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# Four-Flow Path High-Efficiency $NO_x$ and PM Exhaust Emission Control System for Heavy-Duty On-Highway Diesel Engines

**Charles Schenk, Christopher Laroo, and Brian Olson**
U.S. EPA – Office of Transportation and Air Quality

**Lee Fisher**
Analytical Engineering, Inc.



## ABSTRACT

A 5.9 liter medium-heavy-duty diesel engine, meeting the emissions performance of a MY 2000 US heavy-duty on-highway engine, was tested with and without a diesel exhaust emission control system consisting of catalyzed diesel particulate filters and $NO_x$ adsorber catalysts arranged in a four-flow path configuration. This four-flow path system represents a significant reduction in catalyst volume when compared to previous systems tested by EPA. The goal of this project was to achieve high $NO_x$ reduction over the Heavy-Duty Diesel Engine Federal Test Procedure (HDDE-FTP) and Supplemental Emission Test (SET), consistent with the 2007 U.S. heavy-duty engine emissions standards, using this reduced volume system. Supply of hydrocarbon reductant for $NO_x$ adsorber regeneration was accomplished via a secondary exhaust fuel injection system. Alternating the restriction of the exhaust flow between the four-flow paths allowed reductant injection and adsorber regeneration to occur under very low space velocity conditions. Initial system tests showed impressive reductions of regulated pollutants. Emissions of $NO_x$ were reduced by 78% over the HDDE-FTP and 89% over the SET; and particulate matter (PM) emissions were reduced by 86% over the HDDE-FTP and SET. System improvements were identified during this testing which should allow the system to meet the 2007 emission targets. These improvements will be validated in future testing.

## 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 HDDE-FTP and the SET starting in 2007.[1] 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 covers the fifth phase of the continuing program under way at the U.S. EPA – National Vehicle and Fuel Emissions Laboratory (U.S. EPA-NVFEL) to evaluate advanced exhaust emission control systems for heavy-duty on-highway diesel engines. The results of the first four testing phases have been previously reported.[2-5] The results of phases 1 and 2 have shown that $NO_x$ adsorbers can achieve $NO_x$ reduction efficiencies greater than ninety percent after a modest accumulation of hours.[2,3]

A large amount of research has been performed and is still ongoing with respect to catalyst development; including the effects of thermal aging and poisoning due to sulfur exposure.[4,6-21] Little or no work has been published addressing system integration and packaging, particularly with respect to system size and catalyst volume, in on-road heavy-duty diesel applications.[2,3,22-26]

Previous work by Schenk *et. al.* has shown that greater than 90% reductions in $NO_x$ and PM could be met using 72 liters of catalyst volume (37 L CDPF, 28 L $NO_x$ adsorber, and 7 L Diesel Oxidation Catalyst [DOC]) in a dual-flow path configuration.[2,3] The primary focus of this paper will be to demonstrate an emission control system capable of providing large reductions in $NO_x$ and PM emissions over a broad range of engine operating conditions, while significantly reducing the catalyst volume and overall system cost when compared to previous systems. 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. All testing was performed using a newly developed four-flow path exhaust emission control system. Additional phases of this project not covered in this particular paper will be published in subsequent papers. Future related work is expected to include:

1. Further investigation of issues related to the thermal durability of $NO_x$ adsorber catalysts;

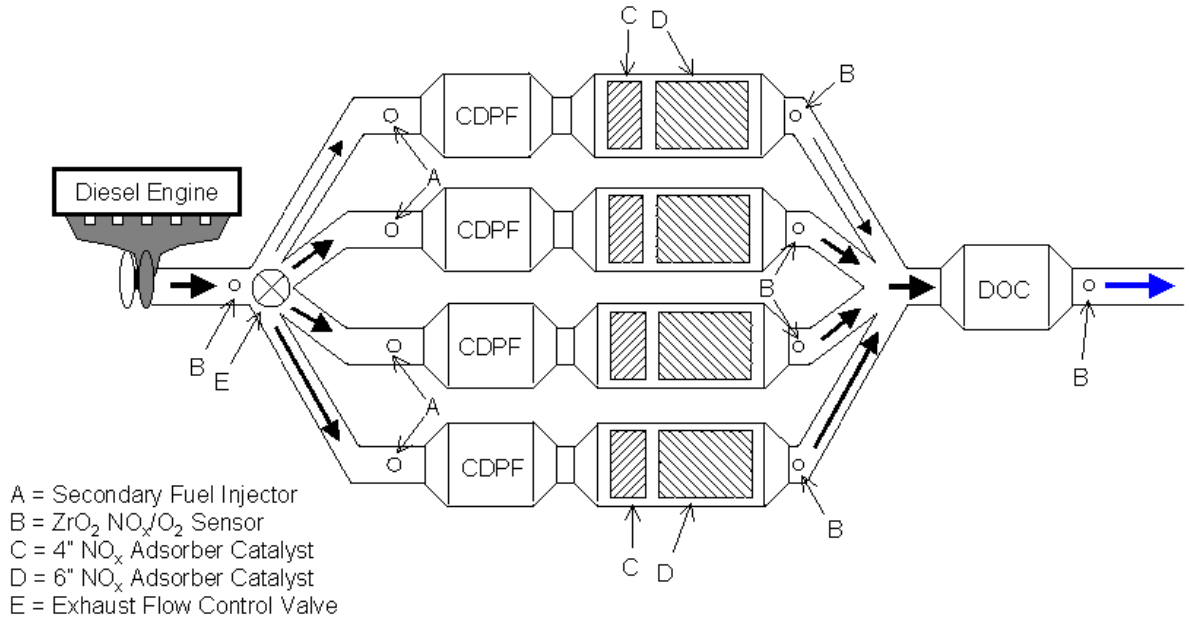



**Figure 1. Schematic representation of the layout and function of the four-flow path exhaust emission control system (not to scale).**

2. An extended catalyst durability test using the four-flow path exhaust emission control system;
3. Further investigation into the optimization of desulfation parameters;
4. System integration of the four-flow path exhaust emission control system onto a class 7 Freightliner demonstration truck.

## TEST PROCEDURES

### ENGINE DESCRIPTION

The engine used for testing the four-flow path exhaust emission control system was a 5.9-liter displacement Cummins ISB. The engine was identical to the engine used in phases 1 and 4 of this program and has been previously described.[2,5] The major engine specifications are summarized in Table 1.

### EXHAUST SYSTEM DESCRIPTION

$NO_x$ adsorber catalyst systems for lean gasoline and diesel applications have been previously described in detail.[27-30] The regeneration/$NO_x$ reduction control strategies used in this application are similar to the ones previously used and have been described as parts of phases one, two, and four of this work.[2,3,5]

Figure 1 is a functional schematic of the four-flow path exhaust emission control system tested with the Cummins ISB engine. The configuration of this system was chosen to minimize system size and cost with respect to hardware.

**Table 1. Summary of major engine specifications.[2,4]**

| | |
|---|---|
| **Engine:** | 2000 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 |
| **Engine Management:** | Stock |
| **Cylinder Displacement:** | 5.88 L |
| **Compression Ratio:** | 16.3:1 |

The emission control system was fabricated from 316 stainless steel. A four-flow path configuration was chosen to minimize backpressure while still allowing $NO_x$ adsorber regeneration and desulfation to occur under low exhaust space velocities. The system was sized to approach the footprint of a typical medium-heavy-duty muffler. A size comparison can be seen in Figure 2. While the emission control system is approximately 30% longer than the muffler in its current state, opportunities for further reduction of the system size still exist.

In addition to a reduction in overall system size a significant reduction in catalyst volume was also achieved. Total catalyst volume for the system was reduced from 72 L in the two-flow path system to 33 L in the four-flow path system. While total $NO_x$ adsorber volume was reduced, total adsorbing volume remained nearly the same (14 L adsorbing volume for two-flow path system vs. 12 L adsorbing volume for four-flow path

**Figure 2. Size comparison of four-flow path system with a typical medium-heavy-duty diesel muffler.[31]**

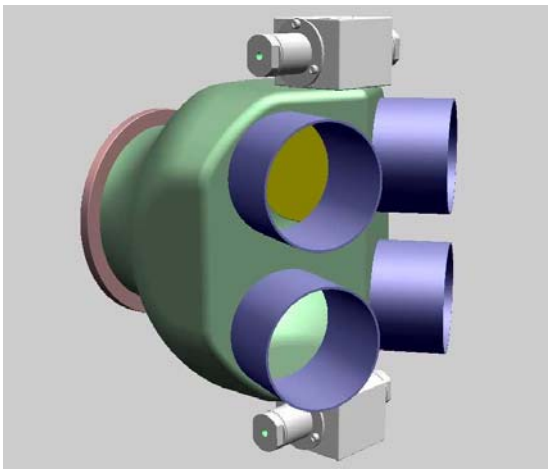


**Figure 3. Schematic of four-flow path valve system.[31]**

system). Each flow path contained one CDPF followed by two $NO_x$ adsorber substrates. The four flow paths rejoined at the collector, which houses the DOC. A summary of the major specifications of the CDPFs and $NO_x$ adsorbers used in this system can be found in Table 2. A prototype catalyzed Corning DuraTrap EC™ diesel particulate filter was used for PM reduction. This diesel particulate filter is similar in PM reduction performance to a Corning DuraTrap CO™ (EX-80), but is designed for lower soot-loaded pressure drop for both catalyzed and uncatalyzed diesel particulate filters.

