

High-Efficiency NO_x and PM Exhaust Emission Control for Heavy-Duty On-Highway Diesel Engines

Charles Schenk, Joseph McDonald, and Brian Olson
U.S. EPA – Office of Transportation and Air Quality

ABSTRACT

A diesel exhaust emission control system consisting of catalyzed diesel particulate filters and NO_x adsorber catalysts arranged in a dual-path configuration was developed and evaluated using a 1999-specification 5.9 liter medium-heavy-duty diesel engine. NO_x adsorber regeneration was accomplished via a secondary exhaust fuel injection system. An alternating restriction of the exhaust flow between the two flow paths allowed injection and adsorber regeneration to occur under very low space velocity conditions. NO_x and PM reductions in excess of 90% were observed over a broad range of steady-state operating conditions and over the hot-start HDDE-FTP transient cycle.

INTRODUCTION

The U.S. Environmental Protection Agency (U.S. EPA) has promulgated heavy-duty on-highway diesel engine emission standards of 0.2 g/hp-hr NO_x, 0.01 g/hp-hr PM, and 0.14 g/hp-hr NMHC over the Heavy-Duty Diesel Engine Federal Test Procedure (HDDE-FTP) and the Supplemental Emission Test (SET). These new standards will require highly efficient catalysts and other exhaust emission controls that can provide an order of magnitude reduction in diesel emissions beyond the 2004 emissions standards. This paper summarizes the initial results of an ongoing U.S. EPA program to evaluate advanced exhaust emission control systems for heavy-duty on-highway diesel engines. The goals of the program as reported here are to demonstrate emission control systems capable of providing greater than 90% reductions in NO_x and PM emissions over a broad range of engine operating conditions. Our efforts are currently focused on the evaluation of a system that integrates catalyzed diesel particulate filters (CDPFs) for PM control with multiple-path NO_x adsorbers for NO_x control. This paper covers only the initial stages of a continuing program under way at EPA's National Vehicle and Fuel Emission Laboratory (EPA-NVFEL). Future related work will:

1. Investigate issues related to desulfation and thermal durability of NO_x adsorber catalysts;
2. Test a similar exhaust emission control system using a prototype engine having technology more consistent with engines available in the 2002-2004

time-frame (i.e., common-rail injection and cooled EGR);

3. investigate systems integration and systems control issues, particularly with respect to cold-start emissions performance.

TEST PROCEDURES

ENGINE DESCRIPTION

The engine selected for the initial phases of this test program was a Cummins ISB 5.9 liter-displacement, turbocharged-aftercooled direct injection diesel engine. This engine was chosen for this program due to its position as a medium-heavy-duty diesel engine. As such this engine exhibits exhaust properties that have similarities to both heavy- and light- heavy-duty diesel engines. Major specifications of the engine are summarized in Table 1. All testing was conducted using a manual transmission configuration (i.e., curb-idle transmission torque set to zero).

Table 1: Summary of major engine specifications.

Engine:	1999 Cummins ISB
Engine Configuration:	6-cylinder, turbocharged-aftercooled, DI diesel with 4-valves/cylinder
Rated Power:	194 kW (260 bhp) @ 2500 rpm
Peak Torque:	895 N-m (660 ft-lb) @ 1600 rpm
Fuel System:	Bosch VP44 (Electronic Rotary)
Bore X Stroke:	102 mm X 120 mm
Displacement:	5.88 L
Compression Ratio:	16.3:1

EXHAUST SYSTEM DESCRIPTION

NO_x adsorber catalyst systems for lean gasoline and diesel applications have been previously described in detail.^{1,2,3,4} Typically one of two methods are used to create the reducing ($\lambda < 1$) conditions necessary in the exhaust to regenerate NO_x adsorber catalysts. The first is to cause the engine to run fuel-rich through some combination of reduced intake airflow and/or very late fuel injection. This method has the advantage of adding very little additional hardware for regeneration of the adsorber, but has the penalties of potentially negative

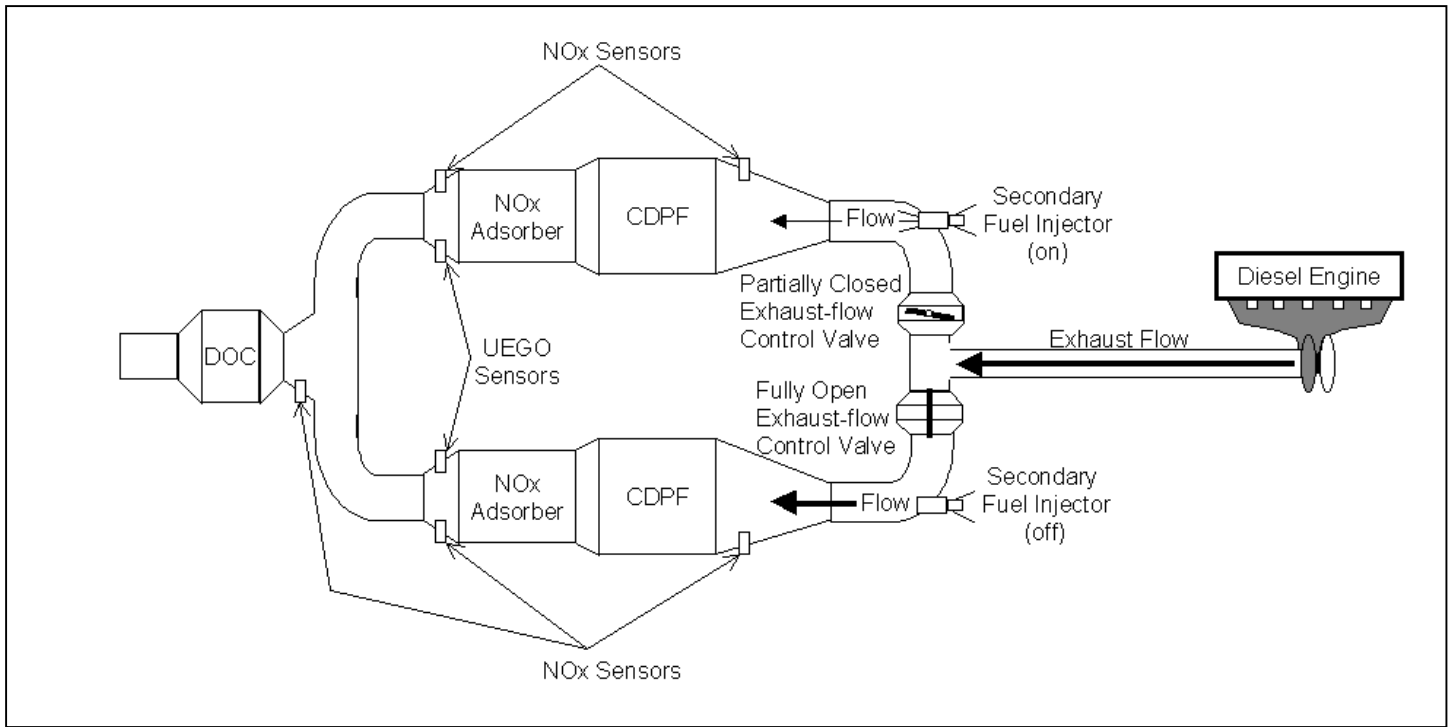


Figure 1: A schematic representation of the layout and functioning of the exhaust emission control system tested at NVFEL.

