

FINAL REPORT

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**Cummins, Incorporated
Columbus, IN**



FreedomCAR – Aftertreatment Subsystem Development

DoE Program: DE-FC26-02EE50577

Prepared by:

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Program Objectives:

The primary objective of this program was to develop generic aftertreatment technologies applicable for LDV and LDT engines ranging from 55 kW to 200kW, to develop an optimized and integrated aftertreatment system for a LDT (Light Duty Truck) type vehicle, and to demonstrate the technology which will enable light duty diesel engines to meet Federal Tier II regulation with minimum impact on fuel economy. Specifically, the development targets for emissions reduction and fuel injection penalty are given below:

- | | |
|------------------------------------|-------------------------------|
| - NOx conversion efficiency | > 90% (hot), > 84% (combined) |
| - PM conversion efficiency | > 90% (hot), > 84% (combined) |
| - Fuel penalty over FTP-75 | Less than 5 % |
| - Fuel penalty at Cruise condition | Less than 3 % |

Executive Summary

Development of cost-effective, highly efficient diesel exhaust aftertreatment systems in combination with very low engine out emission combustion development are essential elements for realization of Federal Tier II emission standards for Light Duty Trucks and Vehicles.

Evaluation of several aftertreatment technologies was completed as part of this program. A combination of Diesel Oxidation Catalyst, NOx Adsorbing Catalyst and Catalyzed Soot Filter was found to provide the levels of conversion efficiency required to achieve the emission targets.

While early systems required relatively large catalyst volumes, external dosing, sulfur traps, full bypass configurations and high levels of Platinum metals; the final system is a compact, scalable, flow-through, fully-integrated and engine-managed aftertreatment system capable of commercial application for Light Duty Vehicles and Trucks.

NOx adsorber/particulate filter technology is particularly attractive for Light Duty applications due to the lower exhaust flow and temperature requirements as compared to Heavy Duty engines. Despite these strong positive aspects, NOx Adsorbers are challenged by their regeneration requirements and susceptibility to sulfur poisoning and thermal degradation.

Capability was developed to regenerate the NOx Adsorber for NOx and SOx as well as the Particulate Filter for soot. This system was fully integrated into a truck and evaluated over the chassis dynamometer for emissions capability and in real-world winter field testing. Durability of the system was evaluated over a variety of accelerated and real-time dynamometer tests. Excellent NOx and PM conversion efficiency was demonstrated, even following 3000 hrs of endurance testing.

Unregulated emissions emitted by the system were evaluated as was the fuel penalty associated with the DeNOx and DeSOx regeneration processes. In the final evaluation, the system demonstrated 90% NOx conversion and 99% PM conversion at a 6% fuel penalty over the FTP-75 test cycle.

While target fuel penalty levels were demonstrated using full-bypass configuration systems, the cost associated with those systems was prohibitively high and would preclude successful commercialization of the technology. Although the flow-through configuration fell 1% short of the 5% fuel penalty target, the cost of this configuration is such that commercial application is feasible. Cost drivers for the final system configuration were identified and demonstrate areas where future development areas could focus.

Program Tasks – Phase 1 (from original 1999 Statement of Work)

Task 1

Procure Cummins B5.9 and Ford/FEV/Diata mule engines, Select a laser for generating nozzle spray holes and design a piezoelectric driven high speed actuator and driver

Task 2

Cost drivers for the final system configuration were identified and demonstrate areas where future development areas could focus.

Task 3

Exhaust emission measurement strategy. Laser spray hole characterization and piezoelectric actuator tests.

Task 4

Develop Plasma Catalytic, NOx Adsorber and Lean NOx Catalyst reduction systems including supplemental microwave heating and sulfur trap

Task 5

Procure and develop particulate reduction systems and supplemental microwave heating systems.

Task 6

Exhaust aftertreatment system model development and application. Procurement of laser drilled nozzle and engine test piezoelectric actuator.

Task 7

Final development and integration of exhaust aftertreatment systems. Determine effects of aging on exhaust aftertreatment systems. Spray visualization of small-holed nozzles.

Task 8

Prepare final aftertreatment system for delivery. Demonstrate the effect of small spray holes on emissions.

Project Summary – Phase 1 (1999-2002)

Introduction

Due to their excellent fuel efficiency, reliability, and durability, compression ignition direct injection (CIDI) engines have been used extensively to power almost all highway trucks, urban buses, off-road vehicles, marine carriers, and industrial equipment. CIDI engines burn 35 to 50% less fuel than gasoline engines of comparable size, and they emit far less greenhouse gases (Carbon Dioxides), which have been implicated in global warming. Although the emissions of CIDI engines have been reduced significantly over the last decade, there remains concern with the Nitrogen Oxides (NOX) and Particulate Matter (PM) emission levels. In 2000, the US EPA proposed very stringent emissions standards to be introduced in 2007 along with low sulfur (< 15ppm) diesel fuel. The California Air Resource Board (CARB) has also established the principle that future diesel fueled vehicles should meet the same emissions standards as gasoline fueled vehicles and the EPA followed suit with its Tier II emissions regulations.

Meeting the Tier II standards requires NOX and PM emissions to be reduced dramatically. Achieving such low emissions while minimizing fuel economy penalty cannot be done through engine development and fuel reformulation alone, and requires application of NOX and PM aftertreatment control devices. This program developed generic aftertreatment subsystem technologies applicable for both Light-Duty Vehicle (LDV) and Light-Duty Truck (LDT) engines.

Overall Approach – Phase 1 (1999-2002)

Various aftertreatment technologies including NOx absorbers, catalyzed particulate filters and sulfur traps, in conjunction with active reductant injection were investigated and developed for emission control subsystem integration and development. The areas of NOx adsorber development included catalyst formulation for high conversion over an increased catalyst/exhaust gas temperature range, catalyst structure for increased exhaust gas residence time on active catalyst sites, and an understanding of the various factors that cause deactivation of the catalyst. Fuel reformulation concepts were investigated to increase the activity of the hydrocarbons introduced into the catalyst systems. Even with the availability of 15 ppm sulfur fuels, the development of a sulfur management scheme is critical to prevent catalyst poisoning and deactivation. The application of a sulfur trap that can be regenerated offline or periodically replaced was explored.

PM emissions were addressed by developing a CPF. The key areas of development include developing catalyst formulation with improved low temperature performance, exploring synergies between particulate and NOx aftertreatment strategies, and determining the need for supplemental heating. A supplemental heating system may be required to help the CPF get through those portions of the duty cycle where temperature is too low to achieve a high rate of particulate burning to prevent soot accumulation.

Finally, the improved aftertreatment components were integrated and configured optimally in a system developed for a light duty application. This system was calibrated and tested in a controlled environment on a light duty sized engine. Phase 1 of the project culminated in the chassis dynamometer emission testing of this initial system.

The high level flow of the project is illustrated in Figure 1.

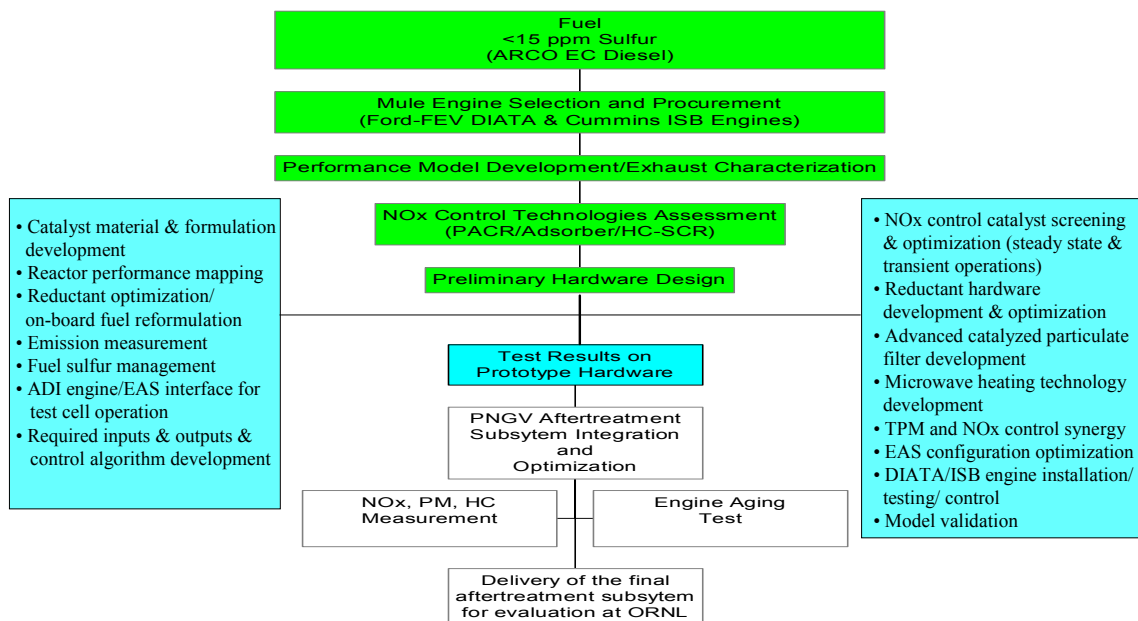


Figure 1 – Flowchart of Phase 1 Approach

Fuel Selection

Specifications for the test fuel are included in Figure 2.

ARCO EC-D Specifications		
Property	Target	Limit
Sulfur, ppmw	<10	15 Max
Aromatics, %v	<10	12 Max
Natural Cetane Number	60	57 Min
Nitrogen, ppmw	5	10 Max
API Gravity	37-42	42.5 Max
Distillation IBP (D-86), deg. F	375	350 Min

Figure 2 - Test Fuel Specification

Mule Engine Selection

A key objective of this program is to develop and understand the generic aftertreatment technologies applicable for LDV and LDT engines ranging from 55kW to 200kW, and to demonstrate the capability of the selected aftertreatment technologies in meeting Tier II, Bin 5 emission standards. This involves engines with displacements ranging from 1.2 to 6.0 liters. A fundamental and “displacement-size” transparent understanding is required. The 5.9 liter

Cummins ISB and 1.2 liter Ford DIATA engines were selected for aftertreatment subsystem development. The DIATA engine was developed under the Ford Hybrid Propulsion System Development Program. Specifications for the mule engines are shown in Figure 3.

	<u>Diata</u>	<u>ISB</u>
Configuration	4 valve per cylinder, central injector	4 valve per cylinder, central injector
Number of Cylinder	4	6
Number of valves	16	24
Displacement	1.2 L	5.9 L
Bore x Stroke	70 x 78	102 x 120
Bore/Stroke Ratio	0.90	0.85
Compression Ratio	19.5:1	19:1
Maximum BMEP	16 bar	19 bar
Fuel System	HPCR	VP44/HPCR
Air Handling System	VG Cooled EGR	VG/WG Cooled EGR
Reference SAE 981916-Keppeler, Stefan, et al		

Figure 3 - Specification of Test Mules

Exhaust Characterization

Test results confirmed the LDV and LDT exhaust operating characteristics can be simulated with the Cummins ISB mule engines, as shown in Figure 4. Therefore, most of the aftertreatment subsystem screening and fundamental understanding was conducted on the ISB mule engine. The typical engine-out NOX contribution as a function of exhaust gas catalyst-in and mean catalyst temperatures for the FTP-75 cycle is given in Figure 5.

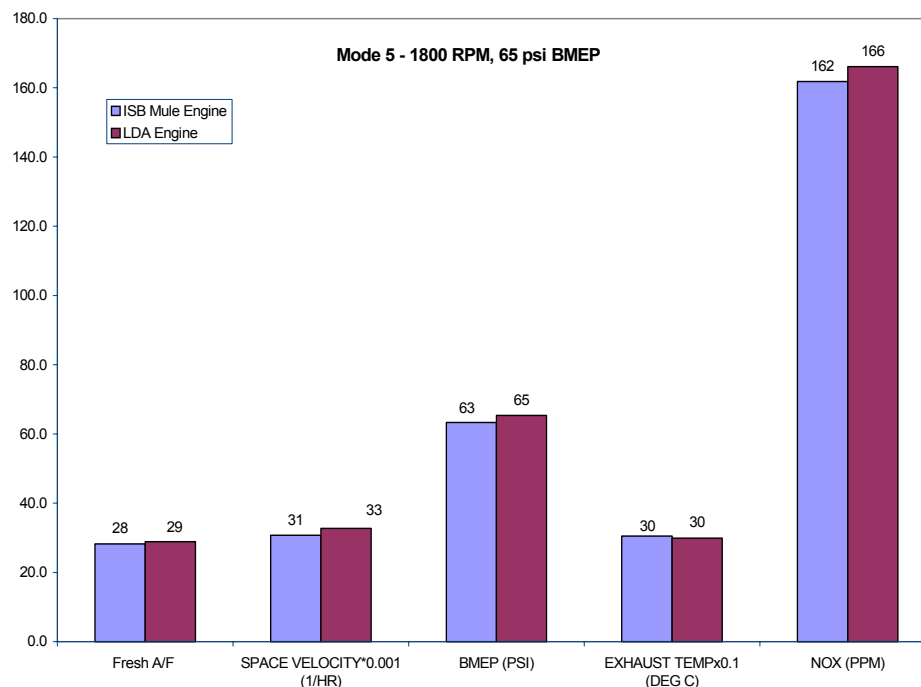


Figure 4 – Exhaust Characteristics Comparison

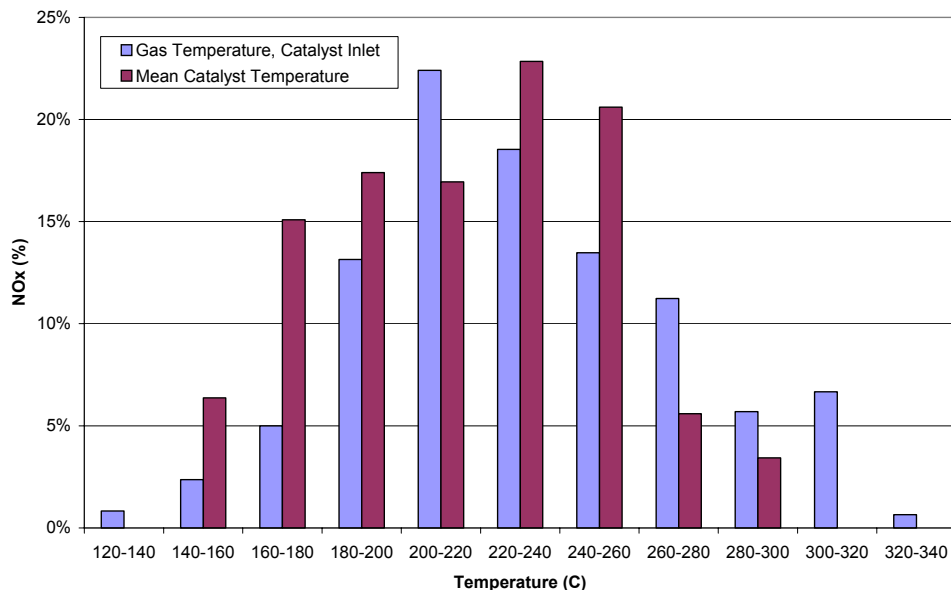


Figure 5 - FTP-75 Emission Cycle Temperature Breakdown

NO_x Technology Assessment and Selection

In phase I of this project, three NO_x reduction technologies including plasma assisted catalytic NO_x reduction, active lean NO_x catalyst, and adsorber catalyst technology using intermittent rich conditions for NO_x reduction were investigated in parallel in an attempt to select the best NO_x control approach for light-duty aftertreatment subsystem integration and development. The investigation included preliminary design and analysis, critical lab/engine experiments, and ranking then selection of NO_x control technologies against reliability, up-front cost, fuel economy, service interval/serviceability, and size/weight. The results of this investigation are summarized below.

Non-Thermal Plasma Catalysis

The principle of the non-thermal plasma for NO_x control is to pass the exhaust gas through a reaction chamber where a rapid electrical pulse of short duration (25kV, 28MHz, 10 nano-second) is introduced as shown in Figure 6. The non-thermal plasma generates electrons, ions, and radicals in the exhaust stream. The active particles then react with NO molecules to form NO₂ molecules that are reduced over a catalyst. Figure 7 shows the results of NO_x conversion with diesel fuel as a reductant. Higher levels of NO_x reduction have been obtained with propene as shown in Figure 8. Models and test results have shown that NO_x reduction in the presence of oxygen is not possible by plasma alone. Additional technology such as selective catalytic reduction (SCR) is necessary to reduce NO_x to N₂. The key findings of the PACR technology are summarized below.

Positives

- Conversion of NO to NO₂ at low temperatures, without SO₂ to SO₃ oxidation
- Can enhance NO_x conversion at low temperatures
- Can use diesel fuel as reductant
- Simple reductant injection strategy similar to active lean NO_x

Negatives

- Additional power required for plasma generation
- Very low space velocity/very large catalyst volume required for high conversion efficiency, a 40% NOX reduction was achieved with 90 liter SCR catalyst
- Potential safety issues due to high voltage/possible EMI generation
- Benefit of non-thermal plasma decreased as the temperature increased. No benefit was observed at temperatures greater than 300°C
- Evidence of NOX adsorption as significant NOX consumption pathway

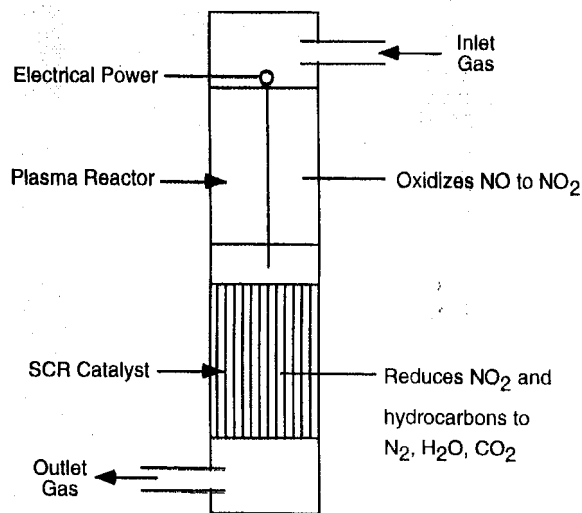


Figure 6 - Schematic of Plasma-Assisted Catalytic Reduction System (PACR)

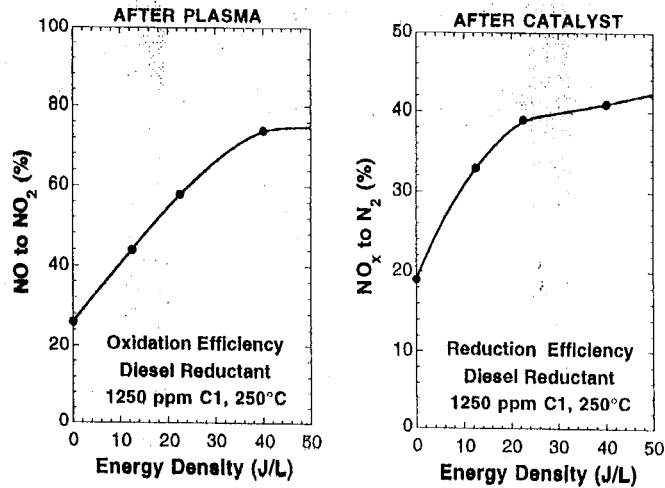


Figure 7 - NO_x reduction with PACR system using diesel fuel reductant

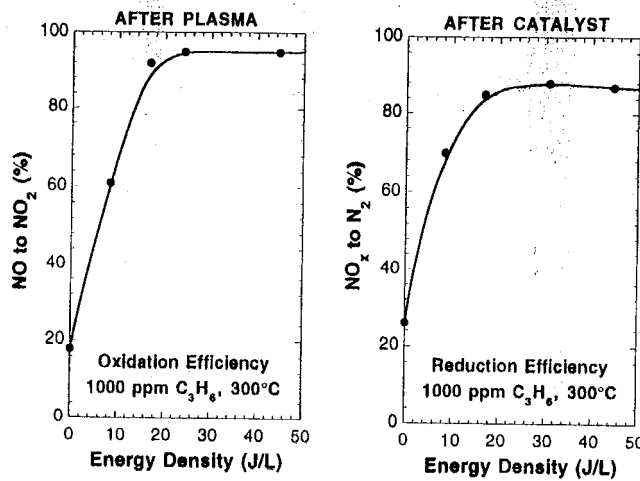


Figure 8 - PACR of real diesel exhaust using propene reductant

Active Lean NO_x Catalyst

There are several types of lean NO_x catalysts currently under development by many catalyst companies. The general trend is to use two types of catalysts to cover the temperature range between 200°C to 500°C. The low temperature catalyst is platinum on alumina (Pt/Al₂O₃) and the higher temperature catalyst is a copper exchanged zeolite (Cu/ZSM5). The steady-state combined effectiveness could be as high as 50-60% of NO_x removal with the addition of reformulated diesel fuel in front of the catalyst as a chemical reductant. The addition of fuel would have to be controlled such that the right amount of fuel can be added over the engine operating conditions where most NO_x is generated. A breadboard control system and a low pressure fuel

injection system were developed to evaluate and understand the potential of lean NO_x catalyst technology. A breadboard ISB engine was used to test an optimized low temperature lean NO_x catalyst under transient FTP-75 cycle conditions. Instead of using a chassis dynamometer, the engine was installed in a CVS test cell and a simulated FTP-75 cycle was run with a specified engine speed and load history obtained from computer simulation of a typical Dodge Ram as shown in Figure 9.

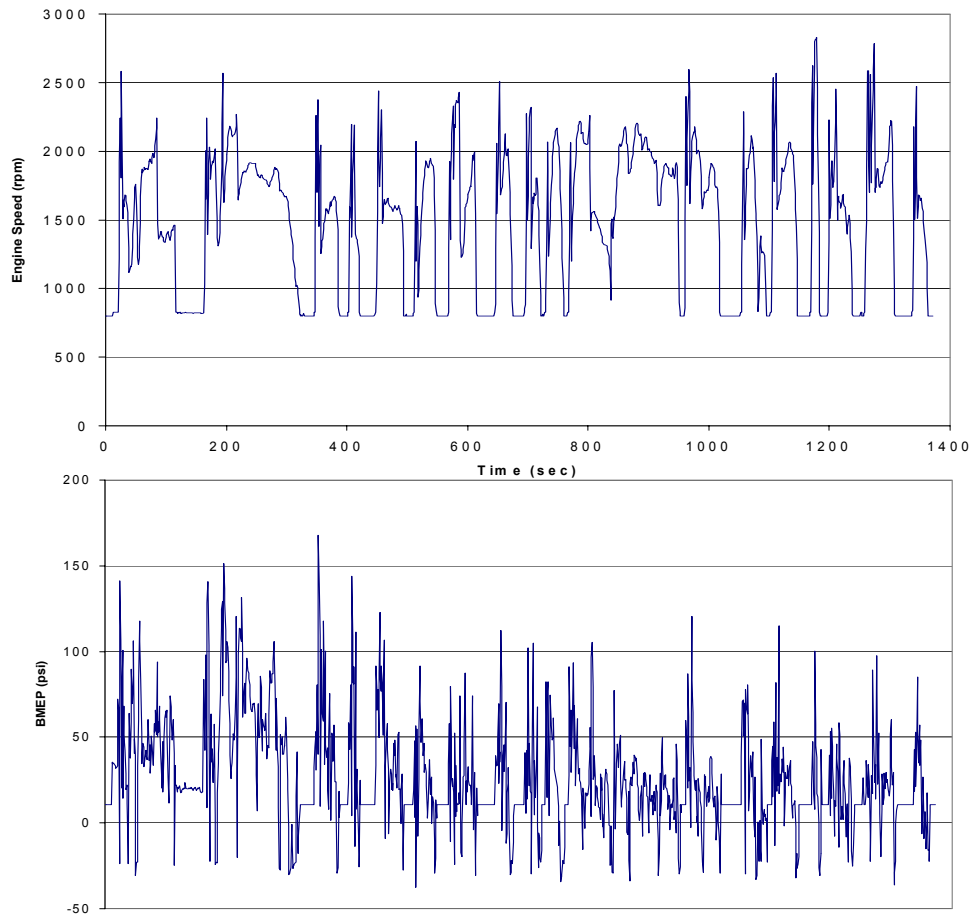


Figure 9 – Simulated FTP-75 Transient Cycle of Dodge Ram

The transient speed and load history was validated on an actual chassis dynamometer test of a Dodge Ram vehicle with an ISB engine. Since human inputs were minimized with well specified engine speed and load history in the CVS test cell, the repeatability of test results was significantly improved. Over the FTP-75 cycle, the mean catalyst temperature varied between 150 and 300°C. Only hot cycles were tested. The catalyst size was selected to be 14 liters, representing about 2.5 times engine displacement. Current certification fuel (~350ppm sulfur) was used for the engine and supplemental exhaust fuel injection. The transient C₁/NO_x ratio target was set to be around 9 to 12, representing about 4 to 6% fuel penalty. An average NO_x conversion efficiency of 38% was obtained in the test as shown in Figure 10.

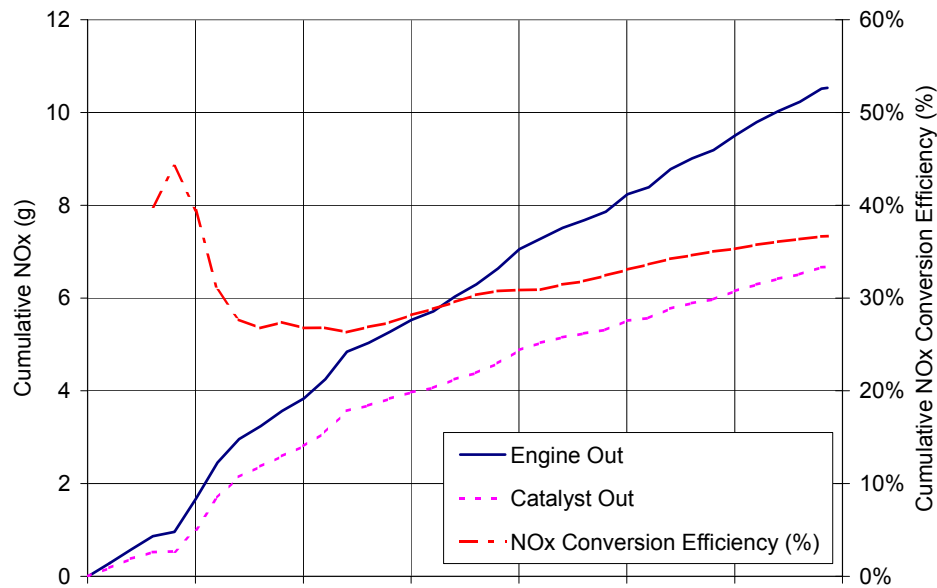


Figure 10 – Simulated FTP-75 Transient Cycle of Dodge Ram

The key findings of active lean NO_x catalyst technology are summarized below.

