Characterizing Emission Rates of Regulated Pollutants from Model Year 2012+ Heavy-Duty Diesel Vehicles Equipped with DPF and SCR Systems

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ABSTRACT

The regulated emissions of five 2012 and newer, low-mileage, heavy-duty Class 8 diesel trucks equipped with diesel particulate filters (DPFs) and selective catalytic reduction (SCR) systems were evaluated over test cycles representing urban, highway, and stop-and-go driving on a chassis dynamometer. NOx emissions over the Urban Dynamometer Driving Schedule (UDDS) ranged from 0.495 to 1.363 g/mi (0.136 to 0.387 g/bhp-hr) for four of the normal emitting trucks. For those trucks, NOx emissions were lowest over the cruise (0.068 to 0.471 g/mi) and high-speed cruise (0.067 to 0.249 g/mi) cycles, and highest for the creep cycle (2.131 to 9.468 g/mi). A fifth truck showed an anomaly in that it had never regenerated throughout its relatively short operating lifetime due to its unusual, unladed service history. This truck exhibited NOx emissions of 3.519 g/mi initially over the UDDS, with UDDS NOx emissions decreasing to 0.39 g/mi after a series of parked regenerations. PM, THC, and CO emissions were found to be very low for most of the testing conditions, due to the presence of the DPF/ SCR aftertreatment system, and were comparable to background levels in some cases.

KEYWORDS

NO_X emissions; Emission inventories; Heavy-Duty Diesel Vehicles; Selective catalytic reduction

1. Introduction

Heavy-duty diesel trucks (HDDTs) are a significant source of oxides of nitrogen (NOx) and particulate matter (PM) emissions in urban areas. In order to reduce emissions of NOx and PM from HDDTs, a series of regulations for heavy heavy-duty diesel engines (HDDE) were implemented starting in 1974, and were last made more stringent in 2007 and 2010. Those rules have required that emissions of NOx and PM be reduced from an estimated unregulated emission level of 16 g/bhp-hr to 0.20 g/bhp-hr, and from 1.0 g/bhp-hr to 0.01 g/bhp-hr, respectively. Current-technology diesel engines are now equipped with diesel particulate filters (DPFs) to meet the PM standards for 2007 and newer engines, and selective catalytic reduction (SCR) systems to meet the NOx standards for 2010 and newer engines.

While there are extensive data on the effectiveness of DPF and SCR systems over certification test cycles run on an engine-dynamometer, data on in-use emissions from modern diesel engines are scarce and show some variation depending on the type of truck tested and the testing conditions (Miller et al., 2013; Carder et al., 2014; Misra et al., 2015; California Air Resources Board 2015a, b; Quiros et al., 2017). The need for in-use emissions data is particularly important because HDD engines are certified to meet emission standards before the engines are integrated into a vehicle chassis for commercial use, which can span a broad range of applications. The Coordinating Research Council’s (CRC) E-55/59 program was the first chassis dynamometer study to acquire in-use emissions data from a vast number of HDDTs and evaluate the impacts of different cycles on in-use emissions (Clark et al., 2004, 2006, 2007). A study conducted under funding by the South Coast Air Quality Management District (SCAQMD) collected chassis dynamometer emissions test data from twenty-four 2007-2012 model year (MY) heavy-duty HDDTs (Miller et al., 2013; Carder et al., 2014). The California Air Resources Board (ARB) also has initiated a pilot truck and bus surveillance program that includes chassis dynamometer testing from randomly selected trucks representing a range of manufacturers and mileages (Quiros et al., 2017). Some on-road studies using portable emissions measurement systems (PEMS) also have been conducted on 2007 and newer trucks equipped with DPF and/or SCR systems (Carder et al., 2014; Lee, et al., 2017; Tu et al., 2016; Misra et al., 2013, 2016).

The ARB has been utilizing in-use emissions testing results in the development of emission factors for its EMFAC model for a number of years (California Air Resources Board, 2015a, 2015b). Those emission factors are developed from “zero-mile” emission rates (ZMRs) that can be adjusted to account for engine deterioration with age and for variations in vehicle speed. For the EMFAC2007 and EMFAC2011 model, in-use emissions data were primarily obtained from the CRC E-55/59 study (Clark et al., 2006, 2007), which was limited to 2003 and older vehicles, coupled with estimates for 2007 and newer model year vehicles.

For the EMFAC2014 model, a greater emphasis was placed on developing emission factors for vehicles equipped with newer PM and NOx aftertreatment control devices, and incorporating in-use emissions data from 2007 and newer engines/vehicles. Those data were derived from studies conducted by the ARB (2015a, 2015b) and testing associated with the SCAQMD study (Miller et al., 2013; Carder et al., 2014). Those studies included some chassis dynamometer testing and some over-the-road testing with a PEMS. While this represented an important step in better quantifying emissions from 2007-2009 and 2010 and later model year vehicles, the data were still relatively scarce to serve as the basis for making important emissions inventory projections out to 2020 and beyond. In particular, for the 2010 and later model year technology engines, only 5 vehicle/engines were included in the ARB/SCAQMD studies, with all the engines being in the 2010-2011 model year range, which only covers the earliest implementation years for advanced NOx control strategies. More importantly, of those 5 engines, only 2 were certified to the 0.20 g/bhp-hr NOx standard, and both of those engines were from the same manufacturer. Additionally, 2 of the 5 engines utilized only exhaust gas recirculation (EGR) for NOx control, an approach that had a very limited production run.

