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On-road NO_x Emissions Evaluation of the Repair Effectiveness for Recalled Volkswagen Group Light-duty Diesel Vehicles in the United States

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KEYWORDS

Dieselgate, diesel emissions, NO_x emissions, on-road remote exhaust sensing.

ABSTRACT

The admission by the Volkswagen Group in the fall of 2015 that they had duped the United States new vehicle emissions certification testing resulted in perhaps the most expensive violation of U.S. environmental vehicle emission regulations in its history. As part of the subsequent recall of more than 500,000 vehicles in the U.S., owners could sell their vehicles back to the companies or have them repaired. We have used a number of large on-road emission measurement data sets that were routinely collected before and after the recall to evaluate the fuel specific NO_x emissions benefit for the vehicles that were repaired and remained in service.

We found that on-road fuel specific NO_x emissions were reduced by 83% from the pre-repair group. The reductions increased to 91% if we only compare with vehicles that were fully repaired. NO_2 emissions were dramatically reduced by an even larger percentage >95%. We find that the repairs resulted in fuel specific NO_x emissions that are comparable or slightly lower than in-use light and medium-duty diesel trucks measured in Denver in 2020 indicating the repairs were a success.

SYNOPSIS

To report on the in-use effectiveness of NO_x emission repairs in VW Group diesel vehicles in the United States.

Introduction

In the late 1800's when Rudolf Diesel wanted to improve upon the thermal efficiency of the steam engine he settled on a design that relied on high compression of the air in the cylinder to self-ignite the fuel and the diesel engine was born.[1] The ability to operate at high air-to-fuel ratios make diesel engines particularly cost efficient for the amount of work produced and they are still the engine of choice for large on- and off-road vehicles, locomotives and ships.[2] The utilization of diesel engines in passenger cars did not occur until the 1930's and remained relatively small until the 1990's. European leaders, seeing an opportunity to reduce carbon dioxide (CO_2) emissions to combat climate change, encouraged sales of diesel vehicles through various tax reductions, especially on fuel.[3, 4] This led to a rapid rise in the percent of diesel powered vehicles, and in many European countries they grew from less than 10% to a majority of the fleet.[5]

Uncontrolled diesel emissions can include large amounts of soot and oxides of nitrogen emissions ($NO_x \equiv NO + NO_2$) that can produce negative health effects and contribute to ozone and secondary particulate formation.[6-9] As the diesel vehicle percentage of the on-road fleet grew across Europe researchers began to report worrisome rises in ambient NO_2 emissions through significant increases in the observed NO_2/NO_x ratios along roadways.[10, 11] Jerksjö and Sjödin first reported in 2008 the curious observation that on-road NO_x emission reductions from Swedish diesel powered passenger cars, with increasingly stringent European certification standards, were significantly less than their gasoline counterparts and that NO_2 comprised a majority of the NO_x emissions in the newest diesel models.[12] This was followed with similar reports from the United Kingdom and Switzerland suggesting that something had gone awry in the emissions certification process for light-duty diesel powered vehicles.[13-16]

In the United States (U.S.) there were no incentives to own light-duty diesel powered vehicles. Because of their negative health consequences California actively discouraged their use resulting in a very small percentage in the on-road fleet.[17] However, the "clean diesels" introduced in 2009 by Volkswagen, Audi and Porsche (VW Group) and other manufacturers' significantly reduced soot and NO_x emissions using advanced after-treatment devices, and sales of light-duty diesels increased. Not long after their introduction in the U.S. the International Council for Clean Transportation contracted with West Virginia University to perform in-use and certification emissions testing on three light-duty diesel vehicles to help understand the source of the high in-use NO_x emissions observed in Europe. The results were unexpected: the two VW Group vehicles easily met NO_x emission limits during the laboratory certification testing but emitted several orders of magnitude higher NO_x emissions when operating on-road. The third vehicle from a different manufacturer had on-road emissions that were higher than certification limits but substantially lower than the two VW Group vehicles.[18] The West Virginia results were corroborated by on-road emission measurements we collected from a larger fleet of VW Group vehicles in Denver, CO., Los Angeles, CA. and Tulsa, OK. showing no reductions in NO_x emissions between the light-duty pre-control diesels (2006 & older) and the new "clean diesels" (2009 & newer) that included significant increases in tailpipe NO_2 emissions (Figure S1).[19]

In the fall of 2015 the VW Group admitted to gaming the system – vehicles operated in a controlled (low NO_x) emissions mode under certification tests but in an uncontrolled emissions mode for on-road operations. While not the first manufacturer to be charged by the United States Environmental Protection Agency and the State of California for using a "defeat device" it will likely be the most expensive in history.[20-22] As a part of its settlement the VW Group agreed to offer U.S. owners the options of having their vehicle repurchased along with additional cash or additional cash plus an approved emissions repair.[23] While many of the vehicles were sold back to the companies, some owners had their vehicles repaired and they remain in the fleet today. This paper uses on-road NO_x emission measurements to evaluate the effectiveness of those repairs and how the repaired vehicles compare to other diesel vehicles in the fleet.

