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IN-USE NO_x EMISSIONS AND COMPLIANCE EVALUATION FOR MODERN HEAVY-DUTY VEHICLES IN EUROPE AND THE UNITED STATES

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EXECUTIVE SUMMARY

Emissions of nitrogen oxides (NO_x) from heavy-duty diesel vehicles (HDVs) are a significant contributor to ambient air quality issues and ozone and particulate pollution in many areas of the world. The current emission standards for heavy-duty engines and vehicles in the United States and Europe, EPA 2010 and Euro VI respectively, lead the way globally toward reducing NO_x emissions from diesel engines.

A significant gap between real-world and certified NO_x emissions from these diesel engines has been identified. This gap is especially wide during urban driving conditions and other low-load operations in diesel HDVs certified under the U.S. EPA 2010 program. The 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 the weaknesses in the current standard. In Europe, preparatory work for formulating a new version of heavy-duty emission standards is underway. These regulatory developments present important opportunities to identify the cause of high real-world NO_x emissions and address the issue before new regulations are finalized.

This report presents a comparison of real-world NO_x emission from HDVs certified under U.S. and European emission programs and provides an analysis of the regulatory tools employed by each program to determine in-use compliance. The first part of the report compares NO_x emission values from 11 HDVs designed to meet the EPA 2010 NO_x standard with five European trucks designed to meet the Euro VI NO_x standard. The vehicles have similar characteristics. NO_x emission data were collected via portable emission measurement systems (PEMS). Second-by-second data were analyzed for both groups by vehicle speed and power demands.

We found that European HDVs are better designed than U.S. trucks to control NO_x emissions under low-speed, low-load, and idle conditions (Figure ES-1):

- The U.S. HDVs studied emit on average 1.4 times more NO_x per unit work than the European vehicles. During urban driving conditions, work-specific NO_x emissions of U.S. HDVs almost quadruple in magnitude compared to their total route emissions. European HDVs tend to exhibit a more consistent performance across the speed range, with urban driving emissions being twice as much as their total route emission values.
- The analysis by power conditions shows the U.S. trucks analyzed for this study emit more NO_x than the European trucks at the lowest power range. Below 10% of maximum rated power, the sample of U.S. trucks emits twice as much NO_x as the sample of European trucks studied.

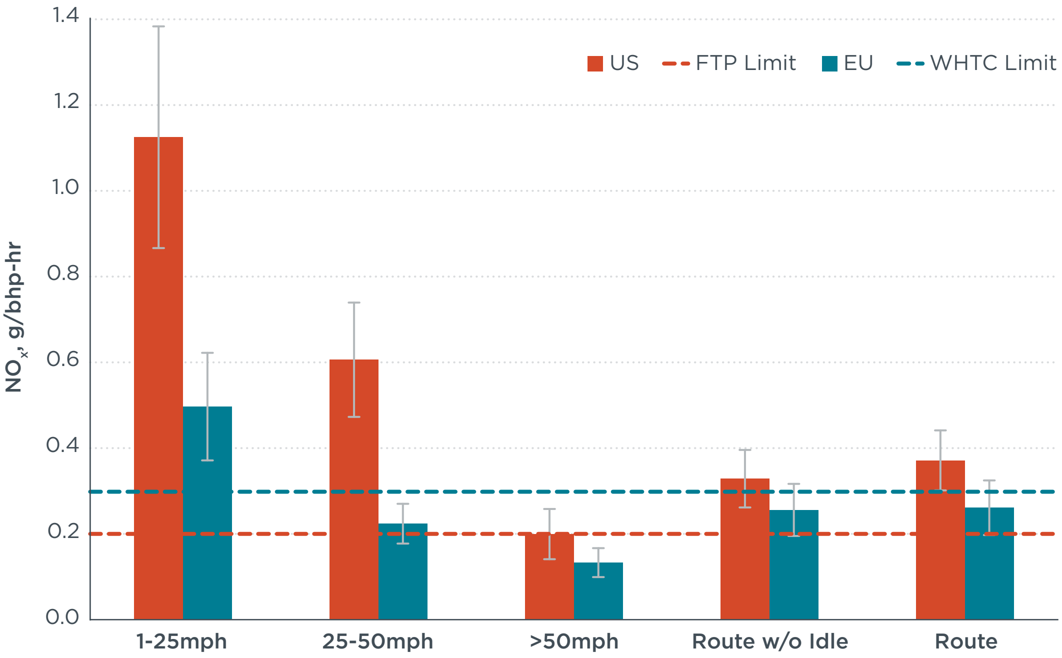

Figure ES-1. NO$_x$ emissions by speed bin for European and U.S. HDVs. Dotted lines represent engine emission NO$_x$ limits for U.S. and European HDVs. Error bars show confidence intervals at 95%.

The second part of this report studies the regulatory tools used in each program for analyzing PEMS data and determining in-use emissions compliance. PEMS data from five HDVs, two from Europe and three from the United States, were analyzed following the current regulatory in-use evaluation protocols as defined by the U.S. Not-to-Exceed (NTE) and the European moving average window (MAW) protocols. Changes to the current regulations were studied in order to provide recommendations for the current regulatory updates for HDV emission control in the United States and Europe.

The analysis of the in-use compliance tools, NTE and MAW, indicates that excluding data from the regulatory evaluation directly impacts NO$_x$ emission values. We found that:

» High urban NO$_x$ emission values found in U.S certified HDVs potentially can be attributed to the current NTE design. The U.S. NTE protocol evaluates in-use NO$_x$ data only under a narrow band of vehicle operating conditions, exclusively during highway driving. The rejection of data under all other conditions is caused primarily by engine power, torque, and exhaust temperature data validity requirements set by the NTE protocol.

» Reducing or removing the majority of the NTE data validity conditions would not be sufficient to incentivize significant urban NO$_x$ control. Any expansion of the current NTE zone conditions would result in an NTE evaluation value between what is obtained with the current NTE and a total route evaluation (total mass of NO$_x$ divided by total work).

» The European MAW method for in-use compliance evaluation better captures NO$_x$ emissions at the most challenging conditions, which is to say low-speed and low-power demands, that are characteristic of urban driving.

» Improvements could be made to the MAW protocol to further incentivize urban NO$_x$ reductions. These include expanding window validity to all power conditions and evaluating compliance at the 95th percentile. These changes would better evaluate future HDVs designed to meet currently proposed low-load cycle requirements.

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INTRODUCTION

Heavy-duty vehicle (HDV) NO_x emission standards and their in-use testing provisions have been in place for more than a decade in the United States and Europe. Euro VI standards were adopted in 2009 and implemented in 2013 for new models. The U.S. standards, known as EPA 2010, were adopted in 2001, started implementation in 2007, and were fully phased-in in 2010. The adoption of the EPA 2010 and Euro VI heavy-duty engine emission standards introduced significant NO_x emission reductions in the laboratory and added compliance requirements for real-world emissions control.

In the United States, the engine laboratory emission limit measured over the Federal Test Procedure (FTP) was designed to improve NO_x emission levels from around 2.0 grams per brake horsepower-hour (g/bhp-hr) for engines produced until 2004 to 0.2 g/bhp-hr for engines produced since 2010. In Europe the Euro VI engine NO_x emission limit over the World Harmonized Transient Cycle (WHTC) was set at 0.46 g/kWh (~0.34 g/bhp-hr), a 77% reduction with respect to the Euro V limit set under the older European Transient Cycle (ETC).

A key component of the EPA 2010 and Euro VI regulations was the introduction of in-use testing to ensure that real-world emissions are in line with the limits set by the engine standards. The in-use compliance program entails measuring HDV pollutant emissions with portable emissions measurement systems (PEMS) and evaluating those measurements against a compliance target value. This compliance process is known in Europe as the In-Service Conformity (ISC) program, and in the United States as the manufacturer run heavy-duty in-use testing program (HDIUT).[1]

The in-use programs in the United States and Europe implement different protocols for compliance evaluation. The HDIUT program follows the not-to-exceed (NTE) protocol for compliance evaluation (CFR, 2014). Under the NTE test protocol, HDVs are driven under normal operating conditions and the emissions are continuously measured with PEMS. Only the data that meet a set of engine operation conditions for a period of time are used for compliance evaluation. Those data groups are defined as NTE events. A vehicle is deemed compliant if the time-weighted average emissions of at least 90% of all valid NTE events are below the NTE limit.

The European ISC program follows the moving average window (MAW) evaluation method. Under the MAW method, the mass emissions are calculated for subsets of complete data sets, called windows. The window size is defined by the work (or CO_2 emissions) over the window which must be equal to the work (or CO_2) produced during the engine certification cycle. A vehicle is deemed compliant if the average emissions of at least 90% of all valid windows are below the ISC limit.

In-use emissions testing has shown that there is still a gap between real-world measured NO_x emission levels and engine certification levels. Analysis by the International Council for Clean Transportation (ICCT) of 160 PEMS tests from the EPA's HDIUT program shows that real-world average emissions of HDVs certified to the 0.2 g/bhp-hr NO_x standard are higher than the laboratory-based engine certification limit. Average NO_x emissions calculated from all the data (i.e., total route) were found at 0.42 g/bhp-hr, or twice the engine NO_x emission limit (Badshah, Posada, & Muncrief, 2019).

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[1] The European program is defined in the EU Commission Regulation No 582/2011 (European Commission, 2018), and the U.S. HDIUT program is defined in the Code of Federal Regulations (CFR) Title 40 Part 86 subpart T (CFR, 2005).

A closer look at the HDIUT PEMS data reveals that a disproportionate amount of NO_x emissions occur during urban driving. Urban driving NO_x emissions are, on average, 5 times higher than the engine NO_x certification limit, 2.4 times higher than total route values, and 5 times the emissions measured during high-speed operation (Badshah et al., 2019).

The trend of higher NO_x emissions at low vehicle speeds representative of urban driving also has been reported by researchers in Europe. An analysis of PEMS test results on three European long-haul HDVs shows that NO_x emissions during urban driving conditions at speeds less than 20 mph were, on average, 3.4 times higher than the total route emission values (Grigoratos, Fontaras, Giechaskiel, & Zacharof, 2019). Extensive PEMS testing carried out in a single Euro VI HDV in Italy, over different testing conditions, showed the highest NO_x emissions during urban driving conditions (Mendoza-Villafuerte, et al., 2017). The Netherlands In-Service Emissions Testing Programme for Heavy-Duty Vehicles also concluded that urban conditions present the biggest challenge for NO_x control in some of the Euro VI vehicles tested (Vermeulen, Vonk, van Gijlswijk, & Buskermolen, 2016).

These results indicate that real-world NO_x emissions are not adequately evaluated across all vehicle operating conditions by current regulatory in-use compliance tools. In the United States, compliance values obtained through the NTE protocol consistently underestimate in-use NO_x emissions. The NTE compliance data from the HDIUT dataset of 160 PEMS tests show that the average NTE-based NO_x emissions are 0.18 g/bhp-hr. In contrast, average real-world NO_x emissions across all manufacturers are 2.3 times higher than the average NTE reported value. Even more concerning is that the urban fraction of the data shows, on average, 5.6 times higher NO_x values than the compliance average NTE value (Badshah et al., 2019). An analysis of the European ISC PEMS data evaluation methods by Mendoza-Villafuerte et al. (2017) shows that real-world emission values for one Euro VI HDV were 1.8 times higher on average than the results of the ISC evaluation method.

To address the gap between real-world and certification NO_x emissions in the United States, the California Air Resources Board (CARB) and the U.S. EPA are updating and improving the U.S. EPA MY2010 HDV engine and vehicle emissions regulation. California has announced the HDV Low NO_x regulation, aimed at reducing the FTP NO_x standards by up to 90%, introducing testing conditions that would require improved emissions control at conditions commonly encountered in urban driving, as well as an improved in-use testing protocol (CARB, 2018). At the federal level, the U.S. EPA announced the development of the Cleaner Trucks Initiative (CTI), which explores similar changes to the current EPA 2010 NO_x emission standard, also aiming at measurable real-world emission reductions (U.S. Environmental Protection Agency [EPA], 2018).

CARB and EPA's regulatory proposals would likely rescind the current NTE protocol and adopt a new tool to properly evaluate in-use performance for compliance certification of heavy-duty diesel engines. In addition, CARB is considering the adoption of low-load cycle (LLC) engine dynamometer tests in the 2024 and 2027 time frame (CARB, 2018). The LLC tests would likely require the adoption of technologies to control NO_x at low-load conditions that are often found in urban driving.

