Indirect Injection Heavy-Duty Diesel Engine Emission Control Concept - Achieving the 2007 Emission Standard

ABSTRACT

The AM General Optimizer 6500 requires sophisticated aftertreatment controls to allow its continued production during the 2007 through 2010 model years, This engine utilizes Indirect Injection – swirl chamber (IDI) to maintain its fuel economy and durability.

Utilization of the relatively inexpensive and simple base engine with a distributor pump and waste-gated turbocharger was one of the primary goals of this development program. Adding specific hardware and software components allow the phase-in emission standards for 2007 through 2010 to be achieved. The hardware components of the aftertreatment system include a Diesel Oxidation Catalyst (DOC), NOx Adsorber Catalyst (or DeNOx Trap – DNT) and a Diesel Particle Filter (DPF). Installation of an intake air throttle valve and an in-exhaust fuel injector were also added to the engine as a part of the hardware package.

This paper outlines the development process for compliance with the 2007 heavy-duty emission standards, using a 2004 certified 6.5L IDI heavy-duty diesel engine. Packaging the engine in the projected vehicle platform was determined primarily by a system architecture evaluation. Achieving the required NOx and NMHC standards were only accomplished based on temperature profile, using the DOC-DPF-DNT configuration. The development of the strategy for DPF regeneration, deNOx and deSOx were based primarily on a multi-variable controls approach using temperature or lambda interventions depending on the system request.

The HD-FTP and SET (13-mode Supplemental Emissions Test) results illustrate that the tailpipe emissions and the NTE (not-to-exceed) limits can be achieved with a considerable margin for safety margin, allowing for reasonable degradation factors.

A project vehicle with all of the system components installed was used to conduct multiple climate testing trips that covered DPF regeneration under cold ambient, high altitude and hot ambient conditions.

The concept proved that a comparably cost-effective base engine, with an advanced aftertreatment control system and indirect injection, is capable of meeting the U.S. 2007-2010 phase-in emission standards.

INTRODUCTION

All HD engine manufacturers for 2010 will be have to apply NOx aftertreatment in addition to the PM aftertreatment that is introduced with the MY 2007 engines in order to achieve the required emission standards. Direct injected diesel engines from 2007 through 2010 will control NOx through internal engine measures, such as increased EGR levels and retarded injection timing. The initial testing conducted on the Optimizer Engine proved that the NOx levels required to meet 2007 phase-in standards could not be achieved without PM and fuel economy penalties. Therefore, it becomes essential to implement NOx aftertreatment with reduction efficiencies in excess of 60%. Achieving the desired NOx reduction efficiencies is the key to the success of the concept, provided the DNT (DeNOx Trap) catalysts are commercially available.

The gaseous and PM emission standards are highlighted in Figure 1, along with the engineering targets for this system.

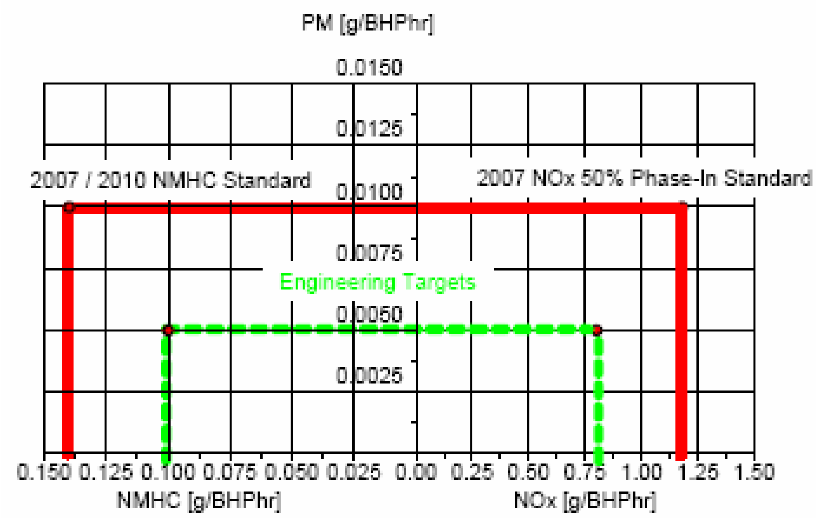

Figure 1: Emission Standards and Engineering Targets

HARDWARE

ENGINE SPECIFICATIONS

Table 1 lists the main engine parameters of the MY2008 Optimizer Engine.

Table 1: Engine Specifications

Performance	*Unit*	*Value*
Rated Power	kW	153
Rate Power Speed	rpm	3200
Rated Torque	Nm	598
Rated Torque Speed	rpm	1700
Redline Speed	rpm	4500
Low idle speed	rpm	625
BSFC WOT	g/kWhr	262
BSFC Best Point	g/kWhr	262

Table 2: Additional Engine Specifications

Engine Mechanics	*Unit*	*Value*
Configuration	-	V
Bank Angle	degrees	90
Number of Cylinders	-	8
Valvetrain Configuration	-	OHV
Valves per Cylinder	-	2
Displacement	liters	6.5
Bore	mm	102.87
Stroke	mm	97.03
Compression Ratio	-	20.2 : 1
Firing Order	-	1-8-7-2-6-5-4-3
Engine Mass	kg	365
Glow Plugs	-	1 per Cylinder
Max. Boost Pressure	bar	0.7
Intake Manifold	-	Cast Aluminum
Valve Lift I and E	mm	10.7
Cylinder Block	-	Cast Iron
Lower Structure	-	5 Bearings
Connecting Rods	-	Forged Steel
Length	mm	159.5
Piston	-	Cast Aluminum
Piston Rings	-	2 Compression 1 Oil Control
Camshaft	-	Forged Carbon Steel
Intake Valve Opens	°CA BTDC	14
Intake Valve Closes	°CA ATDC	226
Exhaust Valve Opens	°CA BTDC	250
Exhaust Valve Closes	°CA ATDC	28

The engine is certified to U.S. 2004 emission standards meeting 2.4 g/BHPhr NOx and 0.1 g/BHPhr PM levels.

Figure 2 illustrates the engine and accessories.