The $NO_x$ adsorbers were chosen based on their performance over our thermal aging tests.[5] These adsorbers were known to have good aging characteristics and reasonable high temperature performance. This combined with their desulfurization performance made them the choice for this testing. The adsorbers were relatively unaged during this testing and had about 33 hours at various speed and loads.

Exhaust path flow control was accomplished through the use of a four-flow path valve system. Figure 3 shows a schematic of the valve. The valve design incorporates the use of two Bimba Three-Position Rotary Actuators (Model #CPT-822), which act as pneumatic actuators to control exhaust flow to each flow path. The valve positions were monitored using four Bimba Current Sinking (NPV) Hall Effect Switches (Model #HSK-04). The sensors were attached to the pneumatic actuators using Bimba Band Mounts (Model #D-35875-6).[31] The space envelope required for this valve, as designed for a medium-duty diesel truck platform, is about 2.5 L. The valve is constructed such that any one or two flow paths can be closed to restrict exhaust flow during regeneration (though normally only one is closed at a time), or all of the flow paths can be opened to normal exhaust flow if desired. Valve response time is approximately 0.5 seconds, and a control algorithm insures that only one flow path at a time is closed during $NO_x$ adsorber regeneration.

Reductant injection was performed using a low cost, low-pressure fuel injector. This fuel injector was designed to deliver a fine atomization of fuel at injection pressures below 50 psi. A low-pressure fuel injection system was desired so that fuel can be supplied to the injectors from the engine lift pump circuit on most current diesel engine configurations.

Low cost is achieved by the simple construction of the

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

| Device | Monolith Type | Cell Density (cpsi) | Wall Thickness (mil) | Diameter (inches) | Length (inches) | PGM Pt/Pd/Rh | PGM Loading ($g/ft^3$) | Base Metal Type** | Monolith Volume (L) | Total Volume (L) |
|---|---|---|---|---|---|---|---|---|---|---|
| CDPF | Corning DuraTrap EC™ | 200 | 12 | 5.66 | 6 | 1/0/0 | 50 | n/a | 2.47 | 9.88 |
| $NO_x$ Adsorber | Corning Celcor® | 400 | 4 | 5.66 | 10 | Trimetal* | ~100 | Ba, K | 4.12 | 16.48 |
| DOC | Corning Celcor® | 400 | 4 | 9.5 | 6 | 1/0/0 | 10 | n/a | 6.97 | 6.97 |

*Supplier did not provide the PGM ratio for combined 4" and 6" two substrate $NO_x$ adsorber assembly (totaling 10" in length per flow path).
** Supplier did not provide base metal loading information for the $NO_x$ adsorbers tested.

**Figure 4. Injector cap and body (actual size).[31]**

injector, which comprises only two components, an injector cap and body, both machined from stainless steel (Figure 4).[31] An ASCO two-way solenoid (Model #8225B008V) is used to control fuel flow to the injector. The solenoid is mounted with the injector in each individual flow path downstream of the valve (Figure 5). The valve body, reductant injectors, collector, and valve/injector drivers were fabricated, under contract, by Analytical Engineering Incorporated.

Preliminary testing of the four-flow path emission control system produced higher than expected exhaust lambda ($\lambda$) values in the regenerating flow paths during $NO_x$ adsorber regeneration. The quantity of reductant injected during these events was more than sufficient for adsorber regeneration, yet measured exhaust lambda values remained greater than 1. This can be seen in the

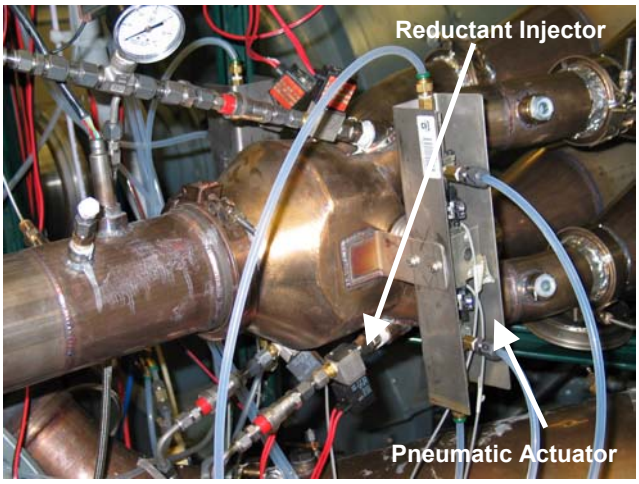



**Figure 5. Valve assembly with reductant injectors as installed in NVFEL Heavy-Duty Engine Site 1.**

"without cones" curves for flow paths 1, 2, and 3 in Figure 6. It is the authors' belief that the lambda sensor's proximity to the collector inlet (2.5 inches upstream) led to the elevated and inconsistent exhaust lambda values. This was due to a combination of flow stratification in the regenerating flow path and wrap around of lean exhaust from the three full flow paths into the rich regenerating flow path. This would dilute the rich pulse at the sensor, biasing the exhaust lambda

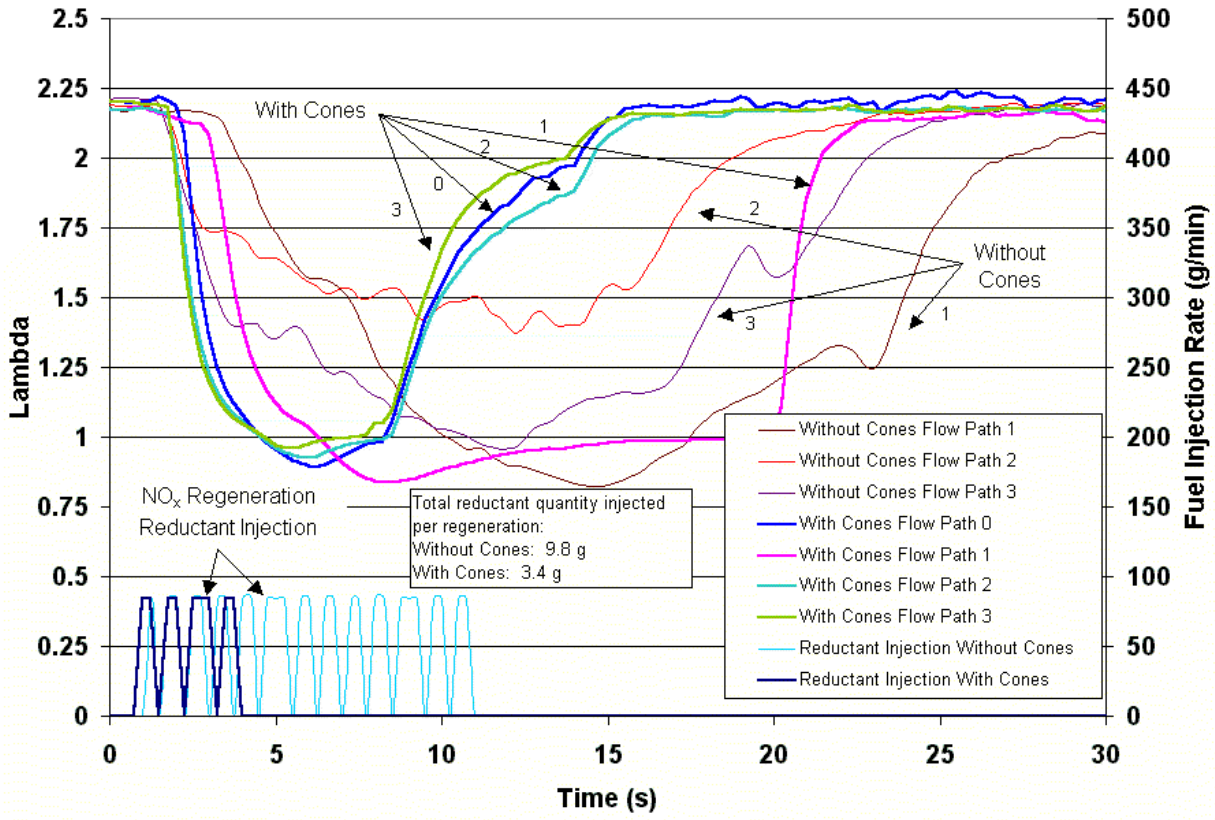



**Figure 6. Lambda and reductant injection values with and without the use of the 18-inch long extension during $NO_x$ adsorber regeneration (each exhaust lambda trace was time aligned with the start of reductant injection.**

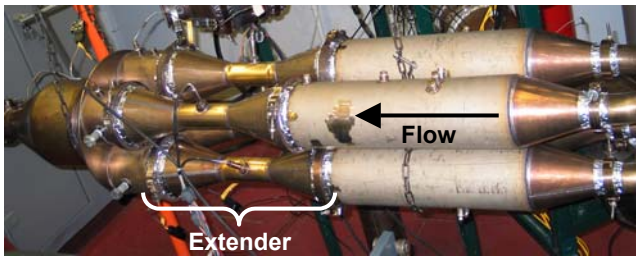



**Figure 7. Emission control system as tested in Heavy-Duty Engine Site 1 with 18-inch extenders located between adsorber outlet and collector inlet.**

measurement lean.

