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Differences between emissions measured in urban driving and certification testing of heavy-duty diesel engines

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ABSTRACT

Emissions from eight heavy-duty diesel trucks (HDDTs) equipped with three different exhaust after-treatment systems (ATS) for controlling nitrogen oxide (NO_x) emissions were quantified on a chassis dynamometer using driving schedules representative of stop-and-go and free-flow driving in metropolitan areas. The three control technologies were: 1) cooled exhaust gas recirculation (CEGR) plus a diesel particulate filter (DPF); 2) CEGR and DPF plus advanced engine controls; and 3) CEGR and DPF plus selective catalytic reduction with ammonia (SCR). Results for all control technologies and driving conditions showed PM emission factors were less than the standard, while selected non-regulated emissions (ammonia, carbonyls, and C_4–C_{12} hydrocarbons) and a greenhouse gas (nitrous oxide) were at measurement detection limits. However, NO_x emission factors depended on the control technology, engine calibration, and driving mode. For example, emissions from engines with cooled-exhaust gas recirculation (CEGR) were 239% higher for stop-and-go driving as compared with free-flow. For CEGR plus selective catalytic reduction (SCR), the ratio was 450%. A deeper analysis was carried out with the assumption that emissions measured for a drive cycle on either the chassis or in-use driving would be similar. Applying the same NTE rules to the chassis data showed emissions during stop-and-go driving often exceeded the certification standard and >90% of the driving did not fall within the Not-To-Exceed (NTE) control area suggesting the NTE requirements do not provide sufficient emissions control under in-use conditions. On-road measurement of emissions using the same mobile lab while the vehicle followed a free-flow driving schedule verified the chassis results. These results have implications for scientists who build inventories using certification values instead of real world emission values and for metropolitan populations, who are exposed to elevated emissions. The differences in values between real world emissions and certification cycles should be narrowed. For example, one might use a different mix of cold and hot start testing to greater emphasize low temperature/load operation, a separate cycle to specifically characterize low-load operation, or broaden the in-use compliance testing requirements and associated conformity factors to incorporate a wider envelope of vehicle operation, especially at low load conditions. .

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1. Introduction

Emissions from heavy heavy-duty diesel trucks (HDDTs) are a concern for both local and regional communities due to their adverse impacts on air quality and human health (Sawyer et al., 2000). This is especially true for areas that fail to meet air quality standards and for areas with considerable truck activity, such as near a port or distribution center. For example, Los Angeles (LA) fails to meet federal air quality standards and yet over 10,000 trucks operate in local ports where about 40% of all containerized cargo enters the United States (U.S.). These trucks remain a significant source of emissions and the substandard air quality represents a health concern for the population located near the port (San Pedro

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Bay Ports, 2006; SCAQMD, 2012).

In order to reduce emissions of nitrogen oxides (NO_x) and particulate matter (PM) from HDDTs, a series of Federal regulations for heavy heavy-duty engines (HDDE) were implemented starting in 1988. These rules required emissions of NO_x and PM to be reduced from 10.7 g/bhp-hr to 0.2 g/bhp-hr and from 0.60 g/bhp-hr to 0.01 g/bhp-hr, respectively (U.S. EPA). The EPA also expanded the required emission testing from solely a transient federal test procedure (FTP) on an engine dynamometer to include: 1) the Supplemental Emission Test (SET) on an engine dynamometer to ensure that heavy-duty engine emissions are controlled during steady-state type driving, (Title 40 Code of Federal Regulations [CFR] Part §86.1360, 2007a) and 2) Not-to-Exceed (NTE) testing (40 CFR §86.1370, 2007b).

NTE testing is more complex since emissions are measured during on-road, real-world conditions rather than on an engine dynamometer in a laboratory with controlled conditions. NTE testing quantifies emissions while operating over a broad range of normal speed and load points in the so called NTE control area. NTE test conditions include that power and torque must be $\geq$ 30% of its maximum, and that the engine operates in the NTE control area for at least 30 s continuously. An important feature of the in-use test procedure is that only emissions meeting the NTE conditions are included when calculating the emission factor; all other data are excluded. Emission factors from this test procedure are compared to the NTE limits specified in the 40 CFR §86.1370 (2007b).

Meeting tough PM and NO_x emissions standards required advanced fuels and engine technology and the addition of exhaust aftertreatment systems. For example, PM control shifted from simple control of the sulfur in the fuels to an added diesel particulate filter (DPF). Similarly, NO_x control required both cooled exhaust gas recirculation (EGR) and a selective catalytic reduction (SCR) unit with urea added to the exhaust. SCR's operating efficiencies in reducing NO_x were reported to be greater than 75% for SCR-equipped trucks for cruise and transient operating conditions in chassis dynamometer testing (Herner et al., 2009). Research showed the optimum operation of the SCR systems depended on a number of factors including: catalyst composition, exhaust flow and exhaust temperature. With the catalyst composition fixed, the exhaust temperature became the key design parameter in determining when urea is introduced and the catalyst conversion efficiency that could be achieved (Zhao et al., 2011). Outside the design region, the catalyst efficiency for NO_x conversion is lower and ammonia (NH_3) emissions may result (Strots et al., 2009).

Numerous studies have shown that it is essential to understand emissions under conditions representative of in-use driving. Studies in the 1990s showed that heavy-duty engines were programmed to operate in a high fuel efficiency, high NO_x emissions mode that exceeded emissions standard levels during extended highway operation. Additional studies in the early to mid-2000s showed that emissions vary significantly under different driving conditions and differ from estimates used in models (Shah et al., 2006; Cocker et al., 2004a; Durbin et al., 2008). More extensive chassis dynamometer testing over a wider range of cycles representing different driving conditions was conducted as part of the E-55/59 program, and this information was utilized to provide updated emissions inventory estimates (Clark et al., 2004, 2006, 2007). More recently, studies have shown that heavy-duty vehicles with the most advanced emissions control strategies have varying emissions under different operating conditions. Bishop et al. also found, during remote sensing studies of trucks exiting scales, that SCR equipped HDDTs were frequently operating at or below SCR operational threshold conditions leading to high NO_x emissions (Bishop et al., 2012, 2013; Dallmann et al., 2011). Misra et al. (2013) in a study of in-use emissions of MY 2010 and 2011 vehicles showed that SCRs provided good control of NO_x emissions at sustained highway speeds, but NO_x emissions elevated under cold-start operation, low load, and load speed operation. Additional studies by researchers from the California Air Resources Board and West Virginia University have supported these findings, emphasizing the importance of understanding in-use emissions under low load driving conditions (Misra et al., 2016; Tu et al., 2016; Yoon et al., 2016; Dallmann et al., 2011; Carder et al., 2014; Thiruvengadam et al., 2015).