effects on engine durability, a potentially large impact on fuel economy (FE) and considerably increased PM emissions during regeneration of the adsorber. A second method injects fuel directly into the exhaust to reach the necessary conditions of $\lambda < 1$. This method has the advantage of not directly affecting engine operation. Since diesels frequently run with $\lambda > 1.5$, large quantities of additional fuel would be necessary to regenerate at some operating conditions which would increase the FE impact. In order to reduce the FE impact, this test program chose to divide the exhaust flow path and utilize two NOx adsorbers with a means to selectively restrict exhaust flow to one exhaust flow path at a time. We refer to this approach as a dual-path NOx adsorber catalyst system. While regenerating one of the two flow paths, only a very small fraction of the exhaust flows through the regenerating NOx adsorber. The very small exhaust flow rate is advantageous because less fuel is required to remove excess oxygen and initiate the regeneration of the NOx adsorber. A low exhaust flow rate during NOx adsorber regeneration was also expected to provide a more complete release and reduction of the NOx stored on the adsorber due to the fairly low space velocities exhibited during regeneration.

Figure 1 is a functional schematic of the exhaust emission control system tested with the Cummins ISB engine. The configuration of this particular system was chosen to accomplish the goals of this test program, and should not be seen as an ideal configuration. The exhaust system was insulated with a fibrous ceramic matt from immediately downstream of the turbocharger outlet to just upstream of the CDPF inlet. A brief summary of the major specifications of the CDPFs and NOx adsorbers used with this system is included in

Table 2. NOx reduction with this system was accomplished in the following manner:

1. At any given time, half of the exhaust system operated with a majority of the exhaust flow in an “adsorption mode”, where the exhaust was well fuel-lean of stoichiometric ($\lambda > 1$ or $\lambda \gg 1$, typical diesel exhaust), NO was converted to NO₂ over a Pt-catalyst, and then stored as a metallic nitrate (usually barium nitrate) within the NOx adsorbent material. This is represented by the lower half of the exhaust system in Figure 1.
2. Simultaneously, the other half of the exhaust system had its exhaust flow restricted to just a small fraction (<5%) of the total flow and operated in a regeneration mode.
 - a) While exhaust flow was restricted for regeneration, fuel was sprayed into the regenerating exhaust flow over the CDPF for the first 1 to 5 seconds of regeneration. The goal was to use the CDPF to partially oxidize the fuel to lower molecular weight compounds (lighter hydrocarbons, CO, H₂) which are more suitable NOx reductants.
 - b) Sufficient fuel was injected to react with oxygen in the exhaust until enough oxygen was depleted for the stored NOx to be released. This occurred at exhaust conditions of $\lambda < 1$, and typical values of $0.85 < \lambda < 0.95$ were targeted during testing.
 - c) At these net reducing conditions in the exhaust, NOx was efficiently reduced to N₂ and O₂ by the available reductant compounds in the exhaust over a precious metal catalyst.

- At the completion of regeneration, the majority of the flow was reintroduced into the regenerated half of the system by opening the flow control valve. Total time for regeneration (from the beginning of the introduction of fuel into the exhaust to the opening of the valve) ranged from 15 seconds to greater than 1 minute.
- Simultaneously, flow was restricted to the other half of the system to allow it to regenerate, starting the process again.
- Under conditions that were fuel-lean of stoichiometric (i.e., NO_x adsorption), the CDPF functioned in the usual manner, trapping PM using a wall-flow monolith, and oxidizing the PM using NO₂ formed chiefly via oxidation of NO over Pt.
- A DOC was used downstream of where the lean and rich exhaust flow paths converged (net-fuel-lean) for additional HC control during some of the tests as noted in the text.

Table 2: Summary of the major specifications of the exhaust emission control system components.

Device	Cell Density (cps)	PGM Loading (g/ft ³)	Volume / Monolith (L)	Total Volume (L)
CDPF (1/side)	100	high*	19	38
NO _x Adsorber Catalysts (2/side)	300	high*	7	28
DOC	300	10	5	5

*Suppliers did not provide PGM loading information for the devices tested. The CDPF is known to have a sufficiently high Pt content to promote ~ 50% conversion of NO to NO₂ for soot oxidation. The NO_x adsorber likely has a PGM loading consistent with other automotive 3-way catalysts with similar reduction efficiencies (i.e., ~ 60 to 180 g/ft³).

The entire emission control system was built using readily obtainable components. As such, the CDPF and NO_x adsorber volumes were not optimized to this engine. Two standard exhaust brakes were used as “exhaust flow control valves” to select which half of the dual-path system was exposed to the major portion of the exhaust flow and which half was regenerating. The exhaust brakes have small orifices in their throttle plates, which were blocked to further reduce exhaust space velocity during regeneration. The two exhaust fuel injectors were adapted from a commercially available urea-SCR system. These injectors were chosen because they have been designed for use in a diesel exhaust environment. The injectors were used without the impingers typically used with these injectors. The two divergent diffuser cones leading into the CDPFs were designed to accommodate the injector spray pattern. In addition to providing partial oxidation of fuel injected into the exhaust, the two high-Pt content catalyzed diesel particulate filters (CDPFs) also served their more typical role of providing effective PM control. Rich partial oxidation of the fuel across a wall-flow device like the CDPF, instead of a diesel oxidation catalyst (DOC) with a flow-through monolith, was done

to reduce the emission of soot typically formed as a by-product of partial oxidation of heavier hydrocarbon fuels like diesel fuel.

Regeneration events could be time based, or could be triggered by NO_x emissions measured by zirconia-NO_x sensors mounted immediately downstream of the NO_x adsorber catalysts. The exhaust system joined together into one exhaust pipe downstream of the NO_x adsorber catalysts. Immediately after the sections join together, a DOC with a light PGM loading (~ 10 g/ft³ Pt) was used to evaluate its effectiveness at controlling hydrocarbon slip. Exhaust stoichiometry was measured using both the zirconia-NO_x sensors and using wide-range linear UEGO sensors.

TEST FUEL

The fuel used for all NO_x adsorber testing was Phillips Chemical Company Lot 9CP05L01. This fuel was specified by the DOE Diesel Emission Control-Sulfur Effects (DECSE) program to have similar properties to today’s on-highway fuel with the exception of very low sulfur content⁵. The fuel properties are shown in Table 3. A very low sulfur fuel was chosen to minimize the impact of sulfur poisoning on NO_x adsorber performance, since the immediate testing goal was to evaluate the NO_x reduction potential of NO_x adsorbers. The impact of sulfur on adsorber performance has been investigated through the DECSE program and others, and will be the focus of the next stage of our program. Partway through testing, a second batch of this fuel was received that measured 6 ppm sulfur, but otherwise the properties were virtually identical.