This exhaust lambda measurement discrepancy was corrected through the addition of 18-inch long extensions added to all four-flow paths between the outlet of the rear $NO_x$ adsorber and collector inlet. This extension consisted of an inlet cone transitioning from a 5.9 inch id to a 2.5 inch id over 6 inches of length at 60°, followed by a 2.5 inch id X 6 inch long tube, followed by an outlet cone identical to the inlet cone, but in reverse. The $ZrO_2$ $NO_x/O_2$ sensor was positioned in the center of the tube located between the two cones, positioning the sensor 16.5 inches from the collector inlet. This essentially eliminated the effects of backflow and stratification, allowing proper exhaust lambda measurement during $NO_x$ adsorber regeneration. Figure 7 shows the emission control system as tested at NVFEL Heavy-Duty Engine Site 1 with the addition of the 18-inch extenders. Future systems will integrate the small diameter tube into a more compact package than the current prototype.

Figure 6 shows the regeneration exhaust lambda values for flow paths 0, 1, 2, and 3 after installation of the sensors in the extensions. It can be noted from the figure that the indicated exhaust lambda values became much more consistent flow path to flow path and significantly less fuel was required to achieve the indicated $\lambda < 1$. The figure also shows very clearly that flow path 1 has a different valve leakage rate when compared to the other 3 flow paths. The low leakage was indicated by the long duration that the flow path held $\lambda < 1$ during regeneration and that flow path required approximately half of the fuel for adsorber regeneration when compared to the other three flow paths. This was a desirable feature, and efforts will be made to obtain similar regeneration flow rates on the other three flow paths for future testing.

## TEST FUEL

The fuel used in this work was Phillips Chemical Company Lot 1HPULD01. This fuel was similar to the fuel specified by the U.S. Department of Energy's (U.S. DOE) Diesel Emission Control – Sulfur Effects (DECSE) program to have similar properties to today's on-highway diesel fuel with the exception of zero sulfur content.[20,21]

**Table 3. Summary of diesel fuel properties.**

| Test Method | Results |
|---|---|
| **Net Heat of Combustion, ASTM D3338-92 (MJ/kg)** | 43.06 |
| **Density @ 15.5°C (g/cm$^3$)** | 0.8348 |
| **Cetane Number** | 44.8 |
| **Cetane Index** | 50.6 |
| **Olefins, FIA D1319-93 (% Vol.)** | 3.2 |
| **Aromatics, D1319-93 (% Vol.)** | 24.5 |
| **Sulfur, ASTM D2622 (ppm mass)** | < 0.7 |
| **Carbon, ASTM D3343-95 (% mass)** | 0.8659 |
| **Distillation Properties, ASTM D86** | |
| IBP (°C): | 181 |
| 10 % (°C): | 205 |
| 50 % (°C): | 259 |
| 90 % (°C): | 318 |
| End Point (°C): | 351 |
| Residue Diesel (mL): | 0 |
| Recovery: | 100% |

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. Fuel sulfur content was measured using x-ray fluorescence spectroscopy (XRF), which had a 0.7-ppm limit of detection (LOD) for sulfur. XRF indicated a fuel sulfur concentration that was below the LOD for the instrument.

## TEST CYCLES

The engine was tested over two different dynamometer test cycles:

1. The Supplemental Emission Test weighted steady-state modes[1]
2. The hot-start Heavy-Duty Diesel Engine Federal Test Procedure transient cycle[1]

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 N.[1] The SET was run as a sequence of steady state modes, from the coldest to the hottest in order to minimize stabilization time and to allow individual PM measurements to be taken at each mode.

## LABORATORY

The engine and exhaust emission control system 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 hp 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 N.[1] 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 testing.[1] This included the use of new high-efficiency PM filter sample media and filter sample holders as specified for low-concentration PM measurement. A bag system was also used to provide a redundant measurement of dilute $NO_x$ emissions in addition to the more usual continuous dilute $NO_x$ measurement.[1] PM measurements for SET testing did not follow the single test filter procedure outlined in 40 CFR § 86.1360-2007. Individual sample filters were used for each mode and the modal weighting factors were applied to PM emission rate and power.

$NO_X$ ADSORBER REGENERATION STRATEGY

Steady State Testing

Testing at SET steady-state speed-load conditions was conducted using a semi-automatic controller implemented in LabView. The general strategy was to inject sufficient fuel during regeneration to achieve exhaust conditions fuel-rich of stoichiometric ($0.85 < \lambda < 1$). The fuel quantity injected was calculated based on engine speed, engine load, and catalyst outlet temperature. The regeneration frequency was set to fixed intervals to achieve the desired tradeoff between $NO_x$ performance and fuel consumption.

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 at this time. Catalyst preconditioning, particularly with respect to catalyst temperature, was found to be very critical. In order to best simulate the standard “cold-soak-hot” procedure, the catalyst system was soaked for 20 minutes between each cycle (i.e. hot HDDE-FTP-soak-HDDE-FTP).

Regeneration control for the hot-start HDDE-FTP transient testing was accomplished using an automatic regeneration controller. Instead of the fixed regeneration frequency used in the steady state modes, the regenerations were controlled automatically. Regenerations were triggered by $NO_x$ slip measured downstream of the catalyst system. The $NO_x$ slip targets were calculated from engine speed and load. Once regeneration was initiated, the end of the regeneration cycle was determined by a $\lambda > 1$ or time. As the exhaust lambda value in the regenerating flow path rose back above $\lambda = 1$ or a maximum regeneration time was exceeded, the regenerating flow path was opened to full flow again (all flow paths open) until $NO_x$ slip triggered regeneration of the next flow path.

**Table 4. Exhaust fuel-reductant injection schedule over the SET.**

| SET Mode | Regeneration Period (s) | Injection Duration (s) | Injection Rate (g/min) |
|---|---|---|---|
| 1 | -- | -- | -- |
| 2 | 30 | 3.8 | 85 |
| 3 | 45 | 3.5 | 85 |
| 4 | 40 | 4.5 | 85 |
| 5 | 38 | 3.8 | 85 |
| 6 | 40 | 4.5 | 85 |
| 7 | 60 | 2.1 | 85 |
| 8 | 23 | 3.8 | 85 |
| 9 | 60 | 2.4 | 85 |
| 10 | 20 | 3.8 | 85 |
| 11 | 30 | 2.8 | 85 |
| 12 | 37 | 4.5 | 85 |
| 13 | 40 | 3.8 | 85 |

## RESULTS

STEADY-STATE SET RESULTS

The regeneration calibrations for each of the SET modes are shown in Table 4. Modal and composite SET $NO_x$, hydrocarbon, and PM emission results are presented in Tables 5 and 6. The weighted composite SET $NO_x$ emission of 0.36 g/hp-hr represented an 89% reduction from conditions without the $NO_x$ adsorber catalyst system. $NO_x$ reduction efficiency over the SET was comparable to the results of phases 1 and 2 of this test program which used the two-flow path emission control system.[2,3] Since the adsorbers used in this testing were different formulations than those used in previous testing, the $NO_x$ reduction performance as a function of temperature (Figure 8) was also different. The high temperature performance of the new formulation was not quite as good as the older formulation as evidenced by high temperature modes 8 and 10. The old formulation had $NO_x$ reductions of 91% and 95% respectively at these modes, compared to 85% and 75% with the new formulation. The tradeoff is that the new formulation has the ability to be desulfated at lower temperatures and has been shown to provide better aging performance.[5]

PM emission results of 0.009 g/hp-hr were demonstrated for the SET. This was a substantial reduction from the baseline emissions. Hydrocarbon emissions for the SET composite were 0.11 g/hp-hr, which was a reduction from the 0.17 g/hp-hr without the catalyst system. The fuel economy penalty for the SET due to reductant injection was 1.6%.

