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CURRENT STATE OF NO_X EMISSIONS FROM IN-USE HEAVY-DUTY DIESEL VEHICLES IN THE UNITED STATES

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EXECUTIVE SUMMARY

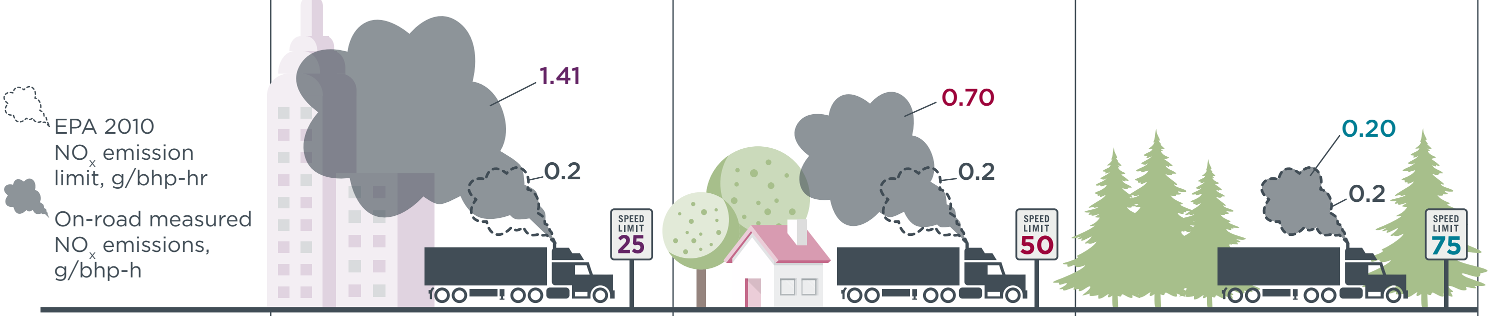
Emissions of nitrogen oxides (NO_x) from heavy-duty diesel engines are a significant contributor to ambient air quality issues and ozone pollution in many areas of the United States. Although the EPA's 2010 emissions standard for heavy-duty engines went a long way toward reducing NO_x emissions, there is still a significant gap between real-world and certified NO_x emissions from these engines. The two main regulatory agencies in the United States responsible for addressing NO_x from heavy-duty engines, the California Air Resources Board (CARB) and the U.S. Environmental Protection Agency (EPA), are developing new regulations to address weaknesses in the current standard. An important element in this process is to have a good understanding of the current real-world baseline emissions from existing diesel vehicles.

This report presents an assessment of the real-world NO_x emissions behavior of heavy-duty diesel vehicles in the United States measured using portable emissions measurement systems (PEMS). The real-world emissions data source is the publicly available Heavy Duty In-Use Testing (HDIUT) program, managed by the EPA. This assessment is based on 160 PEMS tests from engines certified to 0.2 grams per brake horsepower-hour (g/bhp-hr) of NO_x. The tests include data from eight manufacturers and 26 unique engine families certified between 2010 and 2016. Second-by-second data was analyzed to compare against the compliance evaluation results and to assess the impact of vehicle speed, vehicle type, and manufacturer on real-world NO_x emissions.

KEY FINDINGS:

- The Not-to-Exceed (NTE) protocol evaluates less than 10% of the total emissions data to determine compliance for heavy-duty in-use NO_x emissions. The average emission value of 0.18 g/bhp-hr obtained from the NTE evaluation is significantly lower than the value of 0.42 g/bhp-hr obtained when evaluated on a total route basis (total mass of NOx emitted divided by total work).
- A disproportionate amount of NO_x emissions from heavy-duty vehicles is emitted during the low-speed operation characteristic of urban driving. Vehicle operation at speeds of less than 25 mph results in NO_x emissions of more than five times the certification limit for the average heavy-duty vehicle in the study.
- At mid-speed driving conditions, between 25 and 50 mph and characteristic of suburban driving, average NO_x emissions from heavy-duty vehicles (HDVs) are 2.7 times the certification limit. Only at highway speeds, above 50 mph, do HDVs present average NO_x emissions at the certification limit and below the in-use NTE emissions limit of 0.3 g/bhp-hr.
- Line-haul trucks, defined as class 8 trucks for long-distance goods transport, have the highest average NO_x emissions at less than highway speeds. Their average NO_x emissions of 1.41 g/bhp-hr are more than 7 times the engine certification limit in urban driving and more than 3 times the limit in suburban driving (Figure ES-1). Only during high-speed operation do line-haul trucks emit NO_x at engine certification limit levels.
- A single line-haul truck emits the NO_x equivalent of 100 cars for each mile driven in urban driving. The data shows that under urban driving conditions, line-haul trucks are emitting on average 7.0 g/mi of NO_x, compared with less than 0.07 g/mi for a gasoline car. The PEMS data shows that these trucks, which are optimized

for highway driving, spend on average 43% of their time and emit 40% of the total mass of NOx in urban-like operation, including low-speed driving and idling.



Driving condition **Speed range**	**Urban** 0-25 mph	**Suburban** 25-50 mph	**Highway** > 50 mph
Average time spent at this condition	**43%**	**11%**	**46%**
Average share NO_x mass	**40%**	**23%**	**37%**
Brake specific NO_x emissions, g/bhp-hr	**1.41***	**0.70**	**0.20**
Conformity Factor - CF	**7.1***	**3.5**	**1.0**
Distance-specific NO_x emissions, g/mile	**7.0***	**2.4**	**0.6**

* Brake and distance specific NO_x emissions for Urban bin do not include Idle operation, only 1-25 mph operation is included

Figure ES-1 Comparison of line-haul vehicle NO_x emissions under urban, suburban, and highway driving conditions. Conformity factor is defined as ratio of measurement to engine dynamometer emission limits.

As a result of this analysis, it is evident that the current NTE in-use testing protocol is inadequate to evaluate the in-use performance of HDVs in the U.S., especially at low-speed conditions. The prospect of future NO_x standards set over low-load cycle and idle tests, in addition to the traditional federal test procedure, demands the adoption of a different tool for proper in-use compliance. That tool should ensure that in-use compliance is evaluated not only with highway data but also includes low-speed, low-load, and idle data. This would ensure that engine dynamometer emission results obtained in the laboratory translate to real-world benefits.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Nitrogen oxides (NO_x) are precursors to particulate matter with diameter of less than 2.5 micrometers ($PM_{2.5}$) and ground-level ozone, both of which are known to have adverse effects on human health. Long-term exposure to $PM_{2.5}$ and ozone is associated with increased risk of premature death from cardiovascular, lung, and kidney diseases (Burnett et al., 2018; Turner et al., 2016). In addition, direct NO_2 exposure is associated with asthma incidence among children and asthma emergency department visits (Anenberg et al., 2018). Reduction of NO_x emissions can lead to substantial public health benefits from improved air quality, including fewer hospitalizations and emergency room visits, fewer missed days at work, and lowered risk of premature death from cardiovascular, lung, and kidney diseases (EPA, 2018c)(EPA, 2018c). These benefits are the main drivers for decreasing NO_x emissions.

Heavy-duty diesel vehicles are a major source of NO_x emissions. In California alone, HDVs are responsible for more than 70% of NO_x emissions from on-road mobile sources (CARB, 2019). U.S. regulatory agencies have put in place regulations aimed at reducing NO_x emissions from heavy-duty diesel engines. In 2000, the U.S. Environmental Protection Agency (EPA) adopted heavy-duty engine emission standards for model years 2007–2010 and later engines—known as the EPA 2010 emissions regulation—aimed at reducing NO_x emissions by 90% compared with the model year 2004 standard.

A key part of the EPA 2010 regulation was the requirement that manufacturers conduct testing on in-use HDVs to prove compliance with the regulation and to help ensure that real-world emissions are in line with the limits set by the engine emission standards. This testing program is known as the manufacturer-run heavy duty in-use testing program (HDIUT). Under the HDIUT, selected vehicles are operated under normal driving conditions while engine emissions are continuously measured with portable emissions measurement systems (PEMS). The PEMS data collected is then evaluated under the Not-to-Exceed (NTE) protocol for regulatory compliance determination.

The NTE protocol is used to compare the results of the PEMS test data evaluation against the NTE limit. The NTE limit is defined as 0.30 g/bhp-hr, or 1.5 times the engine certification limit, plus an instrument accuracy allowance of 0.15 g/bhp-hr, for a total of 0.45g/bhp-hr, or 2.25 times the FTP certification limit (CFR, 2014).

Compliance with the NTE limit is determined by first calculating the average emissions of each valid NTE event that occurred during testing. A valid NTE event is a segment of PEMS data that meets a number of pre-defined boundary conditions during a minimum of 30 continuous seconds. These boundary conditions are described in Table 1. The average emissions from each valid NTE event window are then compared against the NTE emissions limit (CFR, 2005). A test is considered to pass if a minimum of 90% of time-weighted NTE events result in emissions below the NTE limit.

Table 1 Conditions for PEMS data to be considered valid for an NTE event.

Parameter	PEMS data condition
Engine speed	Engine speed must be greater than a given engine speed (called n_{15}) defined from the engine full load curve **(~850 to 950 rpm)**
Engine torque	Engine torque must be greater than or equal to **30%** of the peak torque
Engine power	Engine power must be greater than or equal to **30%** of the peak power
Exhaust gas temperature	Exhaust gas temperature has to be above **250°C** (measured 1.0 foot from SCR outlet)
Intake manifold temperature[a]	Intake temperature must be greater than a function of intake pressure **(~38°C / 100°F)**
Engine coolant temperature[a]	Coolant temperature must be greater than a function of intake pressure **(~60°C / 140°F)**

Note: For details please see the code of federal regulations 40 CFR Part 86

[a] For engines with an exhaust gas recirculation system (EGR) to reduce NO_x emissions.

The adoption of the EPA 2010 heavy-duty regulations has resulted in positive outcomes, with total fleet NO_x emissions dropping by more than 40% (EPA, 2018b). Remote sensing data from HDVs in California, covering a wide span of vehicle model years, shows significant improvements in average NO_x emissions, moving from close to 20 grams of NO_x per kilogram (gNO_x/kg) of fuel for model year 2004 to a range of 3.8-13.9 gNO_x/kg of fuel for vehicles post-model year 2010 (Bishop, 2019).

At the same time, in-use emissions testing has shown that there is still a gap between real-world NO_x emission levels and certified levels. Remote sensing data from HDVs in California show that the best performers at 3.8 gNO_x/kg of fuel emit about 3.3 times more than the FTP emissions standard would require (Bishop, 2019). Moreover, PEMS testing data on post-model year 2010 line-haul and delivery trucks shows that NO_x emissions reach an average of 0.45 g/bhp-hr, or twice the FTP standard (Besch, 2018; Duncan & Hamady, 2019; Quiros et al., 2016). Using a full-scale mobile laboratory housed in a tractor-trailer for operation on the roadway, CARB and West Virginia University researchers found that NO_x emissions from a group of four Class 8 trucks operating on Californian roads ranged from 0.16– 0.96 g/bhp-hr (Quiros et al., 2016).

As a result, air quality is still a significant problem in certain regions of the United States. California's Los Angeles South Coast Air Basin and San Joaquin Valley are the two areas most affected, classified as "extreme" under the national 8-Hour Ozone standard (EPA, 2019a). In the South Coast Air Basin, reductions of 70% of NO_x emissions from today's levels would be needed by 2023 to meet the national ambient air quality standard for ozone (CARB, 2017; Heroy-Rogalski, Lemieux, & Robertson, 2019).

There is potential to further reduce real-world NO_x emissions from heavy-duty diesel engines. CARB and the EPA are working to update and improve existing regulations targeting this issue. California has announced the HDV Low NO_x regulation aimed at reducing FTP-based NO_x standards by as much as 90% and introducing testing conditions that would require improved emissions control at low loads and low vehicle speeds, as well as an improved in-use testing protocol (CARB, 2016). At the federal level, the EPA announced the development of the Cleaner Trucks Initiative, which explores similar changes to the EPA 2010 NO_x emissions standard, also aiming at real-world emission reductions (EPA, 2018a).

An important input into those regulatory processes is to have a good understanding of the real-world baseline emissions from existing heavy-duty diesel vehicles certified under the EPA 2010 regulation. The objective of this report is to present an independent assessment of the real-world NO_x emissions behavior of EPA 2010-certified diesel HDVs in the United States and identify critical driving conditions that result in excessive NO_x emissions.

HDUIT DATA SUMMARY

The analysis presented here focuses on PEMS data from HDVs with post-2010 model year engines as reported by the EPA (EPA, 2019b). These data are a product of the manufacturer-run HDIUT program from which in-use compliance is determined.[1] Each test file consists of second-by-second data including parameters such as vehicle speed (mph), NO_x and CO_2 emissions (g/s), and engine power (hp). Vehicle and engine specifications as well as the results of the NTE compliance calculations are also provided. For each test, there was no prescribed driving cycle as the PEMS data was being collected while the vehicles were in normal operation as per regulatory requirements. Vehicle loading was not reported.

A total of 287 tests were carried out between 2010 and 2019 for 2010-2016 model year engines, of which 98 were conducted on engines compliant under the banking credit program and 189 were from noncredit engines certified to the 0.2 g/bhp-hr NO_x standard. The credit program allowed manufacturers to use banked credits from prior years to certify engines to a higher NO_x emissions limit, 0.3–0.5 g/bhp-hr. As the credit engines have now been phased out, the noncredit engines are the most representative of the current baseline. Therefore, the analysis we present here is focused on the emissions of noncredit engines only.[2]

We removed all Cummins non-credit engines in the HDIUT dataset because all the diesel engines families tested were covered by recalls or were natural gas engines. The HDIUT dataset contained 18 tests from two engine families manufactured by Cummins that are part of a voluntary recall involving trucks with 2010–2015 model year engines with selective catalytic systems.[3] The removal of those tests ensures that the data reported here corresponds to diesel vehicles and engines operating with no mechanical or technical issues. We also removed 11 PEMS tests that were conducted on vehicles with Cummins natural gas engines and included in the HDIUT Diesel dataset.

