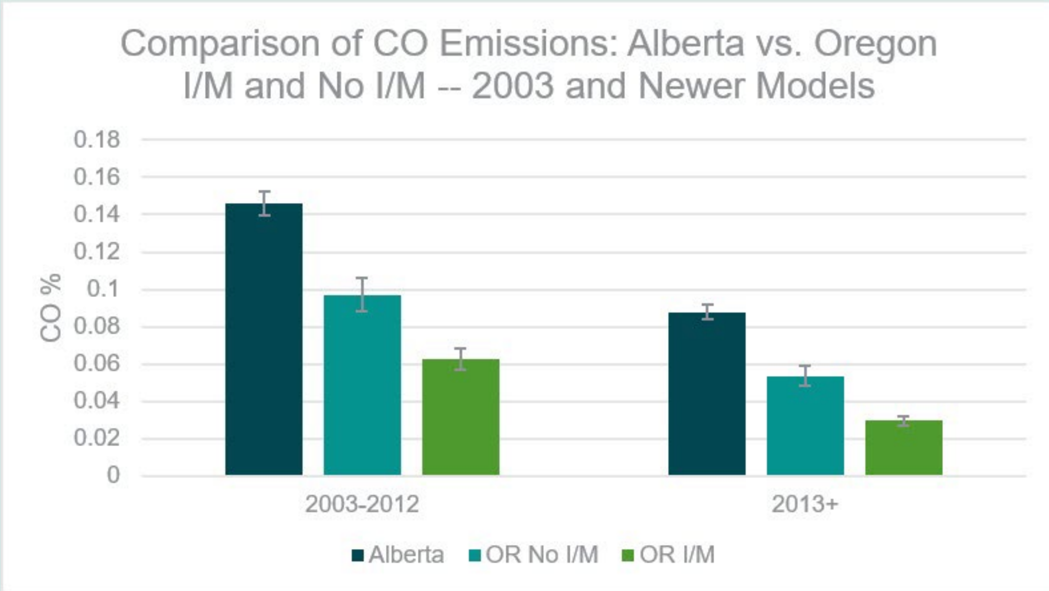
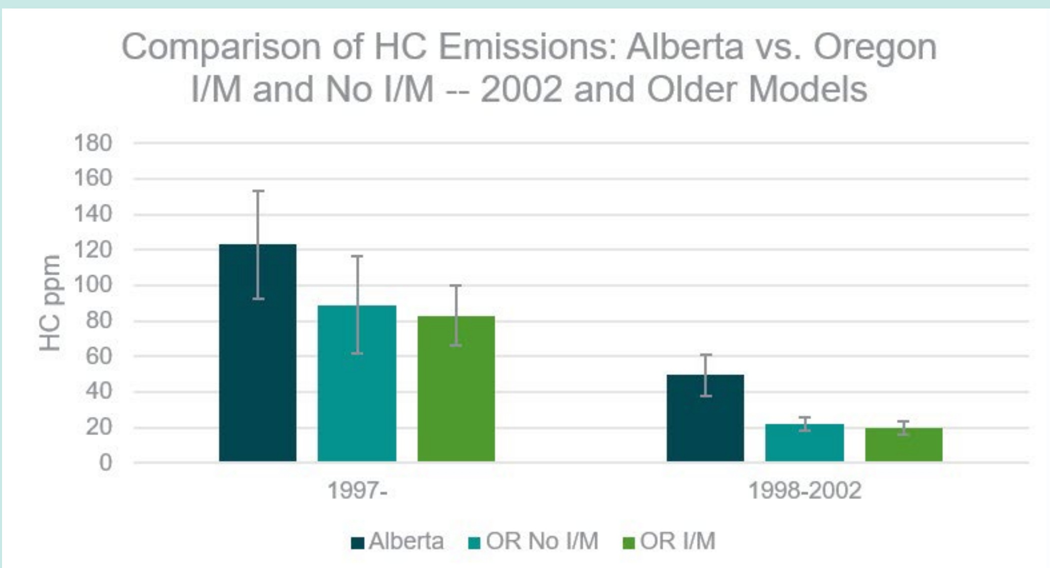


Figure 36: Comparison of LDV HC emissions—Alberta vs. Oregon I/M and no-I/M, 2002 and older models



Classification: Protected A

Figure 37: Comparison of LDV HC emissions—Alberta vs. Oregon I/M and no-I/M, 2003 and newer models

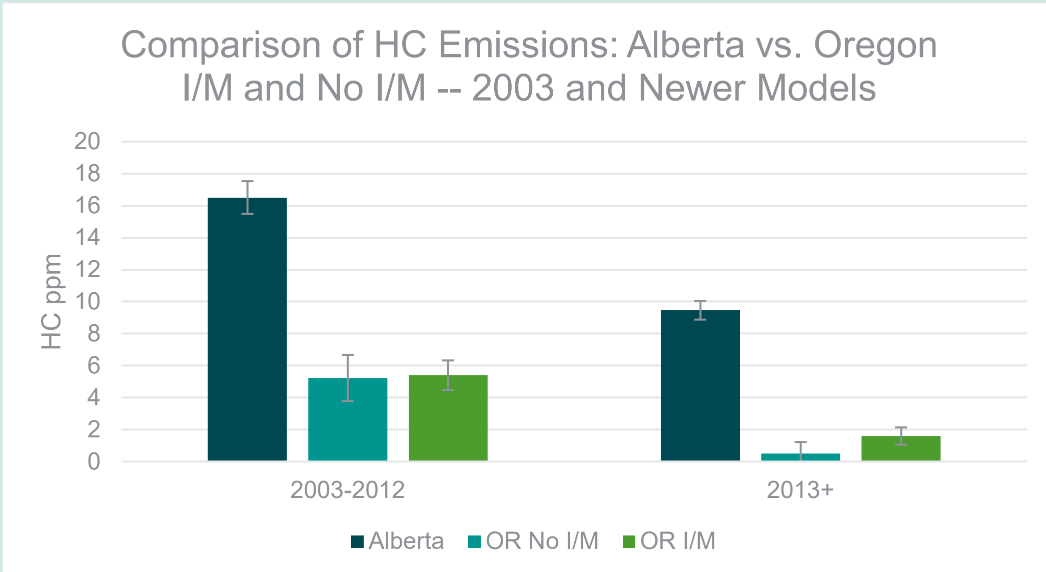


Figure 38: Comparison of LDV NO emissions—Alberta vs. Oregon I/M and no-I/M, 2002 and older models

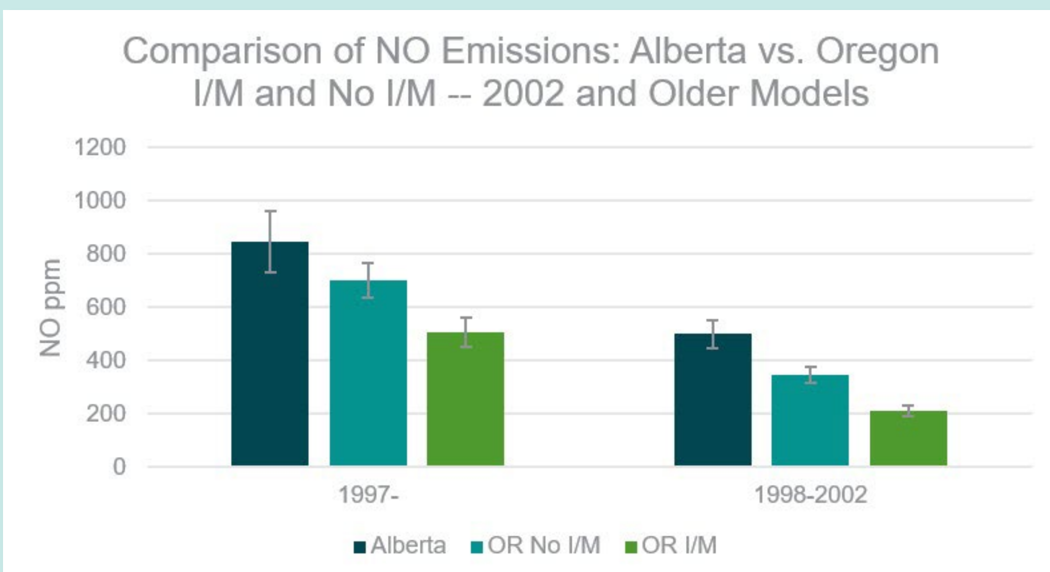


Figure 39: Comparison of LDV NO emissions—Alberta vs. Oregon I/M and no-I/M, 2003 and newer models

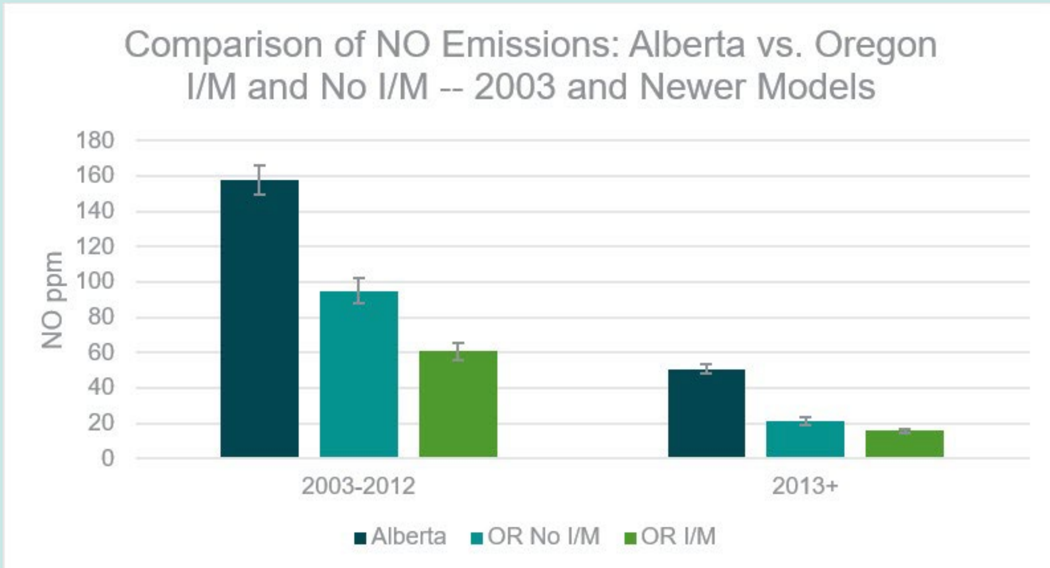


Figure 40: Percentage of LDV high emitters—Alberta vs. Oregon I/M and no-I/M, 2002 and older models

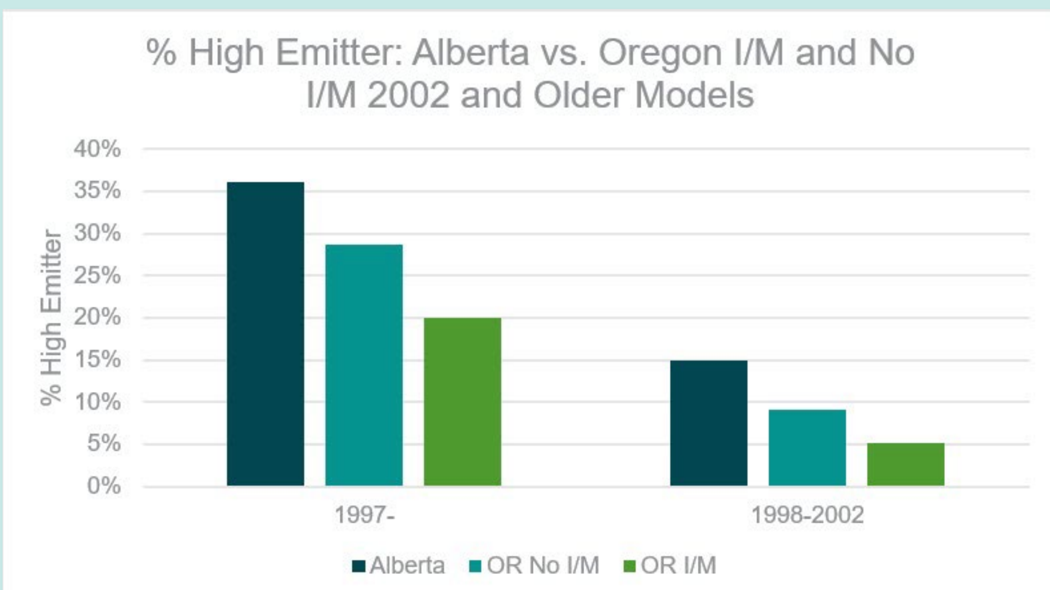
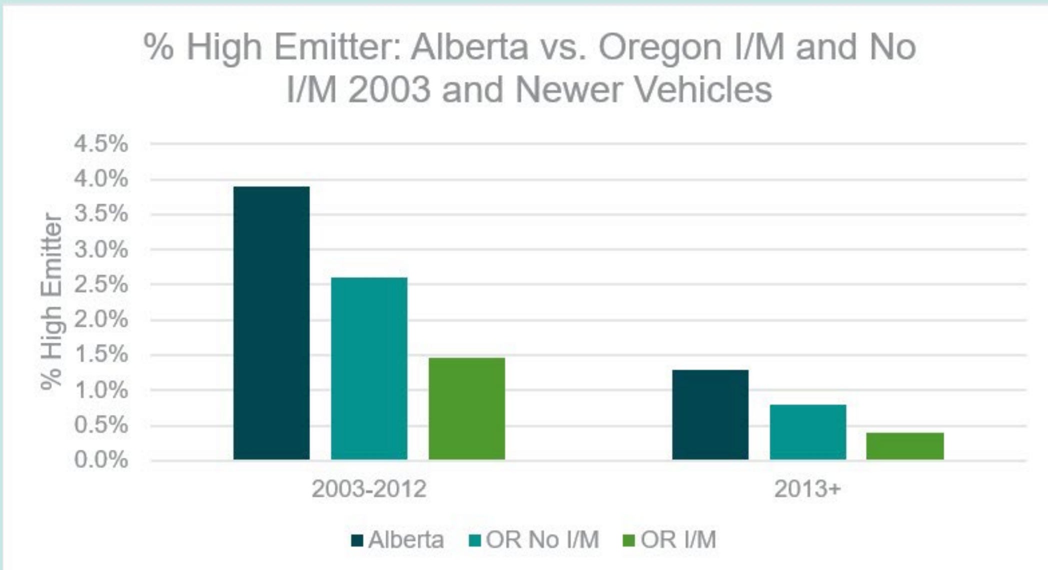


Figure 41: Percentage of LDV high emitters—Alberta vs. Oregon I/M and no-I/M, 2003 and newer vehicles



7.1.6 LDV Emissions by body style

Emissions from light-duty gasoline powered vehicles in Alberta were broken down by body style and model year combinations. Figure 42 through Figure 46 show the results of this analysis. **Pickups consistently have higher emissions than the other body styles.**