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. Details of the regeneration events and cumulative $NO_x$ and HC emissions over the hot-start HDDE-FTP are presented in Figures 9 – 12 (a and b). The combination

**Table 5. Modal and composite SET $NO_x$ and HC emissions results for the Modified Cummins ISB engine.**

| Cummins ISB (baseline) | | | | | | Cummins ISB w/post-combustion emission controls | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SET Mode | SET Weighting | Speed (rpm) | Torque (lb-ft) | BSNO$_x$ (g/hp-hr) | BSHC (g/hp-hr) | Outlet T (°C) | BSNO$_x$ (g/hp-hr) | NO$_x$ (% Reduction) | BSHC (g/hp-hr) | Reductant FE Impact (%)* |
| 1 | 15% | Idle | 0 | 0.00 | 0.00 | 144 | 0.16 | 100% | 0.00 | 0.0% |
| 2 | 8% | 1616 | 649 | 3.48 | 0.10 | 475 | 0.29 | 92% | 0.06 | 1.4% |
| 3 | 10% | 1943 | 331 | 3.06 | 0.22 | 355 | 0.08 | 97% | 0.11 | 1.4% |
| 4 | 10% | 1942 | 495 | 2.98 | 0.13 | 419 | 0.14 | 95% | 0.07 | 1.3% |
| 5 | 5% | 1615 | 335 | 3.50 | 0.26 | 368 | 0.13 | 96% | 0.11 | 2.1% |
| 6 | 5% | 1616 | 500 | 3.45 | 0.15 | 426 | 0.11 | 97% | 0.08 | 1.6% |
| 7 | 5% | 1614 | 169 | 5.25 | 0.53 | 251 | 0.72 | 86% | 0.27 | 1.5% |
| 8 | 9% | 1942 | 635 | 3.16 | 0.09 | 496 | 0.47 | 85% | 0.06 | 1.5% |
| 9 | 10% | 1941 | 167 | 4.46 | 0.57 | 291 | 0.60 | 87% | 0.44 | 4.3% |
| 10 | 8% | 2271 | 594 | 3.24 | 0.08 | 509 | 0.80 | 75% | 0.07 | 1.6% |
| 11 | 5% | 2269 | 153 | 3.81 | 0.71 | 282 | 0.67 | 82% | 0.36 | 2.5% |
| 12 | 5% | 2270 | 453 | 3.21 | 0.11 | 406 | 0.19 | 94% | 0.06 | 1.3% |
| 13 | 5% | 2269 | 303 | 3.17 | 0.19 | 343 | 0.19 | 94% | 0.17 | 1.4% |
| **SET Weighted Composite Results:** | | | | 3.33 | 0.17 | | 0.36 | 89% | 0.11 | 1.6%** |

* Fuel economy impact of fuel-reductant addition for $NO_x$ 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.

**Table 6. Modal and composite SET PM emissions results for the Modified Cummins ISB engine.**

| SET Mode | SET Weighting | Speed (rpm) | Torque (lb-ft) | BSPM (g/hp-hr) Without Post Combustion Emission Controls | BSPM (g/hp-hr) With Post Combustion Emission Controls |
|---|---|---|---|---|---|
| 1 | 15% | Idle | 0 | 0.000 | 0 |
| 2 | 8% | 1616 | 649 | 0.057 | 0.004 |
| 3 | 10% | 1943 | 331 | 0.058 | 0.014 |
| 4 | 10% | 1942 | 495 | 0.067 | 0.010 |
| 5 | 5% | 1615 | 335 | 0.062 | 0.011 |
| 6 | 5% | 1616 | 500 | 0.048 | 0.008 |
| 7 | 5% | 1614 | 169 | 0.113 | 0.012 |
| 8 | 9% | 1942 | 635 | 0.068 | 0.009 |
| 9 | 10% | 1941 | 167 | 0.094 | 0.006 |
| 10 | 8% | 2271 | 594 | 0.073 | 0.008 |
| 11 | 5% | 2269 | 153 | 0.130 | 0.006 |
| 12 | 5% | 2270 | 453 | 0.056 | 0.008 |
| 13 | 5% | 2269 | 303 | 0.000 | 0.015 |
| **SET Weighted Composite Results:** | | | | 0.065 | 0.009 |

of CDPFs, $NO_x$ adsorbers, and DOC reduced brake specific emissions of PM, and CO by 85% or greater and $NO_x$ by 78% when compared to the baseline condition (no post-combustion emission controls). However the HC emissions increased relative to the baseline. The fuel economy impact due to exhaust fuel injection for $NO_x$ adsorber regeneration was 3.4%.

It can be seen from Figures 9 – 12 that there is small but significant $NO_x$ slip occurring over the first 640 seconds of the cycle. During this part of the cycle adsorber temperatures fluctuated between 200°C and 250°C (Figure 13, temperature downstream of DOC with insulation). The $NO_x$ adsorber efficiency is relatively low in this temperature range (Figure 8), allowing the observed slip. More than half the $NO_x$ slip occurred between 640 and 690 seconds (Figure 11). During this time the engine transitions from a very low average BMEP to a much higher BMEP. The engine exhaust has a much higher $NO_x$ mass rate at these high BMEPs, but the $NO_x$ adsorbers were still below their optimum operating temperature. The adsorbers didn't reach their optimum temperature until about 750 seconds into the cycle. The majority of the cycle $NO_x$ slip occurred during this warm-up period when the catalyst temperatures were still below the optimum temperature and engine $NO_x$ output was high.

The low temperatures experienced during the transient cycle were due in part to the low mass and high surface