Positives

- Can use diesel fuel as reductant (diesel fuel can be added to exhaust or in-cylinder)
- A 38% NO_x conversion efficiency was demonstrated with diesel fuel as injection reductant
- Simple injection strategy with low complexity for implementation
- Potential low cost solution for very clean diesel with ultra-low engine out emissions (less than 1.0g/kW-hr NO_x)
- Precious metal catalyst is only slightly inhibited by H₂O

Negatives

- High NO_x conversion to N₂O (about 50-60% of the NO_x reduced), N₂O is a greenhouse gas
- Poor selectivity, needs excess HC
- High sulfate formation rates at high temperature for high sulfur fuel. Not an issue with future very low sulfur fuel
- Requires combination of different catalysts to cover the whole exhaust temperature range for FTP-75 and US-06 cycles

NO_x Adsorber

NO_x adsorber technology relies on removal of NO_x from the exhaust under lean conditions by adsorption, followed by periodic regeneration of the adsorbent along with reduction of the released NO_x under rich conditions. This alleviates the need for maintaining a given C₁/NO_x ratio under transient and fluctuating exhaust NO_x levels, as in the case of the lean NO_x catalyst. For current state-of-the-art catalysts, the lean adsorption step entails the reaction of an acidic gas (NO₂) with a basic adsorbent (alkaline earth oxide, e.g. BaO) to form a nitrate or nitro-species. Since engine-out NO_x is primarily (90%) NO it must first be oxidized to NO₂ over a Pt-based catalyst. When the effective capacity of the adsorber is reached, the NO_x is released by a pulsed introduction of enough HC reductant (e.g. diesel fuel) to establish a rich environment and under this condition the NO_x is reduced to N₂ over a conventional three-way catalyst. In this way, no N₂O is produced. The operating temperature range of the baseline NO_x adsorber catalyst is about 300-420°C. The low limit is due to the light-off of the catalytic NO to NO₂ oxidation step and the upper limit is related to thermal desorption of NO₂ from the BaO. Steady-state engine tests using low sulfur fuel (~3ppm) have shown that greater than 95% NO_x removal can be attained in the temperature range between 320 and 420°C using a repeated cycle of 30 seconds lean absorption followed by a 1 second rich regeneration/reduction at an exhaust A/F ratio of 9:1, as shown in Figure 11. Because of the supplemental HC's injected during the rich

regeneration/reduction pulse, there will be a fuel penalty associated with NO_x adsorber catalysts. The NO_x adsorber catalysts are generally stable to the hydrothermal conditions encountered in diesel exhaust. However, the adsorbent function (e.g. BaO) is extremely susceptible to deactivation from sulfur oxides in the exhaust by the formation of BaSO₄. The sulfate thus blocks the adsorption sites intended for NO₂. The result is rapid deactivation. One of the key enablers for NO_x adsorber catalysts is the availability of ultra low sulfur diesel fuel. A sulfur level of zero would be the best, but is probably not practical. The availability of low sulfur (< 15ppm) diesel fuel together with the application of a SO_x trap to protect the NO_x adsorber may be critical to this technology. The key results of the NO_x adsorber catalyst technology are summarized below.

Positives

- Potential for high NO_x conversion (> 90% steady-state, > 83% transient)
- Wide temperature range of peak operation (320 to 420°C), yet not low enough for light-duty applications
- Can use diesel fuel as reductant, easier enforcement/anti-tampering control
- No infrastructure issues (as with urea distribution)

Negatives

- Rapidly poisoned by sulfur from the fuel and lube, and NO_x conversion efficiency decreases at a rate of approximately 0.1% per hour with 11ppm sulfur fuel, a SO_x trap will be required.
- Rich operation of injected hydrocarbon leading to high fuel penalty, HC slip, and SOF particulate make
- Partial flow regeneration adds complexity but offers lower fuel economy penalty
- Complex reductant injection/control system

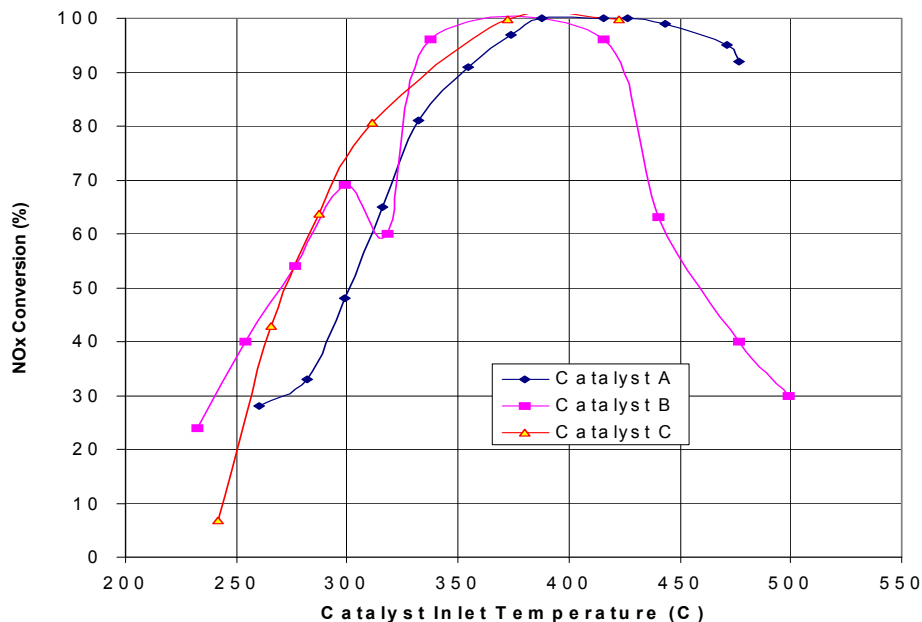


Figure 11 - Benchmarking - NO_x adsorber performance.

NO_x AFTERTREATMENT TECHNOLOGY SELECTION

As part of the technology selection process, the ranking of NO_x technologies against reliability, up-front cost, fuel economy, service interval/serviceability, and size/weight was made, as shown in Figure 12.

	Program Emissions Target Capability	Reliability	Fuel Economy	Up Front Cost	Service Interval/ Serviceability	Size/ Weight	Composite Score
Weighting Factor		10	9	9	7	5	
PACR	No	3	3	3	3	2	0*
SCR-HC	No	5	4	5	5	5	0*
NO _x Adsorber	Yes	4	5	4	4	4	169

* Technology not capable of meeting emission targets

5=Best 1=Worst

Figure 12 - Assessment of NO_x aftertreatment technologies

The results indicated the best NO_x control approach for LDV and LDT applications is the NO_x adsorber catalyst. Both active lean NO_x and PACR technologies are currently not capable of achieving the high conversion efficiency required for DOE/PNGV program objectives. The best NO_x conversion efficiency achieved for active lean NO_x and PACR was about 40%. A decision was made to select adsorber catalyst technology for further development and aftertreatment subsystem integration. All subsequent development work for the program was conducted using NO_x adsorber catalysts as the primary NO_x reduction aftertreatment technology.

ADSORBER FUNDAMENTALS, FORMULATION AND REDUCTANT DEVELOPMENT

NO_x adsorber technology relies on removal of NO_x from the exhaust under lean conditions by adsorption. This is followed by periodic regeneration of the adsorbent along with reduction of the released NO_x under rich conditions. This alleviates the need for maintaining a given C1/NO_x ratio under transient and fluctuating exhaust NO_x levels, as in the case of the lean NO_x catalyst. For current state-of-the-art catalysts the lean adsorption step entails the reaction of an acidic gas (NO₂) with a basic adsorbent (alkaline earth oxide, e.g. BaO) to form a nitrate or nitro-species. Since engine-out NO_x is primarily (90%) NO it must first be oxidized to NO₂ over a Pt-based catalyst. The results indicate that Pt/Base Metal Oxide (BMO) intimate contact is essential for higher NO_x trapping capacity. When the effective capacity of the adsorber is reached, the NO_x is released by a pulsed introduction of hydrocarbon (HC) reductant (e.g. diesel fuel) enough to establish a rich environment and under this condition the NO_x is reduced to N₂ over a conventional three-way catalyst. Nitrate or adsorbed NO₂ can decompose and desorb from BMO thermodynamically, and it is O₂ partial pressure dependent. NO_x can also desorb by HC displacement, partially due to incomplete reduction. Trapped NO₂ can totally desorb in the absence of O₂ at 450 deg C. The Pt/BMO interface is essential for NO_x reduction to N₂ with reductants during rich operation. No reduction of trapped NO_x was observed on BMO without Pt. Experimentally it was determined that the reductant quantity, at least 2 times of stoichiometry of CH₂ is needed for full regeneration, and insufficient reductant leads to NO formation. Trapped NO_x quantity also affects the NO_x reduction, loosely trapped NO_x species tend to release as NO during regeneration. The reduction reaction is kinetic controlled. It depends on reductant type, reduction temperature, especially at low temperature (e.g. <250 deg C), and reduction time.

Engine test results, as shown in Figure 13, indicate the NO_x conversion versus temperature curves are nearly identical between ISB and DIATA exhaust aftertreatment systems. This suggests that a fundamental and "displacement-size" transparent understanding can be made on EAS technology development.

Figure 13 also illustrates that formulation development has extended catalyst operation by about 100°C. However, due to diesel fuel oxidation limitations, the low temperature light-off of an adsorber may not be expected below 200°C. Two alternatives have been analyzed to improve low temperature conversion of NO_x adsorbers: (1) using a reformer to generate reductants which can operate at lower temperatures and (2) raising exhaust temperatures through engine or exhaust heat management so that diesel fuel may be used directly as the reductant.

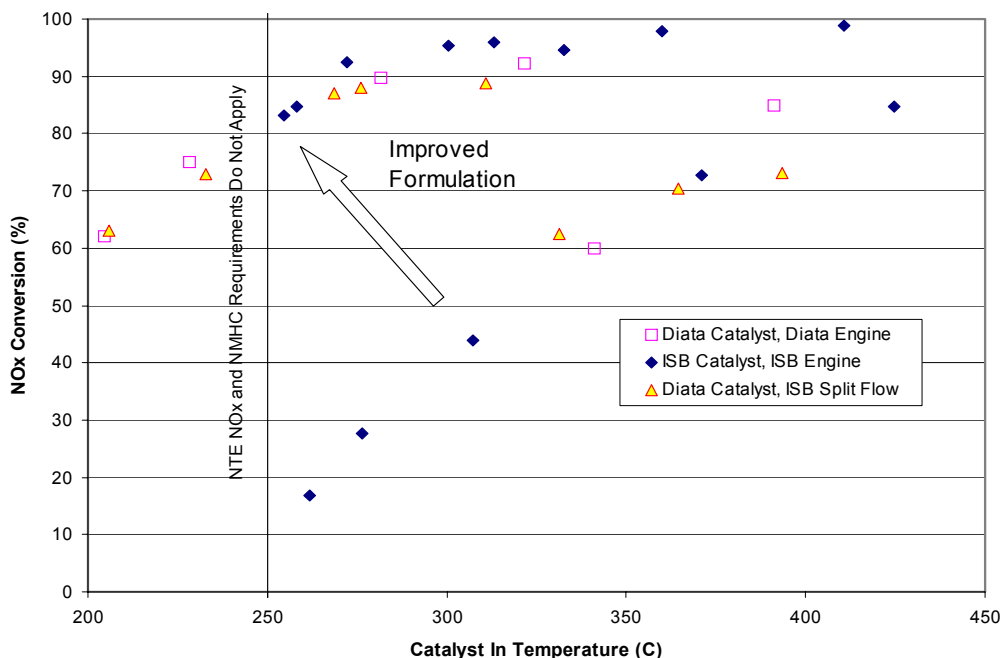


Figure 13 – NO_x Adsorber Performance Comparison

An analysis tool was used to compare the fuel economy penalty between the cases where a reformer is used vs. exhaust temperature enhancement. The reformer produces hydrogen and carbon monoxide, which are active reductants even at 180 C while diesel is active only above 200 C. Reactor test results indicate that H₂ is the best reductant, followed by a mixture of H₂ and CO, followed by CO. Short straight chain (C₄-C₈) hydrocarbons are not good reductants for adsorber catalyst (Figures 14 and 15).

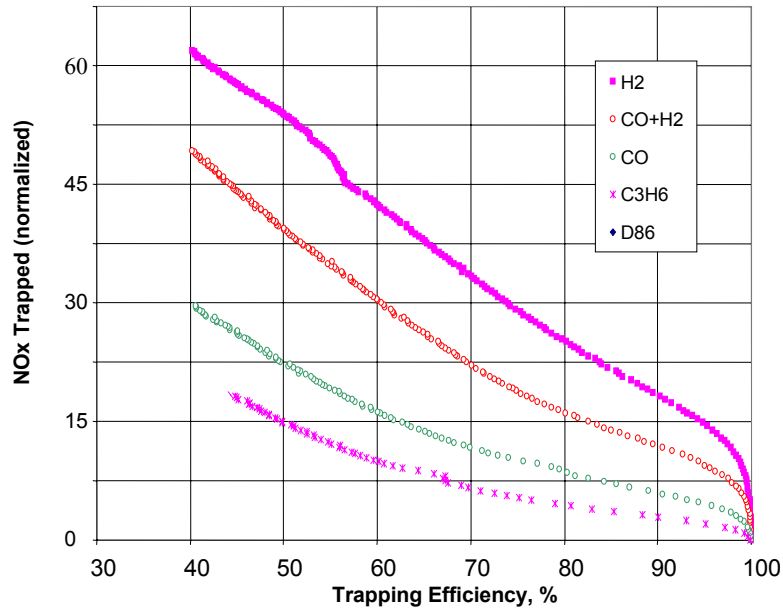


Figure 14 - Impact of reductant type on NOx adsorber trapping capacity vs. efficiency tradeoff @ 225 °C.

Reductant	Cycle NOx Conversion %			
	250°C	225°C	200°C	180°C
D86 diesel	92	81	58	5
CO	100	100	93	81
CO/H ₂ =3	100	100	98	85
CO/H ₂ =1	100	100	100	95
H ₂ /CO=3	100	100	100	95
H ₂	100	100	100	95

Figure 15. Impact of reductant types on NOx adsorber low temperature performance.

For low temperature operation of NOx adsorbers, either a reformer can be used or the exhaust temperature may be raised by 20 C. Analytical results show using the catalytic partial oxidation (CPO) reformer will require about 2% fuel penalty to keep it running, and the total fuel penalty for the reformer option will be almost 7% as compared to 5% for exhaust temperature enhancement.

Using a CPO reactor, the feasibility of using diesel fuel to generate the syngas and use as the reductant was evaluated. The CPO was hooked upstream of the catalyst. During this initial testing Naphtha (Carbon Number chemistry from C7- C10) was used to generate the syngas. During the regeneration cycle the engine exhaust was bypassed 100% and only the reformat (syngas) flowed through adsorber catalyst. GC analysis showed 30% H₂ and 17% CO in the dry reformat. A NOx conversion of greater than 90% was demonstrated for inlet exhaust temperatures ranging from 148 C to 448 C.

PARTICULATE FILTER FUNDAMENTALS AND ACTIVE REGENERATION

Conventional particulate filters that have been catalyzed have exhibited 85 to 90% reductions in PM demonstrating that filter technology can achieve the required levels (Figure 16). With the proper choice of catalyst material, this device has the added advantages of providing reduction in

HC and CO emissions, as well as PM. Catalyzed particulate filters (CPF) have been successfully formulated for HD diesel applications which achieve passive regeneration. Nevertheless, the passive filter regeneration is not robust, and susceptible to cold climates and light-duty cycles.

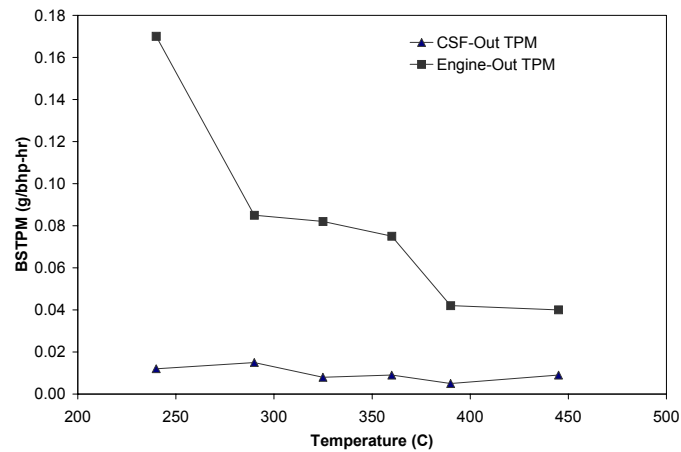


Figure 16 - PM emission control from catalyzed particulate filter, ISB engine

Cummins has conducted a 3+ year demonstration at New Jersey Transit (NJT) with a cumulative total of over 1.1 million miles and over 82,000 hours. The projected catalyzed particulate filter life on NJT buses is 125,000 miles (8000hrs) and is influenced by ash accumulation. Low ash oil formulations are likely to increase filter life and improve catalyst performance. Catalyzed particulate filters are a passive system which requires the engine exhaust temperature to periodically be high enough to regenerate the filter. In addition, one must balance between soot loading rate, engine duty cycle, filter size, and ambient temperature. Typically, application screening must be performed prior to installing the particulate filter on the vehicle, and at least 10% of the duty cycle must be spent with filter inlet temperatures above 315°C. Figure 17 shows the schematic of a DOC and catalyzed particulate filter. Catalyzed particulate filters have been successfully applied, but:

- All field tests have been carefully examined prior to installing a particulate filter
- All testers are staying away from applications that do not meet specific criteria
- It is not expected that passive filters will work for all environments and all duty cycles

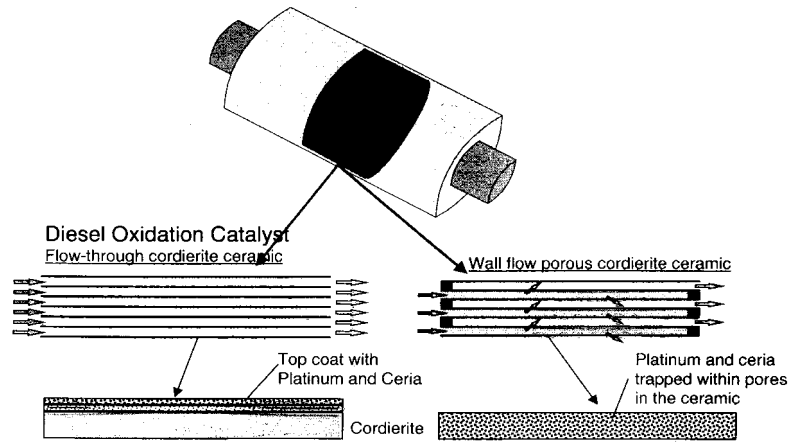


Figure 17 - Diesel oxidation catalyst and catalyzed particulate filter schematic

Identifying a catalyst formulation with improved low temperature performance, creating synergies between PM and NO_x aftertreatment strategies and determining supplemental heating requirements were key areas of development.

Another challenging aspect of passive regeneration of particulate filters is the potential for uncontrolled regeneration. Uncontrolled regeneration of particulate filters can occur when the filter is loaded with soot, and undergoes an event during the duty cycle that initiates soot combustion in the filter. After the soot begins to combust, if the duty cycle is such that the vehicle goes to a stop, idle, or engine motoring condition, producing a low exhaust flow condition, the filter may overheat, and uncontrolled regeneration and subsequent filter failure may occur. The main factors that influence uncontrolled regeneration of particulate filters include: soot loading level, exhaust temperature, exhaust flow, O₂ concentration, NO₂ concentration, and catalyst formulation. Engine results have shown that low precious metal loading filters are more prone to undergo uncontrolled regeneration than filters with high levels of precious metals (Figure 18). This is directly related to the slower soot burning rates associated with low precious metal loading filters.

			800 RPM Idle Speed	
Filter Size (in.)	PM Loading	Soot Loading	T _{out}	FAIL ?
(Dia x Length)	(gms/cu.ft Pt)	(gms/liter)	(°C)	
11.25 x 12	2	15	1000*	Yes (Melting)
		14	993	Yes (Melting)
		12	814	No
		10	525	No
10.5 x 12	2	10	827	Yes (Possible Cracking)
		7	492	No
	50	14	634	No
		10	555	No

Figure 18 - Results of Uncontrolled Regeneration Experiments

Test results with microwave regeneration for active particulate filter regeneration indicated that similar to passive regeneration, active regeneration is most efficient when the filter is regenerated at lower soot loading levels. At high soot loading levels, even with active regeneration, the particulate filter may experience an uncontrolled regeneration, which may result in failure of the filter. Using a 1kW microwave for regeneration results in relatively fast soot burning, approximately 10 minutes to regenerate to clean filter condition as compared to 30 minutes for passive regeneration with a 50g/ft³ Pt catalyzed particulate filter (Figure 19). For some systems, good control of the regeneration event is obtained by using an auxiliary air supply for the oxidant.

A summary of microwave technology for particulate filter regeneration is given below.

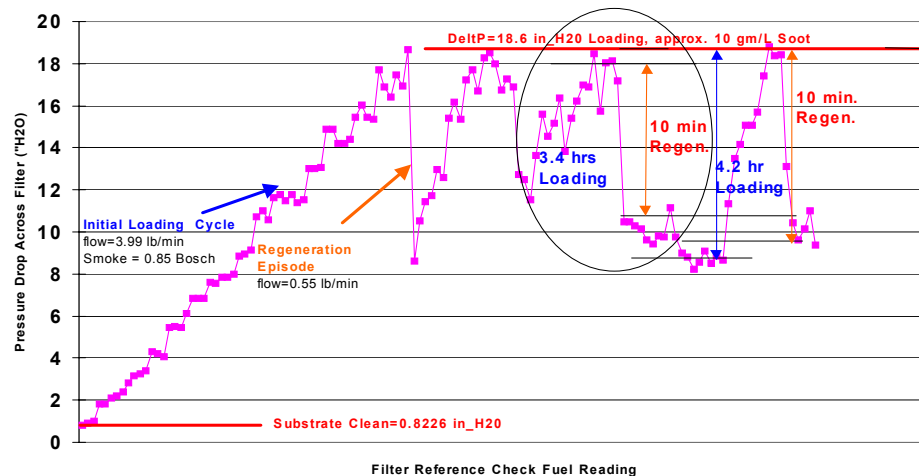


Figure 19 - Microwave regeneration of particulate filter

Positives

- Fundamental advantages of the heating process over conventional methods in achieving uniform heating and low power consumption – volumetric and selective heating nature of microwaves
- Heating elements are not in direct contact with exhaust environment, adding to longer life of the components

- Non-catalyzed particulate filter possible
- High control of the soot regeneration event, with increased flexibility to cover a wider span of duty cycles

Negatives

- System development is still in elementary stages and the technology progress has been slow
- Reliability/durability of systems still not known
- Complex heating process
- Requires very low flow rates, requires bypass system or supplemental air supply control
- Uncontrolled regeneration of particulate filter is still possible if strategy is not optimized
- System is not easily scalable from small engine to larger engines
- Requires additional electrical load on vehicle, may require modifications to the alternator system
- Safety issues due to microwave leakage

In order to determine the most efficient, cost effective, active Diesel Particulate Filter (DPF) system, a technology selection process was initiated. There are two different approaches to active DPF regeneration: (1) using engine management for additional heat from combustion to achieve high exhaust temperatures, and (2) using exhaust heat management systems to apply heat to the DPF. The focus of the technology selection was exhaust heat management with the following systems: electrical heating systems, burner systems, microwave systems, and catalytic systems. The performance of each active technology was measured based on regeneration efficiency, regeneration duration, factors affecting uncontrolled regeneration, total system cost, and fuel penalty. The main objective of the down-selection process was to identify the most efficient, durable, and cost effective exhaust heat management for active DPF. The results of the technology selection process are given in Figure 20. As part of this testing, an advanced

	Microwave	Burner	Electric	Catalytic
A. System Initial Cost/Size/Packaging	3	3	2	1
B. System Reliability/Durability	2	4	3	1
C. System Performance	3	1	2	4
D. System Controls	1	2	3	3
E. Supplier Interaction/System Maturity	4	3	1	2
F. System Service Maintenance	2	3	4	1
G. system Safety	2	3	2	1
Overall Ranking:	3	4	2	1
1 = Best 4 = Worst	Downselected			Critical Experiments

Figure 20 –Results of Active DPF Technology Selection

catalyzed particulate filter was tested with a precat upstream to evaluate the advantage of NO to NO₂ function and catalyst exothermic reaction in terms of balance point temperature (BPT). BPT results for advanced CPF, and advanced CPF with precat are shown in Figure 21.

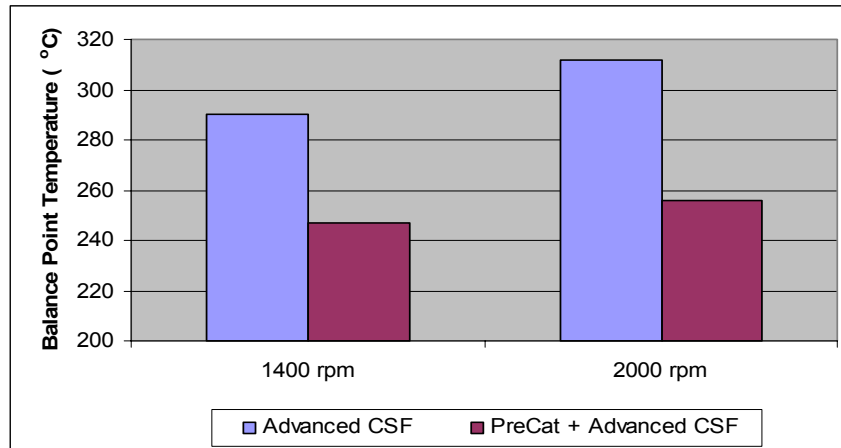


Figure 21 - Effect of precat on CPF balance point temperature.

The precat with advanced CPF gave a 40 to 50°C reduction in the balance point temperature and better regeneration performance.

EXHAUST SULFUR MANAGEMENT

As shown previously, NO_x adsorber catalysts have achieved high NO_x reduction levels using very low sulfur (< 3ppm) diesel fuels during steady-state conditions. However, the degradation of adsorber performance due to sulfur poisoning remains an issue and needs to be addressed. SO_x competes for active NO_x adsorption sites to form thermodynamically stable compounds that require an extremely high temperature (> 650°C) and reductant to regenerate the adsorber. The impact of fuel sulfur levels on NO_x conversion efficiency is given in Figure 22. The results indicate that even with the availability of 15ppm sulfur diesel fuels, an effective exhaust sulfur management scheme is required to keep emission control devices operating near their peak effectiveness. To better understand the effect of adsorber sulfur loading and performance degradation, exhaust sulfur concentration was mapped over a wide range of engine speed and load conditions. The results, as shown in Figure 21, indicate that in addition to the fuel sulfur, the sulfur in the lube oil also plays a major role in adsorber sulfur loading and performance degradation. Two paths were explored for sulfur management: (1) the use of a SO_x trap that can be regenerated offline or replaced periodically, and (2) the use of diesel fuel and high temperature to desorb the sulfates. An assessment of each system is summarized below.