The goal of this study is to provide additional information regarding emission rates of modern heavy-duty diesel vehicles equipped with the newest emission control strategies for reducing NOx. Testing was conducted on 5 HDDTs with model year 2012 to 2015 engines equipped with DPF and

SCR systems. The vehicle matrix included 5 engines from heavy-duty engine manufacturers representing the majority of trucks operating in California, with two engines being from the same manufacturer. The engines/vehicles were certified to a 0.20 g/bhr-hp NOx emission limit, with the exception of one credit-using engine that was certified to a 0.35 g/bhr-hp NOx standard. Each vehicle was tested on the University of California at Riverside's (UCR's) heavy-duty chassis dynamometer over the four phases of ARB's Heavy Heavy-Duty Diesel Truck (HHDDT) cycle (i.e., idle, creep, transient, and cruise), the HHDDT-short or HHDDT-S cycle (which is a high-speed cruise cycle), and the Urban Dynamometer Driving Schedule (UDDS) (which is a cycle considered to be the chassis dynamometer equivalent of the engine dynamometer transient test). The results obtained from this study can augment the data being used in the development of future emissions inventory model that are relied on throughout the regulatory process by the ARB and other governmental agencies.

2. Materials and Methods

2.1 Test Vehicles and Fuels

Five heavy-duty Class 8 diesel vehicles were tested in this program and selected from four heavy-duty engine manufacturers representing the majority of trucks operating in California. All of the vehicles had model year 2012 and newer engines with the mileages less than 30,000 miles. They were equipped with the latest generation of emissions control technology, including a DPF and a SCR system. The engines were certified to a 0.20 g/bhr-hp NOx emission limit, with the exception of one engine that was certified to a 0.35 g/bhr-hp NOx standard. The test fuel was the California No. 2 diesel. A description of the vehicles/engines is provided in Table 1.

Table 1 Engine/Vehicle specifications

Manufacturer	A1	A2	B	C	D
Model Year	2014	2015	2014	2014	2012
Displacement	14.9 L	14.9 L	12.8 L	12.4 L	12.8 L
Horsepower	400 HP	550 HP	450 HP	450 HP	415 HP
Vehicle Mileage	28611	2924	15914	7686	12640
Aftertreatment	DOC/DPF/SCR				
Standard/FEL Level (g/bhp-hr)	NOx:0.35 PM:0.01	NOx:0.20 PM:0.01	NOx:0.20 PM:0.01	NOx:0.20 PM:0.01	NOx:0.20 PM:0.01
Certification Level (g/bhp-hr)	NOx:0.22 PM:0.001	NOx:0.18 PM:0.000	NOx:0.17 PM:0.004	NOx:0.12 PM:0.003	NOx:0.12 PM:0.003

2.2 Test Cycles

There were six different driving cycles in this program, including four phases of ARB's HHDDT cycle (i.e., idle, creep, transient, and cruise) (Gautam et al., 2002), the HHDDT-S cycle (Clark et al., 2004), and the UDDS (U.S. Environmental Protection Agency, 2005). The characteristics of each test cycle are provided in Table 2. The preconditioning for the cycles was designed to be consistent with the procedures utilized in the earlier testing program the ARB (2015b) conducted to update its emission factors for EMFAC2014. Different numbers of replicates of each driving cycle were utilized in order to ensure that a sufficient mass of PM was collected for weighing. Duplicate tests were conducted for each driving cycle on each vehicle.

Table 2 Description of test cycles

Schedule	Time (s)	Avg Speed (mph)	Distance (mi)	Number of Iterations	Description
UDDS	1060	18.86	5.55	3	FTP surrogate
HHDDT Idle	900	0	0	3	Idle of vehicle
HHDDT Creep	256	1.7	0.124	10	Stop and go modes
HHDDT Transient	688	14.9	2.9	4	Local street driving
HHDDT Cruise	2083	39.9	23.1	1	Freeway driving
HHDDT-Short	760	49.9	10.5	2	High speed driving

2.3 Emission Measurements

The vehicles were tested on the chassis dynamometer with the inertial weight of 65,000 lbs. The emissions measurements were made using UCR's Mobile Emissions Laboratory (MEL). A detail description of MEL were provided by Cocker et al. (2004a, 2004b). For all tests, standard emissions measurements included total hydrocarbons (THC), non-methane hydrocarbons (NMHC), methane (CH_4), carbon monoxide (CO), NO_x, carbon dioxide (CO_2), and PM. Fuel consumption was derived from the CO_2, CO, and THC emissions by the carbon balance method, using typical densities and carbon weight fractions for California ULSD.

The mass concentrations of PM were obtained by analysis of particulates collected through an impactor with a 50% cutoff particle diameter of 2.5 µm on 47 mm diameter 2 µm pore Teflon filters (Whatman brand). The filters were measured for net gains using a UMX2 ultra precision microbalance with buoyancy correction in accordance with the weighing procedure guidelines set forth in the Code of Federal Regulations (CFR). Sampling for PM was done cumulatively over the entire duration of the cycles due to the very low mass levels expected for PM.