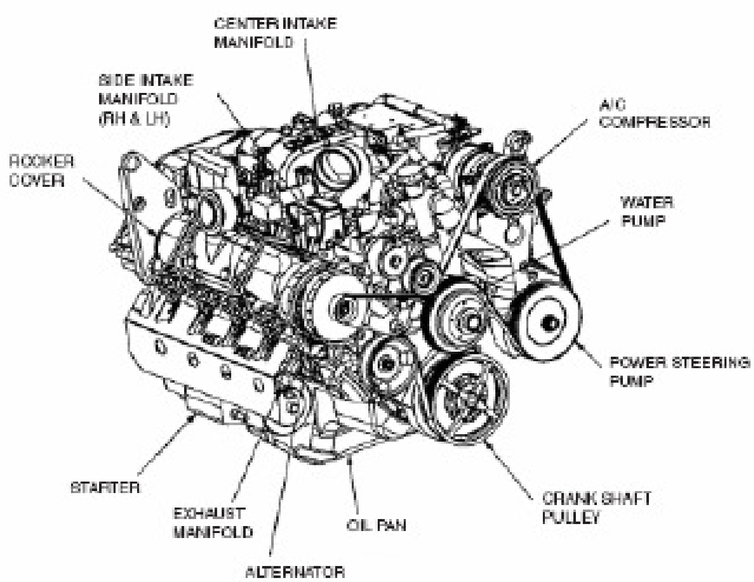

Figure 2: Engine Hardware and Accessories

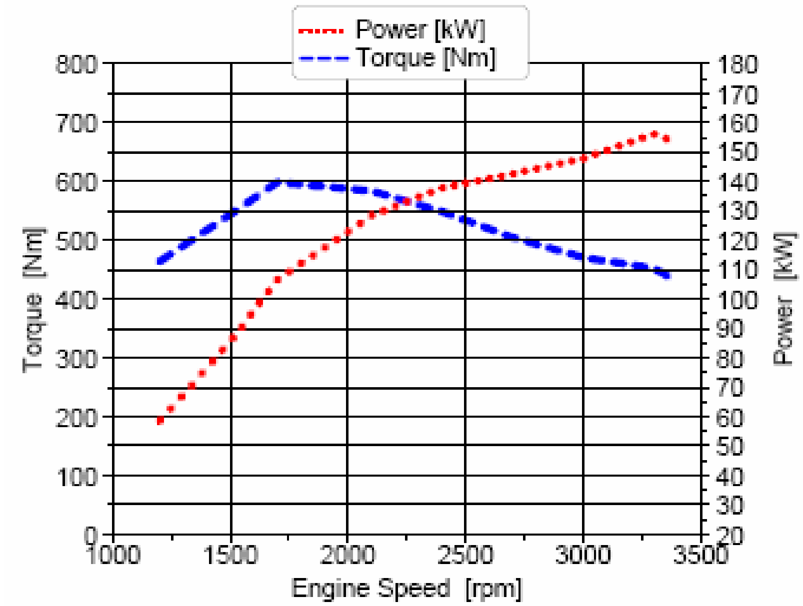

Figure 3: Full Load Curve of the Optimizer

AFTERTREATMENT SYSTEM SPECIFICATION

The exhaust aftertreatment system consists of a DOC located approximately 34 in. downstream of the turbine, a DPF close-coupled to the DOC and a DNT, also close coupled to the DPF in the production intent version. For the development process it was necessary to incorporate short spacer pipes between the components to accommodate additional measurement locations.

Figure 4 shows the aftertreatment layout which is a result of architecture evaluations described in detail in the following chapter.

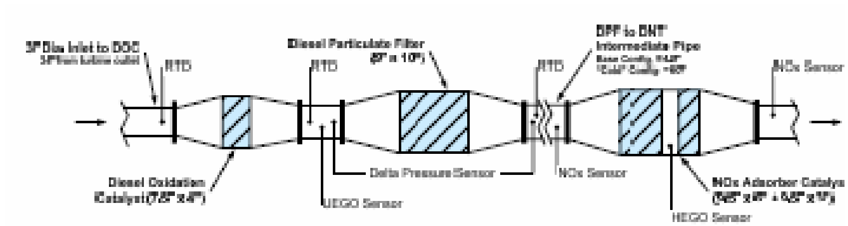

Figure 4: Exhaust Aftertreatment Layout

Table 3 lists the detailed specification of the exhaust aftertreatment components.

Table 3: Exhaust Aftertreatment Specifications

Unit	*Volume [l]*	*Cell Density [cpsi]*	*PGM loading [g/ft^3]*
DOC	2.9	400	70
DPF (Cordierite)	10.4	200	20
LNT	10.5	400	85

CONTROL SOFTWARE

A sophisticated and memory conscious strategy and software design is the result of development efforts concerning the aftertreatment control algorithms. In order to optimize the memory requirements, a multi variable controller design was developed that controls exhaust gas temperature and lambda simultaneously through the use of the available actuators. The use of a controller based structure versus an implementation using a conventional map-based method allowed a reduction in software code size by a factor of 9.

A high level overview of the aftertreatment control structure is displayed in Figure 5. The three main blocks for DPF, DNT regeneration and desulfurization communicate the status of the corresponding component to the intervention handler. The handler is the main interface to the engine and all the associated actuators. In addition to the status of the exhaust aftertreatment components, the catalyst protection block allows an override of any intervention to avoid catalyst damage through over-temperature.

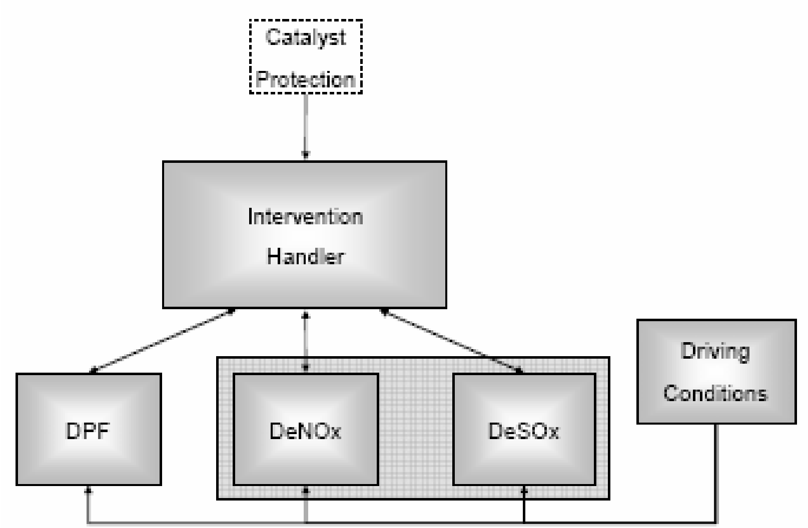

Figure 5: High Level Control Software Structure

The structure of the intervention handler is shown in greater detail in Figure 6. The handler is the only block that transfers data to and from the engine. The conditions of all exhaust aftertreatment components, such as loading level and temperature, are evaluated by the exhaust state controller and scheduler. This block ultimately releases the corresponding intervention to regenerate/purge the aftertreatment units.