Disposable/Offline Regenerable

- High adsorption capacity for sulfur
- High selectivity toward sulfur adsorption
- No release of secondary emissions from trap
- Usable life of SO_x trap is dependent on sulfur level in fuel and lube oil
- Good protection of adsorber catalyst from sulfur poisoning during misfueling
- Good technology for light-duty applications - small size, low cost, and limited useful life requirement

NO_x Adsorber Desulfation Catalyst

- Integrated NO_x trap and SO_x trap function on one catalyst, does not require separate SO_x trap
- Requires on-board exhaust temperature management to release sulfur (> 650°C)
- Additional fuel penalty will be incurred during desulfation process
- Desulfation involves release of secondary emissions hydrogen sulfide and/or sulfur dioxides

- Catalyst material development required compromise among NO_x storage & conversion, SO_x storage & release, and catalyst thermal durability

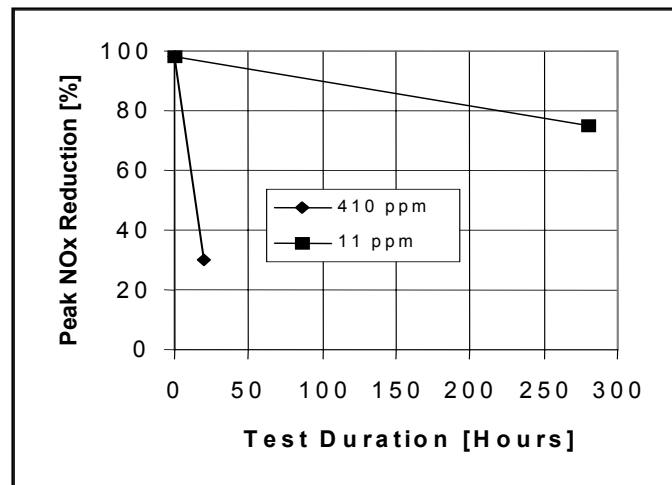


Figure 22 - Impact of fuel sulfur levels on NO_x conversion efficiency

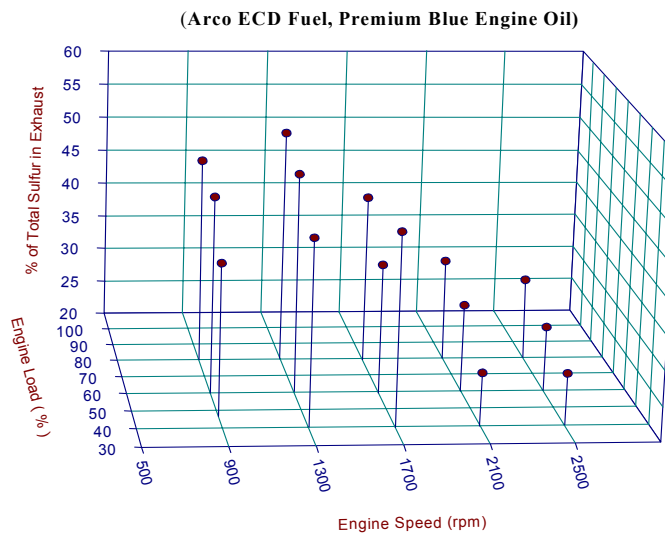


Figure 23 - Contribution of lube oil to exhaust sulfur concentration

In this program, the effort was focused on developing a SO_x trap having sufficient capacity to protect the NO_x adsorber catalyst for at least 20,000 miles before the SO_x trap would need to be changed. The SO_x trapping efficiency needs to be near 100% all the time (< 10ppb break-through), and the stored SO_x should not be released during the hottest driving conditions and during rich transient operation for NO_x regeneration. The current development path uses a formulation containing base metals. A SO_x trap with a 20gm SO₂/l capacity, and an estimated 15,000 mile lifetime before change-out has been demonstrated as shown in Figure 24. Alternate substrates with high pore volume are being investigated to provide increased capacity. A global SO₂ adsorption model was developed to describe the sulfur trap behavior and to correlate the operating conditions and catalyst characteristics effects on the trapping performance. The model

combines adsorption kinetics and mass transfer process in a single equation and is able to express adsorption rate in both kinetics and mass transfer dominated regimes.

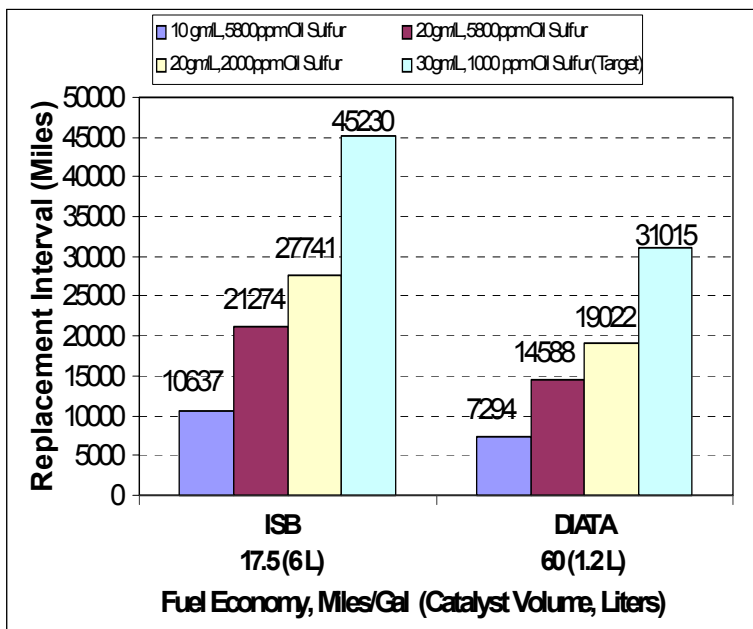


Figure 24 - SOX trap replacement / offline regeneration interval.

SYSTEM CONFIGURATION CONSIDERATIONS

The benefits of using a catalytic system for particulate filter regeneration are many, it is a relatively simple system, low cost, and has synergistic opportunities with the rest of the aftertreatment system. For instance, the CPF can be placed downstream of the NO_x adsorber to make use of the heat generated during regeneration of the NO_x adsorber. In this configuration, the CPF can also make use of the HC slip across the NO_x adsorber, which will cause an additional exotherm with the CPF itself. There can also be synergies by placing the CPF upstream of the NO_x adsorber. An assessment of each configuration is summarized below.

CPF Downstream of NOX Adsorber

Positives

- CPF can use heat generated across the adsorber during NO_x regeneration event
- CPF can make use of HC slip from the NO_x adsorber, which will cause an additional exotherm within the CPF itself.

Negatives

- Removal of NO₂ from the exhaust stream. NO₂ is a very good oxidizer of soot.
- NO_x adsorber is exposed to “dirty” exhaust, and may plug

CPF Upstream of NOX Adsorber

Positives

- Clean exhaust conditions for the NO_x adsorber
- NO to NO₂ oxidation which will assist the function of the NO_x adsorber trapping

Negatives

- CPF is exposed to cool exhaust temperatures, which may hamper CPF regeneration
- High temperature of CPF regeneration might exceed the maximum material limits of the NO_x adsorber material, causing sintering, and degradation of the catalyst function.

Extending this thought process to the full conclusion, the best configuration for an exhaust aftertreatment device is to combine or integrate the functions of the separate components on to one single substrate. In this manner, the maximum synergistic effect can be achieved for catalytic functions, as well as heat management. This also results in a very compact system.

Figure 25 shows two of the exhaust aftertreatment system configurations that were investigated. For both configurations, the systems consist of three major catalyst components: SO_x trap, NO_x adsorber (AC), and catalyzed particulate filter (CPF). The purpose of the SO_x trap is to capture sulfur in the engine exhaust before entering the NO_x adsorber. In addition to the usual function of trapping particulate matter in the engine exhaust, the catalyzed particulate filter has higher Pt loading to reduce HC and CO slip from the NO_x adsorber regeneration as well. The NO_x adsorber is periodically regenerated by injecting low sulfur (< 15ppm) diesel fuel to produce a rich environment for the release of adsorbed NO_x and subsequent conversion to N₂.

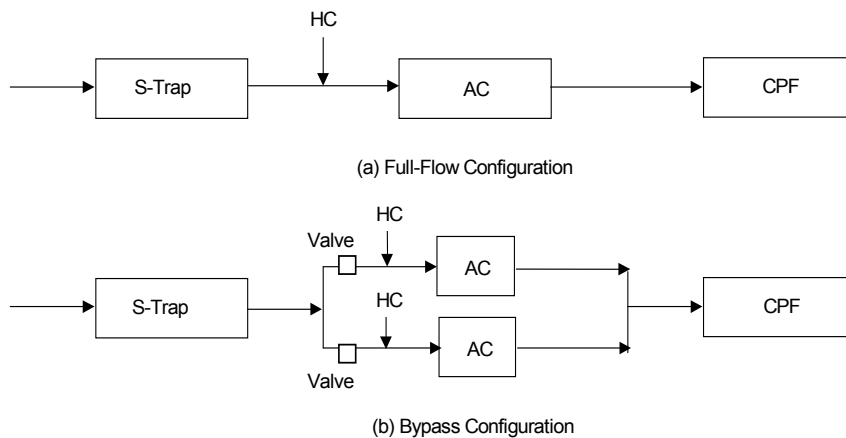


Figure 25 - Aftertreatment System Configurations

Under steady-state engine operating conditions, the NO_x adsorber is normally regenerated at fixed time intervals, for example, every 30 seconds. The quantity of the injected fuel has to be sufficient not only to produce rich conditions ($\lambda < 1$), but also to react with NO_x desorbed from the catalyst and convert it into N₂. To ensure this condition is met, the injection quantity is usually based on a catalyst-in A/F ratio target lower than stoichiometric (14.6 for diesel fuel), such as A/F=9. For diesel engines operating in oxygen rich exhaust conditions ($\lambda > 1$), a significant portion of the injected fuel is used to consume O₂ in the exhaust. While laboratory tests have shown that a longer regeneration period can improve regeneration efficiency, this is usually not practical due to proportionally higher fuel penalty associated with the O₂ reaction. For this reason, fuel injection is typically limited to produce only a very short rich period, for about 1 to 5 seconds. The effectiveness of the injected fuel to produce conditions favorable for NO_x conversion depends on many factors, such as the fuel injection quantity and flow distribution leading to the NO_x adsorber.

For the full-flow configuration, as shown in Figure 25(a), all the engine exhaust flows through the NO_x adsorber during both lean and rich periods. The fuel penalty of the NO_x adsorber regeneration can be calculated based on exhaust flow rate, engine A/F ratio, regeneration frequency, catalyst-in A/F ratio target, and engine brake specific fuel consumption (BSFC). The calculated injected fuel penalty on the breadboard ISB low-NO_x engine over different steady-state operating conditions for the full flow configuration is given in Figure 26(a). The fuel penalty is highest at high speed and low load conditions because the exhaust flow rate and engine A/F ratio

are both higher there. A higher percentage of the injected fuel is used for O_2 consumption when the engine A/F ratio is high, usually at low engine loads.

One way to reduce fuel penalty associated with NO_x adsorber regeneration is to reduce O_2 flow during regeneration. This can be accomplished by using the bypass configuration as shown in Figure 25(b). The flow after the SO_x trap is split equally into two bypass legs. Each leg contains one-half of the total NO_x adsorber volume, and each has a fuel injection system in front of the adsorber for regeneration. During regeneration, the flow through the adsorber under regeneration is restricted to below 50% of the total engine exhaust. For a fixed catalyst-in A/F ratio target, the fuel injection required for regeneration can be proportionally reduced. Figure 26(b) shows the fuel penalty for the ISB breadboard engine when 20% bypass flow is used during regeneration. Since both bypass legs have to be regenerated in turn, the total fuel penalty is two times the 20% bypass flow, resulting in a fuel penalty 60% lower than the full-flow regeneration. In addition, tests have shown that HC slip after the NO_x adsorber is also lower. This is because space velocity and fuel injection quantity are both lower during bypass, resulting in a more complete reaction.

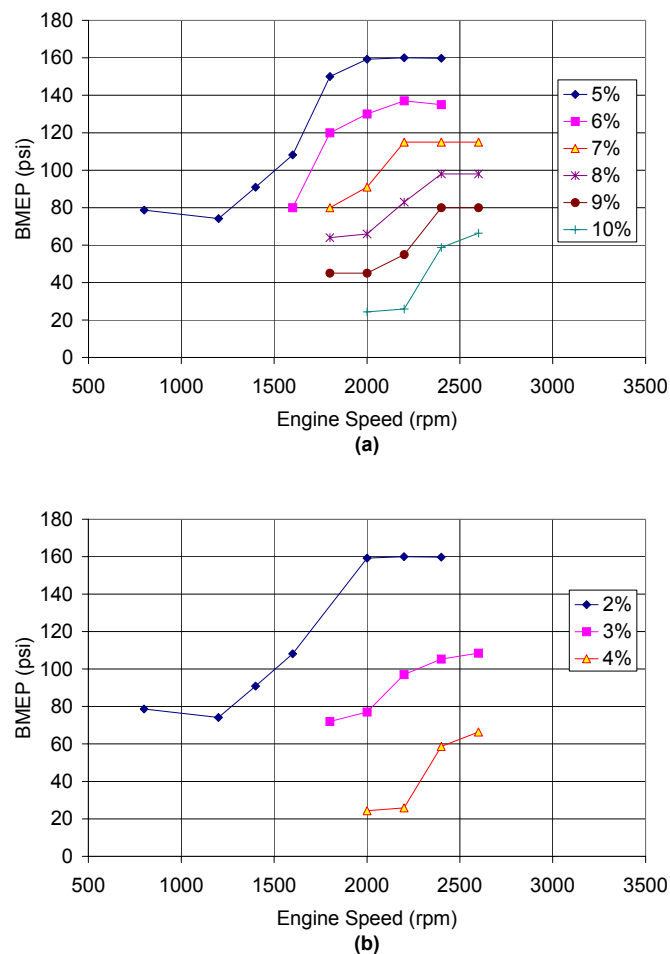


Figure 26 - NO_x adsorber fuel penalty for breadboard ISB (a) Full-flow regeneration, (b) 20% full-bypass

Bypass regeneration is considerably more complex than full-flow. Careful consideration needs to be given to additional influencing factors such as the percent of bypass and the duration of bypass both before and after the fuel injection. If the valves remain fully open during regeneration, 50% of exhaust would pass through each of the bypass legs and no fuel penalty

savings would be realized. On the other hand, if the flow were restricted to the maximum (approaching zero) during regeneration, the injected fuel would take considerable time to travel through the catalyst, resulting in a long regeneration period. In the mean time, the temperature of the catalyst would drop toward the ambient due to the lack of heat from the exhaust flow, and lower temperatures reduce the regeneration effectiveness. Simultaneously, the adsorber on the other leg would pass nearly 100% of engine exhaust flow, resulting in faster NO_x loading. NO_x adsorption efficiency decreases with increasing NO_x loading. In addition, the adsorption would take place at higher space velocity, further reducing the adsorption efficiency. If the catalysts were regenerated in such a way that there is always one catalyst under regeneration, then only one-half of the total adsorber volume is used for NO_x adsorption at any given time, resulting in a poor utilization of the total adsorber capacity. Thus the optimum bypass percentage is somewhere between 0% and 50%. The bypass period should be made as short as possible, without compromising the regeneration effectiveness. To fully utilize the total catalyst capacity, both NO_x adsorbers should be active most of the time. Extensive tests have been performed, and the results indicate that about 10 to 20% regeneration bypass is the optimum, and similar NO_x conversion efficiency as full-flow regeneration can be maintained with reduced fuel penalty.

The reaction of HC with O₂ and NO_x are both exothermic. If the heat loss to the ambient is minimized, the exothermic heat from NO_x adsorber regeneration can be utilized to raise the temperature not only for the NO_x adsorber, but also the CPF. Since the CPF is placed downstream of the NO_x adsorber, the exit temperature from the NO_x adsorber is also the inlet temperature for the CPF. Based on current CPF technology, approximately 300°C and above inlet temperature is needed to regenerate the CPF continuously. Figure 27(a) shows the typical NO_x adsorber inlet temperature of the breadboard ISB engine during steady-state conditions. The inlet temperature is generally a strong function of engine load, and a weak function of engine speed. The NO_x adsorber inlet temperature is lower than the engine turbo-out temperature, due to heat transfer to the ambient from components upstream such as the SO_x trap and exhaust pipe. Improved insulation can reduce this heat loss.

Figure 27(b) shows the CPF inlet temperatures for the 20% bypass, catalyst-in A/F ratio target of 9, and 29s/1s regeneration case. The 300°C CPF regeneration limit is moved to lower engine load as compared to Figure 26(a), due to exothermic heat release of the NO_x adsorber regeneration. The amount of exothermic heat generated is a function of fuel injection quantity and frequency. By increasing the fuel injection quantity or frequency, it is possible to increase the CPF inlet temperature further at low load to enhance active CPF regeneration.

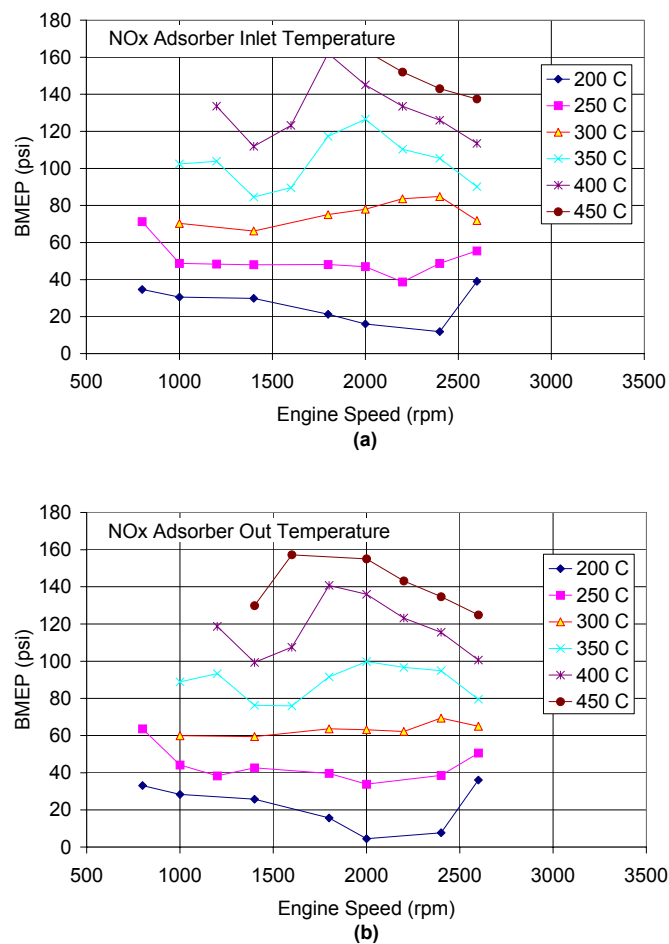


Figure 27 - NOx adsorber out temperature vs. inlet temperature

EFFECT OF CATALYST SIZE

The effect of catalyst size on NOx conversion efficiency and fuel penalty for full flow (FF) regeneration was studied under the control-based strategy at steady state. In FF, the whole exhaust flows through the catalyst during lean as well as rich operation. Under control based strategy the catalyst is regenerated only when the efficiency falls below the target value. The catalyst inlet temperature was varied by changing the engine torque. The NOx concentration was different at each temperature and depended on engine calibration. The Figure 28 shows the effect of catalyst size on NOx conversion efficiency and fuel penalty. The testing was done on a 5.9 L mule engine and the NOx adsorber catalyst size was varied from 7 L to 21 L. As shown, 10.5 L catalyst (~1.8 times engine displacement) can achieve the same NOx conversion efficiency as catalysts of bigger volume. The fuel penalty is similar above 320 °C for all tested

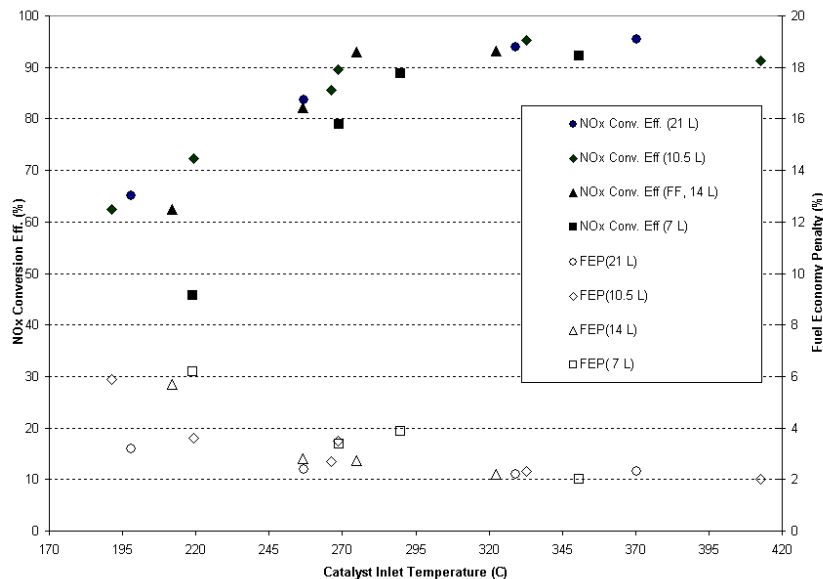


Figure 28 - Effect of catalyst size under control-based regeneration

catalyst sizes. Below 320 °C, fuel penalty becomes higher for smaller catalyst sizes. A 7 L NO_x adsorber has the worst NO_x conversion efficiency and fuel penalty, and is inadequate for the application.

CATALYST DEGRADATION

Catalyst durability is the most critical issue for current aftertreatment systems using NO_x adsorber technology. Spectroscopic characterization of the inlet portion of catalyst samples following the time sequence of an engine test revealed important information related to catalyst deactivation. Deactivation of NO_x adsorbers involves many pathways and S-poisoning is possibly the most recognizable one. The degradation pathways that have been identified under this program are summarized in Figure 29.

Adsorber degradation mechanisms				
	Chemical	Thermal	Mechanical	Capability/Tool
Adsorption	S poisoning (fuel/lube) Lube/ash poisoning Carbonaceous deposits (coking) Condensation/solubility of metal nitrate	Pt & Metal-Oxide sintering	Physical breakage	Surface Analysis DRIFTS Lube oil tests Reactor
Regeneration	Residual nitrate Physical/chemical blockage of pores	Pt-MO interactions MO-support interactions		SpaciMS DRIFTS
Conversion	Poison-induced reconstruction of catalyst surface	Pt & MO sintering		Surface Area Platinum Dispersion
Desulfation	Residual sulfate	Pt & MO sintering Pore / surface changes	Thermal shock	Reactor Engine Tests

Figure 29 – Catalyst Degradation Mechanisms

Simulated FTP-75 Cycle Transient Test Results

The NO_x adsorber transient test is carried out by using a breadboard ISB engine in a CVS test cell. The FTP-75 cycle is simulated by specifying an engine speed and load history obtained from computer simulation and validated in chassis dynamometer tests of a typical Dodge Ram vehicle.

As compared to steady-state tests, transient tests provide some additional challenges. For example:

- The turbo-out temperature is lower than the steady-state operation of the same engine speed and load due to engine thermal inertia. The effect of thermal inertia of the aftertreatment system also becomes more important, and further reduces the peak temperature at catalyst inlet.
- The initial state of the NO_x adsorber is unknown at the beginning of each FTP-75 cycle. For steady-state tests, this can be overcome by a period of stabilized catalyst operation.
- The exhaust flow condition is varying continuously. It is impractical to pre-determine the regeneration timing and injection quantity, especially in real-world applications.
- For bypass regeneration, the two catalysts can experience different inlet conditions (NO_x rate, temperature, etc.), as well as different initial states.

To meet these additional transient testing challenges, a closed-loop regeneration control algorithm using various sensor inputs was implemented with a programmable controller. The regeneration timing and injection quantities are both dynamically determined by the controller during the transient test.

Arco EC-D low sulfur (< 15ppm) diesel fuel was used for both the breadboard ISB engine and exhaust injection. A 7 liter SO_x trap, and a 12.5 liter CPF was used. Two 7 liter NO_x adsorbers were used to form a total of 14 liters volume. The adsorbers are either used in series or in parallel. To relate the bypass flow, two exhaust valves are used, one on each leg of the bypass system.

To illustrate the impact of the initial state of the system, the NO_x adsorbers were first fully cleaned at a favorable steady-state condition (1400 rpm, 200 ft-lb). Subsequent to the pre-cleaning, a hot FTP-75 cycle was run without exhaust fuel injection. Figure 30 shows a 97% NO_x conversion efficiency can be obtained with no fuel penalty on a bypass system. However, this high efficiency can not be sustained. When the tests were repeated without pre-cleaning and regeneration, the

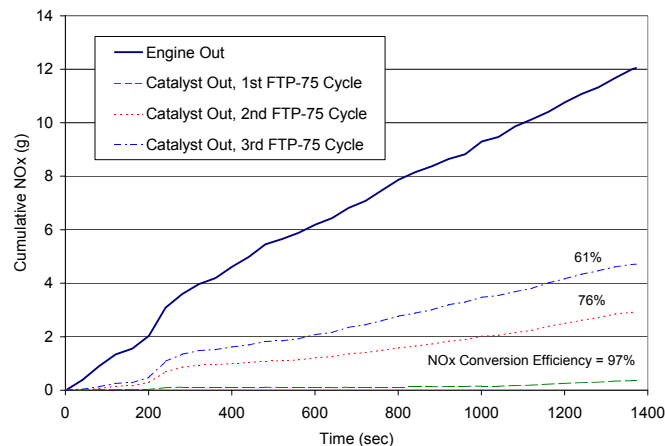


Figure 30 - Impact of NO_x adsorber initial state on NO_x conversion efficiency.

NO_x conversion efficiency dropped to around 76%, and then 61%, as the initial NO_x loading at the beginning of each cycle became higher.

Since the NO_x adsorber is a storage device, it is necessary to demonstrate the effectiveness of regeneration by maintaining the NO_x conversion efficiency over several FTP-75 cycles without pre-cleaning. The final state of these hot FTP-75 cycles can be used to start the cold FTP-75 cycle the next day. Figure 31 shows the bypass regeneration results of using this approach. Because of the low exhaust temperature, 72% NO_x conversion efficiency was obtained for the cold-start cycle. For subsequent hot-start FTP-75 cycles, the NO_x conversion efficiency averaged about 87%. The CPF particulate trapping efficiency averaged about 93%.

	NO _x		PM	
	g/bhp-hr	% change	g/bhp-hr	% change
Engine Out	1.20		0.222	
EAS Out, cold	0.34	-72%	0.019	-91%
EAS Out, hot	0.15	-87%	0.011	-95%
EAS Out, hot	0.13	-89%	0.014	-94%
EAS Out, hot	0.17	-86%	0.017	-92%
EAS Out, hot	0.18	-85%	0.016	-93%

Figure 31 - Transient FTP-75 test results (bypass).

Figure 32 shows the cumulative NO_x and conversion efficiency time history of one of the hot-start cycles. At about 200 seconds, there is a drop in the cumulative NO_x efficiency because a period of high space velocity and high NO_x loading occurs when the catalyst temperature is still relatively low. Subsequent regeneration slowly recovers the NO_x conversion efficiency to the final value.

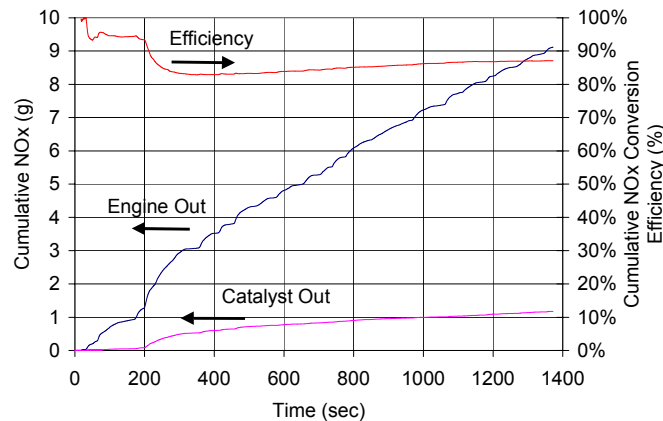


Figure 32 - Cumulative NO_x for a hot FTP-75 cycle (bypass configuration).