Removing the Cummins recalled and natural gas engine tests from the noncredit engine test pool results in 160 tests from 26 unique engine families. Results in this study are based solely on this dataset excluding the recalled and natural gas engines. Appendix A provides a summary of NOx emissions from Cummins engine families available in the HDIUT dataset and their relative performance against the fleet studied here.

Figure 1 shows the breakdown of engine tests in the dataset differentiated by manufacturer and model year. Vehicle types studied are listed by manufacturer. Most PEMS tests were carried out in vehicles with engines manufactured by Volvo, and Detroit Diesel. Line-haul and delivery trucks were more frequently tested under the program. The “other” vehicle category includes applications such as drayage, refuse, and transit buses. PEMS tests were carried out on 76 line-haul trucks, 67 delivery, and 17 in the other vehicle category. The prevalent engine model years in the HDIUT dataset cover

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[1] The HDIUT program requires manufacturers to test up to 25% of engine families per year. The EPA certified 290 engine families between 2010 and 2016. During this period 51 engine families were tested under the HDIUT program (EPA, 2019b).

[2] Tests from credit engines were mainly concentrated in the 2010 and 2011 model years, and a few during the 2013-2015 model years. Credit engines were manufactured by General Motors, Navistar and Cummins.

[3] The U.S. EPA announced in July 2018 that Cummins will voluntarily recall roughly 500,000 model year 2010-2015 medium- and heavy-duty trucks. The recall involved the replacement of SCR systems that were found less durable than is required by the emission regulations (EPA, 2018d).

2010–2014 engines. There were 16 PEMS tests available from 2015 engines and three from 2016 engines.

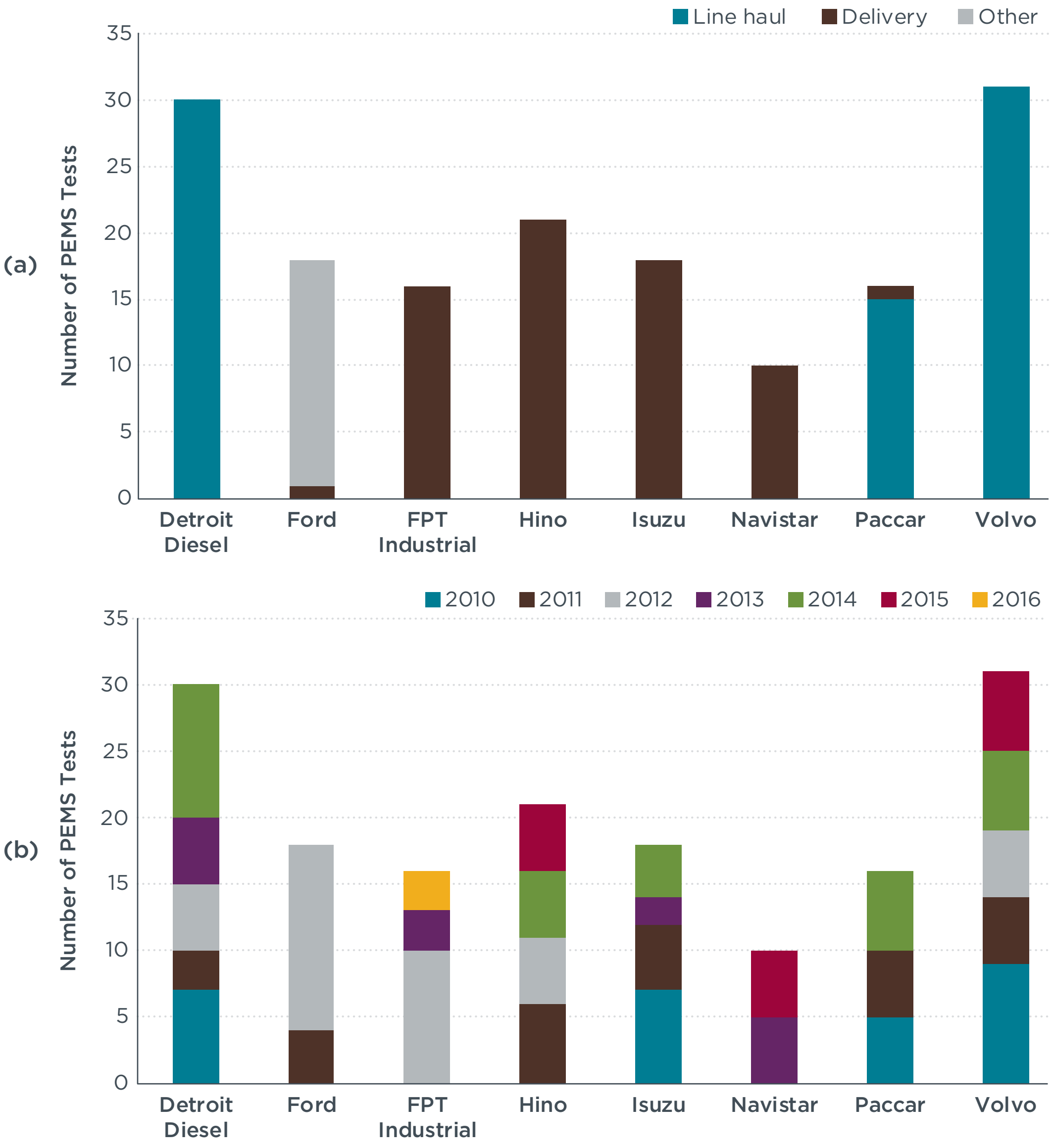

Figure 1 Number of PEMS tests in the HDIUT Database for noncredit engines by (a) vehicle type and (b) engine model year

A breakdown of the number of engine tests and the respective engine families tested by year and by manufacturer is provided in Table 2.

Table 2 Number of Tested Families and Tests

Engine manufacturer	Engine families	PEMS tests
Detroit Diesel	4	30
Ford	3	18
FPT Industrial	2	16
Hino	4	21
Isuzu	3	18
Navistar	2	10
PACCAR	3	16
Volvo	5	31
Total dataset	**26**	**160**

Appendix B presents a table summarizing each PEMS test used in the analysis. The table describes vehicles tested, engine characteristics, driving conditions, environmental conditions, and emission results as reported in the HDIUT tests and as calculated following our methods.

METHODOLOGY

In this paper we analyze second-by-second data from vehicles with heavy-duty diesel engines certified to 0.2 g/bhp-hr NO_x. The analysis includes data from all engine and vehicle operation conditions. This includes all power, torque, and engine rpm conditions, cold-start periods, low exhaust temperature (T < 250°C), and DPF regeneration events. This is done to best capture the overall picture of emissions under real-world driving conditions.

There were two cases when PEMS data was filtered out for the purposes of our analysis:

- The "zero-check" condition, in which the PEMS instrument auto-zeros itself while the rest of the OBD parameters remain live.
- Times when the OBD stream is interrupted for various reasons resulting in invalid data ("blanks," "null," or "NA" strings in the data output).

A key focus of our analysis was to gain an understanding of emissions performance in urban driving conditions. Urban driving is typically defined by low vehicle speed and low engine load. Those conditions lead to lower exhaust temperatures where effective emissions control may be more challenging (Anderson, 2018; Dixit et al., 2017). As the HDIUT dataset does not contain torque values, we rely on reported engine power for load.

As shown in Figure 2, we determined that there is a strong correlation between engine power and vehicle speed in the dataset. Average normalized power values for each speed bin are plotted versus the average speed within each bin. The analysis indicates that low-speed operation is generally associated with low-power operation and high-speed operation is associated with higher-power operation. With this being the case, we chose to report the majority of our analysis on a vehicle speed basis only.

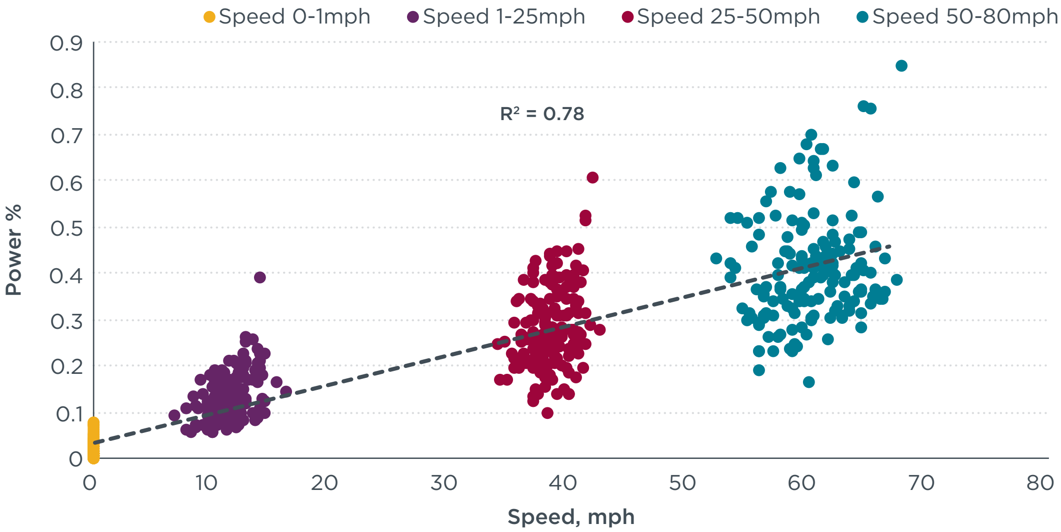

Figure 2 Speed versus normalized power. Each point represents the average engine power and average speed within the given speed bin for all 171 PEMS tests.

Data is segregated by vehicle speed parameter in the following ways throughout the report with approximate engine power ranges in percentage of P_{max} - maximum engine power listed for reference:

- Idle: vehicle speed <1mph, <10% of P_{max}
- Urban: vehicle speed of 1–25 mph, 5–25% of P_{max}
- Suburban: vehicle speed of 25–50 mph, 10–45% of P_{max}
- Highway: vehicle speed ≥50 mph, >25% of P_{max}
- Route w/o idle: all vehicle speeds excluding idle
- Route: all vehicle speeds

Wherever applicable, the data presented in these bins have been compared against current U.S. engine certification and in-use NTE standards for reference. Although there are no obligations for the vehicle to meet any regulatory standards under this binned metric, it allows for a useful comparison between certified and real-world emissions.

RESULTS AND DISCUSSION

NTE VERSUS TOTAL ROUTE NO$_X$ EMISSIONS

As previously mentioned, HDIUT data is assessed for regulatory compliance purposes via the NTE protocol, where a series of exclusions must be applied to evaluate the real-time PEMS dataset. These exclusions reduce the useable portion of the data for compliance evaluation. Figure 3 shows the percentage of total test time spent within a valid NTE event for each PEMS test, differentiated by manufacturer. On average, the total amount of time spent in valid NTE events was 8.7% of the total test time.[4] This number can vary significantly from test to test with a minimum of zero valid NTE events to as much as 50% of the test time within valid NTE events. The average time spent in valid NTE events by different manufacturers varied from 3% (Ford) to 22% (FPT Industrial).

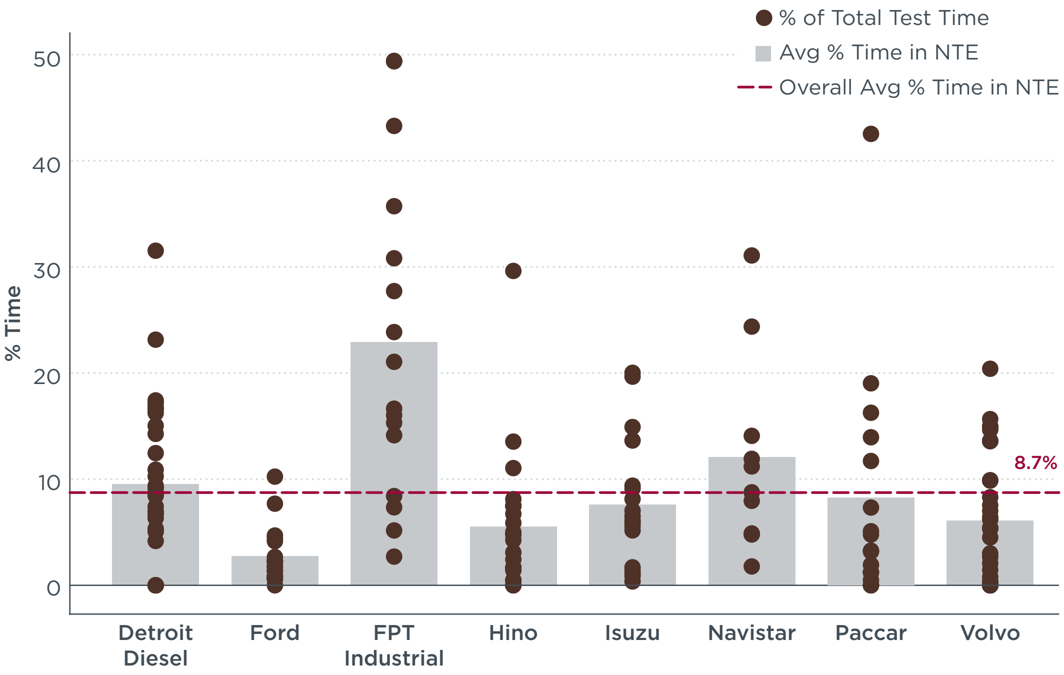

Figure 3 Percentage of time in valid NTE events, manufacturer average (bars) and individual PEMS results (dots).

In Figure 4, we compare the average NO$_x$ over the total route without idle to the average NO$_x$ during valid NTE events by manufacturer. The whiskers on all figures throughout the paper represent the 95% confidence interval for the metric of interest. The average NTE NO$_x$ emissions were 0.18 g/bhp-hr across all manufacturers, while the average NO$_x$ emissions for the entire route without idle were approximately 1.9 times higher, at 0.34 g/bhp-hr. Including idle, total route NO$_x$ emissions increased to 0.42 g/bhp-hr. Our route results are similar to those found in previous studies that have analyzed subsets of this public dataset (Besch, 2018; Duncan & Hamady, 2019; Lee et al., 2019; Spears, 2018).

