THE REAL URBAN EMISSIONS INITIATIVE

CASE STUDY

OCTOBER 2020

Remote sensing of heavy-duty vehicle emissions in the United States

TRUE Initiative U.S. remote sensing database case study

INTRODUCTION

Heavy-duty diesel vehicles (HDVs) are a small percentage of the on-road fleet in the United States, however they contribute a disproportionate amount of nitrogen oxides (NO_x) and particulate matter (PM) emissions. HDVs are a significant source (50%-60%)[1] of mobile source NO_x emissions and are predicted to be one of the largest contributors to ozone in the United States by 2025.[2] In cities, high levels of diesel truck activity on freight corridors and near major goods movement centers, like ports, contribute to elevated air pollution levels to which nearby communities are disproportionately exposed.

Currently, new heavy-duty diesel engines sold in the United States must meet the U.S. Environmental Protection Agency (EPA) 2010 standards. These standards significantly reduced emission limits relative to previous standards and have led to the widespread use of diesel particulate filters (DPFs) to control PM emissions and selective catalytic reduction (SCR) systems to control NO_x emissions. These exhaust aftertreatment technologies have proven effective in reducing emissions in laboratory certification testing; however, evidence is emerging that the standards have not resulted in the same level of control in real-world driving conditions, particularly for NO_x emissions. Real-world emissions testing studies have demonstrated significantly higher NO_x emissions relative to the certification standard, especially during urban, low-speed operations which are not well represented in the EPA's laboratory and in-use certification testing protocols.[3] This divergence between laboratory and real-world emissions highlights the importance of monitoring the real-world emissions performance of diesel HDVs.

Remote sensing is one such well-established method for real-world vehicle emission monitoring. The purpose of this case study is to explore the extent to which HDV remote sensing data compiled in the TRUE U.S. remote sensing database can be used to inform understanding of real-world emissions from HDVs operating in the United States.[4] Specifically, we investigate temporal trends in HDV NO_x emissions and explore how HDV remote sensing data can be used to assess NO_x emissions at a more granular level.[5]

DATA OVERVIEW

Although the TRUE U.S. database contains remote sensing data from three sources, this case study focuses on data provided by the Colorado Department of Public

1 U.S. Environmental Protection Agency, "The 2014 National Emissions Inventory," April 2017, https://www.epa.gov/sites/production/files/2017-04/documents/2014neiv1_profile_final_april182017.pdf.

2 Margaret Zawacki, Kirk Baker, Sharon Phillips, Kenneth Davidson, and Philip Wolfe, Mobile source contributions to ambient ozone and particulate matter in 2025, *Atmospheric Environment* 188 (September 2018): 129–41, https://doi.org/10.1016/j.atmosenv.2018.04.057.

3 Huzeifa Badshah, Francisco Posada, and Rachel Muncrief, *Current state of NO_x emissions from in-use heavy-duty diesel vehicles in the United States,* (ICCT: Washington, DC, 2019), https://theicct.org/publications/nox-emissions-us-hdv-diesel-vehicles; Francisco Posada, Huzeifa Badshah, and Felipe Rodriguez, *In-use NO_x emissions and compliance evaluation for modern heavy-duty vehicles in Europe and the United States,* (ICCT: Washington, DC, 2020), https://theicct.org/publications/inuse-nox-hdvs-us-eu.

4 Yoann Bernard, Tim Dallmann, Uwe Tietge, Huzeifa Badshah, and John German, *Development and application of a United States real-world vehicle emissions database,* (ICCT: Washington, DC, 2020), https://theicct.org/publications/true-us-database-development-oct2020.

5 In addition to NO_x, emissions of PM from diesel HDVs are also of concern. The introduction of DPFs has led to better control of PM emissions from post-2007 MY engines. However, it remains important to monitor real-world performance to detect high PM emitters and monitor the efficiency of DPFs on diesel vehicles. While PM emissions are not the subject of this study, we plan to explore real-world PM emissions further in future work.