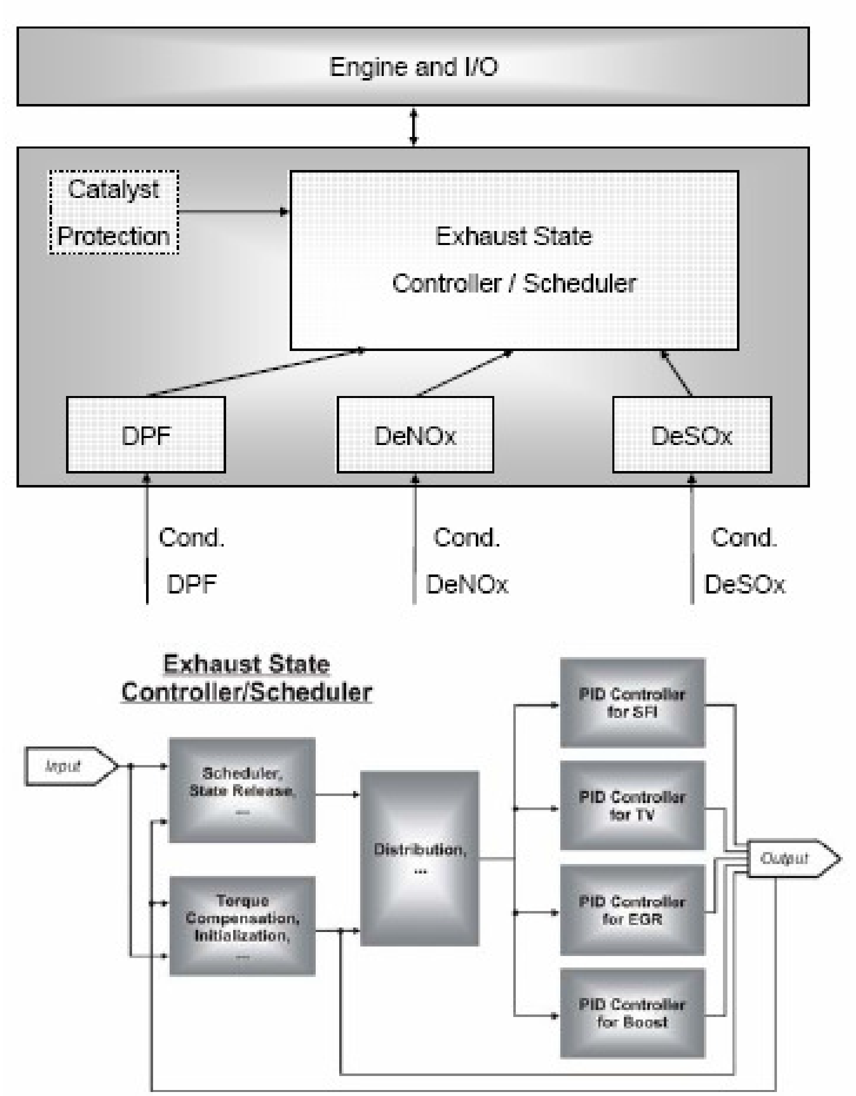

Figure 6: Structure of the Intervention Handler

TEST RESULTS

The development of the engine-aftertreatment system was performed in a development test cell as well as in a project vehicle. In the first step the system architecture is defined, which is primarily driven by the exhaust temperature profile over the certification test cycles, i.e. the 13 mode SET and the HD FTP cycles. Once the aftertreatment layout is defined, the strategy development as well as the calibration commences under steady-state conditions, transient conditions with final transfer to the vehicle.

TEST CYCLES AND BASELINE EMISSIONS

The transient cycle consists of four phases: the first is a NYNF (New York Non Freeway) phase typical of light urban traffic with frequent stops and starts, the second is LANF (Los Angeles Non Freeway) phase typical of crowded urban traffic with few stops, the third is a LAFY (Los Angeles Freeway) phase simulating crowded expressway traffic in Los Angeles, and the fourth phase repeats the first NYNF phase. It comprises a cold start after a parking overnight, followed by idling, acceleration and deceleration phases, and a wide variety of different speeds and loads sequenced to simulate the running of the vehicle that corresponds to the engine being tested. There are few stabilized running conditions, and the average load factor is about 20 to 25% of the maximum horsepower available at a given speed. [1, 2]