Figure 42: LDV CO emissions by body style

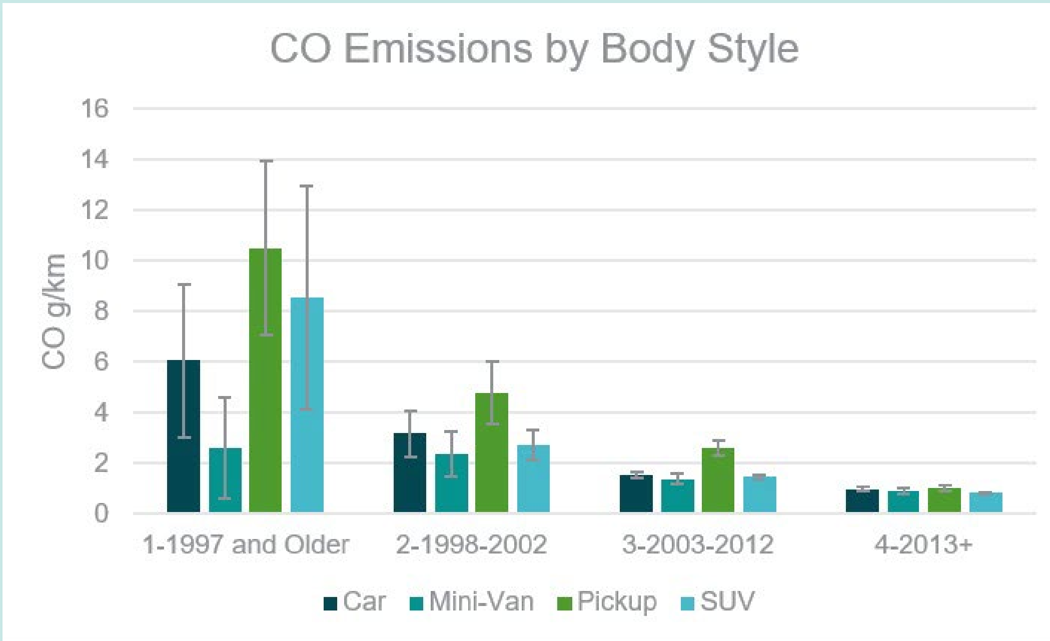


Figure 43: LDV HC emissions by body style

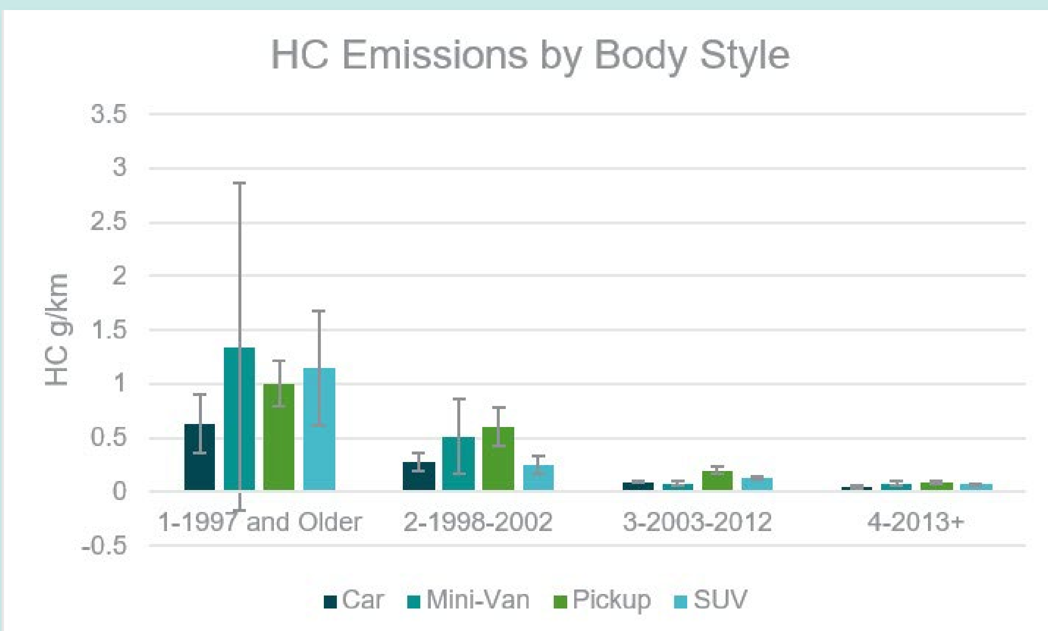


Figure 44: LDV HC emissions by body style, vehicles 2003 and newer

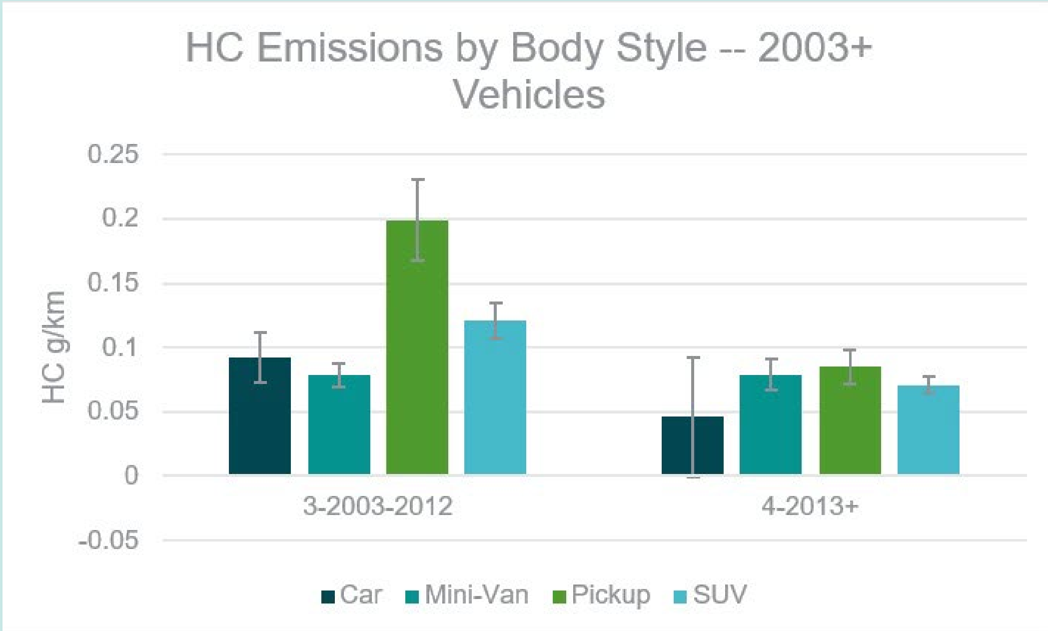


Figure 45: LDV NO emissions by body style

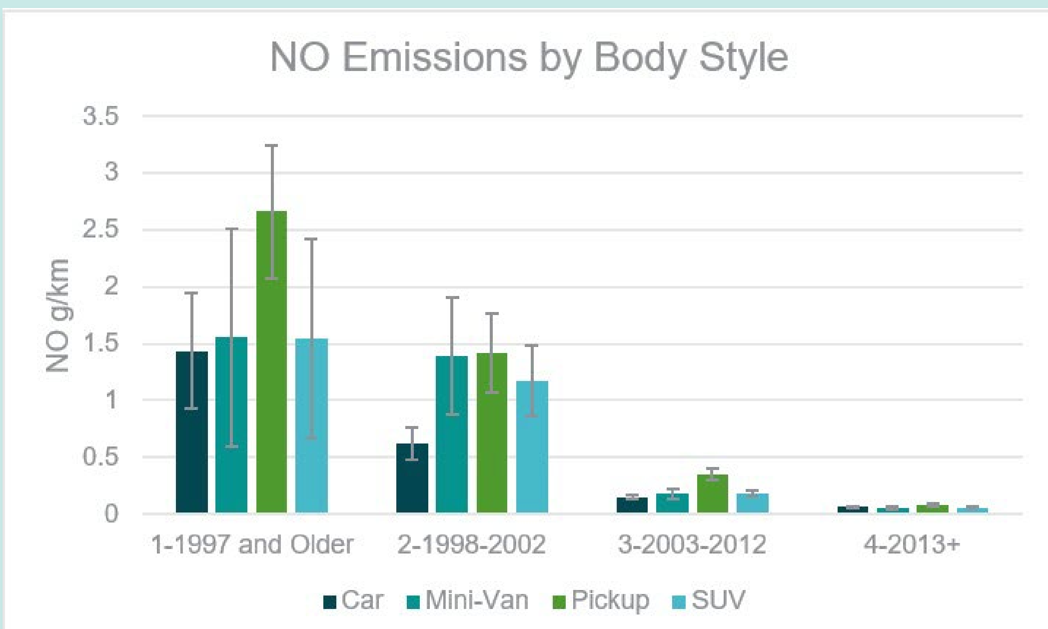
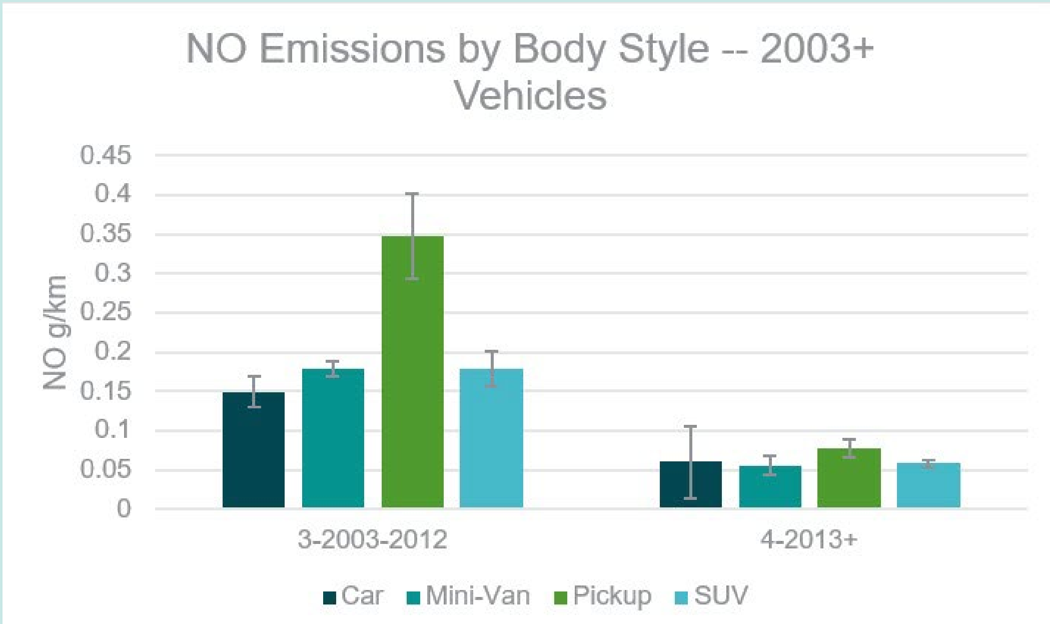


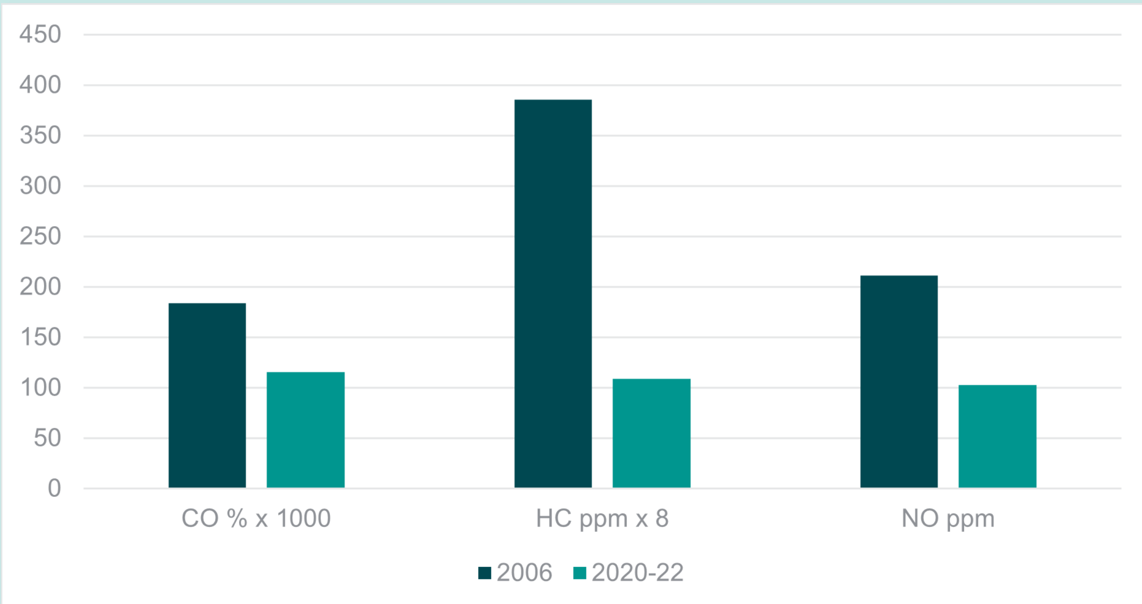
Figure 46: LDV NO emissions by body style, vehicles 2003 and newer



7.1.7 Comparisons of LDV emissions with 2006 Alberta survey

Emissions from light-duty gasoline powered vehicles in Alberta in 2020-2022 were compared with similar vehicles in the 2006 ROVER II survey. Figure 47 compares overall average CO, HC, and NO emissions in 2006 with the 2020-2022 averages. Average emissions were much lower in the 2020-2022 survey than in the 2006 survey, particularly for HC and NO.

Figure 47: Comparison of LDV CO, HC, and NO emissions—Alberta 2006 vs. Alberta 2021



The distribution of HC emissions in particular was found to have skewed significantly in the 15 years since ROVER II, with the dirtiest 5% of LDGVs accounting for 31% of all emissions in 2006 versus 64% in 2021.

- 2006—Dirtiest 5% of vehicles accounted for 60%, 31% and 26% of CO, HC, and NO.
- 2020-2022—Dirtiest 5% of vehicles accounted for 54%, 64% and 38% of CO, HC, and NO.

7.1.8 Multiple observations of the same light-duty vehicle

Large variability in motor vehicle emissions can signal issues with emissions control system performance. dKC identified vehicles that received five or more valid RSD tests. We then plotted the average, minimum, and maximum value for each vehicle, sorted from lowest to highest average value. These plots are shown below in Figure 48, Figure 49, and Figure 50. 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 48: LDV CO—Multiple observations

