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High-Efficiency NOx and PM Exhaust Emission Control for Heavy-Duty On-Highway Diesel Engines – Part Two

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ABSTRACT

A 5.9 liter medium-heavy-duty diesel engine was modified to approximate the emissions performance of a MY 2004 US heavy-duty on-highway engine. The engine was tested with and without a diesel exhaust emission control system consisting of catalyzed diesel particulate filters and NOx adsorber catalysts arranged in a dual-path configuration. The goal of this project was to achieve hot-start HDDE-FTP emissions consistent with the recently announced 2007 U.S. heavy-duty engine emissions standards. Supply of hydrocarbon reductant for NOx 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. NOx and PM emissions over the hot-start portion of the HDDE-FTP transient cycle were 0.13 g/bhp-hr and less than 0.002 g/bhp-hr, respectively.

INTRODUCTION

The U.S. Environmental Protection Agency (U.S. EPA) has promulgated heavy-duty on-highway engine emission standards of 0.20 g/hp-hr NOx, 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 likely require highly efficient catalysts and other exhaust emission controls that can provide an order of magnitude reduction in diesel emissions beyond the 2004 emissions standard. This paper summarizes recent results of an ongoing U.S. EPA program to evaluate advanced exhaust emission control systems for heavy-duty on-highway diesel engines. The primary goal of this program is to demonstrate emission control systems capable of meeting the 2007 U.S. on-highway NOx, HC, and PM emissions standards. Efforts are currently focused on the evaluation of a system that integrates catalyzed diesel particulate filters (CDPFs) for PM control with multiple-path NOx adsorbers for NOx control. This paper covers only the second phase of the continuing program under way at the U.S. EPA – National Vehicle and Fuel Emission Laboratory (U.S. EPA-NVFEL). The results of the first testing phase were reported in SAE 2001-01-1351. The second phase of testing applied the previously developed exhaust emission control strategy to a new engine modified to achieve emissions levels representative of 2002/2004 model-year US on-highway diesel engines. The primary focus of this paper will be the presentation of the HDDE-FTP emission results and how they were obtained. In addition, steady-state modal SET (Euro III) emission results will be presented. Conclusions will be reached concerning the ability of this ‘proof of concept’ engine/catalyst system to achieve 2007 HDDE emission standards. Additional phases of this project not covered in this particular paper will be published in subsequent papers. The additional work will include:

1. Investigation of issues related to desulfation and thermal durability of NOx adsorber catalysts;
2. Investigation of systems integration and systems control issues, particularly with respect to cold-start emissions performance.

TEST PROCEDURES

ENGINE DESCRIPTION

The engine used for this phase of the test program was a modified Cummins ISB 5.9 liter displacement, turbocharged-aftercooled direct injection diesel engine. This engine is generally similar to the engine used in phase one of this work (i.e., displacement, combustion bowl and other major hardware). The modifications consisted of the addition of a high-pressure common-rail (HPCR) fuel injection system, Bosch/ETAS PCM and associated software, and a high-pressure loop cooled EGR system (see Figure 1). Major specifications of the engine are summarized in Table 1.

TEST FUEL

The fuel used for all NOx adsorber testing was Phillips Chemical Company Lot 0EPULD01. This fuel was specified by the U.S. Department of Energy’s Diesel Emission Control-Sulfur Effects (DECSE) program to have similar properties to today’s on-highway fuel with the exception of very low sulfur content.[1] The fuel properties are shown in Table 2. A very low sulfur fuel was chosen to minimize the impact of sulfur poisoning on NOx adsorber performance, since the immediate testing goal was to evaluate the NOx reduction potential of NOx adsorbers on an EGR equipped engine. The impact of sulfur on adsorber performance has been investigated through the DECSE program and others, and is the focus of the following phase of this program.

EXHAUST SYSTEM DESCRIPTION

NOx adsorber catalyst systems for lean gasoline and diesel applications have been previously described in detail.[2,3,4,5] The exhaust system, specifications of the CDPFs and NOx adsorbers used with the system, and regeneration/NOx reduction control strategies used in this application are similar to the ones previously used and have been described as part of phase one of this work.[6] Briefly, fuel is injected directly into the dual-path NOx adsorber catalyst system to reach the necessary conditions of $\lambda < 1$. While regenerating one of the two flow paths, only a very small fraction of the exhaust flows through the regenerating NOx adsorber. Figure 2 is a functional schematic of the exhaust emission control system tested with the modified Cummins ISB engine. Modifications to the previously described exhaust system include removal of the insulated fibrous ceramic matt that ran from immediately downstream of the turbocharger outlet to just upstream of the CDPF inlet and an increase in the length of the exhaust transfer tube between the engine and the CDPF inlet.

The entire emission control system was built using readily obtainable components. CDPF and NOx adsorber volumes were not optimized. The CDPF volume is likely 3 to 4 times the necessary volume. At 4.5 times the engine displacement, the total volume of the NOx adsorber catalysts was approximately 20 to 35% larger than what has been reported for SCR systems for heavy-duty on-highway diesel engines.[7,8,9] It should be noted, however, that considerably higher NOx reduction efficiencies appear to be possible for NOx adsorber catalyst systems over both steady-state and transient conditions when compared to what has been reported in the literature for SCR.[6,7,8,9] With the sole exception of the DOC, all control system components, including exhaust brakes, exhaust fuel injectors, wide-range linear UEGO sensors, and zirconia-NOx sensors (see appendix) remained the same as the final configuration tested in the first phase of this work.[6] Immediately after the exhaust flow-paths rejoin, a DOC with a higher PGM loading than previously used was installed to evaluate its effectiveness at controlling hydrocarbon slip. The DOC was similar in volume and PGM loading to oxidation catalysts used for urea-slip control in SCR systems. Table 3 contains a summary of the major specifications of the post-combustion emissions control system. Performance of the catalyzed exhaust system components represents a system that has operated for approximately 200 hours, using approximately 900 gallons of fuel with a sulfur content of 3 ppm.

TEST CYCLES

The engine was tested primarily over two different dynamometer test cycles:

1. The supplemental emission test (SET) weighted steady-state cycle.[10]
2. The hot-start Heavy-Duty Diesel Engine Federal Test Procedure (HDDE-FTP) transient cycle.[11]

The SET is essentially the same as the European Steady-state Cycle (ESC), except that the test cell conditions and emissions measurement procedures follow those specified in 40 CFR § 86 Subpart N.[11] A summary of the dynamometer set-points for the SET and the NTE zone for this particular engine is included in the Appendix for reference purposes.[6] Tests of the modified Cummins ISB without the post-combustion exhaust emission controls served as a baseline condition for comparison of emissions, fuel consumption, and other measured parameters.

LABORATORY

The engine was tested at Heavy-Duty Engine (HDE) Site 2 at the U.S. EPA-NVFEL facility in Ann Arbor, MI. The test site is equipped with a 600 bhp DC dynamometer and a Horiba full-flow CVS and particulate measurement system. Dilute gaseous regulated emissions were measured per 40 CFR § 86 Subpart N.[11] Gaseous analyses were performed using a gas-analysis bench made up of loose analyzers. Table 4 outlines the type of analyzer used for each species measured. Some of the recent changes to the Subpart N procedures for measurement of NOx and PM emissions from post-2007 heavy-duty on-highway diesel engines were also implemented during this testing.[11] This included the use of new high-efficiency PM filter sample media and filter sample holders as specified for low-concentration PM measurement. An ambient temperature bag system was also used to provide a redundant measurement of dilute NOx emissions in addition to the more usual continuous dilute NOx measurement during the hot start FTP.[12] For some portions of testing, two NOx analyzers were used to insure the accuracy of both the bag and continuous measurements at the low NOx concentrations encountered. SET and FTP NOx emission results were reported from continuous measurements using a Beckman 955.

NOX ADSORBER REGENERATION STRATEGY

Steady State Testing

Testing and NOx adsorber regeneration at SET steady-state speed-load conditions was conducted in a manner similar to phase one of this project.[6] The goal was to meet the new 2007 SET emissions standard while giving consideration to the fuel economy impact of secondary fuel injection.