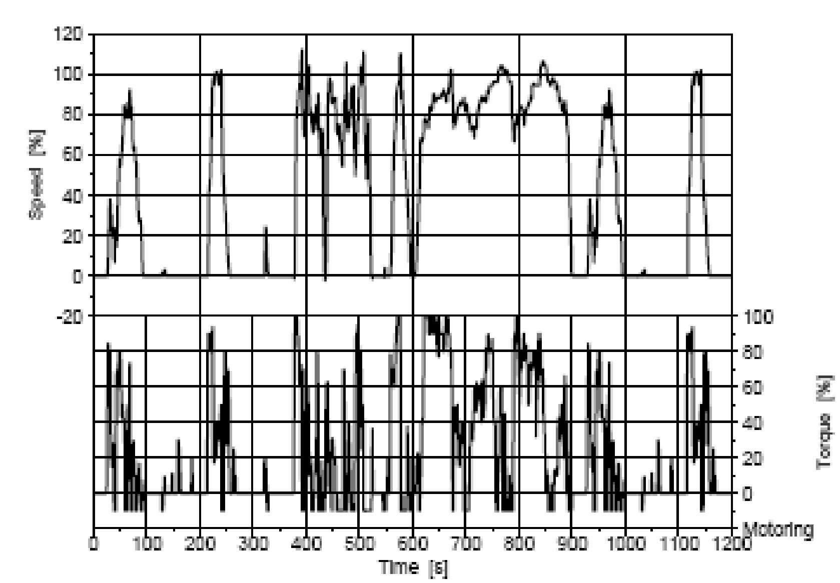

Figure 7: HD-FTP Cycle

The SET (Supplemental Emissions Test) is a carry-over from the European ESC Test also known as OICA or ACEA test. It consists of 13 operating modes including low idle. The engine map is divided into 3 engine speed areas called A, B and C speed. The following description discusses the determination of the engine speed points. The high speed n_{hi} is determined by calculating 70% of the declared maximum net power. The highest engine speed where this power value occurs (i.e. above the rated speed) on the power curve is defined as n_{hi}.

The low speed nlo is determined by calculating 50% of the declared maximum net power. The lowest engine speed where this power value occurs (i.e. below the rated speed) on the power curve is defined as n_{lo}.

The engine speeds A, B, and C to be used during the test are then calculated from the following formulas:

$A = n_{lo} + 0.25(n_{hi} - n_{lo})$

$B = n_{lo} + 0.50(n_{hi} - n_{lo})$

$C = n_{lo} + 0.75(n_{hi} - n_{lo})$

The ESC test is characterized by high average load factors and very high exhaust gas temperatures. [1]

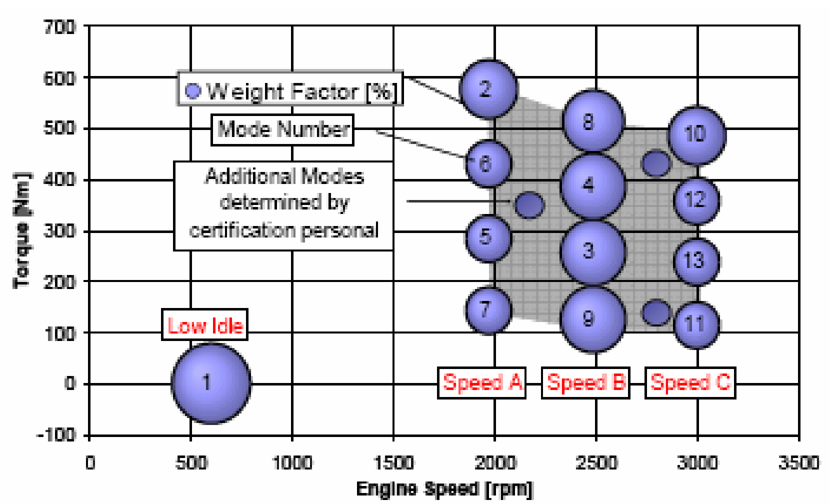

Figure 8: SET Emissions Test

The engine is certified to 2004 emission standards and shows the emissions performance listed in the following table 4:

Table 4: Emission Performance

Species	Value
NOx - SET	2.29 g/BHPhr
NMHC – SET	0.05 g/BHPhr
PM – SET	0.08 g/BHPhr
NOx – FTP	2.39 g/BHPhr
NMHC – FTP	0.16 g/BHPhr
PM – FTP	0.093 g/BHPhr

In order to comply with the 2007 phase in standards for heavy-duty engines the aftertreatment efficiencies need to be approximately 70% for NOx and over 90% for PM.

TEMPERATURE PROFILE– SYSTEM ARCHITECTURE EVALUATION

Two aftertreatment configurations were subjected to the emissions and temperature performance evaluation. The first configuration, commonly known as the typical heavy-duty configuration consists of DOC, DPF and DNT (here referred to as the 'cold' configuration), while the alternative configuration switched the DNT with the DPF (referred to as the 'hot' configuration). The latter is also often referred to as light-duty configuration. The reason for evaluating the light-duty configuration was the intention to allow easier, less challenging desulfurization as well as a less expensive sensor suite.

Figure 9 shows the temperature profiles for the two different configurations over the 13 mode as well as the HD-FTP test cycle.