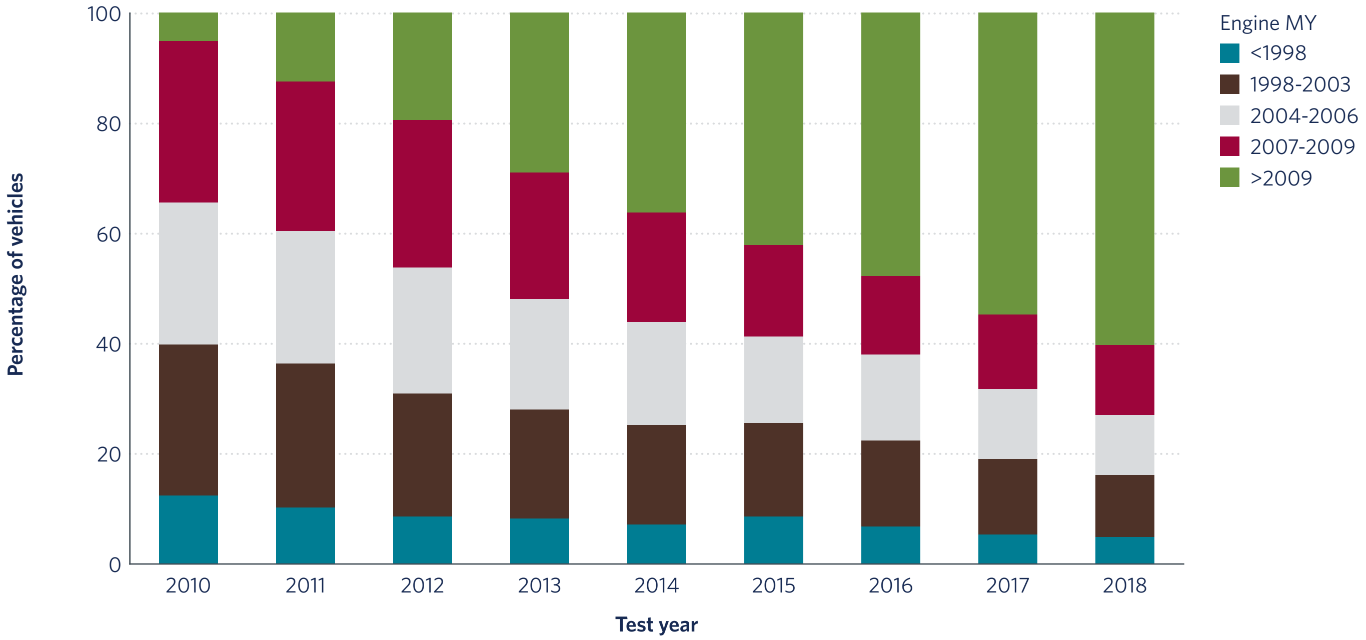

Figure 1. Percentage of unique vehicles by model year group for each test year.

Health & Environment (CDPHE).[6] The CDPHE remote sensing program is focused on light-duty vehicles, and HDVs make up only a small fraction (~0.15 %) of the total measurements. Furthermore, there are additional challenges for measuring HDV emissions, such as the higher orientation of the tailpipe relative to the instrument.[7] Despite these limitations, a considerable amount of HDV remote sensing data has been collected through the CDPHE program.

The CDPHE data contained in the TRUE U.S. database includes emissions measurements for a total of 9,408 unique vehicles spanning engine model years (MY) 1981–2019. These vehicles account for 73,313 individual measurement records, out of which 28,371 are for vehicles with post-2009 MY engines. Vehicles have been divided into five categories by EPA engine emission standard:

- MY <1998: no aftertreatment technology
- MY 1998-2003: lower NO_x regulatory standard
- MY 2004-2006: exhaust gas circulation (EGR) for NO_x control
- MY 2007-2009: DPF for PM control, phase-in of SCR for NO_x control
- MY >2009: DPF for PM control, SCR for NO_x control

Figure 1 shows that vehicles with pre-2004 MY engines comprised about 60% of the vehicles in test year 2010 but decreased to about 20% of vehicles by 2018. Likewise, vehicles with engines newer than MY 2009 only contributed to 5% of the vehicles in test year 2010 but increased to 60% by 2018. These data indicate that between 2010 and 2018, the fraction of trucks tested in the fleet with engines newer than MY 2009 grew by approximately 7% per year. Natural fleet-turnover takes time—even after EPA 2010 standards were in force for 8 years, approximately 40% of the fleet was certified to the higher pre-2010 NO_x standard.