Transient Testing

Transient testing and NOx adsorber regeneration followed the same procedures outlined in phase one of this project.[6] Transient HDDE-FTP results are for hot-start transient cycles only. NOx adsorber catalyst regeneration occurred on a prescribed schedule of time and fuel quantities at predetermined engine conditions during the transient cycle. The objective was to achieve at least 90% NOx reduction in order to achieve hot-start transient FTP exhaust emission levels consistent with the levels that will be needed to meet the 2007 U.S. on-highway NOx, HC, and PM emissions standard of 0.20 g/hp-hr NOx, 0.01 g/hp-hr PM, and 0.14 g/hp-hr NMHC while giving consideration to the effects of secondary fuel injection on fuel economy.

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 HPCR
Engine Management:	Bosch/ETAS
EGR System:	High pressure loop, intake venturi w/ throttled by-pass
Bore X Stroke:	102 mm X 120 mm
Cylinder Displacement:	5.88 L
Compression Ratio:	16.3:1

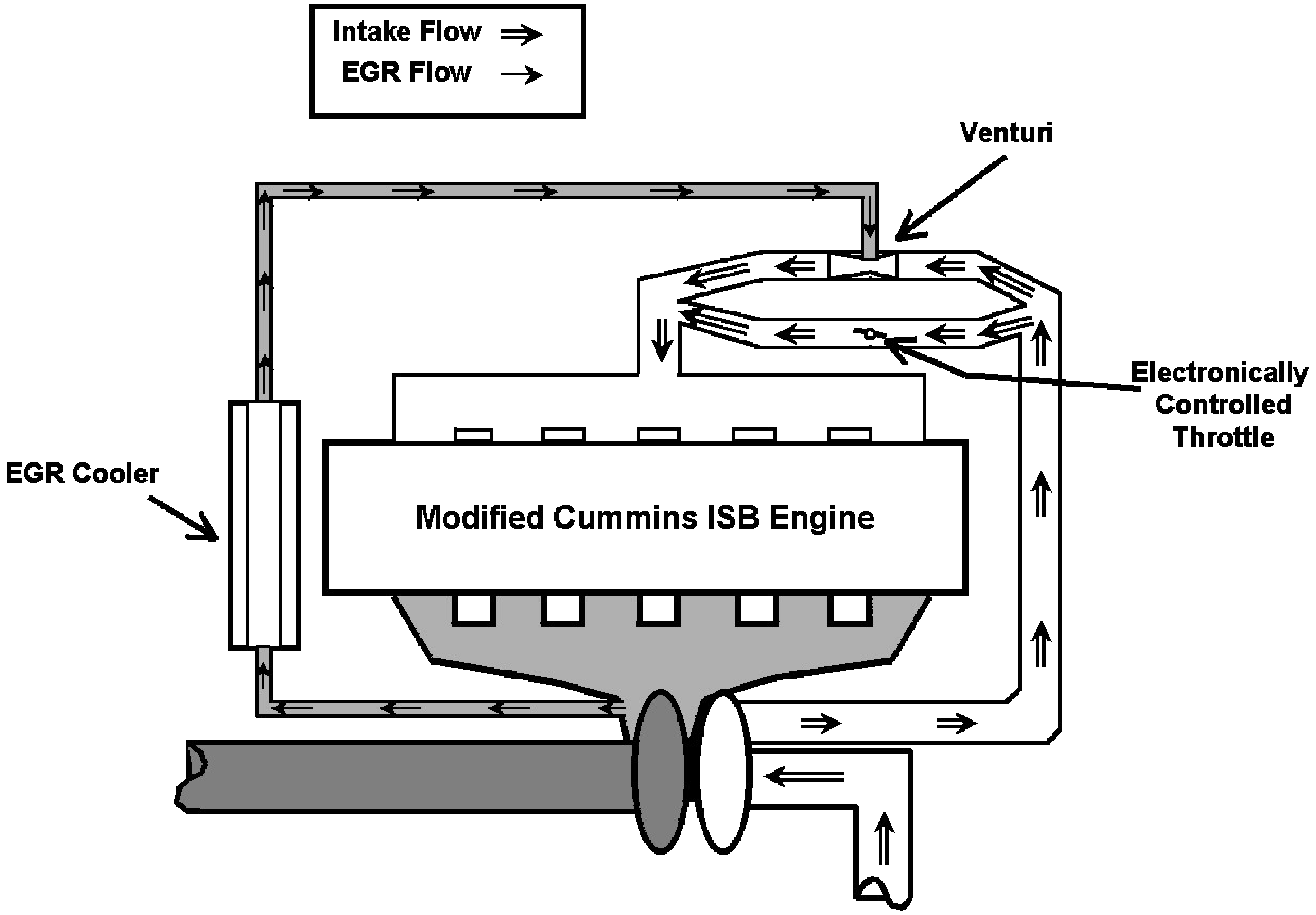


Figure 1: Schematic representation of the high-pressure loop venturi-EGR system with throttle by-pass.

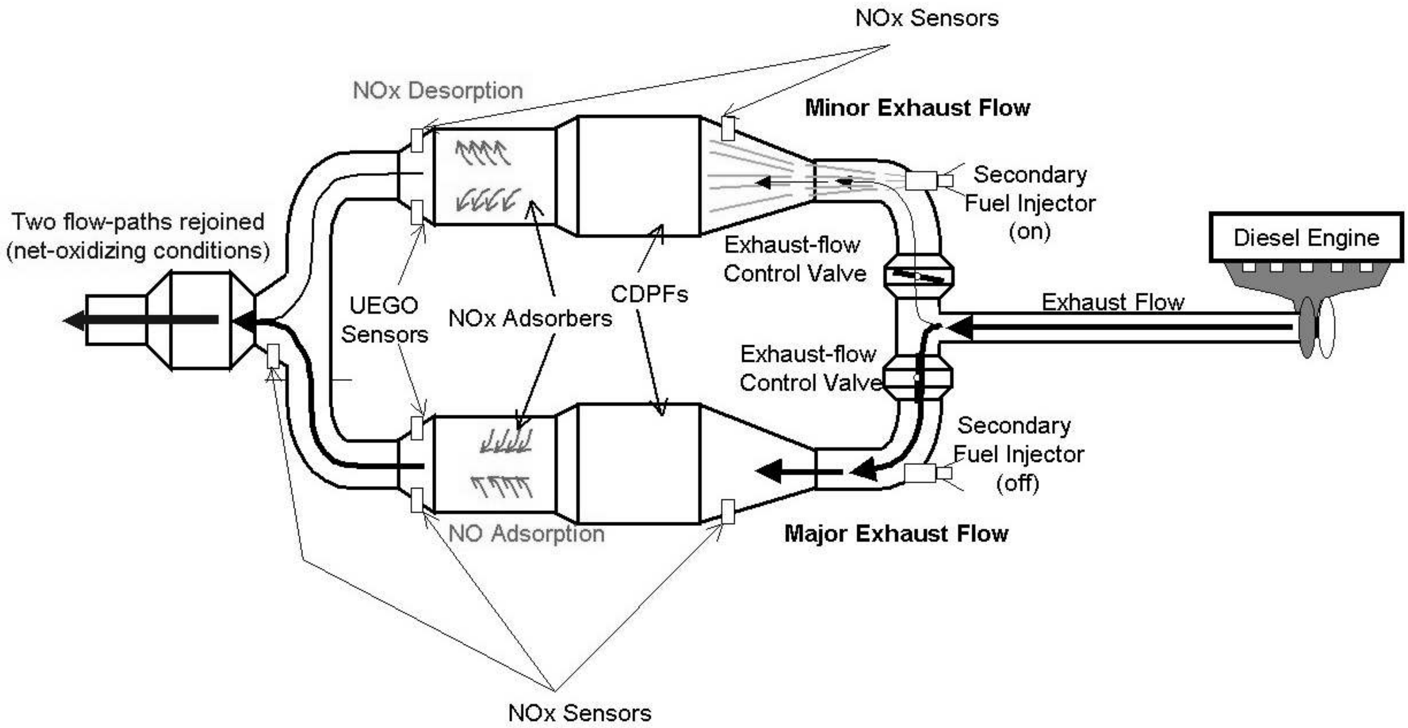


Figure 2: Schematic representation of the layout and functioning of the exhaust emission control system tested at NVFEL.[6]

Table 2: Summary of fuel properties.