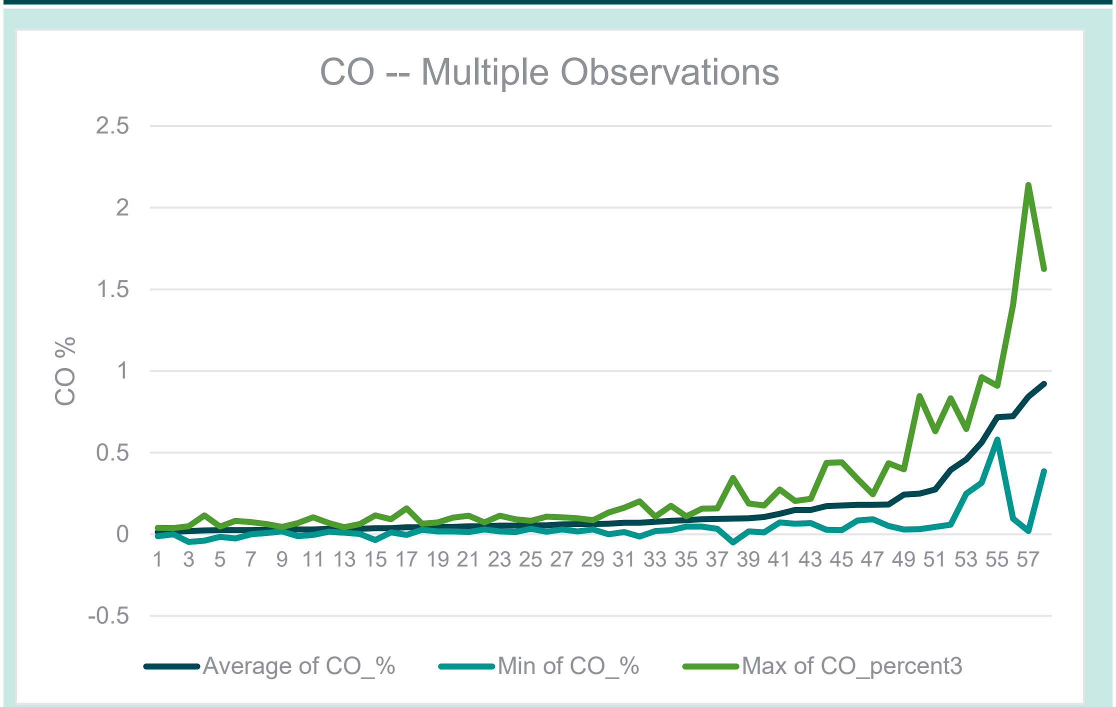


Figure 49: LDV HC-Multiple observations

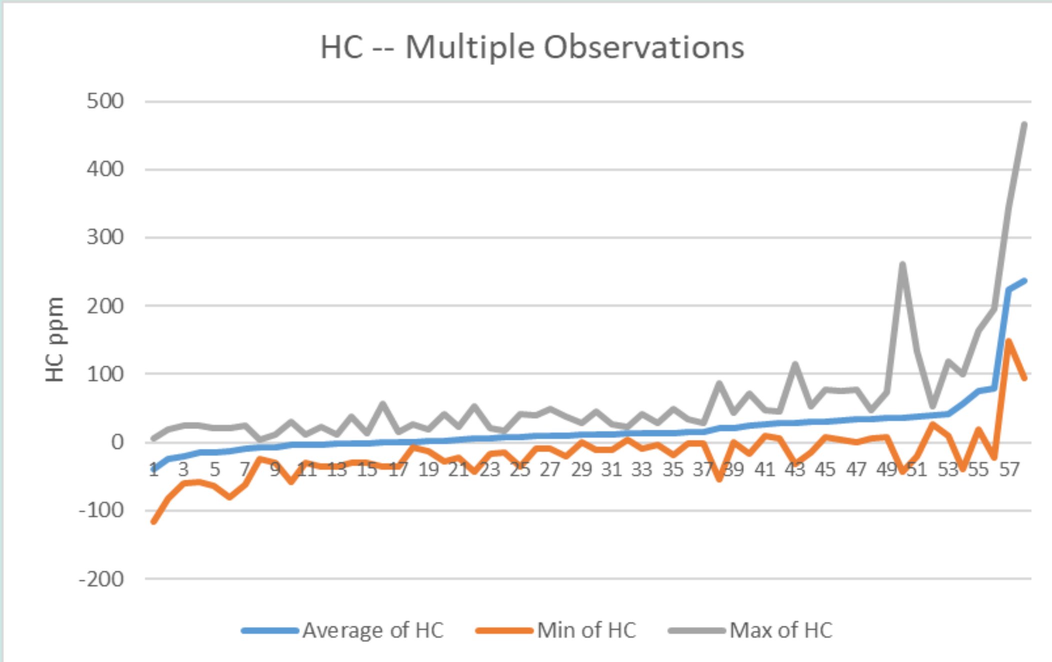
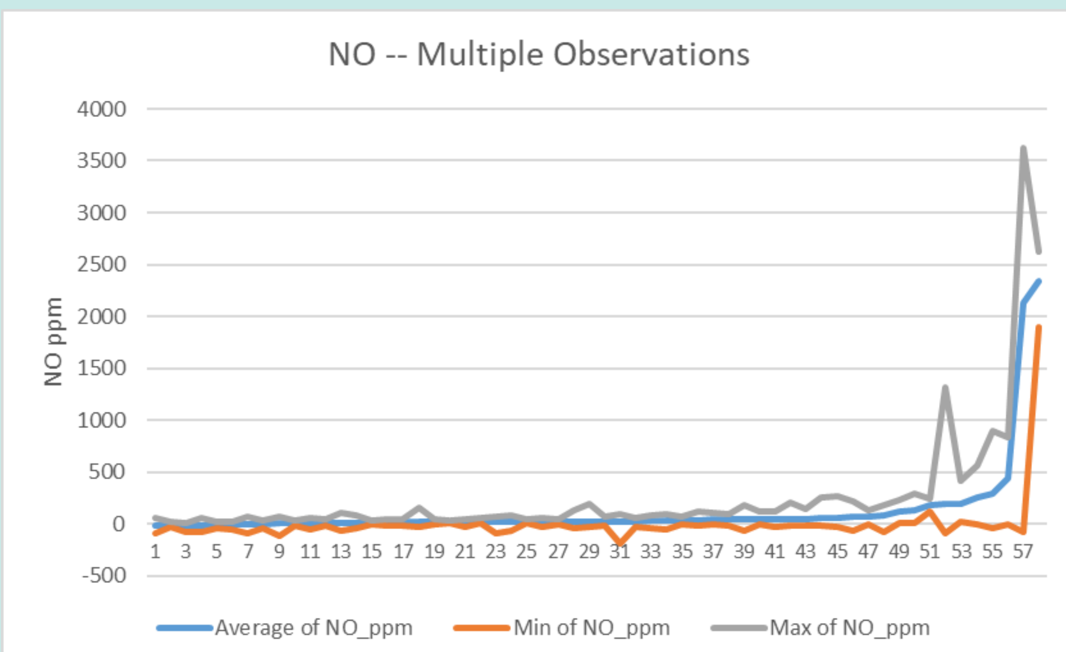


Figure 50: LDV NO—Multiple observations



7.1.9 LDV emissions by site location

Table 8 presents average CO, HC, and NO emissions by site location. Figure 51, Figure 52, and Figure 53 show average CO, HC, and NO emissions for all vehicles by testing location. Confidence limits of 95% are shown. Possibly because it had the highest average (newest) model year and because most Fort McMurray LDV measurements were collected in 2022 vs 2021, CO and NO emissions were lowest for the Fort McMurray observations. HC emissions were lowest for Edmonton observations. Appendix E shows emissions for each site within the municipality.

Table 8: Emissions by site location—LDVs

City	Average CO (g/km)	Average HC (g/km)	Average NO (g/km)	Average of Vehicle Year
CALGARY	1.39	0.12	0.17	2012.92
EDMONTON	1.22	0.06	0.14	2013.76
FORT MCMURRAY	0.92	0.10	0.08	2014.51
GRANDE PRAIRIE	1.37	0.16	0.17	2013.71
RED DEER	1.79	0.11	0.21	2013.40
Overall Average	**1.28**	**0.09**	**0.14**	**2013.71**

Figure 51: Average CO (g/mi) by test city—LDVs

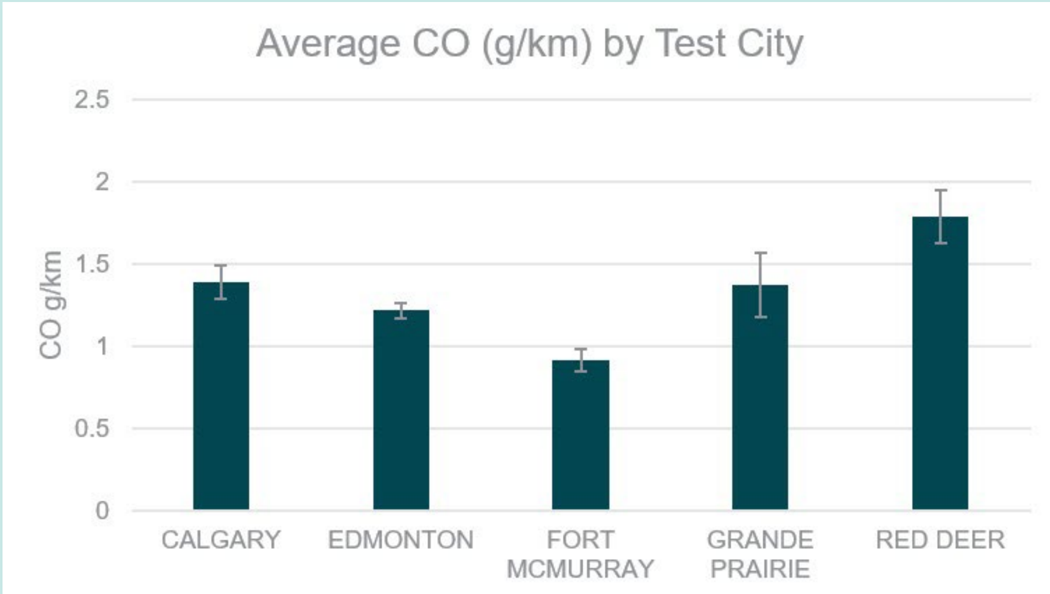


Figure 52: Average HC (g/mi) by test city—LDVs

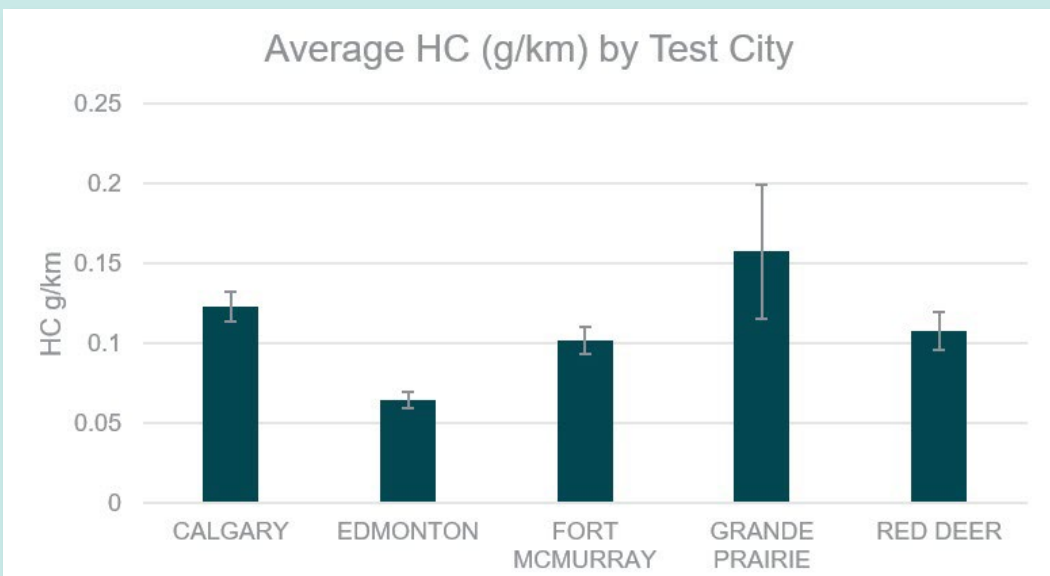
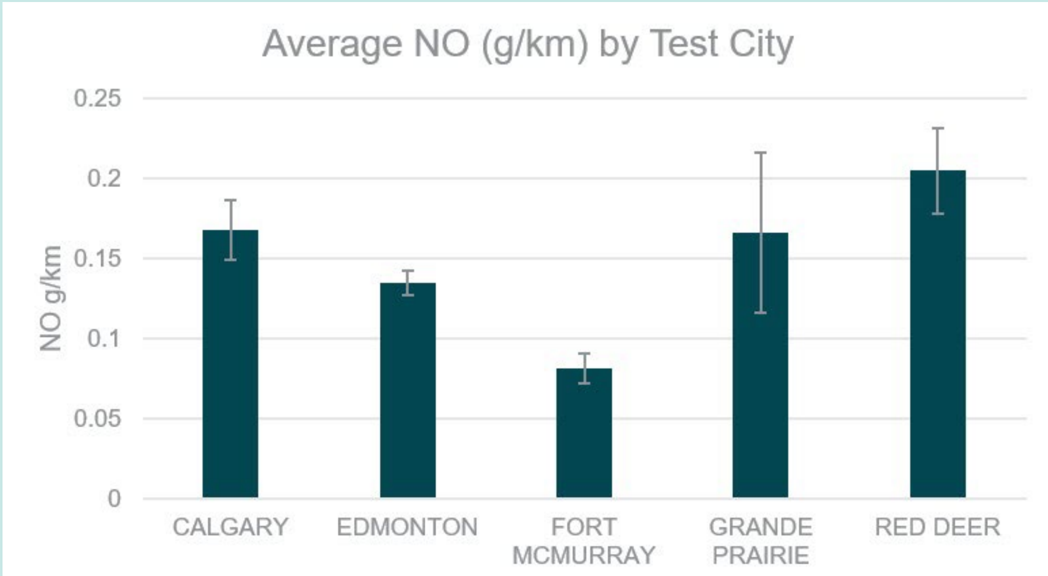


Figure 53: Average NO (g/mi) by test city—LDVs



7.2 Heavy-duty vehicle emissions

7.2.1 HDV Emissions vs. Vehicle Specific Power

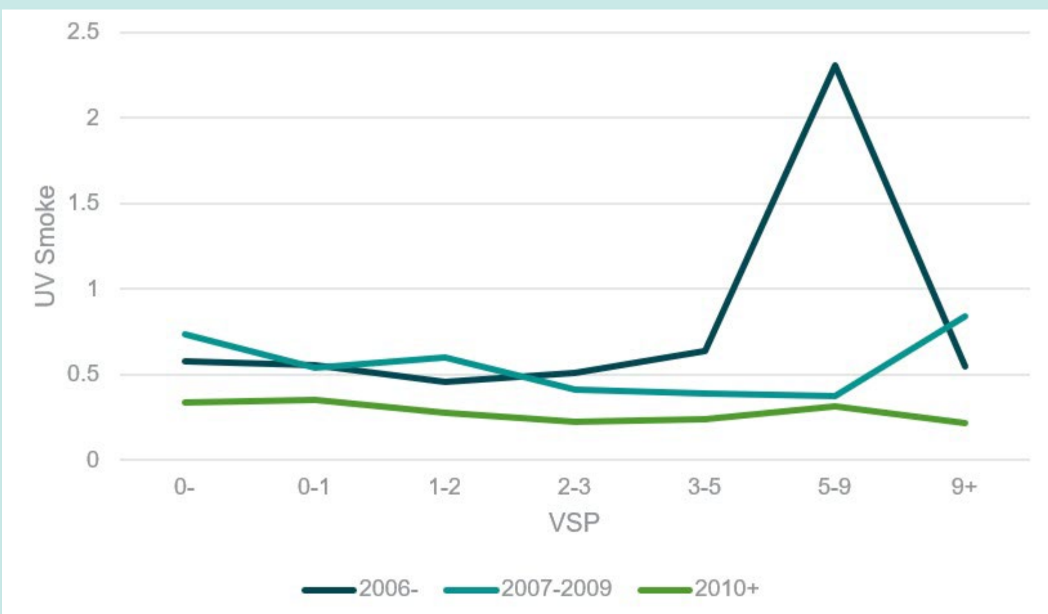
Opus team members used the speed/acceleration and site grade data to determine *vehicle specific power* (VSP). We grouped VSP for HDVs into the following categories:

- < 0: 14% of observations
- 0 to 1: 42% of observations
- 1 to 2: 24% of observations
- 2 to 3: 9% of observations
- 3 to 5: 6% of observations
- 5 to 9: 3% of observations
- >9: 3% of observations

We then plotted NO_x ($NO + NO_2$) and UV Smoke by groups of VSP and model year. Figure 54 shows NO_x by VSP group; Figure 55 shows UV Smoke by VSP group. Except for one outlier (due to a small sample size), NO_x and UV Smoke emissions are fairly uniform across the lower range of VSPs observed at the VIS stations. Therefore, all valid observations regardless of VSP are used in the analysis.

Figure 54: NO_x (g/kg fuel) by VSP and model year group—HDVs

Figure 55: UV smoke by (g/kg fuel) VSP and model year group—HDVs



7.2.2 Comparison of HDV emissions readings with emissions benchmarks

The federal emission standards for heavy-duty engines are expressed in terms of *grams per horsepower x hour (g/hp-hr)*. Using a brake specific fuel consumption estimate of 210 g/kw-hr[40], dKC converted the g/kg fuel estimates to g/hp-hr. The g/hp-hr estimates are used as a *benchmark* in the overall analysis of RSD results and herein referred to as emissions benchmarks. The RSD based g/hp-hr estimates cannot be used to strictly determine the percent of vehicles that meet federal standards based on laboratory tests. **There is more uncertainty in the conversion of UV Smoke into g/hp-hr PM values than in the conversion of NO_x, CO, and HC based on RSD into g/hp-hr.** This analysis is limited to 2010 and newer models which account for 83% of the RSD observations. NO_x represents the sum of NO and NO_2. Appendix C has details on NO and NO_2 emissions by model year group.