Engine brake power was calculated using engine control module (ECM) broadcast J1939 standardized information, including the engine speed in revolutions per minute (rpm), ECM broadcast actual torque in (%) estimated using engine speed and instantaneous fuel flow, ECM broadcast friction torque in (%), and ECM broadcast reference torque in (ft-lb). Those signals are the same signals used for in-use compliance testing according to the test procedures in 40 CFR Part 1065.

3. Results and Discussion

The emission test results are presented in this section. Table 3 shows the emission rates of regulated pollutants on a g/mi basis for each vehicle

/cycle combination based on the average of tests conducted on that particular test combination. Emissions on a g/bhp-hr basis are discussed at various points in the text of this section, and are shown in graphs in the supplementary material.

3.1 NOx Emissions

3.1.1 NOx emission rates

NOx emissions for the test trucks are shown on a mass emitted per distance-traveled (grams/mile or g/mi) units in Table 3. NOx emissions varied depending on the test cycle and the test truck. The manufacturer D truck was an outlier with noticeably higher NOx emissions relative to the other vehicles. Therefore, this truck is discussed separately from other trucks. For the manufacturer A1, manufacturer A2, manufacturer B and manufacturer C engine-powered trucks, NOx emissions ranged from 0.495 to 1.363 g/mi [0.308 to 0.847 g/km] over the UDDS (the cycle most relevant to ZMRs), from 2.131 to 9.468 g/mi [1.323 to 5.883 g/km] over the Creep cycle, from 0.803 to 3.252 g/mi [0.499 to 2.020 g/km] over the Transient cycle, from 0.068 to 0.471 g/mi [0.042 to 0.293 g/km] over the Cruise cycle, and from 0.067 to 0.249 g/mi [0.042 to 0.155 g/km] over the HHDDT-S. The lowest NOx emissions were recorded over the Cruise and HHDDT-S cycles, which produced the highest speeds, loads, and exhaust temperatures. Under those conditions, SCR catalysts are expected to operate at temperatures (>250 °C) where NOx conversion efficiencies are robust, leading to relatively low tailpipe NOx emission (Misra et al., 2013), even though engine-out NOx levels are likely highest. Higher emissions were observed over the other cycles, which include more transient and lower average speed operation, with different vehicles showing higher or lower emissions depending on the vehicle and cycle. The Creep cycle showed the highest NOx emissions since it is comprised of short, low-speed accelerations between periods of idle that yield lower loads and exhaust temperatures (134~179 °C), and that cover a very short distance. It also should be noted that while the NOx emissions on a per mile or per unit of work basis are considerable higher for the Creep, the differences between the Creep and other cycles is less significant in terms of absolute NOx emissions.

The manufacturer D vehicle had poor NOx conversion efficiencies relative to the other vehicles. Upon further investigation, it was found that this specific vehicle had served its entire life as a dealer demonstrator, and as such rarely or ever operated with a loaded trailer, and spent a considerable amount of time operating in an idle mode. This type of low-temperature, high proportion idle operation is known to cause significant exposure of the aftertreatment system to unburned hydrocarbons in the exhaust stream. An examination of the logged electronic history revealed no OBD faults or other indications of failure or system malfunction. A clear anomaly, however, was that due to its unusual, unladed service history and duty cycle, the engine had never undergone a regeneration event, despite having been in service for approximately 2.5 years (albeit with only 12,000 miles on the odometer). A series of conventional parked regenerations were performed. After further operation, there was a significant recovery of the aftertreatment NOx-conversion efficiency, as revealed through PEMS measurements. The regeneration intervention was believed to have been fully effective in driving off the accumulated unburned hydrocarbons that were hindering catalytic reaction. Additional chassis dynamometer testing of the manufacturer D vehicle was conducted at the West Virginia University (WVU) Center for Alternative Fuels Engines and Emissions (CAFEE) Laboratory, replicating the testing that had been performed at UCR, with the exception of a 70,000 lbs. [as opposed to UCR’s 65,000 lbs. test weight]. The results of that testing indicated a NOx emission rate of 0.39 g/mi over the UDDS cycle, near the lower end of the NOx emission rates found in the current study. This example suggests that longtime non-regeneration could lead to poor SCR catalyst performance and high NOx emission rates.

Table 3 Emission rates of regulated pollutants on a distance-specific unit and fuel economy