6 This is mainly due to the considerably higher number of total heavy-duty vehicles and measurements compared to the Virginia and University of Denver (DU) datasets. Although the DU measurement campaigns focused on HDVs, they targeted studies in various cities across the United States periodically, and much of these data have already been analyzed in previous reports published by DU. One of the goals of this case study is to explore trends over a large range of engine model years. The Colorado data provides an appropriate means of doing so with a consistent source of data from each year.

7 The Colorado dataset is assumed to have used ground-level instrumentation since it primary targeted LDVs, however, it is important to note that many HD trucks, especially Class 8 line-hauls in the United States, have stack-type exhaust pipes. Accordingly, some targeted HD test campaigns use dual-instrument setups, one at ground level and another placed on a scaffold to measure emissions at the appropriate exhaust height.

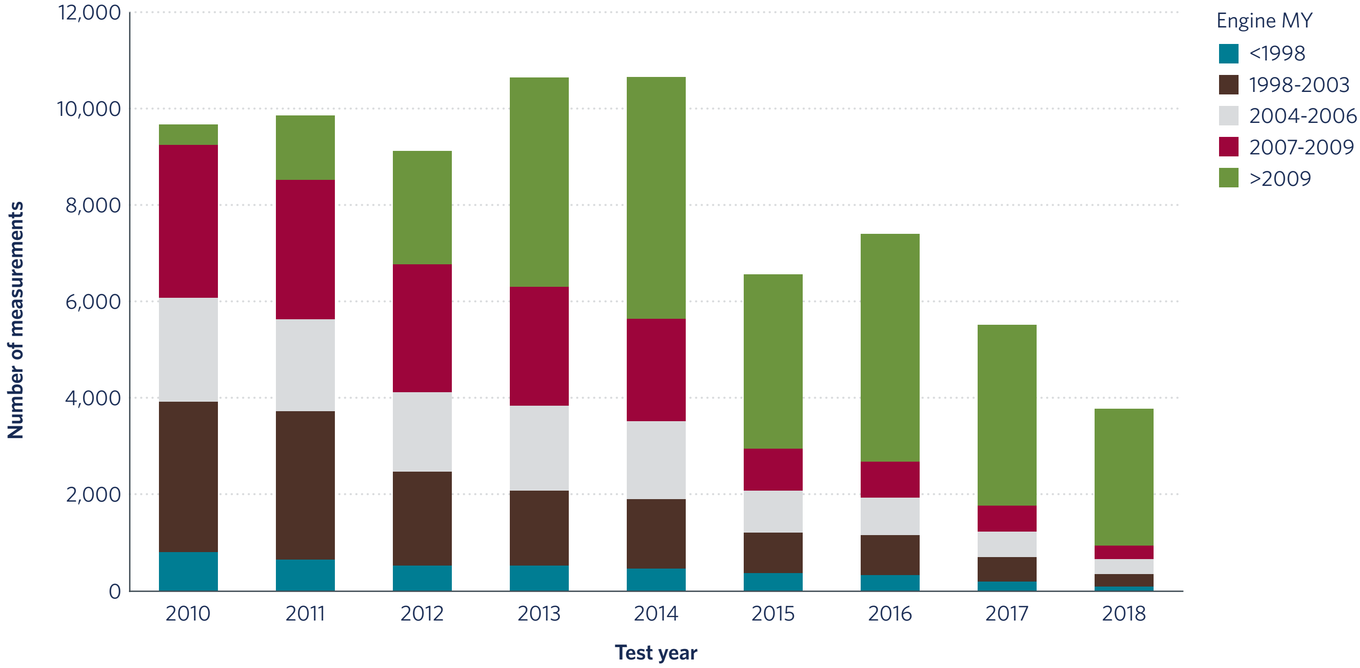

Figure 2. Number of vehicle measurements by grouped model years

The number of HDV emission records for each test year is shown in Figure 2. From 2010 to 2014, approximately 10,000 records were collected each year. This collection rate dropped to about 5,800 records per year from 2015 to 2018. Measurements of vehicles with engines later than MY 2009 substantially increase starting in test year 2013; however, vehicles in this category do not become a majority until test year 2015. This demonstrates that vehicles designed to meet new regulations (EPA 2010 standards) could have taken 5-7 years before becoming a majority of the fleet. This is a direct effect of the rate of fleet turnover rate, which in turn impacts fleet emissions and how quickly benefits can be realized from the introduction of more stringent standards.