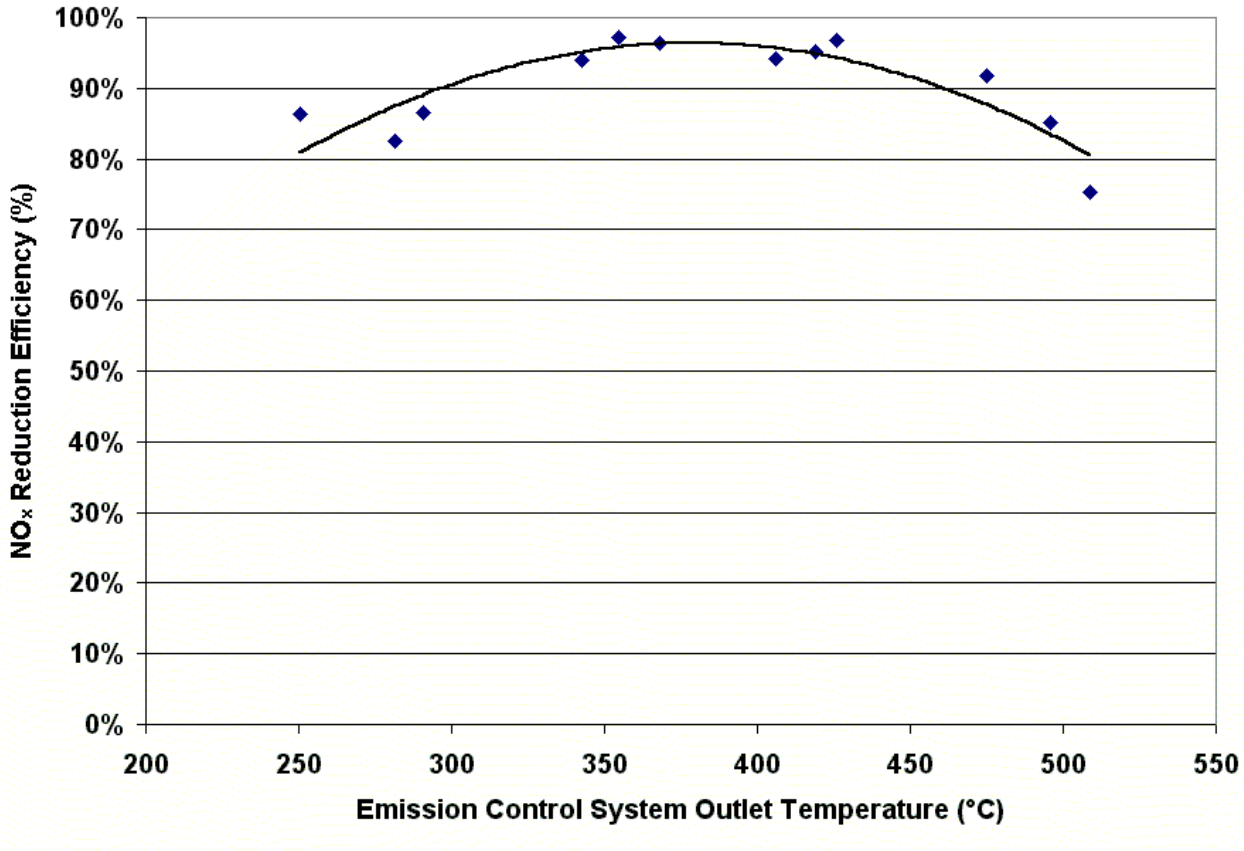



**Figure 8. $NO_x$ reduction as a function of temperature for the $NO_x$ adsorber used during this test program.**

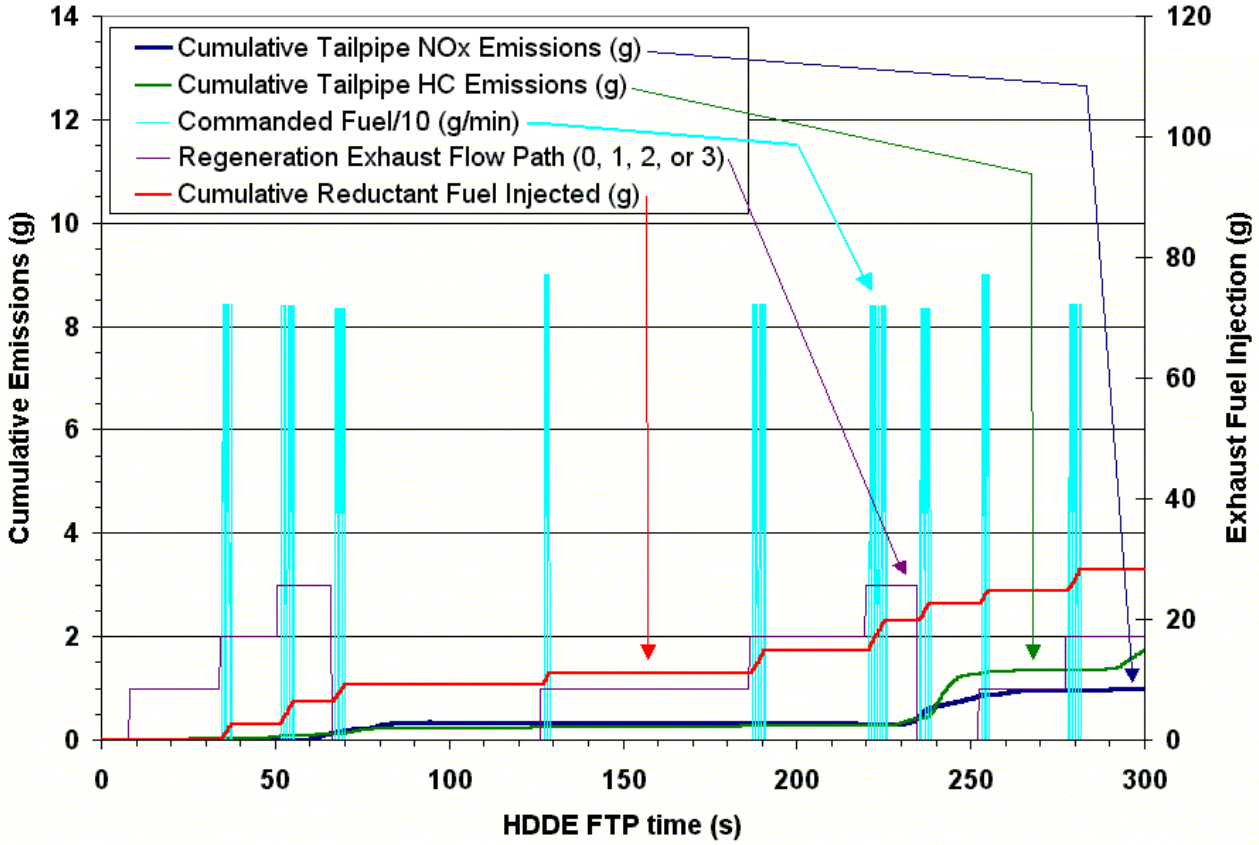
**Table 7. Comparison of brake-specific emissions over the HDDE hot-start FTP transient cycle with and without the exhaust emission control system.**

| Engine Configuration | Average BSNO$_x$ (g/hp-hr) | Average BSHC (g/hp-hr) | Average BSCO (g/hp-hr) | Average BSPM (g/hp-hr) | Reductant FE Impact %** |
|---|---|---|---|---|---|
| Cummins ISB (Baseline) | 3.30 ± 0.02 | 0.19 ± 0.01 | 0.87± 0.01 | 0.09 ± 0.00 | -- |
| Cummins ISB w/post-combustion emission controls | 0.73 ± 0.01 | 0.48 ± 0.15 | 0.01* | 0.01 ± 0.00 | 3.4% ± 0.4% |

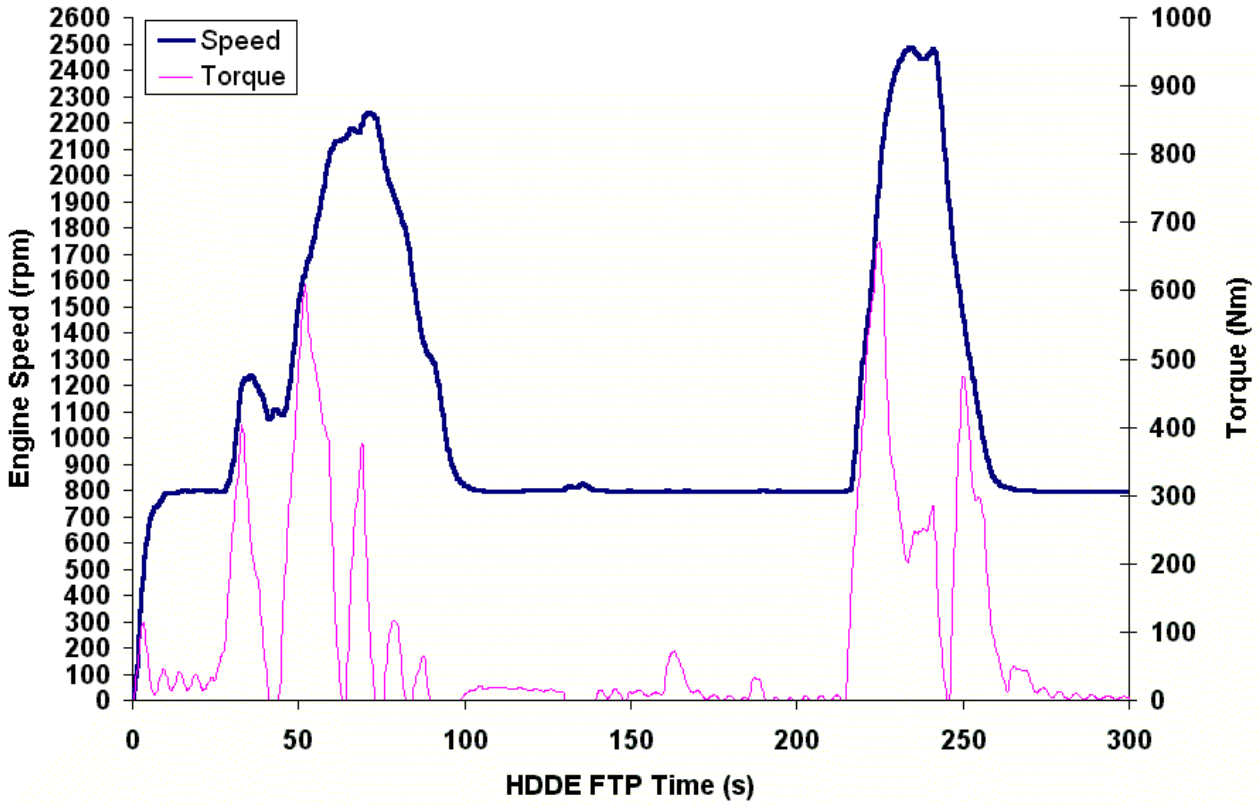
Notes:
± values represent 95% confidence intervals for a two-sided Student's T-test for 3 to 4 repeated tests.
*Below MDL for CO (0.03 g/bhp-hr).
**FE impact of fuel reductant addition. The FE impact due to increased exhaust restriction was not significant (<0.5%) over the FTP.

area of this system that allowed it to cool off rapidly during the soak periods. To minimize soak heat loss between cycles, the system was insulated from the engine to the adsorber outlets. The transient data reported here was with the insulated system. Figure 13 shows the catalyst system outlet temperature with and without insulation over two cycles with the same preconditioning soak. Insulating the system was found to improve the cycle $NO_x$ by approximately 0.7 g/hp-hr. Additional improvements were demonstrated by preconditioning at higher temperatures via shorter soak times, but this preconditioning was not deemed to be realistic and the results were not presented here. While this approach to preconditioning would not be realistic, it does show that improved temperature management through other means would have potential to improve these results.

The transient data presented here highlights the important aspects of catalyst work that the light-duty