PM and NO_x are the greatest concern for heavy-duty diesel-powered vehicles. Model 2010 and newer vehicles must be designed to meet the most stringent NO_x and PM federal standards. The NO_x standard for these vehicles is 0.20 g/hp-hr; the PM standard is 0.01 g/hp-hr. These federal standards necessitate the use of external emission control devices such as selective catalytic reduction (SCR) systems to reduce NO_x and trap oxidizers (diesel particulate filters) to reduce PM. SCR systems require injection of diesel exhaust fluid (DEF) to reduce NO_x. Failure to refill DEF tanks and/or overall tampering with the SCR system has been a concern, as has been removal of trap oxidizers.

Figure 56 through Figure 59 show the distribution of NO_x, PM, CO, and HC emissions in g/hp-hr for 2010 and newer vehicles. Like the grams per kilometer estimates, these are approximations of federal laboratory emission tests. This analysis is useful in showing overall trends. The following percentages of observations were greater than the appropriate emission benchmark in g/hp-hr:

- NO_x: Standard 0.2 g/hp-hr—62% of the observations were greater than the benchmark.
- PM: Standard 0.01 g/hp-hr—72% of the observations were greater than the benchmark.
- CO: Standard 15.5 g/hp-hr—0% of the observations were greater than the benchmark.
- HC: Standard 0.14 g/hp-hr—45% of the observations were greater than the benchmark.

As shown, most NO_x and PM observations of heavy-duty diesel-powered vehicles (HDDV) were greater than the NO_x and PM emission benchmarks. This is different from the trend for light-duty gasoline powered vehicles where most of the emissions observations met the emission benchmarks. Emissions distributions of HDDVs are far less skewed as well with the dirtiest 5% accounting for only 28% of CO, 33% of HC, and 22% of NO.

It can seen in Figure 56 and Figure 57 that approximately 30% and 12% of the observations are 10 times the NOx and PM emissions benchmark, respectively, a strong indication of heavy-duty vehicles with improperly maintained or possibly tampered NO_x and PM emission control systems. Performing RSD tests at truck weighing stations could identify tampered or improperly maintained heavy-duty diesel-powered vehicles.

Appendix F contains decile charts for heavy-duty vehicles by age group (<2006, 2007-2009, >2010).

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[40] Remote sensing of heavy-duty vehicle emissions in Europe, **WORKING PAPER 2022-25;** 2022 INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION, AUGUST 2022

Figure 56: Distribution of HDV NO_x emissions (g/hp-hr) 2010 and newer models

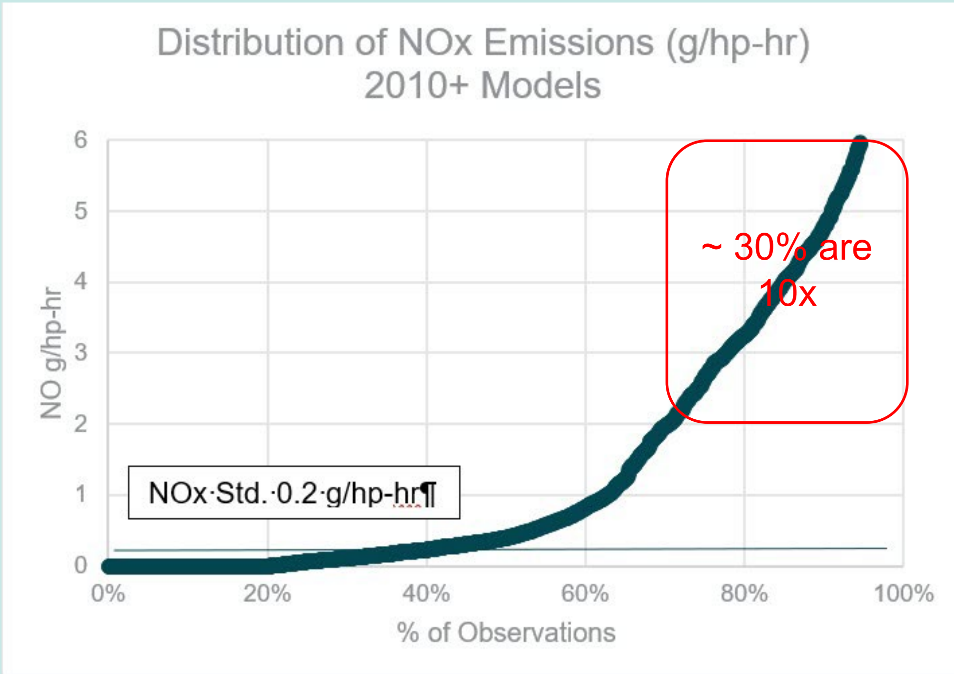


Figure 57: Distribution of HDV PM emissions (g/hp-hr) 2010 and newer models

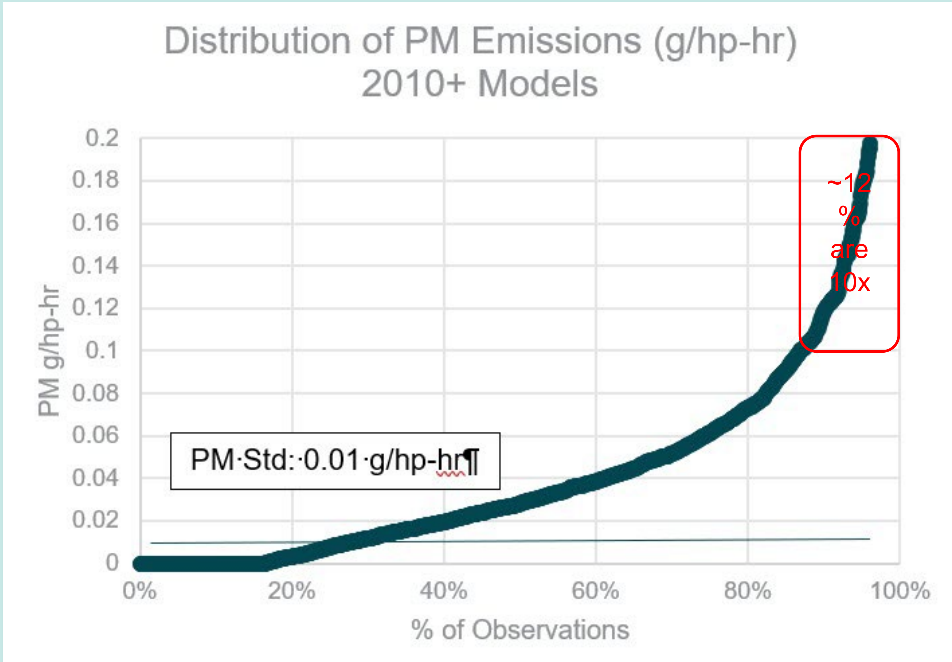


Figure 58: Distribution of HDV CO emissions (g/hp-hr) 2010 and newer models

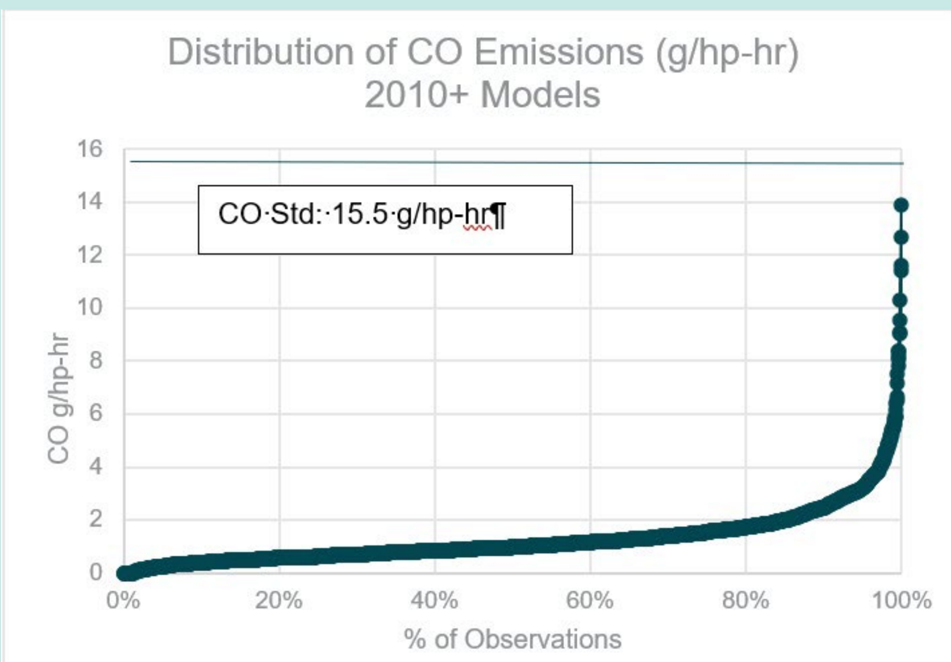
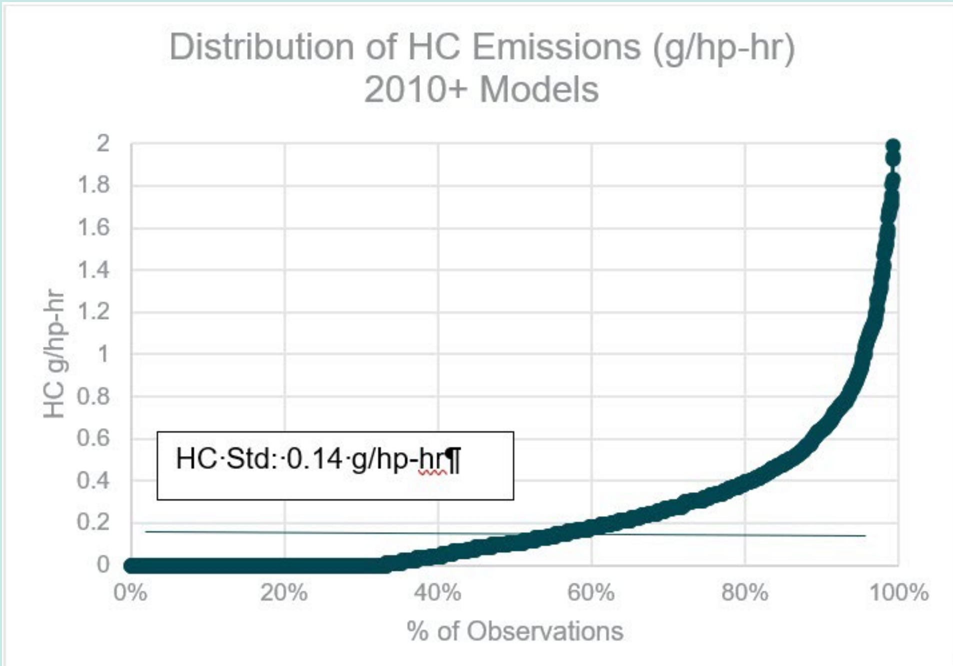


Figure 59: Distribution of HDV HC emissions (g/hg-hr) 2010 and newer models



7.2.3 Comparison of HDV emissions with California and emission benchmarks

The California Air Resources Board (CARB) contracted the Opus team in November 2020 to conduct RSD tests on heavy-duty diesel-powered vehicles at the agricultural inspection station in Mountain Pass, California. Figure 60, Figure 61, and Figure 62 compare distributions of NO_x, PM, and HC emissions for 2010 and newer vehicles registered in California with vehicles registered in Alberta. Both groups are required to meet emission benchmarks of 0.2 g/hp-hr NO_x, 0.01 g/hp-hr PM, and 0.14 g/hp-hr HC. Both sets of measurements were made in comparable weather/temperatures (November at Mountain Pass, California, and July through August in Alberta). These distributions are slightly different than the distributions shown in the previous section. These distributions show the **percent of vehicles** vs. the percent of observations.

The differences in emissions are most pronounced for NO_x, the ozone precursor of primary concern emitted by HDVs. Estimated NO_x emissions in Alberta start to deviate from emissions in California at around the 20% level. California vehicles start to exceed the NO_x emission benchmark at the 55% level while Alberta vehicles start to exceed the emission benchmark at around the 30% level. **Approximately 30% of the Alberta HDVs appear to emit NO_x 10 times the emission benchmark** (Figure 56)**, levels at which malfunctions or tampering are suspected.**

Estimated PM emissions in Alberta start to deviate from emissions in California at around the 15% level. It appears that a greater percentage of heavy-duty vehicles in Alberta have malfunctioning or tampered NO_x and PM emission control systems than in California.

About the same percentage of trucks in both areas exceed the HC emission benchmark. At the tail of the HC emissions distribution, California vehicles have higher HC emissions than Alberta vehicles.