TRENDS IN HEAVY-DUTY VEHICLE NO_X EMISSIONS

Large collections of remote sensing data can be analyzed to evaluate long-term trends in emissions from vehicle fleets and thereby provide insight into the real-world effectiveness of regulatory control programs. Figure 3 shows average fuel-specific NO_x emissions by engine model year for HDVs in the Colorado dataset and compares them to prevailing NO_x emission limits for HD diesel engines. The Colorado remote sensing data do not include NO_2 measurements, therefore total NO_x emissions cannot be evaluated directly. Using NO_2/NO_x ratios (see Table 1) from previous real-world HDV emissions studies,[8] we added estimated NO_2 emissions to NO to derive total NO_x. Federal emission limits, set in units of grams per brake-horsepower hour, were converted to a fuel-specific metric with an assumption of 0.15 kg fuel consumption per brake-horsepower hour.[9]

Table 1. NO_2/NO_x Emission Ratios

Engine Model Year	NO_2/NO_x Emission Ratio
<1998	0.06
1998-2003	0.06
2004-2006	0.06
2007-2009	0.24
>2009	0.19

8 Chelsea V. Preble, Robert A. Harley, and Thomas W. Kirchstetter, Control technology-driven changes to in-use heavy-duty diesel truck emissions of nitrogenous species and related environmental impacts, *Environmental Science & Technology* 53, no. 24 (December 17, 2019): 14568–76, https://doi.org/10.1021/acs.est.9b04763; Timothy R. Dallmann, Steven J. DeMartini, Thomas W. Kirchstetter, Scott C. Herndon, Timothy B. Onasch, Ezra C. Wood, and Robert A. Harley, On-road measurement of gas and particle phase pollutant emission factors for individual heavy-duty diesel trucks, *Environmental Science & Technology* 46, no. 15 (August 7, 2012): 8511–18, https://doi.org/10.1021/es301936c; Molly J. Haugen, Gary A. Bishop, Arvind Thiruvengadam, and Daniel K. Carder, evaluation of heavy- and medium-duty on-road vehicle emissions in California's South Coast Air Basin, *Environmental Science & Technology*, November 8, 2018, https://doi.org/10.1021/acs.est.8b03994.

9 Daniel A. Burgard, Gary A. Bishop, Donald H. Stedman, Viktoria H. Gessner, and Christian Daeschlein, Remote sensing of in-use heavy-duty diesel trucks, *Environmental Science & Technology* 40, no. 22 (November 2006): 6938–42, https://doi.org/10.1021/es060989a.