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[4] Tests with zero time spent in NTE events are included. Excluding these tests would yield 9.8% as the overall average percentage of time in NTE events.

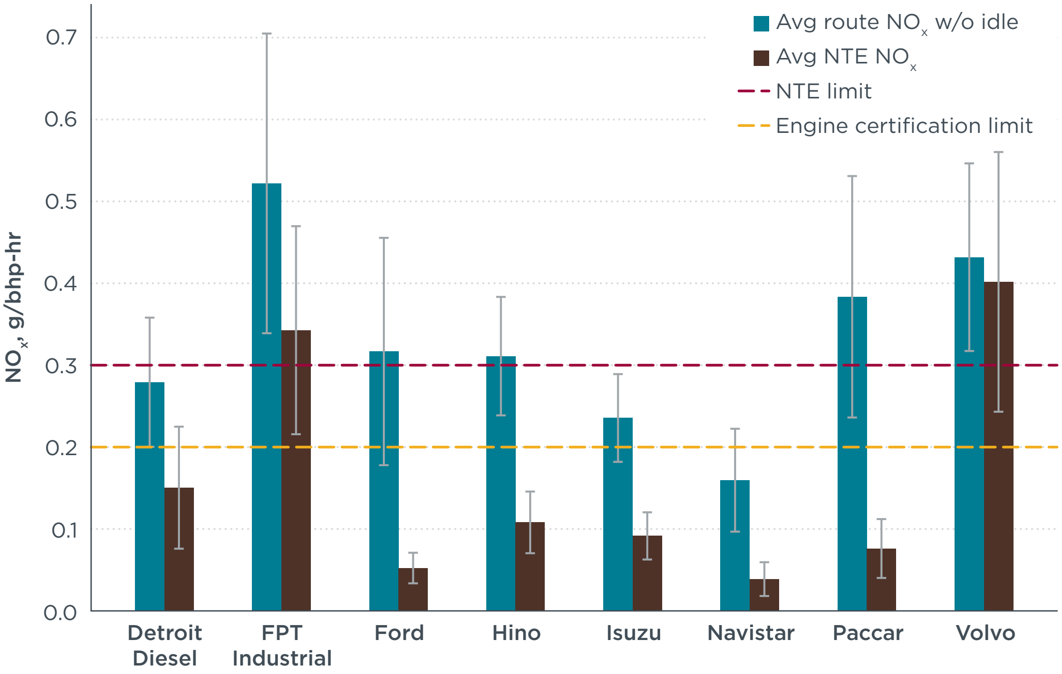

Figure 4 Comparison of Route NO_x to NTE NO_x by manufacturer. Whiskers represent the 95% confidence interval of the mean.

The variability between NTE and overall route emissions can be further assessed by differentiating by engine family (Figure 5). As previously mentioned, 26 engine families were included in the testing database, and each family was tested three to 10 times. Out of 160 tests, 22 had NO_x emissions above the NTE threshold of 0.3 g/bhp-hr when calculated using the NTE methodology (Figure 5a). The HDIUT database shows that 24 of 160 tests (15%) had no valid NTE events, which under the existing regulation triggers an additional PEMS test.

Tests that exhibit NO_x emissions higher than the NTE limit when evaluated using the NTE analysis do not automatically result in a "fail." An additional PEMS accuracy margin tolerance of 0.15 g/bhp-hr is added to the 0.30 limit, which enables NO_x emissions to be as high as 0.45 g/bhp-hr and still result in a pass. Additionally, specific procedures outline the method to be followed if tests lead to NO_x emissions above the NTE limit + accuracy margin limit. [5]

While exceeding the NO_x limit based on NTE type analysis is problematic, the situation is exacerbated when NO_x emissions are evaluated based on the full route analysis, leading to a significant increase in the number of tests and families exceeding the in-use limit. Comparing the test NO_x average route values against the NTE limit shows that 67 tests had NO_x emissions above the limit even after excluding idling (Figure 5b). Of the 26 engine families, 21 had at least one test exceeding the in-use limit when calculated using total route NO_x emissions data excluding idling.

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[5] The initial test campaign is carried out with the selection of five engines from a certain family. If a vehicle test were to fail the NTE limits, a series of conditionals regulate the number of additional engines that must be tested for an engine family to successfully declare a "pass." Refer to 40 CFR § 86.1915 "What are the requirements for Phase 1 and Phase 2 testing?" for further details regarding the pass/fail criteria.

Significant test differences within a single family were also observed, with the highest route average NO$_x$ being 1.4–16.4 times the lowest route average NO$_x$ value. The largest difference in route average NO$_x$ was found for the Volvo AVPTH12.8S01 (D13H 425) family, where average test results ranged from 0.09–1.4 g/bhp-hr.

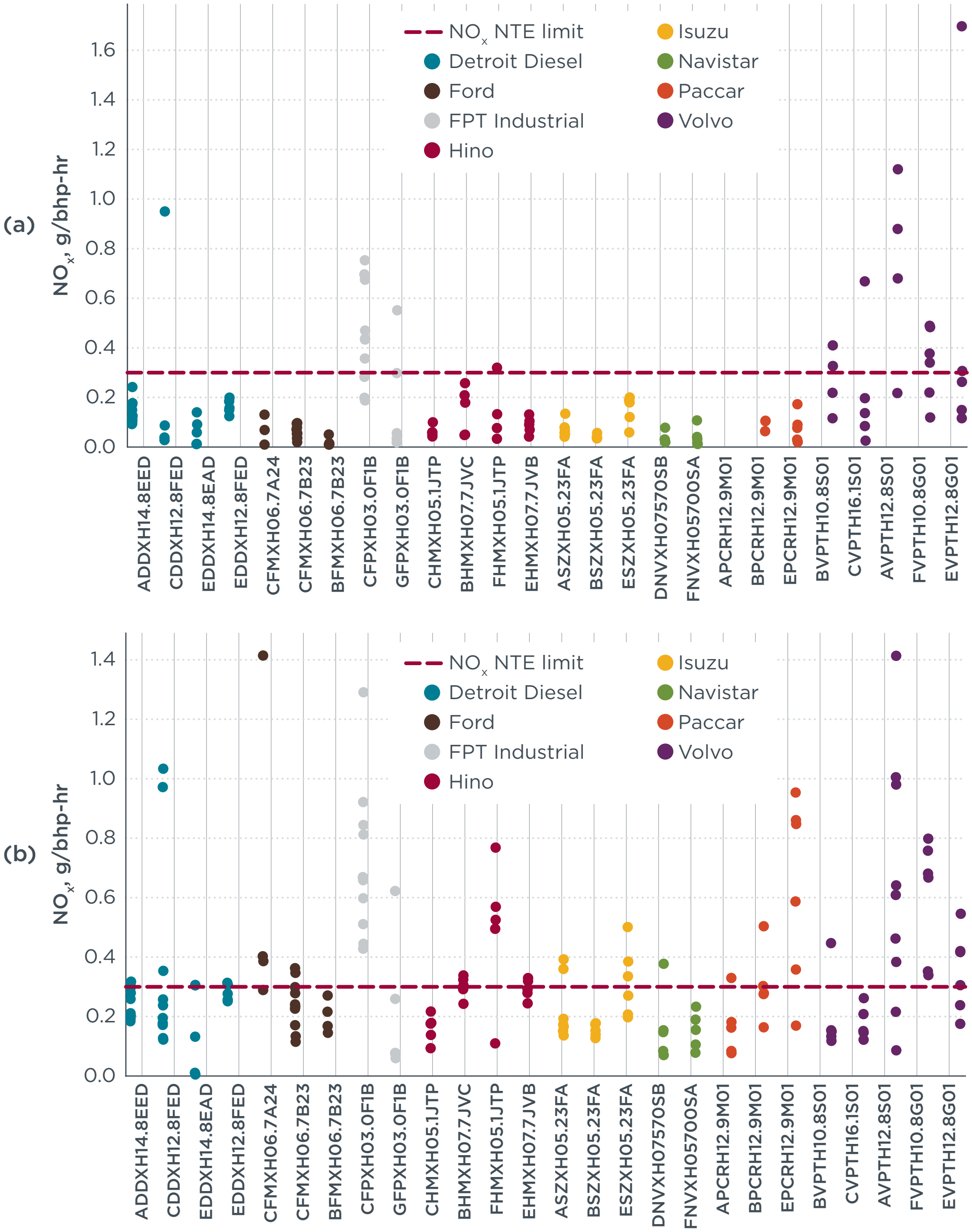

Figure 5 Engine family NOx emissions reported from (a) NTE data from HDIUT, and (b) calculated from route analysis (no data exclusions) of PEMS tests

Because the NTE approach excludes significant amounts of data from the emissions analysis, we focus the remainder of this report on analysis of full datasets differentiated by vehicle speed bins.

NO_x EMISSIONS VERSUS VEHICLE SPEED

Average emissions factor

The average NO_x emissions for all 160 PEMS tests segregated by speed bins are shown in Figure 6. The bars show the average per test NO_x emissions for all the data points that meet the given speed condition. Regulatory limits for engine certification of 0.20 g/bhp-hr and for in-use NTE of 0.30 g/bhp-hr are also included for reference. The average total route NO_x emissions across all manufacturers was 0.42 g/bhp-hr, and 0.34 g/bhp-hr excluding idling (speed < 1.0 mph)[6]. Average brake-specific NO_x emissions ranged from 0.20 g/bhp-hr at highway speeds to 1.05 g/bhp-hr at urban driving speeds. This is most likely because higher speeds result in higher exhaust temperatures where catalytic NO_x control is less challenging. This trend of higher brake-specific NO_x emissions at lower vehicle speeds has also been reported by researchers in the United States and Europe for HDVs with SCR systems (Grigoratos, 2019; Mendoza-Villafuerte, 2017; Sandhu & Sonntag, 2019).

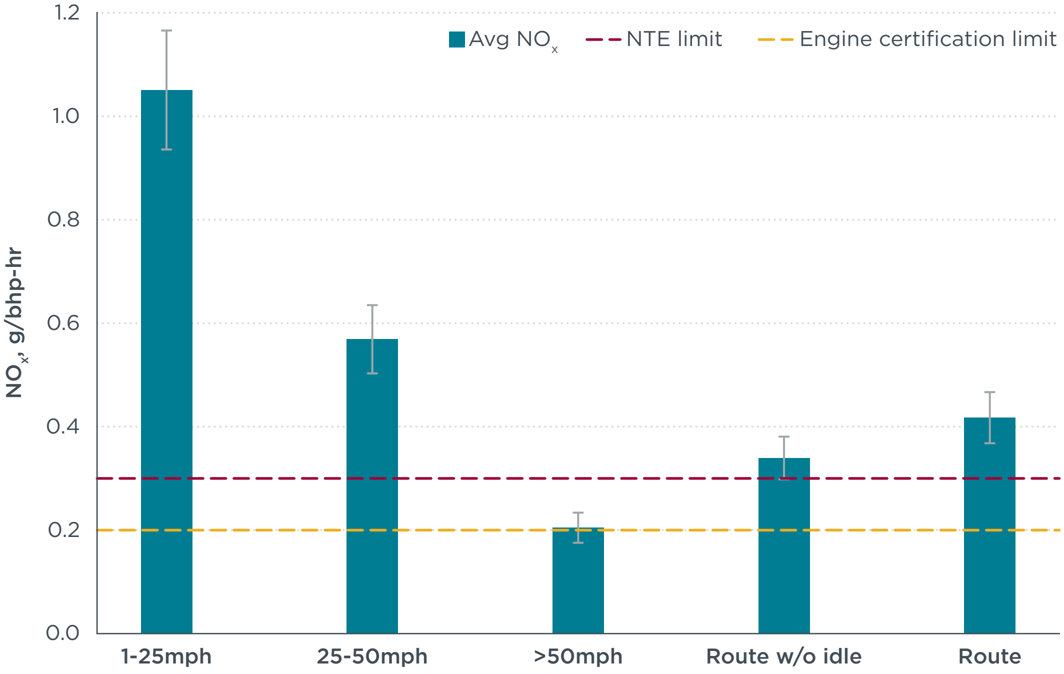

Figure 6 Average NO_x emissions in g/bhp-hr differentiated by vehicle speed. Whiskers represent the 95% confidence interval of the mean.

Exhaust temperature

The average exhaust temperature for each speed bin is shown in Figure 7. Average exhaust temperature increased from 213°C in urban driving to 290°C under highway driving conditions. The average route temperature, excluding idling data, was close to 260°C. Exhaust temperature data is measured within 12 inches downstream of the SCR system, according to in-use testing regulations. The existing NTE protocol does not consider emissions data collected below exhaust temperatures of 250°C, shown as a green dashed line in Figure 7. Catalytic NO_x control is more challenging at exhaust

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[6] At idle conditions, the work term may be small and may yield an artificial increase in NO_x. Brake-specific emissions would asymptotically approach infinite under idle conditions.

temperatures below 250°C. Therefore, it is not surprising that driving conditions at speeds below 25 mph or with higher percentage of idle result in higher average in-use NO_x emissions.