Table 3: Summary of fuel properties.

Test Method	Results
Net Heat of Combustion, ASTM D3338-92 (MJ/kg)	42.94
Density @ 15.5 °C (g/cm ³)	0.8438
Cetane Number	44.4
Cetane Index	47.79
Aromatics, SFC 5186 (% Vol.)	15.3
Olefins, FIA D1319-93 (% Vol.)	1.63
Aromatics, D1319-93 (% Vol.)	27.89
Sulfur, ASTM D2622 (% mass)	0.00031
Carbon, ASTM D3343-95 (% mass)	0.8676
Distillation Properties. ASTM D86	
IBP (°C):	180
10 % (°C):	220
50 % (°C):	262
90 % (°C):	306
End Point (°C):	335
Residue Diesel (mL):	0
Recovery:	100%

TEST CYCLES

The engine was tested over two different dynamometer test cycles:

1. The supplemental emission test (SET) weighted steady-state cycle (Figure 2)⁶
2. The hot-start Heavy-duty Diesel Engine Federal Test Procedure (HDDE-FTP) transient cycle⁷

The SET is essentially the same as the European Steady-state Cycle, except that the test cell conditions and emissions measurement procedures follow those specified in 40 CFR § 86 Subpart N⁷.

LABORATORY

The engine was tested at Heavy-Duty Engine Site 1 at the U.S. EPA – NVFEL facility in Ann Arbor, MI. The test site is equipped with a 600 b.h.p. DC dynamometer and a Horiba full-flow CVS and particulate measurement system. Dilute gaseous regulated emissions were measured using a Horiba MEXA 7200D analyzer bench as per 40 CFR § 86 Subpart N⁷. Some of the recent changes to the Subpart N procedures for measurement of NO_x and PM emissions from post-2007 heavy-duty on-highway diesel engines were also implemented during this testing⁸. This included the use of new high-efficiency PM filter sample media and filter sample holders as specified for low-concentration PM measurement. A heated-bag system was also used to provide a redundant measurement of dilute NO_x emissions in addition to the more usual continuous dilute NO_x measurement⁸.

NO_x ADSORBER SCREENING TESTS

A screening test was devised to compare NO_x adsorber catalysts from various manufacturers. The goal was to evaluate available NO_x adsorber formulations with the objective of choosing an adsorber with 90% or better NO_x reduction for continued evaluation. To this end, the Manufacturers of Emission Controls Association (MECA) obtained four different NO_x adsorber catalyst formulations from three different member companies. It was decided to evaluate the adsorbers using only half of the dual-path system to reduce the number of NO_x adsorber catalyst samples initially required. The emissions and fuel economy impacts were mathematically corrected to reflect a full dual-path system. The trade-off was that only steady-state operation was possible during the screening since the emissions could not be corrected over transient operation. The screening system consisted of one flow path of the system shown in Figure 1. The other flow path consisted of an exhaust brake that opened when the adsorber brake was closed to vent the remainder of the exhaust. The vented emissions were not measured. During the screening tests, the flow path containing the adsorber was directed into the dilution tunnel where the emissions were measured. A restriction was set in the vented flow path to duplicate the restriction of the NO_x adsorber and CDPF. The DOC and insulation were not

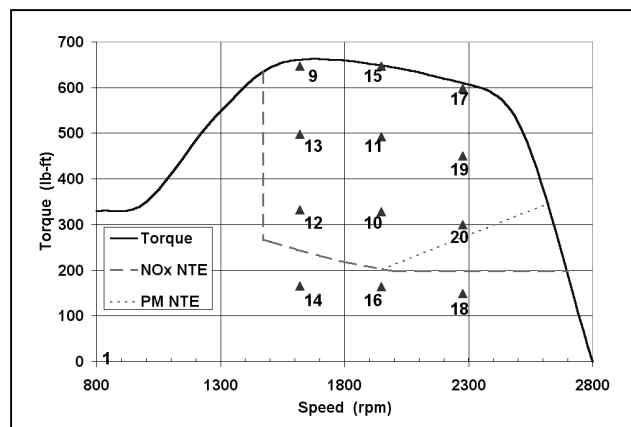


Figure 2: Summary of SET speed and torque set points. The dashed lines represent the NTE

used during the screening tests. Two complete sets of SET modes were run with each NO_x adsorber formulation. For identification purposes, the adsorber formulations were identified as A, B, D, and E. Prior to testing, each set of adsorbers was aged at 2500 rpm, 150 lb-ft (~300 °C) for 40 minutes, then 2500 rpm full load (~520 °C) for 20 minutes, and repeated for a total of 10 hours.

NO_x ADSORBER REGENERATION STRATEGY

Steady State Testing

Testing at SET steady-state speed-load conditions was conducted with varying levels of NO_x regeneration automation, with the general strategy being to inject sufficient fuel during regeneration to achieve exhaust conditions fuel-rich of stoichiometric ($0.85 < \lambda < 1$). The NO_x regeneration intervals were then timed to achieve the desired 90% or greater NO_x reduction while giving consideration to the effects of the secondary fuel injection on fuel economy. Many of the steady-state speed-load conditions were run twice or more using different strategies to investigate the adsorber's emission and fuel usage sensitivity to different combinations of regeneration frequency and fuel injection rates, particularly during the screening tests. Testing of multiple strategies over the SET with the full dual-path system was not possible due to test-cell time constraints.

Transient Testing

The transient HDDE-FTP results presented were for hot-start transient cycles only. The exhaust emission control system was not optimized for cold start performance and would not provide a meaningful assessment of cold-start performance. In order to simulate the standard "cold-soak-hot" procedure, a preconditioning mode was chosen (1947 rpm, 328 lb-ft) to provide adsorber temperatures at the start of the 'hot' cycle that would be similar to those found following the 'cold-soak' portion of the test. Another purpose for the preconditioning was to ensure the adsorbers were in the same condition with respect to adsorbed NO_x at the start of each hot-start.

Given that our regeneration control system did not automatically take into account the starting condition of the NOx adsorbers, this preconditioning was necessary to provide repeatable transient test results. NOx regeneration during preconditioning consisted of 30 second regenerations followed by 30 seconds of NOx adsorption.

Regeneration control for the hot-start HDDE-FTP transient testing was accomplished using a time-based regeneration schedule. Regeneration occurred on a prescribed schedule of time and fuel quantities at predetermined engine conditions during the transient cycle. This control represented an “ideal regeneration controller”, and was used to approximate the capability of a true, non-time based control algorithm. One goal of future work will be development of non-time based controls. As with the steady-state testing, the objective was to achieve at least 90% NOx reduction while taking into consideration the effects of NOx adsorber regeneration on fuel usage and HC emissions.

RESULTS

SCREENING RESULTS

Two sets of steady state SET modes were completed with each adsorber formulation. The SET weighted composite results for all four adsorber formulations demonstrated NOx reductions in excess of 90% with less than 3% FE impact (Table 4). The FE impact was defined as the fuels used for adsorber regeneration divided by the fuel consumed by the engine during the same time interval. The HC emissions varied most

widely, probably due to differences in regeneration strategies, and to some extent, adsorber formulation. The HC emissions in general were very good, with all but adsorber A having less than 0.1 g/hp-hr HC.