CHASSIS DYNAMOMETER TESTING

To evaluate the performance of an integrated aftertreatment system designed for a light duty vehicle, testing was conducted on the chassis-dynamometer at Argonne National Laboratory (ANL). The full bypass NO_x adsorber system with exhaust injection was fitted to a Mercedes A170 vehicle, and several parameters including engine and tailpipe emissions, and catalyst

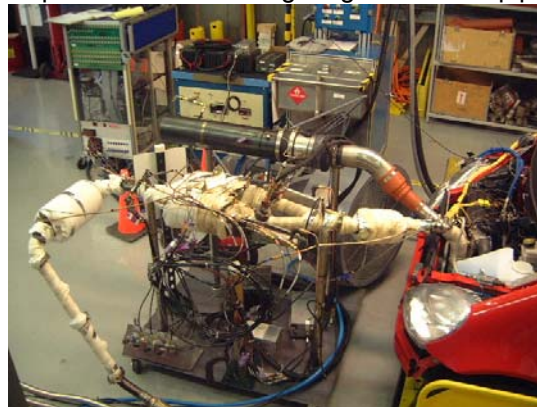


Figure 33 - Full bypass EAS at ANL

efficiency were monitored. To prevent Sulfur poisoning, a sulfur trap upstream of the adsorbers was used during the testing in conjunction of the 15-ppm ARCO ECD low sulfur fuel. A catalyzed particulate filter (CPF) was used to reduce system-out particulates and hydrocarbon emissions. Figure 33 illustrates the test set-up.

To characterize the operation and efficiency of the catalyst system, every emissions bench within the Argonne lab was used. In total, a raw exhaust bench, two fast-response hydrocarbon

analyzers, two fast-response nitric oxide analyzers, a particulate sampler and a dilute bench with CVS were utilized. These emission measurement systems allowed for continuous monitoring of engine out emissions, catalyst efficiency, tailpipe out emissions and fuel consumption. The A170 is a 1.7 L engine and has about 0.9 g/mile engine out NOx. Figure 34 shows the catalyst volumes used in the EAS. The NOx adsorber catalyst volume to engine displacement was selected to be 1.8 based on the system design tradeoff critical experiment discussed earlier. The total catalyst volume to engine displacement was 4. The baseline vehicle performance was evaluated first and is shown in Figure 35. This was collected with additional 2" Hg backpressure to account for the EAS.

Catalyst	Volume, L
SOx	1.25
Adsorber	3.1
CPF	2.5
Total	6.85

Figure 34 - Total EAS Catalyst Volume

Cycle	CO	CO ₂	THC	NOx	mpg
UDDS	1.28	223	0.081	0.957	44.9
HFET	0.62	176	0.035	0.787	57.3

Figure 35 – Baseline Emission/Fuel Economy

The temperature history over the Urban Dynamometer Driving Schedule (UDDS) cycle is shown in Figure 36. As can be seen the temperature was very cold over the cycle, generally below 200 C. Various control algorithms and hardware were tested to obtain the best system performance. Glow plugs were used to simulate engine management for exhaust temperature enhancement. Different injectors with improved atomization were also tested.

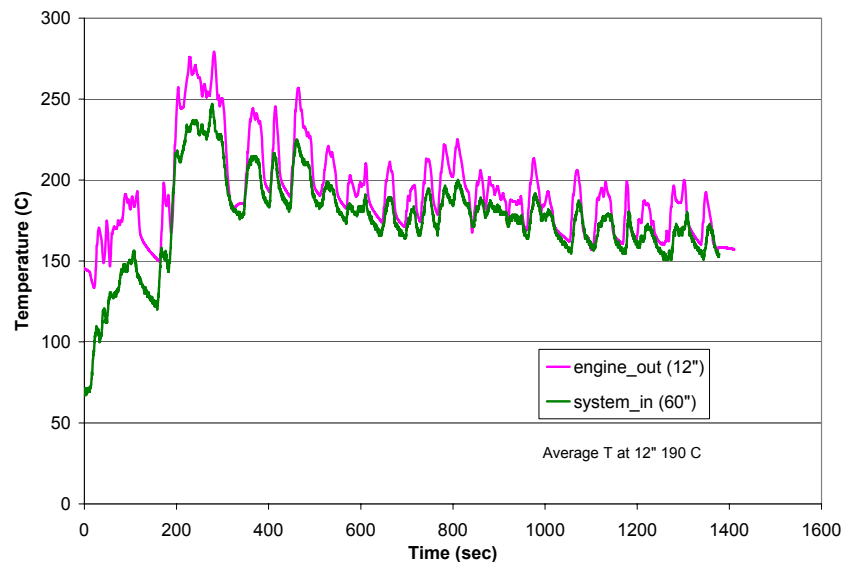


Figure 36 - Temperature history over UDDS cycle

A representative UDDS cycle result is shown in Figure 37. The majority of the NO_x slip from the aftertreatment system occurred around the 200-second hump in the UDDS cycle. A NO_x conversion efficiency of 99 % was obtained with a preconditioned catalyst. Preconditioning was done by running the vehicle at 65 miles per hour for 5 minutes while doing reductant injection. Without preconditioning a NO_x conversion efficiency of 89% could be achieved at about 11.6 % total fuel penalty for the FTP-72 cycle. The PM conversion was close to 99% and was beyond the detection capability of the measurement system at ANL.

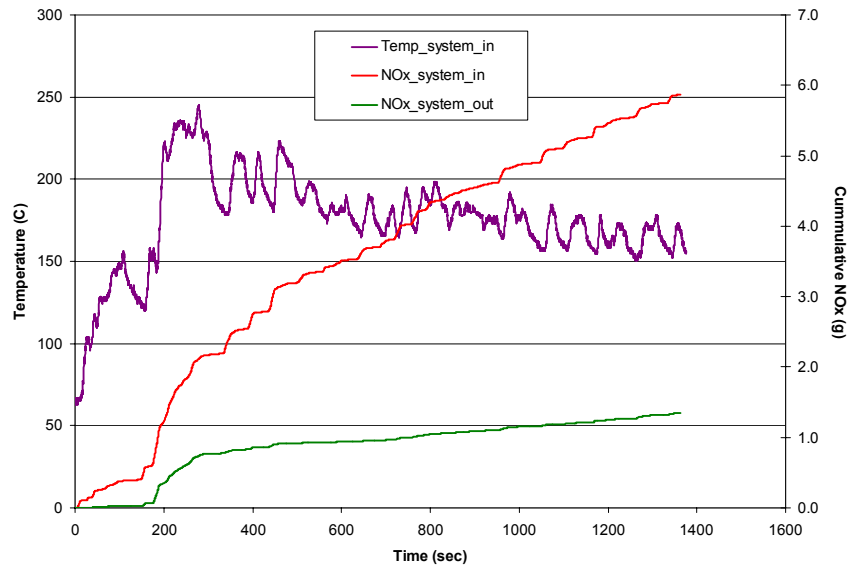


Figure 37 - Representative UDDS cycle results

Synergistic effects of NO_x adsorbers and particulate filters were evaluated by attempting to regenerate CPF using HC injection. The initial steady state results (Figure 38) indicate that CPF can be regenerated using HC injection. At the start of the test the CPF was loaded (13" of water delta pressure). Hydrocarbon (diesel fuel) was injected upstream of the NO_x adsorber which raised the system inlet temperature of 200 °C to almost 400 °C at CPF-in and the CPF was back to its originally clean condition in less than 10 minutes.

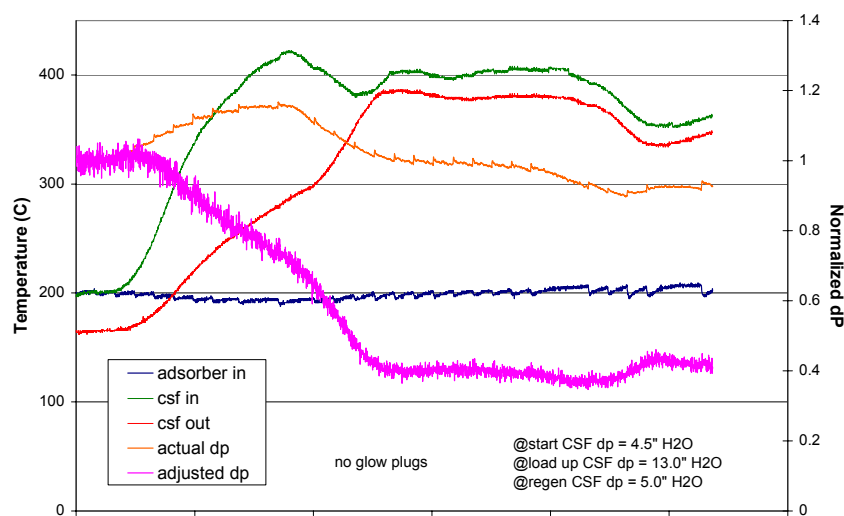


Figure 38 - Catalyzed particulate filter regeneration using HC injection

There has been some speculation that NH_3 is formed over the adsorber catalyst when HC is injected for cleaning up the stored NO_x . A simulated cycle, which closely resembled the temperature distribution of an FTP-72 cycle, was run. When the reductant injection was too frequent (e.g. every 20 seconds) considerable amount of NH_3 was formed with each injection. When the injection frequency was reduced (keeping the injection quantity per shot the same) the NO_x conversion efficiency did not reduce substantially indicating more frequent injection was unnecessary fuel penalty. Excess HC was resulting in substantial NH_3 formation and slip. This result is shown in Figure 39.

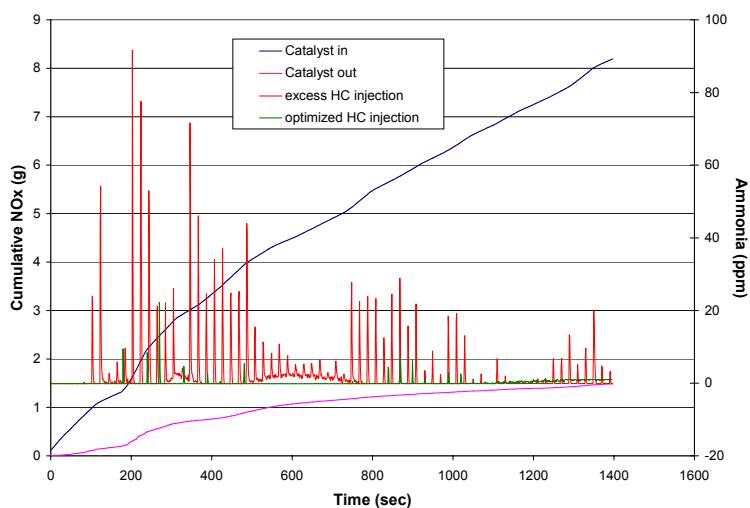


Figure 39 - NH_3 Slip from Aftertreatment system

This testing showed that NH_3 does form over the adsorber but it seems to be a secondary reaction to HC combustion and NO_x reduction. If HC is still left after these reactions, it may form NH_3 if conditions are right for that reaction. So, if the control strategy is well defined to avoid over injection, NH_3 formation may not be a problem.

Based on the target A:F ratio for these tests, the O_2 in exhaust was supposed to be close to zero after each injection. However, the oxygen does not drop to the low levels in the exhaust always. It was noticed that the NH_3 spike was higher every time the HC combustion efficiency was high (oxygen in exhaust was less). It was also noticed in this testing that NH_3 formation was proportional to HC injection quantity. As can be seen in the figure, very little NH_3 is formed when the HC injection is optimized. NH_3 spikes are still seen around 200 sec in the cycle. These spikes are believed to be due to the stored HC over the first 200 seconds.

CONCLUSIONS – PHASE I

On the basis of extensive aftertreatment subsystem design and analysis, NOx adsorber technology was identified as the best NOx control approach for LDV and LDT applications. NOx conversion efficiency greater than 84% is required to achieve 0.07 g/mile NOx vehicle-out emissions. An 84% NOx conversion efficiency and 95% PM conversion efficiency has been demonstrated with a breadboard low emission Cummins ISB engine and an adsorber/CPF exhaust configuration on a simulated FTP-75 emission cycle at about 7% total fuel penalty. Encouraging NOx conversion efficiency results were also obtained at ANL with the present EAS system. A NOx conversion efficiency of 99 % can be obtained with a preconditioned catalyst. Without preconditioning a NOx conversion efficiency of 89% could be achieved at about 11.6 % total fuel penalty for the FTP-75 cycle. The PM conversion was close to 100% and was beyond the detection capability of the measurement system at ANL.

Significant progress was made on adsorber formulation development. As compared to early formulations, the operating range of the catalysts was extended by 50 to 100 °C lower as compared to previous formulations. Progress was also made on NOx adsorber regeneration strategies; reducing the fuel injection penalty by 40 to 50% compared to early tests. There is some NH_3 production during adsorber regeneration. This is manageable through HC injection optimization. Heat release from HC injection for adsorber regeneration may be utilized to keep the CPF clean. These were all key learnings that provided the groundwork for the Phase II which was conducted from mid-2002 through 2005.

Program Tasks – Phase 2

(from 2002 program extension Statement of Work)

Task 1

Complete the preliminary emission testing of a DIATA EAS system on P2000 vehicle at Argonne National Laboratory

Task 2

Continue to develop and optimize catalyst formulations for best NO_x and PM conversion efficiency under exhaust temperatures and space velocities consistent with anticipated light duty applications

Task 3

Continue to develop and design an offline regenerable sulfur trap to provide sufficient capacity to trap 99+ % fuel and oil derived SO_x with greater than 25,000 miles service interval

Task 4

Develop and demonstrate NO_x, and PM regeneration strategy during FTP-75 and real life duty cycle operations.

Task 5

Develop and optimize the reductant injection system and control for enrichment during steady state and transient operations for best aftertreatment performance (conversion efficiency, fuel penalty, and HC slip)

Task 6

Design and develop an integrated NO_x and PM system for minimum package size/cost, maximum performance, and minimum impact on fuel economy.

Task 7

Design and develop an integrated EAS/ISB Engine/LDT vehicle system for FTP-75 emissions cycle demonstration, cost projection, and limited field test.

Task 8

Obtain and minimize the impact of the final optimized system on unregulated emissions

Task 9

Obtain transient FTP-75 results on the LDT vehicle.

Task 10

Exhaust Aftertreatment System Model Development and Application.

Development Approach – Phase II

Phase I of the project identified that a NO_x adsorbing catalyst combined with a soot filter is the best approach for achieving Tier II emissions for LDV & LDT applications. In Phase II of the project, key system architecture evaluations were completed to determine the final engine aftertreatment system configuration.

Figure 40 illustrates the development approach utilized for Phase II of the project.

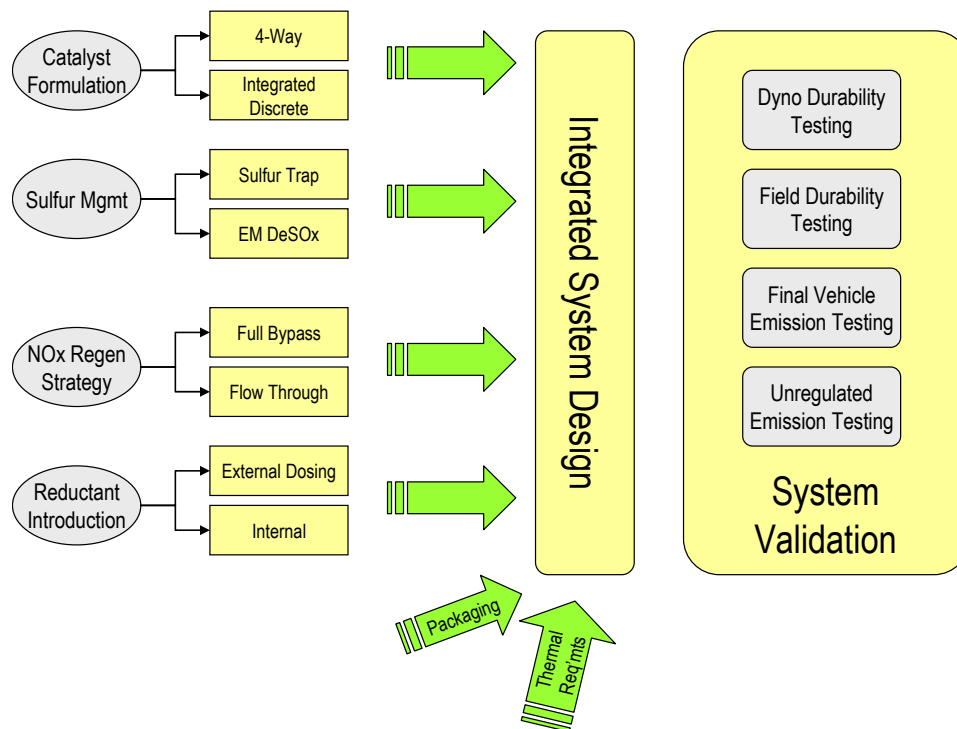


Figure 40 - Phase II Development Approach

CATALYST FORMULATION/CONFIGURATION

To optimize package size, minimize cost and fuel economy penalty, a four-way type catalyst configuration was evaluated.

SULFUR MANAGEMENT

During the FreedomCAR aftertreatment project, two methods of Sulfur management were investigated, (1) Sulfur Trap and (2) Desulfatable NO_x Adsorber. Details of each technology will be presented in the following sections.

Sulfur Trap

In order for the Sulfur Trap to be a viable option, it must be capable of trapping the expected exhaust Sulfur Species before they can poison the NO_x Adsorber, and it must accomplish this function during typical light duty operation. The Sulfur trap is usually placed in front of the NO_x adsorber, and shown in the Schematic in Figure 41.



Figure 41 - NOx Adsorber System with Sulfur Trap

Since the NOx adsorber will also trap any sulfur that is in the exhaust, to be effective, the sulfur trapping efficiency of the trap must be very high, on the order or greater than 99% during operation. The normalized Sulfur trapping efficiency of the Sulfur Trap is shown in Figure 42.

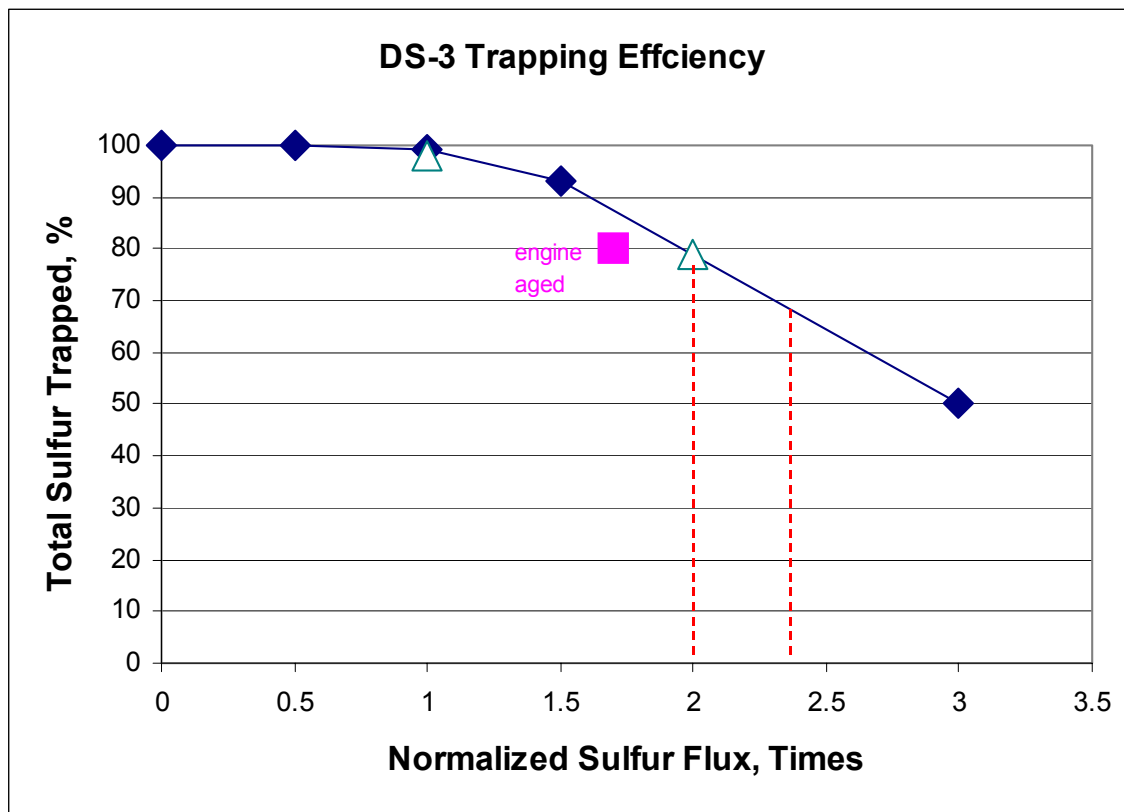


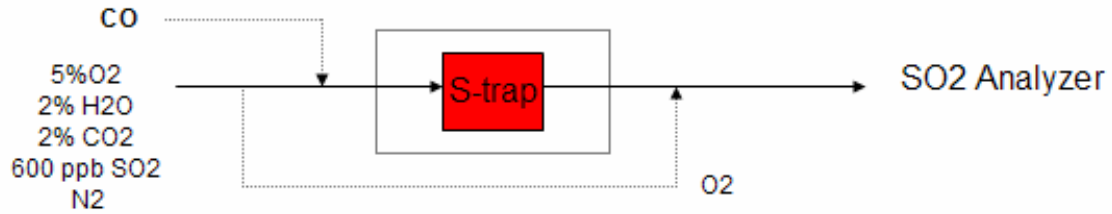
Figure 42 - Normalized Trapping Efficiency of Sulfur Trap

For the Sulfur trap results shown in Figure 42, the “1 times” Sulfur trapping capacity is approximately 15 gS/L. Therefore, for a 3.6L Sulfur Trap, the Sulfur trap can trap 54 grams of elemental Sulfur before any measurable slip would to the NOx adsorber would occur. If this size Sulfur trap was used on a light duty application, this could reduce the total number of DeSOx cycles on the NOx Adsorber by one half. The main benefits of using a Sulfur trap for light duty Diesel applications are therefore:

1. Significantly reduce the total amount of DeSOx cycles of the NOx adsorber during Useful life
2. Add durability to the Aftertreatment system since it will require less high temp DeSOx events (thermal durability)
3. Act as a first line of protection for NOx adsorber for excessive Sulfur from misfueling and oil contaminates.

One of the key concerns of using a Sulfur trap for Sulfur control is the potential for Sulfur release during the rich period of NOx regeneration. To test this further, an experiment was designed to

measure the Sulfur species slip during a simulated NO_x regeneration event. The schematic of the Sulfur release experiment is shown in Figure 43.



- Evaluations: 1 cycle/ minute, 200C to 400C
 - Lean operation - 45 seconds: all components (except CO); 27K VHSV
 - Regeneration operation – 15 seconds: O₂ bypass to downstream, 22K VHSV
 - 5 seconds delay
 - 5 seconds rich: 3% CO injection
 - 5 seconds recover

Figure 43 - Experimental Set-up to Investigate SO_x Release from SO_x Trap

The rich regeneration was accomplished by using a 3% pulse of CO every 55 sec. The result of SO₂ slip from the Sulfur Trap at a temperature of 300°C is shown in Figure 44.

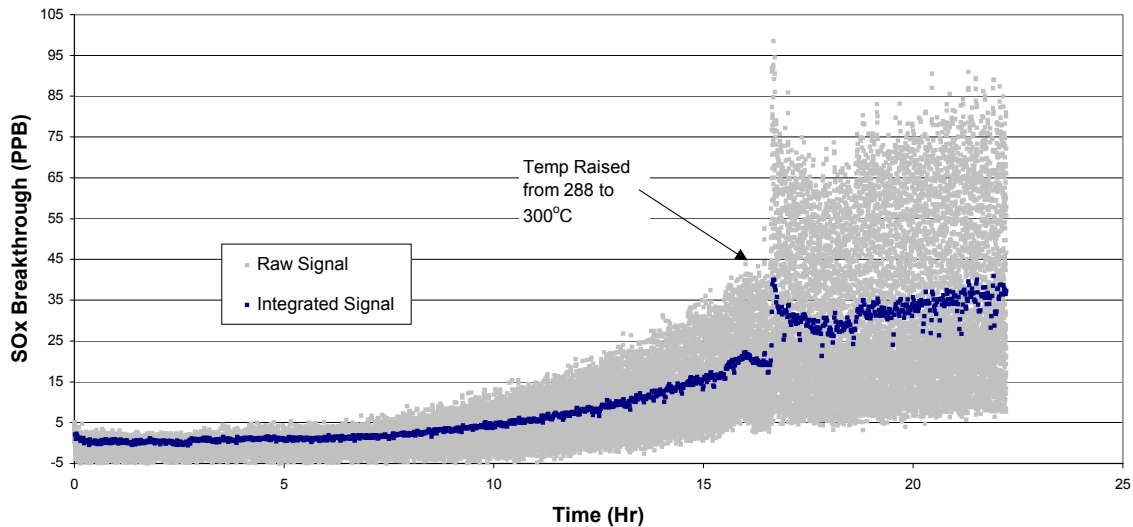


Figure 44 - Steady State and Transient SO₂ Slip from Sulfur Trap

It should be noted that the slip of SO₂ during the transient NO_x regeneration event is small, less than 50 ppb. Based on the results of the sulfur release experiment, the following conclusions may be made:

1. During NO_x regeneration, desorption of trapped sulfur is negligible, and the sulfur trap is able to trap SO₂ even under rich regen conditions.
2. Of the SO₂ breakthrough was in the sub-50ppb range, and is not expected to significantly poison the NO_x adsorber at this level of release.

Desulfatable NO_x Adsorber

The main benefits of using a desulfatable NO_x adsorber is that no Sulfur trap would be required in the system, thereby reducing system cost and complexity, no replacement and disposal of Sulfur trap would be required, and other smaller benefits like reduced total system exhaust restriction and easier packaging on the vehicle. The effect of Sulfur loading on NO_x capacity and NO_x conversion of the NO_x adsorber is shown in Figure 45.

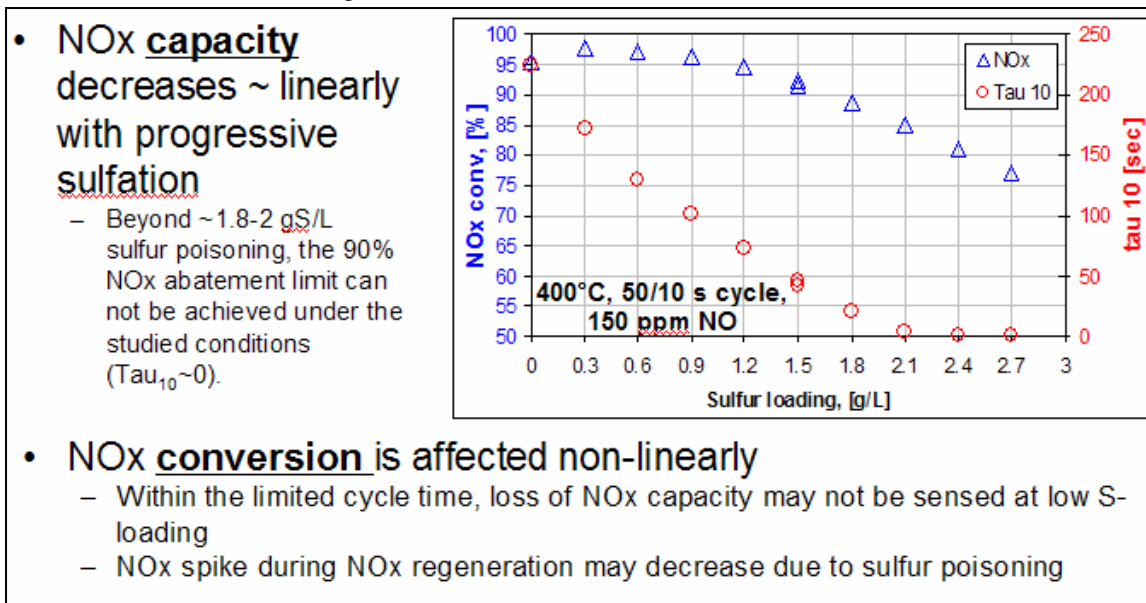


Figure 45 - Reactor Results Confirm Sulfation Effect on Adsorber

Notice that NO_x capacity is affected linearly with increasing sulfation and NO_x conversion is affected non-linearly with increasing sulfation. It should also be noted that NO_x conversion remains at a relatively high value > 90% for a significant period of time during Sulfur loading, but eventually, the NO_x adsorber will have to be cleaned of accumulated Sulfur to recover the NO_x conversion performance back to original conditions (DeSO_x regeneration).