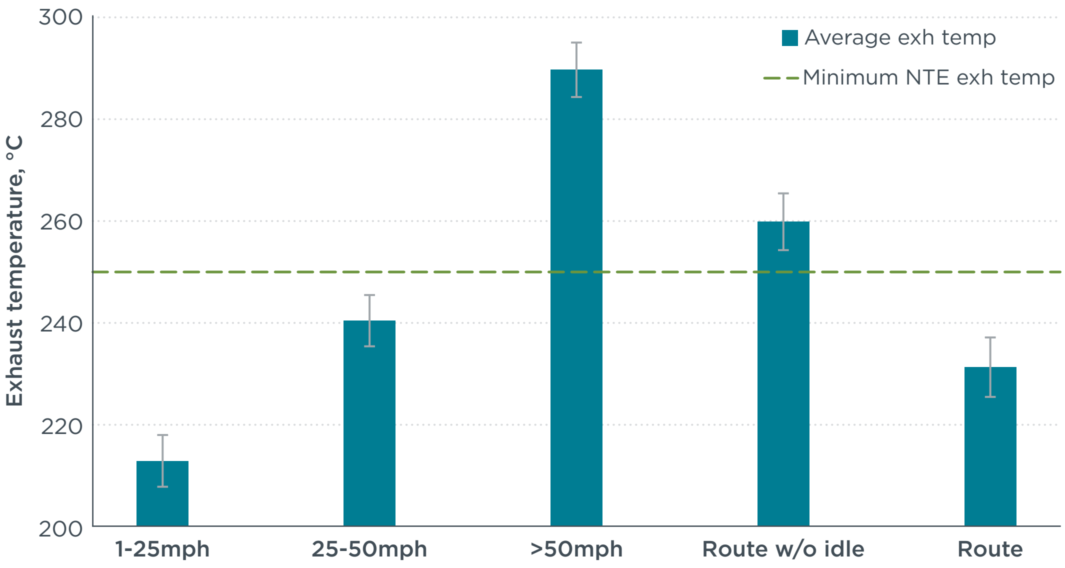

Figure 7 Average exhaust temperature per speed bin. NTE protocol minimum exhaust temperature required for individual datapoint validity is shown as a green dashed line at 250°C. Whiskers represent the 95% confidence interval of the mean.

Vehicle type

Average NO_x emissions in different speed bins were further analyzed by vehicle types: line haul, delivery, and other vehicles.[7] For the line-haul trucks, we analyzed 76 PEMS tests from 12 engine families; for the delivery trucks, 67 PEMS tests from 13 engine families; and for the other vehicle types, 17 PEMS test from three engine families. Note that the number of families does not add up to the previously mentioned count of 26 because several engine families are found in multiple vehicle types.

Line-haul trucks exhibited almost twice the average brake specific NO_x emissions as delivery or other vehicle types during low speed (1–25 mph) urban driving conditions (Figure 8a). Their average NO_x emissions of 1.41 g/bhp-hr are more than 7 times the engine certification limit in urban driving and more than 3 times the limit in suburban driving. At highway speeds, NO_x emissions seemed very similar across vehicle types. The total route average showed almost no differences among the vehicles studied.

Line-haul vehicles also had the highest CO_2-specific emission factors for 1–25 mph and 25–50 mph operation, whereas the emission factors of all three vehicle types were similar for highway-speed operation (Figure 8b). The CO_2-specific metric allows for direct comparison of different PEMS tests by lessening the impact of variations in the duty cycle or other test-to-test variables that impact emissions. It also allows comparisons with available data on HDVs. Bishop et al. captured on-road emissions from

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[7] Line-haul vehicles include class 8 tractor-trailers with a median gross vehicle weight rating (GVWR) of 80,000 lbs. Delivery vehicles includes box, drayage, and local transport trucks with a median GVWR of 19,500 lbs. The “other vehicle” category includes garbage collectors, bucket trucks, and various other localized applications also with a median GVWR of 19,500 lbs.

28 HDVs of model years 2014 and later operating at speeds around 10 mph and reported fuel-specific values of 3.8 gNO_x/kg of fuel, or 1.2 gNO_x/kg of CO_2 (Bishop, 2015). This value is lower than the 1.8 gNO_x/kg of CO_2 average emission values reported across all vehicles under low-speed conditions in the HDIUT dataset but well within the spread of the PEMS-based results.

Under urban driving conditions, line-haul trucks emitted, on average, 7.0 gNO_x/mile (Figure 8c). To put this in perspective, this is 100 times the Tier 2 Bin 5 emissions limit of passenger vehicles in the United States.[8] Previous studies have confirmed that real-world emissions from gasoline light-duty vehicles are generally at or below the Tier 2 standards, even in urban driving (McCaffery, 2019).

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[8] Tier 2 NO_x emissions standard over the FTP 75 for full useful life of Bin 5 passenger vehicles is at 0.07 g/mile.

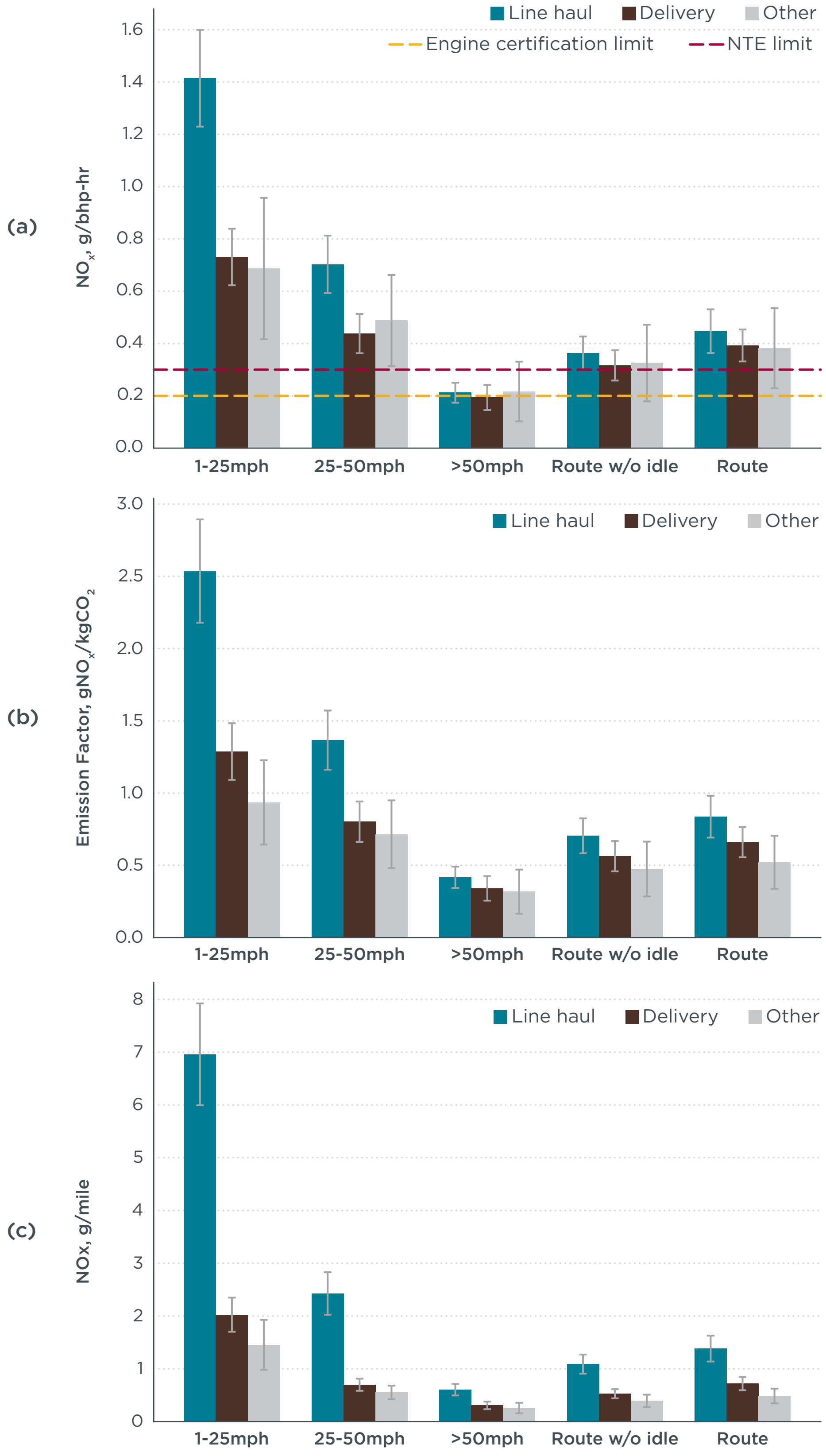

Figure 8 NO_x emissions by vehicle type in speed bins: (a) brake-specific (b) CO_2 specific, and (c) distance specific. Whiskers represent the 95% confidence interval of the mean.

Average exhaust temperature, shown in Figure 9, does not fully explain the higher urban NO_x values for line-haul vehicles than for delivery trucks as both types had very similar average exhaust temperatures. It is likely that the engine and aftertreatment control strategy for line-haul vehicles are optimized for controlling NO_x under higher speeds in line with their primary intended use. Another contributing factor to poor NO_x emissions control under low-speed urban driving could be rooted in the inability of the NTE in-use testing protocol to evaluate that driving condition for compliance purposes which disincentivizes manufacturers from optimizing NO_x around that operating region.

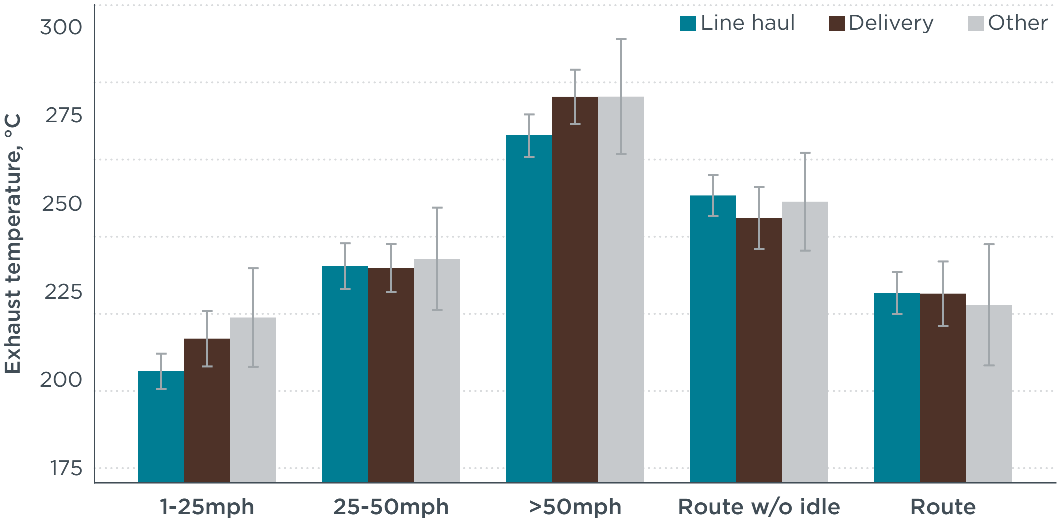

Figure 9 Average exhaust temperature (downstream of the SCR) by vehicle type in speed bins. Whiskers represent the 95% confidence interval of the mean.

Percentage of time spent and mass emitted by driving condition

As mentioned earlier, the EPA's in-use HDV testing program mandates that vehicles be driven as normally in everyday use. Figure 10 shows the percentage of time that each vehicle type spent in the different speed bins. All vehicle types spent a third or more of their time at speeds of less than 1 mph or idling. Combining idle (0–1 mph) with low-speed driving (1–25 mph), the percentage of time rises to 41%–55% depending on vehicle type. Line-haul trucks spent almost twice as much time in highway driving conditions as the two other vehicle types, offset by less time in urban and suburban driving.[9]

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[9] One caveat on this duty cycle summary is that these times are affected by the fact that the vehicles tested under the HDIUT program are expected to return to base at the end of the day for data collection and PEMS calibration work. This daily return to base may not be representative of normal driving for some long-haul and line-haul operations. This may result in idle and low speed shares for line-haul trucks in the HDIUT database to be higher than those found in real-world normal driving. A better source of HDV activity for class 8 heavy-duty trucks can be found in the Fleet DNA database managed and maintained by the National Renewable Energy Laboratory (NREL). The share of time operating at idle for long-haul trucks as measured by NREL fleet DNA data is 15.3% (Kotz & Kelly, 2019). The HDIUT data for line-haul class 8 trucks better matched the time share of combined-unit short-haul trucks in the NREL fleet DNA study, at 31%.

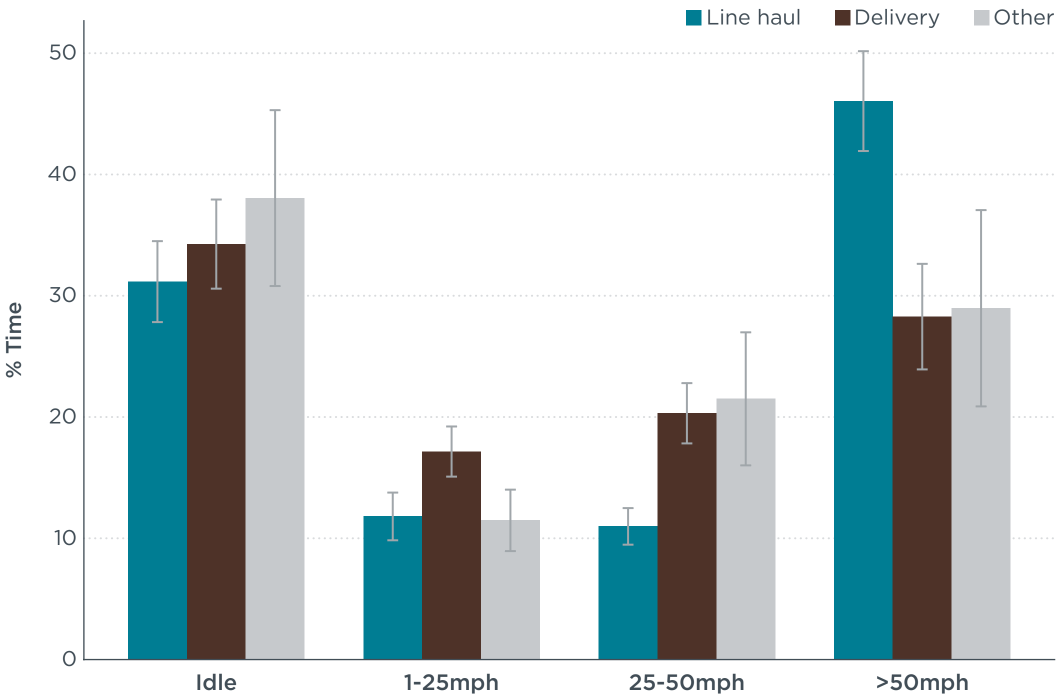

Figure 10 Percentage of time spent at each speed condition by vehicle type. Whiskers represent the 95% confidence interval of the mean.