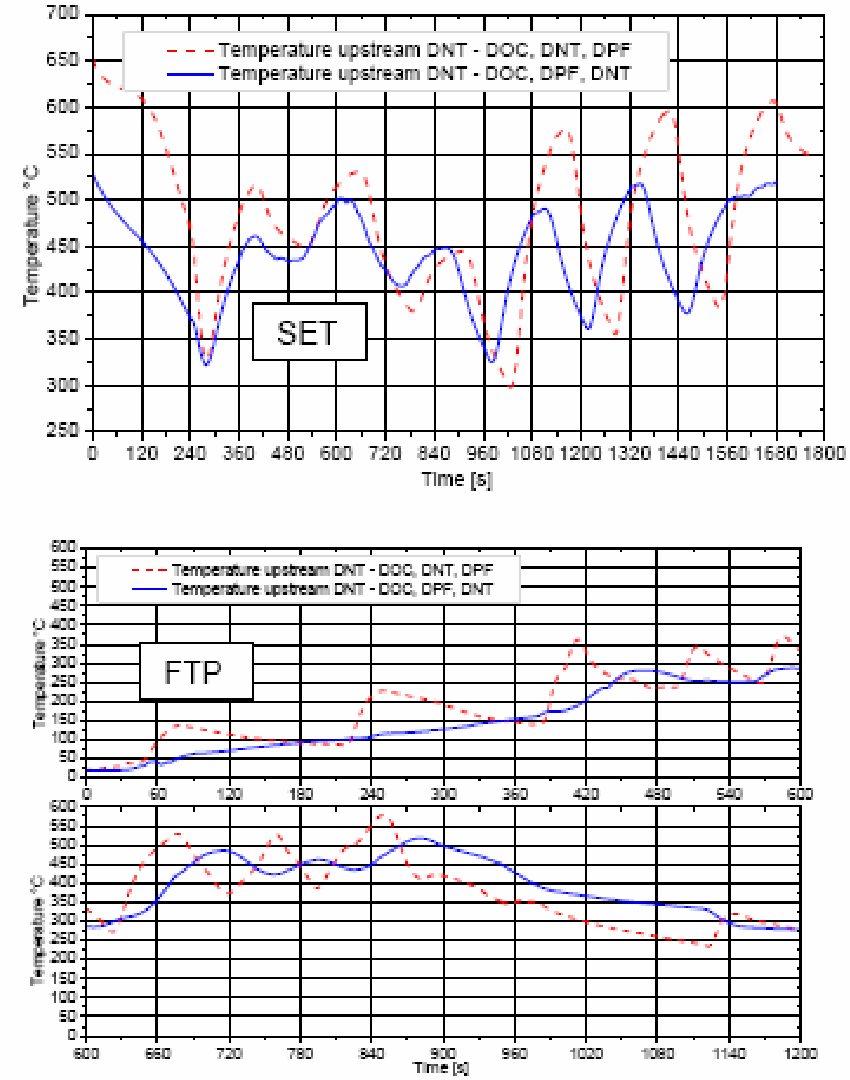

Figure 9: Temperature Profile during the SET Test and HD-FTP

Figure 10 shows the temperature distribution over 13 modes of the SET and HD-FTP for the two configurations discussed.

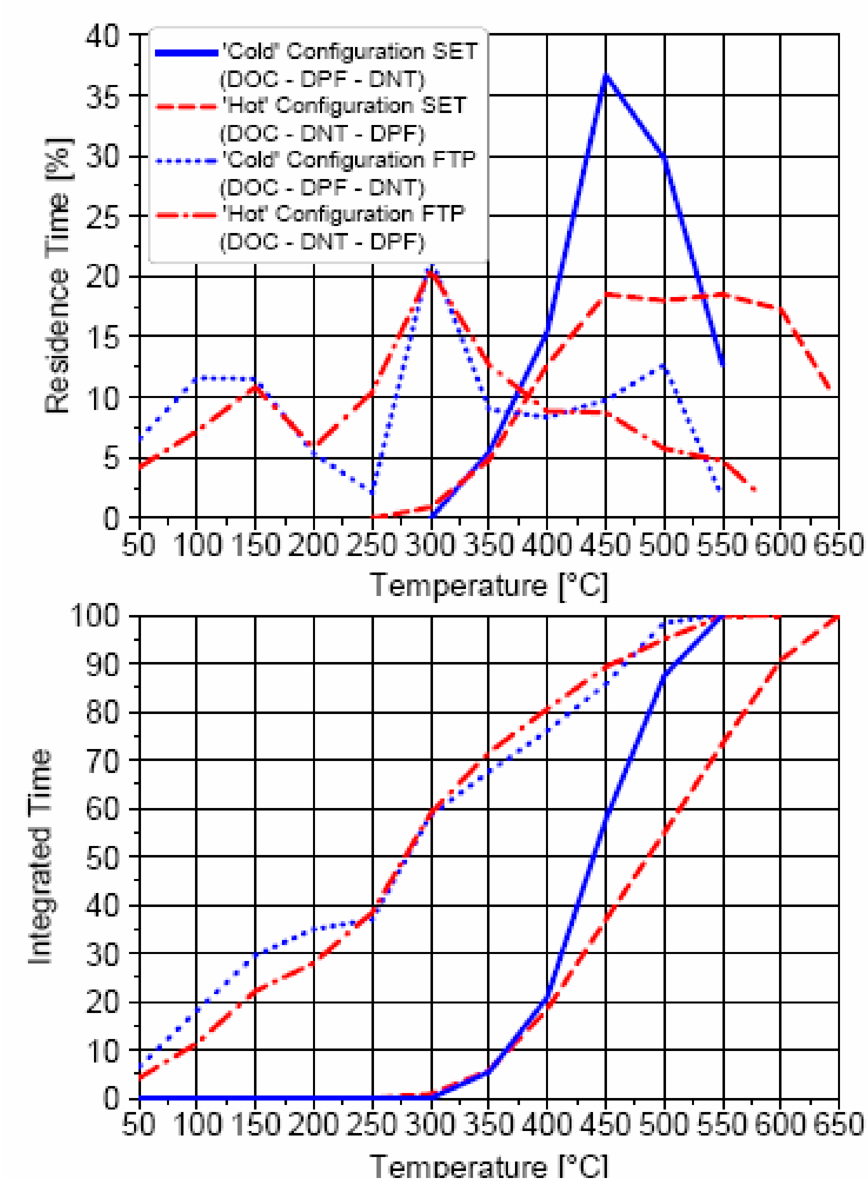

Figure 10: Temperature Residence Time Discussion

The upper portion of the graph illustrates the percent of time spent at each corresponding temperature. It is clear that the HD-FTP cycle time versus temperature distribution is not strongly affected by the component arrangement. Contrary to this observation, the SET time / temperature distribution is affected considerably by the system architecture. This fact is reflected in greater detail at the bottom of the graph. Here the integrated relative time spent at each temperature is illustrated. As stated previously the effects of different system arrangements on the HD-FTP temperature distribution are not as significant as on the SET, where the system spends a significantly longer time at higher temperature (>500°C). With these findings the component placement was defined by the 'cold' configuration for the production intent system.

DEVELOPMENT OF THE AFTERTREATMENT CONTROLS

The development effort for the integrated controls was performed in the following main steps:

1. Lean-rich modulation – development of lambda control mode
2. DPF regeneration – development of temperature control mode
3. Desulfurization – combination of the temperature and lambda closed-loop controls

The Figure in Appendix A illustrates the engine – aftertreatment – sensor layout used for the development work.

Lean-Rich Modulation

In order to determine the areas where the different controllers (EGR, TV, SFI, and PCR) are to be used, a release map is defined within the control architecture. At the current project status, this map includes four areas; an area where all controllers are active, where all but the SFI is active, where just the SFI is active, and where no controller is active.

In medium load points it is possible to accomplish the lambda enrichment without SFI. This improves the fuel economy and the HC emissions. An additional effect of the abandonment of SFI is a reduced NOx release during the lambda enrichment, before rich conditions are reached; details are shown in Figure 11.