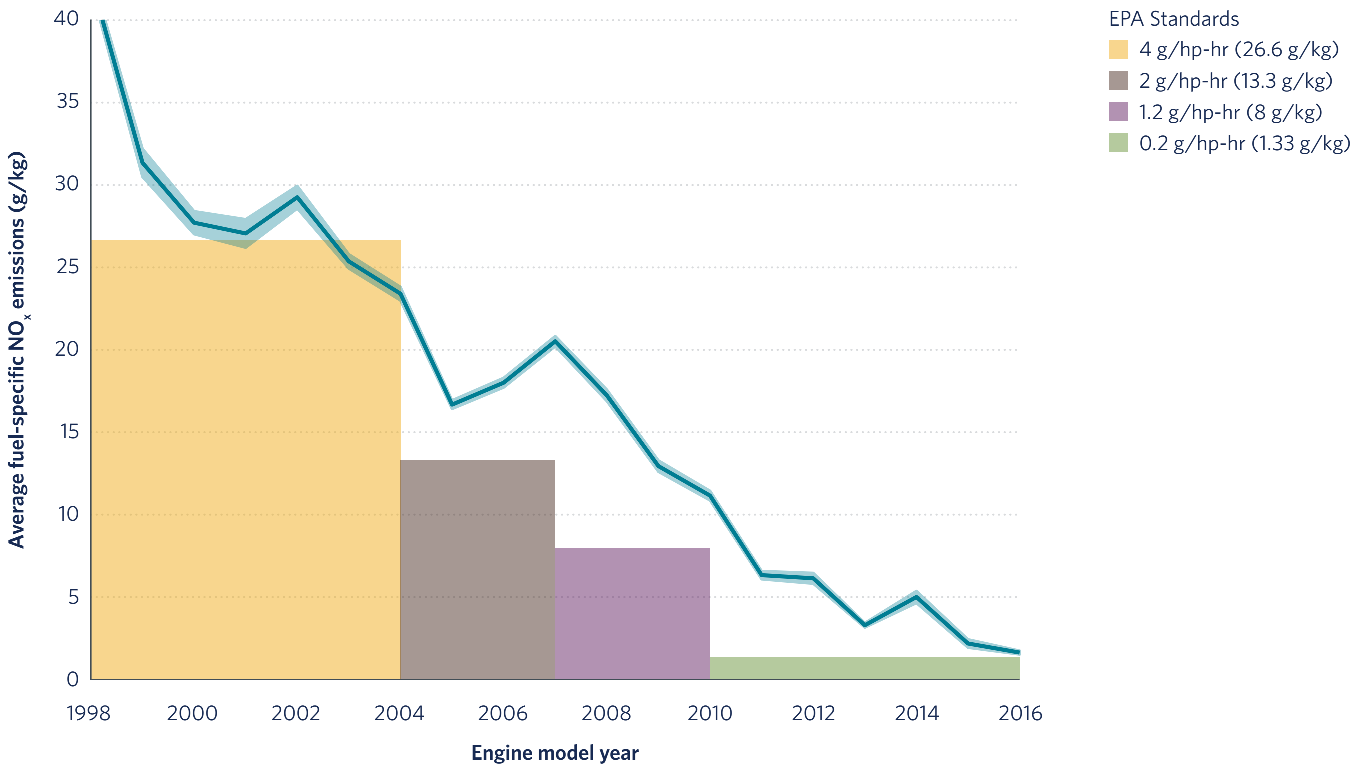

Figure 3. Average fuel-specific NO_x emissions by engine model year and comparison to U.S. EPA standards. Uncertainty band shows the 95% confidence interval.

The remote sensing data clearly show a decreasing trend in average fuel-specific NO_x emissions with the implementation of more stringent emission standards. The application of EGR for NO_x control beginning in the early to mid-2000's and the introduction of SCR aftertreatment in post-2009 MY engines have driven this downward trend. The data show a 43% reduction in NO_x emissions from 1998 MY engines to 2004 MY engines, followed by a 93% reduction in NO_x emissions from 2004 MY engines to 2016 MY engines. These trends are comparable to findings from the University of Denver HDV remote sensing studies.[10]

Despite the improvement in NO_x emissions from HDVs, average real-world emissions are higher than regulatory NO_x limits for almost all engine model years, and real-world emission reductions appear to have lagged despite the adoption of more stringent engine certification standards. One such case is that of post-2009 engines certified to the 0.20 g/bhp-hr EPA 2010 NO_x standards. Remote sensing data show NO_x emissions of 2016 engines to be close to the regulatory limit. However, it took 6+ years following the introduction of EPA 2010 standards for emissions to be reduced to this point. One reason for this lag is likely the phase out of "credit" engines certified to a higher NO_x standard than EPA 2010 standards using engine family credits and replaced with engines certified to lower NO_x levels.

10 Gary A. Bishop, Three decades of on-road mobile source emissions reductions in South Los Angeles, *Journal of the Air & Waste Management Association* 69, no. 8 (August 3, 2019): 967–76, https://doi.org/10.1080/10962247.2019.1611677.