Figure 11 shows the percentage of average total NO_x and CO_2 emitted in each speed bin by vehicle type. The percentage of total emissions in each speed bin does not necessarily align with the percentage of time spent in each speed bin. For all vehicle types, the vehicles were idling at least 30% of the time, but NO_x emissions during idling represent about 20% of the total, and CO_2 emissions represent around 10% of the total. Combining idling and low-speed driving, which was observed 41%–55% of the time, represented 40%–44% of total average NO_x emissions and 15%–20% of total average CO_2 emissions for all vehicle types. For line-haul trucks, which spent 47% of their time at highway speeds, high-speed NO_x emissions represent about 37% of the total and more than 70% of the CO_2 emissions.

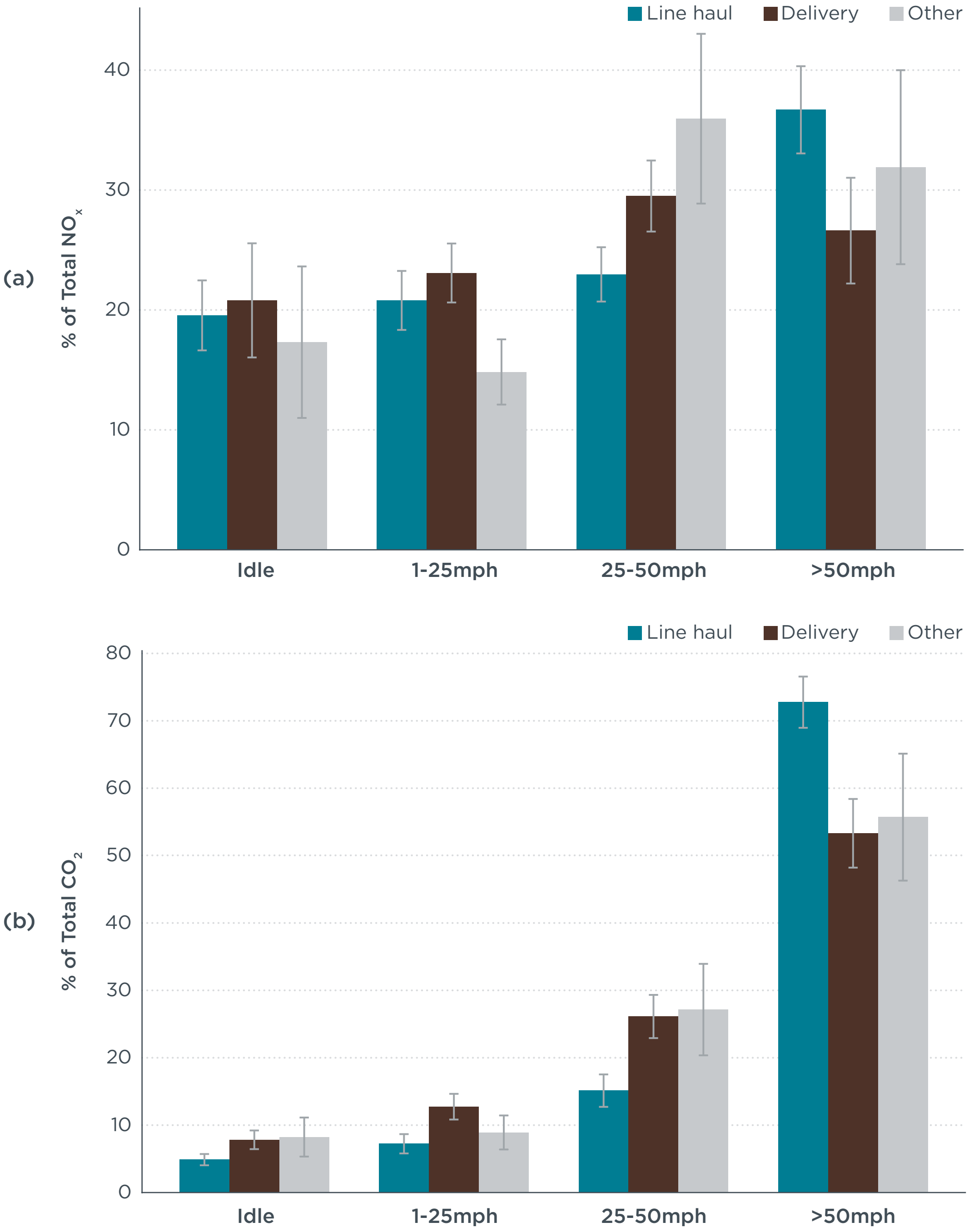

Figure 11 Percentage of total average (a) NO_x and (b) CO_2 emitted at each vehicle speed by vehicle type. Whiskers represent the 95% confidence interval of the mean.

Manufacturer

Because of the significance of urban emissions in terms of mass and share of operating time, we conducted a more extensive analysis of urban NO_x emissions excluding idle by manufacturer and vehicle type (Figure 12). Urban NO_x emissions of less than 0.3 g/bhp-hr were achieved only during 13 of the 160 tests. The high dispersion of urban NO_x performance was found in most manufacturer results, highlighting the wide range of low vehicle speed solutions for NO_x control. This dispersion suggests that porous regulatory provisions for in-use emissions control are generating inconsistent technical solutions for NO_x control across the sector.

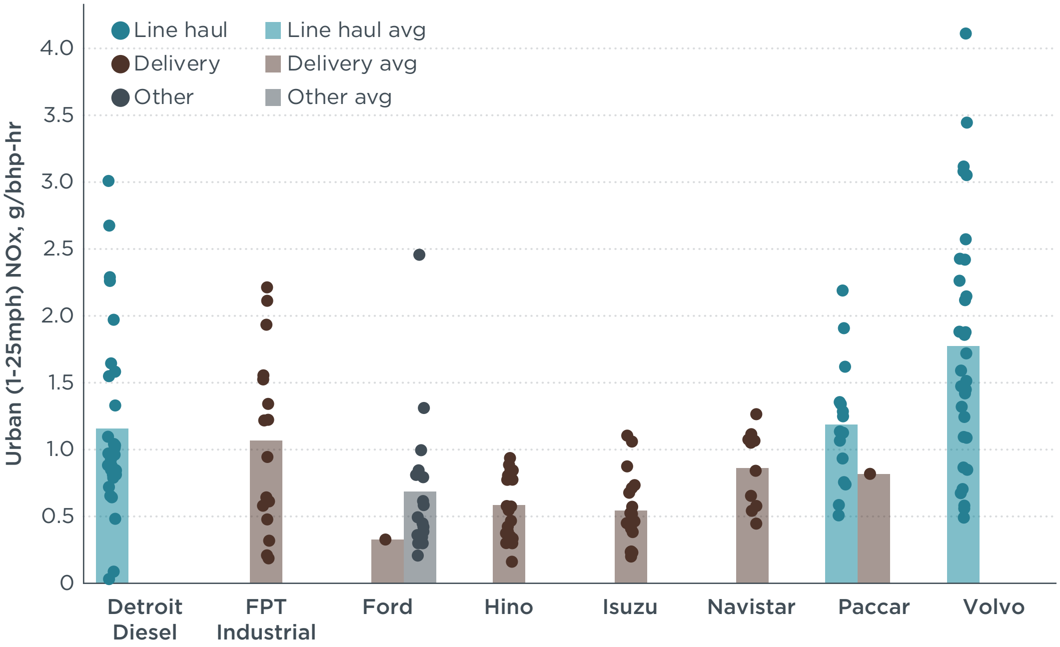

Figure 12 Urban NO_x emissions – g/bhp-hr

The dispersion of NO_x results among line-haul urban driving deserves further analysis. The three manufacturers with line-haul vehicle emissions data were Detroit Diesel, PACCAR, and Volvo. Table 3 shows summary statistics for number of tests, test-to-test differences indicated by minimum and maximum, and averages. Only two of the 76 tests for line-haul trucks had average urban NO_x emissions of less than 0.3 g/bhp-hr. The range of urban emission results between minimum and maximum values for the same manufacturer was orders of magnitude apart, from four to 100 times. Some of the maximum values shown in Table 3 are close to typical engine-out NO_x values found at low-load conditions, 3–4 g/bhp-hr. This suggests that the NO_x aftertreatment system may have been inactive during those sections of the tests.

Table 3 Summary statistics on urban driving (1–25 mph) brake-specific NO_x emissions (g/bhp-hr) for line-haul vehicles

Statistic	Detroit Diesel	Paccar	Volvo
# of Tests	30	15	31
Min	0.03	0.51	0.49
Max	3.01	2.19	4.11
Average	**1.16**	**1.19**	**1.77**

NO_x emissions of less than 0.3 g/bhp-hr under urban driving conditions were found in 13 PEMS tests. Those PEMS came from engine families manufactured by five of the eight companies and cover a wide range of engine displacements and applications.

The 0.3 g/bhp-hr in-use limit was achieved in urban driving excluding idle by Detroit Diesel with one engine family (15.8 L), Ford with two engine families (6.7 L), FPT industrial with one engine family (3.0 L), Hino with two engine families (5.0 L), and Isuzu with two engine families (5.2 L). These results indicate that real-world urban NO_x emissions in line with the existing in-use emissions standard limits are feasible with existing emissions-control technology.

Idle NO_x emission rates in gNO_x/hr are shown in Figure 13 for the different manufactures and vehicle types. Also shown for reference are the current voluntary limits set by CARB for idling emission rates (30 gNO_x/hr) as well as the proposed 2024 limit (10 gNO_x/hr) (CARB, 2019).[10] On average, line-haul trucks produced the highest NO_x emission rates at idle at 24 g/hr, while delivery trucks produced 9 g/hr and other vehicles 5 g/hr. While line-haul trucks are expected to have higher emission rates reflecting larger engine displacements, the CARB idling limit does not have separate targets based on engine characteristics. These findings indicate that future NO_x emission regulations are needed to ensure that idling emissions are accounted for and reductions are incentivized.

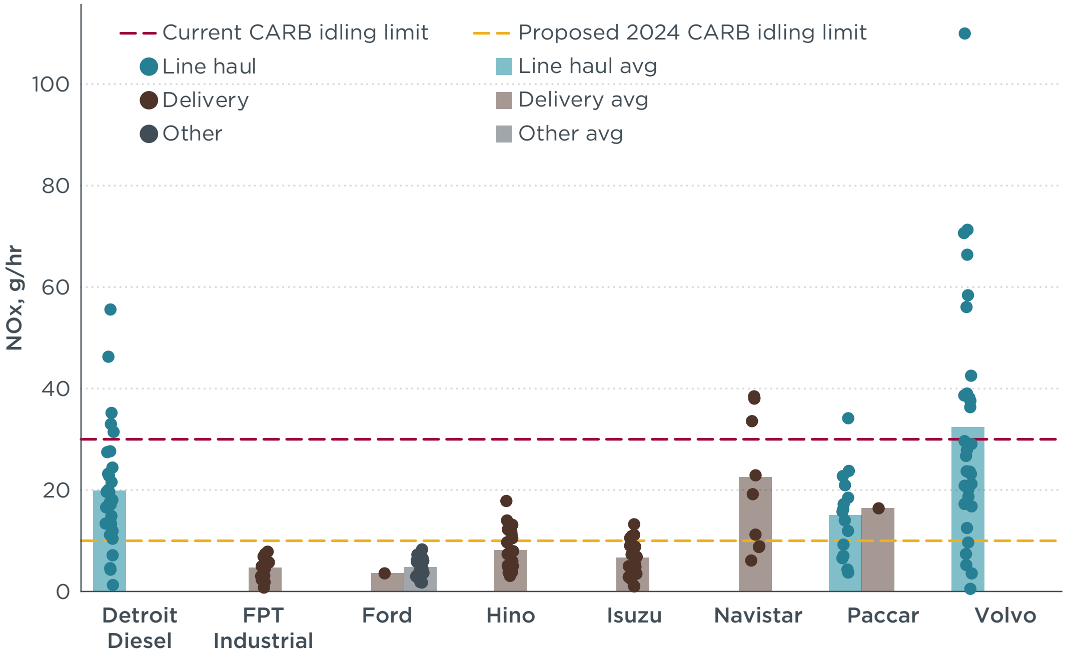

Figure 13 Idling NO_x emission rates (g/hr). The bars represent manufacturer average idle rate values for the entire PEMS dataset. Each dot represents the average idle emissions rate for each PEMS test.

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[10] The CARB idling limit is an optional NO_x standard for HDVs, which can also be fulfilled by implementation of an engine shutdown system that automatically turns off the engine after 300 seconds of continuous idling. The idling limit does not discriminate on engine size, flowrate, etc., and all HDVs must meet the limit in the absence of an automatic engine shutdown strategy.

CONCLUSIONS AND POLICY RECOMMENDATIONS

This report presents a baseline evaluation of NO_x emissions in the United States from on-road hheavy-duty vehicles with diesel engines certified to meet the EPA 2010 emission standards. PEMS data from the manufacturer-run HDIUT program made available by the EPA was the sole source of data for this report. Data from 160 PEMS tests and 26 unique engine families certified under the 0.2 g/bhp-hr FTP standard and the 0.3 g/bhp-hr NTE standard were studied. This evaluation provides an understanding of real-world NO_x emissions, highlighting conditions that contribute significantly to the NO_x inventory.

We compared the NO_x emissions evaluated with the NTE protocol to calculate total route NO_x emissions. The NTE method resulted in average NO_x emissions of 0.18 g/bhp-hr. This NTE compliance evaluation value was calculated, on average, based on less than 10% of the total PEMS data available. Comparatively, total route NO_x for all vehicles tested was 0.34 g/bhp-hr with the exclusion of idle operating conditions and 0.42 g/bhp-hr with idle.