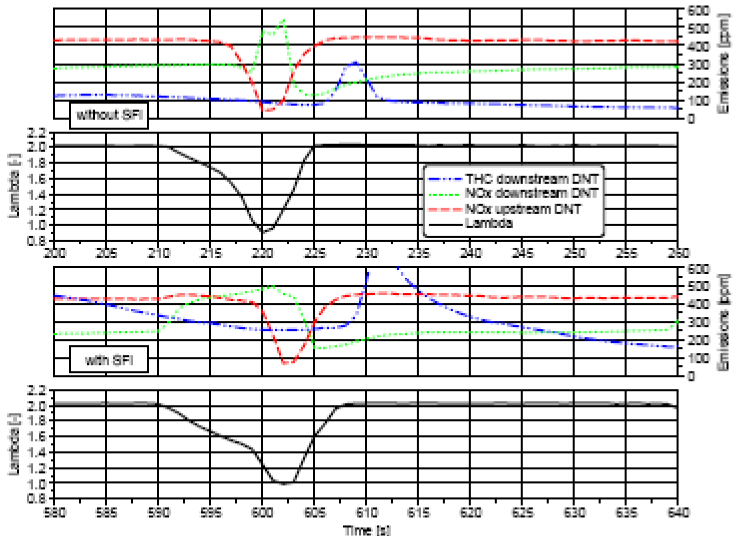

Figure 11: NOx Regeneration with and without SFI

At some full and high load points the exhaust manifold temperatures are higher than 750°C or even 800°C. A reduction of the air mass flow in order to lower the lambda value at these load points leads to even higher temperatures and is therefore not advisable. These points are critical, because DNT temperatures higher than 550°C can easily lead to an unfavorable thermal release of NOx. To convert the released NOx molecules, rich conditions are generated with the SFI only, which is possible because at high load the engine operates at these operating conditions, at lambda values of 1.3 or even lower.

Although the Optimizer Engine has a generally low lambda level, it is not possible to drop lambda below one at low load levels.

The HEGO sensor located after the DNT is not able to detect the completion of NOx regenerations and a termination delay is introduced. The effect of this delay is depicted in Figure 12. Without a time delay in place, rich conditions last for approximately 3 seconds. By adding a delay of 3 seconds the total regeneration time is 6 seconds. The curve of the NOx emissions after the DNT without delay shows that the regeneration is clearly less successful than with a delay. Furthermore, the controller requires approximately 10 seconds to reach rich conditions and another 5 seconds to return to the regular running conditions. Due to the increased fuel utilization of up to 10% (depending on regeneration frequency and duration) during this time (dependant upon regeneration frequency and duration), the trade-off between the speed of the controller and the torque compensation needs to be optimized.

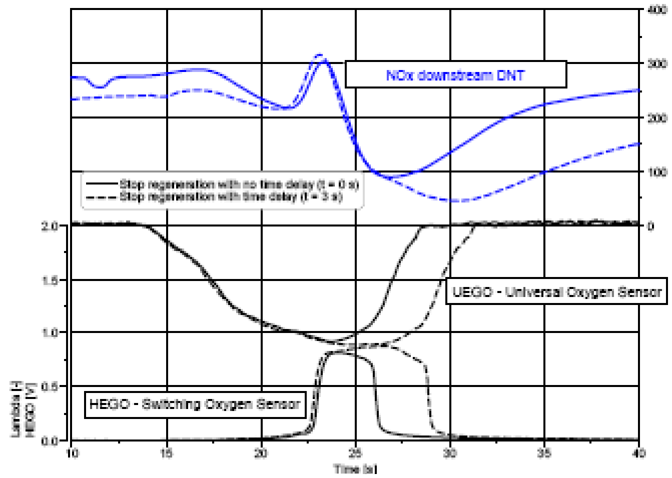

Figure 12: NOx Regeneration Termination

The delay clearly affects the maximum conversion efficiency as well as the shape of the conversion efficiency curve as depicted in Figure 13. It is clear that the longer the regeneration the higher the maximum conversion rate. In addition the curve becomes more linear with longer delays. The test runs with 0, 0.5, and 1 second delay reach very similar results, while runs with 2 and 3 second delay significantly increase the maximum conversion rates.

In order to avoid HC breakthroughs, fuel penalties, and increased PM levels, the delay time should be as short as possible.

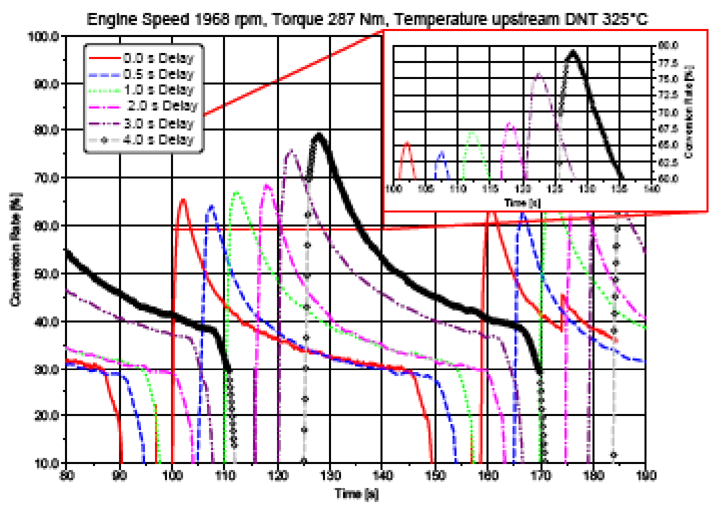

Figure 13: Regeneration Duration Effects

The final NOx purge strategy contains a detailed loading model that defines the loading status of the NOx adsorber based on calculated (modeled) values that are corroborated by measurement devices such as the NOx sensor and the UEGO sensor.