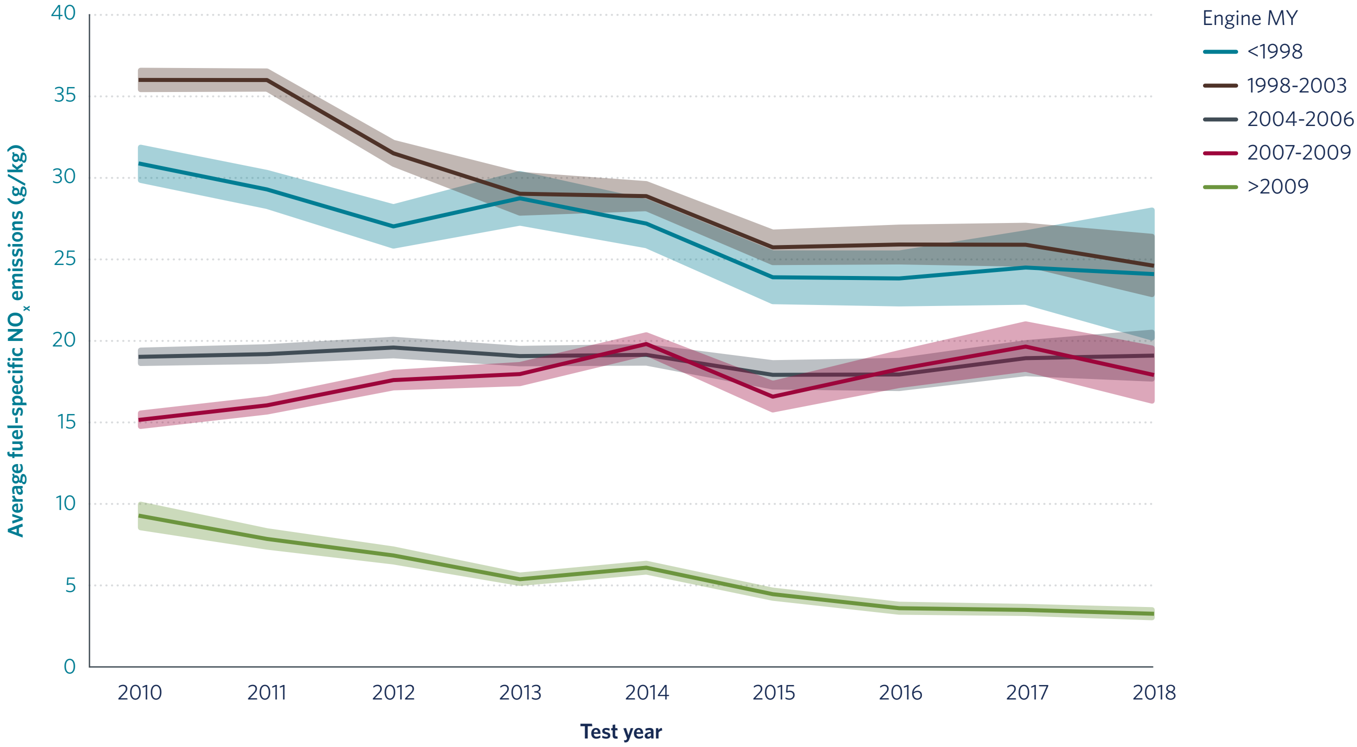

Figure 4. Average fuel-specific NO_x emissions of engine model year groups by test year. Uncertainty bands show 95% confidence intervals.

Remote sensing data can also be used to track the emissions performance of vehicle groups over time. Figure 4 shows the average NO_x emissions of five engine MY groups by test year. For the >2009 MY group average fuel-specific NO_x emissions decreased from 9.30 g/kg in 2010 to 3.30 g/kg in 2018. This can be attributed to a larger percentage of "credit" engines in the fleet mix in earlier measurement years and improvements over time in SCR system design. For 2007-2009 MY engines, which are likely to only have a DPF installed but not an SCR system, a slight deterioration trend (~20%) from 2010 to 2018 is noted. Engines from MY 2004 to MY 2006 show no significant emission change over time, but earlier engines show decreasing emissions over time. This may be due to the highest mileage engines with the most emissions deterioration being scrapped as vehicles age.

IMPACTS OF VEHICLE SPEED ON REAL-WORLD EMISSIONS

This section presents the results of a more granular analysis of the Colorado HDV remote sensing data that looks at variations in NO_x emissions by vehicle speed. This work builds upon a previous study conducted by the ICCT which analyzed real-world HDV emissions data collected using portable emissions measurement systems (PEMS) through the U.S. Environmental Protection Agency's Heavy-Duty In-Use Testing (HDIUT) Program.[11] The study found NO_x emissions from vehicles using engines certified to EPA 2010 standards to be significantly higher during urban, low-speed driving conditions compared to the certification limit. Here, we investigate the extent to which these trends are also observable in the Colorado HDV remote sensing dataset by comparing it against the results of the HDIUT PEMS analysis.