We also analyzed the emissions data with no exclusions and looked at the impact of vehicle speed, vehicle type, and manufacturer on average NO_x emissions. In general, we found:

- On average, NO_x emissions increase to more than five times the certification limit in urban driving.
- Line-haul trucks have the highest urban NO_x emissions at almost seven times the engine certification limit
- Heavy-duty trucks spend, on average, 41%–55% of their total operational time in driving conditions slower than 25 mph, which is typically found in urban settings.
- On average, 40%–44% of total NO_x from HDVs is emitted during urban driving at speeds of less than 25 mph.
- NO_x emissions at levels at or below the 0.3 g/bhp-hr NTE limit during urban driving were found on 13 of 160 tests, corresponding to eight engine families produced by five manufacturers. Only four of the 160 tests had urban NO_x emissions at or below the 0.2 g/bhp-hr engine certification limit.

Based on these findings, we put forward the following policy recommendations for the development of future NO_x standards for heavy-duty engines:

- **A more stringent heavy-duty engine NO_x emissions standard is justified** based on emissions data showing a significant gap between real-world and engine-certified emissions.
- **Adoption of a supplemental low-load cycle with a corresponding emissions standard is necessary** to provide level ground for future development and adoption of emission controls for urban driving.
- **Adoption of a new in-use testing evaluation protocol that purposely targets the most challenging conditions for NO_x control is needed.** The current NTE protocol rejects more than 90% of the data captured during in-use tests. The new evaluation tool should focus on evaluating emissions where NO_x control is more challenging, such as low vehicle speed and engine load. The adoption of a low-load cycle also calls for an in-use protocol that evaluates data captured under such operating condition.

- **Controlling idling emissions requires a separate emissions limit and metric.** A work-specific limit for idling NO_x emissions is not appropriate during near-zero work conditions. A limit based on NO_x emissions rate, analogous to CARB's low NO_x idling standard, would be suitable for this application. Meeting an idle emissions limit would also incentivize compliance with CARB's proposed low-load cycle.

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APPENDIX A

The analysis presented in the body of this report excludes all Cummins non-credit engines available in the HDIUT dataset. This was done because all their diesel engines families tested under the HDIUT program were either covered by voluntary recalls or were natural gas engines. The HDIUT dataset contained 18 tests from two engine families manufactured by Cummins that are part of a voluntary recall and 11 PEMS from two CNG engine families.

This appendix presents NO_x emissions values from Cummins diesel and CNG engines excluded from the analysis. This is relevant as Cummins market share is one of the largest in the United States, where it supplies engines for four of every ten class-8 trucks sold in the United States (Transport Topics, 2019). The data from the recalled engines provides an indication of what NOx emission values can be found in HDVs experiencing SCR deterioration. The CNG results provide a comparison point on NO_x emissions between stoichiometric CNG engines and diesel.

Figure A1 shows NO_x emissions by vehicle speed bins for Cummins diesel recalled engines and Cummins CNG engines compared against the fleet average diesel values presented in this report. Recalled engines emit almost two times more than the fleet average during low speed driving. Comparatively, vehicles with CNG engines emit 40% lower during low speed driving. Total route values compared to the average diesel values are also two times higher for recalled engines while CNG engines are roughly half.

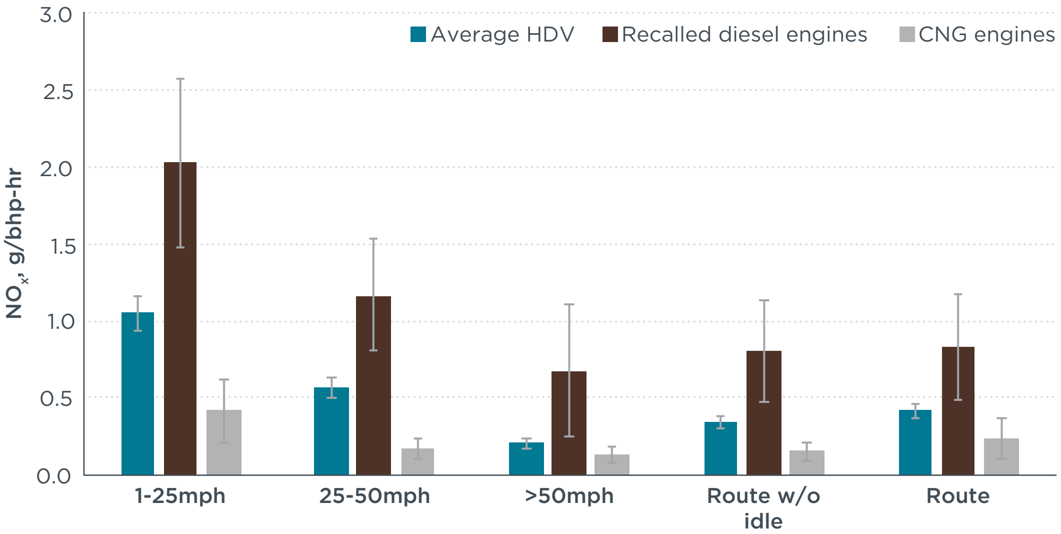

Figure A1. NO_x emissions by vehicle speed bin from the HDIUT dataset. Only non-credit engines. Includes recalled Cummins diesel engines, Cummins CNG engines, and average HDV values as shown in Figure 6. Whiskers represent the 95% confidence interval of the mean

APPENDIX B

This appendix presents a description for each of the 160 PEMS tests used in the analysis. All the tests correspond to vehicles with heavy-duty diesel engines certified to meet the EPA 0.2 g/bhp-hr NO$_x$ emissions standard. Engines certified under the NO$_x$ credit provision program were excluded. Engine families that are the subject of recalls were excluded from this analysis.

Table B1 describes the vehicles tested, engine characteristics, vehicle driving conditions, environmental conditions, and emission results as reported in the HDIUT tests and as calculated by our team. The HDIUT emissions results listed here show the results of the NTE evaluation process and are part of the data available from all PEMS tests studied.

Table B 1. Summary of PEMS Tests

Engine Manufacturer	Test Selection Year	Test Date	Engine Family	Engine Model	Engine Year	Engine Disp (L)	Max Power (hp)	Engine Hours	Vehicle Type	Max Weight (lbs)	Vehicle Miles	Test Duration (secs)	NTE Avg NO_x (g/hp-hr)	NTE Avg CO_2 (g/hp-hr)	Number of NTEs	Total NTE Duration (secs)	Test Duration (secs)	Amb Temp C	Avg Speed	Avg %Power	Avg Exh T[C]	Route NO_x (g/hp-hr)	Route CO_2 (kg/hp-hr)
Detroit Diesel	2011	20120410	ADDXH14.8EED	D472903--------	2010	14.8	475		Line haul	61000	68876	46980	0.11	477	47	2709	42775	19.6	31.9	0.22		0.236	0.516
Detroit Diesel	2011	20120412	ADDXH14.8EED	D472903--------	2010	14.8	475		Line haul	66000	67038	35450	0.17	478	71	3650	33505	19.6	29.1	0.18		0.326	0.546
Detroit Diesel	2011	20120925	ADDXH14.8EED	D472903	2011	14.8	475		Line haul	93107	104796	45217	0.11	493	61	3575	28704	20.1	25.3	0.20		0.294	0.545
Detroit Diesel	2011	20120926	ADDXH14.8EED	D472903	2011	14.8	475		Line haul	78130	5000	45979	0.09	505	95	4900	28612	23.5	35.1	0.25		0.212	0.545
Detroit Diesel	2011	20120927	ADDXH14.8EED	D472903	2011	14.8	475		Line haul	86155	115883	45544	0.10	502	50	2695	31960	19.7	27.7	0.19		0.367	0.545
Detroit Diesel	2012	20130813	ADDXH14.8EED	D472903	2010	14.8	475		Line haul	81000	173235	45162	0.18	453	59	3137	30572	21.9	31.0	0.20	260	0.331	0.480
Detroit Diesel	2012	20131030	ADDXH14.8EED	D472903	2010	14.8	475		Line haul	77238	173538	43024	0.13	457	57	3337	35569	24.4	32.0	0.22	233	0.251	0.520
Detroit Diesel	2012	20131031	ADDXH14.8EED	D472903	2010	14.8	475		Line haul	72272	217707	53955	0.15	455	124	7475	42906	23.3	35.3	0.24	246	0.293	0.510
Detroit Diesel	2012	20131103	ADDXH14.8EED	D472903	2010	14.8	475		Line haul	64825	180115	40568	0.09	484	31	1806	33842	12.7	28.1	0.17	208	0.389	0.550
Detroit Diesel	2013	20140806	ADDXH14.8EED	D472903	2010	14.8	475		Line haul	63365	245549	40308	0.24	478	80	4276	25565	23.8	37.4	0.22	239	0.406	0.510
Detroit Diesel	2014	20150922	CDDXH12.8FED	D471927	2013	12.8	450		Line haul	53000	160472	29355	0.04	498	28	2040	27508	21.0	30.8	0.21	234	0.215	0.496
Detroit Diesel	2014	20150923	CDDXH12.8FED	D471927	2013	12.8	450		Line haul	32000	164307	35541	0.03	504	33	2368	34538	21.1	30.0	0.21	232	0.220	0.489
Detroit Diesel	2014	20150924	CDDXH12.8FED	D471927	2013	12.8	450		Line haul	47227	168205	33501	0.09	495	30	1647	32617	21.1	34.0	0.22	245	0.167	0.485
Detroit Diesel	2014	20151120	CDDXH12.8FED	D471927	2013	12.8	370		Line haul	58577	206168	33857					33067	3.4	33.5	0.30	231	0.214	0.488
Detroit Diesel	2014	20151124	CDDXH12.8FED	D471927	2013	12.8	370		Line haul	58577	215650	25252					24586	7.4	27.6	0.23	260	0.443	0.475
Detroit Diesel	2015	20171102	CDDXH12.8FED	D471903	2012	12.8	470		Line haul	80000	424550	44353					43720	16.4	33.5	0.29	238	0.281	0.494
Detroit Diesel	2015	20171107	CDDXH12.8FED	D471903	2012	12.8	470		Line haul	80000	312937	32796	0.95	498	69	2070	30822	9.6	28.5	0.23	218	0.322	0.521
Detroit Diesel	2015	20171109	CDDXH12.8FED	D471903	2012	12.8	470		Line haul	80000	300904	73672					71067	3.4	29.0	0.23	207	0.465	0.486
Detroit Diesel	2015	20171114	CDDXH12.8FED	D471903	2012	12.8	380		Line haul	80000	246817	40169					39406	8.5	15.5	0.09	192	1.639	0.734
Detroit Diesel	2015	20171116	CDDXH12.8FED	D471903	2012	12.8	380		Line haul	80000	196360	40052					39228	5.0	12.5	0.09	155	2.008	0.625
Detroit Diesel	2016	20170511	EDDXH14.8EAD	D472906	2014	15.8	475		Line haul	56000	186709	27866	0.14	485	26	1056	25276	15.6	32.2	0.16	213	0.494	0.534
Detroit Diesel	2016	20170515	EDDXH14.8EAD	D472906	2014	15.8	475		Line haul	56000	228238	26777	0.06	475	34	1804	25911	21.2	28.4	0.14	212	0.489	0.552
Detroit Diesel	2016	20170518	EDDXH14.8EAD	D472906	2014	15.8	475		Line haul	56000	196523	23207	0.09	479	57	3139	22002	32.6	34.8	0.18	222	0.238	0.545
Detroit Diesel	2016	20170523	EDDXH14.8EAD	D472906	2014	15.8	475		Line haul	56000	228349	39199	0.01	492	94	5562	34265	22.5	50.8	0.26	283	0.015	0.524
Detroit Diesel	2016	20170525	EDDXH14.8EAD	D472906	2014	15.8	475		Line haul	56000	256589	40704	0.01	487	106	6291	37896	16.7	49.8	0.27	278	0.007	0.511
Detroit Diesel	2017	20180710	EDDXH12.8FED	D471927	2014	12.8	410		Line haul	80000	313551	43947	0.20	494	151	12927	41006	32.7	40.6	0.29	283	0.335	0.519
Detroit Diesel	2017	20180712	EDDXH12.8FED	D471927	2014	12.8	410		Line haul	80000	345273	41952	0.18	490	60	3509	40842	28.1	24.5	0.19	228	0.422	0.547
Detroit Diesel	2017	20180718	EDDXH12.8FED	D471927	2014	12.8	410		Line haul	80000	428243	28893	0.15	570	84	6529	28210	23.6	34.7	0.24	243	0.342	0.601
Detroit Diesel	2017	20180719	EDDXH12.8FED	D471927	2014	12.8	410		Line haul	80000	439060	25364	0.12	590	68	3735	24847	28.2	33.5	0.21	256	0.316	0.636
Detroit Diesel	2017	20180723	EDDXH12.8FED	D471927	2014	12.8	410		Line haul	80000	452591	21575	0.16	572	33	1677	18425	22.8	38.0	0.23	255	0.301	0.618
Ford	2013	20140716	CFMXH06.7A24	4V	2012	6.7	300	3034	Other	19000	54089	52249	0.13	671	20	1058	47617	22.0	11.3	0.07		0.521	0.763
Ford	2013	20140718	CFMXH06.7A24	4V	2012	6.7	300	1604	Other	11100	30843	29605	0.01	677	4	207	25098	21.9	26.3	0.11	210	0.467	0.727
Ford	2013	20140722	CFMXH06.7A24	4V	2012	6.7	300	1775	Other	15500	65237	23019	0.07	685	8	286	21765	26.9	30.4	0.13	239	0.407	0.732
Ford	2013	20141023	CFMXH06.7A24	4V	2012	6.7	300	571	Other	8500	47047	22683					21533	11.9	26.5	0.08	195	1.490	0.814
Ford	2015	20160726	CFMXH06.7B23	4VF	2012	6.7	300	19	Other	19500	86975	19371	0.10	628	24	1280	16645	26.5	35.9	0.17	260	0.144	0.696
Ford	2015	20160812	CFMXH06.7B23	4VF	2012	6.7	300	23	Other	19500	82481	22392	0.05	654	3	115	19380	32.0	26.4	0.11	201	0.390	0.733
Ford	2015	20160818	CFMXH06.7B23	4VF	2012	6.7	300	1280	Other	19500	84929	26591	0.02	688	28	1057	25411	26.0	46.7	0.20	274	0.128	0.746
Ford	2015	20160920	CFMXH06.7B23	4VF	2012	6.7	300	83	Other	16500	88736	23663	0.04	594	10	418	17855	25.1	35.8	0.14		0.287	0.663
Ford	2015	20160922	CFMXH06.7B23	4VF	2012	6.7	300	689	Other	16500	73651	30949	0.07	628	37	2911	28432	27.7	24.6	0.12		0.370	0.702
Ford	2011	20121003	BFMXH06.7B23	BFMXH067B23	2011	6.7	303	547	Other	19500	8619	29739	0.01	598	11	418	24772	24.3	16.4	0.06	159	0.457	0.869
Ford	2011	20121004	BFMXH06.7B23	BFMXH067B23	2011	6.7	303	1306	Other	19500	16875	32379	0.01	586	4	167	18923	25.6	21.6	0.09	222	0.260	0.753
Ford	2011	20121002	BFMXH06.7B23	BFMXH067B23	2011	6.7	303	2018	Other	19500	39606	29658	0.05	600	22	954	20325	21.8	31.6	0.14	215	0.197	0.708
Ford	2011	20120829	BFMXH06.7B23	BFMXH067B23	2011	6.7	303	96	Other	19500	4435	22924	0.02	547	4	137	22309	27.0	19.4	0.10	261	0.219	0.704
Ford	2017	20180620	CFMXH06.7B23	4VF	2012	6.7	300		Delivery	19500	74080	26512		579	7	483	25889	26.3	23.8	0.12	242	0.200	0.643
Ford	2017	20180628	CFMXH06.7B23	4VF	2012	6.7	300		Other	19500	67858	25848	0.10	586	19	920	20698	26.4	32.3	0.16	257	0.280	0.624
Ford	2017	20180727	CFMXH06.7B23	4VF	2012	6.7	300		Other	19500	48196	29258	0.06	566	11	744	27872	21.9	20.8	0.12	280	0.368	0.631
Ford	2017	20180822	CFMXH06.7B23	4VF	2012	6.7	300		Other	19500	55488	27031	0.08	561	9	364	26295	21.9	29.7	0.12	225	0.270	0.652
Ford	2017	20180911	CFMXH06.7B23	4VF	2012	6.7	300		Other	19500	49372	25543	0.04	576	10	543	24074	19.9	23.5	0.11	194	0.235	0.644