CARB and EPA have announced the intention to adopt an improved version of the MAW method for the proposed changes (CARB, 2019; EPA, 2020. The new in-use compliance evaluation tool ideally would be capable of evaluating compliance under those low-load conditions as well. This would ensure that emission reductions measured in the laboratory at low loads would also transfer to real-world urban driving and low-load operation.

The objective of this report is to present an independent assessment of NO_x emissions from European and U.S. HDVs and understand the impact of their respective in-use compliance evaluation protocols on real-world NO_x emissions. In-use NO_x emission data from a sample of U.S and European trucks are presented first to illustrate their behavior and highlight the challenges that lead to high NO_x values. The U.S. NTE protocol is the focus of this analysis as the current regulatory proposals in the United States by CARB and EPA are calling for a new PEMS data evaluation tool. We compare the NO_x emissions evaluation tools under their current regulatory design with potential alternatives. The alternatives studied here to replace the current U.S. NTE cover modifications to the NTE protocol and the adoption of the European MAW evaluation method.

SUMMARY OF HDV IN-USE TESTING REGULATIONS IN THE UNITED STATES AND EUROPE

Although the in-use testing principles are similar, the way the programs are structured in each region is different in key areas. The main differences are vehicle and route selection, driving conditions during tests, and data evaluation protocols for determining compliance. In Europe, the program is run by third party testing organizations, known as technical services, that select testing routes according to ISC predefined driving requirements. A minimum of three engines are tested per engine family. In the United States, the program is run by the manufacturers and the EPA chooses the engine families to be tested, up to a maximum of 25% of the total number of engine families produced by the manufacturer per year.

Driving conditions are set differently under each program. In the United States, there are no clear driving conditions requirements, whereas the European Union (EU) requires specific amounts of time driven under urban, rural (or suburban), and motorway (or highway) conditions. The vehicle can be tested with any payload between 10% and 100% of the maximum vehicle payload in the EU ISC program, and at an undetermined “normal load” under the U.S. program. Table 1 summarizes the programs. The difference in data evaluation protocols is detailed in the following section.

Table 1. In-use HDV PEMS testing program summary

Characteristic	Euro VI	EPA 2010
Program name	In service conformity (ISC)	Heavy Duty In-Use Testing (HDIUT)
Implementation dates	2013 new types and 2014 all new vehicles Further implementation steps (e.g., Euro VI-Step E) stretch to 2022	2007 for in-use NO_x, HC and CO testing 2011 for in-use PM testing
Vehicle selection	Three engines per engine family are tested First test at 18 months with minimum of 25,000 km and then every two years Testing allowed up to useful life.	Five vehicles per engine family per year Up to 25% of engine families certified EPA notifies the manufacturer, in advance, which engines are to be tested
In-use limits for diesel engines	$CO/HC/NO_x$ = 1.50 × WHTC for NO_x = 1.5 x 0.46 g/kWh = 0.69 g/kWh (~0.51 g/bhp-hr) PEMS accuracy margin: none	$HC/NO_x/PM$ = 1.50 × FTP + PEMS margin for NO_x = 1.5 x 0.2 + 0.15 g/bhp-hr = 0.3 + 0.15 = 0.45 g/bhp-hr (~0.61 g/kWh) PEMS accuracy margin: 0.15 g/bhp-hr
In-use data compliance evaluation methods	Moving average window (MAW): 90% of valid windows below the in-use limits.	Not-to-exceed (NTE): 90% of valid NTE events below the in-use limits.
Payload	10%–100% for ISC. 50%–60% for type-approval demonstration.	“Normal loads” as they pertain to the actual usage of the vehicle
Test driving requirements	Urban 0–50 km/h; 30%–45%[a] Rural 50–75 km/h; 25%–30%[a] Motorway 75 km/h+; 30%–45%[a]	Not specified. “Normal driving” without any predetermined speed or time distribution rules.
Test length	Long enough to complete from 4 to 8 times the WHTC work or 4 to 8 times the mass of CO_2 emitted during that test	Not specified
Cold start included	Partially. Cold start is not included now, but it would be from 2021.[b] Data analysis starts when coolant temp >70°C, when engine coolant is stabilized within +/-2°C, or 20 minutes whichever is first.	No
Ambient conditions	Temperature: -7 to 38°C (~19 to 100°F) Pressure: < 82.5kPa (~5,577 ft elevation)	Temperature: < 100°F (~ < 38°C) Elevation: < 5,500 ft (~83 kPa of pressure)

[a] U/R/M shares shown here apply to N3 heavy-duty vehicles in Europe. Requirements change according to vehicle segment, with higher urban shares for N1 vehicles (vans) and higher motorway shares for N3 (Class 8) trucks. For N3 vehicles the trip shall consist of approximately 30% urban, 25% rural, followed by 45% motorway operation.

[b] Cold start is excluded from all ISC tests that apply to Euro VI B to Euro VI D engines. Cold start will be included for Euro VI E starting with model years 2021.

U.S. NOT-TO-EXCEED (NTE) REGULATORY PROTOCOL

The NTE protocol is a compliance evaluation tool based on sampling of second-by-second PEMS data with strict data exclusion requirements. In the NTE regulatory protocol, PEMS emission data points are considered for compliance evaluation only when the engine is operating continuously in the NTE zone for at least 30 continuous seconds. The NTE zone is defined by engine speed, torque, and power threshold limits, as well as minimum exhaust temperature requirements ($T_{exh} > 250°C$), and ambient conditions measured at the intake manifold, as presented in Table 2. Only the strings of continuous data (30 seconds or more) that meet the NTE zone requirements become an *NTE event.* NO_x emissions per unit work during NTE events are averaged and compared with the NTE threshold (in-use limit + PEMS allowance). The last step is the calculation of the time-weighted vehicle pass ratio. This is calculated as the sum of time for valid NTE events (below NTE threshold) divided by the sum of all the time during NTE events time. For a vehicle to achieve compliance the vehicle pass ratio should be above 0.9. A description of the NTE zone is presented in the Analysis section.

Table 2. NTE zone conditions and NTE event description per 40 CFR § 86.1370

Parameter	Condition
Engine speed (rpm)	RPM > n_{15}, where $n_{15} = n_{lo} + 0.15*(n_{hi} - n_{lo})$, where n_{lo} is the maximum engine speed as determined by calculating 70% of the maximum power, and n_{hi} is the lowest speed as determined by calculating 50% of the maximum power
Torque (ft-lb)	Torque > 30% peak torque
Power (hp)	Power > 30% rated engine power
Intake manifold temperature (°F)	$IMT_{limit} = (IMP+7.75)/0.0875$, where IMP is intake manifold absolute pressure, in bars
Exhaust temperature (T_{exh})(°C)	$T_{exh} < 250°C$
Engine coolant temperature (ECT) (°F)	$ECT_{limit} = (IMP+9.889)/0.0778$, where IMP is absolute pressure, in bars
NTE event	All the conditions above within NTE zone and met for at least 30 consecutive seconds

EUROPEAN MOVING AVERAGE WINDOW (MAW) REGULATORY PROTOCOL

The MAW approach is a compliance evaluation method that averages second-by-second emissions data over a window size that is defined by a reference number (European Commission, 2018). The ISC program defines the window size, which is to say the number of data points, based on the amount of work produced or CO_2 emitted during the engine dynamometer WHTC test. The first window is attained between the first data point and the data point where the reference work or CO_2 value is achieved; the second window starts at the second datapoint and ends where the reference value is achieved, which may be exactly after the end of the first window or any time thereafter. This means that the size of the windows, in terms of duration and distance, change as they move along the dataset; what remains constant is the work performed or CO_2 emitted during each window. A description of the MAW is presented in the analysis section.

The biggest difference compared to the NTE data analysis protocol is that the MAW method only has one data exclusion condition for window validity based on average window power. To be considered a valid window, the window's average power must be greater than a percentage of the maximum engine rated power value. That minimum average power value was set at 20% from the beginning of the ISC program in 2013 and updated to 10% in 2018 with the adoption of the Euro VI-D program. All the windows that meet this minimum power criteria are then ranked from minimum to maximum window average emission values. The NO_x window average value corresponding to the 90th percentile is then compared with the in-service conformity standard (1.5 x WHTC NO_x standard). The vehicle passes the test if the 90th percentile NO_x window average value is below the ISC limit for NO_x.

DATA SOURCES

DATA FOR IN-USE NO_x EMISSIONS COMPARISONS

The data for the first part of this report, the NO_x emissions comparison, comes from PEMS tests carried out in U.S. and EU trucks by several testing institutions under a wide range of testing conditions. The 16 vehicles selected for this comparison are classified as class 8 in the United States and N3 in Europe. Five Euro VI N3 vehicles certified to Euro VI standards were available for this analysis. Eleven U.S. vehicles certified to meet the EPA 2010 0.2 g/bhp-hr NO_x standard were selected for the comparison. These were chosen from the pool of available HDVs aiming to match engine size and power characteristics between both groups. Engine displacements for the EU and U.S. trucks were, on average, 12.4 L and 12.8 L, respectively. The average engine rated power for European trucks was 449 hp, and 439 hp for U.S. trucks. Table 3 provides a summary of the vehicles studied in the first part of this report. The vehicles listed here were selected as being representative of both the U.S. and European HDV markets. Manufacturer names are not disclosed because some data sources required vehicle and engine anonymization.

Table 3. List of vehicle and engine characteristics used in the regional comparison

Vehicle no.	Engine model year	Engine displacement (l)	Engine rated power (hp)	Max weight (lb)
EU				
1	2014	10.8	420	—
2	2012	12.7	440	69400
3	2016	12.7	450	61000
4	2015	12.8	475	60000
5	2013	12.9	460	65200
EU average	**2014**	**12.4**	**449**	**55120**
U.S.				
1	2013	12.4	411	47400
2	2014	12.8	405	80000
3	2014	12.8	435	71333
4	2013	12.8	450	44076
5	2014	12.8	410	80000
6	2015	14.8	400	62800
7	2015	10.8	403	68940
8	2011	12.9	491	73333
9	2010	12.9	491	64000
10	2014	12.9	455	40040
11	2013	12.4	475	80000
U.S. average	**2013**	**12.8**	**439**	**64720**

DATA FOR IN-USE COMPLIANCE METHODS COMPARISON

For the second part of the report, comparing the in-use compliance evaluation methods in the United States and Europe, only PEMS data from five vehicles were used. Table 4 lists the five vehicles that had sufficient data parameters required to perform a compliance evaluation under both regulations. Two of those vehicles (vehicles 1 and 2) were from the European dataset listed above (EU Vehicle no. 3 and 4); the other three HDVs were from the United States but not included in the dataset above because their data were collected at high average vehicle speed and power and therefore not fit for the comparison. Manufacturer names are not disclosed because some data sources required vehicle and engine anonymization.

Table 4. List of vehicle characteristics

Vehicle no.	Emissions level	NOx engine certification level [a)]	Engine model year	Engine displacement (l)	Engine rated power (hp)	Max weight (lb)
1	Euro VI	0.46 g/kWh (~0.34 g/bhp-hr)	2016	12.7	450	61000
2	Euro VI	0.46 g/kWh (~0.34 g/bhp-hr)	2015	12.8	475	60000
3	EPA 2010	0.2 g/bhp-hr (~0.27 g/kWh)	2015	14.8	400	62800
4	EPA 2010	0.2 g/bhp-hr (~0.27 g/kWh)	2014	12.8	405	80000
5	EPA 2010	0.2 g/bhp-hr (~0.27 g/kWh)	2013	12.4	475	80000

[a)] Transient cycle testing: FTP for the U.S., and WHTC for Europe.

METHODOLOGY

IN-USE NO_x EMISSIONS COMPARISONS

This section of the report includes data from all engine and vehicle operation conditions. It does not follow the current in-use regulatory compliance protocols (NTE or MAW) or consider any data validity conditions. This includes all power, torque, and engine rpm conditions; cold start periods; and low exhaust temperature under 250°C. We did not include PEMS tests that contain data from DPF regeneration events.