Based on the composite data (Table 5), the broad range of temperatures with high NOx reduction, and other factors, NOx adsorber catalyst formulation B was chosen for further evaluation.

Composite SET NOx reductions for this adsorber were well above 90%, with about 2% fuel economy impact. The graph of NOx reduction versus catalyst inlet temperature in Figure 3 shows that this formulation was also a very good match for this engine’s range of

Table 4: Adsorber screening SET composites.

Adsorber	BSNOx (g/hp-hr)	NOx Reduction (from baseline)	BSHC (g/hp-hr)	FE Impact
A	0.31	93%	0.91	2.6%
B	0.27	94%	0.03	2.2%
D	0.28	94%	0.08	1.9%
E	0.33	93%	0.05	2.9%

exhaust temperatures.

Table 5: Modal and composite SET screening NOx and HC emissions results for NOx adsorber B.

Cummins ISB Baseline					Adsorber B Screening Results				
SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (°C)	BSNOx (g/hp-hr)	NOx % Reduction	BSHC (g/hp-hr)	FE Impact (% increase)
1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
2	8%	1619	630	4.6	498	0.18	96%	0.01	1.2%
3	10%	1947	328	4.7	366	0.07	98%	0.04	0.5%
4	10%	1947	493	5.0	446	0.14	97%	0.01	1.5%
5	5%	1619	332	5.0	375	0.06	99%	0.08	0.7%
6	5%	1619	498	5.0	420	0.07	98%	0.10	2.3%
7	5%	1619	166	5.5	296	0.18	97%	0.10	0.3%
8	9%	1947	630	4.0	524	0.46	89%	0.01	3.2%
9	10%	1947	164	5.0	293	0.36	93%	0.05	0.4%
10	8%	2275	599	4.0	537	0.56	86%	0.04	4.3%
11	5%	2275	150	4.8	280	0.29	94%	0.03	0.4%
12	5%	2275	450	5.0	426	0.24	95%	0.04	4.3%
13	5%	2275	300	4.8	357	0.11	98%	0.02	0.9%
Weighted Composite Results:				4.6		0.27	94%	0.03	2.2%

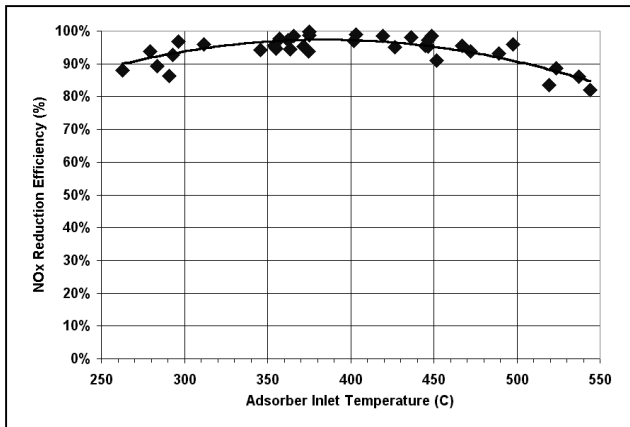


Figure 3: NOx reduction efficiency vs. stabilized catalyst inlet temperature for NOx adsorber “B” during the steady-state screening tests.

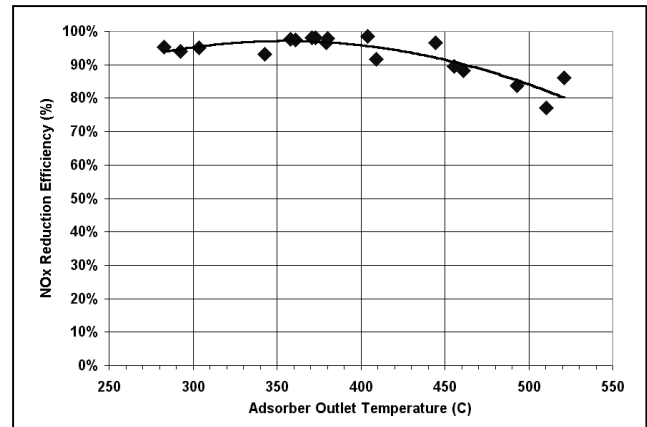


Figure 4: NOx reduction efficiency vs. stabilized catalyst inlet temperature over the SET for NOx adsorber “B” in a dual-path configuration

TEST RESULTS FOR THE DUAL-PATH SYSTEM

Steady-State SET Results

Most of the steady-state modes with the dual-path system were only run once due to restrictions on testing time. Thus, with further testing and careful system tuning, it is likely that the composite SET NOx and FE results could be improved further. The DOC and insulation were used during this testing. The regeneration calibrations for each of the SET modes are shown in Table 6. The values in the table are averaged over the two exhaust flow paths since they could be controlled independently, and there was typically some asymmetry in the behavior of the two NOx adsorber catalysts. The reasons for asymmetry are many, and include the starting condition of the adsorbers, slight differences in the aging of the adsorbers, differences in the control and measurement hardware, etc.

The SET composite NOx reductions (Table 7) for the full dual-path system were slightly lower than the results from the screening tests (90% vs. 94% reductions) shown in Table 4. The difference was most obvious at the high load modes like SET modes 2, 8, and 10. These modes are the most limited by NOx storage capacity and thus most sensitive to sulfur accumulation in the adsorber. At the time testing over these SET modes occurred, the adsorbers had run 172 hours and the engine had used 530 gallons fuel with an average sulfur content of 5 ppm, while NOx adsorber catalysts used for the screening tests had far lower hours and total fuel usage. Consequently, the NOx storage capacity was significantly reduced due to sulfur storage compared to the screening data set. Since the NOx storage capacity of the adsorbers was reduced by sulfur storage, the regeneration frequency (and FE impact) for this data set is fairly high. Desulfation of the adsorbers would lower the regeneration frequency and FE impact at the same level of NOx reduction efficiency. Desulfation will be addressed as part of future work.

The impact of sulfur storage on high-temperature performance can be seen in the exhaust temperature vs.

NOx reduction charts for the screening and dual path configurations in figures 3 and 4, respectively. Even considering the diminished high-temperature performance, using NOx adsorber B in a dual-path configuration resulted in considerably higher NOx reduction efficiency in the 400 to 520 °C temperature range than has been previously reported with other NOx adsorber catalysts.^{4,5,9,10} Oxidation of NO to NO₂ over platinum is equilibrium-limited at high temperatures, but the oxidation reaction can be driven at high temperatures as NO₂ is removed by adsorption. It is possible that more thorough NOx adsorber regeneration achieved with the dual-path configuration may have increased the availability of adsorption sites, which could assist NO₂ adsorption and drive further NO oxidation at high temperatures. It should also be noted that the operating conditions that produced the highest exhaust temperatures also correlate with the highest exhaust concentrations of NOx.