The background shows a number of studies and approaches were used to characterize emissions from HDDTs. The present study provides an expanded data base and effort to characterize the emissions of late model heavy-duty diesel vehicles with differing emission control technologies and driving conditions, with an important distinction in that there is a deeper analysis of why emissions deviate from the standard. In this research, eight HDDTs were tested on a chassis dyno following four driving cycles; the EPA Urban Dynamometer Driving Schedule (UDDS) that mimics the heavy-duty Federal Test Procedure (FTP) engine certification cycle and three cycles that were representative of trucks moving goods in a metropolitan area. The HDDT/HDDEs selected for this research were from different manufacturers and used different NO_x control technologies. A key question for this research was to compare the emissions factors from certification, the in-use NTE program, and HDDT/HDDEs operating over urban driving cycles and identifying parameters that create a gap between the standard and real world emissions.

2. Experimental section

2.1. Test vehicles and fuels

Selected specifications of the engines and controls used in the eight HDDT/HDDEs tested are in Table 1, including: engine make, model year, displacement, rated horse power, aftertreatment system (ATS), a family emission limit (FEL) and a typical certification value for one of many engine ratings within a specific family. When the NO_x standard of 0.2 g/bhp-hr was established in 2007, there were phase-in provisions leading to the creation of an averaging, banking, and trading (ABT) program, and the establishment of the FEL for each engine family (40 CFR §86.007, 2011). The FEL represents the maximum certification emissions value for all engines within the family and this value is allowed to increase up to 150% for in-use NTE compliance maximum, like the driving patterns included in this research. For example, vehicle 4 with a NO_x FEL of 0.5 g/bhp-hr is increased to 0.75 g/bhp-hr for the NTE value. Note 0.75 g/bhp-hr is significantly higher than the NO_x standard of 0.2 g/bhp-hr, but the correct value to use when making a comparison to NTE emissions limits.

The HDDEs in the test matrix represented a mix of manufacturers and control technologies that are in commercial use. Prior to testing, vehicle maintenance records for engine repairs, brakes, steering, fluids, and tires were reviewed to ensure safe operation. The inspection included a download of the electronic control module (ECM) both before and after the test to ensure there were no active fault codes.

CARB #2 diesel fuel was used for the research rather than a certification fuel in order to more closely represent real world conditions. Properties for the two fuels are similar, except the in-use CARB fuel is likely to have an aromatic content closer to 20 vol percent rather than the 10 vol percent in a certification fuel.

2.2. Test cycles

The HDDTs were tested on a chassis dyno following four driving

Table 1
Selected data for the engines in the HDDT's.[a]

Unique ID	Cat.	ATS	Engine						Chassis		FEL g/bhp-hr	NTE g/bhp-hr
			Mfg.	MY	Model	Emissions Family	Disp. (L)	Max Power HP@RPM	Mfg.	Odometer		
Veh1	I	DOC/DPF	NavistarInc.	2009	12WZJ/B	9 NVXH0757AGA	12.4	430@1700	International	80,412	1.20	1.80
Veh2	I	DOC/DPF	DDC	2008	DDC/60	8DDXH14.0ELC	14	425@1800	Freightliner	129,815	1.16	1.74
Veh3	I	DOC/DPF	DDC	2008	DDC/60	8DDXH14.0ELC	14	425@1800	Freightliner	121,766	1.16	1.74
Veh4	II	DOC/DPF + Adv. ERG	Navistar Inc.	2011	A475	BNVXH07570GB	12.4	430@1700	International	80,651	0.50	0.75
Veh5	II	DOC/DPF + Adv. ERG	Navistar Inc.	2011	A430	BNVXH07570GB	12.4	475@1700	International	67,373	0.50	0.75
Veh6	III	DOC/DPF + SCR	Cummins	2010	ISC-300	ACEXH0505CAC	8.3	300@2100	Kenworth	13,918	0.31	0.46
Veh7	III	DOC/DPF + SCR	Cummins	2011	ISX11.9–425	BCEXH0729XAC	11.9	425@1800	Freightliner	4769	0.20	0.30
Veh8	III	DOC/DPF + SCR	Mack	2011	MP8-445C	BVPTH12.8S01	12.8	445@1500	Mack Truck Inc.	36,982	0.20	0.30

[a] Cat. – category of emissions technology I, II, and III, ATS – aftertreatment system, DOC – diesel oxidation catalyst, DPF – diesel particulate filter, Adv EGR – advanced exhaust gas recirculation including specialized shift points to maximize NO_x reductions, SCR – selective catalytic reduction, FEL – family emission limit specified for this engine family (and all its ratings). The FEL may be higher than the certification standard as based on engine dynamometer testing, as per 40 CFR §1039.801, NTE level – not to exceed compliance value calculated from the FEL and measurement and in-use allowances (40 CFR §1045.107).

cycles with a gross-vehicle-weight (GVW) of 69,000 pounds. The first cycle was the UDDS, as values from the UDDS are often compared with values from a FTP "certification test." The UDDS emission value was one of the screening parameters used to confirm that the selected engine was representative of the targeted technology. Emissions were measured from the UDDS cycle during hot and cold-start conditions as is done during the FTP engine dynamometer certification testing procedure.

The three other cycles were developed by TIAX (2011) and represented drayage trucks moving goods from a port or a distribution center in the real-world over localized and regional routes within a metropolitan area. These cycles were based on the analysis of activity data for over 1000 Class 8 drayage trucks with a focus on five characteristic operating parameters: average speed, maximum speed, energy per mile, distance, and number of stops. The final drayage cycles were named Near-dock, Local, and Regional and each was composed of three phases: a creep, a low speed transient phase, and a high speed phase. The creep and low speed transient phases are similar for all three cycles, while the high speed phase differs depending on the different drayage operations. General information for the cycles is provided in Table 2 and detailed traces of velocity versus time are in the Supporting Information.

As part of the test design, a SCR-equipped truck was operated on both the chassis dyno and on-road over similar driving conditions and using the MEL for the emissions measurements to verify that the trends and approximate values found in the lab represented those of real world operation.