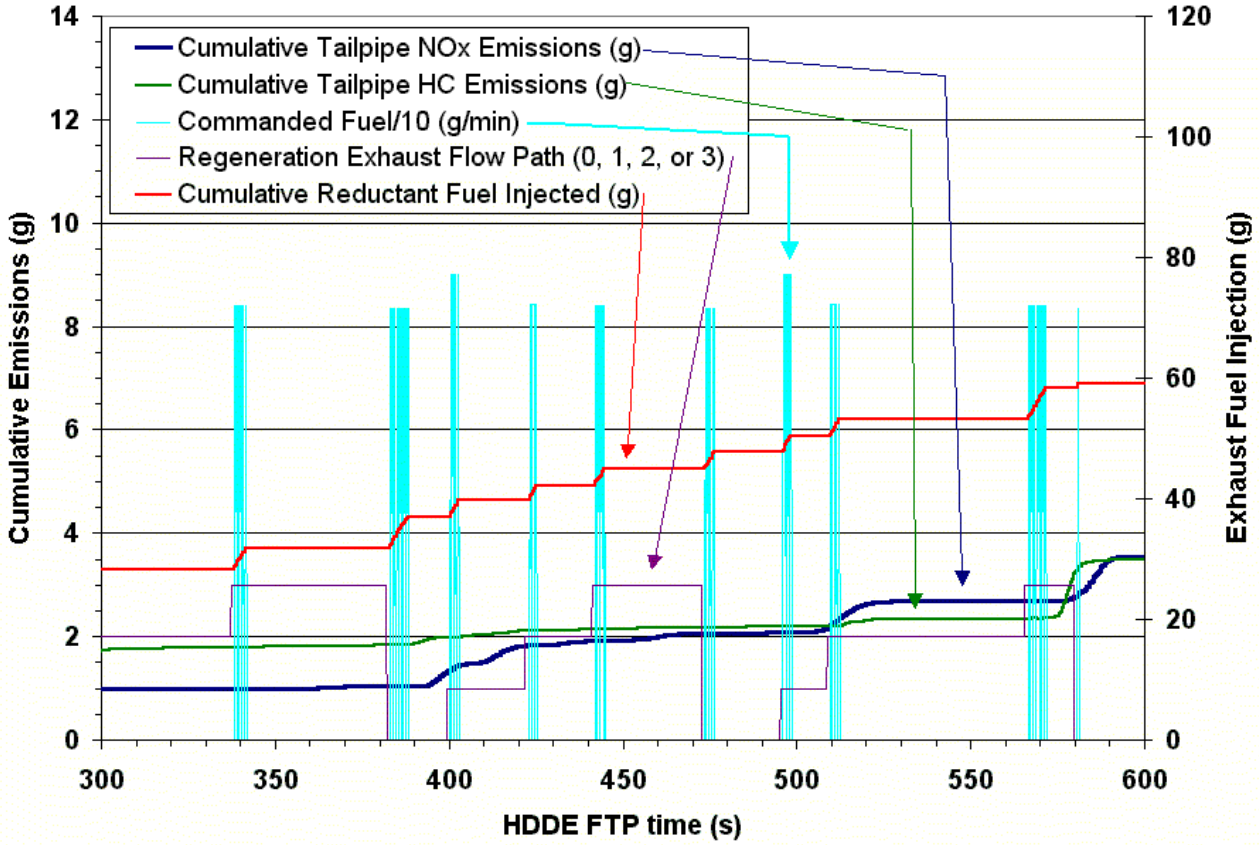



(a)

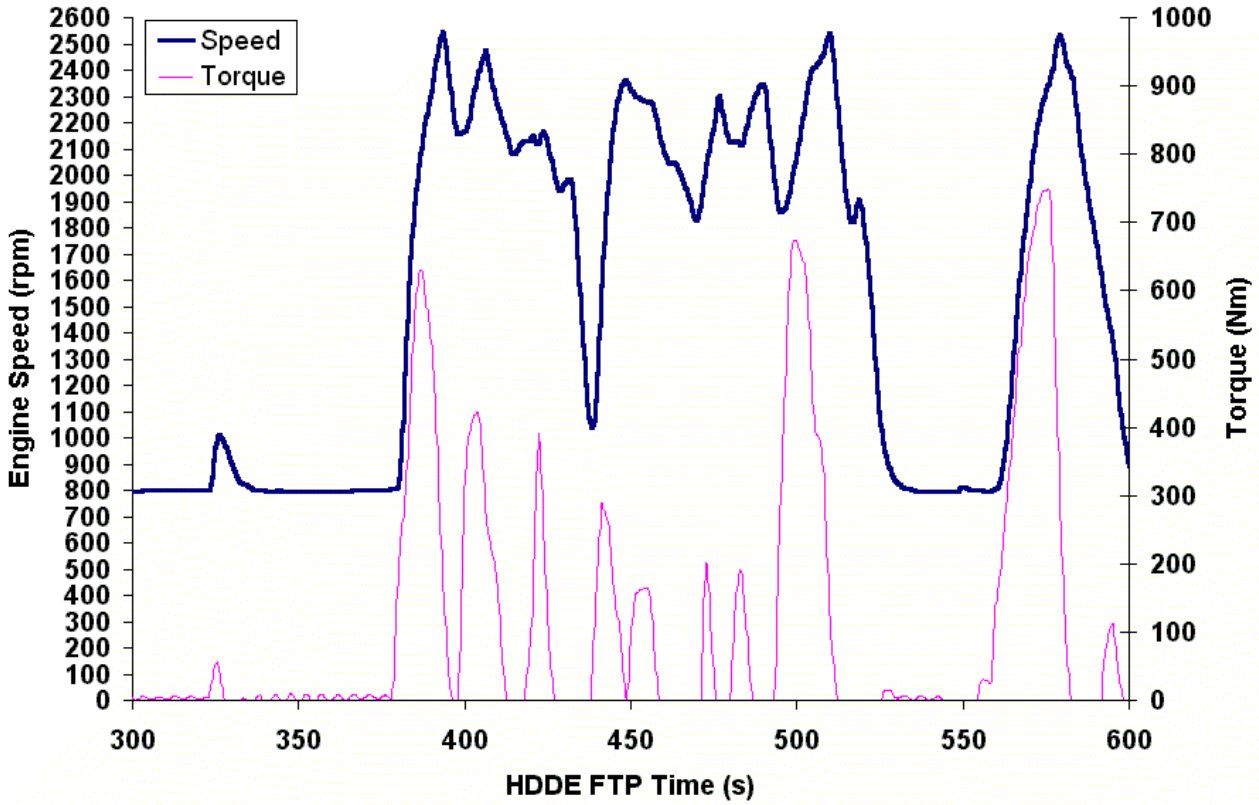



(b)

**Figure 9. Cumulative emissions results (a) for engine operation of the first 300 seconds (New York Nonfreeway) of the HDDE Hot-Start FTP Transient Cycle (b).**

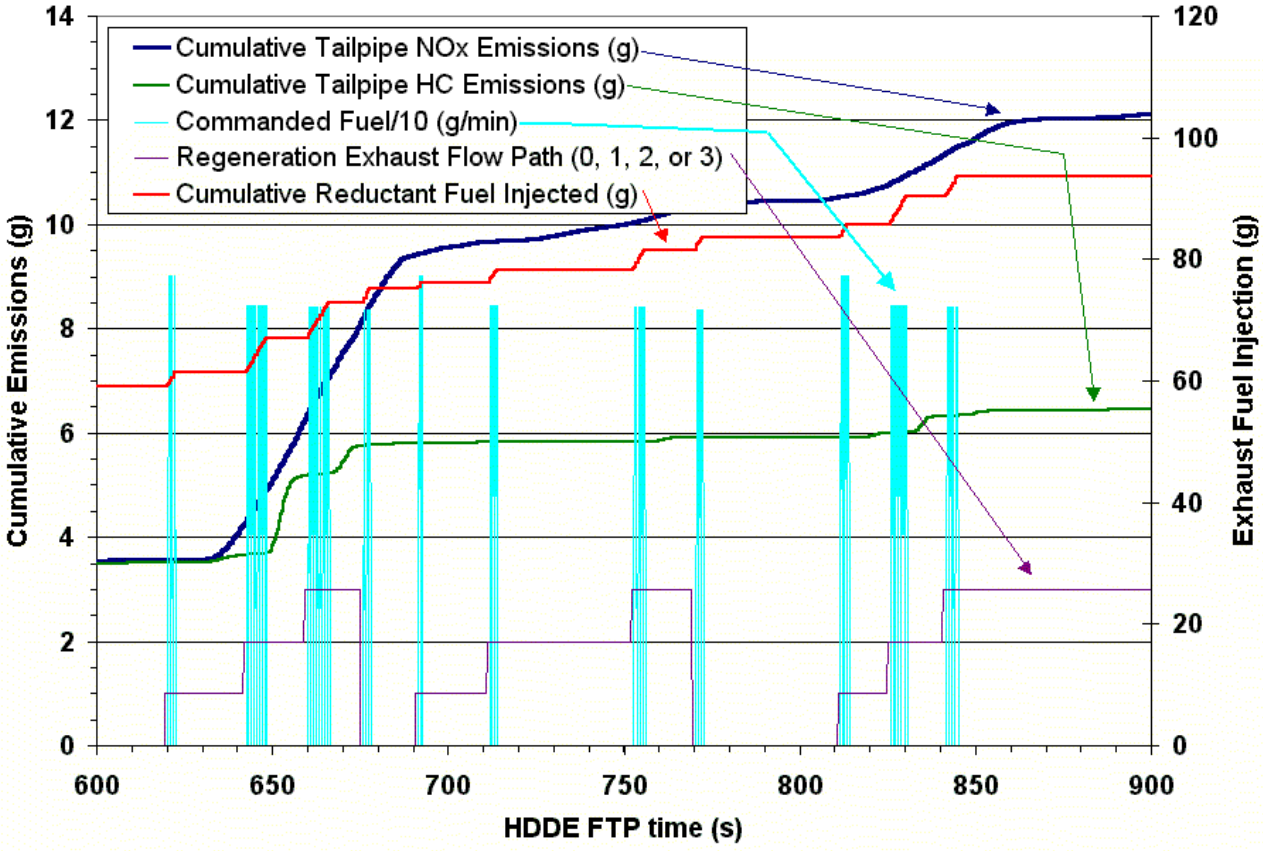



(a)