Table 6: Exhaust fuel injection schedule over the SET with the dual-path system.

SET Mode	Regeneration Period* (s)	Injection Duration** (s)	Injection Rate (lb/hr)
1	-	-	-
2	43.7	1.7	0.21
3	60.0	1.3	0.25
4	39.7	4.2	0.13
5	42.7	1.0	0.21
6	56.0	2.0	0.21
7	62.0	1.0	0.21
8	31.8	4.7	0.10
9	59.7	1.7	0.13
10	45.8	2.3	0.21
11	39.7	1.8	0.07
12	43.8	1.5	0.21
13	42.8	1.2	0.21

*Amount of time from the start of regeneration of one exhaust flow path to the start of the next regeneration of that flow path.
 ** Amount of time fuel is injected at the injection rate.

Transient HDDE-FTP Results

The DOC and insulation were used during the transient testing. A timed regeneration schedule was developed to switch flow paths between the NO_x adsorbers and to control when and how much fuel was injected for NO_x regeneration.

During the idle portions of the HDDE-FTP, one NO_x adsorber could adsorb for several minutes at a time without needing to regenerate, while the other NO_x adsorber was bypassed. Such asymmetric operation initially resulted in very different temperature profiles and performance between the two adsorber paths. The frequency of switching between flow paths was increased to provide more uniform heating of the two adsorber catalysts. This can be seen in figures 5-8, where the flow paths were switched frequently under some conditions even though fuel was not injected to initiate regeneration each time the flow switched.

The final regeneration strategy tested resulted in an average of 0.25 g/hp-hr NO_x, 0.002 g/hp-hr PM, and CO below our current measurement capability when measured over three hot-start HDDE-FTP transient cycles (Table 8). These results represent about 93% reductions from the engine out emission levels. The fuel economy impact due to exhaust fuel injection for NO_x adsorber regeneration was approximately 2%, which was consistent with the SET results. The FE effects of exhaust fuel injection for NO_x adsorber regeneration do not fully indicate the future potential of this approach to emissions control since the testing was conducted using a 1999 model year engine with engine-out NO_x emissions levels just under 4 g/bhp-hr. An engine at this NO_x level requires more frequent NO_x regeneration events than would result using a cooled-EGR equipped engine with engine-out NO_x in the 2.0-2.5 g/bhp-hr range. The engine calibration and emission control system also do not reflect the performance of an optimized, fully integrated system.

HC emissions were also reduced relative to the baseline, but by a much smaller amount. The relatively small reduction in HC emissions was the result of HC slippage during NO_x regeneration. Three factors contributed to the HC slippage. One factor was the relatively low HC oxidation efficiency of the DOC used downstream of the adsorbers. Back-to-back testing with a raw gas analyzer at several steady state modes revealed that the lightly catalyzed DOC described in Table 2 had an oxidation efficiency of less than 60% during steady-state engine operation, while more highly catalyzed DOCs are easily capable of 90% HC reductions. The second factor was that more fuel was injected than was absolutely necessary to release and reduce the stored NO_x. The excess HC then contributed to HC emissions and the FE impact. Improving the strategy for injecting the fuel so that it is more efficiently utilized during regeneration will be addressed as part of planned future work. The third factor was the size and lack of integration of the separate catalyst and CDPF monoliths used in the

exhaust emission control system. A more integrated approach using smaller, more closely coupled components mounted in a single housing would likely lead to considerable improvements in the DOC function.

Although fuel sulfur and thermal degradation effects were not a focus of testing, some useful observations can be made from the results presented here. At the time that the HDDE-FTP emission tests were conducted, the NO_x adsorber catalysts had been used for 190 hours. During that time, 653 gallons of 5 ppm equivalent (some 3 ppm and 6 ppm) sulfur fuel was burned by the engine and for NO_x adsorber regeneration. No desulfation procedures were performed during any of the testing, though it is expected that a NO_x adsorber system in use would have been desulfated at least three to four times at this level of sulfur exposure. Consequently, the adsorbers' performance over the HDDE-FTP might have improved had they been desulfated as anticipated.

Despite the lack of adsorber desulfation, the NO_x adsorbers were still very effective at removing NO_x over the hot-start HDDE-FTP. Figures 5-8 show NO_x emissions upstream and downstream of the NO_x adsorbers. During the portions of the HDDE-FTP containing predominantly idle conditions (Figures 5, 8), the NO_x adsorbers were nearly 100% efficient at removing the NO_x.

The bulk of the HDDE-FTP cycle NO_x emissions occurred between 600 and 700 seconds after the hot-start (Figure 7). This was the high-speed, high-load "LA Freeway" portion of the test cycle where the NO_x reduction efficiency dropped to as low as ~75%. This efficiency level is a reflection of the loss of performance likely caused by sulfur storage in the adsorber and was also evident in the high load SET modes (Table 6). Had these adsorbers been desulfated, the NO_x reduction efficiency during the high load portion of the HDDE-FTP may have been considerably higher. The screening data for high load SET modes 8 and 10 (Table 5) shows that the NO_x adsorber catalysts are capable of nearly 90% NO_x reductions. The screening data may prove to be more representative of NO_x adsorber performance after desulfation. Consequently, we expect that properly desulfated NO_x adsorbers should be capable of higher HDDE-FTP NO_x reduction efficiencies.

Table 7: Modal and composite SET NOx and HC emissions results for NOx adsorber B used in a dual-path configuration.

Cummins ISB Baseline					With Dual-Path Adsorber				
SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (°C)	BSNOx (g/hp-hr)	NOx % Reduction	BSHC (g/hp-hr)	FE Impact (% increase)
1	15%	Idle	~0	13.0	144	0.16	100%	0.00	0.0%
2	8%	1619	630	4.6	493	0.71	84%	0.16	1.8%
3	10%	1947	328	4.7	371	0.09	98%	0.30	2.1%
4	10%	1947	493	5.0	444	0.17	96%	0.24	2.8%
5	5%	1619	332	5.0	404	0.07	98%	0.14	2.6%
6	5%	1619	498	5.0	456	0.51	90%	0.11	1.9%
7	5%	1619	166	5.5	304	0.28	95%	0.11	2.5%
8	9%	1947	630	4.0	521	0.56	86%	0.31	2.2%
9	10%	1947	164	5.0	343	0.34	93%	0.09	1.9%
10	8%	2275	599	4.0	510	0.91	77%	0.54	1.8%
11	5%	2275	150	4.8	283	0.22	95%	0.56	3.0%
12	5%	2275	450	5.0	409	0.41	92%	0.13	1.8%
13	5%	2275	300	4.8	361	0.12	98%	0.10	2.0%
Weighted Composite Results:				4.6		0.45	90%	0.27	2.1%

Table 8: Comparison of brake-specific emissions over the HDDE Hot-start FTP transient cycle with and without the exhaust emission control system.