2.3. Emission measurements

The HDDTs were tested at the University of California, Riverside (UCR) using their heavy-duty chassis dynamometer and Mobile Emission Laboratory (MEL). MEL uses a full dilution tunnel and emissions are sampled and analyzed according to the 40 CFR Part 1065 for heavy duty vehicles (Cocker et al., 2004a, 2004b). Triplicate tests were run for each cycle and the emission rates and factors were calculated as the average of the three tests. For all tests, emissions of total hydrocarbons (THC), non-methane hydrocarbons (NMHC), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_x), were measured continuously at 1 Hz. NH_3 was measured continuously with a tunable diode laser (TDL) (Huai et al., 2003). The greenhouse gas, nitrous oxide (N_2O), and some non-regulated toxics, such as the carbonyl compounds and selected C_4–C_{12} hydrocarbons, were measured off-line.

The mass concentrations of $PM_{2.5}$ were obtained by analysis of particulates collected on 47 mm diameter, 2 μm pore Teflo filters (Whatman brand). The filters were measured for net gains using a UMX2 ultra precision microbalance with a buoyancy correction following the weighing procedure guidelines of the 40 CFR Part 1065. In addition to PM mass, the elemental and organic carbon were determined via the thermal optical reflectance method from a quartz filter (Cocker et al., 2004a, 2004b). Additionally, the real-time particle size distributions and number concentrations were determined with a scanning mobility particle sizer (SMPS).

2.4. Data analysis

Two approaches/methods were used to calculate the NOx emission factor from data. In Method 1 the emission factor is calculated by dividing the total NOx mass emissions by either the total miles measured on the chassis dynamometer or the total work (brake-horsepower-hour) calculated from engine RPM, actual torque, friction torque, and reference torque, as measured in real-time from J1939 engine control module (ECM) signals. For the Method 2 emission factor calculations, the total NOx data were filtered first to remove points that did not meet the NTE criteria, as if the data were generated following the in-use testing protocol. Thus, the emission factor based on Method 2 uses only the portion of the cycle emissions that remain after the NTE exclusion process is applied. The subset of remaining data was calculated using the same procedures as used for Method 1. Method 2 assumes that the data from a chassis dyno would be similar to those found for similar real world cycles. This assumption is based on the fact that the chassis cycles are representative of driving patterns for trucks and developed from thousands of real world activity measurements. It should be noted that for some cases all data are eliminated by applying the NTE process so it is not possible to calculate an emission factor for Method 2.

Table 2
Selected metrics for goods movement cycles.

Description	Miles	Ave Speed mph	Max Speed	Phase 1	Phase 2	Phase 3	Description
Near-dock	5.61	6.6	40.6	Creep	Low Speed Transient	Short High Speed Transient	Near-dock
Local	8.71	9.3	46.4	Creep	Low Speed Transient	Long High Speed Transient	Local
Regional	27.3	23.2	59.3	Creep	Low Speed Transient	High Speed Cruise	Regional

3. Results and discussion

The results showed the emission values for THC, NMHC, and CO, selected toxics, the greenhouse gases CH_4 and N_2O, and ammonia were all at or near background levels, similar to results from the Advanced Collaborative Emissions Study (ACES) (Khalek et al., 2011, 2013). These low emission levels suggest the ATS for modern engines is effective in eliminating these species. The details of results for those emissions are provided in the Supporting Information and Miller et al., 2013 to allow a greater focus and deeper analysis of the PM and NO_x results.

PM mass emissions factors by Method 1 for the three drayage driving cycles are summarized in Fig. 1 with the x-axis being divided into three categories based on the control technology: Category 1 are Model Year 2007 through 2009 HDDEs with DPF and cooled EGR; Category 2 are Model Year 2010 HDDEs with DPFs, advanced cooled EGR and specialized shift points; and Category 3 are Model Year ≥2010 HDDEs with DPFs, cooled EGR and SCR. The y-axis was set to 5 mg/bhp-hr to display the magnitude in relation to 50% of the laboratory certification standard (note the in-use NTE standard is 30 mg/bhp-hr for all HDDVs tested).

The results in Fig. 1 show the PM mass emission factors for all cycles were <10 mg/bhp-hr, the EPA standard. In fact, the emission rates for all but a few of the newer technology vehicles were below 1 mg/bhp-hr, which could be due to some slight modifications to the control strategies for some of the newer vehicles. For all the PM mass emissions presented, the filter weights were below 40 μg at the 2 mg/bhp-hr level and below 20 μg for the 1 mg/bhp-hr emission level, which is near the detection limits of the measurement method (Swanson et al., 2017). Clearly, the DPF provided the needed PM control efficiency for all driving conditions tested in this research. It should be noted that DPF regenerations were not included in this research plan, due to the focus on NOx emissions; however, we recognize regenerations are an important part of real-world driving, as reported by Yamada, (2013).

NO_x emissions factors by Method 1 for the three drayage driving cycles are shown in Fig. 2 and varied over a wide range, from 0.10 to 4.4 g/bhp-h, reflecting that a number of NO_x control technologies were being used during the transition period to the 0.20 g/bhp-hr standard. As expected, engines with cooled EGR and an SCR catalyst provided the lowest overall NO_x emission factors, although in some cases these emissions were comparable to those of the other technologies. Analysis of the NO_x data is divided into three sections; one for each technology category.

3.1. Category 1: model year 2007–2009; cooled EGR

Category 1 HDDEs had the highest NO_x emissions and the Method 1 emissions factors ranged from 1.8 to 4.4 g/bhp-hr for the port cycles. The emission factors depended on engine manufacturer and driving cycle. For example, for Vehicle 1, the average emission factor was 2.1 g/bhp-hr and basically independent of driving cycle. The results for this vehicle were consistent with the findings of a study by Misra et al. (2013), who reported that brake-specific NO_x emissions for a truck equipped only with an EGR were comparable over different driving conditions. However, results for Vehicles 2 and 3, from a different manufacturer, were highly reproducible and showed a dependence on the driving cycle. Note the emission