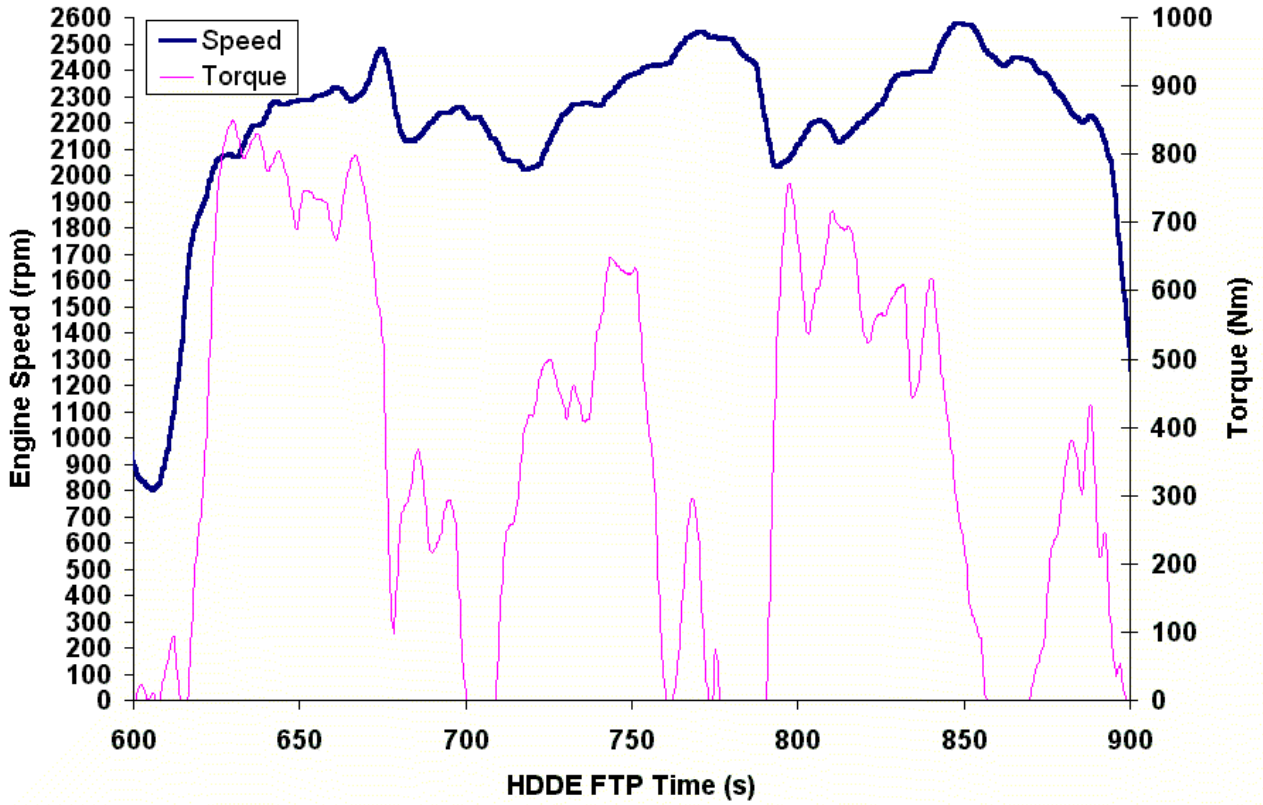



(b)

**Figure 10. Cumulative emissions results (a) for engine operation over the second 300-second period (Los Angeles Nonfreeway) of the HDDE Hot-Start FTP Transient Cycle (b).**

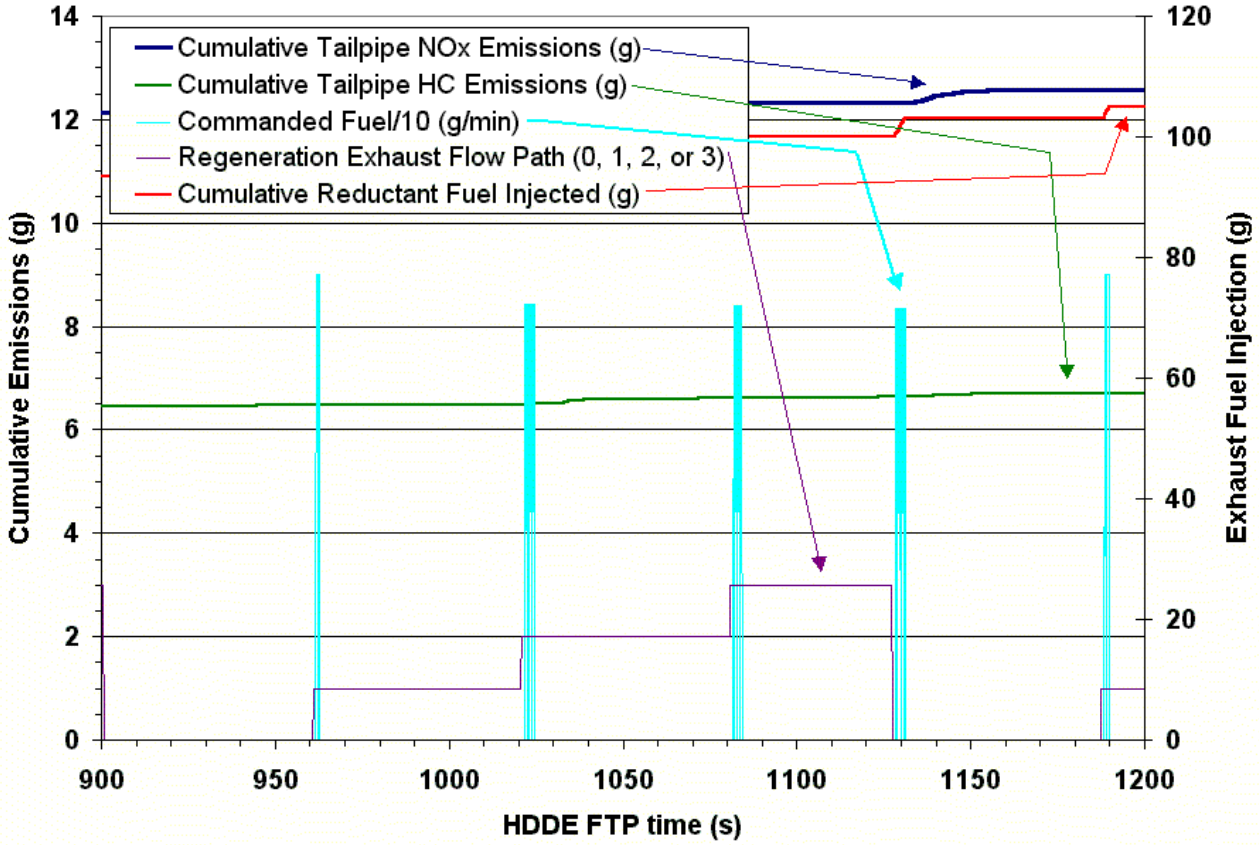



(a)

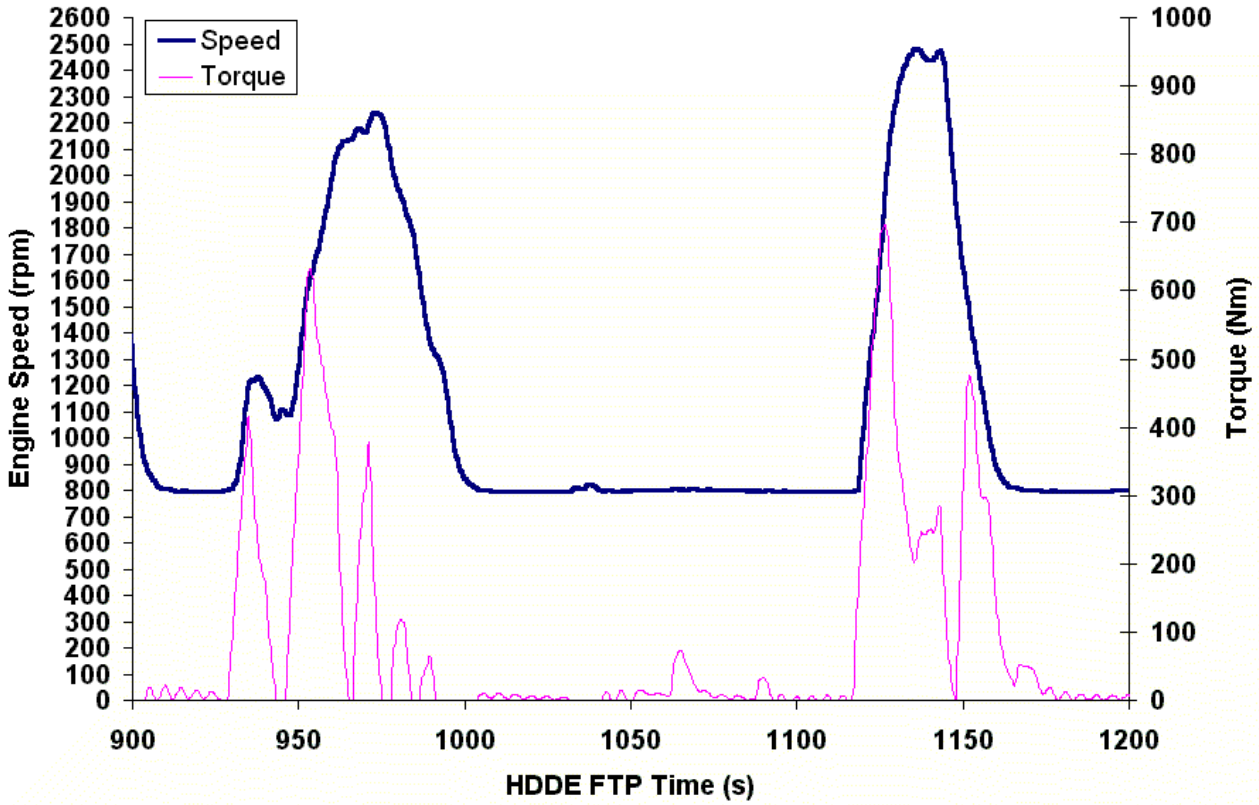



(b)