Engine	Trace	NOx	CO_2	THC	CO	PM	Fuel Economy	Conversion Factor
		g/mi					mi/gallon (mpg)	g/mi→g/bhp-hr
A1	UDDS	0.99 ± 0.38	1865 ± 51	0.017 ± 0.022	0.162 ± 0.069	0.006 ± 0.004	5.41 ± 0.14	3.40
	Creep	5.28 ± 4.16	4148 ± 330	0.391 ± 0.214	0.467 ± 0.287	0.004 ± 0.001	2.44 ± 0.19	
	Trans	1.82 ± 0.42	2260 ± 38	0.010 ± 0.038	0.088 ± 0.060	0.005 ± 0.003	4.46 ± 0.08	
	Cruise	0.07 ± 0.04	1160 ± 10	0.006 ± 0.006	0.024 ± 0.033	0.012 ± 0.001	8.69 ± 0.07	
	HHDDT-S	0.07 ± 0.04	1450 ± 12	0.003 ± 0.005	0.120 ± 0.056	0.010 ± 0.000	6.95 ± 0.06	
A2	UDDS	1.36 ± 0.30	2063 ± 176	0.000 ± 0.029	0.002 ± 0.000	0.002 ± 0.001	4.91 ± 0.37	3.52
	Creep	6.02 ± 4.29	3351 ± 1492	0.263 ± 0.155	0.003 ± 0.001	0.016 ± 0.022	2.11 ± 0.07	
	Trans	3.25 ± 1.66	2580 ± 101	-0.002 ± 0.030	0.003 ± 0.001	0.001 ± 0.002	3.91 ± 0.15	
	Cruise	0.12 ± 0.01	1327 ± 51	-0.007 ± 0.012	0.002 ± 0.001	0.002 ± 0.000	7.60 ± 0.29	
	HHDDT-S	0.08 ± 0.05	1707 ± 22	-0.005 ± 0.007	0.002 ± 0.000	0.007 ± 0.005	5.91 ± 0.08	
B	UDDS	0.50 ± 0.22	2006 ± 58	0.026 ± 0.011	0.174 ± 0.028	0.003 ± 0.001	5.03 ± 0.14	3.63
	Creep	9.47 ± 6.48	3707 ± 288	0.239 ± 0.071	0.864 ± 0.579	0.006 ± 0.003	2.73 ± 0.19	
	Trans	0.80 ± 0.21	2436 ± 118	0.019 ± 0.007	0.105 ± 0.051	0.002 ± 0.000	4.15 ± 0.19	

	Cruise	0.17 ± 0.05	1264 ± 6	0.007 ± 0.004	0.101 ± 0.002	0.002 ± 0.000	7.97 ± 0.04	
	HHDDT-S	0.25 ± 0.15	1587 ± 14	0.003 ± 0.001	0.090 ± 0.025	0.002 ± 0.000	6.35 ± 0.06	
C	UDDS	0.81 ± 0.30	2128 ± 42	0.034 ± 0.004	0.079 ± 0.050	0.004 ± 0.002	4.74 ± 0.09	3.14
	Creep	2.13 ± 0.88	5095 ± 346	0.375 ± 0.105	2.447 ± 2.536	0.005 ± 0.002	1.99 ± 0.14	
	Trans	1.31 ± 0.44	2607 ± 151	0.024 ± 0.008	0.143 ± 0.056	0.012 ± 0.004	3.88 ± 0.21	
	Cruise	0.47 ± 0.03	1232 ± 2	0.003 ± 0.000	0.058 ± 0.033	0.010 ± 0.002	8.18 ± 0.01	
	HHDDT-S	0.22 ± 0.15	1646 ± 29	-0.003 ± 0.007	0.069 ± 0.032	0.033 ± 0.006	6.13 ± 0.11	
D	UDDS	3.52 ± 0.76	2219 ± 144	0.026 ± 0.014	0.178 ± 0.083	0.001 ± 0.000	4.56 ± 0.27	3.64
	Creep	22.50 ± 9.53	4850 ± 185	0.457 ± 0.210	5.042 ± 4.039	0.003 ± 0.002	2.08 ± 0.08	
	Trans	6.27 ± 2.02	2625 ± 47	0.014 ± 0.023	0.246 ± 0.228	0.002 ± 0.001	3.84 ± 0.07	
	Cruise	0.66 ± 0.22	1443 ± 1	0.009 ± 0.006	0.057 ± 0.005	0.003 ± 0.001	6.98 ± 0.00	
	HHDDT-S	0.75 ± 0.14	1744 ± 9	0.006 ± 0.003	0.059 ± 0.003	0.003 ± 0.000	5.78 ± 0.03	

The results of this study can also be compared to the emission factors being used in the EMFAC2014 model. For engines certified to the 0.20 g/bhp-hr NOx level, EMFAC2014 utilizes a ZMR of 1.89 g/mi. This ZMR is adjusted by a fuel correction factor of 0.93 to account for the clean CARB diesel fuel used in California, such that a ZMR of 1.76 g/mi was used for the comparisons in this study for the 0.20 g/bhp-hr NOx engines. The two vehicles used to develop those estimates are shown by the two bars on the right hand side of Fig. 1. The results of this study, utilizing the post-DPF regeneration data for the manufacturer D1 (the four bars on the left side of Fig. 1), can be readily compared with the data for the 0.20 g/bhp-hr engines that were used in developing the EMFAC2014 ZMR. The results of additional tests that were conducted on a subset of vehicles in the present study by the ARB at their heavy-duty chassis dynamometer facility in Los Angeles are also included in Fig. 1 (the two middle bars). Significantly, average UDDS value for the current study for the 0.20 g/bhp-hr NOx trucks are 0.77 g/mi utilizing the post-regeneration results for the manufacturer D1 truck.