<u>DPF-Regeneration</u>

A DPF regeneration request via the DPF state controller is based on the amount of accumulated soot in the filter, the fuel consumption or the mileage as referenced to the last successful regeneration event. The fuel consumption and the driven distance are calculated from Equation 1 and 2 respectively.

$$m_{fuel} = \int_{t_0}^{t} \dot{m}_{fuel}\, dt \qquad 1$$

$$\Psi_{vehicle} = \int_{t_0}^{t} v_{vehicle}\, dt \qquad 2$$

Here m_{fuel} is the absolute fuel consumption, $\dot{m}_{fuel}$ is the fuel mass flow, $\Psi_{vehicle}$ is the mileage, $v_{vehicle}$ is the vehicle speed and t_0 denotes to the initialization after performing a DPF regeneration. Similar to the loading simulation, the fuel and mileage integrals are zero initialized after a successful regeneration or initialized with adjusted values after partial regeneration events.

If any of the integrated values for soot loading, fuel consumption, or mileage exceed their calibrated threshold, a regeneration request is sent to the intervention handler.

The intervention handler module combines the three mentioned measures and derives a factor representing the necessity for regeneration. The factor can be transferred as a continuous value, which is incorporated in the functionality of the scheduler.

A regeneration event can not only be requested by the DPF state controller itself, but also via the intervention handler scheduler. The request is transmitted by the request status of the scheduler, which is currently equally handled with the requests based of filter loading, fuel consumption and mileage. Thus, the regeneration procedure is processed as illustrated in flow chart form in Figure 14.

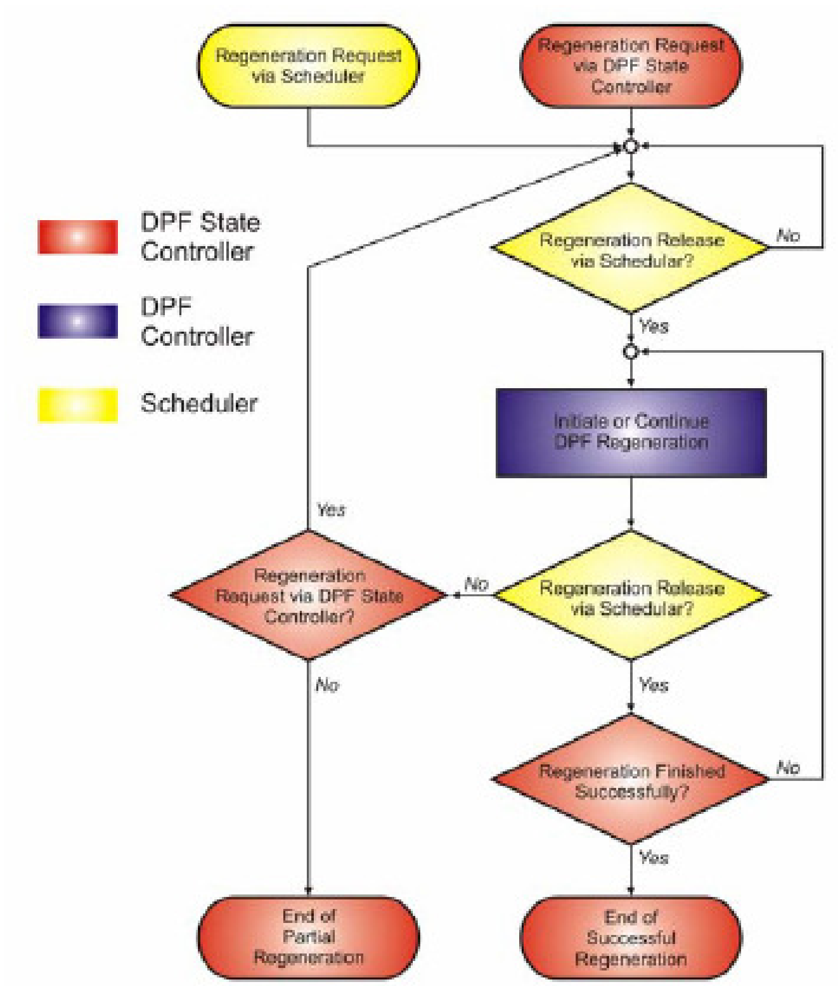

Figure 14: DPF Regeneration Procedure

Two approaches determining the regeneration progress are derived from the temperature difference between the inlet and outlet temperature of the DPF and the gradient of the differential pressure exhibited over the filter, as illustrated in Figure 15.

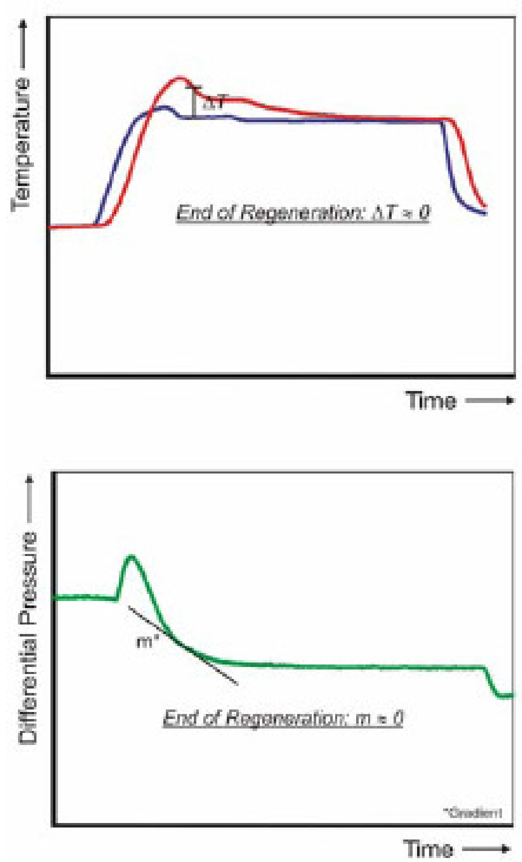

Figure 15: Definition of the End of a Regeneration Event

The temperature difference is based on the exothermic oxidation of soot and might be supported by the reaction of the HC breakthrough at the DOC. If the difference of the inlet and outlet temperature approaches zero or remains constant, the end of the regeneration can be interpreted, due to the abating reaction of soot.

The pressure drop over the DPF is another potential indicator for the completion of the regeneration progress, due to its functional relationship to the amount of particles in the filter. As the regeneration converts soot, the differential pressure decreases and converges asymptotically to the pressure drop of a clean filter. If the differential pressure reaches the pressure drop level of the empty filter, the regeneration is complete.