To match the format of the PEMS data, we classified remote sensing emissions data into three speed bins, defined according to the speed recorded at the time of the remote sensing measurement:

- Urban (vehicle speed of 1 – 25 mph)
- Suburban (vehicle speed of 25 – 50 mph)
- Highway (vehicle speed ≥50 mph)

Further, we converted remote sensing NO_x emissions data from g/kg fuel units to g/kg CO_2 units using a method developed in a previous ICCT report.[12] Since the HDIUT PEMS study only evaluated "non-credit" engines, it was necessary to select comparable vehicles from the remote

11 Badshah, Posada, and Muncrief, *Current state of NO_x emissions from in-use heavy-duty diesel vehicles in the United States.*

12 Yoann Bernard, Uwe Tietge, John German, and Rachel Muncrief, *Determination of real-world emissions from passenger vehicles using remote sensing data*, (ICCT: Washington, DC, 2018), https://theicct.org/publications/real-world-emissions-using-remote-sensing-data.

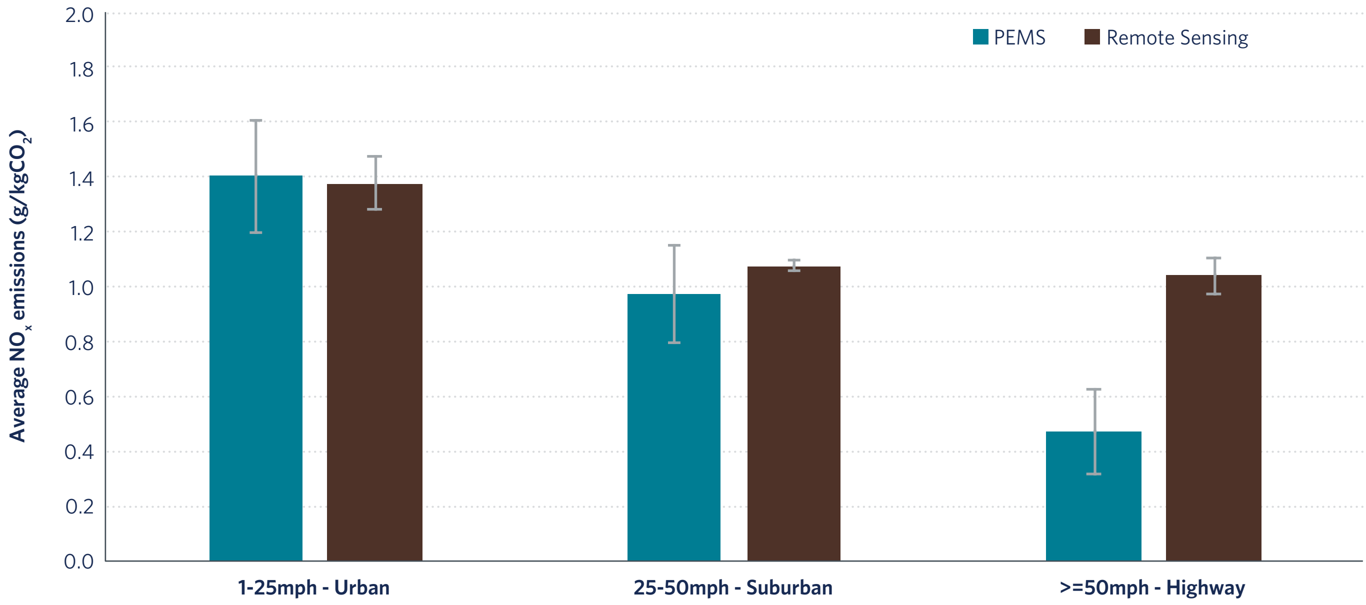

Figure 5. Comparison of speed classified emissions between PEMS and remote sensing. Uncertainty bars show 95% confidence intervals.

sensing dataset.[13] Finally, we estimated total NO_x emissions for remote sensing data assuming a NO_2/NO_x emission ratio of 19% (Table 1).