Engine Manufacturer	Test Selection Year	Test Date	Engine Family	Engine Model	Engine Year	Engine Disp (L)	Max Power (hp)	Engine Hours	Vehicle Type	Max Weight (lbs)	Vehicle Miles	Test Duration (secs)	NTE Avg NO$_x$ (g/hp-hr)	NTE Avg CO$_2$ (g/hp-hr)	Number of NTEs	Total NTE Duration (secs)	Test Duration (secs)	Amb Temp C	Avg Speed	Avg %Power	Avg Exh T[C]	Route NO$_x$ (g/hp-hr)	Route CO$_2$ (kg/hp-hr)
FPT Industrial	2013	20150417	CFPXH03.0F1B	F1C	2012	3	156		Delivery	16000	26187	43695	0.44	678	55	6019	25228	31.9	31.6	0.32	261	0.685	0.694
FPT Industrial	2013	20150430	CFPXH03.0F1B	F1C	2012	3	156		Delivery	16000	34302	32716	0.67	619	21	1087	14795	35.9	22.5	0.23	248	0.935	0.604
FPT Industrial	2013	20150616	CFPXH03.0F1B	CFPXH030F1B	2012	3	156		Delivery	16000	62622	24843	0.70	523	32	1992	23688	24.6	17.2	0.18	227	1.267	0.551
FPT Industrial	2013	20150619	CFPXH03.0F1B	CFPXH030F1B	2012	3	156		Delivery	16000	14427	29763	0.36	557	51	4177	27272	24.2	18.3	0.21	249	0.900	0.584
FPT Industrial	2013	20150623	CFPXH03.0F1B	CFPXH030F1B	2012	3	156		Delivery	16000	124128	31788	0.43	553	62	4725	29485	20.8	27.6	0.32	276	0.620	0.576
FPT Industrial	2013	20150714	CFPXH03.0F1B	CFPXH030F1B	2012	3	156		Delivery	16000	82596	30546	0.75	543	13	702	25951	24.5	16.4	0.19	236	0.840	0.518
FPT Industrial	2013	20150630	CFPXH03.0F1B	CFPXH030F1B	2012	3	156		Delivery	16000	23068	34260	0.19	572	52	5100	30645	20.9	23.1	0.27	248	0.486	0.596
FPT Industrial	2013	20150702	CFPXH03.0F1B	CFPXH030F1B	2012	3	156		Delivery	16000	4960	26551	0.47	563	45	3500	24755	19.3	21.4	0.22	250	0.714	0.602
FPT Industrial	2013	20150708	CFPXH03.0F1B	CFPXH030F1B	2012	3	156		Delivery	16000	84248	26420	0.28	550	64	7952	22264	19.2	36.6	0.36	283	0.534	0.569
FPT Industrial	2013	20150710	CFPXH03.0F1B	CFPXH030F1B	2012	3	156		Delivery	16000	85678	24311	0.20	521	64	7214	23413	24.0	35.8	0.36	304	0.455	0.543
FPT Industrial	2018	20180911	GFPXH03.0F1B	F1C	2013	3	161	191	Delivery	19500	6352	43603	0.04	458	175	15376	31120	19.5	46.6	0.53	322	0.079	0.466
FPT Industrial	2018	20181128	GFPXH03.0F1B	F1C	2013	3	153	2077	Delivery	19500	59785	23759	0.55	478	21	954	18456	-1.9	33.2	0.39	262	0.616	0.438
FPT Industrial	2018	20181129	GFPXH03.0F1B	F1C	2013	3	153	1948	Delivery	19500	63091	23188	0.30	409	55	3566	16936	1.0	45.0	0.48	286	0.262	0.399
FPT Industrial	2019	20190205	GFPXH03.0F1B	F1C	2016	3	153	899	Delivery	19500	28189	27674	0.02	449	47	3993	14405	24.1	28.0	0.35	267	0.076	0.423
FPT Industrial	2019	20190206	GFPXH03.0F1B	F1C	2016	3	153	401	Delivery	19500	15580	15550	0.06	544	39	6518	13203	23.7	52.7	0.67	382	0.079	0.560
FPT Industrial	2019	20190207	GFPXH03.0F1B	F1C	2016	3	153	519	Delivery	19500	14601	17134	0.03	459	54	5402	12481	20.7	44.5	0.52	331	0.066	0.475
Hino	2013	20141216	CHMXH05.1JTP	J05E	2012	5	210		Delivery	19500	22681	29642	0.06	387	15	1130	22571	10.2	29.2	0.29	240	0.217	0.473
Hino	2013	20141217	CHMXH05.1JTP	J05E	2012	5	210		Delivery	19500	35102	23846	0.04	406	21	989	16814	14.7	29.9	0.29	246	0.220	0.489
Hino	2013	20141215	CHMXH05.1JTP	J05E	2012	5	210		Delivery	19500	32784	30813	0.05	424	28	1517	20270	12.8	21.9	0.23	223	0.184	0.491
Hino	2013	20141214	CHMXH05.1JTP	J05E	2012	5	210		Delivery	19500	22940	28069	0.06	473	97	6463	21821	11.2	47.1	0.51	302	0.155	0.489
Hino	2013	20141213	CHMXH05.1JTP	J05E	2012	5	210		Delivery	19500	61638	25479	0.10	471	58	3153	23287	7.2	29.8	0.29	233	0.279	0.501
Hino	2014	20150722	BHMXH07.7JVC	J08E	2011	7.7	220		Delivery	25950	119258	22743	0.21	512	8	366	21678	27.3	28.6	0.26	205	0.320	0.496
Hino	2014	20150723	BHMXH07.7JVC	J08E	2011	7.7	220		Delivery	25950	159955	22332	0.05	506	6	308	19795	27.0	27.5	0.27	211	0.256	0.500
Hino	2014	20150721	BHMXH07.7JVC	J08E	2011	7.7	220		Delivery	25950	107438	22269	0.05	483	2	100	20963	30.3	24.6	0.24	205	0.293	0.474
Hino	2014	20150720	BHMXH07.7JVC	J08E	2011	7.7	220		Delivery	25950	77880	22320	0.18	506	10	611	19718	31.3	24.0	0.24	185	0.379	0.473
Hino	2012	20131206	BHMXH07.7JVC	J08E	2011	7.7	220		Delivery	25950	32576	20098	0.26	569	16	749	17570	10.4	28.4	0.19		0.377	0.816
Hino	2014	20150724	BHMXH07.7JVC	J08E	2011	7.7	220		Delivery	25950	113738	20709					16329	27.7	25.3	0.24	211	0.348	0.481
Hino	2017	20181010	FHMXH05.1JTP	J05E	2015	5.1	210		Delivery	14500	16497	21264	0.08	543	18	847	17775	25.8	36.1	0.20	232	0.115	0.557
Hino	2017	20181017	FHMXH05.1JTP	J05E	2015	5.1	210		Delivery	14500	76545	45111	0.03	544	8	341	24119	19.2	16.7	0.10	169	0.568	0.641
Hino	2017	20181016	FHMXH05.1JTP	J05E	2015	5.1	210		Delivery	14500	81812	38228					19435	15.9	13.4	0.09	170	0.839	0.641
Hino	2017	20181015	FHMXH05.1JTP	J05E	2015	5.1	210		Delivery	14500	28564	43056	0.13	584	6	347	21031	21.1	15.9	0.11	194	0.602	0.650
Hino	2016	20170708	EHMXH07.7JVB	J08E	2014	7.7	260		Delivery	33000	17684	22176	0.13	492	12	486	19919	30.7	24.4	0.17	243	0.351	0.574
Hino	2016	20170710	EHMXH07.7JVB	J08E	2014	7.7	260		Delivery	33000	40019	25739	0.10	503	35	1606	21474	32.2	31.4	0.20	250	0.359	0.593
Hino	2016	20170707	EHMXH07.7JVB	J08E	2014	7.7	260		Delivery	33000	34689	28700	0.09	498	62	2706	24504	28.7	40.7	0.26	270	0.288	0.571
Hino	2016	20170711	EHMXH07.7JVB	J08E	2014	7.7	260		Delivery	33000	60629	25638	0.07	494	43	1746	21505	32.7	35.0	0.22	254	0.263	0.579
Hino	2016	20170712	EHMXH07.7JVB	J08E	2014	7.7	260		Delivery	33000	47611	26310	0.04	507	34	1319	19605	32.6	38.6	0.24	264	0.305	0.586
Hino	2017	20181011	FHMXH05.1JTP	J05E	2015	5.1	210		Delivery	14500	43860	46329	0.32	565	2	85	18000	26.9	19.2	0.12	186	0.601	0.625
Isuzu	2011	20120514	ASZXH05.23FA	4HK1-TC	2010	5.2	210		Delivery	19500	59809	35715	0.08	542	27	1372	23330	21.5	22.7	0.19	223	0.185	0.595
Isuzu	2011	20120507	ASZXH05.23FA	4HK1-TC	2010	5.2	210		Delivery	19500	32655	45698	0.05	546	33	1882	20049	16.1	22.5	0.17	183	0.181	0.637
Isuzu	2011	20120515	ASZXH05.23FA	4HK1-TC	2010	5.2	210		Delivery	19500	33177	38499	0.06	508	29	1639	26878	24.7	17.6	0.15	202	0.153	0.576
Isuzu	2013	20140617	BSZXH05.23FA	4HK1-TC	2011	5.2	210		Delivery	19500	30200	26579	0.04	529	28	1797	22094	30.0	17.7	0.13	200	0.241	0.636
Isuzu	2011	20121019	ASZXH05.23FA	4HK1-TC	2010	5.2	210		Delivery	19500	40397	27320	0.13	692	7	285	25592	13.1	9.5	0.06	155	0.525	0.885
Isuzu	2011	20121022	ASZXH05.23FA	4HK1-TC	2010	5.2	210		Delivery	19500	40468	27491	0.07	703	8	390	23003	19.7	10.6	0.07	157	0.524	0.834
Isuzu	2011	20120521	ASZXH05.23FA	4HK1-TC	2010	5.2	210		Delivery	19500	72062	42256	0.08	528	53	3773	27661	17.8	26.2	0.19	187	0.311	0.674
Isuzu	2011	20120523	ASZXH05.23FA	4HK1-TC	2010	5.2	210		Delivery	19500	52922	29833	0.04	504	23	1189	13044	21.0	32.6	0.23	190	0.239	0.619
Isuzu	2013	20140219	BSZXH05.23FA	4HK1-TC	2011	5.2	210		Delivery	19500	40719	38864	0.04	595	28	3491	17758	23.2	25.3	0.19	212	0.239	0.656
Isuzu	2013	20140224	BSZXH05.23FA	4HK1-TC	2011	5.2	210		Delivery	19500	53760	40592	0.06	595	46	4389	21921	24.5	28.7	0.21	234	0.216	0.651
Isuzu	2013	20140226	BSZXH05.23FA	4HK1-TC	2011	5.2	210		Delivery	19500	37884	41428	0.03	605	26	2529	16959	21.8	22.8	0.18	212	0.230	0.662
Isuzu	2013	20140228	BSZXH05.23FA	4HK1-TC	2011	5.2	210		Delivery	19500	32978	36633	0.04	576	22	1084	19336	18.1	20.2	0.15	215	0.207	0.588
Isuzu	2016	20171030	ESZXH05.23FA	4HK1-TC	2013	5.2	210		Delivery	19500	73036	47486	0.20	667	2	102	28157	5.6	14.7	0.09	162	0.825	0.796
Isuzu	2016	20171103	ESZXH05.23FA	4HK1-TC	2013	5.2	210		Delivery	19500	70435	26642	0.18	576	20	1495	21272	9.2	29.6	0.24	252	0.310	0.620
Isuzu	2016	20180911	ESZXH05.23FA	4HK1-TC	2014	5.2	210		Delivery	19500	54398	32430	0.18	559	7	292	21387	26.1	19.7	0.13	209	0.442	0.643
Isuzu	2016	20180912	ESZXH05.23FA	4HK1-TC	2014	5.2	210		Delivery	19500	44674	30576	0.06	565	17	1013	19581	26.7	24.6	0.17	235	0.240	0.646
Isuzu	2016	20180913	ESZXH05.23FA	4HK1-TC	2014	5.2	210		Delivery	19500	53124	14506	0.19	584	3	108	12306	25.8	14.1	0.10	226	0.486	0.905
Isuzu	2016	20180914	ESZXH05.23FA	4HK1-TC	2014	5.2	210		Delivery	19500	53255	25552	0.12	551	9	659	10114	25.1	32.9	0.23	238	0.245	0.616