Materials and Methods

All of the emission databases used in this analysis (Table S1 and S2) were collected using the Fuel Efficiency Automobile Test (FEAT), a remote vehicle tailpipe exhaust sensor developed at the University of Denver. Using a combination of four non-dispersive infrared detectors (a reference channel (3.9µm), carbon monoxide (CO, 3.6µm), CO_2 (4.3µm) and hydrocarbons (HC, 3.3µm)) and two dispersive ultraviolet spectrometers (NO (205 - 226 nm), ammonia (NH_3, 198 to 215 nm and NO_2 (430 to 450 nm)) FEAT measures vehicle exhaust gases as a molar ratio to exhaust CO_2 (i.e. CO/CO_2, HC/CO_2, NO/CO_2 etc). The detectors sample at 100Hz and the system and method have been fully described in the literature.[24-28]

Each tailpipe ratio measurement (CO/CO_2, HC/CO_2, NO/CO_2 etc) is scaled by its analogous certified gas cylinder ratio (see supporting information) measured daily as needed to correct for variations in instrument sensitivity and in ambient CO_2 levels caused by changes in atmospheric pressure, temperature and background CO_2. The measured molar ratios are converted into grams of pollutant per kilogram of fuel via carbon mass balance using a carbon mass fraction of 0.86.[29] Each measurement includes a video image of the license plate of the vehicle which is manually transcribed and used to retrieve non-personal vehicle information including make, model year, vehicle identification number (VIN) and fuel type from vehicle registration records.

The pre-repair group was selected from seven data sets collected between September 2013 and January of 2016 at sites in Chicago IL., Denver CO., Los Angeles CA. and Tulsa OK. (Table S1).[19, 30] The affected models were 2009 to 2017 model year diesel vehicles manufactured by Volkswagen, Audi and Porsche. Since the VW Group diesel vehicles were a tiny percentage of the on-road fleet, the number of vehicles included in this analysis is restricted despite having an extensive data set to draw from. For this reason all ages, engine sizes and vehicle types (passenger or SUV) have been combined in this analysis.

Emission repairs were approved for most models and generations during 2017 and early 2018 and repairs were completed by early 2019. The 2016 and 2017 model year vehicles that had not been sold to the public at the time of the admission were not technically subject to the recall but were repaired prior to being sold to the public. Each manufacturer established a website (www.vwdieselinfo.com, www.audidiesellookup.com and www.porschediesellookup.com) where the status of emission repairs (Full, Partial or No Record) could be looked up for a specific vehicle by its VIN. However, they did not provide dates for when the repairs were performed and this reduced the number of data sets that could be used for the post-repair analysis (Table S2) to the three that were collected between September 2019 and September 2020, well after the repair program closed.

Results and Discussion

Using the seven databases collected before Volkswagen's admission, we were able to identify 401 diesel vehicles with valid NO_x emissions (Table S1) for the pre-repair group from 152,000 measurements. In general pre-control compression ignition engines will emit higher levels of NO_2 in their exhaust compared to gasoline vehicles but it rarely exceeds 10% of the NO_x emissions. In modern diesel engines with selective catalytic reduction (SCR) after-treatment NO_2 levels are very low due to reaction with soot in the diesel particulate filter and finally catalytic reduction in the SCR.[31] One of the distinguishing characteristics of the pre-repair VW Group diesel vehicles' on-road emissions were high NO_2/NO ratios (>1:1 on a mass basis) observed in the measurements (Figure S1).[19]

The three databases collected after recall repairs were performed included more than 62,000 measurements resulting in 131 vehicles being identified for the post-repair group (Table S2). Many owners chose to sell their vehicles back to the manufacturers in lieu of having them repaired, further shrinking the size of this fleet. The post-repair group is 1.7 model years newer than the pre-repair group (Tables S1 and S2) suggesting that owners favored repairing newer model year vehicles.