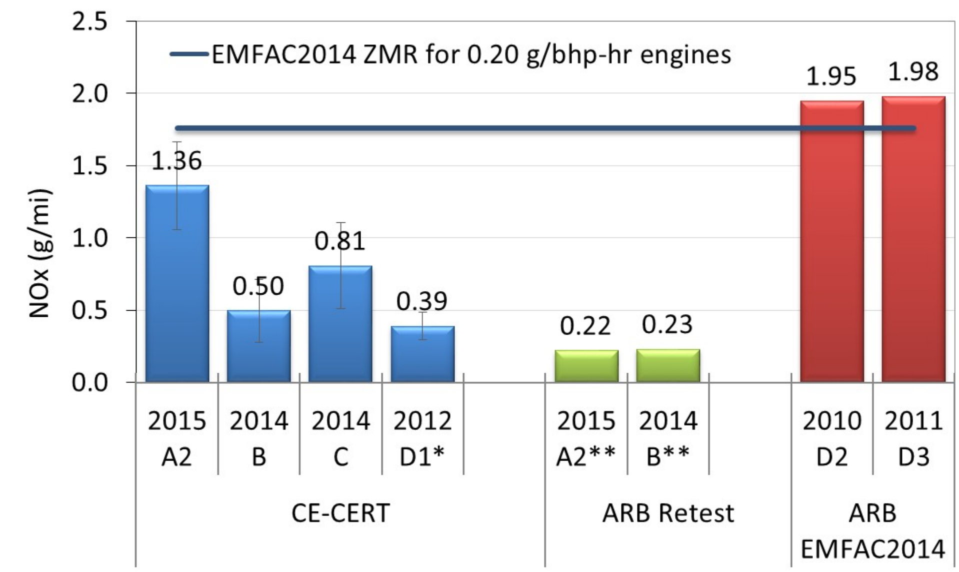

Fig. 1. Comparisons of NOx emission rates over the UDDS from this study, ARB retesting of some of the vehicles from this study, and the ARB study that was used to develop EMFAC2014 emission factors for SCR-equipped 2010+ vehicles; D1* represents the UDDS emission level found after retesting the manufacturer D1 truck after a regeneration; A2** and B** represents results from ARB retest.

The results of this study also can be compared to results from previous and on-going studies. Other studies have shown vehicles with emission rates similar to those seen in the current study. UCR measured UDDS NOx emission rates for trucks equipped a manufacturer A 8.3 liter engine, a manufacturer A 11.9 liter engine, and a manufacturer D 12.8 liter engine, which were found to be 1.07, 0.25, and 1.27 g/mi, respectively (Miller et al., 2013). In a related study, WVU found slightly higher UDDS NOx emissions of 1.98 g/mi for the same manufacturer D vehicle (D4) (Carder et al., 2015), which were more comparable with the manufacturer D vehicle results from ARB EMFAC2014 study (California Air Resources Board, 2015a, 2015b). More recent information from a Truck and Bus Surveillance study being conducted by the ARB also found some of the vehicles with emission rates comparable to the 0.2 g/bhp-hr standard over the UDDS (ARB, 2017; Quiros et al., 2017), while others were not, as discussed below.

Other information has indicated that some heavy-duty vehicles have higher emission rates. Those studies have included higher mileage vehicles or vehicles with emission levels high enough to suggest either major issues with their SCR systems or largely dysfunctional SCR systems, as the NOx emissions are near what might be expected for engine out levels.” In the ARB Truck and Bus Surveillance study, a range of heavy-duty vehicles from 8 different engine families with model years ranging from 2010 to 2014 and mileages from 59,000 to 594,000 miles were tested (Quiros et al., 2017). Although some of the vehicles from the Quiros et al. study had emission rates comparable to the 0.2 g/bhp-hr standard, as discussed above, a number of vehicles had emission rates ranging from 1 to over 2 g/bhp-hr, considerably higher than those found in the present study. Thiruvengadam et al. (2015) also found emission rates of 6.11 and 9.39 g/mi over the UDDS for two 2010 SCR-equipped trucks.

Clearly, there is a significant range between the emission values of lower mileage or otherwise properly functioning heavy-duty vehicles, as tested in our study, and the higher emission rates from certain other studies that indicate significant SCR issues. The vehicles from this study, by design, represent low mileage vehicles that are well maintained and checked for any evidence of tampering, which may best represent the true emission rates for vehicles with mileages near zero. The ZMRs for heavy-duty vehicles for EMFAC incorporate a much wider range of vehicles with higher mileages, potentially different levels of deterioration, and SCR systems with functionality issues, and hence tend to be higher than the values found in the current study. The most recent ARB estimates that have incorporated data from additional heavy-duty vehicles, including those from this study and other studies discussed above have suggested a ZMR of 2.40 g/mi for a baseline pre-CARB diesel fuel and 2.23 g/mi for a CARB diesel fuel for the 0.20 g/bhp-hr NOx engines (ARB, 2017). Overall, understanding the relative populations of heavy-duty vehicles in different states of operating condition will be important in continuing to improve emission inventories going forward.