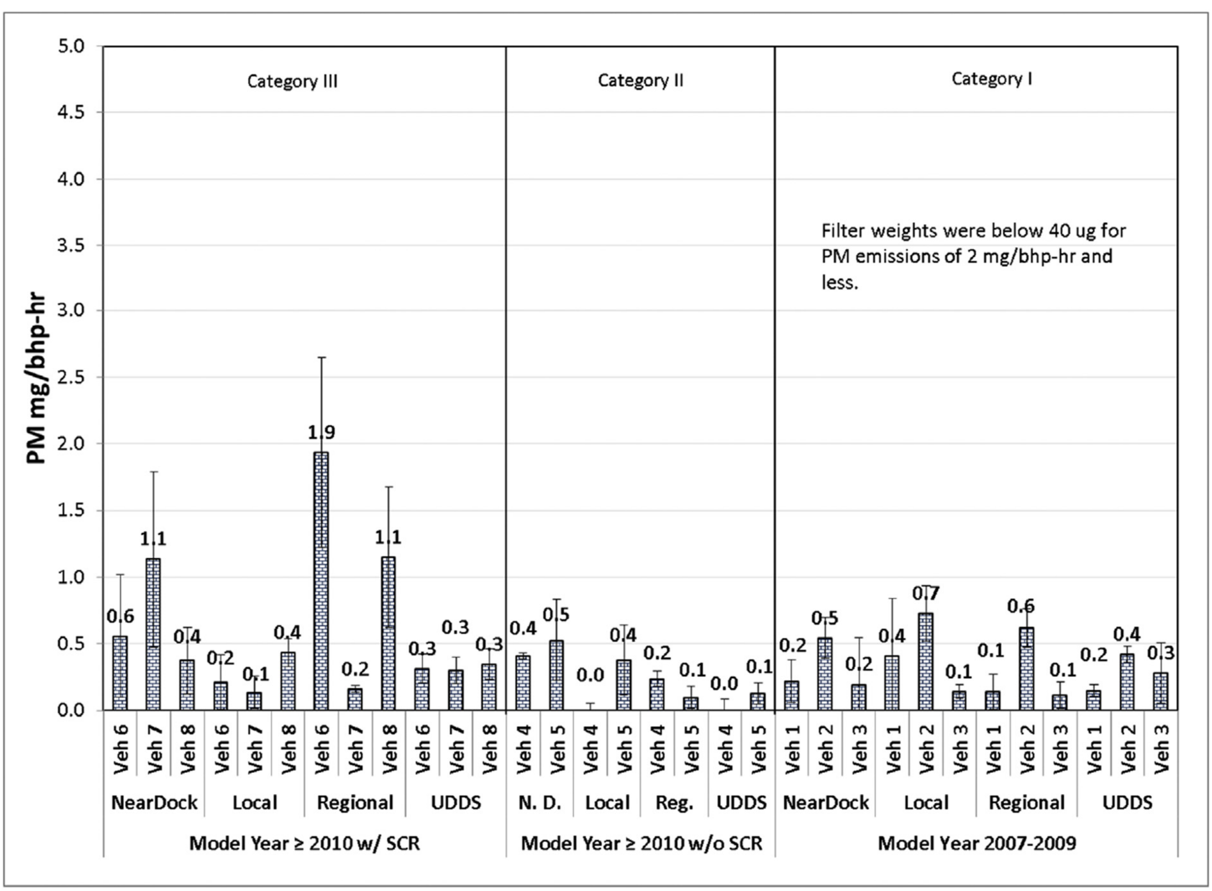

Fig. 1. $PM_{2.5}$ mass emission factors for drayage and UDDS cycles (mg/bhp-hr).
[1] N.D. – near dock cycle, Veh – HDD vehicle, w/o – without.

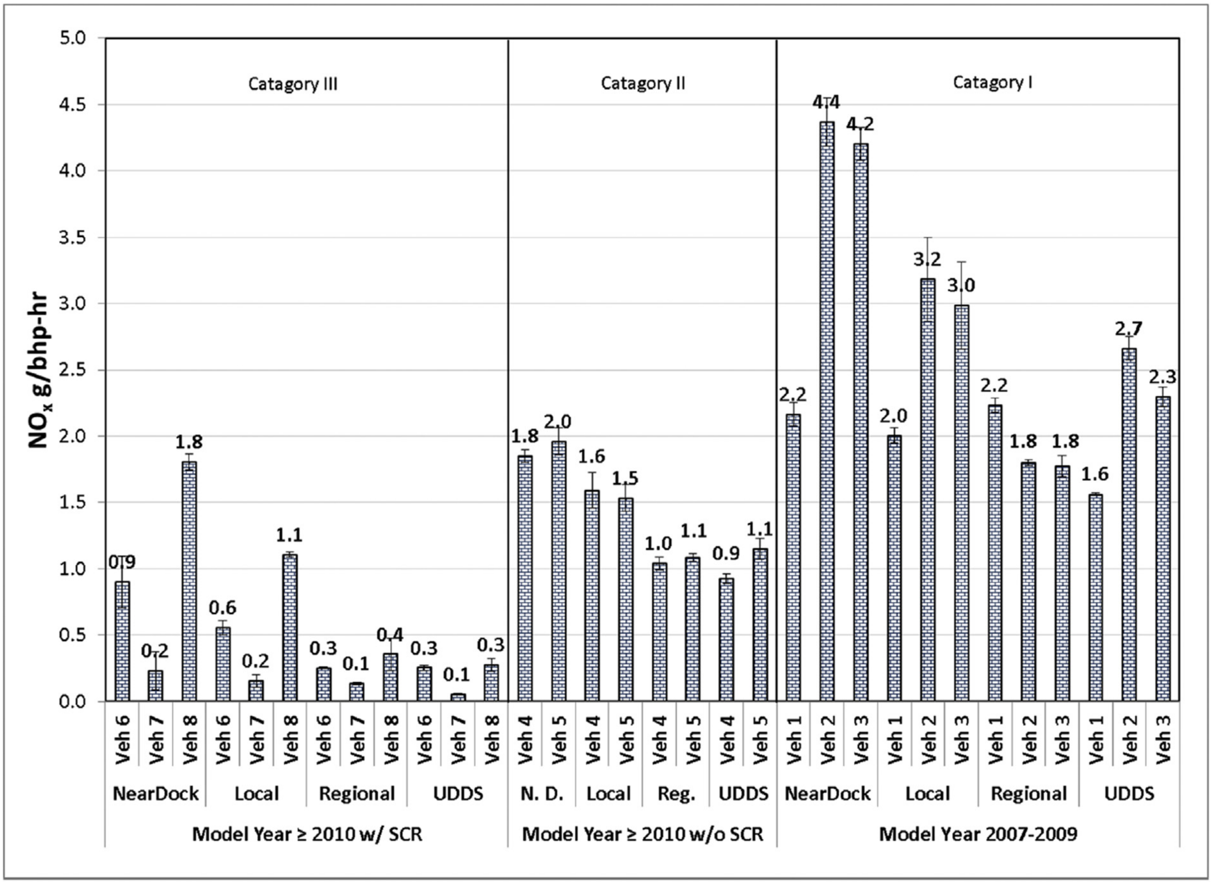

Fig. 2. NO_x emission factors for drayage and UDDS cycles (g/bhp-hr).
[1] N.D. – near dock cycle, Veh – HDD vehicle, w/o – without.

factors of two different HDDTs from the same manufacturer were within 3% of the average for the same driving schedule; thus, providing a snapshot of the excellent reproducibility from these in-use engines. Considering dependence on driving cycle, the emissions factors for vehicles 2 and 3 averaged 1.8 g/bhp-hr for the Regional cycle compared to 4.3 g/bhp-hr for the Near Port cycle, an increase of 239%. The higher emission factors for the near dock cycle can be attributed to the fact that it is composed of short, low speed accelerations between periods of idle that covers a short distance. Such stop and go type of driving tends to create high emissions when evaluated on a per mile basis.