Test Method	Results
Net Heat of Combustion, ASTM D3338-92 (MJ/kg)	43.19
Density @ 15.5 ºC (g/cm^3)	0.8258
Cetane Number	43.4
Cetane Index	53.5
Olefins, FIA D1319-93 (% Vol.)	3.3
Aromatics, D1319-93 (% Vol.)	24.2
Sulfur, ASTM D2622 (ppm mass)	3
Carbon, ASTM D3343-95 (% mass)	0.8638
Distillation Properties, ASTM D86	
IBP (ºC):	191
10 % (ºC):	213
50 % (ºC):	258
90 % (ºC):	312
End Point (ºC):	346
Residue Diesel (mL):	0
Recovery:	100%

Table 3: Summary of the major specifications of the exhaust emission control system components.

Device	Cell Density (cpsi)	PGM Loading (g/ft^3)	Volume / Monolith (L)	Total Volume (L)
CDPF (1/side)	100	*	19	38
NOx Adsorber	300	*	7	28
DOC	300	*	5	5

*Suppliers did not provide PGM loading data for the devices tested. The CDPF is known to have a sufficient Pt content to promote ~ 50% conversion of NO to NO_2 for soot oxidation. The DOC likely had a PGM loading similar to the CDPF, possibly in the range of 40 – 50 g/ft^3. NOx adsorber PGM loading was probably consistent with other automotive 3-way catalysts with similar reduction efficiencies (i.e., ~ 60 to 180 g/ft^3), using either Pt-Rh or Pt-Pd-Rh.

Table 4: Analyzers Used for Gaseous Analysis.

Analyzer Model	Species
Horiba AIA-23	CO
Horiba AIA-23 (AS)	CO_2
Horiba FIA-220	THC
Beckman 955	NOx
Horiba CLA-720MA	NOx

Table 5: Exhaust fuel-reductant injection schedule over the SET.

SET Mode	Regeneration Period (s)	Injection Duration (s)	Injection Rate (lb/min)
1	--	--	--
2	49.7	1.6	0.25
3	119.5	1.0	0.25
4	59.7	1.5	0.25
5	119.5	1.1	0.25
6	59.7	1.4	0.25
7	179.3	0.8	0.25
8	44.0	1.8	0.25
9	179.6	0.8	0.25
10	32.4	2.1	0.25
11	179.6	0.8	0.25
12	79.6	1.5	0.25
13	89.5	1.1	0.25

RESULTS

STEADY-STATE SET RESULTS

The regeneration calibrations for each of the SET modes are shown in Table 5. Modal and composite SET emission results are presented in Table 6. The values in Tables 5 and 6 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 absorber catalysts. NOx reduction efficiencies of greater than 90% were demonstrated for nearly all of the SET modes. The weighted composite SET NOx emission of 0.17 g/bhp-hr represented a 94% reduction from conditions without the NOx adsorber catalyst system. NOx reduction efficiency over the SET was comparable or somewhat improved over the 1999-specification engine (94% vs. 90%).[6] The increased NOx reduction efficiency relative to earlier testing occurred primarily at high speed, high load test conditions such as SET modes 8, 10, and 12; and near the engine's peak torque condition (SET mode 2).

The observed NOx emissions were partially due to NOx slip during regeneration. Such NOx slippage was observed at some steady-state test modes, particularly high-load conditions, and during certain high-load portions of the FTP transient. Examples of NOx slip for steady-state speed-load conditions near peak torque (SET mode 2), near rated power (SET mode 10), and for a mid-speed-light-load condition (SET mode 9) are presented in Figures 3 – 5. Adsorber NOx slip has been previously described for a single flow path, adsorber based, diesel exhaust emission control system and was linked to both the amount of reductant used and the amount of NOx stored on the adsorber at the time of the regeneration event. The origin of the NOx pulse has been described as competition between the NOx desorption and reduction rates. The rapid rate of desorption initially overloads the precious metal adsorber catalyst sites. The reduction step then quickly takes over, reducing the released NOx and halting the brief NOx slip.[13]

In a dual path application such as the one evaluated in this test program, a NOx pulse is evident at high loads in the combined exhaust downstream of the adsorbers, just after one flow-path switches from regeneration to storage mode. The NOx slip has a relatively narrow pulse width and was measured using the fast response zirconia-NOx sensor downstream of where the two exhaust paths recombine. This slip is mechanistically different than that described for a single path NOx adsorber catalyst system. The NOx slip is likely related to residual released NOx still undergoing reduction in the regenerating flow-path. The NOx slip is also related to the rapid increase in space velocity across the NOx adsorber catalyst that occurs when it is switched into an adsorption mode. At exhaust conditions of $\lambda < 1$ there is a high concentration of NOx present until all the NOx in the regenerating flow-path has been released and reduced. If the regenerating flow-path is opened to the full exhaust while $\lambda < 1$, the resulting increase in space velocity and exhaust λ-value will stop the release and reduction processes and result in some of the unreduced NOx being pushed out of the previously regenerating adsorber. This NOx pulse can be clearly seen when the flow-paths are switched at the high load modes (Figures 3, 5). The light load mode in Figure 4 does not exhibit a NOx pulse. Light load modes do not exhibit NOx pulses because the regeneration times are longer than at higher loads. This allows the released NOx to be more completely reduced and it also allows more complete consumption of the reductant present in the regenerating flow path before the flow paths are switched. The regeneration events at high load conditions are limited by NOx storage capacity. The shorter adsorbing time that results is not sufficient for the regenerating flow-path to completely finish the regeneration process, resulting in a NOx pulse.

As can be seen in Figures 3, 4, and 5, there is asymmetry in the NOx slippage between the two exhaust flow paths of the dual-path NOx adsorber catalyst system. This may have been due to differences in thermal sintering or other deactivation mechanisms between the NOx adsorber catalysts in either flow path. Such differences are more readily apparent at high NOx concentrations (Figures 3 and 5) due to the higher concentration of NOx in the exhaust stream and the higher space velocities present. As can be seen from the CVS NOx concentrations (top of each chart), the overall NOx slip concentrations are still relatively low for either flow path.

The frequency of NOx adsorber regeneration was considerably reduced for the modified Cummins ISB when compared with previous work done with the 1999 Cummins ISB engine at the same speed-load conditions.[6] This was due entirely to the reduced engine-out NOx of the modified Cummins ISB used for this phase of testing. The reduced frequency of regeneration resulted in less use of fuel-reductant than the previous configuration, and also reduced NOx emissions due to breakthrough by reducing the total number of breakthrough events for a particular speed-load set-point.

TRANSIENT HDDE-FTP RESULTS

Transient emissions results over the hot-start HDDE-FTP transient cycle are summarized in Table 7. Brake specific values are given for continuous measurements only. Bag NOx values were within 1% of the continuous values for the modified Cummins ISB with post-combustion emission control, but were only within 10% for the baseline measurements. This does not correspond to the results obtained in phase one of this program where bag versus continuous numbers were within 1% for both post-combustion control and baseline measurements.[6] This difference may have been due to problems such as sample line dead volume and temperature control in the bag sampling system in HDE Site 2. Phase one work was done in HDE Site 1, which has a state-of-the-art CVS, a temperature controlled bag enclosure held at 28°C, and a Horiba MEXA-7200D analytical system.

A time-based NOx adsorber regeneration schedule, similar to the strategy used in the first phase of this work, was used for all of the HDDE-FTP transient-cycle tests. Details of the regeneration events and cumulative NOx and HC emissions over the hot-start HDDE-FTP are presented in Figures 6 – 9.