Figure 1 plots fuel specific NO_x emissions versus model year for the pre-repair, post-repair all measurements and post-repair fully repaired groupings (see Table S3). Uncertainties are standard error of the mean determined from the daily measurements and there is only one 2016 model

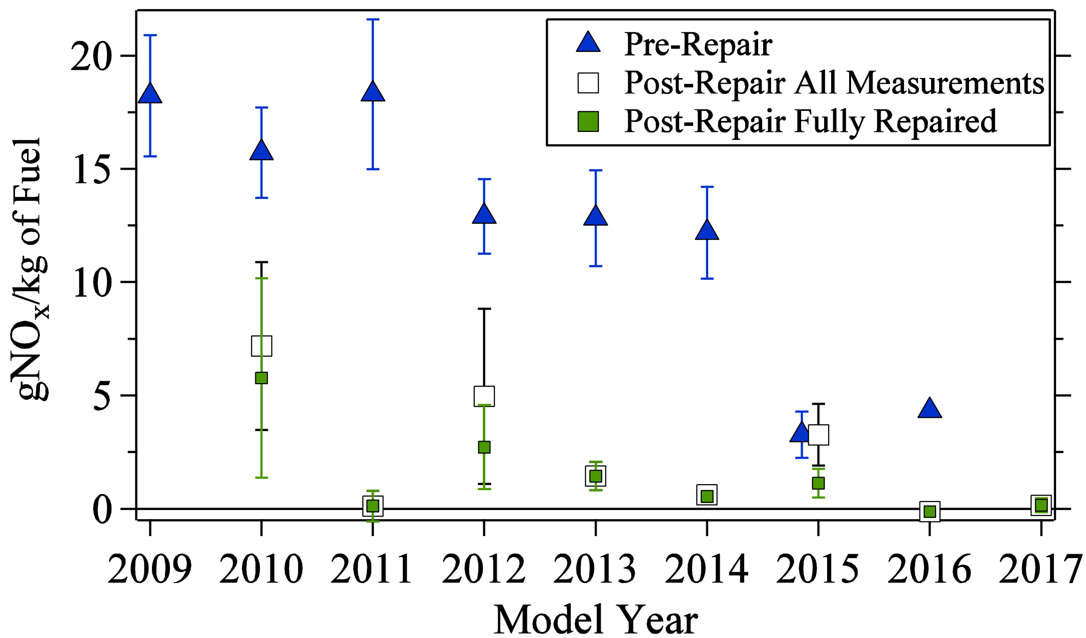

Figure 1. Fuel specific NO_x emissions for the pre-repair (triangles), post-repair all measurements (open squares) and post-repair fully repaired (filled squares) versus model year for the VW Group vehicles. Uncertainties are standard error of the mean calculated from the daily means and there is only one measurement for the 2016 model year for all categories.

year measurement in each group. The fully repaired group only includes vehicles identified by the manufacturers as having completely received the U.S. EPA approved repairs. Partial repairs, as identified by the manufacturers and no record of any repairs are included only in the all measurements group. All model years for the post-repair all measurements group show emission reductions except for 2015 model year vehicles. The pre-repair data suggests that NO_x emissions were lower in the 2015 and 2016 models but there are too few measurements (23) for these models to say this with any certainty.

Table 1 summarizes the mean fuel specific emission measurements for each vehicle grouping. Uncertainties are standard error of the mean determined from the daily measurements for all but the post-repair partial or no record grouping. The post-repair all measurement NO and NO_x emission means are dominated by the 2020 Chicago measurements (see Table S2) which make up almost half (61 out of 131) of the post-repair measurements and include 9 of the 17 post-repair partial or no record group measurements. Four of the nine Chicago measurements are from two vehicles (a 2012 no-record vehicle and a 2015 partial repair vehicle with 3 measurements) and they account for 85% of the total NO (four measurement mean of 20.1 gNO/kg of Fuel) and NO_x (four measurement mean of 33 gNO_x/kg of Fuel) emissions for all of the 17 post-repair partial or no record group measurements. Despite the skewed emissions distribution of the post-repair all measurement group there are statistically significant reductions of 83% in gNO_x/kg of fuel emissions from the pre-repair group. If we restrict the comparison to the pre-repair and post-repair fully repaired group the NO_x reductions increase to 91% and now all model years show reductions (see Figure 1) indicating that the repairs were very successful. The exclusion of the four measurements collected in Chicago account for a majority of this additional reduction. A similar recall program in Europe with much simpler repairs reported NO_x benefits of 30 to 36%.[32]

The very high NO_2 emissions observed in the pre-repair vehicles were reduced by an even larger percentage (95% for the post-repair all measurements and 97% for the post-repair fully repaired) than the overall NO_x emissions. All but three of the vehicles in the post-repair partial or no record group reported partial repairs and it is unknown what those repairs may have been. Overall this group's emissions look like the pre-repair vehicles with only the NO_2 emissions

Table 1. Summary of Mean Model Year and Fuel Specific Emission Measurements for the VW Group Diesels.