3.1.2 SCR temperature

For SCR-equipped vehicles, NOx emissions are typically strongly correlated to the SCR temperature. Specifically, a minimum exhaust temperature is needed to promote hydrolysis of urea into ammonia (NH_3), which then reduces NOx into nitrogen (N_2) and water (H_2O) (Majewski, 2006), with the SCR being most effective at temperatures above 250°C (ARB, 2015b). The average SCR inlet temperature for all vehicles in this study is provided in Fig. 2. Note that the emissions for the Creep cycle are divided by 5 to allow the emissions over all 5 cycles to be more clearly presented on the same graph. The results show that the average SCR inlet temperature is at or above 250°C for the Cruise and HHDDT-S cycles for all of the vehicles. The SCR inlet temperature sensor for the manufacturer A2 vehicle was not working when the Cruise cycle was run. Note that although the SCR inlet temperature was not available for the manufacturer A2 engine, the SCR outlet temperature for that engine over the HHDDT-S cycle was above 250°C, indicating that the average SCR inlet would be above 250°C, as the inlet temperature was higher than the outlet temperature for all test combinations. NOx emissions were lowest in most cases for the Cruise and HHDDT-S cycles, consistent with the effective conversion rate of NOx when the SCR has reached its effective operational temperature, with the increased NOx reduction efficiency more than making up for the increased NOx engine out emissions at high speed, high load operation. For the UDDS and Transient cycles, the average SCR inlet temperature was in the range of 213 to 261°C. This suggests that the SCR is at or above its operational temperature for only part of those cycles, which is consistent with the higher average NOx emissions observed over the UDDS and Transient cycles compared to the two Cruise mode cycles. The lowest temperature was found over the Creep cycle, where the average SCR inlet temperature ranged from approximately 124 to 174°C. At those lower temperatures, the SCR would not be reducing NOx emissions as effectivity and the denominators in term of g/mi would be very low, so that is the cycle where the highest g/mi NOx emissions were observed.

The average measured NOx emissions are also shown in Fig. 2 to provide an additional comparison between NOx emissions and SCR inlet temperature. Overall, the results do not show significant trends in SCR inlet temperature vs. NOx emissions beyond the general trends observed between the cycles discussed above. There are some slight differences in NOx emissions that could be attributed to differences in SCR inlet temperature. For the UDDS, the manufacturer B truck had the lowest NOx emissions and the highest average SCR inlet temperature, while the manufacturer A2 vehicle had the lowest average SCR inlet temperature and highest NOx emissions of the trucks, other than the outlier manufacturer D truck. The manufacturer C truck had the highest SCR inlet temperature and corresponding lower NOx emissions over the Creep cycle. On the other hand, the manufacturer D truck engine did not have appreciably lower SCR inlet temperatures, suggesting that inlet temperature was not the primary factor in its higher NOx emissions (which were determined to be related to an absence of any regeneration event). Overall, although SCR temperature helps explain the difference in NOx emissions between cycles, the results suggest that other factors beyond just SCR temperature are likely responsible for the differences in the trends in NOx emissions for the different vehicles over the same test type. Additional comparisons between the real-time NOx emissions and the SCR temperatures are provided in the supplementary material for each vehicle over the UDDS.