Instantaneous data were grouped by vehicle speed to sort the data into multiple bins: idle (vehicle speed <1 mph), urban (vehicle speed of 1–25 mph), suburban (vehicle speed of 25–50 mph), and highway (vehicle speed ≥50 mph). Total route values, defined as total mass of NO_x divided by total work, were also calculated for all vehicle speeds including and excluding idle operation.

Both in-use compliance programs have data evaluation conditions associated with power. The U.S. NTE rejects all data collected at power values below 30%; the European ISC limited the inclusion of windows with average power values below 20% for certification of new engines until September of 2018, and below 10% since then. To better understand the impact of this condition, the data were also binned by percentage of maximum rated power. The power cut points for the binning cases studied in this document are: 0%, 5%, 10%, 20%, 30%, 70%, and 100%.

IMPACT OF REGULATORY CONDITIONS ON COMPLIANCE EVALUATION

The second section of this report focuses on understanding the capacity of the current protocols to evaluate the in-use performance of HDVs under different driving conditions. The challenges for adequately evaluating NO_x performance are also studied, and potential solutions are suggested. The metrics used to study each compliance tool and its variations are data validity for compliance evaluation and NO_x emissions results. Data validity is defined here as the share of all collected PEMS data that is used for in-use compliance evaluation.

The analysis initially focuses on the current NTE protocol, as defined by the U.S. regulation. We study the critical parameters that define NTE zone and NTE event duration by their impact on data validity and emissions values. The impact on data validity was investigated by calculating the amount of data rejection that each individual NTE parameter causes. The parameters studied were engine torque, speed, power, and exhaust and intake temperatures. Coolant temperature was not studied because it was not reported in the available PEMS datasets.

The impact of NTE event duration on data validity and emissions evaluation results was studied next. This analysis centers on understanding the impact of reducing NTE duration as a way to include more data for compliance evaluation. The NTE event duration is reduced from 30 seconds to 20 and 10 seconds. In this exercise, all other NTE zone definition parameters remain as currently defined in the CFR.

We also studied the impact of multiple parametric changes to the NTE on data validity and compliance evaluation. The parameters that define NTE zone (engine power, torque and speed, and exhaust temperature) and NTE event duration are modified concurrently. Three different alternatives are defined with different levels of conditions for data validity. Each parametric variation discussed here was inspired by potential regulatory proposals that are being discussed as part of CARB's low NO_x proposal regulatory process.

The European MAW compliance evaluation method was also explored. For that exercise, we studied data validity and NO_x compliance results after applying the MAW method to the PEMS data from the five HDVs available. First, we applied the MAW method as defined by the ISC regulation, focusing on the impact of the minimum power threshold. We then studied the impact of changes to power threshold beyond what has been adopted, and changes to the window percentile value.

RESULTS: IN-USE NO$_X$ EMISSIONS FROM U.S. AND EU HDVS

This section provides an overview of in-use NO$_x$ emissions for U.S. and EU trucks of similar engine sizes and rated power operated under similar driving conditions. Aiming to retain a considerable level of similarity in the driving conditions to better compare both groups of vehicles, this section of the report focuses only on the PEMS tests that were carried out at average maximum power below 30% and at average vehicle speeds below 45 mph, which are the maximum average values for the set of European trucks.

The PEMS trip selection resulted in average driving conditions that were comparable for both groups. Table 5 presents environmental and driving conditions for each of the vehicles studied The time-weighted average speed and average normalized power for PEMS trips in all U.S. trucks was 34 mph and 24%, compared to 32 mph and 21% for European trips. The share of time spent at urban conditions (speed < 25 mph) was 43% for U.S. trucks, just a few points above the European trucks' urban time share of 37%. The biggest difference was found for time spent at highway driving conditions (speed > 50 mph), with 45% of the time for trips in the United States and only 30% for European trips.

Table 5. Time-weighted average environmental conditions and driving conditions

Vehicle no.	PEMS tests	Total test, hr	Average ambient temp., Cº	Average ambient humidity, %	Average speed, mph	Average normalized power, %	Urban time share	Suburban time share	Highway time share
EU									
1	1	2.6	16.0	53.1	43	19%	16%	37%	47%
2	5	9.6	19.4	60.1	29	21%	43%	28%	29%
3	4	8.8	-	-	39	26%	25%	30%	45%
4	10	13.8	22.1	52.4	34	22%	30%	39%	30%
5	7	12.6	23.6	57.1	26	18%	50%	34%	15%
EU average					**32.2**	**21%**	**37%**	**34%**	**30%**
U.S.									
1	3	24.5	24.5	77.1	30	18%	50%	14%	36%
2	3	4.5	26.1	-	22	25%	51%	34%	14%
3	3	28.3	18.1	57.7	41	26%	33%	8%	59%
4	3	26.3	21.1	62.3	32	21%	46%	6%	48%
5	5	42.6	27.1	-	34	23%	45%	8%	46%
6	1	1.2	14.9	-	21	28%	60%	33%	7%
7	4	44.2	15.7	36.8	38	28%	37%	15%	48%
8	2	9.9	20.3	64.1	30	23%	49%	16%	36%
9	1	7.9	6.5	30.5	29	20%	48%	15%	37%
10	2	19.4	14.5	31.2	35	26%	42%	10%	48%
11	3	4.1	140.2	-	25	23%	45%	29%	26%
U.S. average					**34.1**	**24%**	**43%**	**12%**	**45%**

Notes: Average values for U.S. and EU trucks shown here are time-weighted. Dash line means no data available

Figure 1 compares the average NO_x emissions for the sample of U.S. and EU HDVs that share common driving conditions. The bars indicate average total route emissions for 11 U.S. trucks and 5 EU trucks. The average route values indicate that U.S. trucks present NO_x emission values above the engine certification limit (0.2 g/bhp-hr) and close to the NTE standard (0.3 g/bhp-h). These selected U.S. HDVs emit on average 1.4 times more NO_x per unit work produced than the European vehicles studied. The results for each of the vehicle speed bins show that for both groups NO_x emissions increase at lower speeds. This trend is consistent with the findings of Badshah et al. (2019) which studied 160 PEMS tests from U.S. HDVs.

Figure 1 also shows excessive NO_x emissions from U.S. trucks at low speeds, and much higher compared to European trucks. During urban driving conditions, NO_x emissions of U.S HDVs are almost 3.7 times the total route emissions; by contrast, highway driving emissions are about 40% lower than the average total route emissions. On the other hand, European HDVs tend to exhibit a more consistent behavior across the speed range: Urban driving emissions are twice as much as the total route emissions and highway NO_x emissions are similar to U.S. HDV emissions, at a level close to 40% below total route emission values.

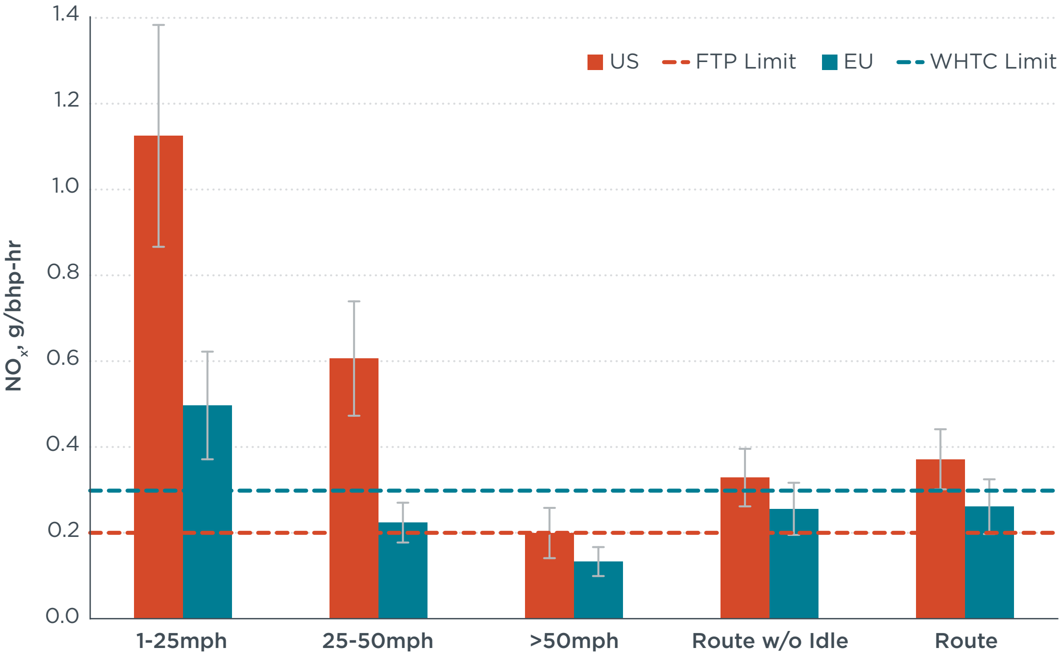

Figure 1. NO_x emissions by speed bin for European and U.S. HDVs. Dotted lines represent engine emission NO_x limits for U.S. and EU HDVs. Whiskers show confidence intervals at 95%.

The average NO_x emissions for U.S. and European HDVs by power condition are presented in Figure 2. Power bins are defined here as normalized power, or the percentage of maximum rated power for each engine. Work-specific NO_x emissions between zero and 5% of maximum rated power are excluded from this analysis to avoid the effect of a near-zero denominator for that power range.

Similar to what was found under the speed bin analysis, the sample of European vehicles emit lower levels of NO_x across all power bins. The work-specific emission values exhibit a consistent behavior for both datasets, with the lowest NO_x emissions at the mid power ranges (30%–70%), higher NO_x at the upper power bin range (70%–100%) and the highest NO_x at the lowest power bin (5%–10%).

The consequences of excluding in-use test data with power levels below 30%, as done in the U.S. NTE protocol, is evident. Figure 2 shows that work-specific NO_x values dramatically increase above the route average values for bins not covered under the NTE data evaluation protocol. Below the 30% NTE condition for power, NO_x doubles in value with respect to route average for the 10%–20% power bin, and more than quadruples for the 5%–10% bin.

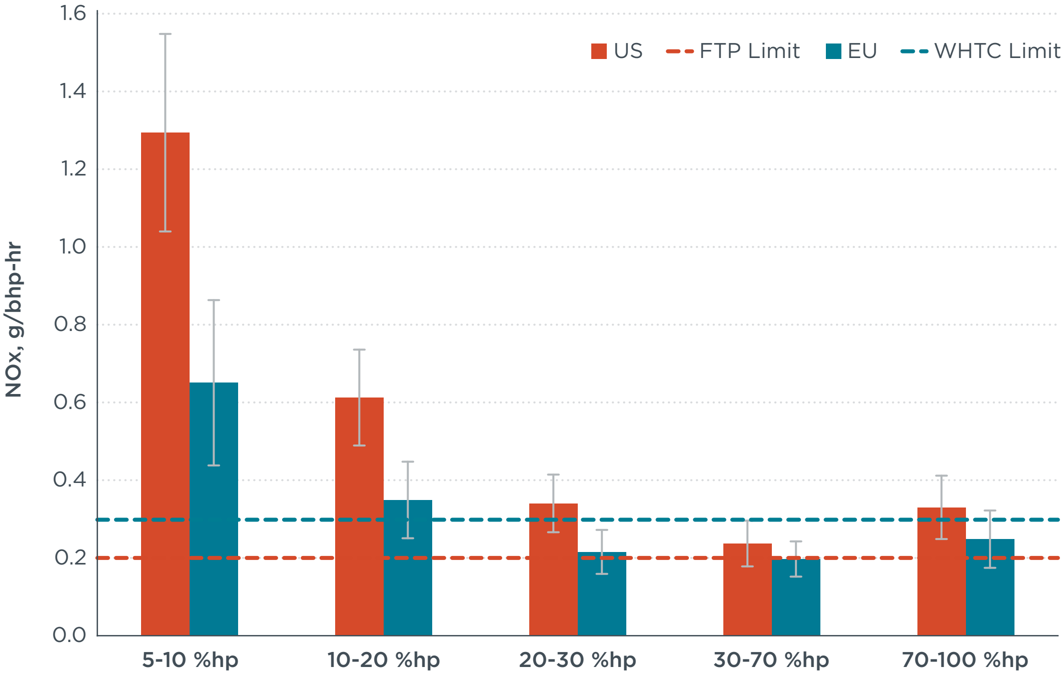

Figure 2. Brake specific NO_x emissions for US and EU trucks by percentage of maximum rated power conditions. Whiskers represent the 95% confidence interval of the mean.