The removal of Sulfur from the NO_x adsorber requires several conditions to be met: (1) High temperature, in the range of 600-700°C NO_x adsorber bed temp, and (2) Net rich conditions for the NO_x adsorber catalyst. Total DeSO_x regeneration event lasts about 10 to 15 minutes. The release of Sulfur from the NO_x adsorber during regeneration is strongly dependent on catalyst temperature, as shown in Figure 46.

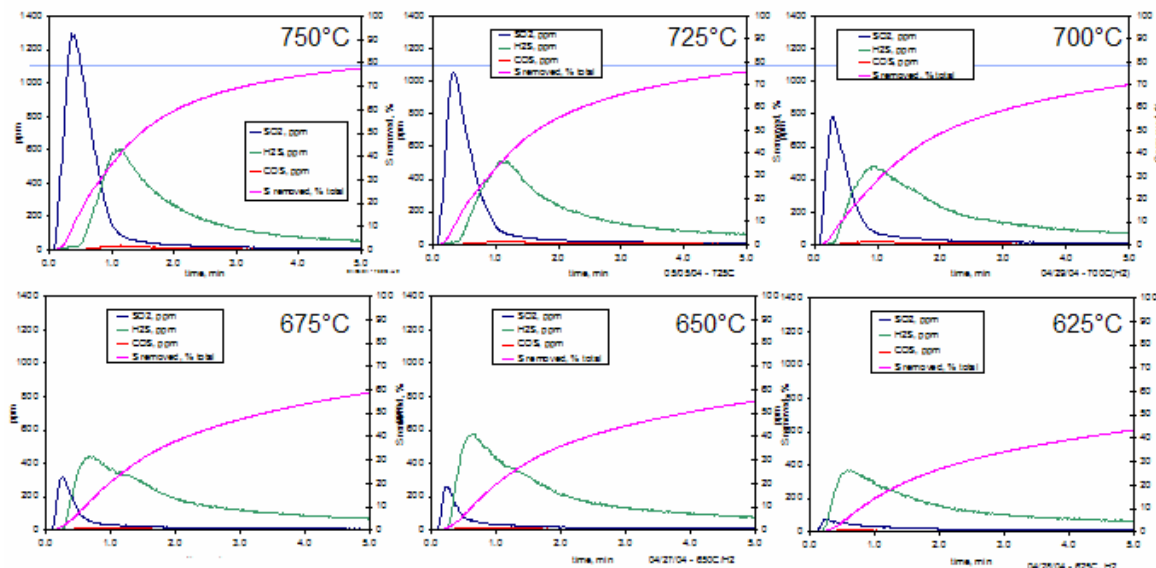


Figure 46 - Sulfur Species Rate of Release is Dependent on DeSOx Temp

Notice from the figure that the release of Sulfur species during regeneration is exponential with temperature, ie, a 75°C increase in temperature (eg, 625°C to 700°C) can increase the release of SO₂ from the surface by a factor of 8 times.

The high temperatures required for DeSOx regeneration are not readily achievable from typical diesel exhaust. In addition to engine management, the aftertreatment system is used to increase the exhaust temperature required for DeSOx, as shown in Figure 47.

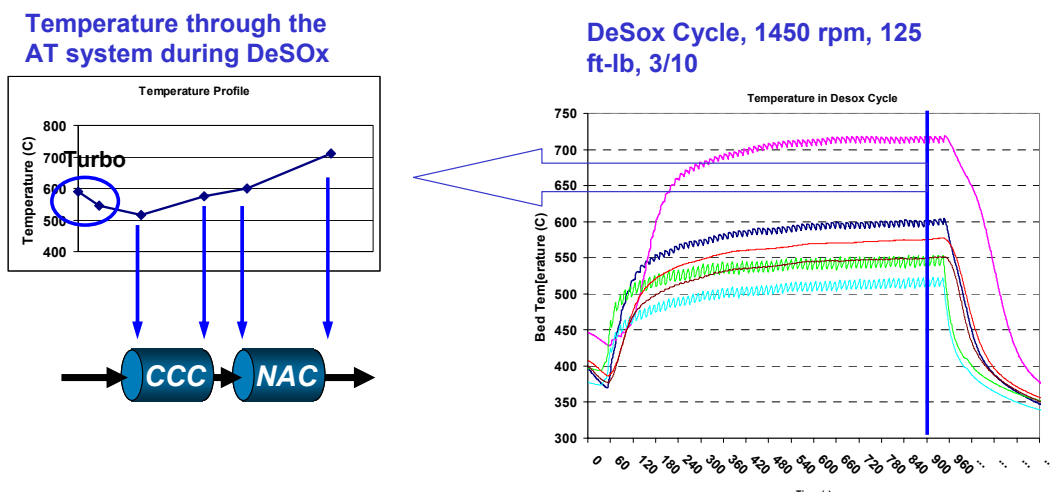


Figure 47 - DeSOx is Achieved with Both Engine and Aftertreatment

This is mainly accomplished by oxidizing hydrocarbons across the aftertreatment components during the regeneration event. An effective DeSOx regeneration can significantly recover NOx performance (NOx capacity) as shown in Figure 48.

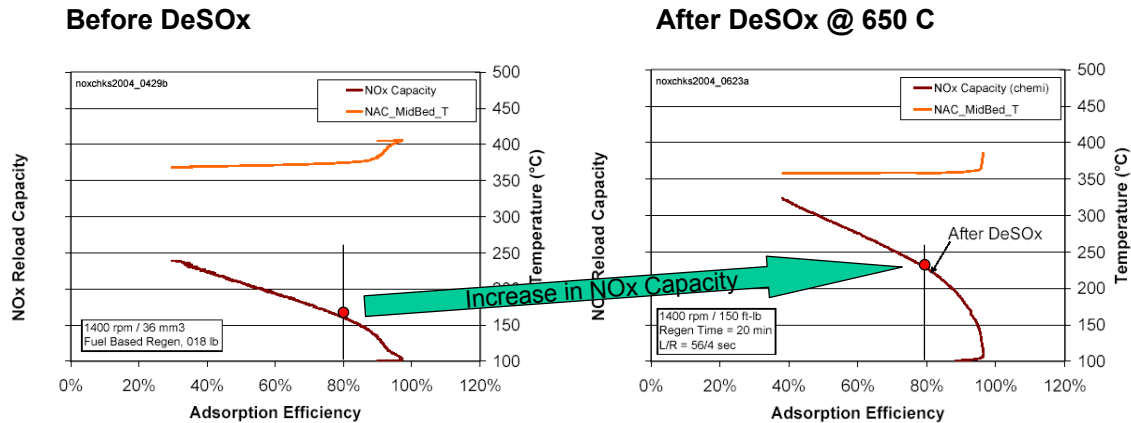


Figure 48 - Effective DeSOx can Recover NOx Capacity

Sulfur regeneration development centered on DeSOx strategy for achieving a narrow lambda window around stoichiometry (lean/rich cycling) and also identifying conditions that DeSOx can be achieved on the vehicle. DeSOx strategy development included lean/rich cycling optimization to maintain catalyst temperature, as well as suppression of H₂S during the regeneration. In addition, lean lambda control was identified as a critical parameter for smoke control during DeSOx. The zone of engine-managed DeSOx is shown in Figure 49.

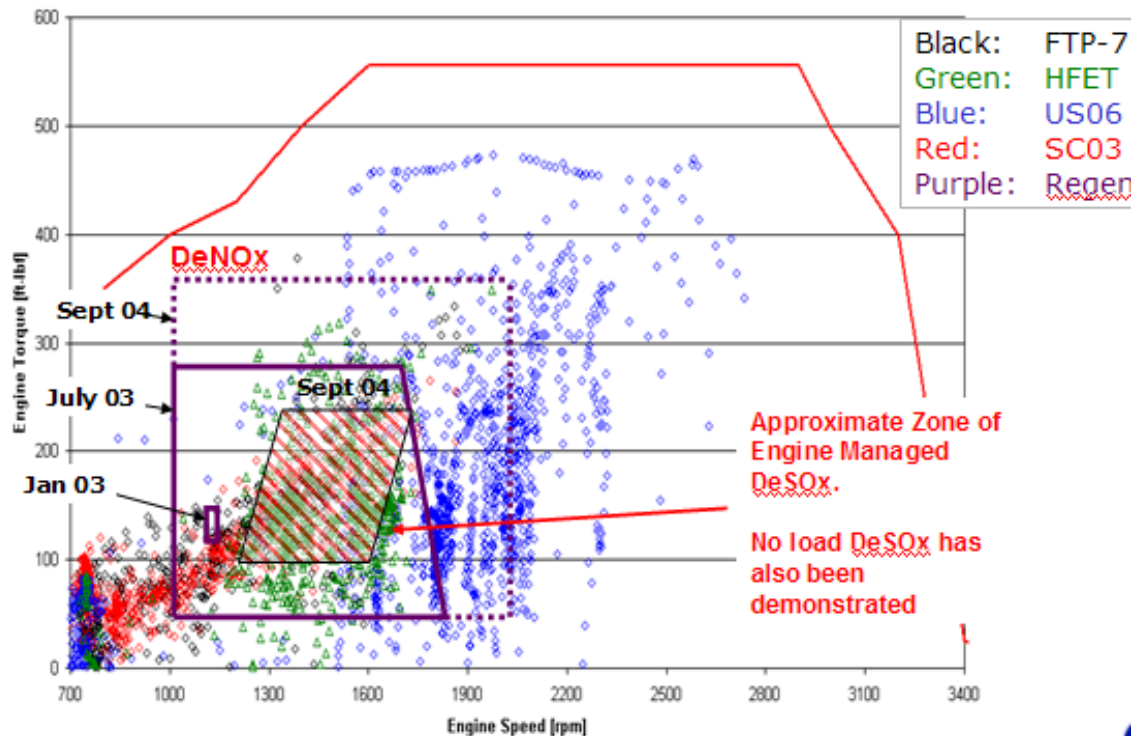
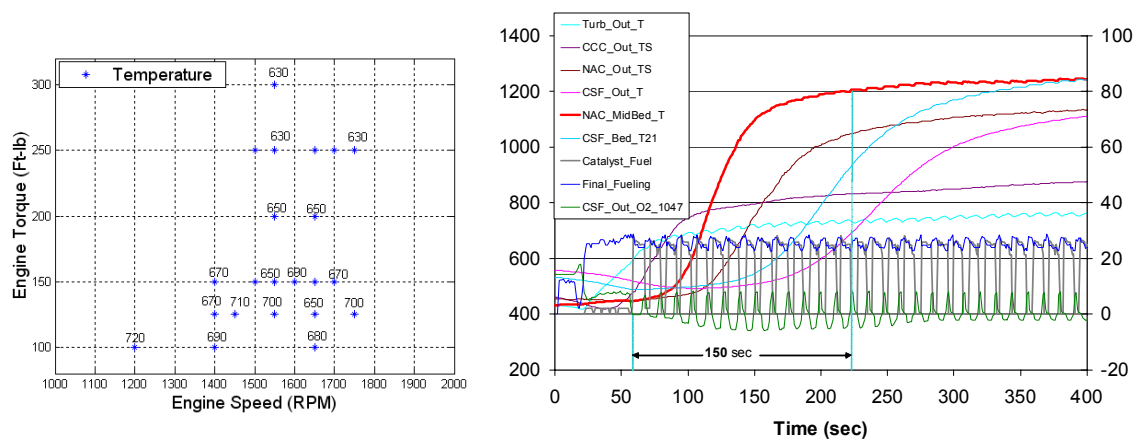


Figure 49 - Engine Managed DeSOx Zone

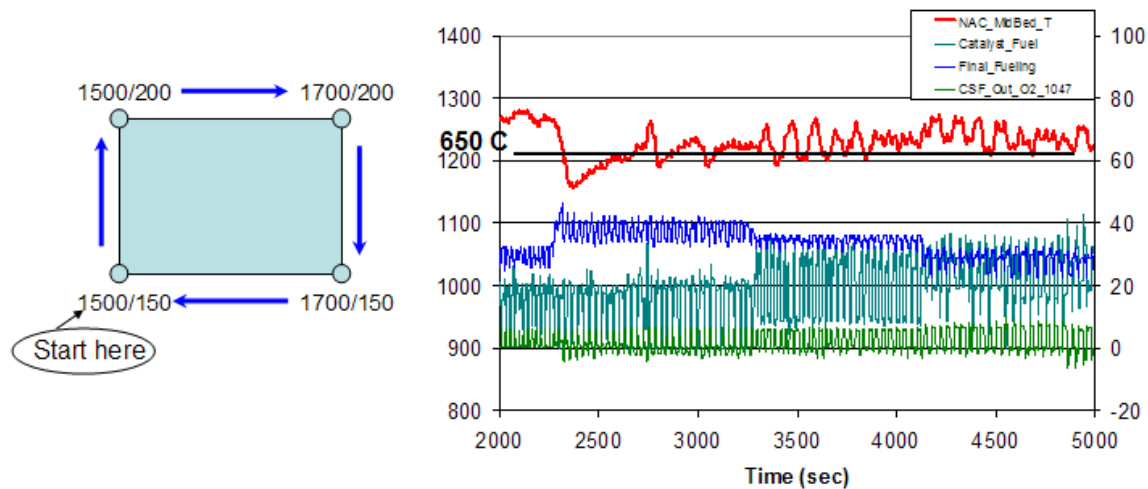
The engine can achieve DeSOx temps across the DeSOx zone, but heat capacity of the aftertreatment system requires a finite warm-up time to initiate DeSOx, as shown in Figure 50.



Engine can achieve DeSOx temps across DeSOx zone, but heat capacity of aftertreatment system requires warmup time to initiate DeSOx

Figure 50 - Capability of Engine To Achieve DeSOx Temperature

Notice that the target temperature of approximately 650°C was achievable at most conditions. It should be noted that approximately 2.5 minutes is required to reach the DeSOx temperature at this condition. Mild transient testing was also conducted in order to evaluate the ability of the closed-loop control to maintain DeSOx temperatures, as shown in Figure 51.



Transient temperature control is key for effective DeSOx, urban stop-and-go duty cycle is most challenging

Figure 51 - Transient Control of DeSOx Temperature

Notice that the controller was able to maintain temperature reasonably well during the transient. During the testing, it was noticed that the controller gains must be adjusted at each condition for good temperature control, indicating that an engine-based gain map will be necessary. Also, tuning the lean time portion of the lean/rich cycling was identified as the main parameter for robust temperature control.

REGENERATION – DENOX & DESOOT

NOx Regeneration

In order to complete NOx regeneration (DeNOx) in an effective and efficient manner, several critical factors must be identified, as shown in Figure 52.

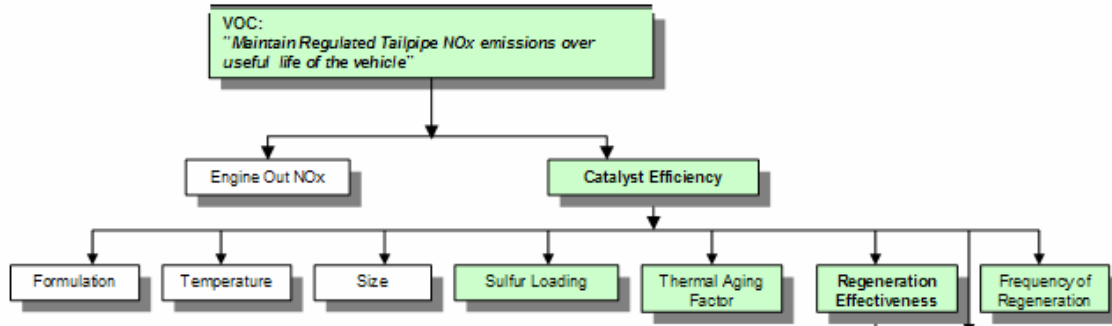


Figure 52 - Factors That Affect NOx Conversion Efficiency

These include degradation effects such as thermal degradation, as well as poisoning effects such as excessive accumulation of Sulfur. An effective NOx regeneration event requires net rich conditions on the catalyst, and lasts on the order of 2 to 5 seconds duration. For light duty diesels, the FTP75 certification cycle is used. A strategy for successful NOx performance during the cycle is to get exhaust temperatures warm as soon as possible during Bag 1, in preparation to trap engine-out NOx during hill 1 and hill 2, as shown in Figure 53.

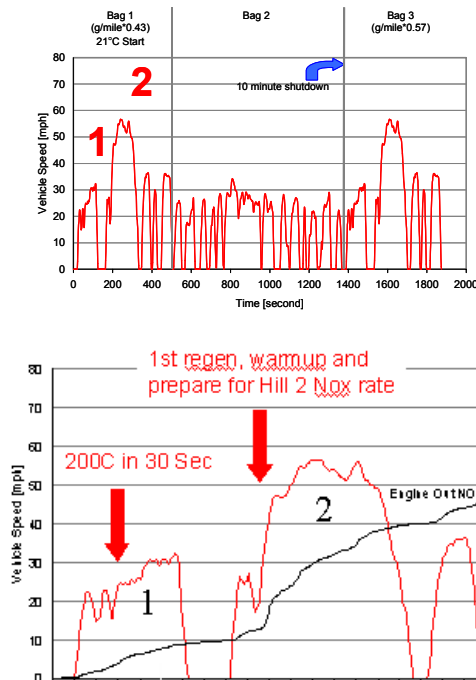


Figure 53 - Strategy to Address Cold Start on FTP-75 – Heat Management

Calculation of Weighted Mass Emissions

US HD Transient Emission Cycle

$$gm / bhp - hr = \frac{\left(\frac{1}{7}\right)gm_{cold} + \left(\frac{6}{7}\right)gm_{hot}}{\left(\frac{1}{7}\right)(bhp - hr)_{cold} + \left(\frac{6}{7}\right)(bhp - hr)_{hot}}$$

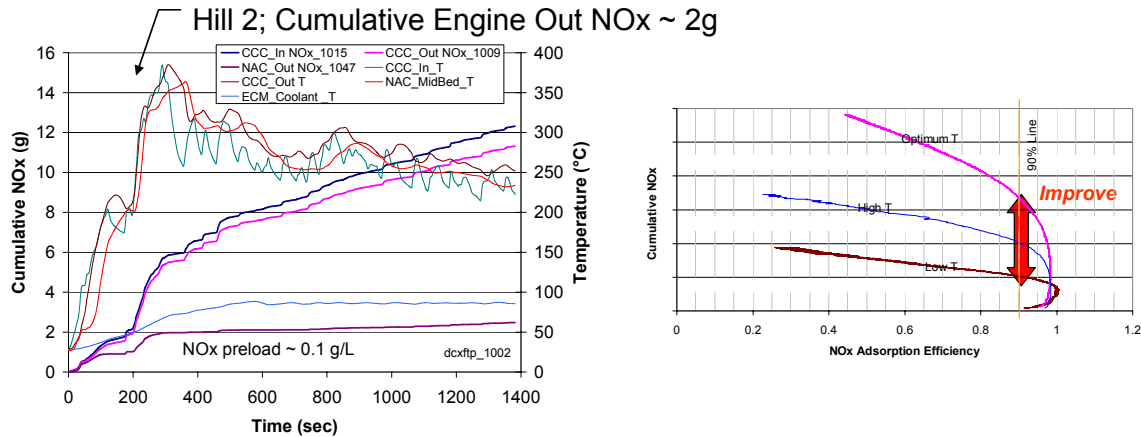
FTP-75 Transient Emission Cycle

$$gm / mile = (0.43) \frac{gm_{ct} + gm_s}{mile_{ct} + mile_s} + (0.57) \frac{gm_{ht} + gm_s}{mile_{ht} + mile_s}$$

Focused effort is to get exhaust temps up during bag 1.

Closer focus on catalyst preparation for hill 1 and hill 2

Capacity curve data suggests that the warm up of NAC to 300°C before 200 seconds could significantly improve Hill 2 NOx performance due to increased effective NOx storage capacity, as shown in Figure 54.

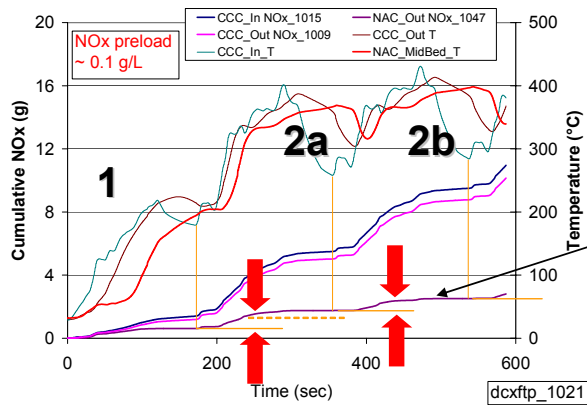


Test Conditions:

- The NAC was thermally aged with minimum sulfur exposure.
- Preloaded w/0.1 g/L NOx, no regeneration during the testing cycle.
- **Capacity curve data suggests that the warm up of NAC to 300°C before 200 seconds could significantly improve Hill 2 NOx performance due to increased effective NOx storage capacity.**

Figure 54 - EAS Thermal Management – Heat Management during FTP-75

As the catalyst system warms up, the effective NOx capacity increases, and therefore resulting in better performance over hill 2 of cycle. Test results (repeated Hill 2 test) demonstrate that warming up NAC before Hill 2 is important for success during FTP75 Cycle (Figure 55).



Repeated "Hill 2" Test

Approx. 40% less NOx

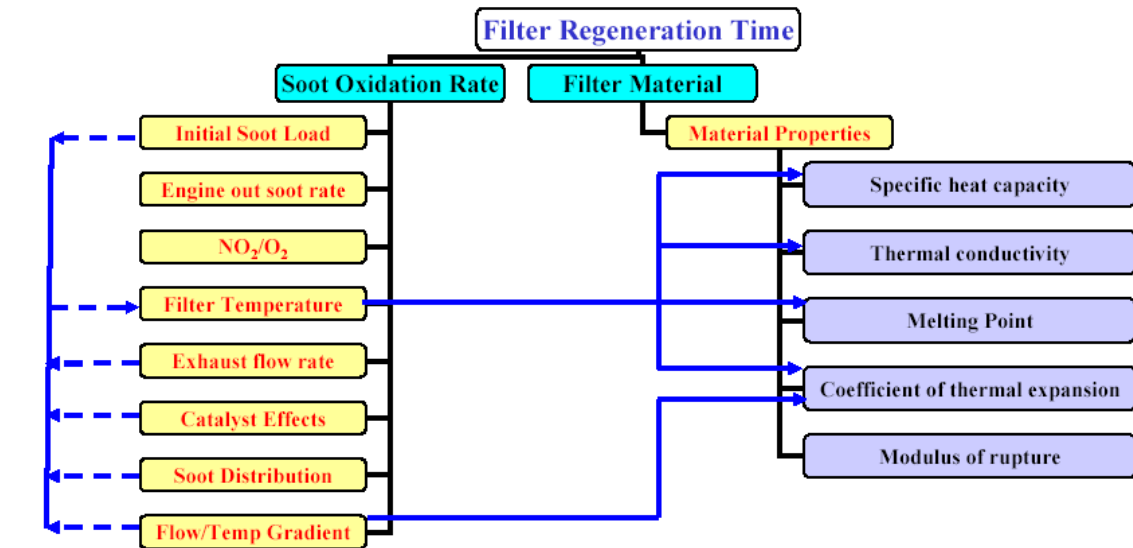
- *As the catalyst system warms up, the effective NOx capacity increases, and therefore resulting in better performance over hill 2 of cycle.*
- *Test results demonstrate that warming up NAC before Hill 2 is important for success during FTP75 Cycle.*
- *Active heat management is accomplished via engine management (air handling and in-cylinder fuel control)*

Figure 55 - Effect of NAC temp on Transient Performance

During the repeated Hill 2 testing, active heat management was accomplished via engine management (air handling and in-cylinder fuel control).

Soot Regeneration

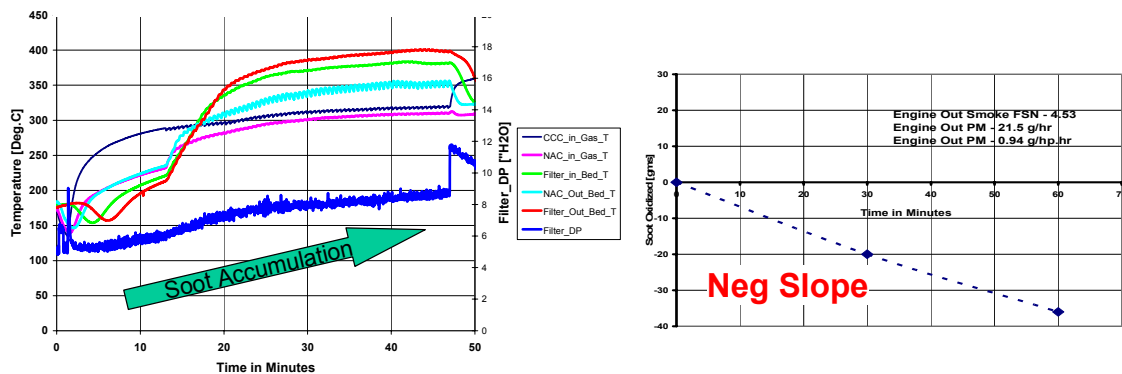
Similar to NOx Regeneration, critical parameters that affect soot regeneration were also identified, and shown in Figure 56.



Soot Oxidation process needs to be well managed to minimize regen time within material limitations

Figure 56 - DeSoot – Critical Parameter Flow-Down

Notice that critical factors that affect soot regeneration include Initial soot load, Engine-out soot rate, Filter temperature, Exhaust flow rate, Soot distribution and Flow and temperature gradients in the filter. Material properties such as heat capacity, thermal conductivity, melting point, coefficient of thermal expansion and MOR also affect the design of the filter for Diesel applications. For aftertreatment applications containing NO_x adsorbers placed in front of the soot filter (as is the case with IDAS), the main mode of soot regeneration is Oxygen based, requiring soot filter bed temps greater than 500°C. Similar to DeSO_x regeneration, this is accomplished via both engine management and thermal management with the aftertreatment system. For IDAS, the low temperature soot oxidation does not occur since the NO_x adsorber removes most of the available NO₂ in the exhaust gas, therefore produced a net soot-accumulating condition on the soot filter as shown in Figure 57.



At low temperature the NAC removes available NO₂ from exhaust, and thereby inhibiting the soot oxidation (indicated by negative slope on oxidation curve).

Figure 57 - DeSoot – Low Temperature Operation – NAC will inhibit soot oxidation

In order for DeSoot to be effective on IDAS, high temperature Oxygen based regen must be used. Since the engine is not capable of producing the Soot filter bed temps required for Oxygen based regeneration (>500°C Filter bed temp), the aftertreatment system must be used to produce additional heat. Figure 58 shows the capability of producing a significant amount of heat across the close-coupled catalyst for Oxygen based soot oxidation.