3.2. *Category 2: model year ≥2010 advanced cooled EGR without SCR*

Two vehicles from the same manufacturer were tested in this category. While other HDDE manufacturers opted for SCR technology to control NOx, this manufacturer enhanced its cooled EGR design and added prescribed shift points to modify engine operation and control NO_x emissions. Reproducibility for the two tested trucks was excellent, as emission values were within 5% for a given cycle. These two vehicles did show a dependence on driving cycle, however, as emissions ranged from 1.0 to 1.1 g/bhp-hr for the Regional cycle to 1.8–2.0 g/bhp-hr for the Near Dock cycle, an increase of 180%. This is in contrast to vehicle 1 in Category 1, from the same manufacturer, which showed smaller differences between cycles compared to the other vehicles. Even though this manufacturer received a higher emission limit from the EPA, their commercial approach was discontinued as the NO_x standard proved difficult to meet with predominantly EGR alone. Their new HDDEs use cooled EGR plus SCR, same as in Category 3 of this report.

3.3. *Category 3: model year ≥2010 cooled EGR with SCR*

The added control technology in Category 3 was a DPF for PM and cooled EGR with SCR for NO_x control. This combination offered the highest level of NO_x control to meet the 0.2 g/bhp-hr NO_x standard. Data in this Category were collected from one HDDE from one manufacturer and two HDDEs from a second manufacturer. Surveying all data showed the emission factors ranged from 0.1 to 1.8 g/bhp-hr, with NO_x emissions depending strongly on the driving cycle for some vehicles but not for others. The NO_x emission factor was the highest for the near port driving and lowest for the regional driving. The emission factor from the regional driving compared well with the value from the UDDS cycle. For Category 3 HDDTs, the ratio of the emission factor for Regional and Near Dock driving ranged from 100 to 450%.

3.4. *NTE analysis*

Given the wide range of NO_x emission factors for different driving cycles, a question was whether emissions from the HDDEs would comply with the NTE testing program and emission standards. Chassis data were treated the same as data accumulated during an in-use testing program and emission factors were calculated after data outside the NTE zone were excluded. Of all the NTE criteria, the most difficult criterion is for the engine to operate 30 continuous seconds in the NTE zone. Accordingly, Table 3 shows the percentage of data from the chassis dynamometer meeting the NTE criteria for both 30 and 1 s durations. Note that even if only 1 s of operation in the NTE control area is needed, the percentage of data meeting the NTE requirements is still low for near dock operation.

A major finding of this research is the relatively low percentage of data remaining after the NTE rules/filtering are applied for some driving conditions. For example, for Category I vehicles in near dock operation, 0% of the data meet the conditions for having an NTE event, and for the regional driving, only 25%, 7% and 11% meet the conditions for having an NTE event for vehicles 1, 2, and 3, respectively. Thus, NTE emission factors cannot be calculated for near dock/local driving, so there is no way to compare values with the NTE limits. For regional driving, some data met the NTE exclusion process, and emission factors calculated from these data met or were below the in-use compliance values. This is shown in Fig. 3, which shows NOx emissions for individual NTE events for different cycles.

For the Category 3 vehicles, an additional NTE criteria is that the ATS temperature is > 250 °C. The percentage of time for ATS >250 °C is important parameter as the reduction efficiency of the after treatment for NO_x is strongly temperature dependent. The percentages of time meeting the requirement of ATS >250 °C are compared with the percentage of time within the NTE zone for 30 continuous seconds and 1 s in Table 4. The results show that only a small portion of the data meet the NTE criteria on a second by second basis for the Near Dock and Local cycles, with even less data meeting these criteria for the full 30 s duration needed for an NTE event. These cycles also showed lower percentages of time <250 °C compared to the other cycles. For Vehicles 7 and 8, none of the data met the NTE criteria for the near dock and local driving cycles, so no emission factor can be calculated by Method 2. Further analysis of data passing through the NTE rejection process for the regional and other driving cycles is shown in Fig. 4. These data show that most of the data points are either at or below the 0.2 g/bhp-hr level.

3.5. Further analysis of category 3 and ATS temperature

Fig. 5 shows the percentage of time where the ATS temperature >250 °C and the accompanying emissions factor for the portion of the cycles where the ATS temperature >250 °C for the Category III vehicles. As expected, the regional cycle has the highest percentage of time with ATS temperature >250 °C of the goods movement cycles, with the lowest corresponding emission rates, as shown in Fig. 2. This finding was expected as the ATS temperature is the key parameter determining NO_x conversion. Note for Vehicle 8 the NO_x emission factor for the near dock cycle is reduced from 1.8 g/bhp-hr when all NO_x data are included (see Table 2) to 0.77 g/bhp-hr when only data where the ATS temperature >250 °C are included. This value is still nearly four times the FEL value. Another observation is that the percentage of time the ATS temperature is > 250°C for Vehicle 8 is less than either Vehicles 6 or 7, hence, the HDDT emitted more NOx emissions when operating in drayage cycles. As certification cycles differ from off-cycle drayage cycles, this suggests that some element of drayage operation should be included in the certification process to make the emissions closer to the FEL value under all operating cycles.

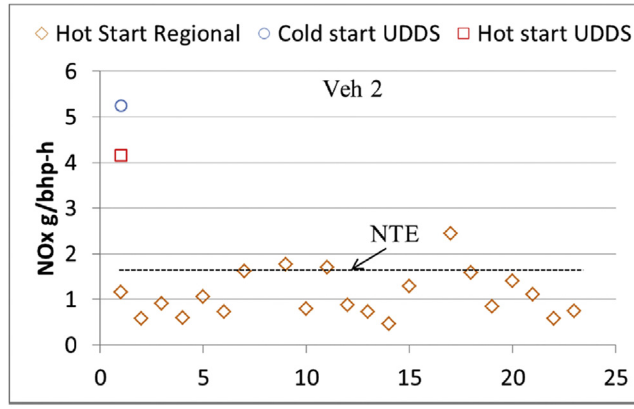

Fig. 3. NO_x emissions for different NTE events vs. the NTE emission standard (Veh 2). This was a 2007-09 engine certified to a FEL of 1.16 g/hp-hr of NOx.