The European ISC also shows higher NO_x emissions in the lower power bins. Because the ISC power requirement applies to an average window—not to individual datapoints as in NTE—emissions during low power operation, including idle, are not necessarily excluded. European HDVs exhibit work-specific NO_x values above total route values for power bins below the 20% bin. NO_x increases to 1.4 times the total route average for the 10%–20% P_{max}, and up to 2.7 times the total route average for the 5%–10% power bin. Note that the European HDVs studied here were certified under the ISC program requirements that rejected windows with average power below 20%. However, since 2018 the ISC program for Euro VI-D requirements include windows with 10% average power.

As reported by Badshah et al. (2019), vehicle operation information calculated from vehicle speeds less than 1 mph covers a wide range of power conditions, from motoring to around 8% of normalized power. Calculating the cumulative mass of NO_x emitted in each power bin provides insight into what fraction is emitted under very low power and not included by current in-use testing protocols.

The U.S. trucks analyzed for this study emit more NO_x by mass than the European trucks at the lowest power range. Figure 3 shows that NO_x contributions at the 0%–5%

of maximum rated power are, on average, 24% of the total mass of NO_x emitted for the sample of U.S. HDVs, and 12% of the total mass for the sample of EU HDVs. This higher NO_x behavior at the low end of the power range is not explained by significantly higher operating times at that condition. The time shares figure shows that the percentages are comparable across regions, with 44% and 39% of time operating at 0%–5% rated power for U.S. and EU trucks, respectively.

NO_x emissions below 20% of maximum rated power are about 37% and 28% of total NO_x emissions by mass for the U.S. and EU trucks in this study, respectively. Again, time shares do not explain the higher share from U.S. trucks because both groups spent 56% of their time operating below 20% of rated power. Expanding the low power bin analysis to 30% of maximum rated power shows similar mass of NO_x for both groups at lower time shares for U.S. trucks than for European trucks (62% and 72%, respectively).

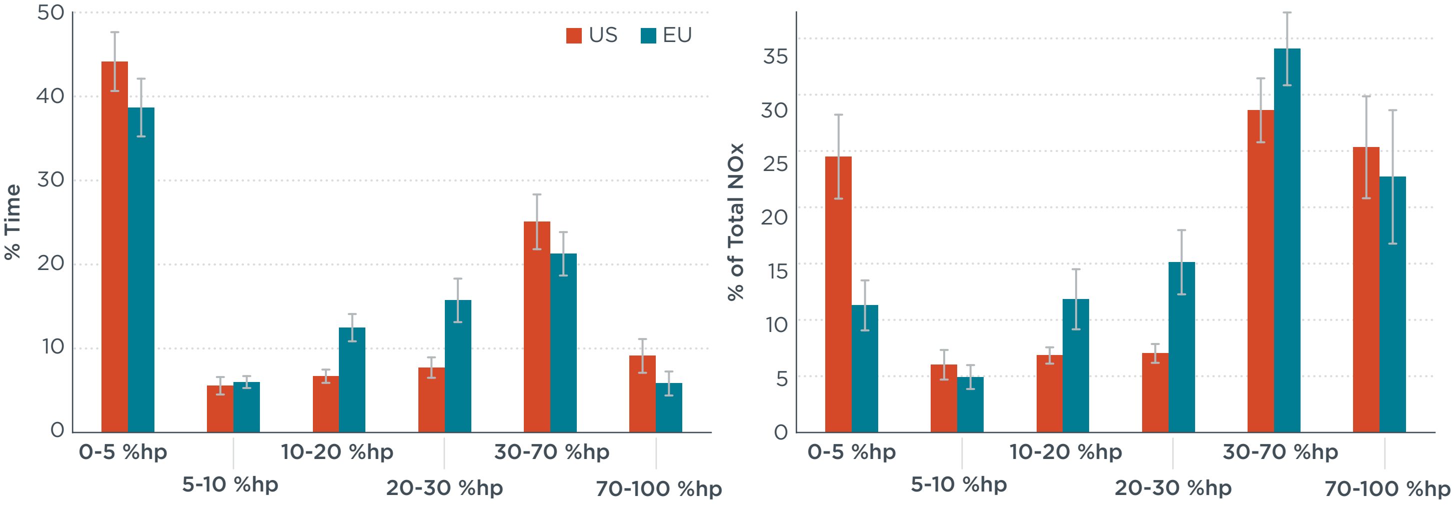

Figure 3. Percentage of time spent at each power condition (left) and corresponding contribution of NO_x (mass) (right) by percent of maximum rated power for U.S. and EU HDVs. Whiskers represent the 95% confidence interval of the mean.

ANALYSIS: NO$_X$ EMISSIONS EVALUATED UNDER THE NTE AND MAW METHODS

The HDV in-use emission results indicate that real-world NO$_x$ emissions are not adequately controlled across all vehicle operating conditions, especially in the United States. HDVs in the United States spend a significant amount of time and emit large quantities of NO$_x$ at conditions that are partially or totally excluded from in-use testing compliance evaluation.

The purpose of this section is to understand the regulatory conditions that are responsible for most of the data exclusion and respective alternatives that can be adopted to reverse that. The alternatives proposed here target the limitations of the regulatory NTE and MAW protocols to properly evaluate the emissions of heavy-duty vehicles under normal driving conditions. This analysis was performed on PEMS data from a group of five HDVs from the U.S. and Europe that had key parameters available for in-use regulatory compliance study.

IDENTIFICATION OF NTE CRITICAL PARAMETERS

The current NTE protocol sets conditions for data exclusions that are dependent on engine parameters as well as intake and exhaust temperatures. The impact of each independent parameter on the amount of valid data for regulatory compliance evaluation is discussed here. The first step in understanding how each parameter affects regulatory compliance is to visualize how driving conditions are reflected in engine speed and load map.

Figure 4 presents an example of vehicle speed driving conditions on a second-by-second basis associated with its engine conditions for engine speed and load. Each datapoint is a second's worth of information that describes the vehicle speed on the road and the engine rotational speed (rpm) and torque (ft-lb). The boundary line represents the engine lug curve, or maximum power response at each engine rpm condition. Figure 4 also shows the three engine operating parameters that define the NTE zone. The NTE zone condition defined by torque, the horizontal red line, is set at 30% of maximum engine rated torque; the NTE zone condition defined by engine power, the purple dotted hyperbola,[2] is set at 30% of maximum engine rated power; and engine speed, the gray vertical dotted line, is set at a function of its operating range, typically around 30% of its maximum range (between 950 rpm and 1100 rpm).

The NTE engine operating conditions set by power, torque, and speed exclude more than 60% of the data presented in this example. Overall, the individual torque condition eliminates 56% of the data, the power condition eliminates around 62% of the data, and the engine speed condition eliminates 21% of the data.

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[2] Engine power is defined as the product of torque and engine rotational speed.

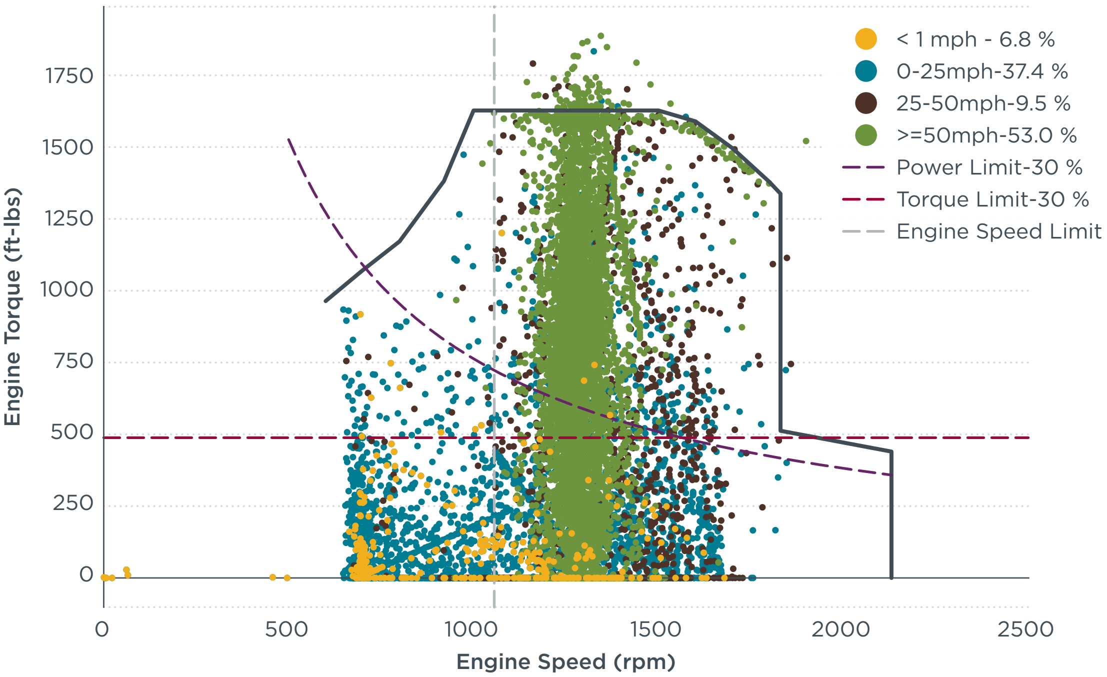

Figure 4. Engine operating conditions visited during a PEMS trip, and corresponding vehicle speed conditions and their time shares spent at that condition. NTE zone limits are shown as dashed lines. Engine lug curve is shown as a continuous black line.

Besides the engine operating conditions, the NTE also applies intake and exhaust temperature data exclusion conditions, which results in a combined data rejection of 87.4% of the total data. In this example, 46% of the time the exhaust temperature was reported below 250°C and therefore rejected from NTE evaluation. Intake manifold pressure readings showed intake manifold air temperatures below the limit for 26% of the data. This makes exhaust temperature the third biggest factor in NTE data rejection after engine power and torque.

Almost all data collected during urban operation (speeds less than 25 mph) are eliminated from compliance evaluation by the NTE conditions. In this example 100% the data collected when the vehicle is operated at speeds below 1 mph, shown as yellow dots, falls under one or more exclusions. The impact of all the NTE engine and temperature conditions (intake and exhaust) is extremely severe for urban driving conditions. For this example, 99.7% of data generated below 25 mph is excluded from the NTE evaluation.

This data rejection analysis was extended to 23 available datasets with complete PEMS parameters from five HDVs from the United States and EU for NTE evaluation. Table 6 shows the average impact of each individual parameter for each HDV and the time-weighted average combined data rejection value for all parameters (right column). On average, 80% of this sample of PEMS data falls outside the NTE zone.

The parameters that exclude most of the data from the NTE zone are engine power, torque, and exhaust temperature. It should be noted that a vast share of data points are rejected due to failing two or more conditions. The impact of intake manifold temperature conditions was not studied for vehicles 1, 2, or 3 because of the lack of data on this parameter from the respective PEMS datasets. Coolant temperature data was not available for any test.

Table 6. NTE data rejection by condition criteria and combined.

Vehicle no.	PEMS tests	Total time tested (seconds)	Rejected by engine torque	Rejected by engine speed	Rejected by engine power	Rejected by intake manifold temperature	Rejected by exhaust temperature	Combined parameter NTE zone data rejection
1	4	31702	59.8%	22.5%	62.8%	-	32.3%	72.0%
2	10	47048	61.1%	26.7%	68.5%	-	56.8%	81.6%
3	7	22371	52.3%	18.8%	52.7%	-	76.0%	87.9%
4	1	12464	55.7%	20.8%	61.6%	25.8%	46.4%	87.4%
5	1	12043	49.3%	22.5%	55.4%	8.9%	34.7%	68.5%
Sample	**23**	**125628**	**57.5%**	**23.2%**	**62.3%**	**17.5%**	**50.9%**	**79.6%**

Note: Vehicles 1 and 2 are from Europe; vehicles 3,4, and 5 are from the United States.

After all the NTE rejection criteria are applied to this example, only 12.6% of the data collected fall within the NTE zone and are available for subsequent reduction under the NTE events evaluations.

The data remaining within the NTE zone should meet the 30-second minimum continuity criteria to qualify as an NTE event. Thus, an additional data exclusion is applied to the data left within the NTE zone. Figure 5 shows the NTE events in the engine map introduced in Figure 4.