The combination of CDPFs, NOx adsorbers, and DOC reduced brake specific emissions of PM, NOx, and CO by 95% or greater and HC by more than 80% when compared to the baseline condition (HPCR, cooled EGR, but no post-combustion emission controls). BSNOx emissions over the hot-start HDDE-FTP cycle were 0.13 g/hp-hr ± 0.02 g/hp-hr. Average BSPM emissions over the cycle were below current minimum detection limits (>2 mg/bhp-hr). CO emissions were below the current measurement capabilities of the NDIR used at NVFEL HDE Site 2 (MDL of ~ 0.1 g/bhp-hr for CO). The fuel economy impact due to exhaust fuel injection for NOx adsorber regeneration was approximately 1.5%, which was consistent with the steady-state SET results.

Cycle-average BSNOx emissions were approximately halved compared to the first phase of this work, which had applied the same post-combustion emission controls to an unmodified 1999 Cummins ISB.[6] NOx slippage over the HDDE-FTP was greatly reduced relative to the earlier work (Figures 6 – 9), particularly at the higher-load LA-Freeway segment of the cycle (Figure 8). Cycle-average BSHC emissions were considerably reduced relative to the baseline, and relative to the first phase of this work. This was due to the substitution of a more active DOC into the exhaust emission control system. The DOC greatly reduced HC slippage due to injection of fuel reductant (Figures 6 – 9) when compared to the previous phase of this work.[6]

Table 6: Modal and composite SET NOx and HC emissions results for the Modified Cummins ISB engine.

Modified Cummins ISB (HPCR, cooled EGR)						**Modified Cummins ISB** (Baseline + CDPF and NOx adsorber catalysts)				
SET Mode	**SET Weighting**	**Speed (rpm)**	**Torque (lb-ft)**	**BSNOx (g/hp-hr)**	**BSHC (g/hp-hr)**	**Outlet T (°C)**	**BSNOx (g/hp-hr)**	**NOx (%-Reduction)**	**BSHC (g/hp-hr)**	**Reductant FE Impact (%)***
1	15%	Idle	0	6.95	6.77	144	0.16	100%	0.00	0.0%
2	8%	1649	633	3.10	0.08	529	0.33	89%	0.03	1.6%
3	10%	1951	324	1.79	0.21	403	0.06	96%	0.01	1.0%
4	10%	1953	490	1.98	0.12	486	0.07	96%	0.02	1.3%
5	5%	1631	328	1.90	0.22	403	0.10	95%	0.01	0.9%
6	5%	1626	496	2.35	0.09	504	0.07	97%	0.02	1.6%
7	5%	1623	161	2.05	0.56	313	0.02	99%	0.03	0.9%
8	9%	1979	609	2.09	0.08	524	0.19	91%	0.03	1.7%
9	10%	1951	159	1.68	0.49	323	0.01	100%	0.02	0.8%
10	8%	2348	560	1.95	0.11	524	0.10	95%	0.04	2.3%
11	5%	2279	145	1.66	0.57	306	0.01	99%	0.02	0.7%
12	5%	2275	447	1.84	0.14	465	0.10	95%	0.01	0.9%
13	5%	2274	296	1.76	0.25	400	0.03	98%	0.01	0.9%
SET Weighted Composite Results:				2.10	0.17		0.12	94%	0.03	1.4%**

Notes:

* Fuel economy impact of fuel-reductant addition for NOx adsorber regeneration.

** Increased exhaust restriction from the wall-flow and flow through monoliths results in a further FE impact of approximately 1-2% over the SET composite.

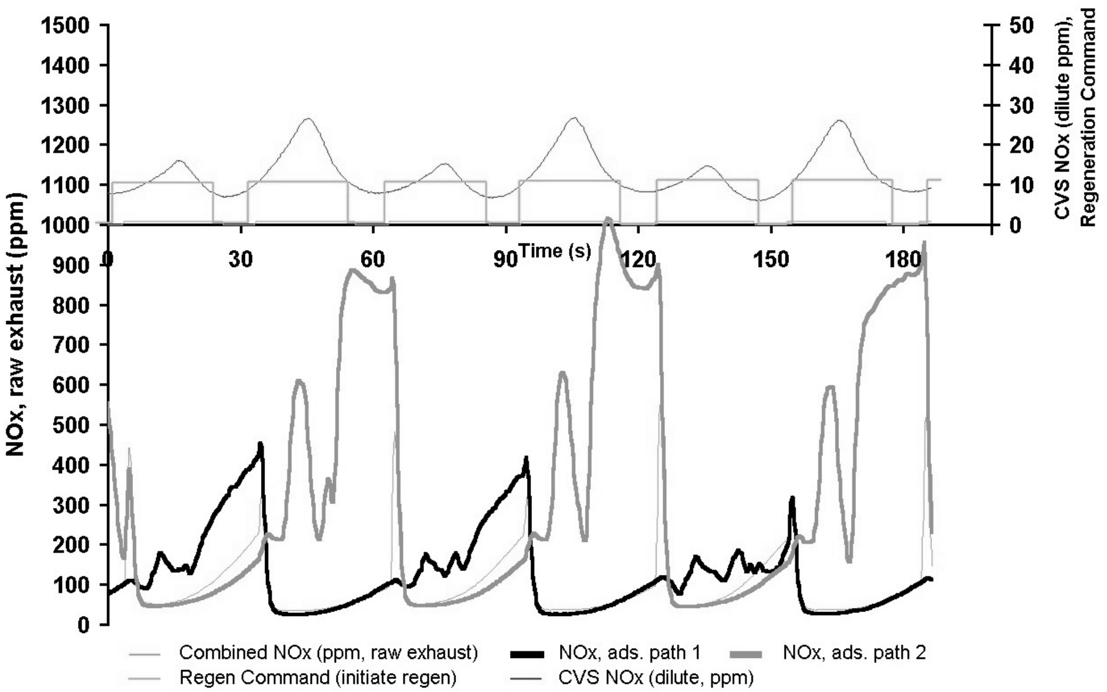


Figure 3: NOx breakthrough during adsorption, 18.3 bar BMEP, 1650 rpm (peak torque). Note that the concentrations of each regenerating path are considerable based on observation of the CVS NOx or the combined raw NOx concentrations. This is due to the very low mass flow through the regenerating path during the NOx release events.

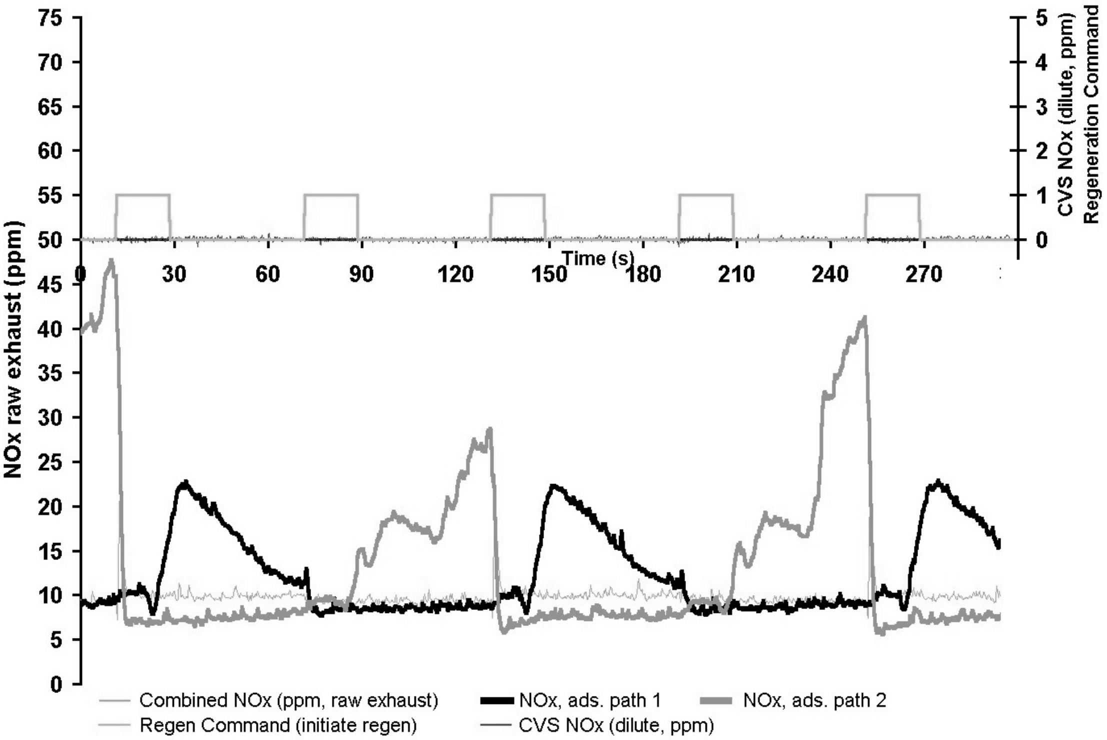


Figure 4: NOx breakthrough during adsorption, 4.6 bar BMEP, 1950 rpm.