Grouping	Model Year	gNO/kg of Fuel[a] Records	gNO_2/kg of Fuel[b] Records	gNO_x/kg of Fuel[b] Records
Pre-Repair	2012.2	4.31 ± 0.58 415	6.97 ± 0.59 401	13.62 ± 1.29 401
Post-Repair All Measurements	2013.9	1.28 ± 0.43 132	0.33 ± 0.07 131	2.27 ± 0.68 131
Post-Repair Fully Repaired	2013.9	0.65 ± 0.32 114	0.24 ± 0.04 114	1.24 ± 0.48 114
Post-Repair Partial or No Record	2014.5	5.2 ± 2.1 18	1.0 ± 0.5 17	9.2 ± 3.6 17

[a]grams of NO. [b]grams of NO_2.

being statistically lower than the pre-repair group, though they are also statistically higher than the other post-repair groups.

To further gauge the effectiveness of the repairs to VW Group vehicles, Figure 2 plots the on-road fuel specific NO_x emissions versus model year comparing the VW post-repair all measurements group to diesel trucks (largely light and medium-duty pickups) measured in Denver in 2020. Uncertainties are standard error of the mean determined from the daily measurements and there is only one 2016 model year measurement in the post-repair VW Group.

On-road NO_x emissions from diesel trucks did not decrease as rapidly as their gasoline counter parts over the past two decades but the newest models are close (factor of 2) to achieving those emission levels (Figure S2). In general the post-repair VW Group diesel vehicles NO_x

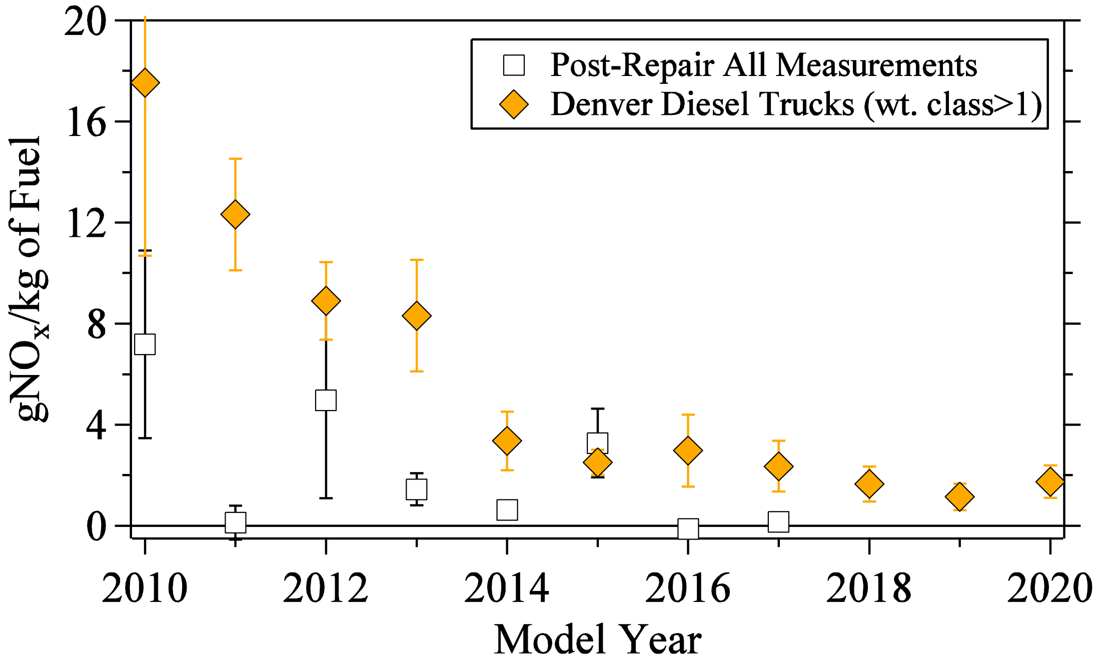

Figure 2. Fuel specific NO_x emissions versus model year comparing the post-repair all measurements VW Group vehicles (squares) and light and medium-duty diesel trucks (diamonds, weight class > 1) measured in Denver in 2020. Uncertainties are standard error of the mean calculated from the daily means and there is only one measurement for the post-repair 2016 VW Group model year.

emissions compare favorably to the obviously larger engine diesel truck fleet, again indicating that the repairs performed on these vehicles were very effective.