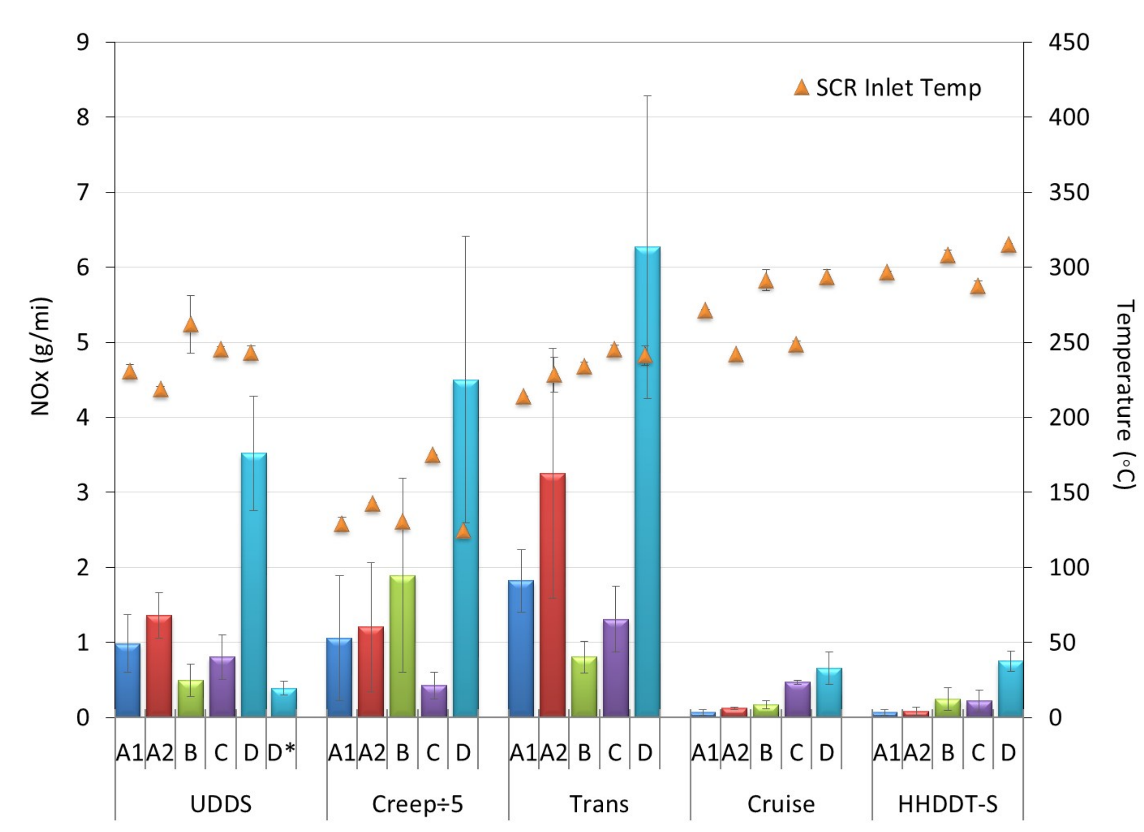

Fig. 2 Average SCR inlet temperature

3.2 Other Regulated Pollutants

The emission rates of THC, CO and PM are shown on a distance-specific basis in Table 3. Overall, the values of those regulated pollutants were very low for most of the test cycles, due to the presence of the DOC/DPF/SCR aftertreatment system, and are comparable to background levels in some cases. Separate discussions of those pollutants are provided below.

3.2.1 PM mass

PM mass emissions were very low for most of the test cycles. PM emissions were below 0.015 g/mi [0.009 g/km] for all vehicles over all cycles, except for the manufacturer C truck over the HHDDT-S cycle and the manufacturer A2 truck over the Creep cycle. The PM levels are significantly below the 0.01 g/bhp-hr [0.013 g/kW-hr] PM standard under all test conditions, except the manufacturer C truck over the HHDDT-S cycle. The HHDDT-S PM data for manufacturer C were examined and it does not appear that any regenerations occurred during these outlier tests. It should also be noted that even these PM levels were comparable to the 0.01 g/bhp level, and were below the NTE limits, which are 1.5 x standard.

3.2.2 THC emissions

As expected, THC emissions were very low for most of the test cycles, due to the presence of the DOC/DPF/SCR aftertreatment system, and are comparable to background levels in some cases, as indicated by the negative values for some tests. THC emissions were below 0.034 g/mi [0.021 g/km] for all test vehicles over the UDDS, Transient, Cruise, and HHDDT-S cycles, and were below 0.458 [0.285 g/km] g/mi for all vehicles over all test cycles. The Creep cycle did show considerably higher THC emissions on a per-mile basis, ranging from 0.241 to 0.458 g/mi [0.150 to 0.285 g/km] due its short, low-speed accelerations and longer idle periods.

3.2.3 CO emissions

CO emissions were very low for most of the test cycles. CO emissions were below 0.2 g/mi [0.12 g/km] for all vehicles over all cycles, except over the Creep cycle and the manufacturer D truck over the Transient cycle. Emissions over the Creep cycle ranged from 0.004 to 5.042 g/mi [0.02 to 3.133 g/km] and from 0.001 to 1.011 g/bhp-hr [0.001 to 1.356 g/kW-hr]. Overall, the CO emission rates were considerably below the 15.5 g/bhp-hr [20.8 g/kW-hr] and 14.0 g/bhp-hr [18.8 g/kW-hr] standards established by EPA and ARB, respectively, for all vehicles and cycles.

3.3 CO_2 Emissions and Fuel Economy

3.3.1 CO_2 emissions

CO_2 emissions for the five test trucks are shown in units of g/mi in Table 3. CO_2 emissions over the UDDS cycle ranged from 1864 to 2219 g/mi [1159 to 1379 g/km]. CO_2 emissions over the Transient cycle were similar to those over the UDDS, ranging from 2260 to 2624 g/mi [1404 to 1631 g/km]. CO_2 emissions over the Cruise and HHDDT-S cycles were slightly lower on a g/mi basis. CO_2 emissions ranged from 1160 to 1443 g/mi [721 to 897 g/km] and 1450 to 1743 g/mi [901 to 1084 g/km] for the Cruise cycle and the HHDDT-S cycle, respectively. CO_2 emissions were highest over the Creep cycle, where loads were lowest, ranging from 3351 to 5095 g/mi [2082 to 3166 g/km].

The ranges of CO_2 emissions observed in the current study are comparable to ranges found in other studies in the literature. In comparison, CO_2 emissions as measured in the earlier ARB study ranged from 1831 to 2964 g/mi over the UDDS, from 2034 to 2432 g/mi over the Transient cycle, from 1014 to 1558 g/mi over the Cruise cycle, from 1310 to 1898 g/mi for the High Speed Cruise cycle, and from 3805 to 5006 g/mi over the Creep cycle (ARB, 2015a, 2015b). For the previous UCR-SCAQMD study (Miller et al., 2013), CO_2 emissions for the Class 8 diesel trucks ranged from 2379 to 3117 g/mi over the hot UDDS cycle. For the previous WVU-SCAQMD study (Carder et al., 2014), CO_2 emissions for 2009 model year and newer Class 8 goods-movement diesel trucks ranged from 2115 to 2757 g/mi over the UDDS cycle. Note that some of the differences between those various studies could be due to differences in test weight loading, as the ARB study used a weight of 56,000 lbs., the SCAQMD study used a test weight of 69,500 lbs, and the present study used 65,000 lbs. It should also be noted that the range in CO_2 emissions for trucks tested over the same cycle in those two earlier studies is similar to that found in the current study.