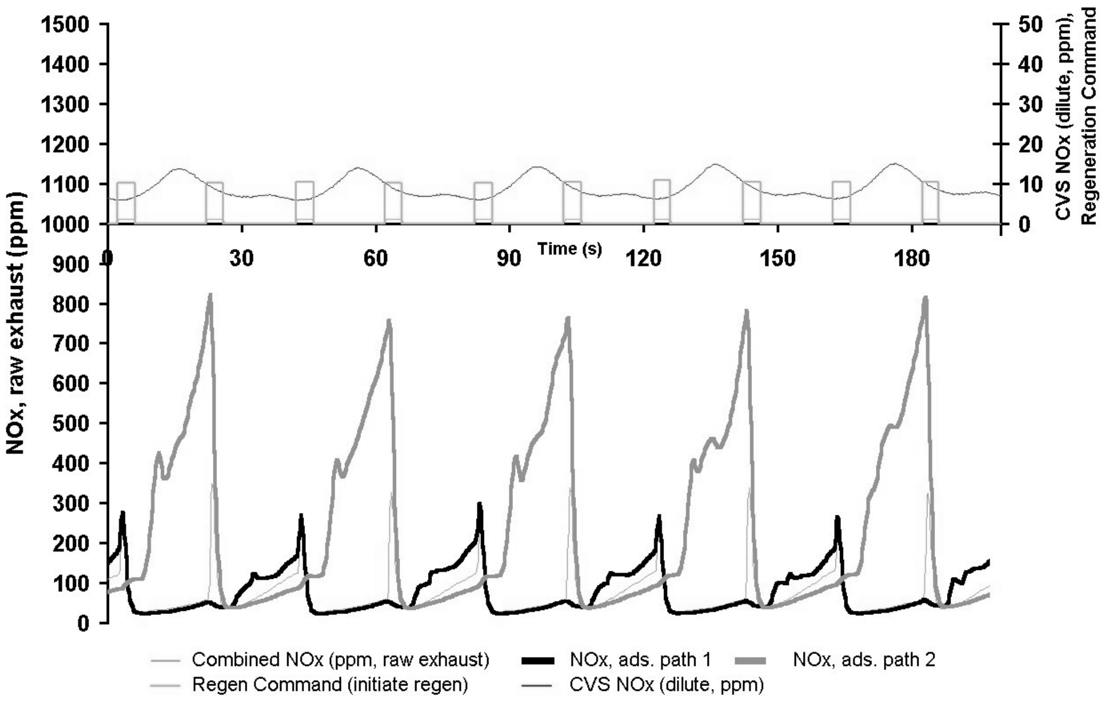


Figure 5: NOx breakthrough during adsorption, 16.2 bar BMEP, 2350 rpm (rated power).

Table 7: 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)	Reductant FE Impact %***
Modified Cummins ISB (Baseline)	2.67 ± 0.08	0.33 ± 0.04	2.1 ± 0.1	*	--
Modified Cummins ISB w/post-combustion emission controls	0.13 ± 0.02	0.06 ± 0.05	>0.03**	>0.002**	1.49 % ± 0.02 %

Notes

± values represent 95% confidence intervals for a two-sided Student's T-test for 5 to 6 repeated tests.

*Baseline PM did not pass QC checks for the PM sampler. Subsequent testing showed that baseline PM emission was 0.29 g/hp-hr.

**Below MDL for CO and PM (0.03 and 0.002 g/bhp-hr, respectively).

***FE impact of fuel reductant addition. The FE impact due to increased exhaust restriction was not significant (<0.5%) over the FTP.

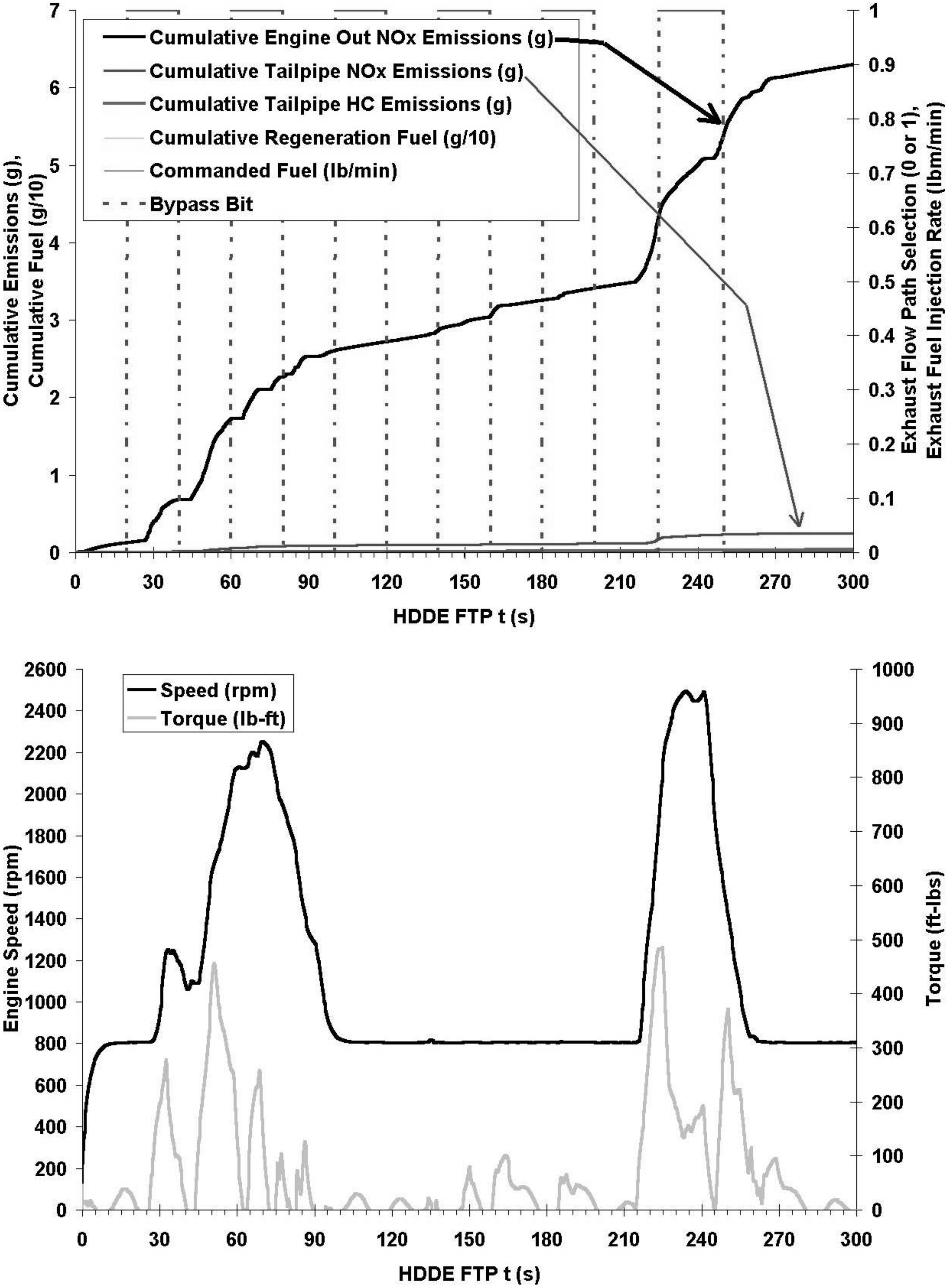
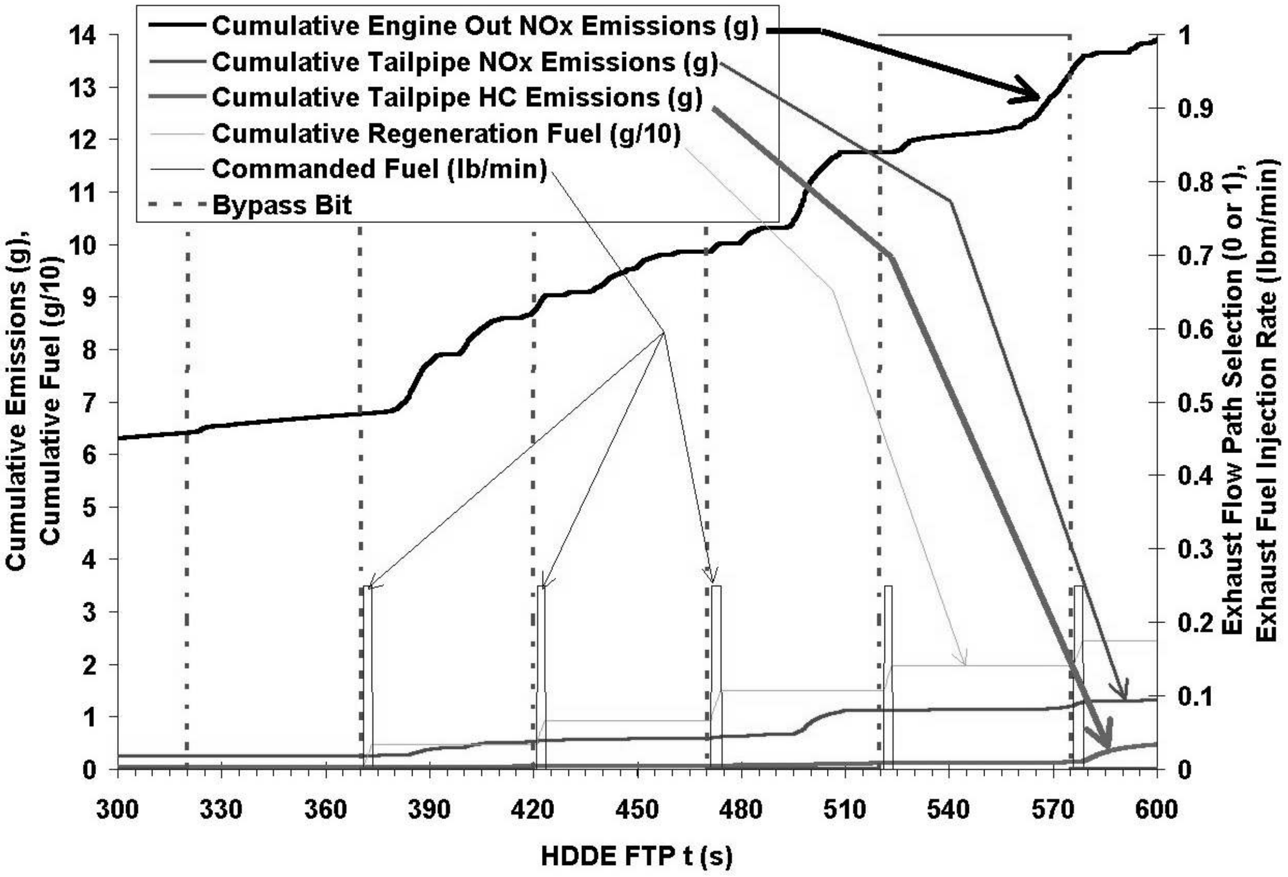