The on-road NO_x emission reductions achieved with the VW Group repairs are not uniform over their entire emissions distribution. Figure 3 is a cumulative probability plot with an x-axis that has been transformed for a normal distribution. Plotted are the fuel specific NO_x emissions distributions for pre-repair, post-repair all measurements, post-repair fully repaired VW Groups and the 2020 on-road Denver diesel trucks (2010 & newer and weight class >1). This plot gives

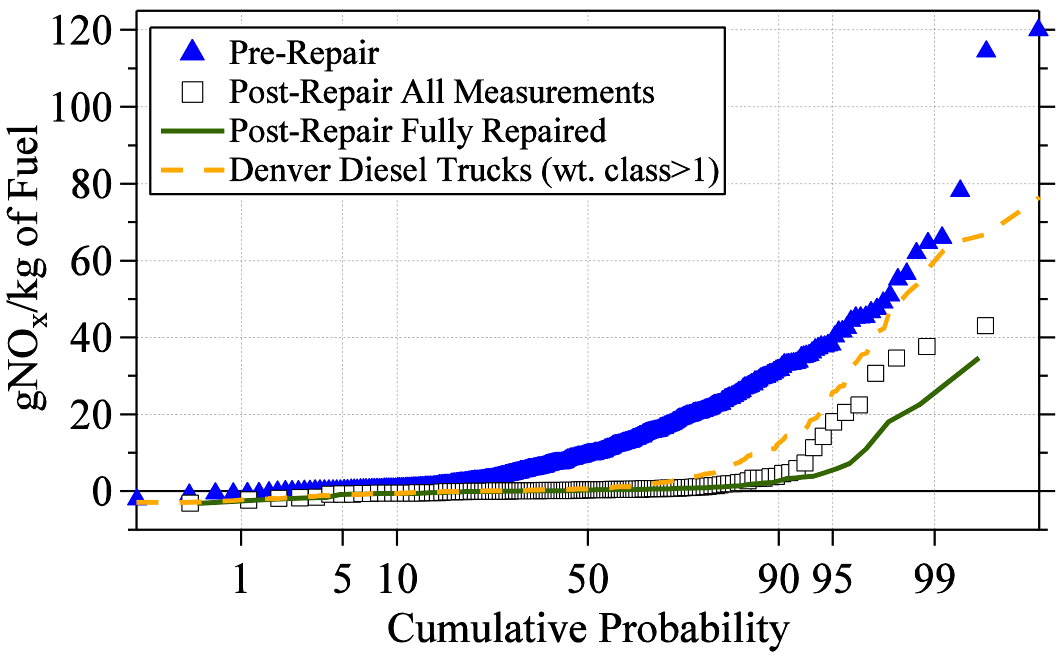

Figure 3. Cumulative probability plot of fuel specific NO_x emissions for the VW Group pre-repair (triangles), post-repair all measurements (squares), post-repair fully repaired (solid line) and the 2010 and newer on-road Denver diesel truck fleet (weight class>1, dashed line) measured in 2020. The x-axis has been transformed to a normal distribution.

the probability of finding a gNO_x/kg of fuel emissions reading that is less than or equal to a value on the y-axis. If the data were normally distributed they would plot as a diagonal straight line.

The pre-repair group is the closest to a normal distribution of the four groups plotted with mean and median gNO_x/kg of fuel values reasonably close to each other (13.6 versus 9.5). The remaining three groups show highly skewed emission distributions where a majority of the vehicles have NO_x emissions at or very near zero with the post-repair fully repaired group having the largest percentage. While the mean emissions for the post-repair all measurements group has been notably reduced by a factor of six (see Table 1) the plot shows that the median emissions have shrunk by more than a factor of 30 (9.5 versus 0.3 gNO_x/kg of fuel) and the 90th percentile vehicles by a factor of 10. Comparing the post-repair VW Groups to the on-road Denver diesel trucks shows that the repairs have more than brought their emission levels to being on-par with the Denver truck fleet. The post-repair all measurement VW Group median NO_x emission value is less than half that observed for the Denver diesel trucks (0.3 versus 0.68 gNO_x/kg of fuel).

This analysis only reports on the differences in the measured on-road fuel specific emissions rates between the pre- and post-repair VW Group diesel vehicles and finds that the repairs were quite successful in lowering these vehicles NO_x emissions to comparable fleet levels. However, from an inventory perspective fuel specific emissions are only one part of the equation and will need to be paired with fuel usage before and after the repairs. Any changes in the fuel economy between the pre- and post-repair VW Group vehicles will directly affect the total grams of NO_x emitted into the atmosphere. If the fuel economy decreased in the repaired vehicles then the NO_x percent reductions observed in this study will decrease as well though overall NO_x reductions should dominate due to the number of diesel vehicles completely removed from the fleet as a result of the buy backs.