Figure 60: HDV NO_x distribution—Alberta vs. California

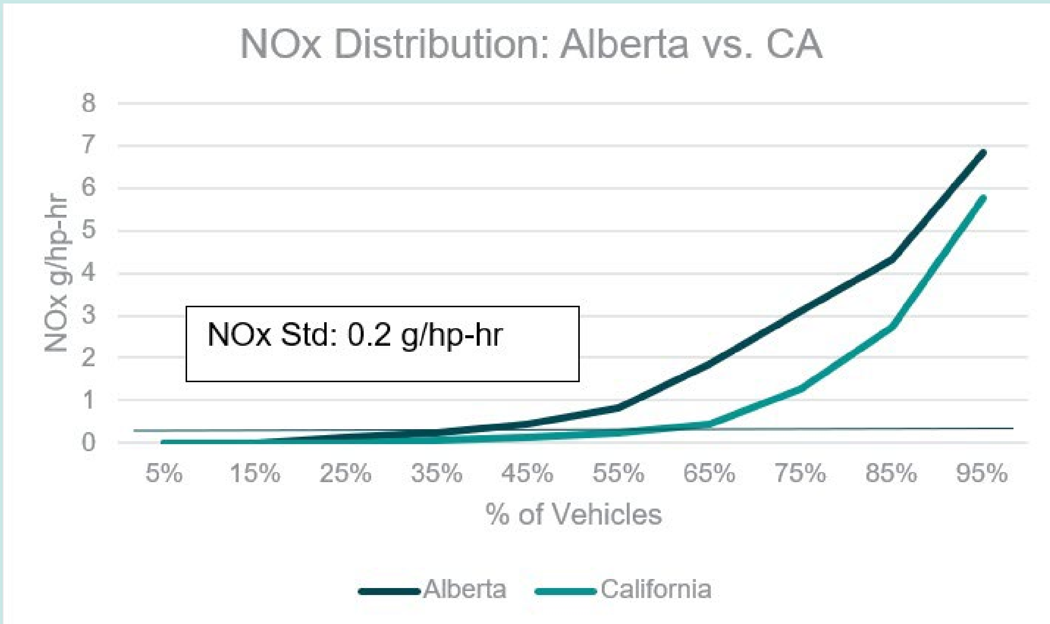


Figure 61: HDV PM distribution—Alberta vs. California

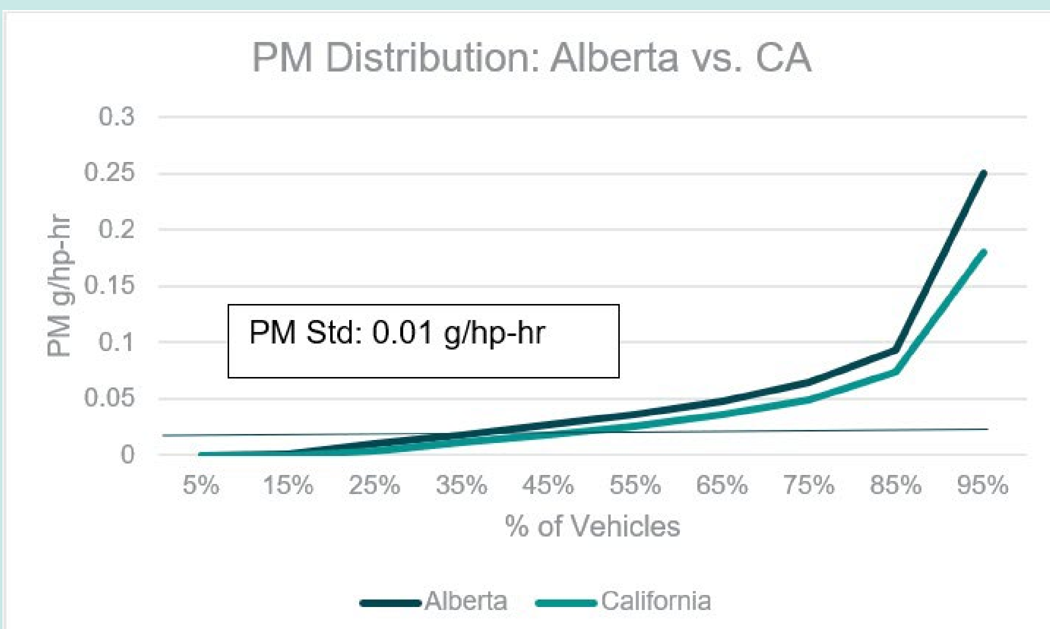


Figure 62: HDV HC distribution—Alberta vs. California

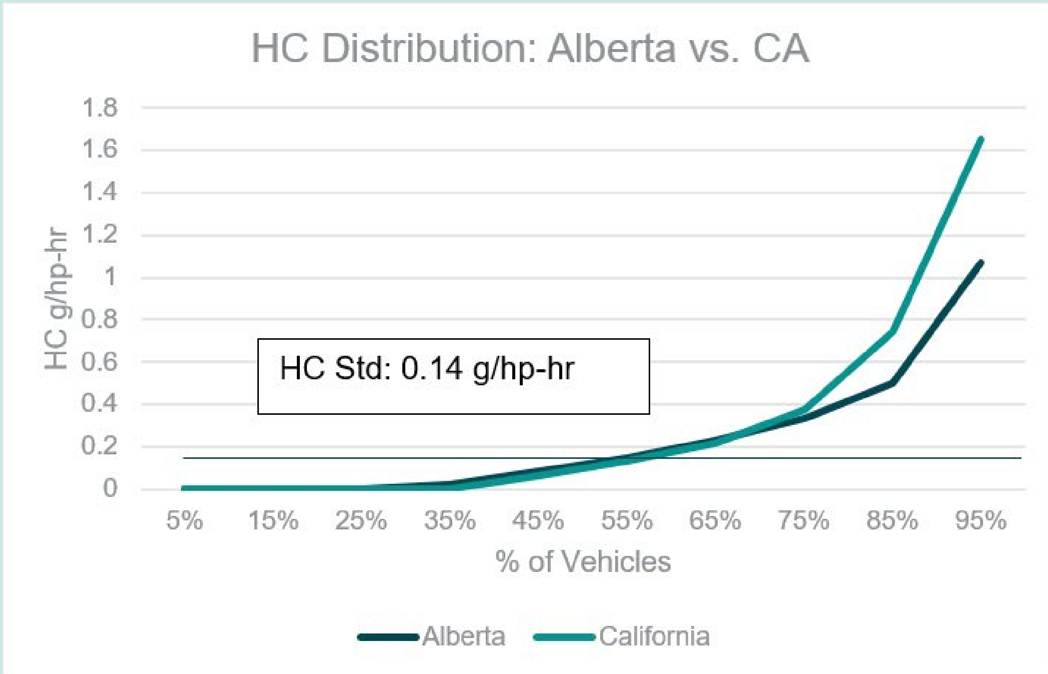


Figure 63, Figure 64, and Figure 65 compare average NO_x, PM, and HC emissions for two groups of heavy-duty diesel powered vehicles, 2010 to 2015 models and 2016 and newer models. Average NO_x and PM emissions for vehicles registered in Alberta are much greater than for vehicles registered in California. For the 2010 to 2015 group, both samples exceed the NO_x emission benchmark by a significant margin. Average PM emissions exceed the emission benchmark by a significant margin for both groups of 2010 to 2015 and 2016 and newer vehicles.

Figure 63: Comparison of HDV NO_x emissions—Alberta vs California

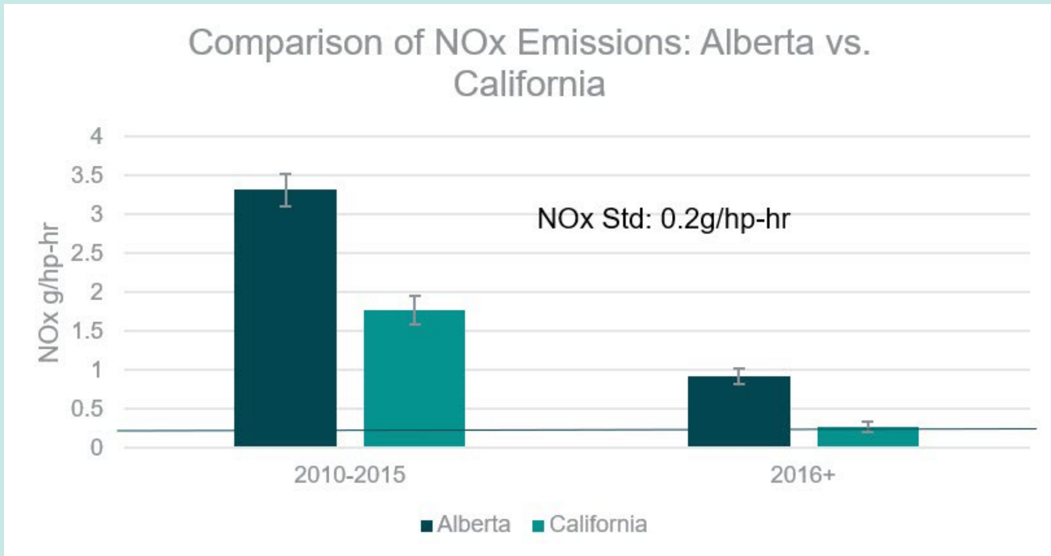


Figure 64: Comparison of HDV PM emissions—Alberta vs. California

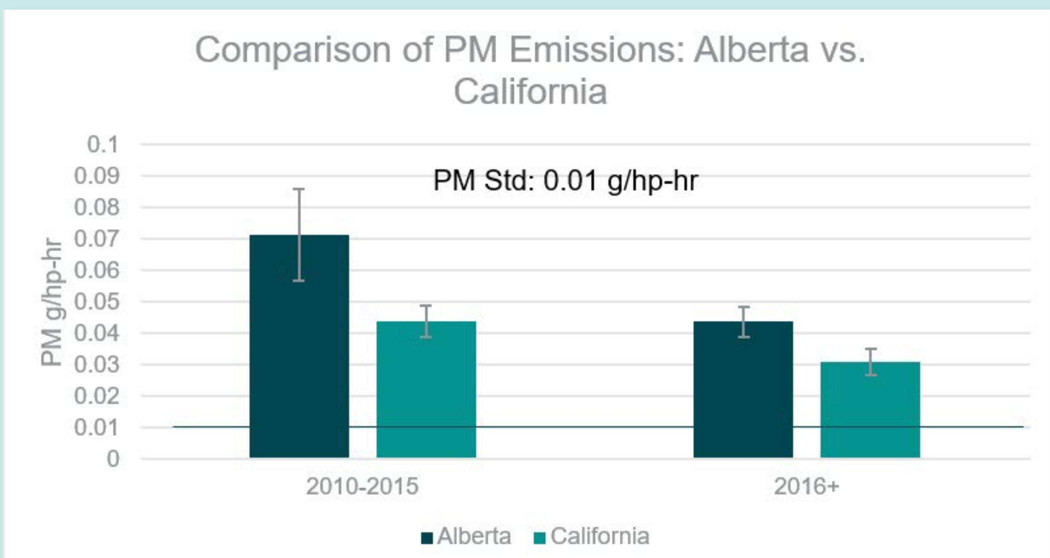
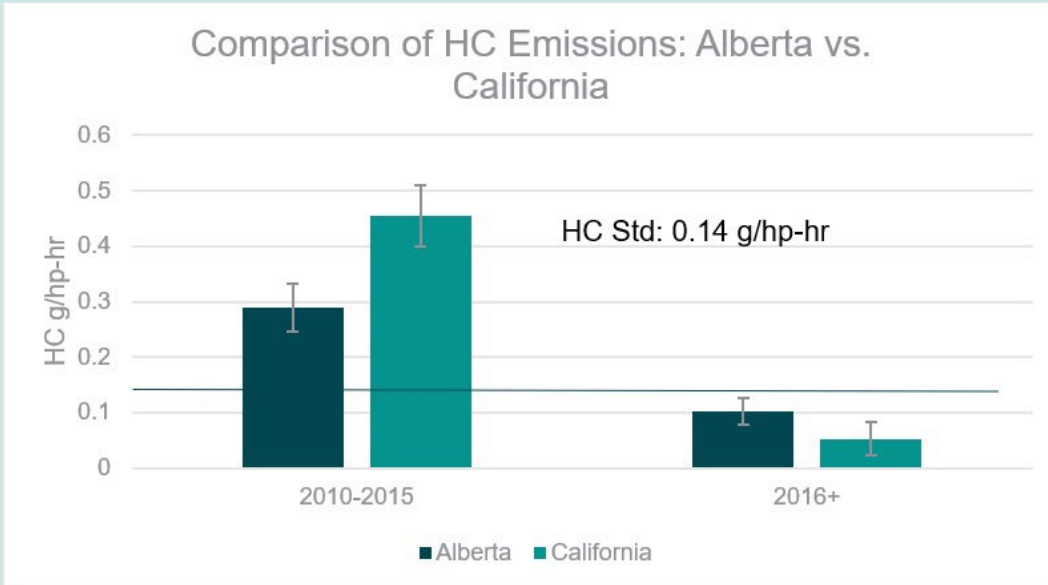


Figure 65: Comparison of HDV HC emissions—Alberta vs. California



7.2.4 Multiple observations of the same heavy-duty vehicle

Large variability in motor vehicle emissions can signal issues with emissions control system performance. dKC identified 2010 and newer vehicles that received four or more valid RSD tests. We then plotted the average, minimum, and maximum NO_x and UV Smoke for each vehicle, sorted from lowest to highest average value. These plots are shown below. As shown in Figure 66, about 60% of the vehicles observed four or more times had very low average, minimum, and maximum NO_x emissions, which indicates that their SCR systems were working correctly to keep levels low. About 30% of the vehicles are suspected of having malfunctioning or tampered systems because their NO_x emissions were higher on average and achieve much higher levels even at the relatively low VSPs observed at the vehicle inspection stations. Trends in UV Smoke are not as clear (Figure 67). Details on each test are provided in Appendix B.

Figure 66: NO_x emissions for HDV seen more than 4 times—model year 2010 and newer

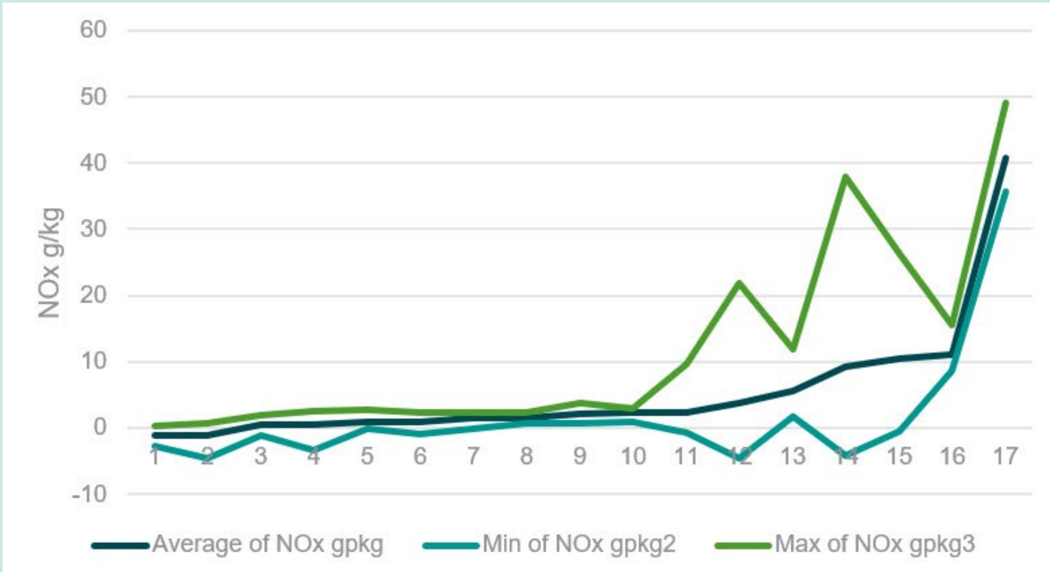
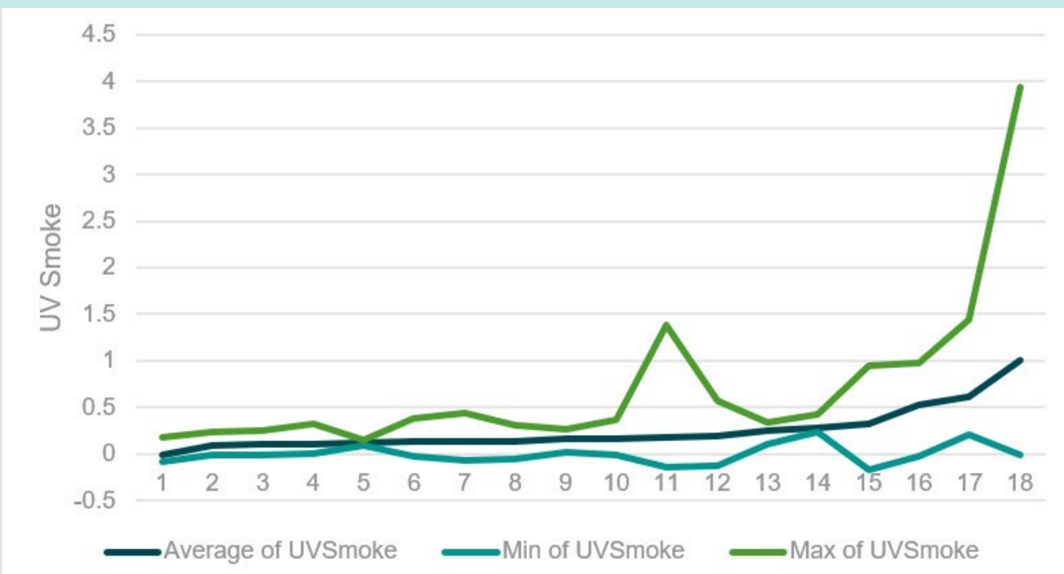


Figure 67: UV smoke emissions for HDV seen more than 4 times—model year 2010 and newer



7.2.5 Multiple observations of the same HDV fleet

In the case of dump and delivery trucks, the rear plate of the vehicle could not be recorded, so Opus personnel used the specially modified HDV TagEdit® software to log other identifying information for individual vehicles or commercial fleets that were observed multiple times. Figure 68 and Figure 69 shows NO_x and UV Smoke emissions grouped by the fleets and vehicles seen most often, sorted from lowest to highest value. Observations labelled 5367 and LOGO were individual vehicles. Several trends are evident. Some fleets, such as RGS and RGS-P, have mainly low values with one or two high values. Some vehicles, such as 5367 and LOGO, have high values for all observations.