Figure 6: Cumulative emissions results for engine operation over the first 300 seconds (New York Nonfreeway) of the HDDE Hot-start FTP Transient Cycle.



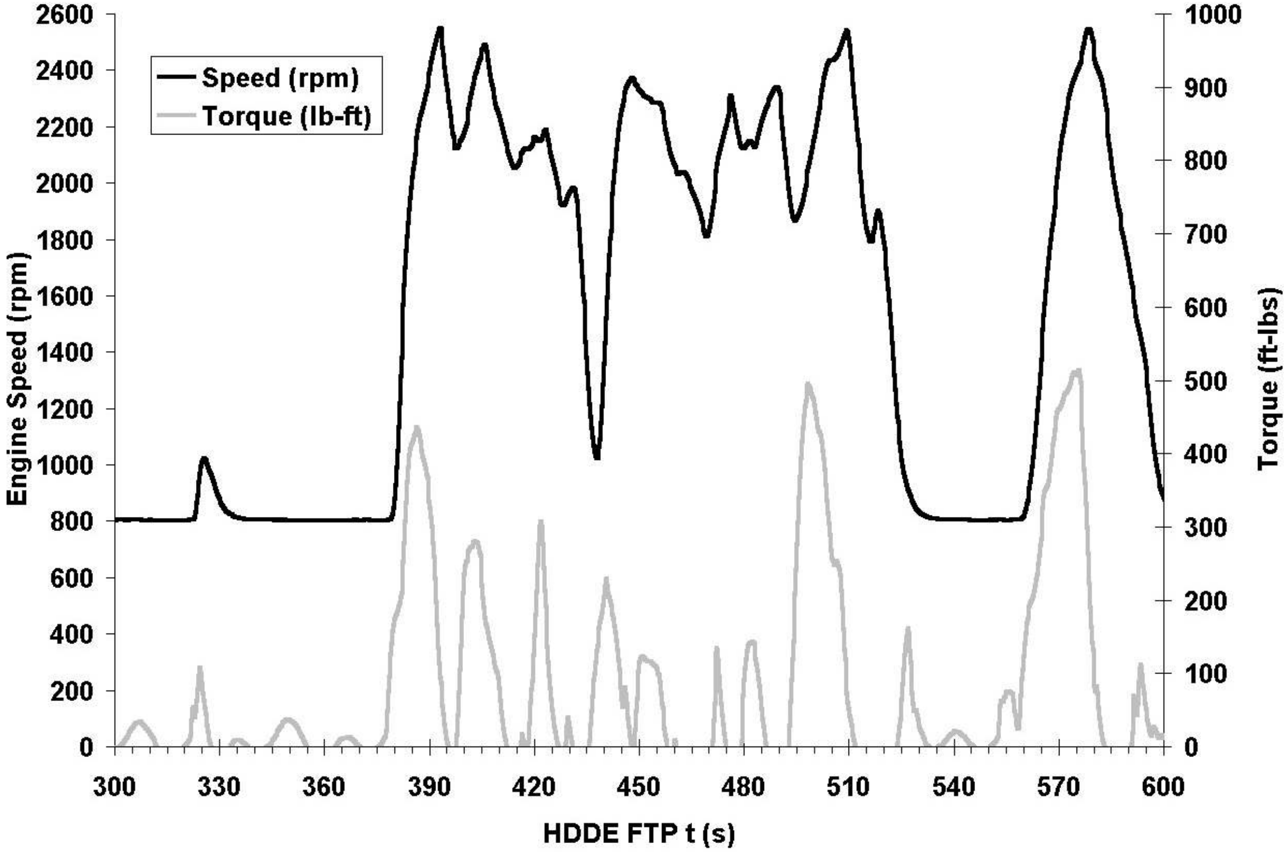


Figure 7: Cumulative emissions results for engine operation over the second 300 seconds (Los Angeles Nonfreeway) of the HDDE Hot-start FTP Transient Cycle.