Another perspective of the importance of the driving conditions and ATS temperature is seen in Fig. 6(A) and (B); which shows continuous plots of exhaust temperature, accumulated NOx, and speed with an overlay of accumulated work in bhp-hr for both the regional and near dock driving cycles. Vehicle 8 was selected due to the large differences in NO_x emission factors between the near dock and regional cycles. Different portions of the cycle are separated in the figure, and the brake specific NO_x emission factor is listed above for each segment. In Fig. 6 (A), the near-dock cycle, 25 g of NOx are accumulated in the first 10 brake horsepower-hour (bhp-hr) of engine work, leading to an emission factor of 2.5 g/bhp-hr or ~8 times the FEL/NTE value. In the remainder of the cycle an ATS temperature >250 °C is reached for a portion of the time and the

Table 3
Percentage of data remaining after applying the NTE rules for 30 s and 1 s.

ID	Category	30 Seconds				1 Seconds			
		Near Dock	Local	Regional	UDDS	Near Dock	Local	Regional	UDDS
Veh 1	I	0%	2%	25%	11%	6%	13%	35%	32%
Veh 2	I	0%	0%	7%	0%	4%	8%	27%	24%
Veh 3	I	0%	0%	11%	3%	4%	9%	28%	27%
Veh 4	II	0%	0%	4%	0%	4%	10%	23%	25%
Veh 5	II	0%	0%	17%	2%	3%	8%	31%	25%
Veh 6	III	1%	3%	30%	19%	9%	16%	41%	36%
Veh 7	III	0%	0%	4%	0%	4%	11%	25%	27%
Veh 8	III	0%	0%	14%	2%	3%	8%	32%	24%

[1] The Not-to-Exceed (NTE) official sample duration for exclusion is 30 s. The 1 s duration analysis was to considered percentage of data within the NTE for 1 s duration durations (i.e., any data within the NTE engine zone). Note that the NTE exclusion criteria for vehicles equipped with ATS includes an additional criterion that the ATS temp >250C, as discussed in greater detail below. Engines for vehicles 1 to 3 were 2007–2009 model years certified to FELs from 1.16 to 1.2 g/bhp-hr of NOx. Engines for vehicles 4 and 5 were 2010 and newer model years and certified to an FEL of 0.5 g/bhp-hr of NOx. Engines for vehicles 6 to 8 were 2010 and newer model years certified to FELs from 0.2 to 0.31 g/bhp-hr of NOx.

Table 4
Percentage of data remaining after applying NTE rules.

Cycle	Veh 6			Veh 7			Veh 8		
	ATS>250	30 Sec	1 Sec	ATS>250	30 Sec	1 Sec	ATS>250	30 Sec	1 Sec
Near Dock	16%	1%	9%	29%	0%	4%	8%	0%	3%
Local	32%	3%	16%	49%	0%	11%	17%	0%	8%
Regional	64%	30%	41%	63%	4%	25%	41%	14%	32%
UDDS	78%	19%	36%	71%	0%	27%	52%	2%	24%

These are 2010 and newer engines certified to FELs of 0.31 (vehicle 6) and 0.2 (vehicles 7 & 8) g/hp-hr.

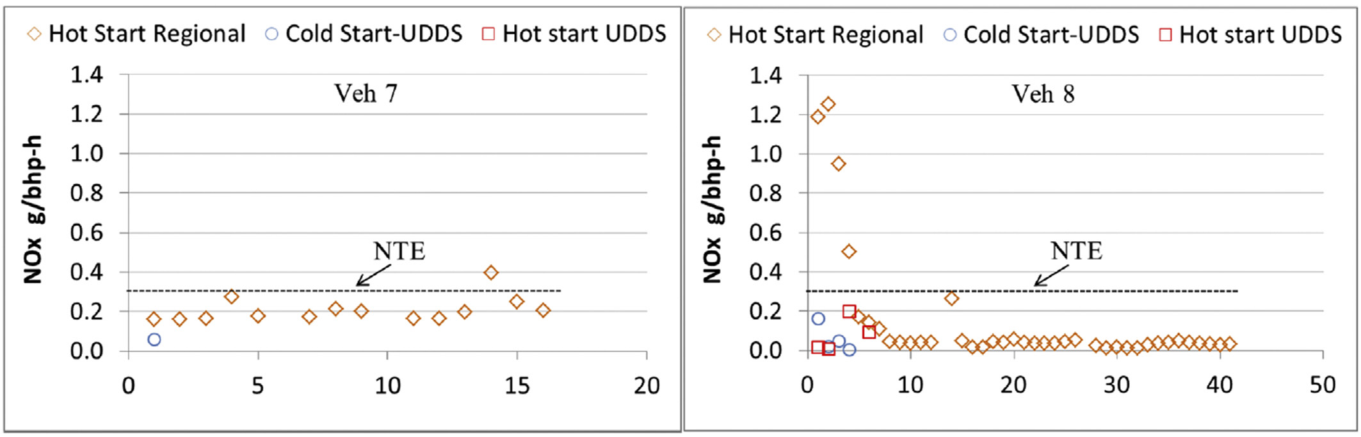

Fig. 4. NOx emissions for different NTE events for Veh 7 and Veh 8.
These were 2010 and newer engines certified to a FEL of 0.2 g/hp-hr of NOx.