Engine Configuration	Average BSNOx (g/bhp-hr)	Average BSHC (g/bhp-hr)	Average BSCO (g/bhp-hr)	Average BSPM (g/bhp-hr)	Average Fuel Economy Increase
Cummins ISB Baseline*	3.66 ± 0.07	0.29 ± 0.04	1.46 ± 0.03	0.089 ± 0.008	--
Cummins ISB w/exhaust emission control system**	0.25 ± 0.02	0.28 ± 0.06	0***	0.002 ± 0.001	2.3 % ± 0.1 %
Notes ± values represent 95% confidence intervals for a two-sided Student's T-test for triplicate tests. *Emissions measured using 40 CFR 86 Subpart N procedures for MY 2000. **Emissions measured using 40 CFR 86 Subpart N procedures for MY 2007. ***Below measured CO background levels					

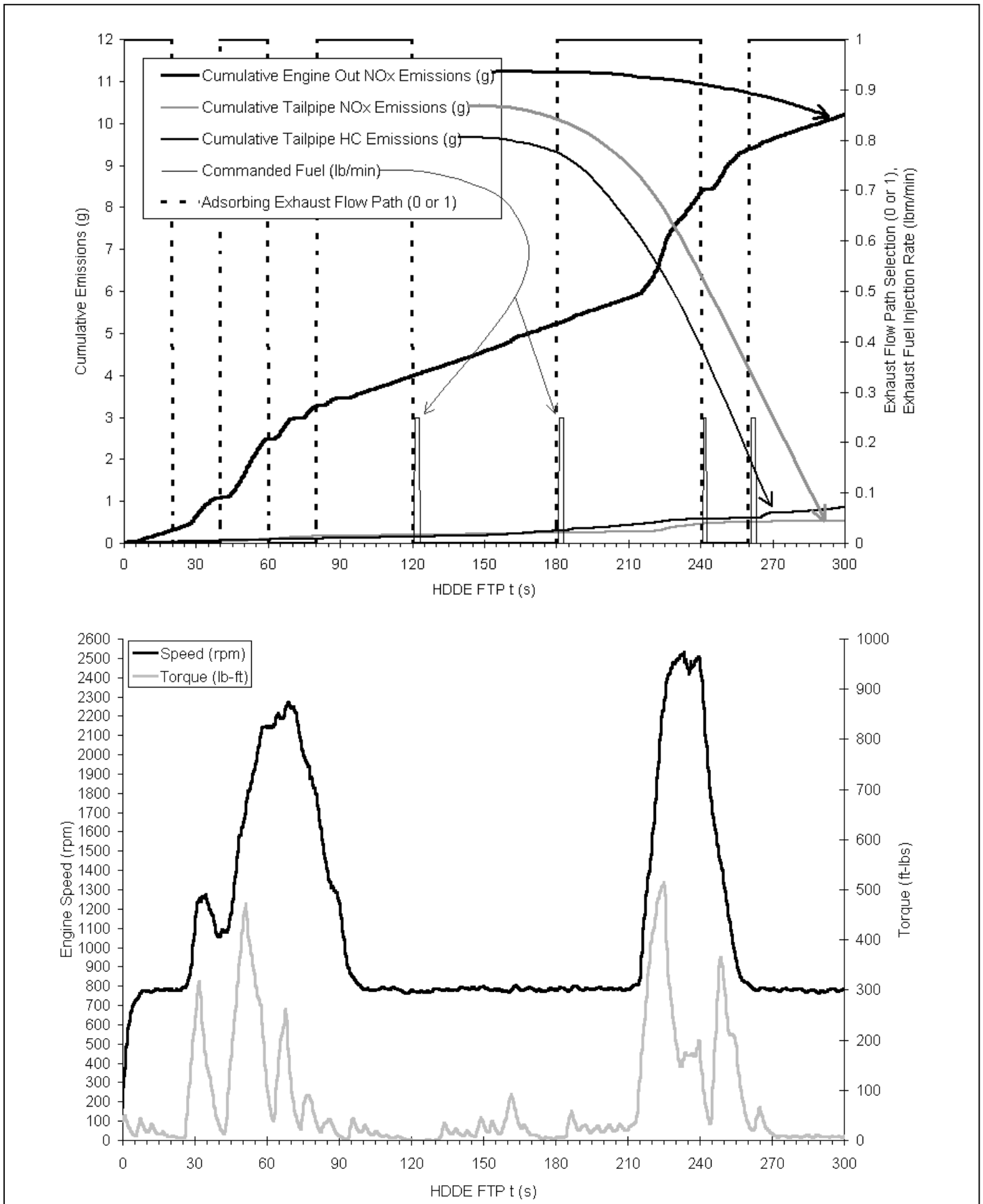


Figure 5: Cumulative emissions results for engine operation over the first 300 seconds (New York Nonfreeway) of the HDDE Hot-start FTP Transient Cycle.