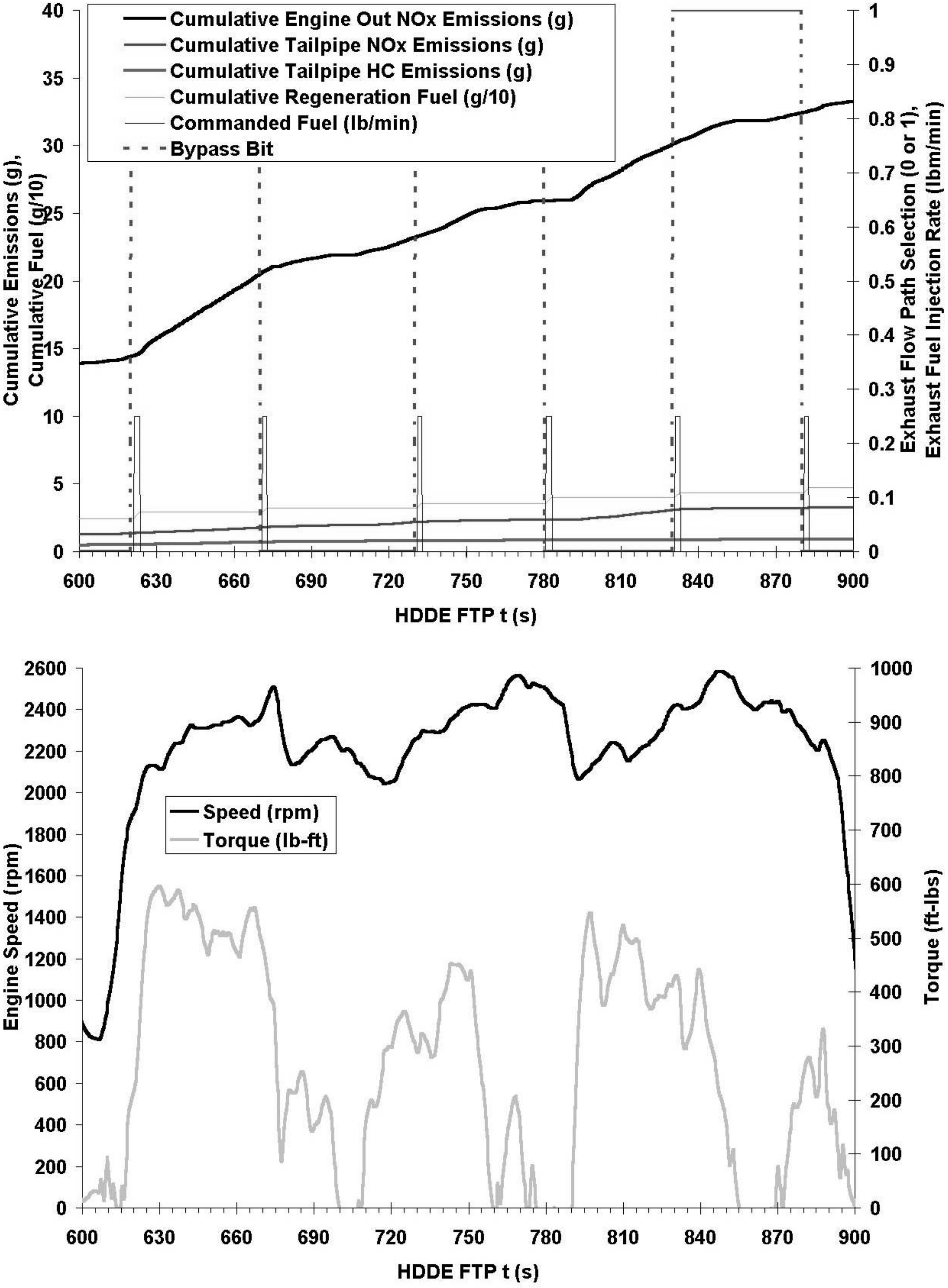


Figure 8: Cumulative emissions results for engine operation over the third 300 second period (Los Angeles Freeway) of the HDDE Hot-start FTP Transient Cycle.

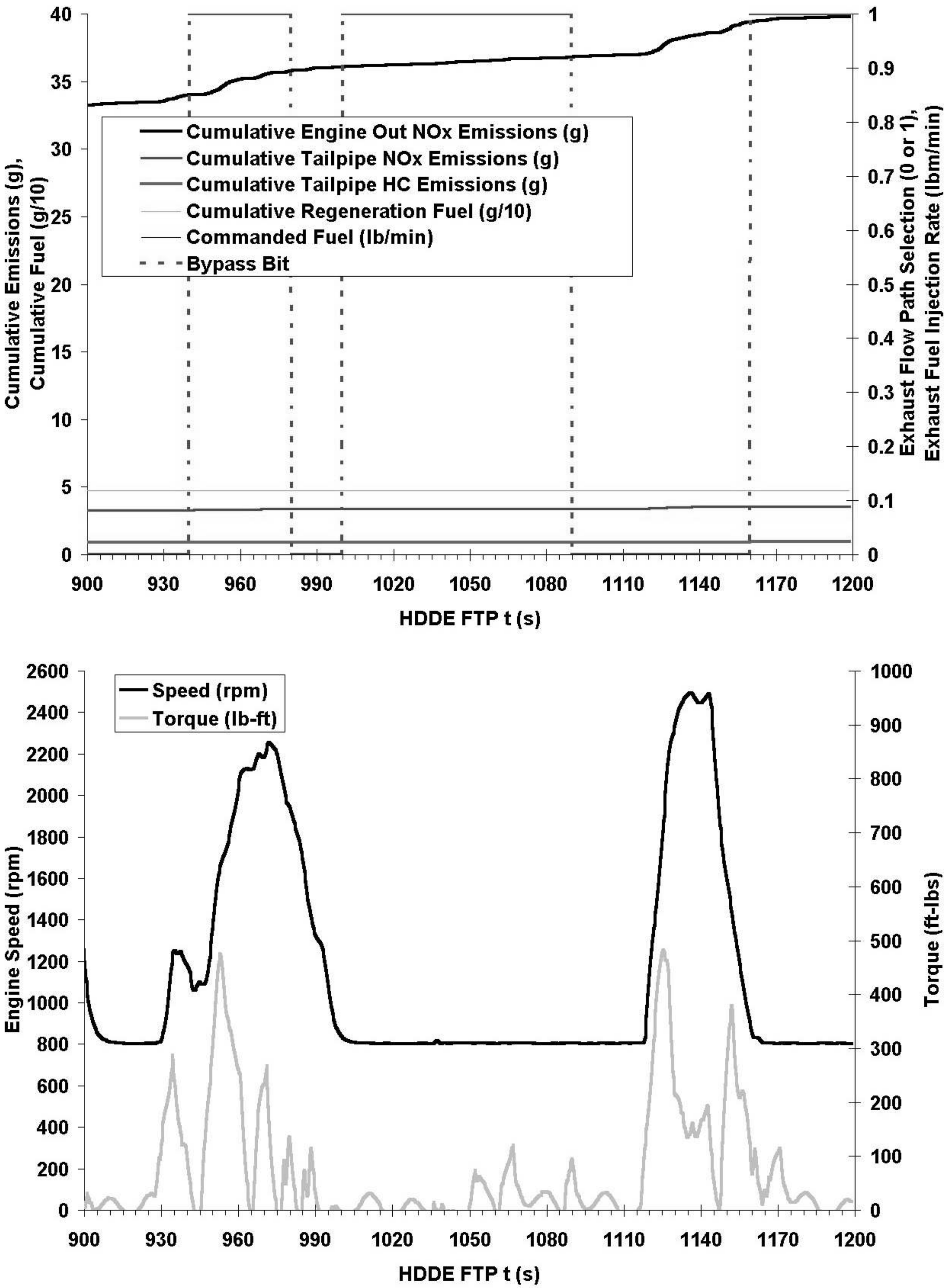


Figure 9: Cumulative emissions results for engine operation over the fourth 300 second period (repeat of New York Nonfreeway) of the HDDE Hot-start FTP Transient Cycle.

CONCLUSION

This test program has shown that a NOx adsorber /CDPF system is capable of hot-start HDDE-FTP emissions that are consistent with the 2007 standards. This approach has also demonstrated steady-state emissions that are consistent with the 2007 SET requirements. Regulated emissions were reduced from the baseline engine configuration by greater than 90 to 95% over the hot-start transient HDDE-FTP and SET composite. Nine of the thirteen SET modes occur within the NTE zone of the engine. Although specific NTE tests within the zone were not conducted, NOx emissions for all of the SET points within the NTE zone were within the 1.5X multiplier with the exception of the peak-torque point, which was slightly above the NTE limit (0.33 vs. 0.30 g/bhp-hr). The baseline modified ISB also fell outside of NTE compliance at this same point, so additional engine calibration and hardware (i.e. VG turbocharger) will be necessary to reduce engine-out NOx at peak torque.