Figure 5 shows a comparison of average NO_x emissions for MY 2009 and newer engines by speed bin for the remote sensing and HDIUT PEMS data. The majority of remote sensing data were collected at vehicle speeds between 25–50 mph (24,893 records). Smaller amounts of data were available for urban (1,749 records) and highway (1,729 records) operating speeds. Average remote sensing estimates of NO_x emissions for the <25 mph and 25–50 mph speed-bins are comparable to PEMS. Consequently, we can reach similar conclusions from remote sensing and PEMS data. Recent evaluation of in-use PEMS testing data found that urban NO_x emissions are significantly higher compared to average route-based emissions. While we cannot derive a true route-based NO_x average via remote sensing measurements, due to the agreement with PEMS data we can confirm that remote sensing measurements also reveal high urban/low-speed emissions from on-road heavy-duty diesel engines.

However, there is a greater degree of uncertainty in the remote sensing data for the >50mph, highway speed bin as evidenced by the wider confidence interval. The disagreement between PEMS and remote sensing data for the high-speed bin can plausibly be attributed to the lack of remote sensing measurements conducted on highways where cruise conditions can be expected. It is therefore likely that the remote sensing measurements belonging in the >50 mph speed bin are only acceleration events at a higher speed. From the data, average acceleration is roughly on the same order of magnitude for measurements in the >50mph and 25-50mph speed bin, confirming that the vehicles were still accelerating when the measurement was captured. On the other hand, PEMS based >50mph speed bin data reflects true highway/cruise conditions, and thus result in lower emissions in comparison to remote sensing derived >50mph speed bin.

CONCLUSION

Focusing on data from the CDPHE remote sensing program in the TRUE U.S. database, this case study evaluated long-term emissions trends and the extent to which the HDV data could support more granular analysis. Key findings include:

- From initial introduction, it took almost 6 years for engines certified to EPA 2010 standards to become a majority of the fleet due to fleet-turnover.
- NO_x emissions from HDVs equipped with 2016 MY or newer engines have decreased by more than 94% compared to HDVs using 2004 MY engines.
- For most engine model years, real-world NO_x emissions exceed EPA engine emission standards. Remote sensing data show a considerable lag of 6 years or more between the adoption of EPA 2010 standards and the time when real-world emissions approached certification limits.

13 Non-credit refers to engines that are certified to the current 2010 NO_x standard of 0.20 g/bhp-hr. Certain engine manufacturers (such as Navistar) certified their engines to a higher NO_x standard using previously earned family engine credits. Vehicle manufacturer and engine model data was identified via the VIN decoded by the NHTSA database. Remote sensing measurements from these vehicle manufacturers and selected engine models known to be "credit" engines were eliminated for comparison purposes to the "non-credit" PEMS dataset.

- PEMS and remote sensing measurements of emissions under low-speed urban (<25 mph) operation and suburban (25-50 mph) operation agree well. Consequently, analysis of in-use PEMS data and remote sensing data lead to similar conclusions. For example, both show that urban/low-speed NO_x emissions are high relative to EPA certification standards.

The same Colorado dataset as well as the continued expansion of the TRUE U.S. database with additional HDV remote sensing data could be used for further research. Future analysis could include evaluating durability trends by engine model year, tracking individual trucks over time to find evidence of malfunctions or recall repairs, or demonstrating the use of remote sensing for clean pass/fail or screening of individual vehicles via in-use inspection and maintenance programs.

This case study offers just a snapshot of the types of analyses that can be conducted with more targeted studies of HDV emissions. Multiple remote sensing measurement campaigns across the United States with a focus on HDVs could help develop a more expansive inventory of real-world emissions. This could greatly help in detection of high-emitting vehicles across the nation as well as shape future policies regarding in-use emissions. Future work should include measurements of NO_2 in addition to NO in order to provide a more detailed picture of NO_x emissions from HDVs. Current-generation remote sensing systems are capable of providing these speciated NO_x emissions information.

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This case study is based on an analysis of the TRUE Initiative U.S. remote sensing database.

For more information, please see:
"Development and application of a United States real-world vehicle emissions database"
https://theicct.org/publications/true-us-database-development-oct2020

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