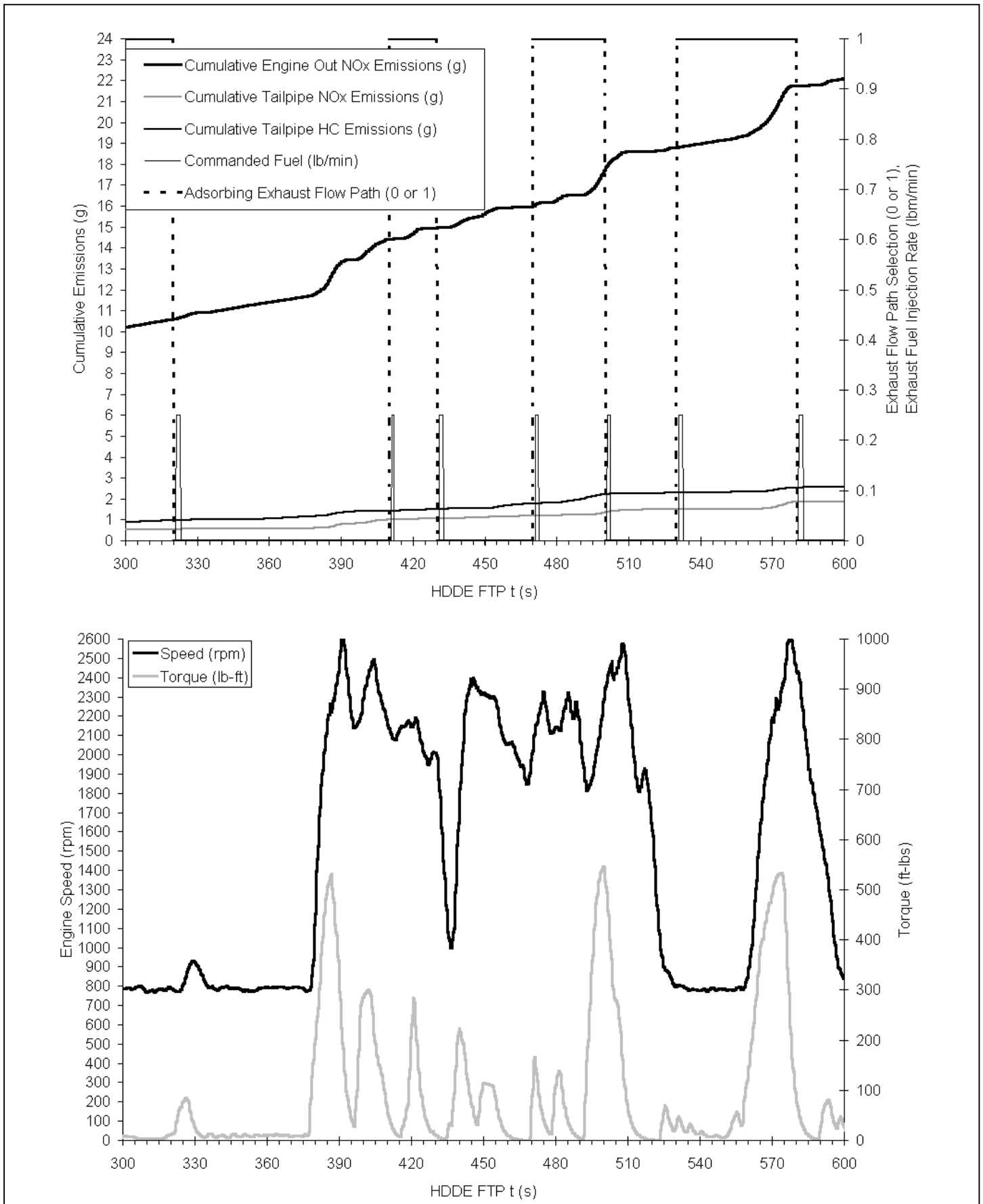


Figure 6: Cumulative emissions results for engine operation over the second 300 seconds (Los Angeles Nonfreeway) of the HDDE Hot-start FTP Transient Cycle.

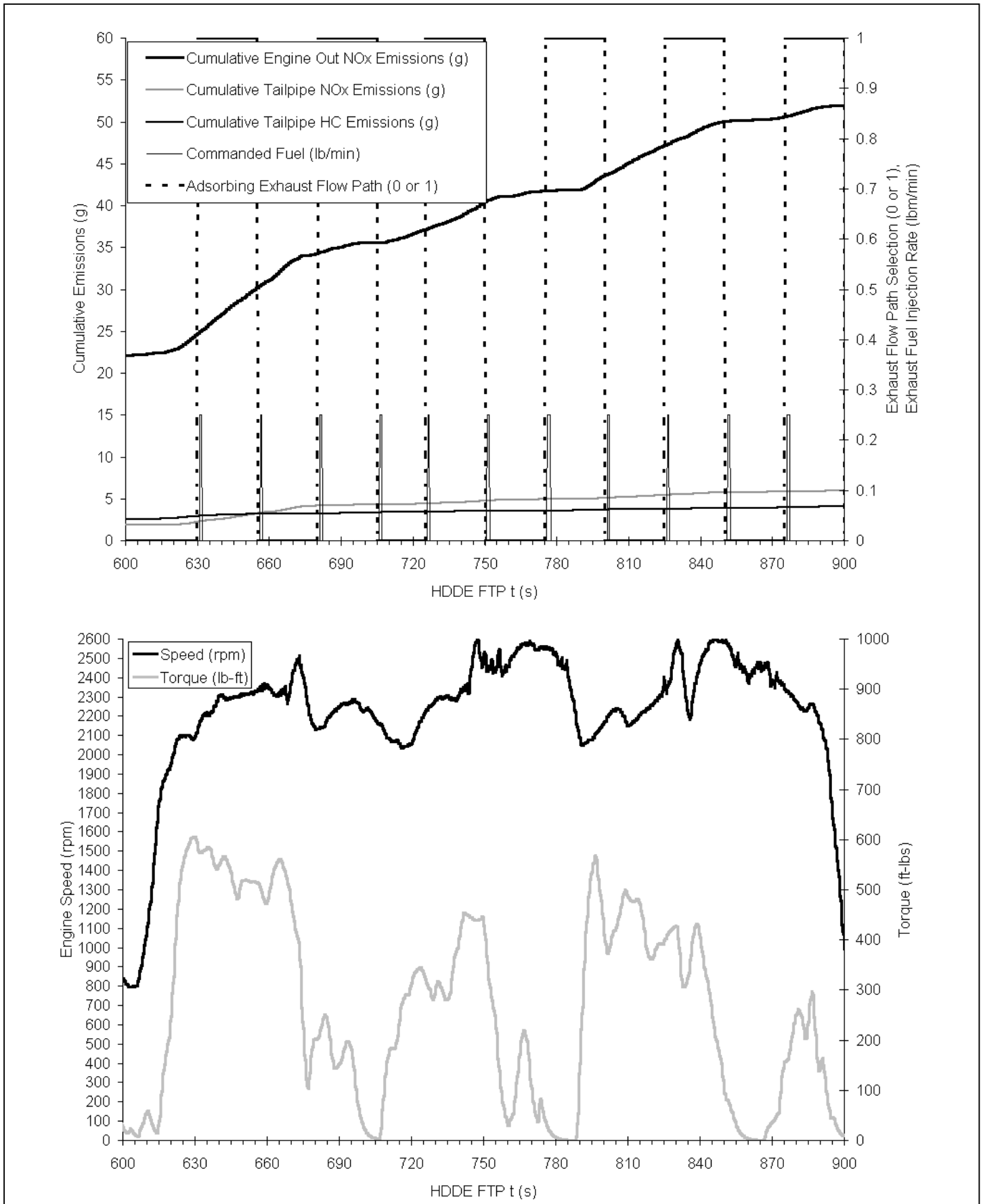


Figure 7: Cumulative emissions results for engine operation over the third 300 second period (Los Angeles Freeway) of the HDDE Hot-start FTP Transient Cycle.