ASSOCIATED CONTENT

Supporting Information. The Supporting information is available free of charge at https://pubs.acs.org.

Previously published figure in ES&T of fuel specific NO_x emissions versus model year for light-duty diesel vehicles. FEAT calibration bottle specifications. Summary of pre-repair measurements for the VW Group diesel vehicles. Summary of the post-repair measurements for the VW Group diesel vehicles. Listing of measurements by model year used in Figure 1. Figure of fuel specific NO_x emissions versus model year for the 2020 Denver gasoline and diesel truck fleet.

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Notes

The author declares the following competing financial interest(s): G. A. Bishop acknowledges previous receipt of patent royalty payments from Envirotest, an operating subsidiary of Opus Inspection, which previously licensed vehicle emissions testing technology developed at the University of Denver.

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Supporting Information For:

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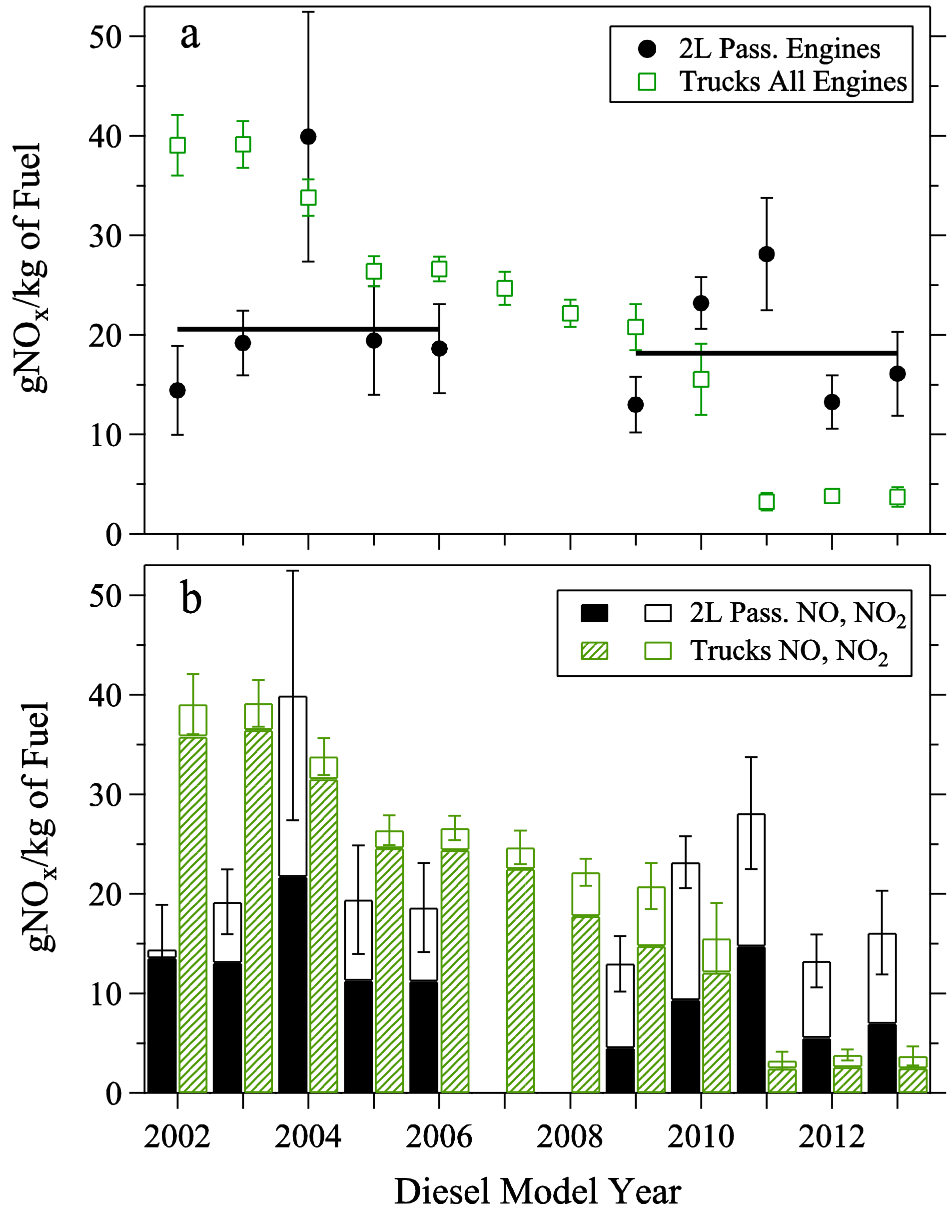