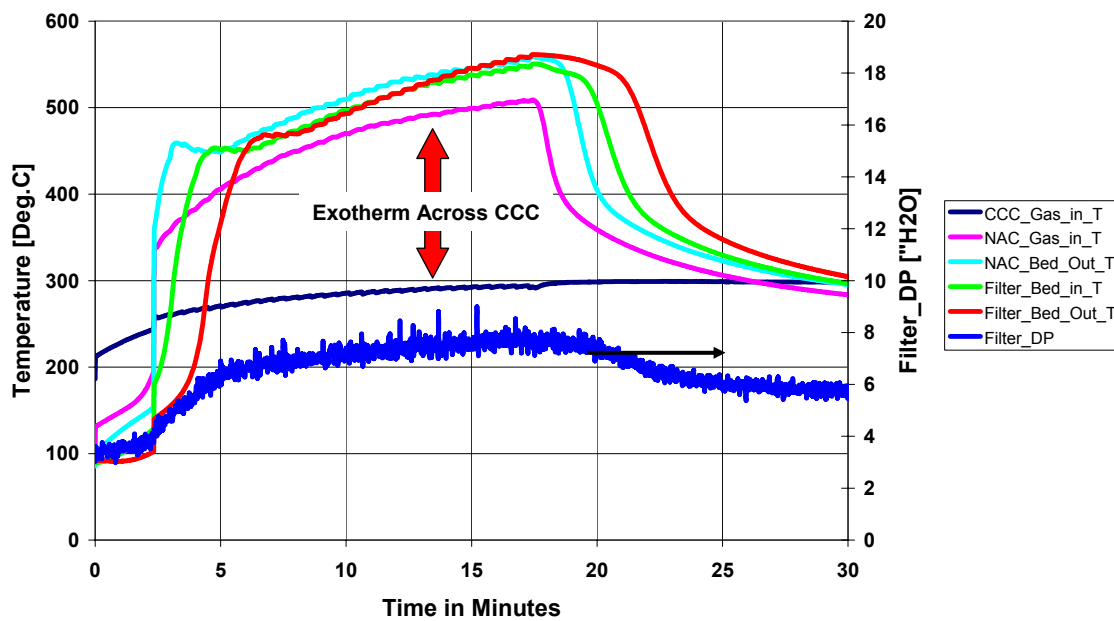


Figure 58 - CCC enables high temp in CSF

In this case, the heat generated across the close-coupled catalyst was able to generate an exotherm of approximately 200°C, resulting in a soot filter bed temperature of 550°C. This high temperature Oxygen based soot oxidation resulted in a positive slope on the soot oxidation curve, indicating net soot reduction on the filter, as shown in Figure 59.

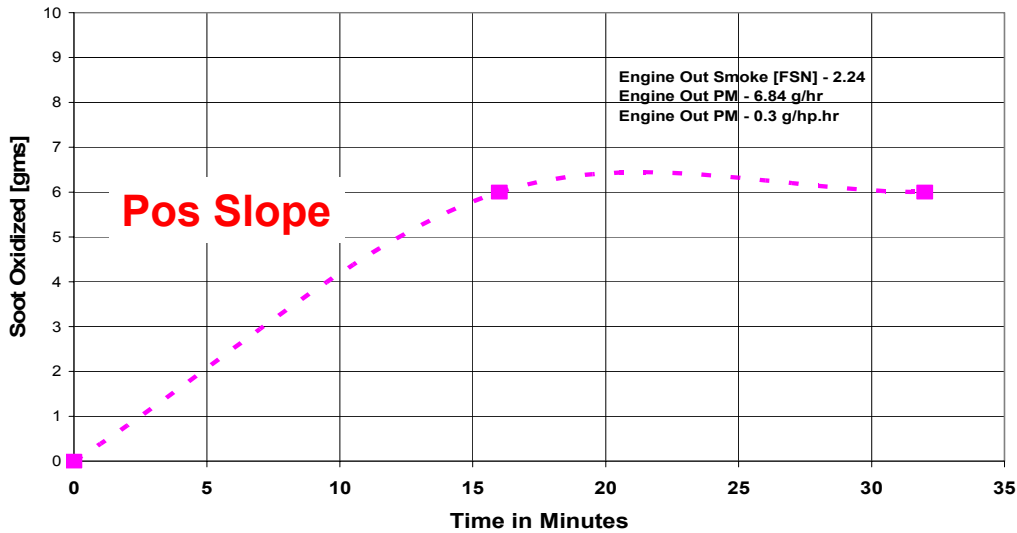
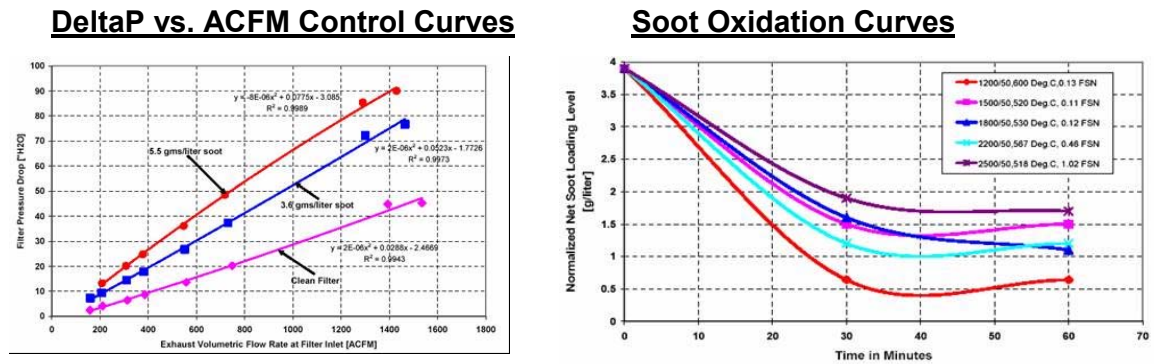


Figure 59 - High Temperature Operation

DeSoot Performance development included mapping DeSoot trigger curves as well as Soot Oxidation curves for O₂ Based regeneration (Figure 60). DeSoot performance curves were generated at several soot loads, (1) clean filter, (2) light soot loading, (3) heavy soot loading.



$$m_{\text{soot}} = \int (\dot{m}_{\text{soot}} - \dot{m}_{\text{by NO}_2} - \dot{m}_{\text{by O}_2}) dt$$

DeSoot Performance development included mapping DeSoot trigger curves as well as Soot Oxidation curves for O₂ Based regeneration

Figure 60 - DeSoot Performance

These DeSoot trigger curves are then mapped into the controller and used to determine the soot loading on the filter under vehicle operation. If the controller detected that the soot filter loading

was above a certain level, then the controller would initiate a DeSoot regeneration event to clean the soot from the filter. The DeSoot regeneration event would last as long as required to remove the soot from the filter, usually on the order of 20 to 30 minutes duration. The required duration of the DeSoot regeneration is dependent on engine and soot filter conditions as described previously, ie, higher filter temps and lower engine-out soot rates will require shorter DeSoot duration, and lower filter temps and higher engine-out soot rates will require longer DeSoot duration.

INTEGRATED AFTERTREATMENT SYSTEM DESIGN

The Integrated Discrete Aftertreatment System (IDAS) is shown in Figure 61. The system contains discrete catalyst components with dedicated function, fully integrated into a complete system to remove emissions from the Light Duty Diesel exhaust environment. Details of how the IDAS system was developed will be described later in this report, in this section, the design function of each discrete catalyst component will be given in detail.

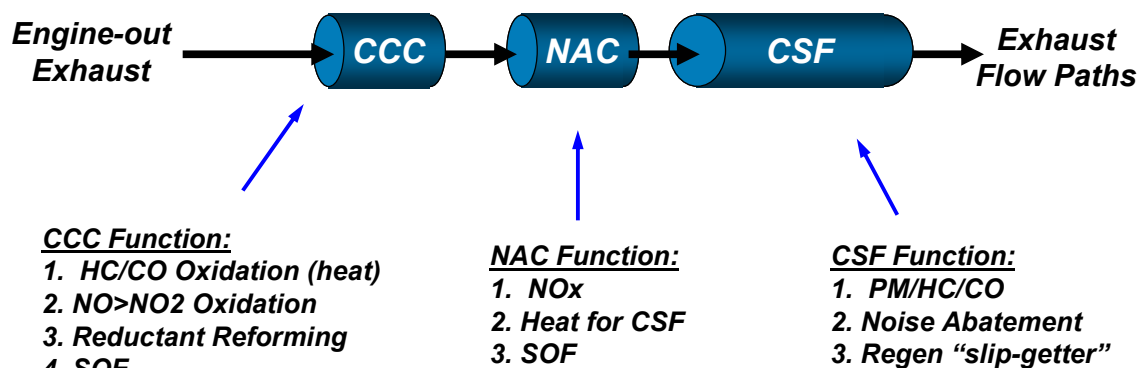


Figure 61 - Integrated Discrete Aftertreatment System Architecture

Close-coupled Catalyst – The main functions of the close-coupled catalyst are:

1. Hydrocarbon and CO oxidation for heat
2. NO to NO₂ oxidation for effective storage on the NO_x adsorber
3. Reductant reforming
4. Oxidation of Soluble organic fraction of Particulate matter

The close coupled catalyst by design is placed as close to the turbo outlet as possible to make use of the available heat to ensure quick light of the catalyst.

NO_x Adsorber Catalyst – The main functions of the NO_x adsorber catalyst are:

1. Storage of NO_x (in form of NO₂)
2. Hydrocarbon oxidation for heat for soot filter regen
3. Oxidation of Soluble organic fraction of Particulate matter.

Catalyzed Soot Filter – The main functions of the Catalyzed soot filter are:

1. Trapping of particulate matter
2. Oxidation of excess Hydrocarbon and CO
3. Oxidation of excess regeneration species

The layout of the IDAS system on a light duty vehicle is shown in Figure 62.

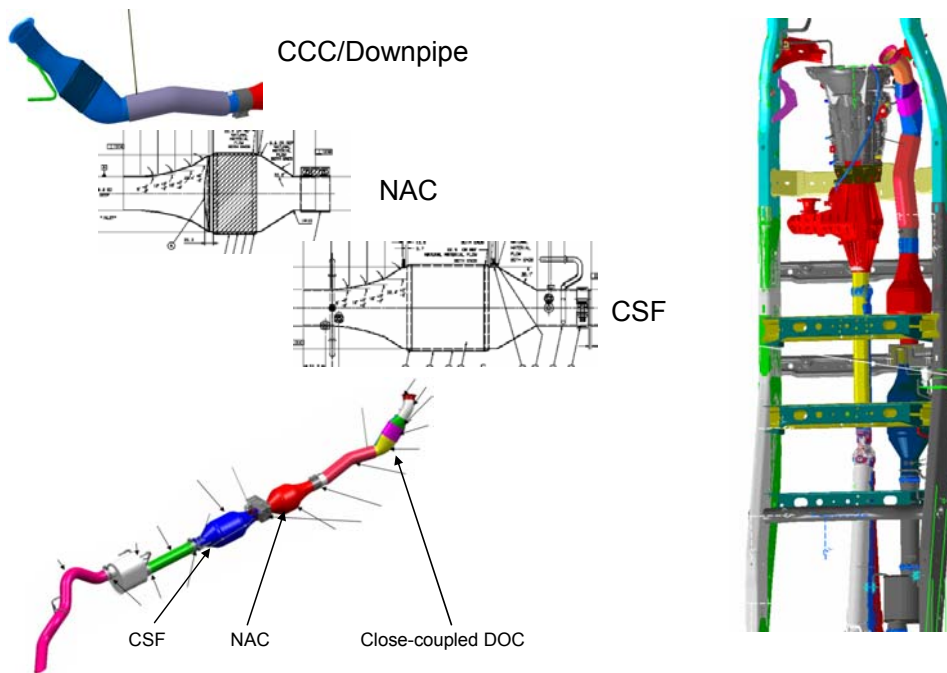


Figure 62 –Aftertreatment System Vehicle Packaging

Notice that the integrated system fits nicely on the vehicle, and since each component is canned separately, it is flexible to fit in available space under the vehicle and within available clearances from frame members and engine drivetrain components.

SYSTEM INTEGRATION AND OPTIMIZATION

The original development path intended to transition from a discrete aftertreatment system to a multi-function, 4-way aftertreatment system. Original designs were based on half and full bypass catalysts and were regenerated via exhaust fuel dosers. Due to cost and size constraints, these designs were replaced by single leg, full flow exhaust systems using engine management for regeneration. The original goal of development was to achieve a low cost, reliable and durable, multi-function 4-way aftertreatment system that could be easily packaged on the vehicle, as shown in Figure 63.

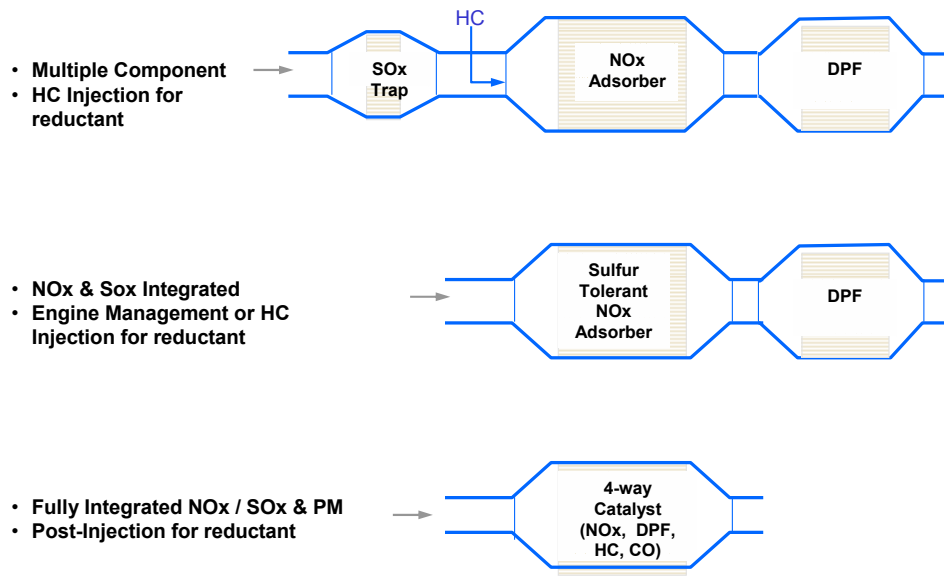


Figure 63 - Original Configuration Path

As part of concept validation testing, a durability runoff test was designed. The durability runoff was conducted as a 500 hour accelerated durability test (thermal only) between the 4-way catalyst system and the integrated discrete catalyst system. The results of the 500 hour durability runoff test are shown in Figure 64. The plot shows NOx conversion performance for each aftertreatment system during the test. The results clearly indicate that the discrete catalyst system was more durable than the 4-way catalyst system, and the Integrated Discrete Aftertreatment System (IDAS) was chosen as the best option for further development.

Durability Results - 4way vs. Discrete

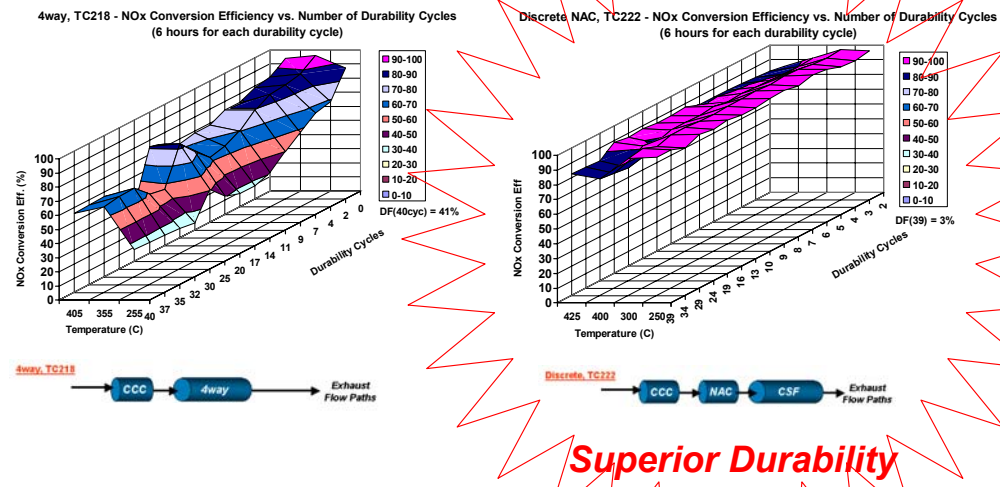


Figure 64 - 500 hour Catalyst Durability runoff

Following the runoff durability test, the IDAS system was run across a 500 hour accelerated durability test, and in addition to high temperature thermal regens being applied, the system was exposed to an End of Useful Life (EUL) amount of Sulfur (>360g S). The results of the 500 hour accelerated durability test with Sulfur is shown in Figure 65.

NAC was exposed to >360 g S in test

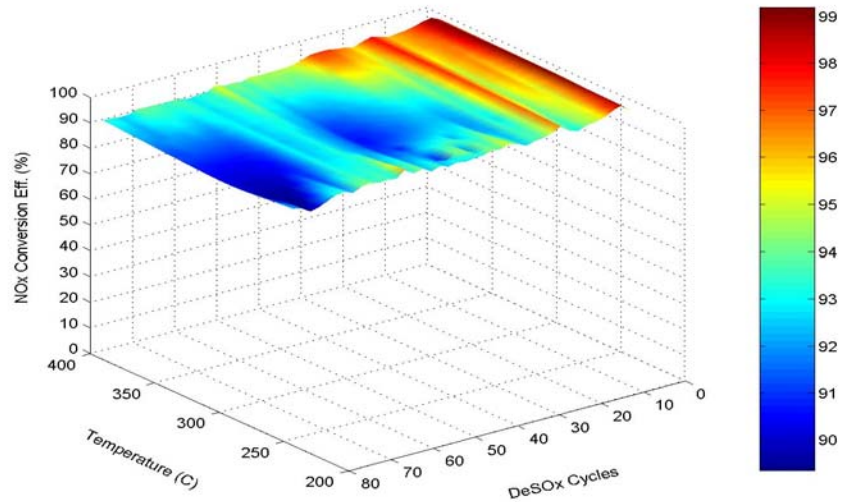
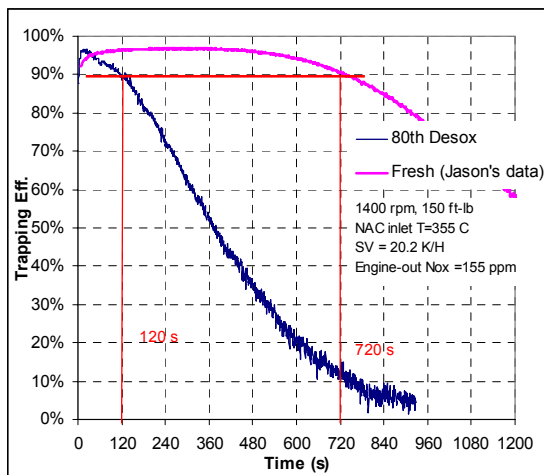


Figure 65 - 500 hr Durability Test with Sulfur

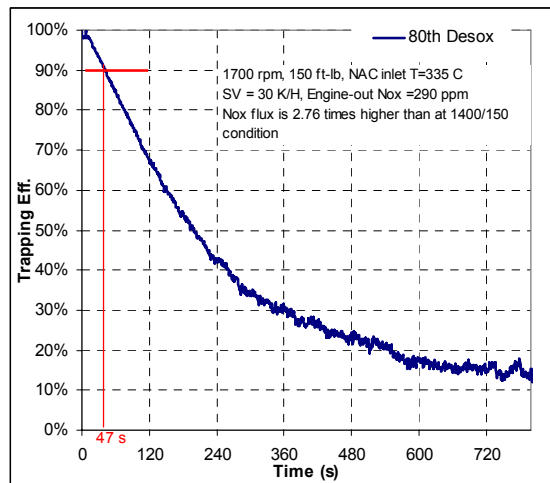
Notice from the figure that the IDAS system was able to maintain high NOx conversion (> 90%) over the entire duration of the test. It also was noted during the durability test that a significant amount of NOx capacity was lost (Figure 66).

1400 rpm, 150 ft-lb, T=355 C, SV=20.2k/h,
Engine-out NOx=155ppm



NOx performance is Still OK at lower NOx flux

1700 rpm, 150 ft-lb, T=335 C, SV=30k/h,
Engine-out NOx=290ppm



NOx Performance is hurt at higher NOx flux

Figure 66 - NOx Performance & Trapping Capacity Over 500 hr Test

As shown in the figure, the effect of loss of NO_x capacity on NO_x conversion would not be as noticeable during operating conditions of low NO_x flux on the catalyst, but at conditions of higher NO_x flux, where the available NO_x capacity is challenged, the NO_x conversion performance may be affected. The explanation of loss of NO_x capacity on the NO_x adsorber is shown in Figure 67. Loss of NO_x capacity can occur from thermal factors (sintering), poisoning factors (Excessive Sulfur, Oil species, etc), and fouling factors (excessive soot, coking, masking of storage sites). Notice that in addition to the loss of NO_x storage capacity, the affect of aging and degradation can also affect the NO_x release during the conversion step. Loss of NO_x storage capacity would also require more frequent NO_x regeneration to maintain NO_x conversion performance.

Effect of Aging/Degradation on NO_x Adsorber Operation Influences NO_x capacity and conversion efficiency

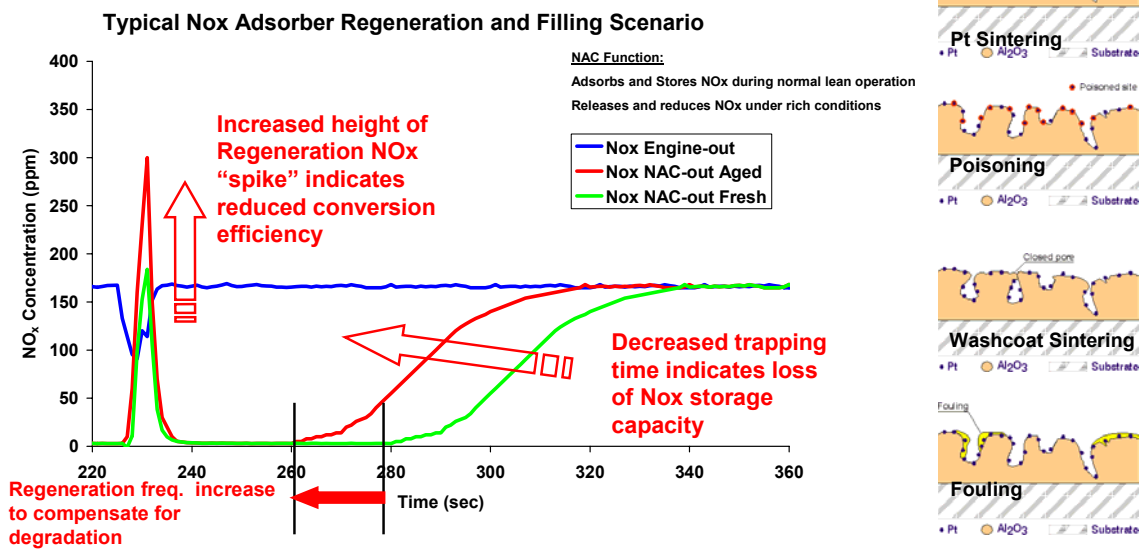


Figure 67 - Aging Effects on NO_x Adsorbers

In order to test realtime durability, a 1,250 hour non-accelerated durability test was designed (Figure 68).

Test Cycle

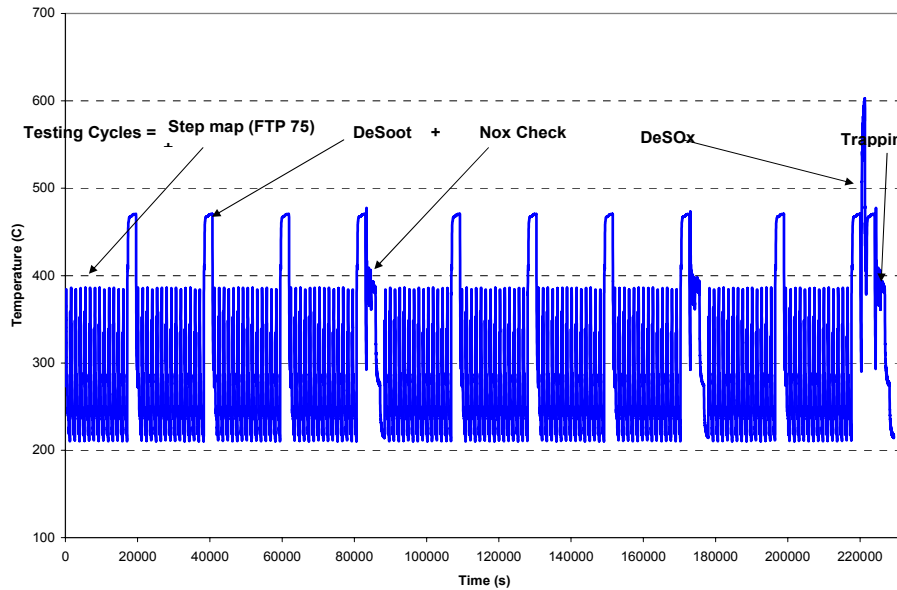


Figure 68 - 1,250 hr Durability Test Cycle

The objectives of the 1,250 hour test was to evaluate the performance of the IDAS system under realworld conditions, complete with all regens (DeNOx, DeSOx, DeSoot). The results of the 1,250 hour non-accelerated durability test are shown in Figure 69. Notice that NOx conversion performance remained relatively high (>90%) during the test.

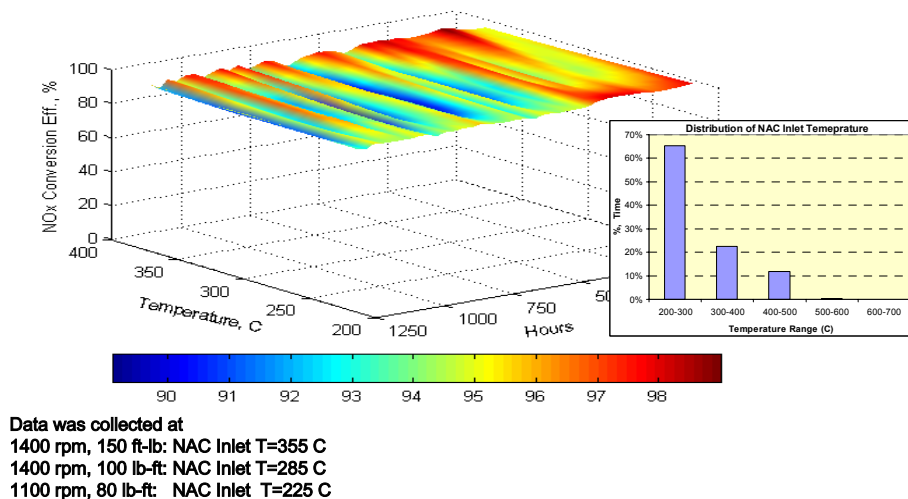
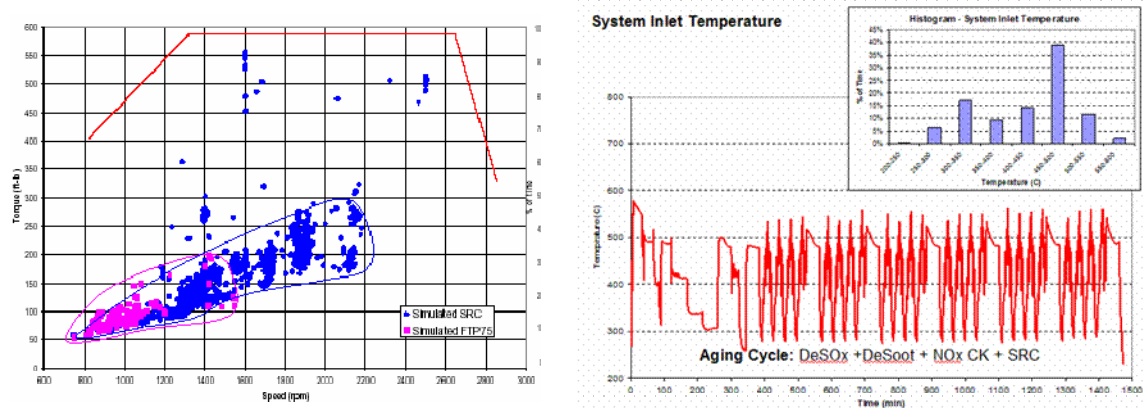


Figure 69 - Results of NOx Performance During 1250 hour durability test

To further evaluate the durability performance of the IDAS system, a 3,000 hour, non-accelerated durability test was designed. The 3,000 hour durability test was designed to test the IDAS system under real world conditions, with all regeneration cycles (DeNOx, DeSOx, DeSoot) used. In addition, the 3,000 hour durability test was designed to use the EPA standard road cycle (SRC) for the durability cycle, which has a higher load factor than the 1,250 hour durability test that used a “FTP75” like durability cycle. Details of the 3000 hour durability test are given in Figure 70.