3.3.2 Fuel Economy

Fuel economy for the five test trucks is shown in Table 3. Fuel economy was similar over the UDDS and Transient cycles. Fuel economy over the UDDS ranged from 4.56 to 5.41 mi/gal [1.94 to 2.30 km/l], while fuel economy over the Transient ranged from 3.84 to 4.46 mi/gal [1.63 to 1.90 km/l]. Fuel economy over the Cruise and HHDDT-S cycles was slightly better, ranging from 6.98 to 8.69 mi/gal [2.97 to 3.69 km/l] for the Cruise cycle, and from 5.78 to 6.95 mi/gal [2.46 to 2.96 km/l] for the HHDDT-S cycle. The lowest fuel economy was found over the Creep cycle, and ranged from 1.98 to 2.73 mi/gal [0.84 to 1.16 km/l], due to the slow speeds and stop-and-go nature of the cycle. Again, it should be noted that some of the differences in fuel economy between different vehicles for the same cycle at the same test weight could be more a function of the differences in the dynamometer loading between trucks due to different frontal areas, as opposed to differences in engine technologies/manufacturers. A more detailed discussion of the CO_2 emissions, as a surrogate for fuel economy, is provided in the supplementary material.

4. Conclusions

This study tested five heavy-duty Class 8 diesel trucks equipped with DPFs for PM emissions control and SCR systems for NOx emissions control. The vehicles tested ranged in model year from 2012 to 2015, and were certified to a 0.20 g/bhp-hr [0.27 g/kW-hr] NOx emissions standard, with the exception of one engine that was certified to a 0.35 g/bhp-hr [0.47 g/kW-hr] standard. Each vehicle was tested on UCR's heavy-duty chassis dynamometer over the four phases of ARB's HHDDT cycles, the HHDDT-S cycle, and the UDDS. The conclusions of this study are summarized below.

NOx emissions varied depending on the test cycle and the test truck. For the manufacturer A1, manufacturer A2, manufacturer B and manufacturer C trucks, NOx emissions over the UDDS cycle ranged from 0.495 to 1.363 g/mi (0.136 to 0.387 g/bhp-hr) [0.308 to 0.847 g/km (0.182 to 1.341 g/kW-hr)]. On a bhp-hr basis, those emission levels are comparable to or below the 0.20/0.35 NOx [0.268/0.469 g/kW-hr] level for three of the four vehicles, while one vehicle was higher than the certification standard at

0.387 g/bhp [0.519 g/kW-hr]. NOx emissions over the ARB chassis dynamometer transient cycle were slightly higher than for the UDDS (0.803 to 3.252 g/mi [0.499 to 2.020 g/km]). The lowest emissions were found over the two cruise cycles, with NOx emissions ranging from 0.067 to 0.249 g/mi [0.042 to 0.155 g/km g/km] for the HHDDT-S and from 0.068 to 0.471 g/mi [0.042 to 0.293 g/km] for the Cruise cycle. The highest NOx emissions were seen for the Creep cycle, which showed NOx emission ranging from 2.131 to 9.468 g/mi [1.323 to 5.883 g/km g/km].

The manufacturer D truck was an outlier with noticeably higher NOx emissions relative to the other vehicles. In this study, on a g/mi basis, its NOx emissions were 3.519 [2.187 g/km] over the UDDS. Subsequent to the initial testing of this vehicle, it was found that the engine had never undergone a regeneration event, due to its unusual, unladed service history and duty cycle. After a series of conventional parked regenerations were performed, additional chassis dynamometer testing showed a NOx emission rate of 0.39 g/mi [0.24 g/km] over the UDDS cycle, near the lower end of the NOx emission rates found in the current study.

The NOx results of this study and other recent studies suggest that there is a wide range of NOx emission levels in the in-use fleet. The results of this study, by design, best represent low mileage, well maintained heavy-duty vehicles, while other studies have shown higher NOx emission rates for higher mileage vehicles or vehicles that appear to have SCR system issues. The ZMRs for heavy-duty vehicles for EMFAC incorporate a wide range of vehicles with higher mileages, potentially different levels of deterioration, and SCR systems with functionality issues, and hence tend to be higher than the values found in the current study. Understanding the relative populations of heavy-duty vehicles in different states of condition will be important in continuing to improve emission inventories going forward.

PM, THC, and CO emissions were found to be very low under most of the testing conditions. PM emissions were below 0.015 g/mi [0.009 g/km] for nearly all vehicle/cycle combinations. THC emissions were below 0.05 g/mi [0.03 g/km] for all test cycles except the Creep cycle, which showed THC emissions ranging from 0.241 to 0.458 g/mi [0.150 to 0.285 g/km]. CO emissions were below 0.2 g/mi [0.12 g/km] for almost all vehicles and cycles, except over the Creep cycle. Fuel economy ranged from 3.84 to 8.69 mi/gal [1.63 to 3.69 km/l] for the non-Creep cycles, with higher fuel economies found for the cycles representing drivingat highway cruising speeds.

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