Figure 68: HDV NO_x emissions for fleets/vehicles seen multiple times

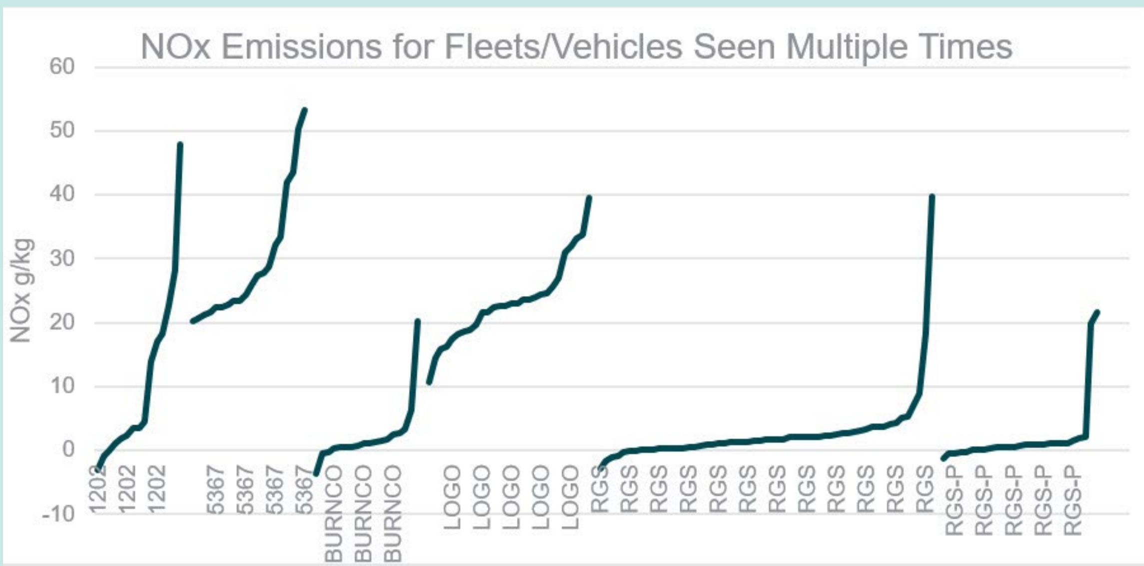
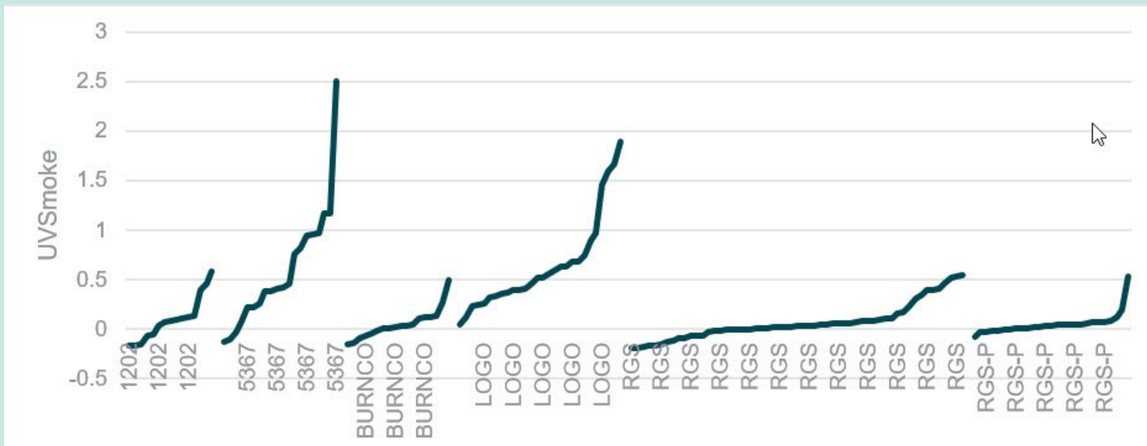


Figure 69: HDV UV smoke emissions for fleets/vehicles seen multiple times



7.2.6 HDV emissions by testing site

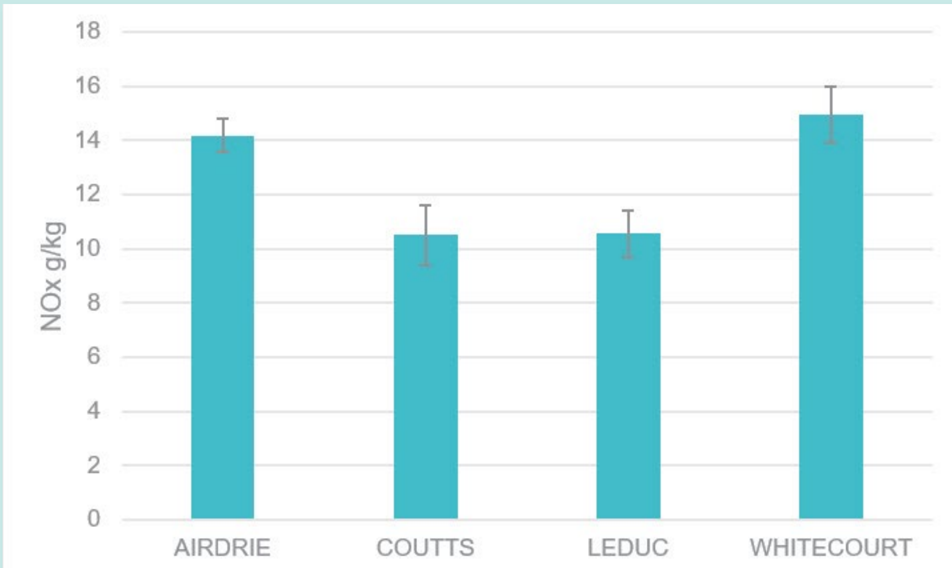
Table 9 presents the number of observations and average NO_x by testing location. Despite having the newest fleet, Demmitt, with its relatively large population of specialized heavy trucks supporting the oil and gas industry, had the highest average NO_x emissions.

Table 9: RSD Observations of heavy-duty vehicles by testing location

City	# of Obs	Average NO_x g/kg	Average Model Year	Location Notes
AIRDRIE	3025	14.18	2014.7	N of Calgary, measuring NB traffic
ATMORE	105	8.08	2016.7	NNE of Edmonton
COUTTS	817	10.51	2017.8	SSE of Edmonton Near US Border
DEMMITT	88	19.69	2016.5	WNW of Edmonton Near BC Border
LEDUC	1256	10.56	2016.6	S of Edmonton, measuring SB traffic
WHITECOURT	956	14.94	2015.0	WNW of Edmonton

Figure 70 shows average NO_x for all vehicles by testing location. Two locations with few observations (Atmore and Demmitt) are not shown. Error bars (95%) are shown. Average NO_x was significantly lower at the Coutts and Leduc sites than at the Airdrie and Whitecourt sites. Average model year for observations at the Coutts and Leduc sites was higher (newer) than average model year at the Airdrie and Whitecourt sites, which could explain some of the differences. Also, the type of truck varied by testing location. Airdrie had the lowest percentage of tractor trailers (62%) and the highest percentage of dump trucks (24%). Coutts had the highest percentage of tractor trailers (97%).

Figure 70: Average HDV NO_x (g/kg) by testing location



Appendix G has the results of RSD tests on HDVs in Vancouver that were performed in 2012.

7.2.7 Emissions by truck type

Table 10 presents the number of observations and average NO_x by HDV Vehicle type. As explained in Section 6.2.5, Opus team members tried to maximize use of the valid measurements, even when the license plates were not available, by at least binning them into four discernible categories. This made it possible to include 6181 of the 6339 (97.5%) valid HDV measurements in this analysis. The analysis indicates tractor trailers had the lowest NO_x emissions among the HDVs.

Table 10: Average RSD NO_x Emissions by HDV Vehicle Type

Truck Type	Average NO_x (g/kg)	# of Observations	% of Total
Delivery—HDV/MDV	9.45	410	6.6
Dump—HDV	17.93	846	13.7
Pickup—MDV	14.21	410	6.6
Tractor Trailer—HDV	12.37	4515	73.0
Total		**6181**	

8. Conclusions

The goal of the ROVER III project was to characterize emissions of passenger cars, light-duty trucks, and heavy-duty trucks in Alberta in hopes of identifying non-point source opportunities for emissions reduction from the transportation sector. Key conclusions from our analysis are listed below.

Light-duty vehicles

- For light-duty vehicles (LDV), almost all (99.4%) RSD observations across the five Alberta cities were on vehicles registered in Alberta; 95.1% of the observations were on gasoline fuelled vehicles. About two-thirds of the vehicles measured were light trucks (including SUVs) versus cars.
- LDV emissions varied by city with some significant differences; CO and NO emissions were lowest for the Fort McMurray observations, in part due to a slightly newer fleet, while HC emissions were lowest for Edmonton observations. [Section 7.1.8]
- A majority of model year 2003 and newer LDVs (which account for 97% of the LDV kilometres travelled) met emission benchmarks for CO and NO emissions; that is, 83% and 63% of the CO and NO measurements met emissions benchmarks. In contrast, 45% of the HC measurements of 2003 and newer LDVs met emission benchmarks. Model year 2003 and newer vehicles with excess HC emissions (55% of the vehicles) account for 90% of the total HC excess emissions from this group, an opportunity of HC emissions reductions. [Sections 7.1.3, 7.1.7]
- Although overall LDV emissions have decreased substantially in the 15 years since ROVER II, all model year groups had ***high emitters***. Even the 2013 and newer group, which are within their useful life and expected to meet the emissions benchmarks, harbor 53% of the excess HC emissions. [Section 7.1.4] Conversely, well-maintained older model vehicles have low emissions. [Section 7.1.3]
- The uninspected Alberta LDV fleet exhibited typical gamma-distribution emissions trends (mostly clean with a long ever-diminishing tail of increasingly dirty), albeit from a higher base level of emissions than both the periodically inspected and uninspected LDV fleets in Oregon, particularly for HC; and as expected, had a greater percentage of high emitters. [Section 7.1.5]
- Models 1998 and newer have OBD-II systems, which might partially account for their drastically lower emissions compared to 1997 and older models. An advisory **high emitter** program might be effective in getting motorists to seek repairs when their Malfunction Indicator Lamp (MIL) is on, even if they are not directly seen by RSDs.

Heavy-duty vehicles

- For heavy-duty vehicles (HDV), 73% of the measurements at the six vehicle inspection stations (VIS) across Alberta were of tractor-trailers and 17% were registered outside of Alberta.
- HDV emissions varied by VIS testing location with some significant differences. NO_x emissions in Demmitt appeared the highest on average despite having the newest fleet of rather specialized oil and gas vehicles. Coutts and Leduc had the lowest of largely long-haul tractor-trailers. [Section 7.2.6]
- NO_x and estimated PM emissions for HDVs registered in Alberta are much higher than for HDVs registered in California. [Section 7.2.3]

- There is evidence that a significant portion of the HDV fleet have emissions far exceeding the emissions benchmarks, indicating potential malfunctions, or tampering of emission control systems. [Section 7.2.2]
  - Most NO_x observations (62%) of diesel-powered HDVs at VIS stations in Alberta exceed the NO_x emission standards.
  - NO_x and particulate matter (PM) emissions for most 2010 and newer models, all of which are required to be designed with the latest emissions control devices, exceed their emission benchmark, a signal of a potential problem, but not necessarily a definitive indicator of non-compliance with the federal vehicle emissions standard. [Section 7.1.2, 7.2.2]
  - However, approximately 30% of all Alberta HDVs appear to emit NOx 10 times the emission benchmark, and sustained high average NOx in HDVs measured multiple times under the low engine loads observed at vehicle inspection stations support an estimate that 30% of the HDV fleet may have malfunctioning or tampered emissions control systems. [Section 7.2.4]
- RSD can serve to identify heavy-duty vehicles with the highest NO_x emissions, suspected of having malfunctioning or tampered emission control systems. One approach can be screening of the highest emitters at vehicle inspection stations and issuing an advisory notice during a secondary inspection that includes checks of emissions control systems.

9. Appendix A—Average of All Observations vs Average by VIN

The charts in the figures below compare average emissions by model year for all observations vs averages by VIN. The trends are nearly identical.