The 3000 hour durability test is using the EPA SRC cycle, which has a larger load factor than FTP75 step map cycle.

Figure 70 - 3000 hr Durability Test

Results of NOx conversion over the 3000 hour durability test are shown in Figure 71

Notice that the NOx conversion over the 3000 hour durability test remained relatively high (>90%), with exception for a “Dip” in the conversion results at 2000 hours. This “dip” in NOx conversion at the 2,000 hour point was due to ineffective (DeSOx temp < 620°C) DeSOx regeneration. Performance was recovered after a “Deep DeSOx (1 hour @ 675°C)” cycle was conducted. These durability results indicate the importance of effective Sulfur management over

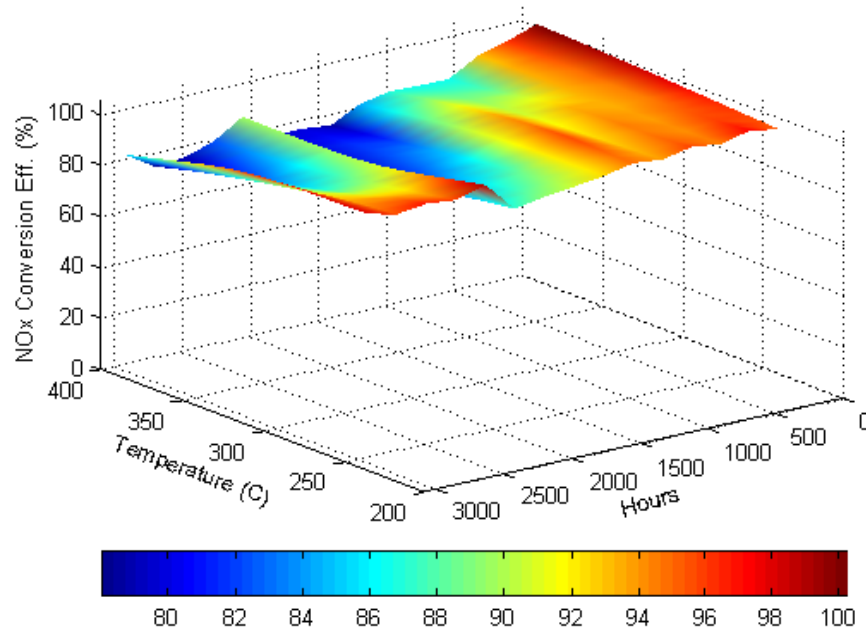


Figure 71 - Results of 3000 Hour Durability Test

the lifetime of the NOx aftertreatment system.

COLD FIELD TEST

In addition to the durability testing conducted in the test cell, a Cold Field Test was designed. The main objectives of the Cold Field Test were:

- Continue to develop and optimize catalyst formulations for best NOx and PM conversion efficiency under exhaust temperatures and space velocities consistent with anticipated light duty applications.
- Develop and demonstrate NOx and PM regeneration strategy during FTP-75 and real life duty cycle operations.
- Gain durability/reliability experiences in cold ambient condition

Details of the Cold Field test are given in Figure 72.

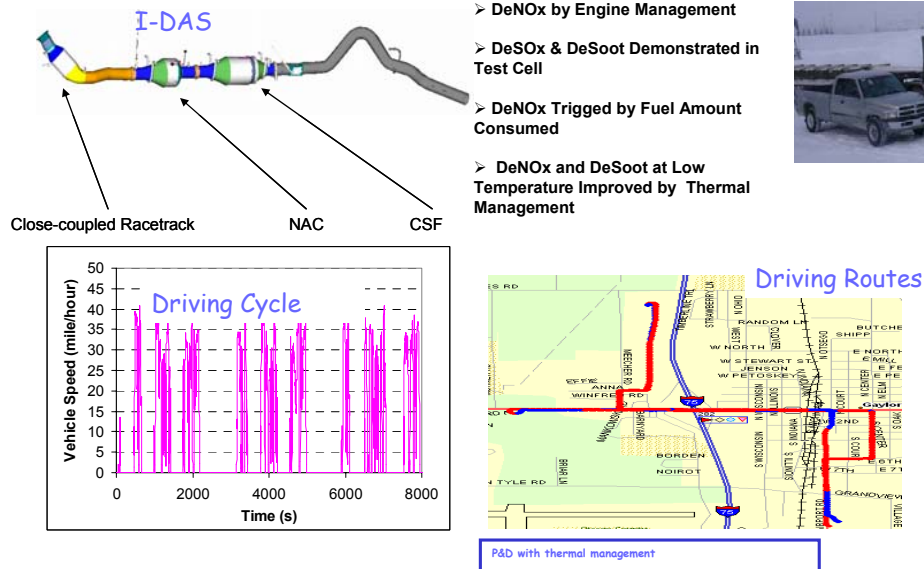


Figure 72 - Set-up, Cycle and Controls for Cold Ambient Field Test

A pickup and delivery route was run in Gaylord Michigan for the majority of the test. During the test, system temperatures and pressures were recorded, Filter weights were recorded, and daily inspection of the aftertreatment components were conducted. High level results of the Cold Field test are shown in Figure 73.

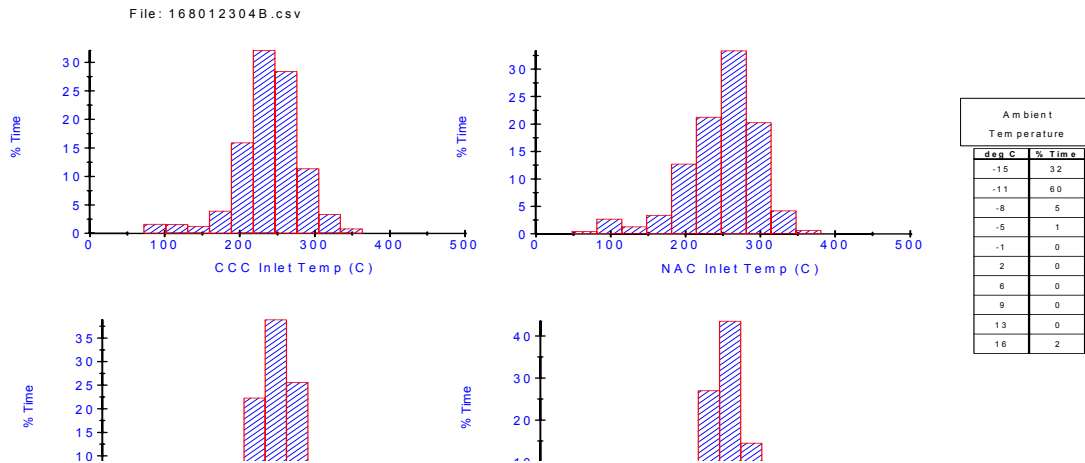


Figure 73 - High Level Results from Cold Ambient Field Test

The main conclusions from the Cold Field test were:

1. The light duty vehicle ran in Michigan from January to April of 2004 experiencing cold temperatures down to -20C
2. 12,250 miles were accumulated on the vehicle
3. 850 gallons of low Sulfur Diesel fuel consumed.
4. No face plugging or any failure observed on IDAS system.

NOX ADSORBER MODEL DEVELOPMENT & VALIDATION

A NOx Adsorber Catalyst model has been developed that can be used in a dynamic system analysis framework.

The model is a “zero dimensional” lumped mass model where the entire catalyst brick is assumed to be at the same temperature. Maps of the different catalyst functions are created from test data and used within the model. The model also has a simple heat transfer model and transient thermal response model. The functionality of the model is shown in the following list.

- NOx storage during lean operation
- NOx release during rich operation
- NOx conversion during rich operation
- Hydrocarbon Oxidation and Heat Release
- Exhaust to Catalyst Heat Transfer
- Ambient Heat Transfer
- Catalyst Thermal Response
- Aged and Fresh Catalyst Performance

A schematic diagram of the model is shown in the figure below.

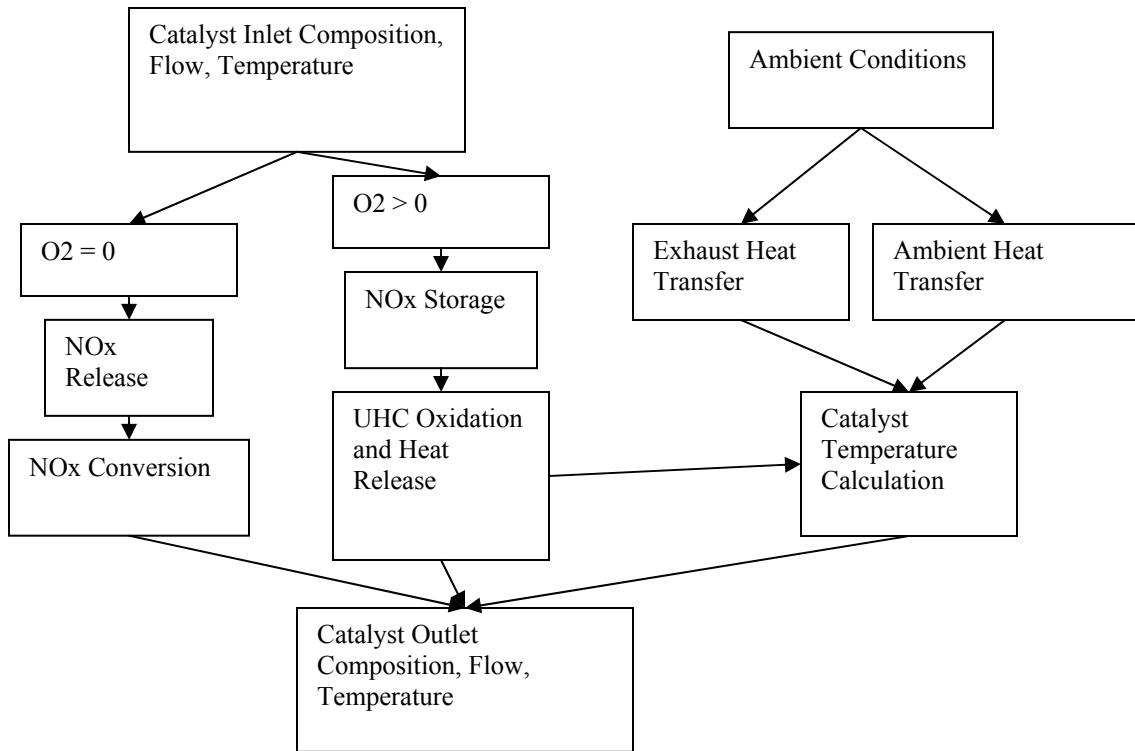


Figure 74 - NOx Adsorber Model Schematic

Each of the main functionalities of the model is described below.

NOx Storage

The capability of the catalyst to store NOx is assumed to be of the functional form:

$$\text{Storage Efficiency} = f(T_{\text{cat}}, \text{SV}, \text{Load})$$

Where

T_{cat} = catalyst bed temperature

SV = space velocity

Load = amount of catalyst already stored

The actual performance of the catalyst in these coordinates is measured on an engine or reactor test and then input into the model via tables.

When the exhaust gas has excess oxygen, the model calculates the adsorption rate of NOx and integrates this rate to calculate the cumulative stored NOx on the catalyst.

NOx Desorption

The capability of the catalyst to release NOx is assumed to be of the functional form:

$$\text{Desorption Rate} = f(T_{\text{cat}}, \text{SV}, \text{Load})$$

Where

Tcat = catalyst bed temperature
SV = space velocity
Load = amount of catalyst already stored

The actual performance of the catalyst in these coordinates is measured on an engine or reactor test and then input into the model via tables..

When the exhaust gas has no oxygen, the model calculates the desorption rate of NOx and releases this amount of NOx into the exhaust stream.

NOx Conversion

The rate of conversion of NOx is assumed to be of the form:

$$\text{NOx Conversion Efficiency} = f(\text{Tcat}, \text{Load})$$

Where

Tcat = catalyst bed temperature
Load = amount of catalyst already stored

The actual performance of the catalyst in these coordinates is measured on an engine or reactor test and then input into the model via tables.

When the exhaust gas has no oxygen, the model calculates the conversion rate of NOx and reduces the NOx in the exhaust stream to nitrogen and oxygen components.

HC Conversion

The rate of oxidation of unburned hydrocarbons (HC) is assumed to be of the form:

$$\text{HC Oxidation Efficiency} = f(\text{Tcat}, \text{SV})$$

Where

Tcat = catalyst bed temperature
Load = amount of catalyst already stored

The actual performance of the catalyst in these coordinates is measured on an engine or reactor test and then input into the model via tables.

When the exhaust gas has excess oxygen, the HC will be converted based on these tables. The oxidation will release heat that is used in the calculation of the catalyst bed temperature.

Aged vs. Fresh Performance

Test data is obtained for fresh and aged catalyst performance and the model can then be used to represent an aged or fresh catalyst.

Heat Transfer

The model assumes that the catalyst acts as a perfect heat exchanger with the exhaust gas. This assumption means that the temperature of the gas leaving the catalyst is equal to the temperature of the catalyst brick.

$$T_{exh_out} = T_{cat}$$

Based on this assumption, the heat rate into the catalyst can be calculated (Q_{in}).

$$Q_{in} = \dot{m}_{exh} * C_{pexh} * (T_{exh_in} - T_{cat})$$

Where

Q_{in} = Heat Transfer to the catalyst from the exhaust
 \dot{m}_{exh} = Mass flow of the exhaust gas
 C_{pexh} = Specific heat of the exhaust
 T_{exh_in} = Temperature of the exhaust gas at the inlet of the catalyst
 T_{exh_out} = Temperature of the exhaust gas at the outlet of the catalyst
 T_{cat} = Average catalyst bed temperature

There is also a calculation of the heat transfer out of the catalyst (Q_{out}) to ambient conditions due to radiation (Q_{rad}) and convection (Q_{conv}) from the outside of the can.

$$Q_{out} = Q_{rad} + Q_{conv}$$

The radiation and convection equations used are standard textbook formulas (Incropera and Dewitt, "Fundamentals of Heat and Mass Transfer").

With these heat rates the transient catalyst temperature is calculated from:

$$M_{cat} * C_{pcat} * dT_{cat}/dt = Q_{in} - Q_{out} + Q_{gen}$$

Where

M_{cat} = mass of the catalyst
 C_{pcat} = specific heat of the catalyst
 T_{cat} = Average catalyst bed temperature
 Q_{in} = Heat transfer from exhaust to catalyst
 Q_{out} = Heat transfer from catalyst to ambient
 Q_{gen} = Heat generated within the catalyst (from HC oxidation)

This equation is solved using Simulink's differential equation solving capability to calculate a catalyst temperature vs. time. This catalyst temperature is the temperature used in the performance tables.

Model Validation

The model has been compared to test data for thermal response and NO_x reduction performance on an FTP cycle as shown in figure 75.

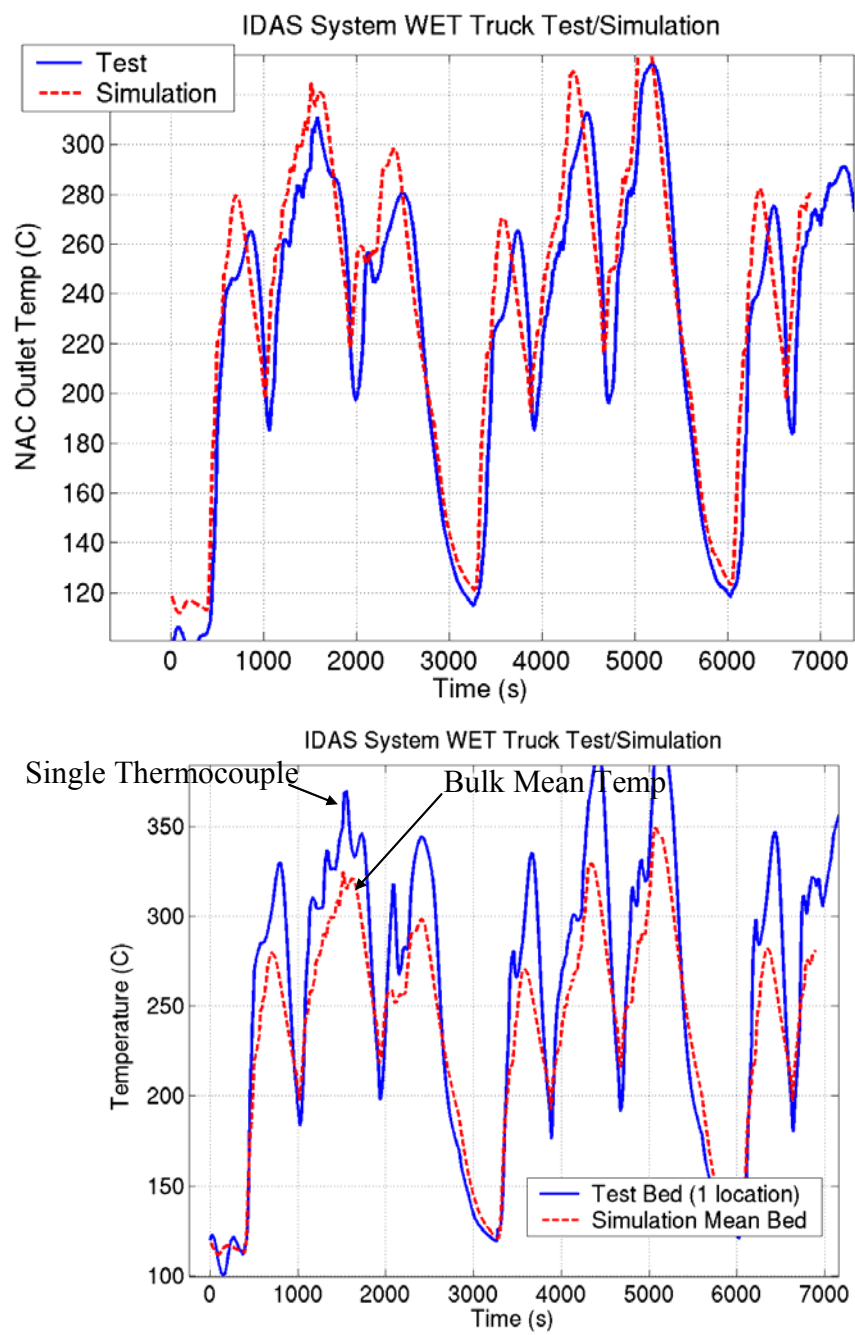


Figure 75 - Model Validation Using Field Test Data

FTP75 Aftertreatment NOx Reduction (%)		
	Cold Cycle	Hot Cycle
Test	~83	~90
Simulation	~72	~92

- Hot cycle model performance is good
- Cold cycle model improvements needed
 - Catalyst warm-up
 - Low temperature NOx adsorption

Figure 76 -FTP-75 NOx Reduction Prediction

The results indicate some need for improvement in the cold cycle performance, but some general results that follow the test data trends. These results are considered adequate for the current modeling needs, but continued improvements will be desired.

Integration with Vehicle System Model

The NOx adsorber catalyst model has been integrated with other aftertreatment component models into an aftertreatment system model as shown below.

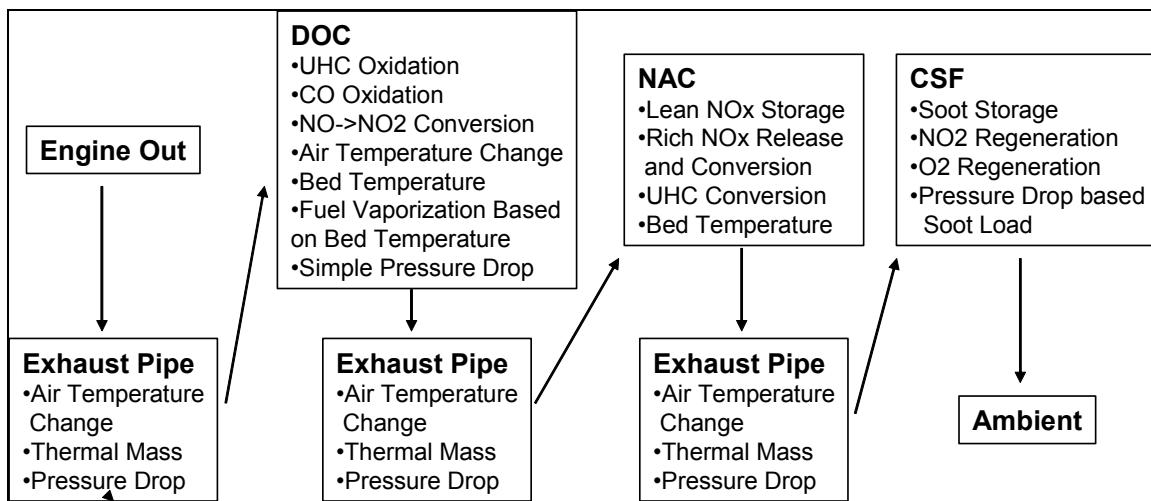


Figure 77 - Schematic of Integrated Aftertreatment System Model

This aftertreatment system model has been integrated with a vehicle system model for investigations into vehicle drive cycle impact on the aftertreatment system performance.

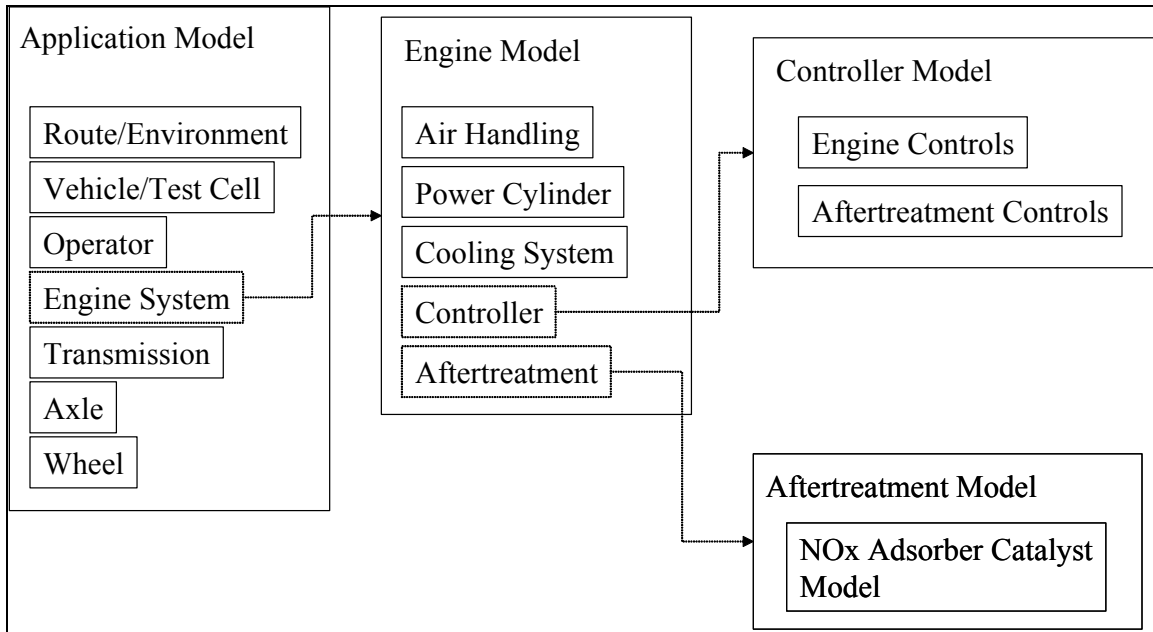


Figure 78 – Integrated Engine/Aftertreatment/Vehicle Model

This integration allows investigations of the aftertreatment system performance on varying drive cycles and vehicle configurations, as well as different engine configurations.

Hardware in the Loop Model Integration

The NOx adsorber catalyst model has also been integrated with a hardware in the loop simulation system. This system contains models of the vehicle, engine, and aftertreatment systems, but links to the real engine controller as shown in the following diagrams.