**Figure 11. Cumulative emissions results (a) for engine operation over the third 300-second period (Los Angeles Freeway) of the HDDE Hot-Start FTP Transient Cycle (b).**




(a)




(b)

**Figure 12. Cumulative emissions results (a) for engine operation over the fourth 300-second period (repeat of New York Nonfreeway) of the HDDE Hot-Start FTP Transient Cycle (b).**

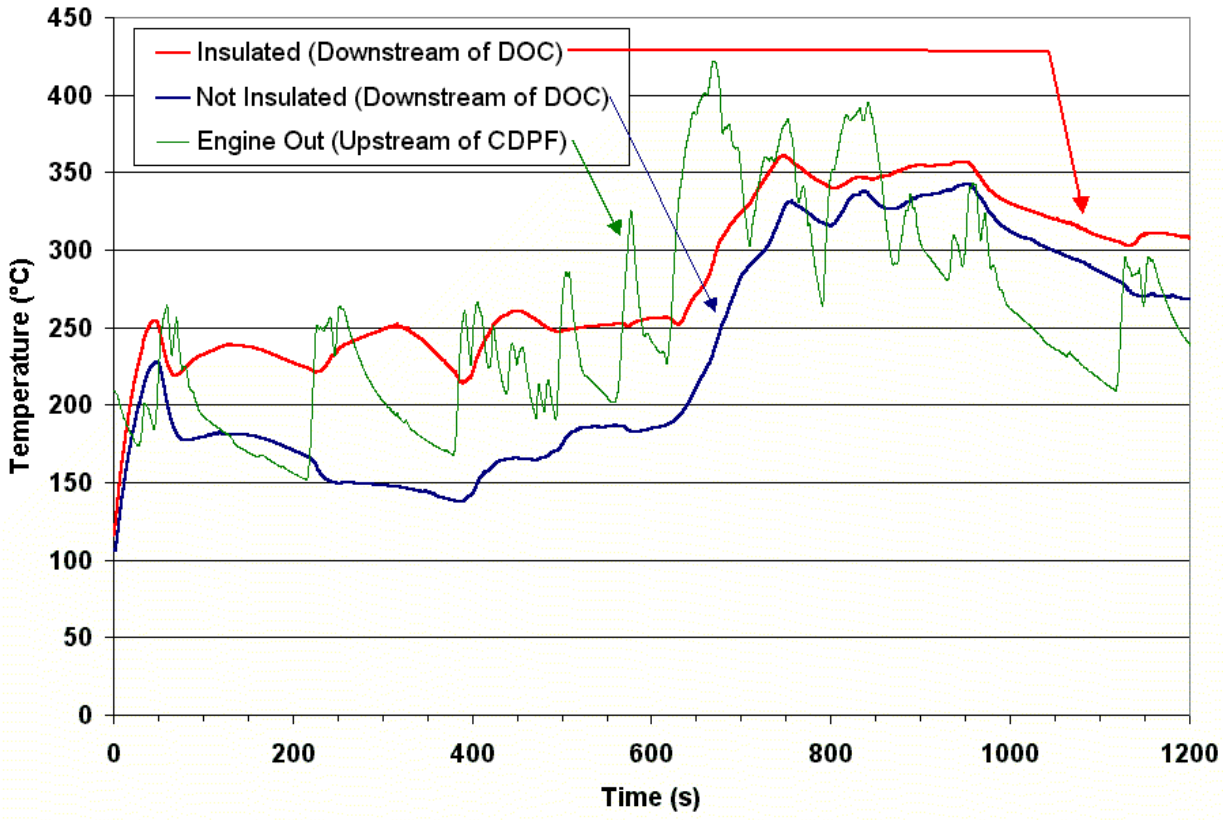



**Figure 13. Exhaust temperature profile of engine out exhaust, emission control system outlet with insulation, and emission control system outlet without insulation over HDDE-FTP (each test preceded by a 20-minute soak). Temperature measurement location is denoted in parenthesis in the legend.**

sector has known for years: Thermal management and engine/catalyst integration are the keys to success. Though insulating the system improved system performance, it was clear that other measures would be required. Close mounting the catalyst system would help system warm-up, but the engine out temperature for our test engine does not exceed 300°C until nearly 600 seconds into the HDDE FTP. Therefore, the improvement due to location alone is not likely to be significant. Reducing the thermal mass of the catalyst system would also help, but with engine out temperatures hovering below 250°C over the first half of the cycle, the catalysts will still not be in their optimum operating temperature window.

Increasing exhaust temperatures through engine management could significantly improve the results shown here. Toyota has published a number of papers detailing their efforts to integrate the diesel catalysts and engine systems for passenger car applications.[23-26] One of the key aspects of their integration is controlling the catalyst temperature. EGR, post injection, exhaust injection, and other strategies are used to keep the adsorber at its optimum $NO_x$ reduction temperature. These strategies are also used to periodically regenerate the PM trap.

Hydrocarbon emissions were also higher than desired due to slip during $NO_x$ regenerations (Table 7). This HC slip was caused by a combination of factors that still need to be optimized in our system. The primary factor is, again, the low catalyst temperature and the resulting low oxidation efficiency. Second, the four-flow path system's regeneration exhaust mass flow has not been optimized yet. The leakage past the exhaust valve was higher than necessary when it was closed, increasing both the fuel consumption due to reductant injection and the HC slip, as well as effecting $NO_x$ control. This hardware issue can be resolved by improving the valve seal. Third, the automatic controller had a 'choke'-like function that increased regeneration fueling when the catalyst temperature was cold. This 'choke' function was overcompensating for the cold catalyst temperatures, particularly at high engine loads (note the HC increase at the 650 second mark in Figure 11). This and other refinements to the controller will contribute to much lower HC emissions. Finally, the DOC function could be improved, both by increased oxidation activity and perhaps improved collector mixing. The DOC used for this testing had modest PGM loading and commensurate performance. Higher loadings would improve oxidation performance. The collector's ability to mix exhaust has also not yet been well determined. The DOC works best in a net lean environment, but as currently configured, the flow through the DOC may be stratified such that the three lean flow paths do not significantly mix with the rich flow from the regenerating

flow path. The high HC emissions also, to some extent, contributed to the measured PM level.

## CONCLUSION

The compact four-flow path system achieved approximately 90% $NO_x$ reduction over the SET composite test and approximately 80% $NO_x$ reduction over the HDDE-FTP. PM emissions were also reduced by 86% over both tests to a level compliant with the 2007 U.S. heavy-duty engine emission standard. These reductions were accomplished with less than half the catalyst volume of the previous system. The system hardware is still very early in its development. This is most evident in the high HDDE-FTP HC and $NO_x$ emissions. The target for this program is ultimately to achieve greater than 90% $NO_x$ reductions over both cycles (with > 2.5 g/hp-hr engine out) and to meet the 2007 $NO_x$, PM and HC standards with a minimal impact on fuel economy. Currently the PM targets have been achieved, but the $NO_x$ and HC emissions are greater than desired.

The primary path of improvement will be to integrate the engine with the catalyst system in order to raise the exhaust temperature at light loads, improving the systems ability to store and reduce $NO_x$. So far the testing performed at our lab has treated the engine and catalyst systems as separate entities. Future testing will integrate the engine and catalyst controls to better tailor the engine exhaust to the needs of the catalysts.

In addition to the integration work, there are a number of improvements that can be made to the current four-flow path system hardware and control algorithm. Regeneration exhaust flow can be lowered to reduce regeneration HC slip and overall fuel consumption. Improved mixing of the four flow paths upstream of the DOC may also reduce HC slip. Improvements are also needed in the method used by the control algorithm to determine the regeneration fuel calculation.

Further cooperative development of the $NO_x$ 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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## CONTACT

Charles Schenk
United States Environmental Protection Agency
Office of Transportation and Air Quality
Assessment and Standards Division
2000 Traverwood Dr.
Ann Arbor, MI 48105
Phone: (734) 214-4700
E-mail: Schenk.Charles@epa.gov