Figure 71: Average NO light-duty vehicles—All observations vs average by VIN

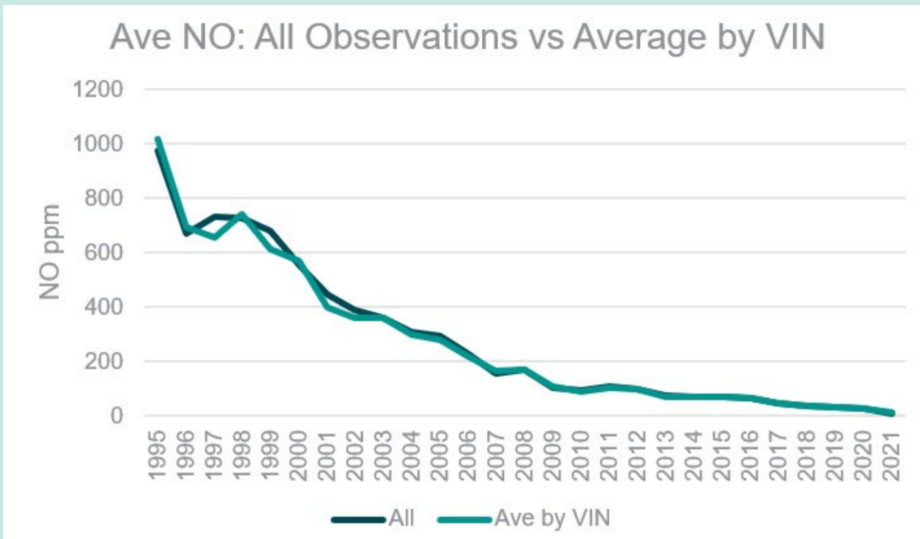


Figure 72: Average NO heavy-duty vehicles—All observations vs average by VIN

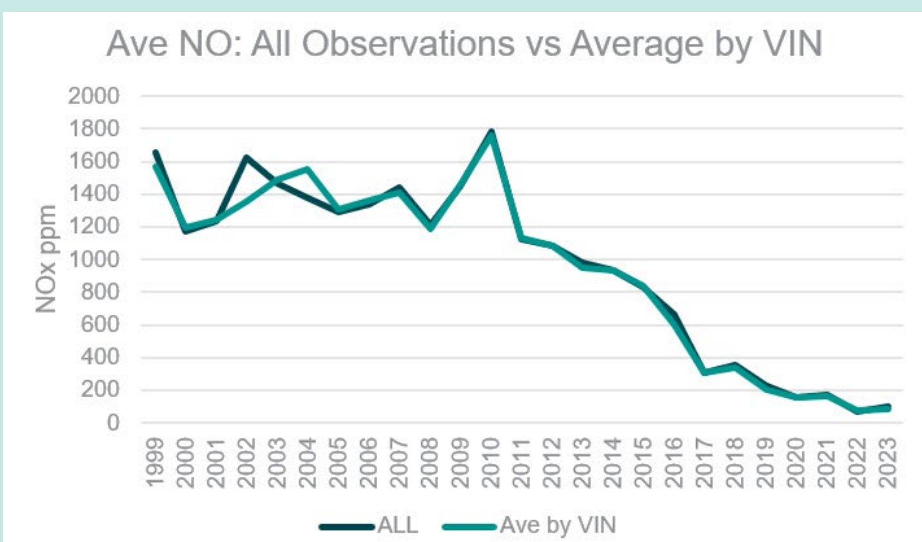


Figure 73: LDVs average CO—All observations vs by VIN

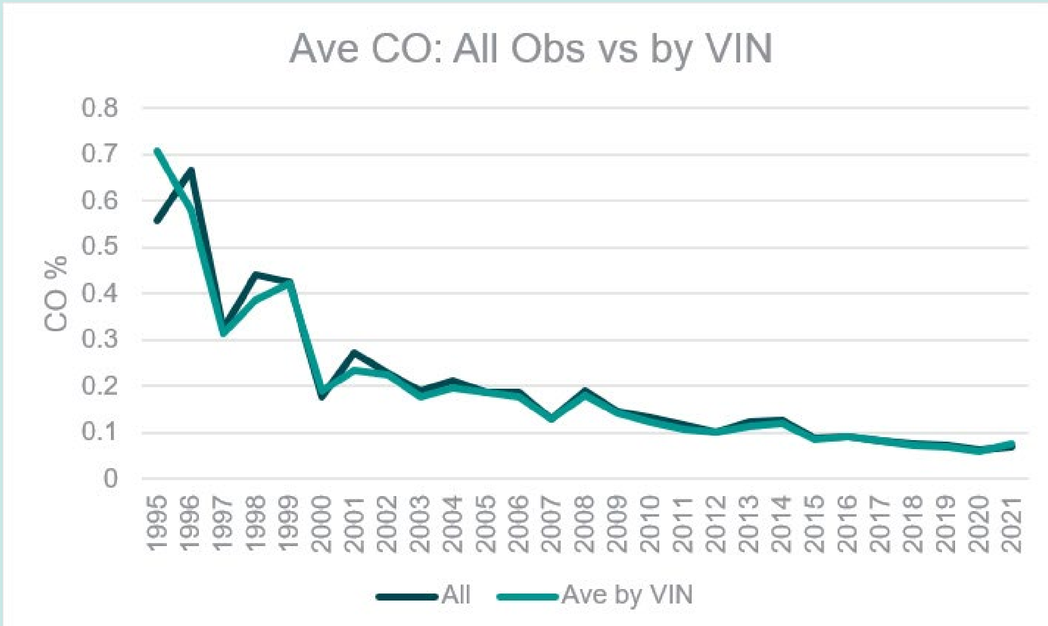
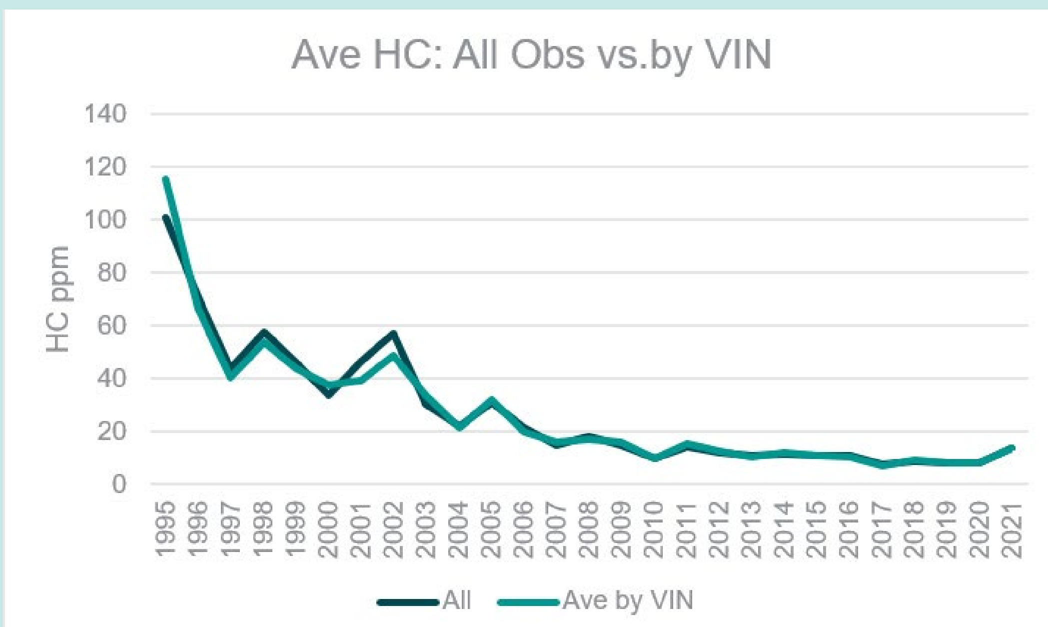


Figure 74: LDVs average HC—All observations vs by VIN



10. Appendix B—NO_x Recorded for 2010 and newer Heavy-Duty Vehicles with Multiple Observations

Table 11 presents all the NO_x readings for 2010 and newer vehicles that were seen four or more times. NO_x is expressed in g/hp-hr assuming a fuel consumption rate of 200 g/KWH. Observations that met the 0.2 g/hp-hr emission benchmark are highlighted.

Table 11: Multiple NO_x readings on the same 2010 or newer vehicle—g/hp-hr

VIN	Model Year		Ave NO_x	Min NO_x	Max NO_x	Individual Tests					
						1	2	3	4	5	6
1	2020		-0.18	-0.40	0.03	-0.40	-0.24	-0.12	0.03		
2	2022		-0.17	-0.68	0.10	-0.68	-0.13	-0.08	-0.04	0.10	
3	2023		0.07	-0.17	0.27	-0.17	0.05	-0.02	0.19	0.27	
4	2020		0.07	-0.51	0.37	-0.51	-0.08	0.15	0.20	0.31	0.37
5	2022		0.14	-0.02	0.43	-0.02	0.14	0.04	0.43		
6	2019		0.15	-0.13	0.34	-0.13	0.12	0.23	0.20	0.34	
7	2021		0.22	-0.02	0.33	-0.02	0.26	0.32	0.33		
8	2020		0.24	0.10	0.35	0.10	0.30	0.19	0.35		
9	2020		0.31	0.12	0.56	0.12	0.22	0.34	0.56		
10	2020		0.34	0.12	0.43	0.12	0.40	0.40	0.43		
11	2019		0.36	-0.11	1.45	-0.11	0.07	0.10	0.28	1.45	
12	2023		0.55	-0.68	3.28	-0.68	-0.35	-0.06	3.28		
13	2020		0.85	0.27	1.77	0.29	0.27	1.07	1.77		
14	2019		1.39	-0.64	5.70	-0.64	-0.20	0.70	5.70		
15	2020		1.56	-0.07	3.95	-0.07	0.11	0.85	2.96	3.95	
16	2015		1.67	1.30	2.34	1.35	2.34	1.67	1.30		
17	2013		6.11	5.36	7.35	7.35	5.55	5.36	6.19		

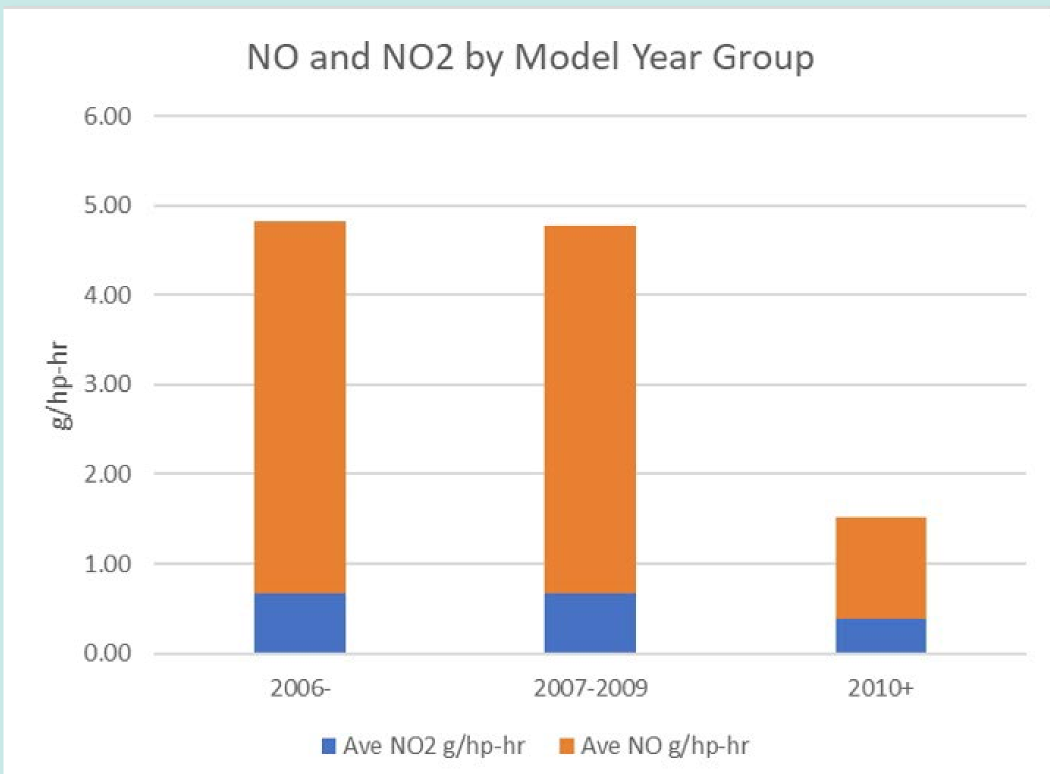
11. Appendix C—NO, NO_2, and NO_x Emissions from Heavy-Duty Vehicles

Table 12 and Figure 75 present average NO and NO_2 in *grams per horsepower x hour* by model year group. Vehicle age has a greater impact on NO emissions than NO_2 emissions. NO_x emissions are the sum of NO and NO_2 emissions.

Table 12: NO and NO_2 Emissions by model year group

Model Year Group	Ave NO_2 g/hp-hr	Ave NO g/hp-hr
2006-	0.66	4.17
2007-2009	0.67	4.11
2010 and newer	0.39	1.12

Figure 75: NO and NO_2 by model year group



12. Appendix D—Canadian Emission Standards for Light-Duty Vehicles

Assumed standards used as benchmarks in the analysis of LDV emissions is seen Table 13 below.

Table 13: Emissions standards assumed in the analysis of light-duty vehicles

Model Year	CO Std (g/km)	HC Std (g/km)	NO_x Std (g/km)
1984	6.20	0.50	0.74
1985	6.20	0.50	0.74
1986	6.20	0.50	0.74
1987	6.20	0.50	0.74
1988	6.20	0.50	0.74
1989	6.20	0.50	0.74
1990	6.20	0.50	0.74
1991	6.20	0.50	0.74
1992	6.20	0.50	0.74
1993	6.20	0.50	0.74
1994	3.41	0.25	0.37
1995	3.41	0.25	0.37
1996	3.41	0.25	0.37
1997	3.41	0.25	0.37
1998	3.41	0.25	0.37
1999	2.60	0.08	0.19
2000	2.60	0.08	0.19
2001	2.60	0.08	0.19
2002	2.60	0.08	0.19
2003	2.60	0.08	0.19
2004	2.28	0.07	0.16
2005	1.95	0.06	0.12
2006	1.63	0.05	0.08
2007 and later	1.30	0.04	0.04

13. Appendix E—Light-Duty Vehicle Emissions by City and Site Combinations

Table 14: Light-duty vehicle emissions by city and site combinations

City	Site	Avg. CO (g/km)	Avg. HC (g/km)	Avg. NO (g/km)	Avg. Model Year	Count
CALGARY	CG01	1.38	0.13	0.16	2012.93	3912
	CG02	1.47	0.10	0.19	2012.85	741
CALGARY Overall		**1.39**	**0.12**	**0.17**	**2012.92**	**4653**
EDMONTON	ED01	1.28	0.06	0.14	2013.77	7794
	ED02	1.06	0.07	0.13	2013.75	2919
EDMONTON Overall		**1.22**	**0.06**	**0.14**	**2013.76**	**10713**
FORT MCMURRAY	FM0001	0.92	0.14	0.06	2014.55	1529
	FM001A	1.23	0.12	0.13	2014.61	687
	FTMAC01HI	0.86	0.08	0.08	2014.52	2868
	FTMAC02LO	0.86	0.08	0.06	2014.23	478
FORT MCMURRAY Overall		**0.92**	**0.10**	**0.08**	**2014.51**	**5562**
GRANDE PRAIRIE	GP01	1.36	0.16	0.16	2013.67	939
	GP02	1.58	0.18	0.21	2014.17	88
GRANDE PRAIRIE Overall		**1.37**	**0.16**	**0.17**	**2013.71**	**1027**
RED DEER Overall	RD01	1.79	0.11	0.21	2013.40	4123

14. Appendix F—Emission Deciles

14.1 Light-duty deciles

Emission measurements by model year group were divided into ten groups or deciles each containing an equal number of ordered measurements. Figure 76, Figure 77, and Figure 78 present the decile charts for light-duty vehicles by model year group. The 1, 2 … 10 values correspond to the average emissions of each decile. These results are for gasoline powered vehicles only.

Emissions for all model year groups are much greater for the higher deciles. This leads to the conclusion that a program that identifies high emitters could result in significant emissions reductions. The charts demonstrate that older model vehicles can have low emissions. Up to the 6th decile, emissions for 1998 to 2005 models are about the same as the 2006 to 2010 and 2011 and newer models. Model year 1998 and newer vehicles have OBD-II systems, which might partially account for their drastically lower emissions compared to 1997 and older models.