Engine Manufacturer	Test Selection Year	Test Date	Engine Family	Engine Model	Engine Year	Engine Disp (L)	Max Power (hp)	Engine Hours	Vehicle Type	Max Weight (lbs)	Vehicle Miles	Test Duration (secs)	NTE Avg NO_x (g/hp-hr)	NTE Avg CO_2 (g/hp-hr)	Number of NTEs	Total NTE Duration (secs)	Test Duration (secs)	Amb Temp C	Avg Speed	Avg %Power	Avg Exh T[C]	Route NO_x (g/hp-hr)	Route CO_2 (kg/hp-hr)
Navistar	2014	20150522	DNVXH07570SB	A475	2013	12.4	483	4577	Delivery	47400	191598	43722	0.03	587	150	10201	41850	19.5	46.0	0.24	253	0.125	0.622
Navistar	2014	20150528	DNVXH07570SB	A475	2013	12.4	483	4840	Delivery	47400	230123	38006	0.03	598	202	11301	36365	28.1	53.0	0.28	263	0.083	0.624
Navistar	2014	20150730	DNVXH07570SB	A410	2013	12.4	411	3650	Delivery	47400	97906	39174	0.02	572	57	4001	33576	27.6	31.4	0.20	254	0.188	0.631
Navistar	2014	20150731	DNVXH07570SB	A410	2013	12.4	411	3171	Delivery	47400	75118	31796	0.02	562	49	2330	29278	27.7	31.9	0.20	231	0.169	0.619
Navistar	2014	20150921	DNVXH07570SB	A410	2013	12.4	411	3171	Delivery	47400	75022	26517	0.08	585	24	1244	25443	18.1	26.0	0.15	212	0.438	0.674
Navistar	2016	20170725	FNVXH05700SA	S330	2015	9.3	330		Delivery	80000	32459	36996	0.04	517	16	645	36286	20.0	15.1	0.13	186	0.769	0.574
Navistar	2016	20171121	FNVXH05700SA	S330	2015	9.3	330		Delivery		58213	40877	0.02	585	31	1920	40104	7.6	15.0	0.15	188	0.638	0.621
Navistar	2016	20170801	FNVXH05700SA	S330	2015	9.3	330	1470	Delivery		21544	49184	0.11	513	64	4012	45782	26.5	13.3	0.12	184	0.823	0.583
Navistar	2016	20170919	FNVXH05700SA	S300	2015	9.3	300	1382	Delivery		48141	58936	0.03	562	101	6205	55412	24.8	17.9	0.16	204	0.521	0.630
Navistar	2016	20170922	FNVXH05700SA	S330	2015	9.3	300	1922	Delivery		50970	26211	0.01	563	63	3586	25461	25.9	21.1	0.19	213	0.284	0.602
Paccar	2010	20111001	APCRH12.9M01	MX 280 T	2010	12.9	395	2311	Line haul	75000	98956	31156					22349	24.0	45.9	0.26		0.184	0.477
Paccar	2010	20111003	APCRH12.9M01	MX 280 T	2010	12.9	405	2379	Line haul	68000	102141	19430			11	522	16421	19.9	45.0	0.25		0.081	0.475
Paccar	2010	20111006	APCRH12.9M01	MX 280 T	2010	12.9	405	896	Line haul	68000	34175	21753			32	2159	18433	15.1	44.1	0.28		0.087	0.482
Paccar	2010	20111010	APCRH12.9M01	MX 280 T	2010	12.9	405	1067	Line haul	68000	39544	31511			29	1667	22751	24.2	44.8	0.32		0.165	0.512
Paccar	2010	20111031	APCRH12.9M01	MX 360 T	2010	12.9	491	1013	Line haul	64000	23804	31581			22	1356	28354	6.5	28.5	0.20		0.377	0.544
Paccar	2015	20151113	BPCRH12.9M01	MX 360 T	2011	12.9	491	6268	Line haul	60000	268474	40878					8047	13.3	27.2	0.27	237	0.550	0.521
Paccar	2015	20160525	BPCRH12.9M01	MX 321 T	2011	12.9	449	11374	Line haul	79920	394653	32719	0.11	492	17	959	29375	29.1	28.0	0.20	251	0.364	0.537
Paccar	2015	20160606	BPCRH12.9M01	MX 360 T	2011	12.9	491	8723	Line haul	80000	370400	35750	0.06	491	127	10064	23662	16.9	50.5	0.32	253	0.179	0.503
Paccar	2015	20160609	BPCRH12.9M01	MX 360 T	2011	12.9	491	8927	Line haul	80000	368831	37480	0.10	495	45	3828	27442	27.4	32.7	0.20	250	0.302	0.530
Paccar	2015	20160811	BPCRH12.9M01	MX 340 T	2011	12.9	491	7559	Delivery	60000	308336	25698		511	2	81	16762	21.4	34.4	0.18	232	0.336	0.549
Paccar	2017	20180627	EPCRH12.9M01	MX-13 360 V	2014	12.9	482	8170	Line haul	99060	288943	34335	0.17	452	14	838	16447	19.4	22.6	0.16	211	0.611	0.500
Paccar	2017	20180628	EPCRH12.9M01	MX-13 360 V	2014	12.9	482	8176	Line haul	102560	289056	41616	0.02	451	5	252	20535	20.2	15.5	0.09	181	1.023	0.549
Paccar	2017	20180702	EPCRH12.9M01	MX-13 360 V	2014	12.9	482	6844	Line haul	105500	230438	40369	0.09	462	7	398	20609	19.3	24.1	0.13	219	0.897	0.566
Paccar	2017	20180703	EPCRH12.9M01	MX-13 360 V	2014	12.9	482	8041	Line haul	105500	282861	33389	0.03	482	3	237	19505	20.6	16.0	0.11	224	0.873	0.584
Paccar	2017	20181112	EPCRH12.9M01	MX-13 340 V	2014	12.9	455	9127	Line haul		332716	37165	0.02	458	76	6454	33912	16.5	38.7	0.28	233	0.171	0.466
Paccar	2017	20181115	EPCRH12.9M01	MX-13 340 V	2014	12.9	455	4685	Line haul	80000	260050	40799	0.08	474	60	5815	35766	12.5	30.4	0.24	219	0.390	0.485
Volvo	2014	20141029	BVPTH10.8S01	MP7-395C	2011	10.8	409	5069	Line haul	50000	203488	39938	0.41	502	2	72	38840	16.6	21.9	0.15	212	0.504	0.551
Volvo	2014	20141027	BVPTH10.8S01	MP7-395C	2011	10.8	409	5038	Line haul	50000	192844	39929	0.12	504	49	2066	38748	22.9	34.7	0.20	246	0.154	0.562
Volvo	2013	20140501	CVPTH16.1S01	D16H 500	2012	16.1	529	4019	Line haul	80000	166211	40095	0.08	536	54	2384	37053	17.7	38.6	0.20	257	0.162	0.593
Volvo	2013	20140513	CVPTH16.1S01	D16H 550	2012	16.1	579	3304	Line haul	80000	126711	33548	0.67	525	50	2246	32095	17.9	28.8	0.17	261	0.165	0.597
Volvo	2013	20140429	CVPTH16.1S01	D16H 500	2012	16.1	529	2140	Line haul	80000	78364	39511	0.03	550	62	3184	38369	8.7	37.2	0.22	249	0.218	0.592
Volvo	2013	20140515	CVPTH16.1S01	D16H 500	2012	16.1	529	5107	Line haul	102000	153331	40480	0.14	495	70	3893	39315	17.0	29.7	0.16	223	0.369	0.654
Volvo	2013	20140516	CVPTH16.1S01	D16H 500	2012	16.1	529	3255	Line haul	102000	106731	36802	0.20	538	44	2568	34078	20.6	33.7	0.18	230	0.322	0.660
Volvo	2011	20120626	AVPTH12.8S01	D13H 425	2010	12.8	435	5952	Line haul	80000	256633	43200					48953	21.6	13.5	0.12	171	0.765	0.460
Volvo	2012	20131120	AVPTH12.8S01	D13H 425	2010	12.8	435	8550	Line haul	107000	354249	43200	0.88	556	15	952	45817	1.2	40.6	0.40	246	0.640	0.615
Volvo	2012	20131001	AVPTH12.8S01	D13H 425	2010	12.8	435	3028	Line haul	60000	310226	43200	0.68	510	26	1407	46838	19.8	16.7	0.12	180	1.064	0.531
Volvo	2011	20120628	AVPTH12.8S01	D13H 425	2010	12.8	435	4986	Line haul	60000	217660	43200					43752	25.1	50.2	0.23	250	0.106	0.545
Volvo	2012	20131119	AVPTH12.8S01	D13H 425	2010	12.8	435	7430	Line haul	107000	314482	43200	0.22	489	14	719	49341	-0.3	37.5	0.33	226	0.504	0.523
Volvo	2011	20120510	AVPTH12.8S01	D13H 425	2010	12.8	438	1862	Line haul	77160	53485	32714					31704	14.9	30.1	0.18	220	0.357	0.536
Volvo	2012	20131126	AVPTH12.8S01	D13H 425	2010	12.8	438	4769	Line haul	78000	124864	32443					30423	2.2	21.4	0.17	179	1.286	0.499
Volvo	2011	20120508	AVPTH12.8S01	D13H 425	2010	12.8	438	697	Line haul	70000	21222	42492					41594	19.2	22.0	0.17	210	0.488	0.542
Volvo	2012	20131022	AVPTH12.8S01	D13H 425	2010	12.8	438	3408	Line haul	70000	103657	37603	1.12	513	6	288	36520	7.6	15.4	0.09	151	1.640	0.551
Volvo	2014	20141012	BVPTH10.8S01	D11H 385	2011	10.8	396	7923	Line haul	80000	344060	27183	0.22	491	26	1640	26464	15.1	47.6	0.38	270	0.130	0.512
Volvo	2014	20141015	BVPTH10.8S01	D11H 385	2011	10.8	396	8596	Line haul	80000	397935	31839	0.33	481	27	1675	30952	11.9	49.5	0.35	254	0.153	0.515
Volvo	2014	20141014	BVPTH10.8S01	D11H 385	2011	10.8	396	6124	Line haul	80000	253493	26386					25665	14.1	46.9	0.36	247	0.158	0.617
Volvo	2017	20180410	FVPTH10.8G01	MP7-395C	2015	10.8	403	9554	Line haul	65000	332822	39887	0.34	483	58	5805	37066	11.9	42.5	0.37	237	0.764	0.490
Volvo	2017	20180522	FVPTH10.8G01	MP7-395C	2015	10.8	403	7207	Line haul	88640	238632	49098	0.22	493	117	9122	44710	21.7	28.8	0.33	268	0.397	0.502
Volvo	2017	20180410	FVPTH10.8G01	MP7-395C	2015	10.8	403	7689	Line haul	65000	270151	44530	0.49	471	87	5347	39401	12.0	43.6	0.30	223	0.799	0.489
Volvo	2017	20180412	FVPTH10.8G01	MP7-395C	2015	10.8	403	5101	Line haul	65000	177991	42814	0.12	475	124	6102	40716	17.5	32.9	0.30	233	0.449	0.488
Volvo	2017	20180412	FVPTH10.8G01	MP7-395C	2015	10.8	403	5885	Line haul	65000	202762	41911	0.48	478	95	5584	37423	20.0	39.4	0.26	217	0.863	0.480
Volvo	2017	20180411	FVPTH10.8G01	MP7-395C	2015	10.8	403	6109	Line haul	65000	202583	45007	0.38	485	90	5666	41580	13.2	34.3	0.28	214	0.770	0.505
Volvo	2016	20170417	EVPTH12.8G01	D13J425	2014	12.8	435	4450	Line haul	79000	292385	43060	0.26	454	29	1575	34907	16.3	41.6	0.28	231	0.461	0.468
Volvo	2016	20170419	EVPTH12.8G01	D13J425	2014	12.8	435	8161	Line haul	79000	225317	43621	1.70	439	4	137	36047	10.9	39.4	0.29	235	0.458	0.454
Volvo	2016	20170719	EVPTH12.8G01	D13J425	2014	12.8	435	6881	Line haul	60000	229362	40598	0.15	443	91	4529	30889	27.0	41.5	0.22	238	0.335	0.473
Volvo	2016	20161108	EVPTH12.8G01	D13J425	2014	12.8	435	7013	Line haul	50000	302670	13459					13123	9.4	52.5	0.34	244	0.601	0.467
Volvo	2016	20161115	EVPTH12.8G01	D13J425	2014	12.8	435	5042	Line haul	80000	212457	39938	0.31	453	3	445	16600	4.5	49.4	0.40	254	0.367	0.467
Volvo	2016	20161115	EVPTH12.8G01	D13J425	2014	12.8	435	5186	Line haul	80000	218119	23188	0.12	436	38	2034	20605	17.7	50.0	0.40	273	0.255	0.450