After all the NTE rejection criteria are applied to this example, the non-gray colored dots indicate the 12.6% of the data collected that fall within the NTE zone and are available for subsequent reduction under the NTE events evaluations. The blue dots represent NTE zone valid points that did not meet the continuity time requirement of a minimum of 30 continuous seconds. In the end, 99% of the data are rejected. The remaining 1% of data generate four NTE events, shown as red, brown, yellow and orange dots, one color per event.

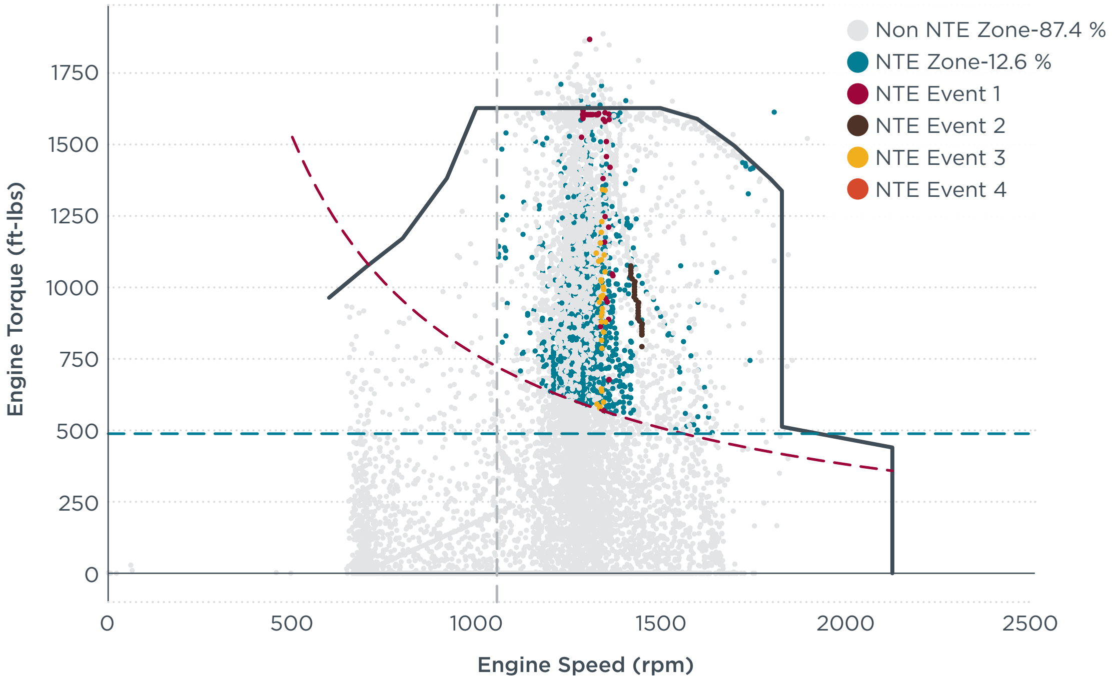

Figure 5. Example of NTE events, shown in non-gray colors, during the PEMS test shown in Figure 4. NTE zone limits are shown as dashed lines. The engine lug curve is shown as a continuous black line. Gray dots represent data excluded due to engine power, torque, speed, and temperature conditions. Blue dots are data points excluded because they do not meet continuity time requirements for the NTE event.

The data that fall within the NTE events represent a very small fraction of PEMS data collected and contain very little information on the performance of the vehicle. A total of 0.9 grams of NO_x is emitted during these events, out of the total of 103 grams emitted during the total route, or about 0.9% of the total NO_x. The four NTE events shown here last between 30 and 48 seconds. These events are associated with very narrow vehicle speed conditions, between 61 and 64 mph, and power ranging from 42% to 74% of maximum rated value. As a result, the NTE evaluation results rely on four events with brake-specific NO_x emissions between 0.04 g/bhp-hr to 0.11 g/bhp-hr, for an average of 0.09 g/bhp-hr for that specific vehicle. The route average NO_x in this example was calculated at 0.25 g/bhp-hr, a factor of 2.8 higher than the NTE evaluation value.

The incidence of NTE events for the 23 PEMS tests studied shows that on average the amount of data that becomes part of an NTE event is less than half of the remaining data in the NTE zone (see Table 6). The amount of NO_x that is captured during NTE events is on average 11% of the total emitted, proportional to the amount of time in the NTE zone. The average NTE event from these 23 PEMS tests occurs at high-speed conditions and at about 60% of maximum rated power. This suggests that the current NTE evaluation protocol is suited for evaluating NO_x emissions data only under highway conditions.

Table 7. Share of data in the NTE zone and share of data that becomes an NTE event

Vehicle no.	Share of data in NTE zone	Number of NTE events	Share of data in NTE events	% of NO_x in NTE events	Average NTE event vehicle speed (mph)	Average NTE event vehicle power
1	28.0%	56	17.9%	22.4%	54.0	49.4%
2	19.4%	70	9.0%	12.4%	45.7	56.2%
3	12.1%	22	6.7%	1.9%	48.0	81.1%
4	12.6%	4	1.1%	0.9%	62.9	54.7%
5	31.5%	22	13.9.0%	18.9%	56.2	59.2%
Sample	**16.8%**	**-**	**9.6%**	**11.4%**	**49.2**	**60.3%**

Note: Vehicles 1 and 2 are from Europe; vehicles 3, 4, and 5 are from the United States.

As suggested by the average speed and power of NTE events, NO_x values from NTE evaluations consistently fall below the average values for highway operation, as illustrated in Figure 6. This figure compares the average work-specific NO_x emissions under urban, suburban, highway, and total route driving with the average NO_x values captured only by NTE events and are on average about one half of the total route average values. NTE values tend to consistently underrepresent NO_x emissions for urban driving conditions.

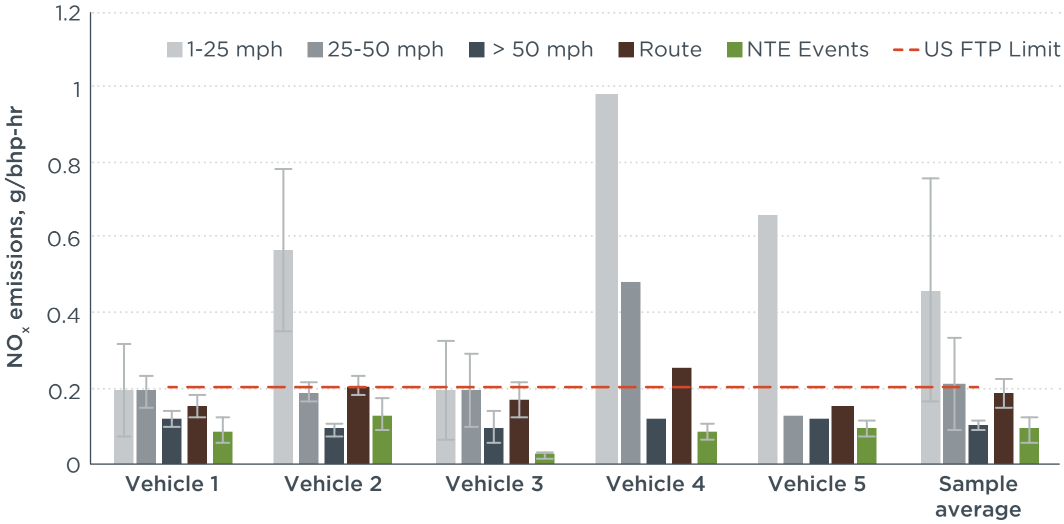

Figure 6. Work-specific NO_x emissions for different driving conditions and NTE events evaluation. U.S. FTP NO_x emission limit shown for reference. Results are presented for each vehicle and for the sample average. Whiskers show confidence intervals at 95% for vehicles with more than one PEMS test.

IMPACT OF CHANGES TO THE NTE EVENT DURATION

The NTE event duration has an important impact on NTE data validity and NO_x evaluation. Figure 7 shows the impact of changing the baseline NTE event duration from 30 seconds to 20 seconds and to 10 seconds, while keeping all other NTE zone conditions as defined in the regulation (i.e., baseline case). The reduction of the NTE duration increases the share of data that is evaluated for compliance. For the PEMS dataset from the five vehicles studied, the share of data that becomes an NTE event increased from 9.6% on average for all the vehicles in the baseline case (30 seconds minimum) to 14.9% for an NTE event of 10 seconds minimum.

The reduction of NTE event duration requirements and the subsequent increase of data validity were associated with a small change in the average vehicle speed of the NTE event. On average, reducing the minimum NTE event size from 30 to 10 seconds reduced the NTE event average speed from 49.2 mph to 46.5 mph, a 5.5% change. Figure 7 shows that reducing the NTE duration resulted in a higher share of suburban (25–50 mph) data validity, from an average of 1.6% in the baseline case to 4.1%. Data from urban operation experienced a negligible change, from zero to 0.2% of the total data collected. Vehicles 2 and 3, which had the lowest average vehicle speeds, presented the greatest increase of NTE event data from suburban driving.

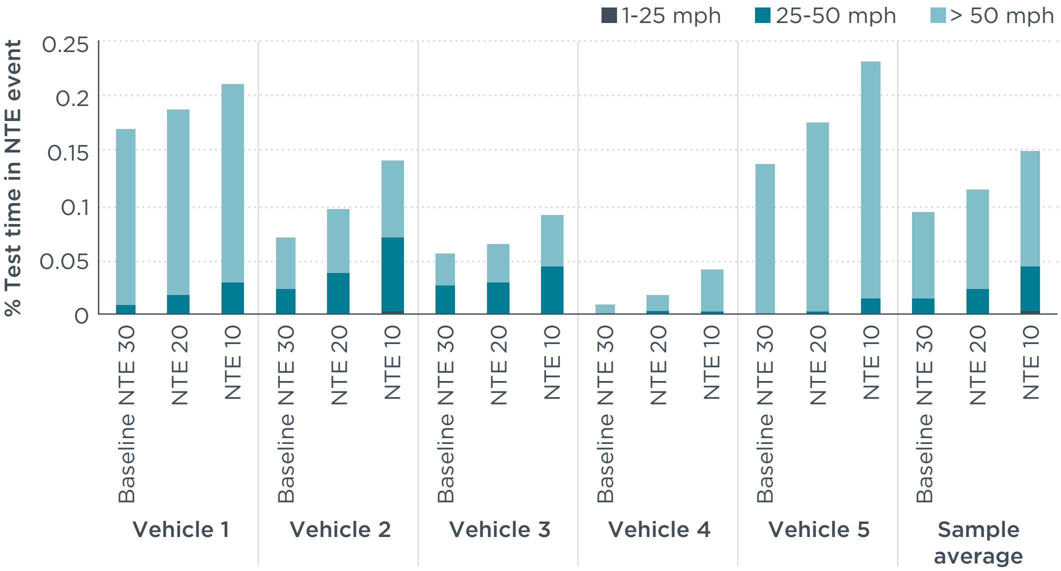

Figure 7. NTE data validity across all PEMS data collected. NTE event data as a percentage of total test time for the baseline NTE case (30 seconds minimum as defined in the CFR) and under alternative cases with 20 and 10 seconds of minimum event duration required. Sample average values are time weighted.

Reducing the NTE event duration requirement resulted in an overall reduction in average NO_x emission values for the sample of vehicles studied (see Figure 8). The overall work-specific NO_x value captured during NTE events under the 10 second minimum condition was 16% lower than the baseline value of 0.10 g/bhp-hr. The changes fall within the variability of the sample averages and tend to be around the average highway NO_x emission value.

The NTE NO_x evaluation change due to NTE duration reduction was not consistent among vehicles and PEMS tests. Most PEMS tests, 14 out of 23, experienced a reduction of NTE NO_x values by 25% on average. Seven tests show an increase of NTE NO_x values, averaging 31% more. Vehicle 2 presented the most extreme changes resulting from NTE duration reductions. One PEMS test shows NTE NO_x values increase by a factor of 2.2, from 0.04 g/bhp-hr baseline to 0.10 g/bhp-hr under the 10-second minimum duration. Another test from the same vehicle exhibited a reduction, from 0.17 g/bhp-hr baseline to 0.07 g/bhp-hr under the 10-second minimum requirement. The NTE NO_x value changes are driven by the changes on the relative share of urban/suburban/highway data with respect to the baseline condition. In most cases of NTE duration reduction, more highway data with lower work-specific emissions are included in the evaluation, which drives the NTE value down.