Figure S1. Diesel vehicle grams of NO_x per kilogram of fuel emissions from a combined data set for the 2013 measurements in Denver, Los Angeles, and Tulsa by model year. The top panel graphs average grams of NO_x per kilogram of fuel data for 2 L diesel passenger vehicles (circles) and diesel trucks (squares) as defined by the Polk VIN decoder. The black horizontal lines show the mean emission levels for the 2002–2006 (left) and 2009–2013 (right) 2 L diesel passenger vehicles, which are before and after Tier II/LEV II implementation. The bottom panel graphs the contribution that NO (converted to NO_2 equivalents) and NO_2 make to the NO_x emissions for the same vehicle groupings. The uncertainties plotted are SEMs determined from the daily means for the 2 L passenger vehicles and diesel trucks. (Bishop and Stedman, *Environ. Sci. Technol.* **2015,** 49, (18), 11234-11240.)

FEAT Calibration Cylinder Specifications

Bottle 1:

6% carbon monoxide
0.6% propane
0.3% nitric oxide
6% carbon dioxide
nitrogen balance
(Praxair, +/- 2%)

Bottle 2:

0.05% nitrogen dioxide
15% carbon dioxide
air balance
(Praxair, +/- 2%)

Bottle 3:

0.1% ammonia
0.6% propane
nitrogen balance
(Air Liquide, +/- 2%)

Table S1. Summary of Pre-repair Measurements Collected for Volkswagen, Audi and Porsche Diesels.

Location	Collection Dates	Total Records	VW Group (Model Years >=2009)			
			Records[a] (Mean Model Year)	Mean[b] gNO/kg of Fuel	Mean[c] gNO_2/kg of Fuel	Mean[c] gNO_x/kg of Fuel
Chicago	9/11/2014 to 9/13/2014	20,395	74/71/71 (2012.7)	3.79±0.27	6.46±0.31	12.25±0.56
Denver[d]	12/12/2013 12/13/2013 1/3/2014	19,242	88/85/85 (2011.9)	3.74±0.26	10.91±1.89	16.77±2.25
Denver[d]	12/9/2015 12/10/2015 1/13/2016 1/27/2016 to 1/29/2016	23,297	66/65/65 (2012.9)	3.30±0.62	3.36±0.89	8.29±1.65
Los Angeles	4/27/2013 to 5/4/2013	27,196	44/43/43 (2011.0)	8.14±1.84	7.81±1.39	19.87±3.31
Los Angeles	3/28/2015 to 4/3/2015	22,124	62/62/62 (2012.7)	6.56±0.88	8.71±1.11	18.77±2.14
Tulsa	9/30/2013 to 10/4/2013	21,115	29/23/23 (2012.2)	2.99±1.26	6.61±1.21	12.28±3.32
Tulsa	9/14/2015 to 9/18/2015	19,601	52/52/52 (2012)	2.08±0.74	3.13±0.67	6.32±1.33
Totals		152,970	415/401/401 (2012.2)	4.31±0.58	6.97±0.59	13.62±1.29

[a]Valid measurements for $NO/NO_2/NO_x$.
[b]grams of NO.
[c]grams of NO_2.
[d]Winter measurements in Denver are only collected on dry and fair weather days and as such are usually not sequential.
Uncertainties are standard error of the mean determined using the daily means.
All of the databases can be accessed at https://digitalcommons.du.edu/feat/

Table S2. Summary of Post-repair Measurements Collected for all the Volkswagen, Audi and Porsche Diesels.

Location	Collection Dates	Total Records	VW Group (Model Years >=2009)			
			Records[a] (Mean Model Year)	Mean[b] gNO/kg of Fuel	Mean[c] gNO_2/kg of Fuel	Mean[c] gNO_x/kg of Fuel
Chicago	9/14/2020 to 9/18/2020	19,025	61/61/61 (2014.1)	2.26±0.68	0.34±0.06	3.81±1.04
Denver[d]	1/16/2020 1/22/2020 1/24/2020 2/21/2020	19,909	33/32/32 (2013.1)	0.33±0.10	0.46±0.20	0.83±0.47
Tulsa	9/9/2019 to 9/13/2019	23,376	38/38/38 (2014.4)	0.51±0.34	0.22±0.07	1.00±0.54
Totals		62,310	132/131/131 (2013.9)	1.28±0.37	0.33±0.09	2.27±0.62

[a]Valid measurements for $NO/NO_2/NO_x$.
[b]grams of NO.
[c]grams of NO_2.
[d]Winter measurements in Denver are only collected on dry and fair weather days and as such are usually not sequential.
Uncertainties are standard error of the mean determined using the daily means.
All of the databases can be accessed at https://digitalcommons.du.edu/feat/

Table S3. Number and Percent Total of NO_x Measurements by Model Year for each Repair Category from Figure 1.