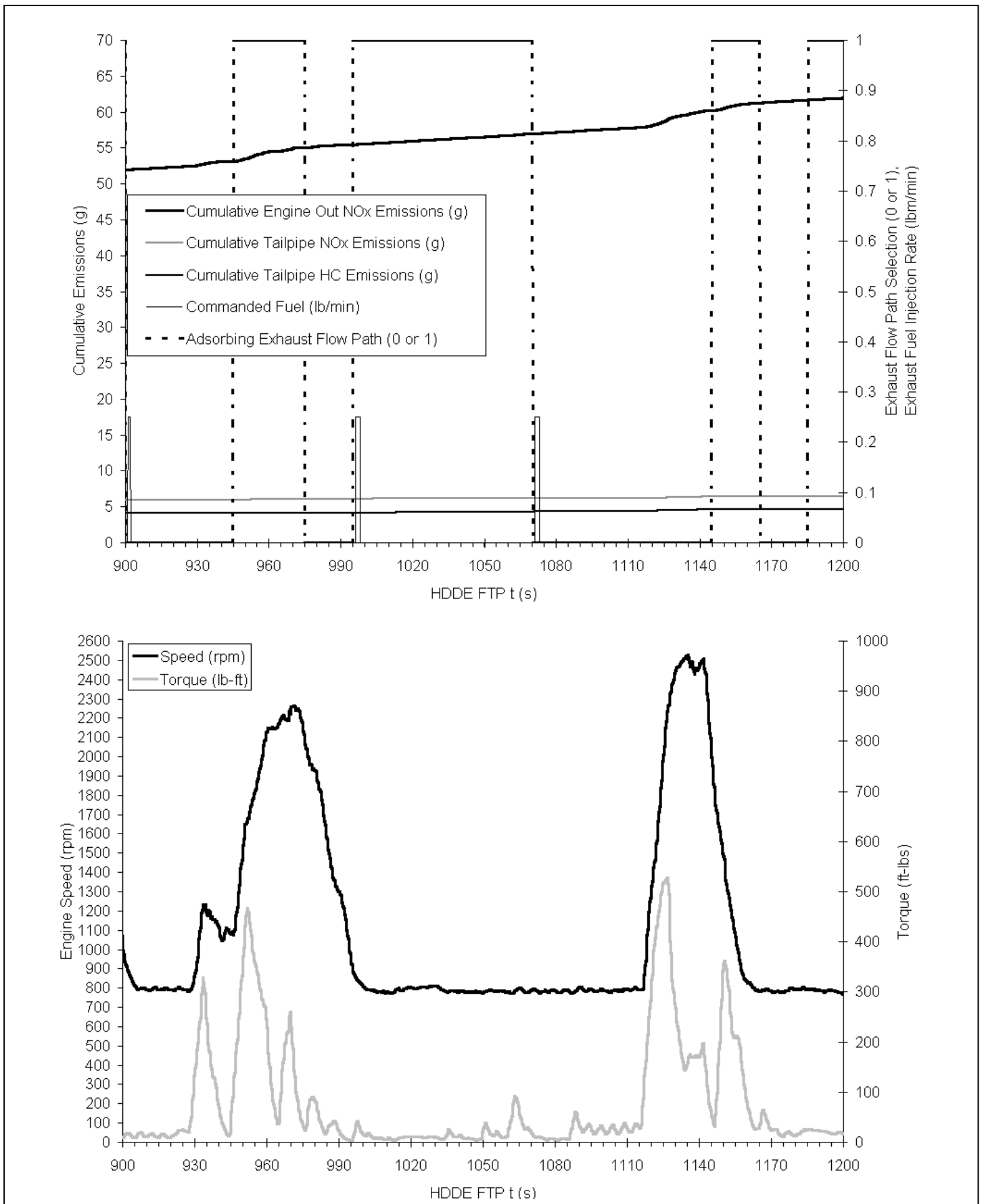


Figure 8: Cumulative emissions results for engine operation over the fourth 300 second period (repeat of New York Nonfreeway) of the HDDE Hot-start FTP Transient Cycle.

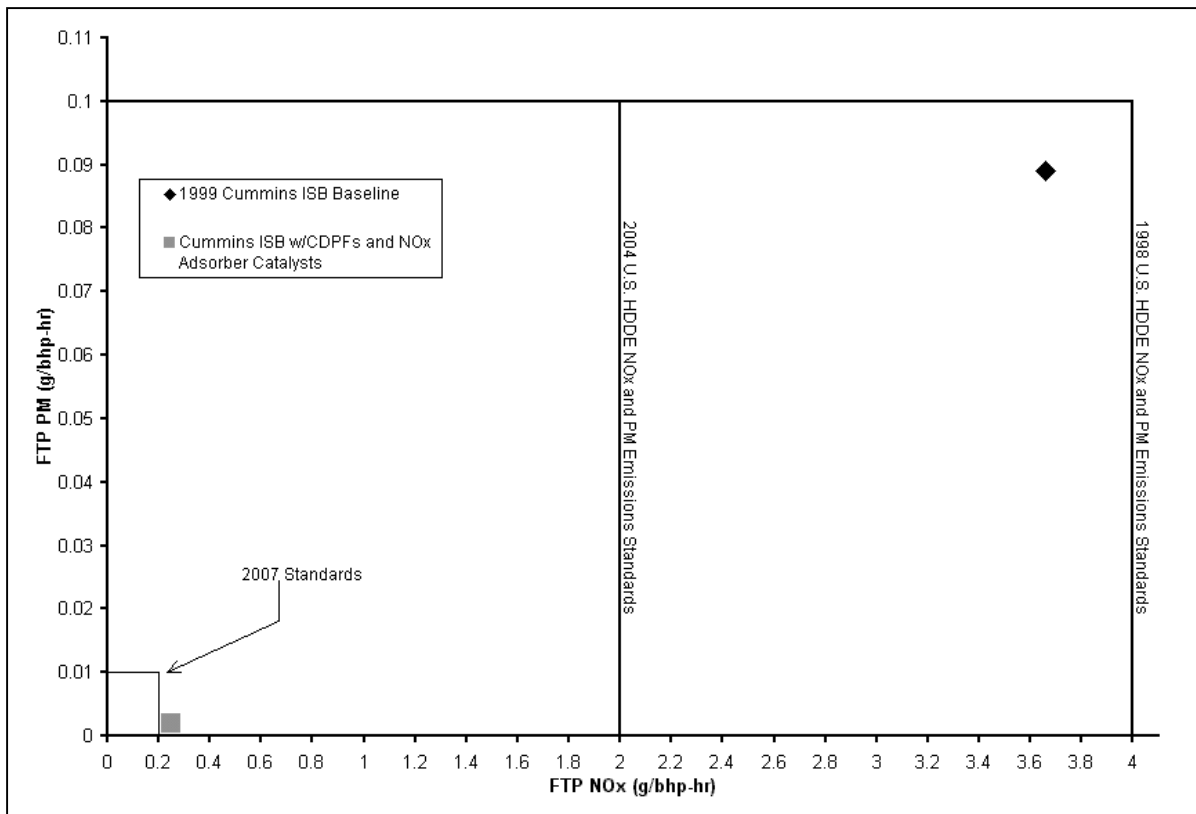


Figure 9: Comparison of HDDE Hot-start FTP emissions results with current and future US HDDE emission standards

CONCLUSION

This test program has shown that NOx adsorbers and CDPFs are capable of greater than 90% emission reductions over the hot-start transient HDDE-FTP and SET composite after running approximately 200 hours on 5 ppm sulfur equivalent fuel, without desulfation.

With reasonably expected desulfation, the expected NOx reduction efficiency would be higher. This indicates that the NOx and PM aftertreatment technology are capable of achieving > 90% emission reduction efficiencies. Figure 9 shows the hot-start HDDE-FTP results from this program in comparison with current and future HDDE emission standards. Results with the 1999 Cummins ISB engine approach the emissions performance necessary to meet the 2007 standards. Applying a similar type of exhaust emission control system to a 2004-compliant HDDE should result in PM and NOx emissions that would comply with the 2007 standards.

ACKNOWLEDGMENTS

The authors would like to acknowledge the NVFEL Diesel Test Team for the extraordinarily hard work and long hours put into this project. Also, we would like to thank MECA and its member companies for their assistance in obtaining the devices crucial to this test program.

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