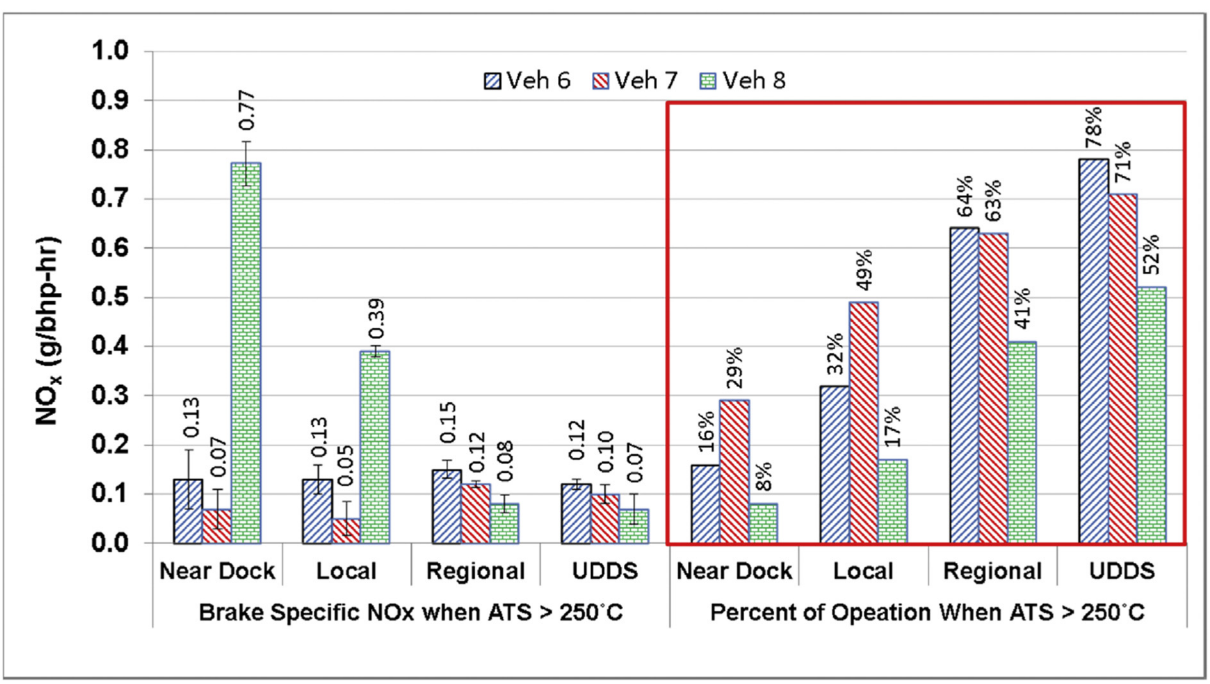

Fig. 5. NO_x emissions for ATS >250 °C (g/bhp-hr) b) percent time for ATS >250 °C.

emission factor is ~1.5 g/bhp-h., still significantly exceeding the FEL/NTE value. Fig. 6 (B), the regional driving cycle, has a significant portion of the time with an ATS temperature >250 °C, where the catalyst efficiency is high. During startup in this case, ~30 g of NO_x were accumulated doing 20 bhp-hr of work, leading to an emission factor of 1.5 g/bhp-hr. Then temperature increases to ~350 °C, where 3 g of NOx are accumulated doing 75 bhp-hr of work, leading to an emissions factor is 0.04 g/bhp-hr, a value well below the FEL. The results show the strong influence of SCR temperature on the NOx emissions and suggest a better thermal management systems is needed to ensure the NOx emissions are near FEL values for all operating cycles.

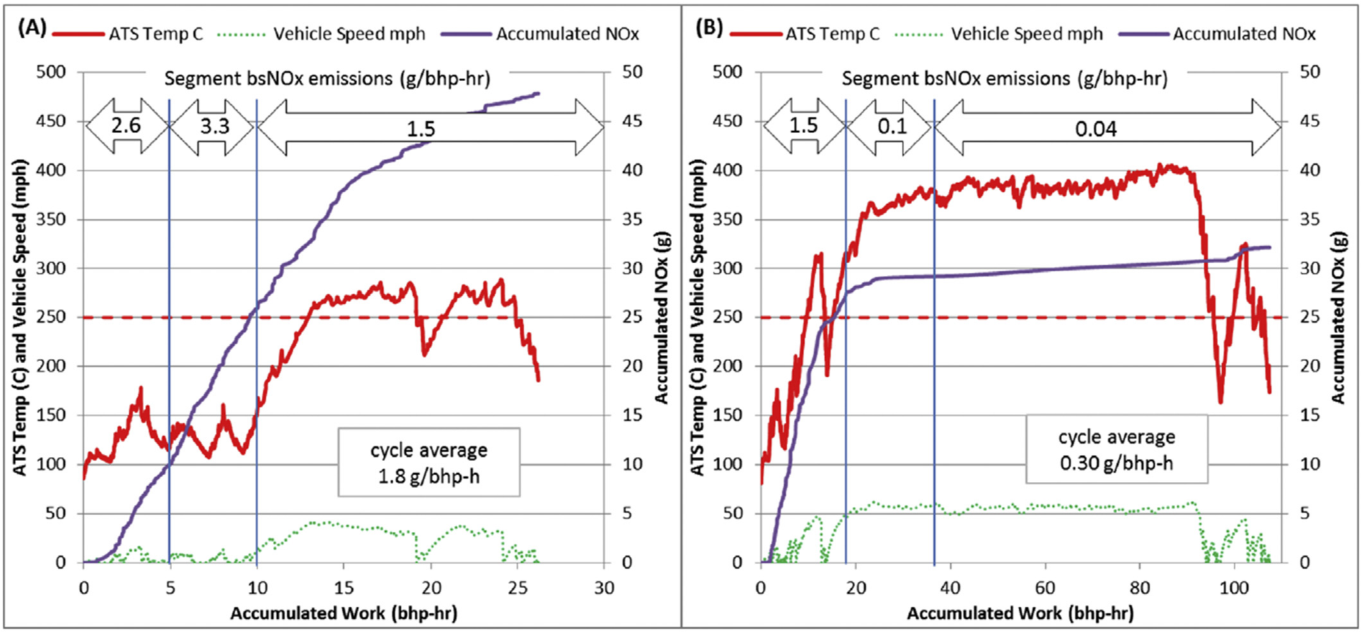

Fig. 6. Real-time accumulated NO_x emissions A) Near Dock, B) Regional Cycles: Veh 8.

3.6. Comparison of chassis and on-road NO_x emission data

Emissions were measured for Vehicle 7 both on-road and on the chassis dynamometer as part of the quality assurance/verification element of the research. The on-road vehicle operation included a startup and some low speed operation, but was predominantly high speed cruise driving, so it was compared with the regional driving on the dyno in Fig. 7B.

The continuous data was separated into segments in Fig. 7 with the brake specific NO_x emission factor listed above each segment. For example, emissions when the truck was driven the first few miles led to an emission factor of 0.7 g/bhp-hr, a level above the 0.3 g/bhp-hr in-use NTE emission limits. However, most of the emissions accumulated during this segment would be excluded from the determination of the in-use NO_x NTE emission factor, as the ATS temperature was <250 °C. After the HDDTs reach cruising speed, the SCR temperature is ~375 °C and the emission factor is 0.07 g/bhp-hr, considerably below the standard. During some minor congestion, in the middle of the test, the NO_x emission factor increased from 0.07 to 0.15 g/bhp-hr, but averaged to 0.1 g/bhp-hr for the segment from 70 bhp-hr to 200 bhp-hr.