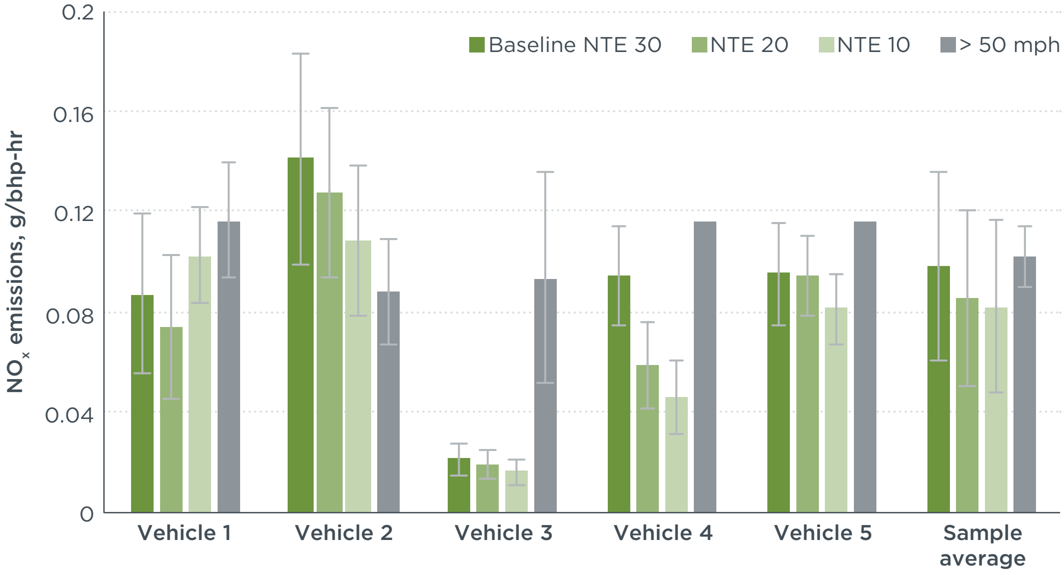

Figure 8. Work-specific NO_x emissions values for the baseline NTE case and modified NTE duration cases (20- and 10-second minimum event durations). Gray bars show the average highway NO_x emission values for comparison. Sample average value is time weighted based on PEMS duration.

These results suggest that reducing the minimum NTE event duration without changing current NTE zone exclusion conditions would have negligible impacts on in-use compliance evaluation. Reducing the NTE duration condition would increase the amount of data available for NTE evaluation, which is a positive change. However, the additional data included would not cover the low speed and low power characteristic of urban driving. This is because the power, torque, and exhaust temperature NTE conditions would still exclude urban driving data from being included in the NTE zone.

IMPACT OF CHANGES TO THE NTE PROTOCOL

The NTE evaluation protocol excludes the vast majority of the data collected during a PEMS test. This section discusses the impacts of modifications to the NTE conditions, aimed at significantly increasing the share of data considered for evaluation and to induce NTE work-specific values that better evaluate all driving conditions, not only highway driving. The studied NTE alternatives cover multiple parameters changed concurrently and listed in Table 8.

Table 8. Description of alternative changes to current NTE parameters

Parameter	Baseline NTE	Alternative 1	Alternative 2	Alternative 3
Power threshold	30% of maximum	20% of maximum	10% of maximum	10% of maximum
Torque threshold	30% of maximum	20% of maximum	10% of maximum	10% of maximum
Engine speed threshold	Per CFR	Per CFR	Per CFR	No condition
Engine exhaust temperature	T_{exh} > 250°C	T_{exh} > 200°C	No condition	No condition
Intake manifold temperature	Per CFR	Per CFR minus 20°C	No condition	No condition
NTE event minimum duration	30 seconds	20 seconds	10 seconds	10 seconds

Notes: "Per CFR" means that the equation used to calculate the condition applies according to what is written in the Code of Federal Regulations that govern the NTE protocol. "No condition" means that the parameter is not used as a criterion to exclude data.

The reduction of data exclusion conditions generates a large positive impact on the amount of data and type of data that are considered for an NTE event and used for regulatory compliance evaluation. Figure 9 shows the impact of the changes on the NTE baseline conditions on data inclusion for each of the alternatives studied. Alternative 1, which yields an expansion of data validity by a small reduction on thresholds for power, torque, exhaust temperature and IMT conditions results in an increase from 11% to 26% of data included in NTE events. Alternatives 2 and 3 present further positive results: an increase in NTE event data validity of more than 4 times the baseline.

Figure 9 also shows that reducing the power and torque requirements to a minimum of 10% of the rated values increases the share of suburban and urban valid data. On average, the suburban data grows from 2% to 14% and the urban portion grows from near zero to 4%.

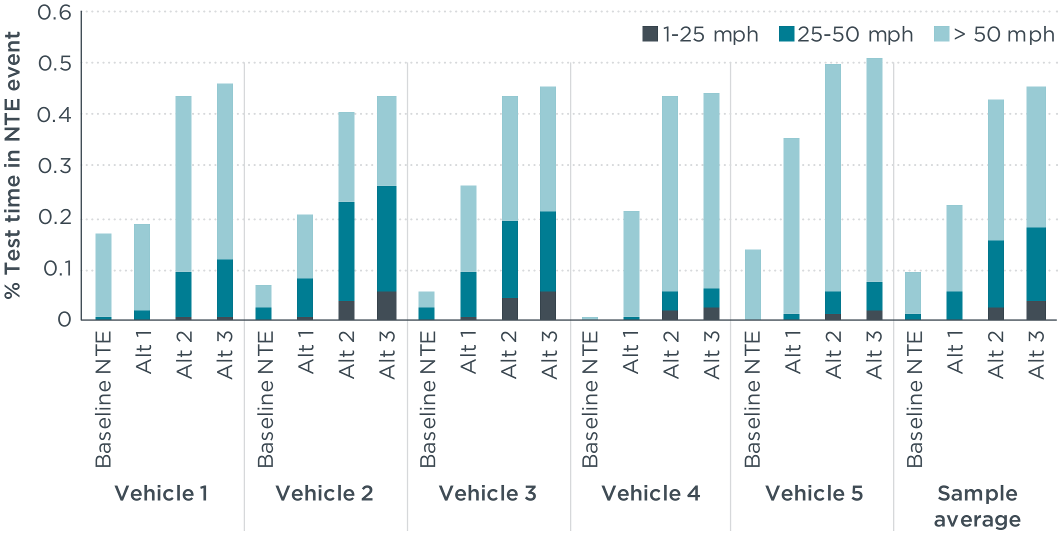

Figure 9. Impact of NTE protocol changes on NTE event data validity. NTE alternatives (Alt 1, Alt 2, Alt 3) are explained in Table 8.

Expanding data inclusion results in higher NTE NO_x values for most vehicles studied. Figure 10 shows the effect of the NTE parametric changes on NO_x emissions. Alternative 1 resulted in a small average increase, 11% in NTE NO_x values. However, alternative 1 induced reductions in NTE NO_x values for vehicles 2 and 4. This may be explained by the large incremental share of highway valid data which typically present lower NO_x emission values. Alternatives 2 and 3 consistently resulted in higher NTE NO_x values, reaching 0.17 g/bhp-hr, almost twice the NTE NO_x obtained under the baseline case (0.09 g/bhp-hr). This increase in NO_x values comes as a result of increasing the amount of data from low-load and low-power operation from urban and suburban driving conditions that is rejected under the existing NTE protocol, as illustrated in Figure 9.

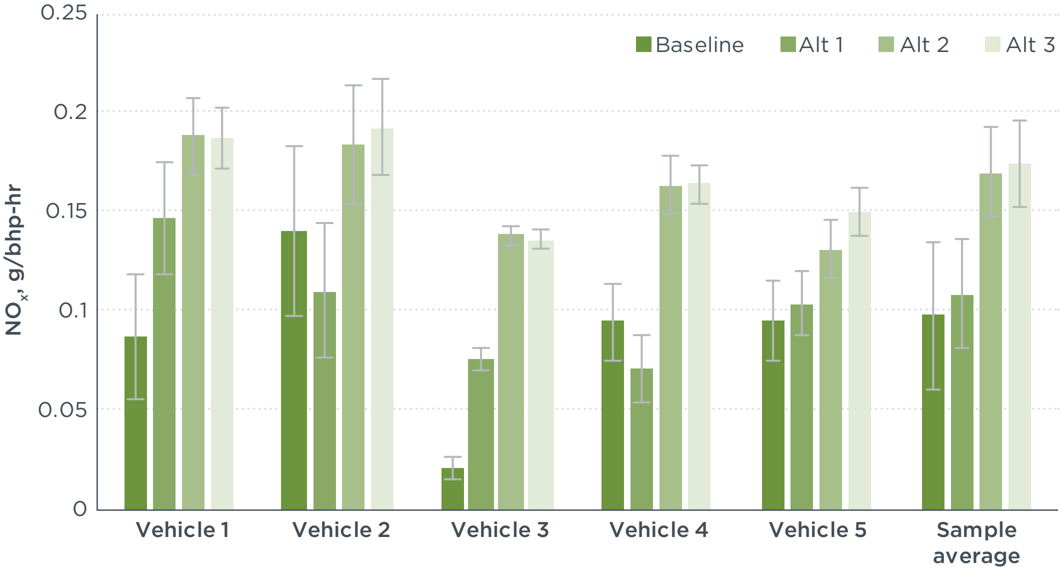

Figure 10. Impact of NTE protocol changes on average NTE event work-specific NO_x values.

Figure 11 shows a per-vehicle comparison of NO_x emissions for urban, suburban, and highway driving conditions and the total route to the NO_x values from the current NTE protocol and alternative 3. The time-weighted NO_x average values for the sample of vehicles tested is shown on the right. Alternative 3 NO_x values are very close to total route values. This result indicates that removing the data evaluation conditions would necessarily converge toward the most basic of PEMS data evaluations: total route emissions. For the vehicles that exhibit the wider range of variability in emission values by driving condition (vehicles 2, 4, and 5) the most data-inclusive NTE alternative 3 is still unable to properly evaluate the vehicles performing in the critical conditions that emit the most NO_x per work unit.

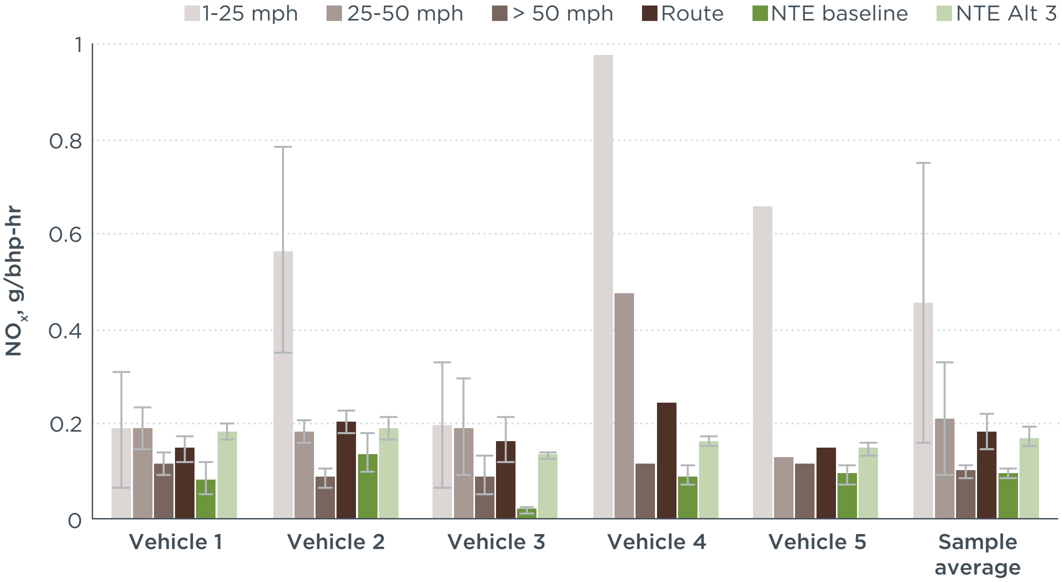

Figure 11. Average work-specific NO_x emissions under urban, suburban, and highway driving conditions compared to the average baseline NTE (as per CFR) and alternative 3 NTE (with fewer data exclusion conditions).