Further cooperative development of the NOx adsorber/CDPF approach to diesel exhaust emission control will continue at the U.S. EPA-NVFEL facility, and will be the topic of subsequent papers.

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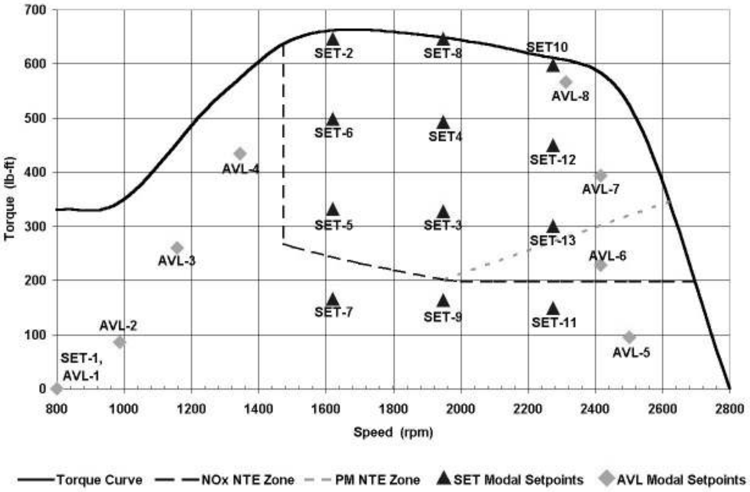
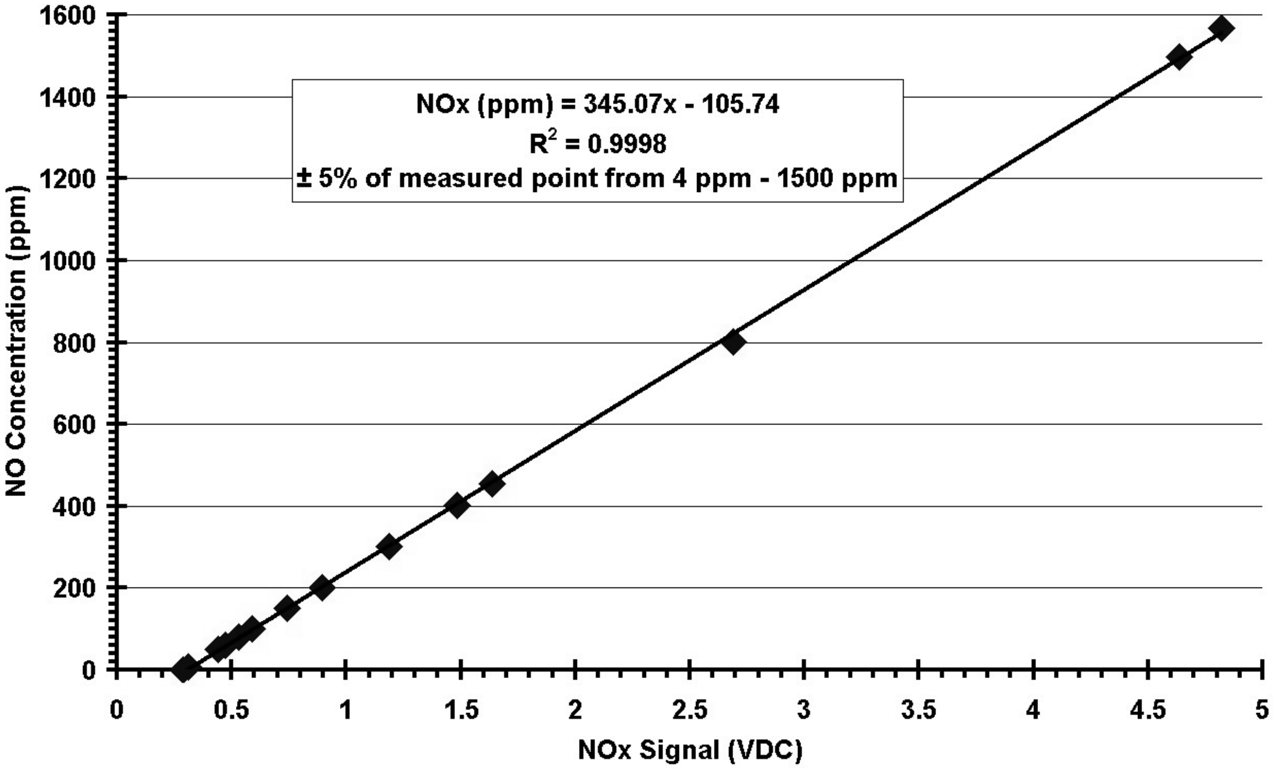
APPENDIX

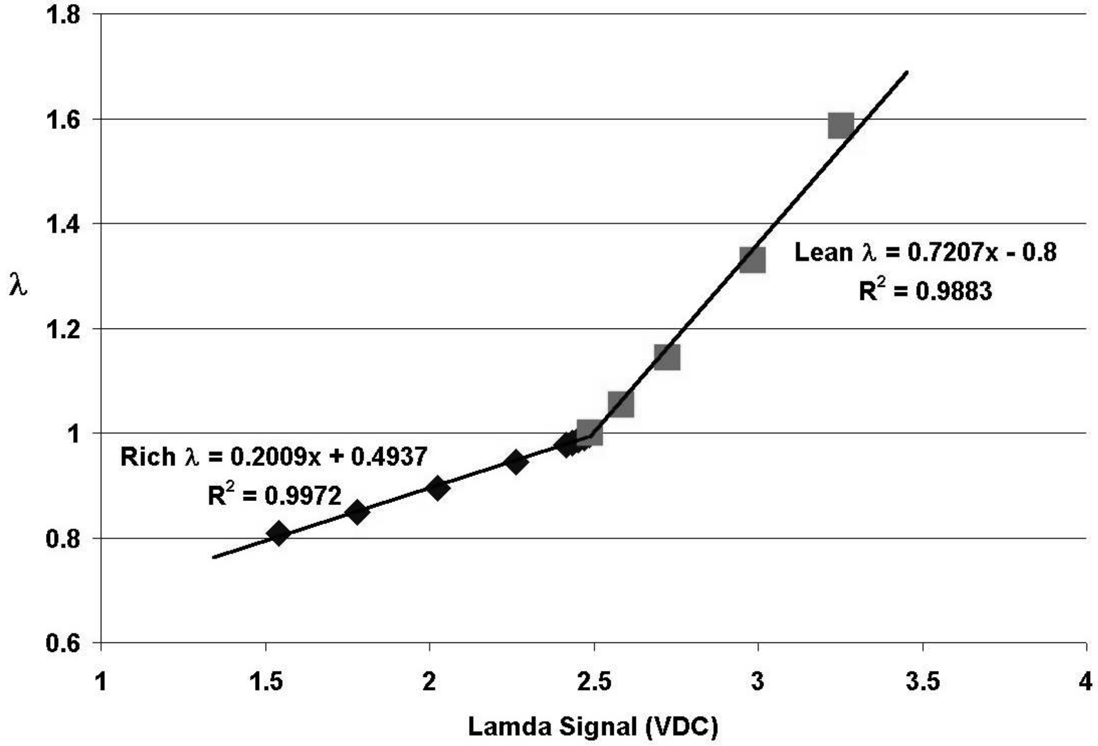


Appendix Figure i: SET 13-mode and AVL 8-mode steady-state speed and torque set-points for the Cummins ISB engine. The additional AVL set-points provided a broader range of exhaust temperatures for evaluation of NOx reduction efficiency.

Zirconia Sensor NOx Calibration



Zirconia Sensor Lamda Calibration



Appendix Figure ii: NOx and lamda calibration data for one of the zirconia NOx sensors. NOx calibration for this example was conducted using 3 concentrations of NO primary span gases (250 ppm, 450 ppm, and 2300 ppm) cut with high purity N_2 using a capillary gas divider. NO_2 response for this sensor is approximately 95%. The lamda calibration was comparable to that of similar UEGO sensors.