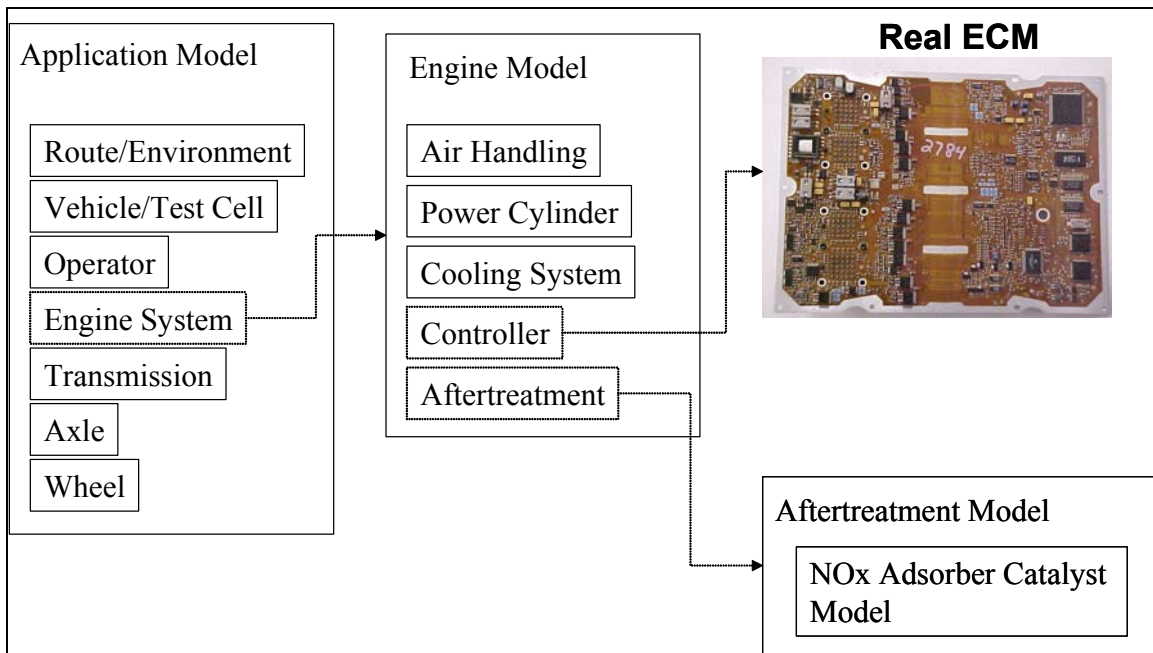


Figure 79 - Hardware in the Loop Model Integration

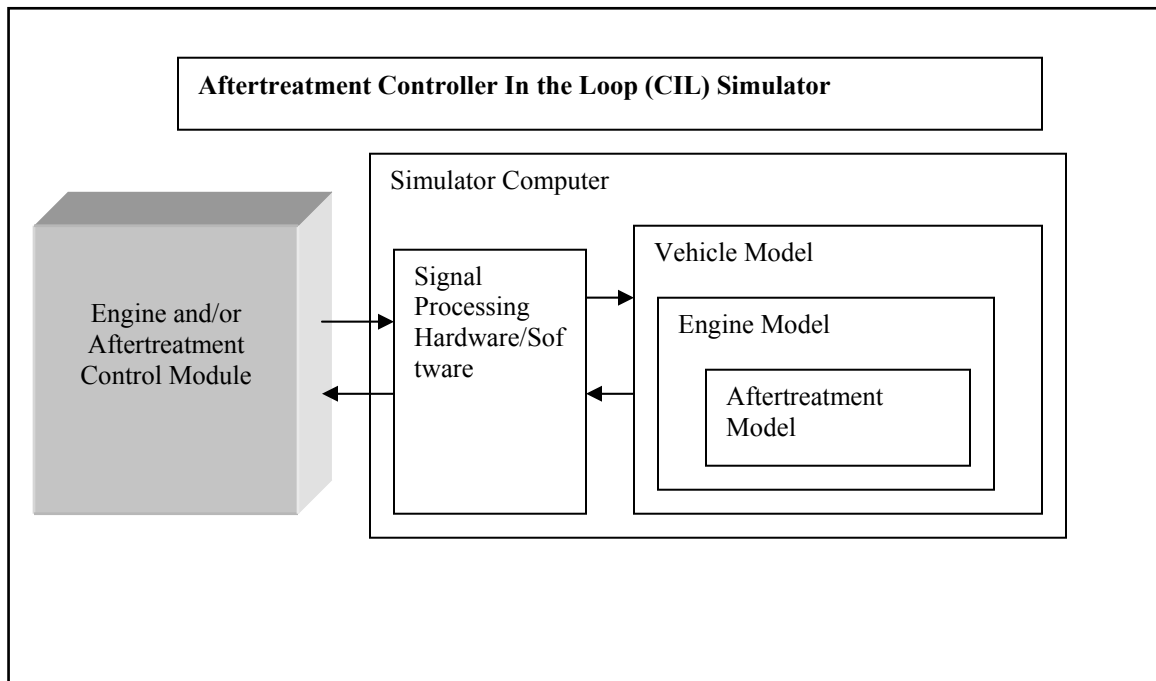


Figure 80 - Aftertreatment Controller in the Loop Simulator

With this system, actual engine controls can be evaluated before being placed onto a vehicle for testing. This development step saves development time and money in finding controls issues before they get into vehicles.

Example Model Use

One use of the model was to evaluate the potential sulfur removal opportunities during a representative drive cycle for different vehicle configurations. The model results are shown in the table below.

Transmission	Vehicle Mass (lbs)	# of Regen Opportunities							
		Continuous Time (min) > 3	4	5	6	7	8	9	10>
Auto	8500	1	1	0	0	0	0	1	2
Auto	22500	3	1	0	0	0	0	0	0
Man	8500	1	0	0	0	0	0	0	3
Man	22500	1	1	0	0	0	0	1	0

Figure 81 - Modeling Duty Cycle Based Regeneration

This type of evaluation depends only on the thermal response of the model versus the engine output conditions on the drive cycle. It incorporates the ability to model vehicle, operator, engine, and aftertreatment system components. The model has also been used to evaluate warm-up performance of different size catalysts and emissions reduction performance at different levels of engine output NO_x.

UNREGULATED EMISSIONS

The objective of this work was to begin realizing and measuring the unregulated, byproduct emissions that are generated using an aftertreatment and emissions control system that contains a NO_x adsorber (NAC) catalyst. A preliminary analysis of emissions originating as byproducts from an integrated aftertreatment system (IDAS) equipped with a NAC catalyst has been completed. NAC catalyst operation requires intermittent rich periods of operation and it is therefore expected that previously unrealized emissions may be formed. Unregulated byproduct emissions associated specifically with NAC catalyst operation that were observed include CH₄, NH₃, and N₂O. The quantities of each were dependent on the conditions associated with the NAC catalyst regeneration event. Specifically, NH₃ was only observed under relatively rich conditions, while N₂O was observed in less rich conditions.

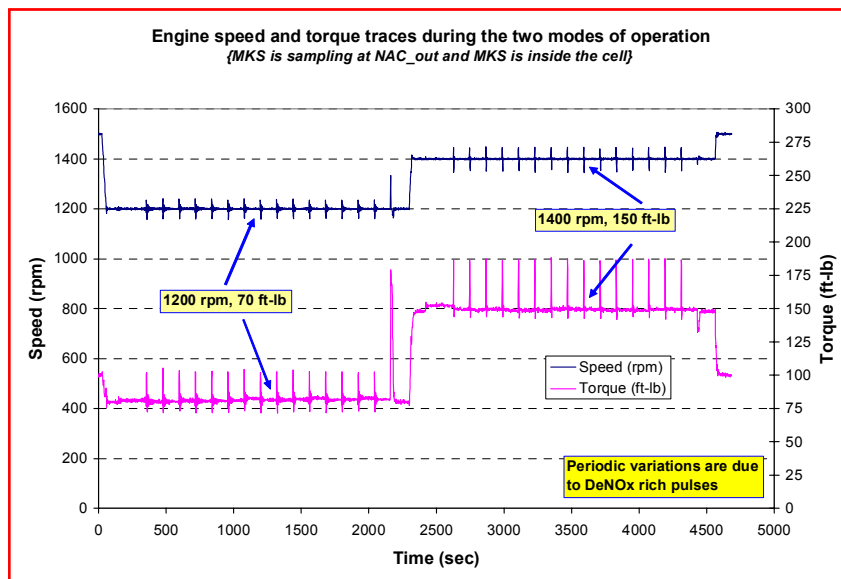


Figure 82 – Two Modes Evaluated

Two steady-state engine modes were chosen as representative points for testing. Characteristics of these are shown in Figure 82. The first test was run at a temperature (turbo-out) of 290-300°C and had an associated lambda value of approximately 1.6 during lean operation. As mentioned previously, NAC catalyst operation requires intermittent rich pulses of exhaust gas which are applied to remove trapped NO_x from the catalyst surface and reduce the NO_x to N₂. The periodic spikes in the readings shown are associated with changing engine conditions that produce these brief rich excursions. At approximately 2400 seconds into the experiment, the steady-state mode was changed, resulting in a higher turbo-out temperature, 430-450°C, and a lean lambda value of 1.4.

The NO_x emissions data shown in Figure 83 were obtained from different locations along the exhaust aftertreatment system during mode 1 operation. These data represent a summation of NO, NO₂, N₂O and NH₃. Throughout this report, NO_x will be used to represent not only NO, NO₂,

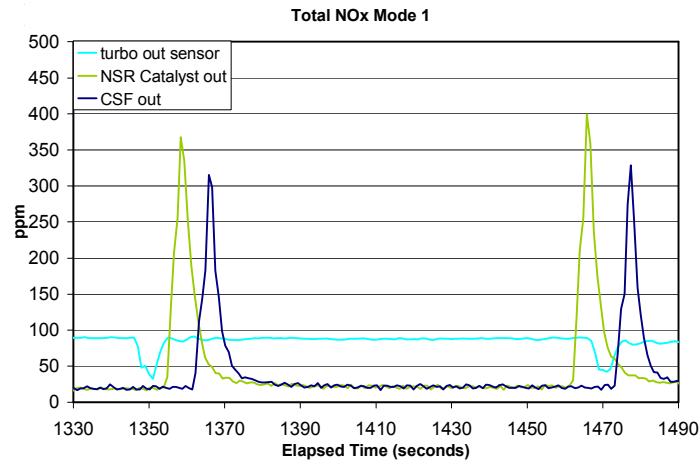


Figure 83 - NO_x Levels at Mode 1

N₂O but also will include NH₃ species. A steady value of approximately 88 ppm NO_x was emitted from the engine (sampled upstream of all catalysts) during lean operation at this steady-state condition. This was solely comprised of NO and NO₂. The intermittent rich event used for the NAC catalyst regeneration resulted in less NO_x emissions, as seen at a time of approximately 1350 seconds (the times are offset for clarity; there is not a 10-20 second delay between the rich event in the engine vs. at the catalyst). The upstream oxidation catalyst did not reduce any of the emissions (data not shown). The NAC catalyst trapped NO_x throughout the lean period. At the onset of the rich period, the trapped NO_x was released from the catalyst surface, but some did not get converted to N₂ and a NO_x release “puff” was therefore observed. The catalyzed soot filter had some apparent NO_x reduction activity during the rich event as the total amount of NO_x that exited the tailpipe during the rich event was less than that exiting the NAC catalyst.

The N₂O amounts monitored at the same sampling points are shown in Figure 84. No N₂O was observed at either turbo- or oxidation catalyst-out locations under the specific conditions of this test. However, at the outlet of the NAC catalyst there was a significant amount of N₂O measured during the rich/regeneration event.

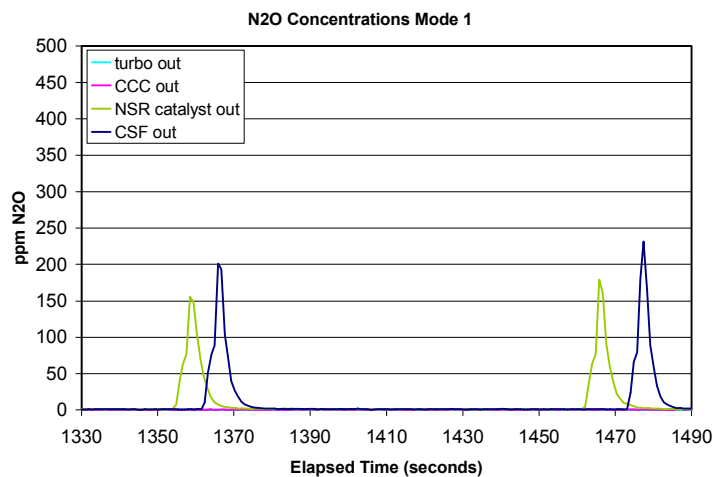


Figure 84 - N₂O Concentrations at Mode 1

Furthermore, the data show that even more was present at the CSF outlet. This indicates that the CSF converted some of the released N-species from the NAC catalyst to N_2O . Under these conditions, no NH_3 emissions were observed at the tailpipe outlet. A small amount was observed evolving from the NAC catalyst during the regeneration event, but this was eliminated by the CSF. The balance of the NO_x species emitted, the difference between the plots in Figures 85 and 86, consisted of NO and NO_2 .

The second steady-state mode examined was set at a higher temperature and had an associated deeper rich stage. The total NO_x data are shown in Figure 85. The engine-out NO_x was composed solely of NO and NO_2 . And again, the oxidation catalyst did not remove any NO_x . The NAC catalyst trapped NO_x during the lean phase and as in mode 1, during the rich phase there was an observed release as some of the trapped NO_x was not converted to N_2 . Also as in mode 1, the amount of NO_x species exiting the CSF was less than that exiting the NAC catalyst; the CSF converted some of the escaping NO_x species to N_2 . However unlike the case above, little N_2O was observed exiting the system. A small amount during the regeneration event was observed downstream of the NAC catalyst, with a maximum concentration during the release of 16 ppm. An example of these data is shown in Figure 86; please note the differences in the ordinate scales. Overall, these data demonstrate that at higher temperature, richer regeneration operating condition, less N_2O is formed as a byproduct of the NO_x reduction process when compared to the amounts formed in mode 1.

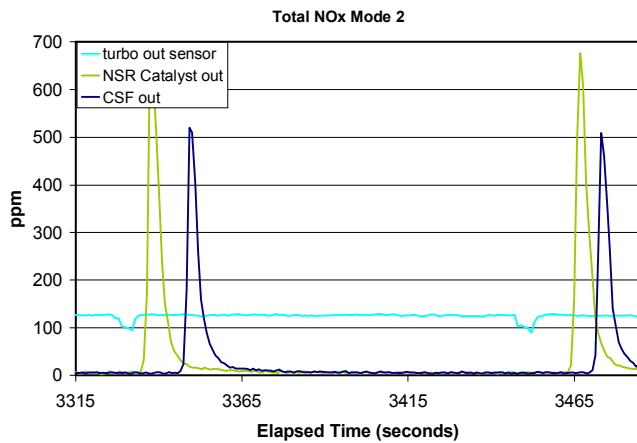


Figure 85 - NO_x Output Mode 2

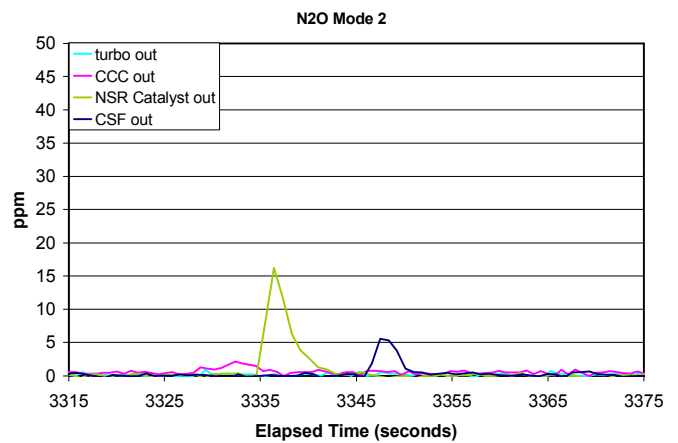


Figure 86 – N_2O Output Mode 2

The NH_3 emissions data during mode 2 operation are shown in Figure 87.

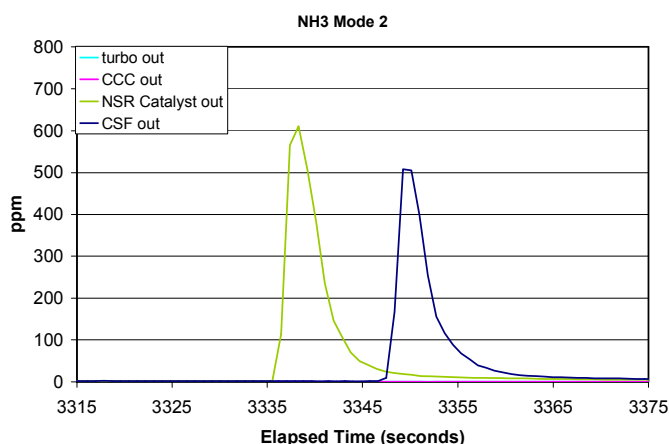


Figure 87 - NH3 Output Levels Mode 2

In comparing the data, it is apparent the primary component of the N-species not evolving as N_2 , was NH_3 . Furthermore, the data demonstrate that the NH_3 originated from the NAC catalyst during the regeneration phase of the cycle. This amount of NH_3 produced is quite significant. For just NO and NO_2 , the regulated species, the conversion would be calculated as 97.5% as only 2.5% of the incoming NO_x was exhausted as NO or NO_2 .

In summary, measurements have shown that N_2O and NH_3 can be formed during the NAC catalyst regeneration events. These species are not easily converted by the CSF under the conditions of the tests conducted. The data also indicate that the formation of both is a function of engine conditions. However, these data indicate that it maybe possible to reduce the amount of one species, but at the expense of increasing the other species. For example, in the data sets described above, N_2O emissions were lower in mode 2 of operation, but NH_3 emissions were significantly larger.

Hydrocarbons-Methane

One of the findings was that CH_4 was generated during the engine-managed rich event required for NAC catalyst regeneration. The CH_4 originated from the engine, not from the catalysts. The CH_4 amounts during mode 1 of operation from the NAC catalyst and CSF outlet sampling points are shown in Figure 88. These data indicate that the CSF did not reduce the amount of CH_4 in the system under these conditions.

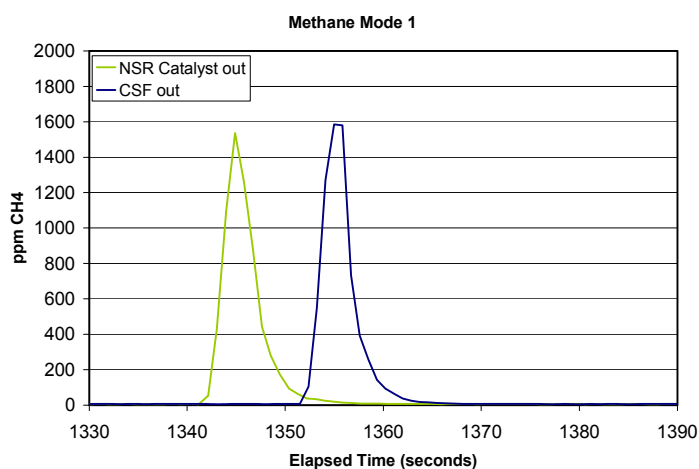


Figure 88 - Methane Output Mode 1

Previous data sets, not shown, demonstrated that the oxidation catalyst and NAC catalyst did not result in decreased CH₄ amounts in this operating mode either. Slightly more CH₄ was generated during mode 2 operation, as expected with the richer regeneration event.

FINAL DEMONSTRATION OF EMISSION/FUEL PENALTY

The combined engine/aftertreatment system was installed into a Daimler-Chrysler Dodge Ram 2500 truck and tested at the chassis emission testing facility at the Daimler-Chrysler Technical Center.

- Vehicle tests were conducted on a Mule Vehicle
 - 5.9L (4x4, quadcab, automatic, 3.73 axle ratio)
- Test was conducted at the maximum test weight required for a 0.2 g/mi NO_x limit: 8500 lb
- Catalyst system initially aged for 100 hours of stop-and-go driving simulation.
- Catalyst system was then aged for 1,250 hrs on-engine using a real-time aging protocol.

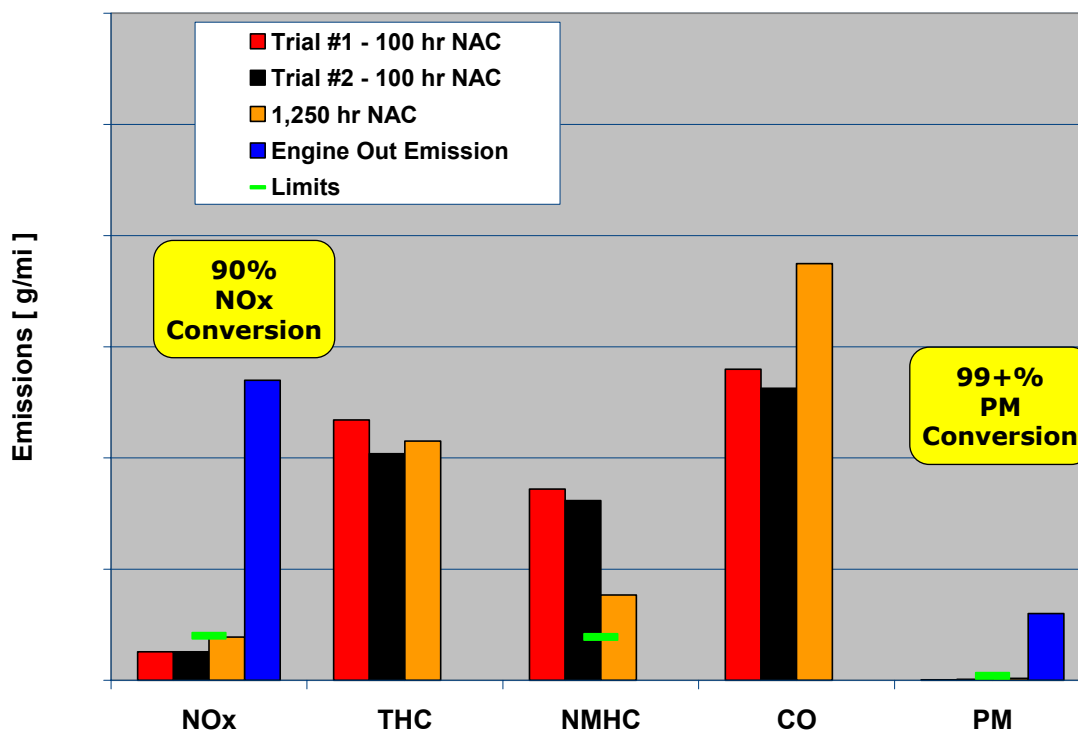


Figure 89 - Conversion Performance Over FTP-75

The fuel penalty associated with the system was determined by running two back-to-back tests; one with DeNOx regeneration activated and then with DeNOx turned off. Results over the FTP-75 cycle are shown in Figure 90. DeNOx fuel penalty was found to be about 6%. Subsequent testing has shown DeSOx processes add another 1% to this for a total of 7% fuel penalty for regeneration of the NOx Adsorber.

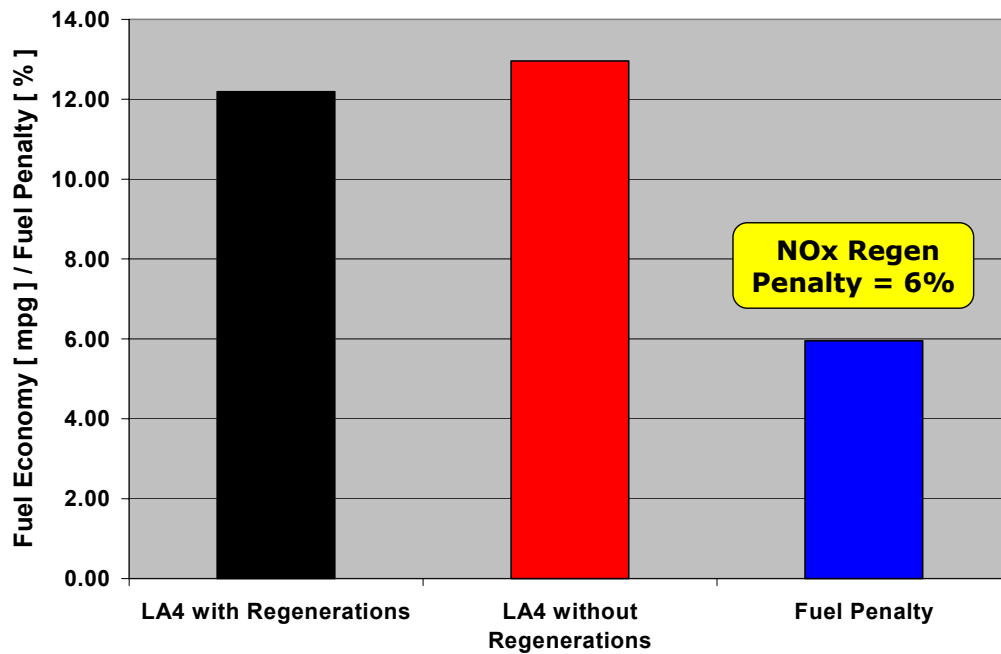


Figure 90 - DeNOx Fuel Penalty

COST EVALUATION OF HIGH VOLUME PRODUCTION SYSTEM

The cost of the aftertreatment system is dependent on the engine out emission levels and the exhaust flow, temperature and speciation particular to that engine. For the system developed in this program, the relative cost breakdown is shown in Figure 91. Precious metal is the largest single cost contributor. Platinum loading is a critical parameter and performance requirements versus cost limitations must be considered in system design. The second largest contributor to the cost of the system is the substrate cost for the soot filter. Reducing engine out particulate levels to allow reduced soot filter size may be a way to reduce this aspect of the cost.

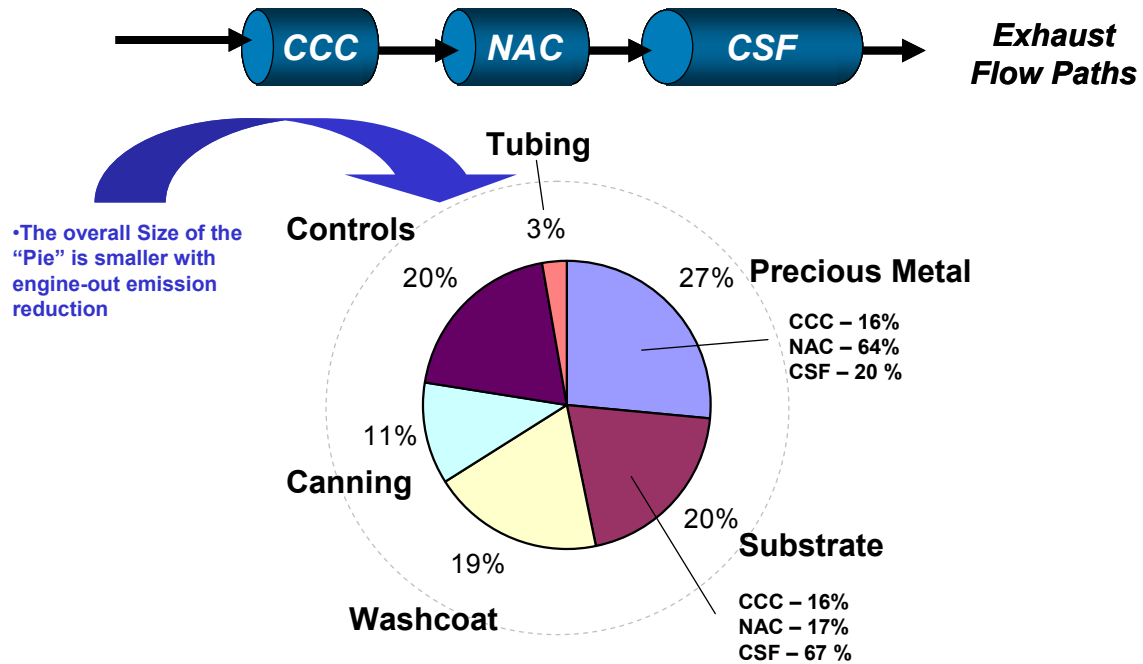


Figure 91 - Cost Analysis of Aftertreatment System

GUIDE TO ACRONYMS

AC	Adsorber Catalyst
A/F	Air to Fuel Ratio
ANL	Argonne National Laboratory
BPT	Balance Point Temperature
CARB	California Air Resource Board
CCC	Close Coupled Catalyst (DOC mounted very close to turbine outlet)
CIDI	Compression Ignition Direct Injected
CPF	Catalyzed particulate filter (see CSF)
CSF	Catalyzed soot filter
CTR	Coefficient of
CVS	Constant Volume Sampling
DeNOx	Process of removing NOx from a NOx adsorbing catalyst
DeSOx	Process of removing sulfur from a NOx adsorbing catalyst
DeSoot	Process of removing soot from a particulate filter
DOC	Diesel Oxidation Catalyst
EAS	Engine Aftertreatment System
ECM	Engine Control Module
EM	Engine managed
EMI	Electro-magnetic interference
HC	Unburned hydrocarbons
IDAS	Integrated Discrete Aftertreatment System
IR	Infrared
ISB	Cummins B Series Automotive Engine
LA4	Hot portion of the FTP-75 cycle
LDT	Light duty truck
LDV	Light duty vehicle
LNC	Lean NOx Catalyst
MOR	Modulus of Rupture
NAC	NOx adsorbing catalyst
NOx	Regulated oxides of nitrogen
PACR	Plasma Assisted Catalytic Reduction
PM	Particulate Matter
PNGV	Partnership for a New Generation of Vehicles
SCR	Selective Catalytic Reduction
SOx	Sulfur Oxides
SV	Space Velocity
UDDS	Urban Dynamometer Driving Schedule
WET	Winter Engine Testing