The regional test results in Fig. 7B performed on the chassis dynamometer showed a trend similar to the on-road testing. The emission factor was highest during the low speed transient

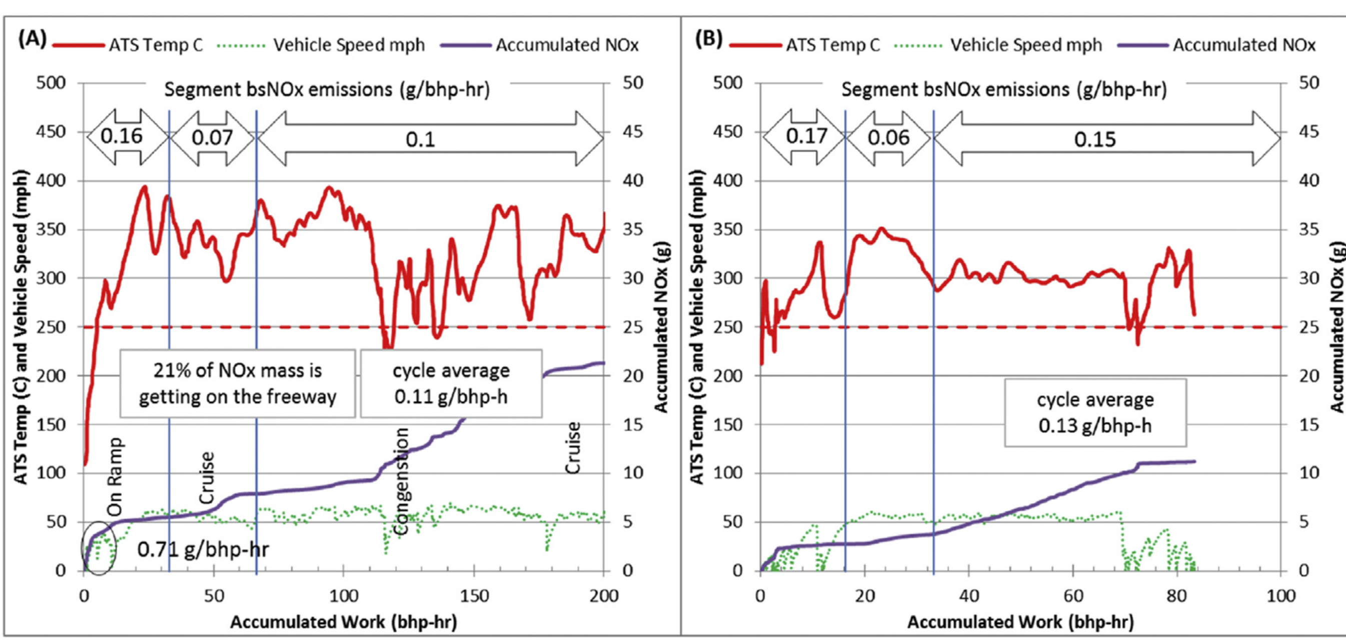

Fig. 7. Accumulated NO_x emissions for A) On-road, B) Regional Cycles: Veh 7.

operation (0.17 g/bhp-hr), and lowest at 0.06 g/bhp-hr during the high temperature portion of the cruise. The stabilized cruise with some slow speed operation averaged 0.15 g/bhp-hr. Overall, the on-road data are consistent with the findings found on the chassis dynamometer, providing some verification of the chassis dynamometer findings.

3.7. Implications for future research

The goal of the research was to investigate whether emission factors for PM and NO_x determined using certification and NTE compliance protocols represent emission factors based driving within a metropolitan area. Results, excluding regenerations, showed that values for PM mass emission factors were lower than certification values for all driving cycles. However, NO_x emission factors depended on driving cycle for some HDDEs, and in some cases exceed certification values. This is a serious problem for non-attainment cities. For example, for some HDDEs equipped with only cooled EGR, the NO_x emissions factor was up to 239% greater when driven short distances from a port/distribution center as compared to regional driving within the metropolitan area. For engines equipped with cooled EGR and SCR, this ratio increased to 450%. Analysis showed emissions associated with real world driving within a metropolitan area are higher than values from the certification cycle, are often referred to as off-certification cycle emissions. Furthermore, the analysis showed that EPA's Not to Exceed (NTE) rules, which were designed to ensure emissions are controlled over the full range of speed and load combinations commonly used, do not represent driving within a metropolitan area nor does the NTE provide regulatory controls in these areas. For example, after applying the NTE exclusion rules to data from short trips within a city, none (0%) of the data remain, so it is not possible to compare a calculated emission factor with the NTE limit. As currently designed, data associated with the highly transient nature of driving within a metropolitan area, so called stop-and-go driving, were not expected to be within the NTE zone (European Commission, 2002; U.S. EPA, 2004).

An important question related to these findings is how to capture the in-use emissions and how to design a compliance test for driving within a metropolitan area. One way to reduce in-use emissions is to design cycles for chassis and engine dynos that better represent emissions from city driving with current control technology. An indirect approach with the existing certification cycle is to lower the certification value. Perhaps the mix of cold and hot starts could be changed in the final certification calculation when SCR controls are used, since the ATS temperature is crucial, or a separate cycle could be incorporated into the certification procedure to specifically characterize low-load operation. Another approach could be to broaden the in-use compliance testing requirements beyond the current NTE procedures to incorporate a wider envelope of vehicle operation, especially at low load conditions. This could include time windows for compliance based on moving averages, or the total work over fuel consumption over different periods of time. To the extent that more low load operation is included in in-use compliance testing, conformity factors specific to low load operation would also need to be developed.

Another important issue is whether people living near a port or distribution center are disadvantaged by the higher emissions. Looking at PM and NO_x separately, the results showed PM levels, excluding regenerations, were below the standard and independent of the drive cycles, so there is no disproportionate local impact for PM, a toxic air contaminant, on a per vehicle basis. There may be a higher local PM impact from regenerations, idling, higher truck densities, and deterioration and mal-maintenance, but these factors were not examined in this study. For NO_x there were higher levels associated with operation near ports/distribution centers. However, NO_x emissions from HDDTs are mainly NO, a precursor to regional ozone formation, so there is not a disproportionate effect on a neighborhood. Recent regulations address the local measurement of NO_2 as that would have local impact. In any case, this research points to the need for more real world measurements, especially as new NO_x control technology is introduced and as the PM and NO_x control technology ages over time.

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