APPLYING THE EUROPEAN MOVING AVERAGE WINDOW FOR IN-USE CONFORMITY EVALUATION

The performance of European trucks presented in the first section of this report suggests that the European in-use testing protocol is incentivizing the adoption of emission control technologies to more adequately address NO_x emission under urban driving conditions. The European ISC program uses the moving average window as the protocol for PEMS data evaluation. The only parameter used under the MAW program for data (i.e., windows) rejection is the average normalized power. In this section we compare the amount of data included for evaluation and the resulting NO_x value by using the MAW method.

Figure 12 presents the window average NO_x and window average speed for one PEMS trip. The results presented here correspond to the data discussed in detail in Figures 4 and 5. The data are presented as a function of window number, a proxy for time. A total of 11,578 windows were generated by this trip of 3.5 hours. In this example the first half of the trip was conducted in urban driving and presents a strong incidence of high NO_x average windows. As window average speed increases NO_x values tend to group below 0.4 g/bhp-hr.

Figure 12 also shows window average NO_x values by normalized power ranges, differentiated by color. The lowest power range, up to 10% of maximum rated values (in orange), was associated with windows with the lowest window average speed values. These windows, ranging from 0.37 to 0.77 g/bhp-hr, are excluded from the current MAW analysis. The windows in the 10%–20% of normalized power range are currently included in the Euro VI-D step. The windows with average normalized power above 20% tend to be associated with the lower work-specific values along the high-speed section of the trip. This showcases the importance of including all power conditions in the regulatory compliance decision.

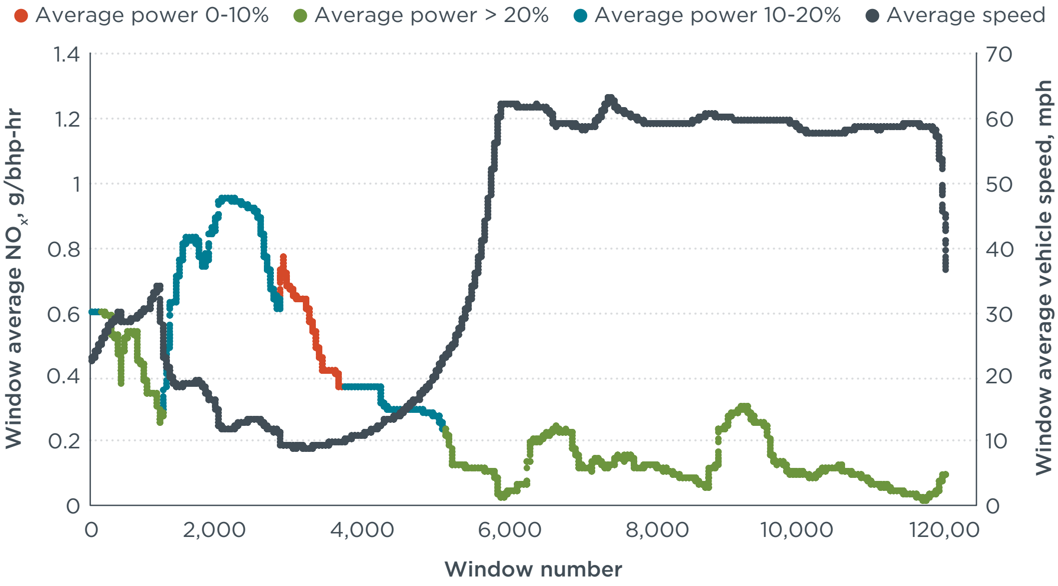

Figure 12. Moving window average work-specific NO$_x$ and average speed along one PEMS test. Window average speed values are shown as black dots. PEMS data from vehicle 4.

NO$_x$ emissions as a function of vehicle speed and the impact of the average power on emissions evaluation is shown in Figure 13. The window average NO$_x$ values are higher for windows with lower average speed. Below 25 mph the NO$_x$ values range between 0.27 and 0.96 g/bhp-hr. At the higher end of window average vehicle speeds, around 60 mph, the NO$_x$ window average values range between 0.05 and 0.3 g/bhp-hr. This tendency of higher NO$_x$ window average values at lower average speed values was observed in most PEMS tests studied (Badshah et al., 2019). Note that this trend of higher NO$_x$ at lower speeds is consistent with the bin-average value presented in Figure 3.

The impact of the minimum average power window exclusion criterion is also shown in Figure 13. In this example, the green dots represent 7587 windows that meet the 20% minimum average power. The 20% minimum power requirement eliminates windows with average speed below 22 mph, which more closely represent urban driving conditions. Windows with normalized power above the 20% minimum (green dots) reported a maximum NO$_x$ value of 0.6 g/bhp-hr. This is 40% lower than the maximum NO$_x$ value found in windows below the 20% power exclusion. Extending the window validity below 20% power allows for windows generated at lower vehicle speeds and power to be included in the compliance evaluation. In this example the power windows in the 10%–20% normalized power range (blue dots) include the windows with the highest average NO$_x$ values.

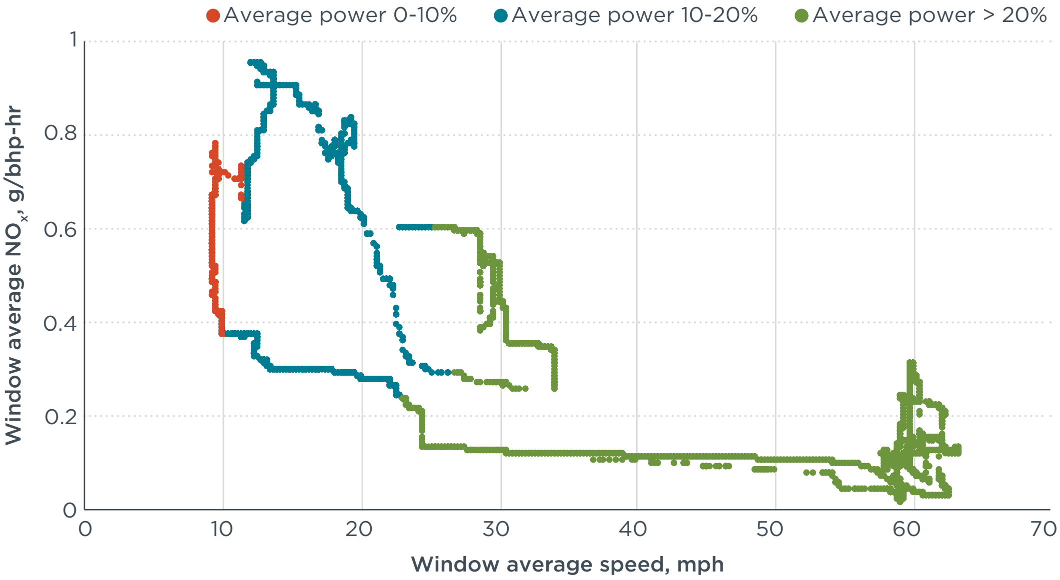

Figure 13. Window average work-specific NO_x emissions as a function of window average vehicle speed. Each dot represents one window. Window color represents the range of normalized power according to the relevant ISC definition for window validity. PEMS data from one test on vehicle 4.

The ranking of window average NO_x emissions for compliance evaluation using the MAW method is presented in Figure 14 for vehicle 4 as example. The windows presented here are segregated by average normalized power. Both the outdated 20% minimum and the recently adopted 10% minimum normalized power validity criterion are shown. Windows below 10% normalized power are not shown because these are not part of the current ISC protocol.

Valid windows are categorized from low to high NO_x average values, and the 90th percentile value is then compared with the ISC standard. The 90th percentile window average NO_x is 0.77 g/bhp-hr, meaning that 90% of the windows consisted of average NO_x below that value. The highest window NO_x value was 0.95 g/bhp-hr.

The average power criterion has a strong effect on data evaluation. Under the previous version of the ISC the 20% minimum power requirement would have rejected all the blue dots on Figure 14. This would have resulted in a 90th percentile of 0.34 g/bhp-hr, less than half the value obtained with the more inclusive 10% minimum power criterion.

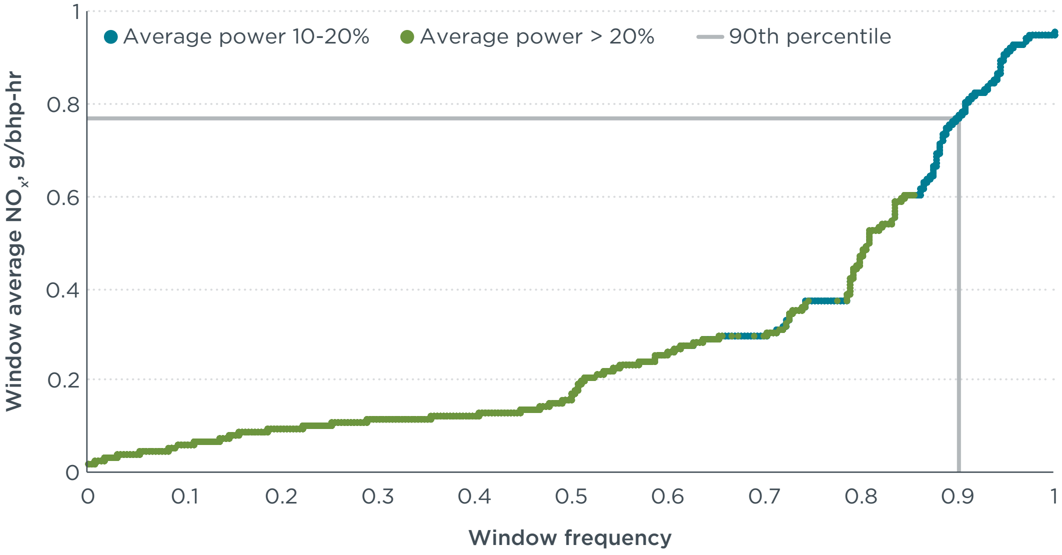

Figure 14. Ranking of window average NO$_x$ values. The gray line shows the 90th percentile value. Each dot represents one window. Window color represents the range of normalized power. PEMS data from vehicle 4.

IMPROVEMENTS TO THE MAW PROTOCOL

The current European work-based moving average window protocol has two main conditions that affect the outcome of the regulatory evaluation. The first is the window validity criterion, which relies on the average power as a percentage of the maximum rated power to filter out invalid windows.

The second condition is the share of windows that should be below the ISC threshold to meet the standard. The current ISC program requires that 90% of windows with average power above 10% of normalized power should present average NO$_x$ values below the standard. The impact of including all windows and increasing the percentile value from 90% to 95% on NO$_x$ evaluation values is discussed here.

Figure 15 shows the impact of evaluating the 90th and 95th percentile highest work-specific NO$_x$ window for one PEMS trip of vehicle 4. All windows are considered valid, regardless of average power. Note the orange dots for windows below 10% power (around 0.75 window frequency). NO$_x$ value increase in this example from 0.77 g/bhp-hr to 0.91 g/bhp-hr, an 18% increase.

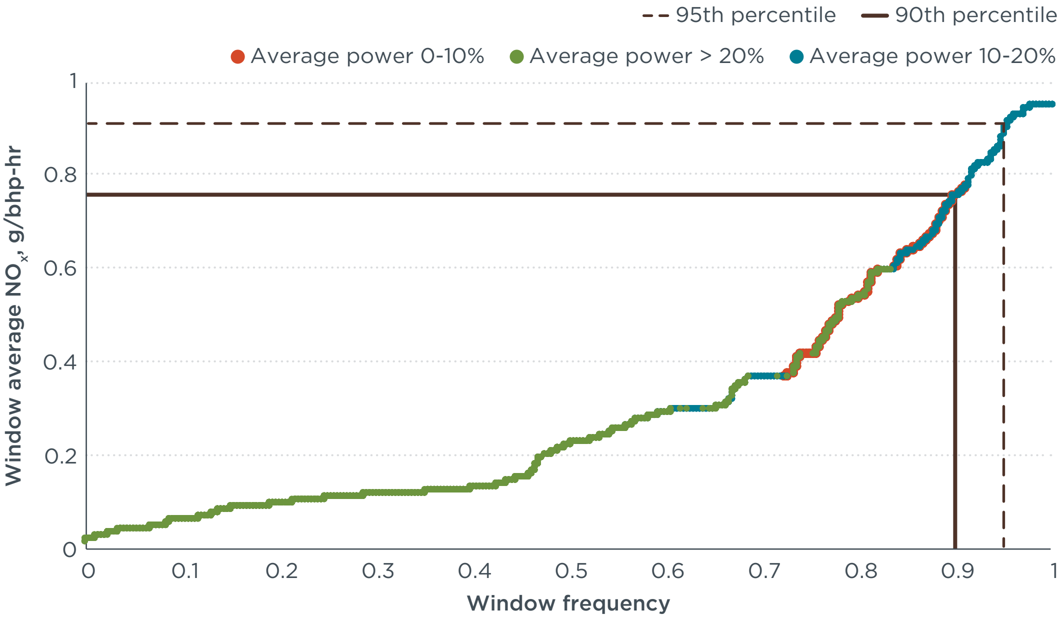

Figure 15. Window average work-specific NO$_x$ values ranked from lowest to highest value. Solid black line shows 90% of windows, and dashed black line shows 95% of windows.