Model Year	Number of NO_x Measurements		
	Pre-Repair (% Total)	Post-Repair All Measurements (% Total)	Post-Repair Fully Repaired (% Total)
2009	32 (8.0%)	0	0
2010	42 (10.5%)	6 (4.6%)	5 (4.4%)
2011	53 (13.2%)	12 (9.2%)	12 (10.5%)
2012	67 (16.7%)	18 (13.7%)	17 (14.9%)
2013	105 (26.2%)	18 (13.7%)	18 (15.8%
2014	79 (19.7%)	16 (12.2%)	15 (13.2%)
2015	22 (5.5%)	38 (29.0%)	24 (21.0%)
2016	1 (0.2%)	1 (.8%)	1 (0.9%)
2017	0	22 (16.8%)	22 (19.3%)
Total Measurements	401	131	114

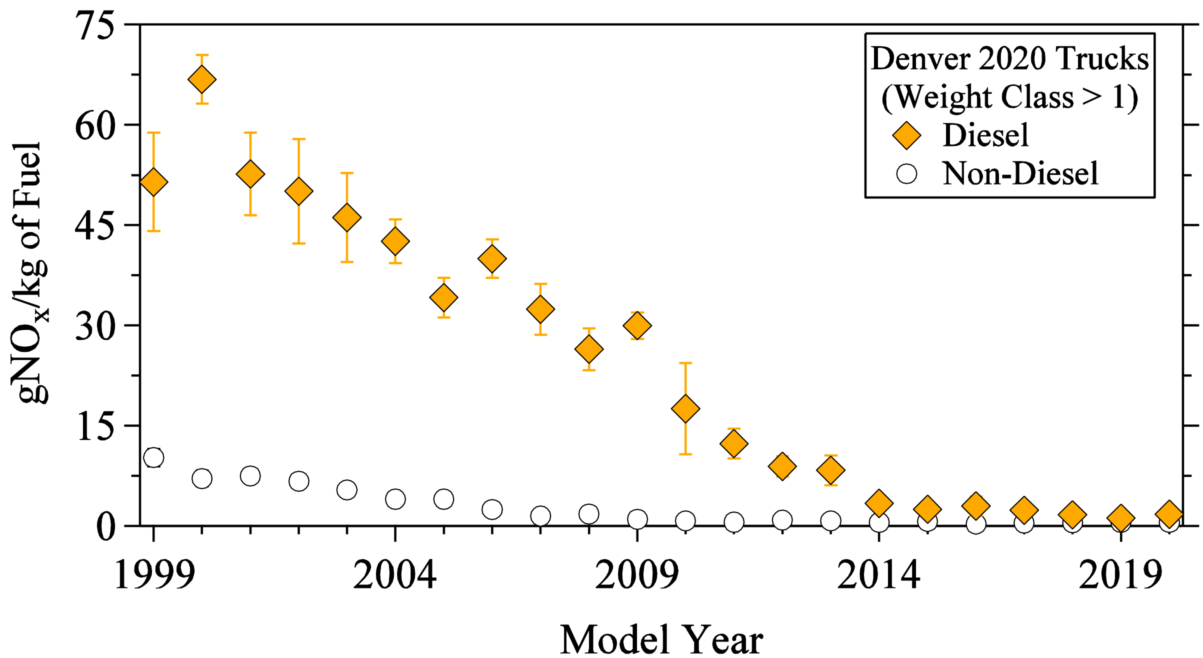

Figure S2. Fuel specific NO_x emissions by model year for the Denver 2020 diesel (diamonds) and non-diesel trucks (circles) in weight classes larger than 1. Uncertainties are standard error of the mean calculated using the daily means for each model year.

Literature Cited:

1. Bishop, G. A.; Stedman, D. H., Reactive Nitrogen Species Emission Trends in Three Light-/Medium-Duty United States Fleets., *Environ. Sci. Technol.* **2015,** 49, (18), 11234-11240, DOI: 10.1021/acs.est.5b02392.