Figure 76: CO Emission Deciles—LDVs

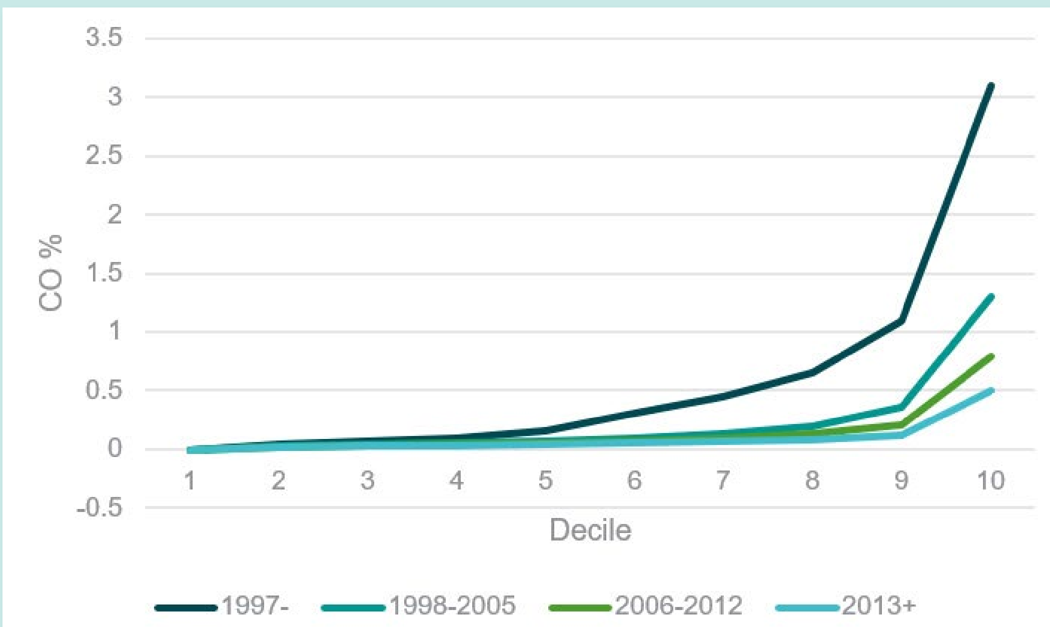


Figure 77: HC Emission Deciles—LDVs

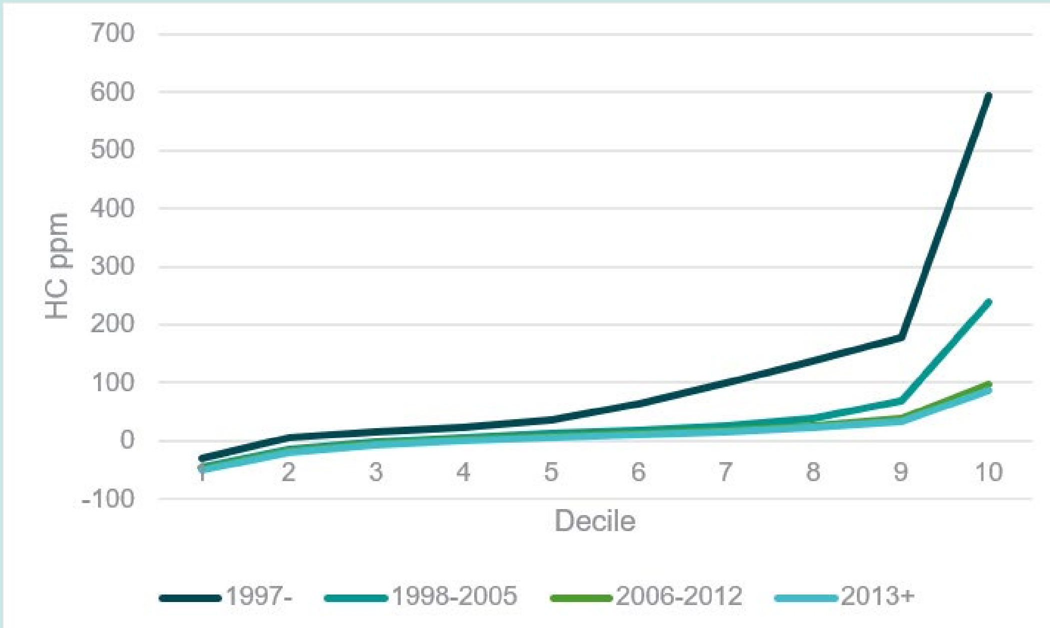
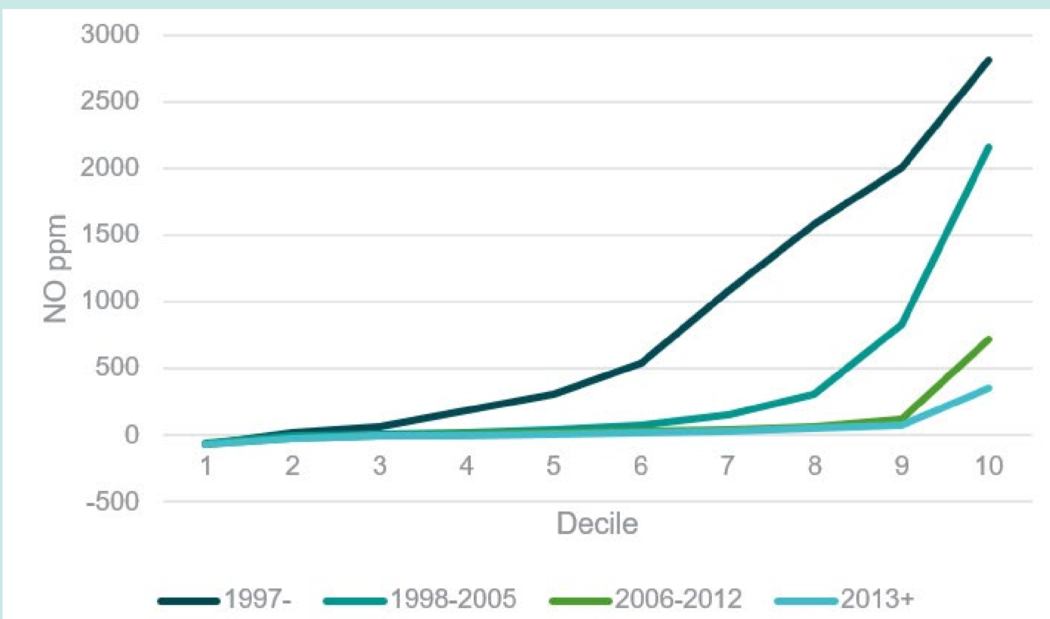


Figure 78: NO Emission Deciles—LDVs



14.2 Heavy-duty deciles

NO_x and smoke emission measurements by model year group were divided into ten groups or deciles each containing an equal number of ordered measurements. Figure 79 and Figure 80 presents the resultant NO_x and smoke decile charts by model year group. The 1, 2 … 10 values correspond to the average emissions of each decile. There is no difference in the decile plot for 2006 and older models and 2007 to 2009 models. Model year 2010 and newer models have much lower NO_x and smoke emissions than the other groups across the range of deciles.

Figure 79: NO_x (g/kg) deciles by model year group—HDVs

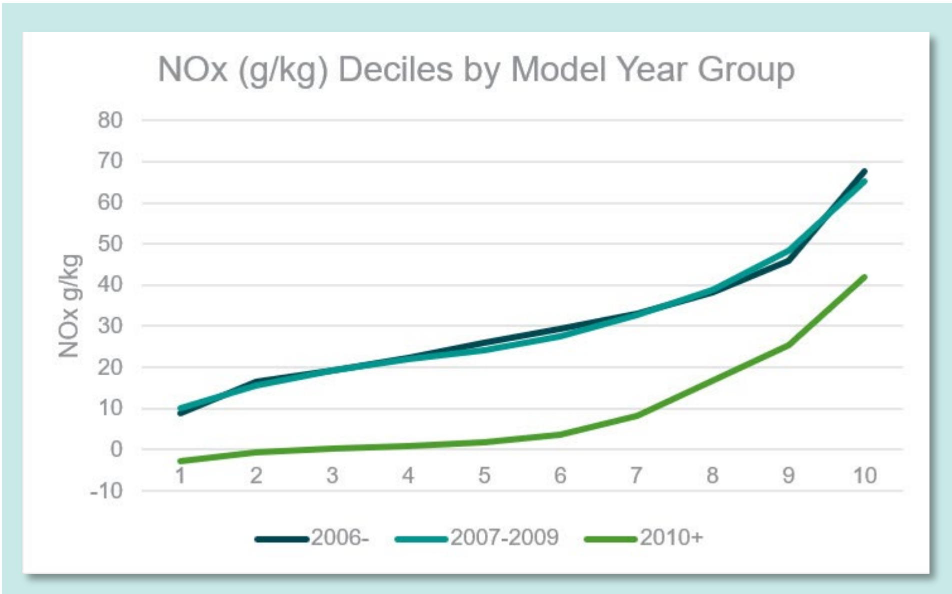
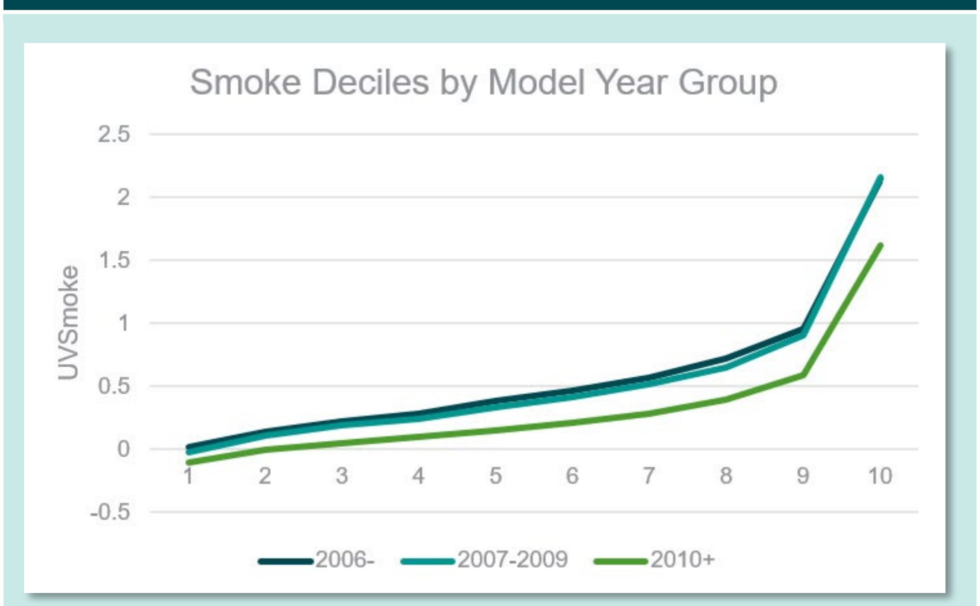


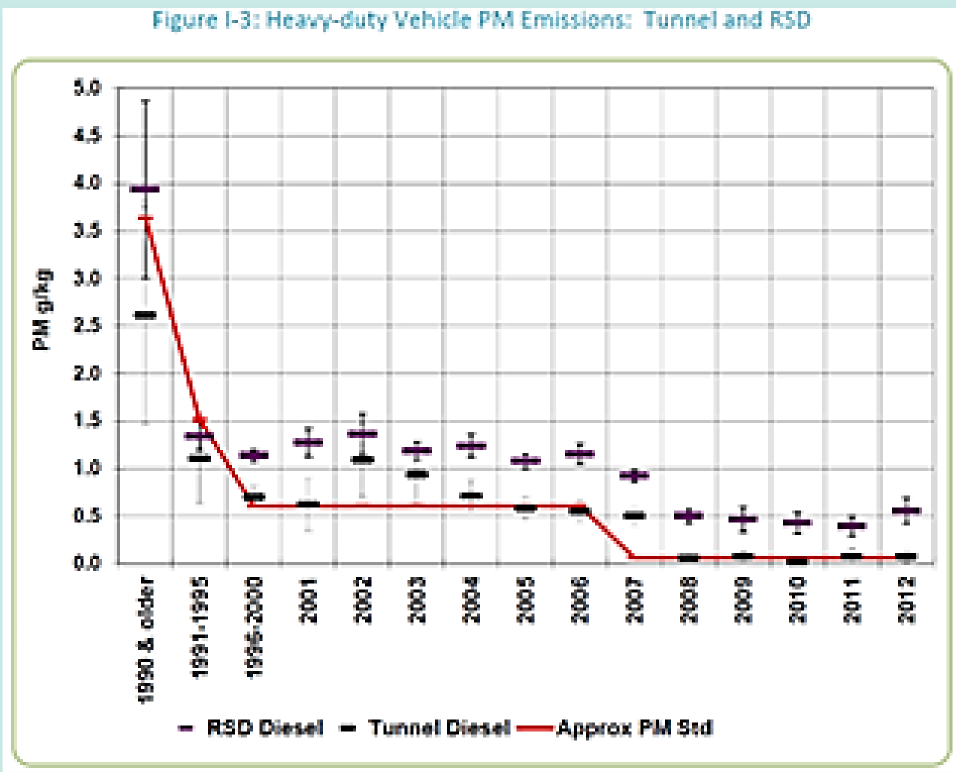
Figure 80: Smoke deciles by model year group—HDVs



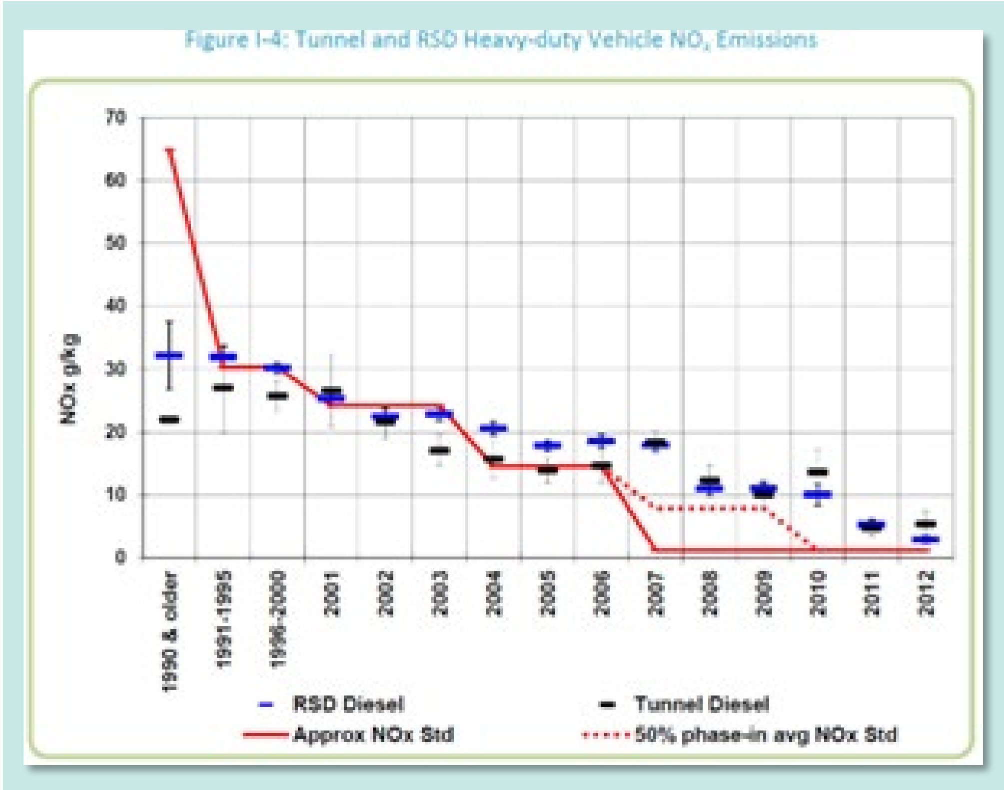
15. Appendix G – 2012 Vancouver HDDV Remote Sensing Study

Heavy duty vehicles were first tested by RSD in Canada in 2012 by Envirotest (now Opus). The Vancouver study used a generation older model 4000 which did not measure NO_2. The study was the first to compare the optical technique of the RSD to the extractive technique of Denver University's Heavy-Duty Tunnel (HDET) which CARB later adopted to develop its PEAQS. HDET applied more conventional NO, NO_2, and PM measurement techniques. Both sets of equipment show similar trends, and agreement between RSD NO and HDET total NOx was very good (Figure 81, bottom graph). Average RSD PM emissions were 0.4 g/kg higher than the HDET measurements across all model years, which may be partially a consequence of the operating mode of the vehicles.

Figure 81: Vancouver study trends—2012



Classification: Protected A



More than 76% of the HDVs measured were 2007 and older, and likely equipped with Diesel Oxidation Catalyst and Exhaust Gas Recirculation, but not DPF and SCRs.[41] The 2007 and older vehicles emitted 90% of the NOx and 98% of the PM. PM dropped significantly with the adoption of DFPs in 2008 and NOx with the adoption of SCRs in 2011.

Average PM emissions hovered at or above certification standards with no evidence to suggest tampering of DPF was prevalent. The existence of AirCare On-Road (ACOR), which tested trucks for (snap acceleration) opacity each year may have played a factor. An earlier evaluation of ACOR impacts on opacity testing found *the percentage of HDDV with exhaust opacity less than 20 percent had steadily risen from 62% in 1995 to over 98% in 2002. The large change in the opacity distributions between 1995 and 2000 is the result of both an improvement in the engine control technology and the deterrent and enforcement effect of the ACOR program.*[42]

NOx standards were phased in for diesel engines between 2007 and 2010 on a percent-of-sales basis: 50% from 2007 to 2009 and 100% in 2010. 2011 was likely the first year SCR-equipped HDDVs were observed in Vancouver and tampering of these devices and the sale of commercial SCR Delete devices was not as prevalent as today.[43]

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[41] Tampering and Aftermarket Defeat Devices; Acevedo & Yarborough, USEPA, April 25, 2019; https://www.epa.gov/sites/default/files/2019-05/documents/tampering-aftermarket-defeat-devices-2019-mcdi-mtg-33pp.pdf.

[42] Review of the AirCare On-Road (ACOR) Program; G.W. Taylor Consulting, May 2002; AirCare On-Road (ACOR) Program - Review May 2002 (metrovancouver.org)

[43] Illegal Emissions Tampering on Diesel Trucks is Rampant - and Apparently a Big Business; Green Car Reports, November 2020; https://www.greencarreports.com/news/1130445_illegal-emissions-tampering-on-diesel-trucks-is-rampant-and-apparently-a-big-business