Expanding the number of valid windows by removing the power requirement and evaluating at the 95th percentile increases the NO$_x$ evaluation value to better represent urban driving emissions. Figure 16 compares the speed bin results with the results of the current MAW evaluation and an improved case that includes all windows (regardless of power) and evaluates the compliance at the 95th percentile. For all vehicles studied, the inclusion of all windows and evaluation at the 95th percentile results in NO$_x$ values that are, on average, 19% higher than the current MAW evaluation. Compared to the urban driving average emissions bin, average results from the improved MAW method were 13% lower.

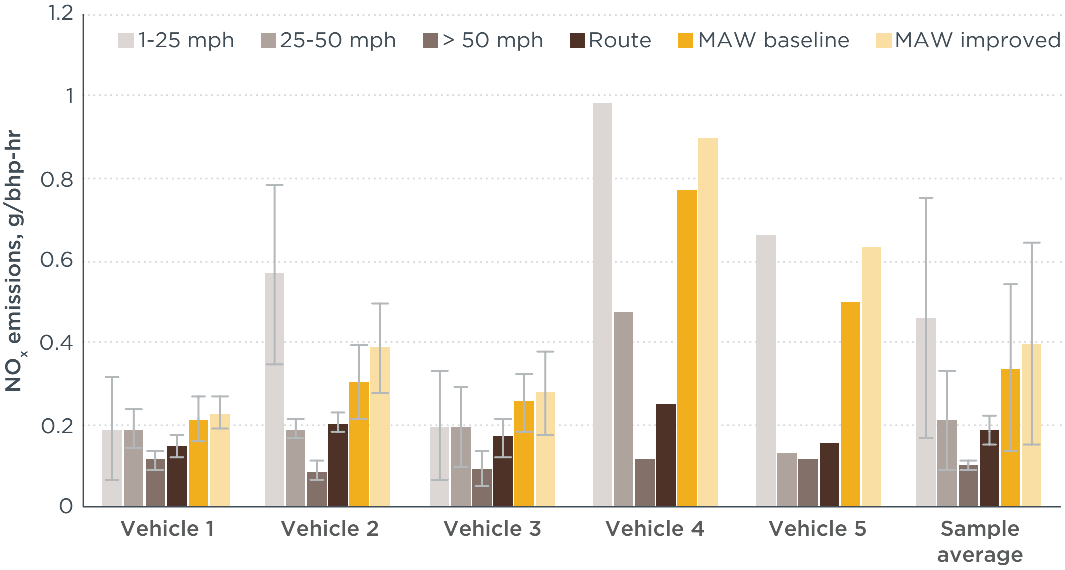

Figure 16. Work-specific NO$_x$ emissions under urban, suburban, and highway driving conditions and the total route compared to results for the MAW baseline case according to current European regulations (window validity defined by 10% minimum average normalized power at 90th window percentile), and a MAW improved case that includes all windows and evaluates compliance at the 95th percentile.

DISCUSSION: COMPARING CURRENT AND IMPROVED NTE AND MAW PROTOCOLS

The first section of this report comparing NO_x emissions for European and U.S. trucks suggests that European trucks are better designed to control NO_x during urban driving. Engine emission standards and in-use compliance regulations shape the calibration strategies and technologies to control NO_x emissions. The positive results of the European trucks, in particular the fact that urban NO_x is only twice as much as their route NO_x, suggest the region's regulations are contributing to that success.

In the compliance evaluation section, we showed that the current U.S. NTE protocol is designed to evaluate HDV NO_x compliance almost exclusively at highway speeds. Improving the NTE protocol by allowing more data inclusion would only result in NTE evaluation values that closely resemble total route NO_x emissions (total mass of NO_x divided by total work). This would not properly incentivize manufacturers to address the high NO_x emissions observed across U.S. HDVs during urban driving conditions.

On the other hand, the MAW protocol as designed today focuses on evaluating more challenging NO_x performance operation: low engine loads and power demands, typically found under urban driving conditions. Improving the MAW by allowing windows with lower average power and evaluating compliance at the 95th percentile would result in increased windows validity and would focus the evaluation on urban driving and low-load conditions, where NO_x control is more challenging today.

Figure 17 compares work-specific NO_x values by vehicle speed condition and total route with NTE and MAW evaluation results. The NTE and MAW values are shown as currently specified in the regulations (baseline) and as improved options. The NTE alternative 3 (labeled as NTE Alt 3) removes all NTE zone conditions except power and torque, which are reduced to 10% of maximum power, and reduces the NTE event minimum duration to 10 seconds. The MAW alternative removes the minimum power requirement and increases the selection of the ranked average window NO_x value from the 90th to the 95th percentile.

Figure 17 shows that NO_x values from improved NTE tend to be below the values from the current and improved MAW protocol by a significant margin. On average, the NTE values from significantly revised exclusion criteria are still 45% lower than the MAW generated values. Only vehicle 1, with the best NO_x emission performance overall, shows little variation in response to the PEMS evaluation redesign except for NTE values. For the rest of the vehicles, the adoption of an improved MAW protocol would result in evaluation values that closely align with the high values obtained under urban driving conditions.

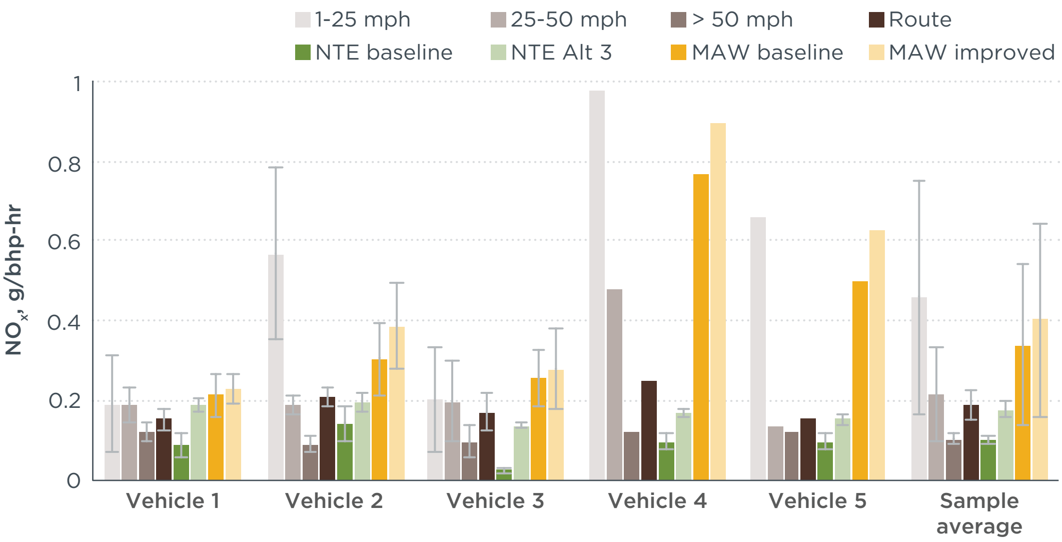

Figure 17. Work-specific NO_x emissions under urban, suburban and highway driving conditions compared to NTE results (baseline and improved, in green) and MAW results (baseline and improved, in yellow).

One additional consideration for future in-use evaluation regulatory changes in the United States and Europe is to ensure that enough urban and low-load driving time and cold start evaluation are stipulated in the regulation. Our analysis of the U.S. EPA HDIUT program shows that heavy-duty vehicles operate below 25 mph around 41%–55% of the time (Badshah et al., 2019). As it stands today, the regulation in the United States does not require a minimum vehicle testing time for low-speed (urban) driving. Stating a requirement on low-speed operation minimum test times would ensure that data are available to generate enough valid windows to properly evaluate urban operation.

Also, there is no in-use cold start requirement for U.S HDVs. Such a requirement is already scheduled for inclusion in Europe starting with new trucks in January 2021 for Euro VI-E. PEMS testing carried out in Europe by the Joint Research Center shows that HDV diesel NO_x emission during cold start (while the coolant fluid temperature is below 70°C) can amount up to 63% of all NO_x by mass generated during a trip (Mendoza-Villafuerte et al., 2017). The authors explained that this was due to SCR system inactivity during that period of operation. The addition of cold start for in-use compliance evaluations would ensure that engine calibration and aftertreatment systems are better designed to control NO_x during this challenging condition.

CONCLUSIONS AND RECOMMENDATIONS

In-use emissions testing of heavy-duty vehicles has shown that there is still a gap between real-world measured NO_x emission levels and engine certification levels. The data studied reveal a disproportionate amount of NO_x emissions occur during urban driving. This study shows that the urban NO_x gap is much broader in U.S. trucks certified to meet the EPA 2010 standard than in similar European trucks meeting the Euro VI standard.

One key factor affecting the calibration and design of aftertreatment systems for NO_x control is the variance in in-use emissions compliance evaluation protocols. This study explains the fundamental design flaws of the current U.S. NTE program and the limitations to improving it, and supports the adoption of the European MAW approach as a better way to evaluate in-use emissions from HDVs.

Our analysis revealed that European HDVs are better designed than U.S trucks to control NO_x emissions under low-speed, low-load, and idle conditions. The results show that:

- The U.S. HDVs studied here emit on average 1.4 times more NO_x per unit work than the European vehicles. During urban driving conditions, work-specific NO_x emissions of U.S. HDVs almost quadruple in magnitude compared to their total route emissions (total mass of NO_x emitted divided by total work). European HDVs tend to exhibit a more consistent performance across the speed range, with urban driving emissions only twice as much as their total route emission values.
- The analysis by power conditions shows that U.S. trucks analyzed for this study emit more NO_x than the European trucks at the lowest power range. Below 10% of maximum rated power, the sample of U.S. trucks emit twice as much NO_x than the sample of European trucks studied. NO_x emissions below 20% of maximum rated power are about 37% and 28% of total NO_x emissions by mass for the U.S. and EU trucks in this study, respectively. The time spent at each condition was similar for both groups, which does not explain higher NO_x values for U.S. trucks.

The analysis of the in-use compliance tools NTE and MAW indicates that excluding data from the regulatory evaluation negatively impacted emission values around excluded operating areas. We found that:

- The current U.S. NTE evaluates in-use NO_x PEMS data only under a narrow band of vehicle operating conditions, exclusively under highway driving conditions. The rejection of data under all other conditions is caused primarily by engine power, torque, and exhaust temperature requirements. This is potentially the main cause of poor urban in-use NO_x emission in U.S certified HDVs.
- Reducing or removing the majority of the NTE data validity conditions would not be sufficient to incentivize significant urban NO_x control. Any expansion of the current NTE zone conditions would result in an NTE evaluation value between what is obtained in the current NTE and what is obtained with total route evaluation (total NO_x divided by total work).
- The European MAW method for in-use compliance evaluation better captures NO_x emissions under the most challenging conditions, low speed and low power demands, which are characteristic of urban driving.
- Improvements could be made to the MAW protocol to further incentivize urban NO_x reductions. Such improvements include expanding window validity to all

power conditions and evaluating compliance at the 95th percentile. These changes would better evaluate future HDVs designed to meet currently proposed low-load cycle requirements.

- Developing a regulatory requirement on low-speed operation minimum test times would ensure that enough data are available to generate valid windows to properly evaluate urban operation.

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