The determination of the most efficient DPF regeneration conditions in terms of fuel and regeneration efficiency was performed in four main steps under steady-state conditions:

1. 550°C, 600°C, 650°C for 20 minutes with SFI actuation only
2. 650°C for 2 minutes with subsequent 500°C, 550°C and 600°C for the remaining 18 minutes, SFI actuation only
3. Full utilization of the temperature controller, including activation of SFI, EGR and TV at 625°C and 650°C for 20 minutes
4. Full utilization of the temperature controller, including activation of SFI, EGR and TV at 625°C, 650°C and 675°C for 10 minutes

In order to assess the efficiency of the DPF regeneration process, a parameter defining the amount of fuel consumed to combust the accumulated amount of soot $\rightarrow g_{fuel}/g_{soot}$ is used. Table 5 shows all the results of the conducted tests.

Table 5: Comparison of Regeneration Strategies

Test Condition	Description	Regeneration Efficiency [%]	Specific Fuel Consumption g_{fuel}/g_{soot}
1	550°C	77.2	9.9
	600°C	93.8	16.8
	650°C	93.3	8.3
2	**650°C → 500°C**	**61.2**	**5.6**
	650°C → 550°C	65.9	14.5
	650°C → 600°C	93.7	12.2
3	625°C	92.4	8.0
	650°C	**96.6**	**5.8**
4	625°C	78.3	4.8
	650°C	87.4	7.7
	675°C	90.3	7.5

As the specific fuel consumption takes the regenerated or combusted soot into account, the most efficient regeneration condition can be found at the lowest specific fuel consumption. The lowest fuel consumption however does not necessarily coincide with reasonably high regeneration efficiency (definition of combusted versus accumulated soot before and after a regeneration event). As expected, the higher the regeneration temperature the higher the regeneration efficiency. Depending on the employed strategy the relative fuel consumption number varies between 5.8 and 16.8 g_{fuel}/g_{soot} for regeneration efficiencies greater than 90%. As a result of this investigation the regeneration set point temperature was defined as 650°C with a regeneration duration of 20 minutes provided the soot mass limit of the DPF was reached.

The final regeneration strategy employs deterministic strategies that allow initiation of a DPF regeneration based on the favorable conditions (e.g. using DeSOx regenerate the DPF).

Desulfurization

Desulfurization, being the intervention task with the highest risk in terms of controls and the resulting part durability, needs careful development of control strategy and calibration. Due to the system layout with the DNT in the downstream location the controls need to allow transportation of temperature through the DPF to the DNT location. Under part load conditions this poses a significant stress to the DOC which is forced to generate very high exotherms. To allow H_2S suppression a frequent lean-rich transition at high temperature is necessary. The DNT desulfurization development was conducted with focus on the vehicle application for a heavy truck, assuming higher loads during operation. The operating condition for the desulfurization optimization was mode point 5 in the SET test.

Figure 16 illustrates the temperature and lambda profile during a desulfurization with discontinuous rich phase. The upper portion of the graph shows the DNT inlet temperature as well as the lambda. The lower portion shows the released sulfur species measured with a mass spectrometer at the tailpipe position. The effectiveness of the discontinuous rich phase is reflected in the reduced H_2S release during the entire event. All the accumulated sulfur is released in the form of SO_2.

After the desulfurization boundary conditions were defined, the desulfurization effectiveness was tested by employing accelerated catalyst sulfur poisoning. The engine was operated on 400 ppm sulfur fuel in several steady-state modes with NOx adsorber regenerations engaged using the NOx loading model as part of the strategy (i.e. each regeneration was enabled on an as-needed basis). The NOx storage capacity of the DNT was checked frequently to determine the poisoning level of the catalyst.

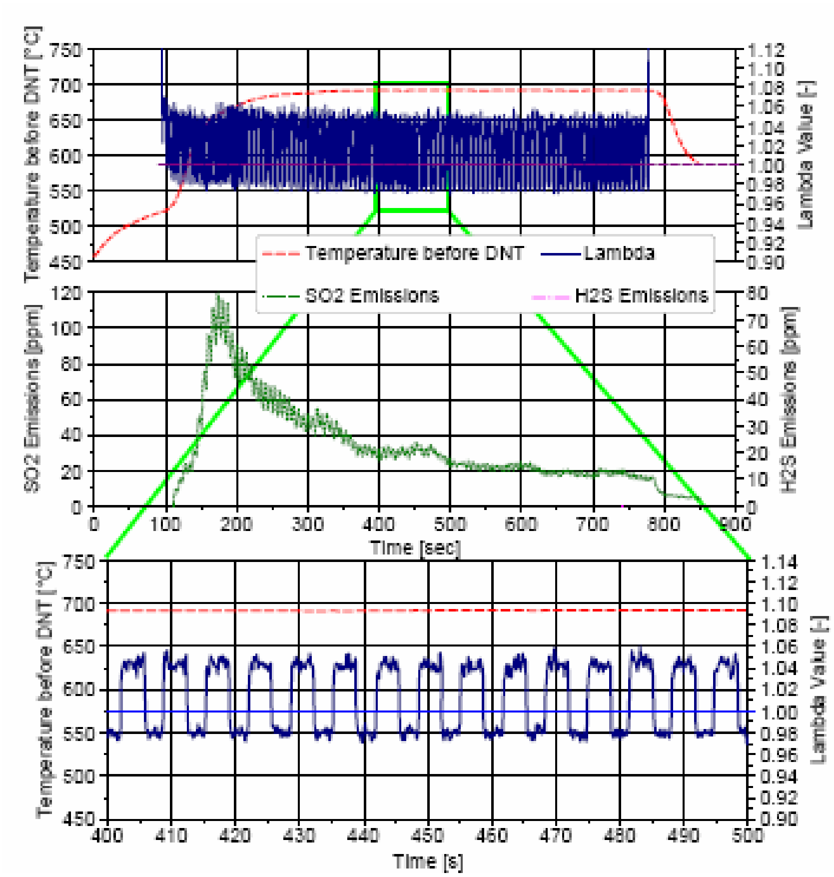

Figure 16: Steady-state Desulfurization in Mode 5

The NOx storage capacity of the catalysts during the poisoning is illustrated in Figure 17. The procedure was repeated twice to demonstrate repeatability.

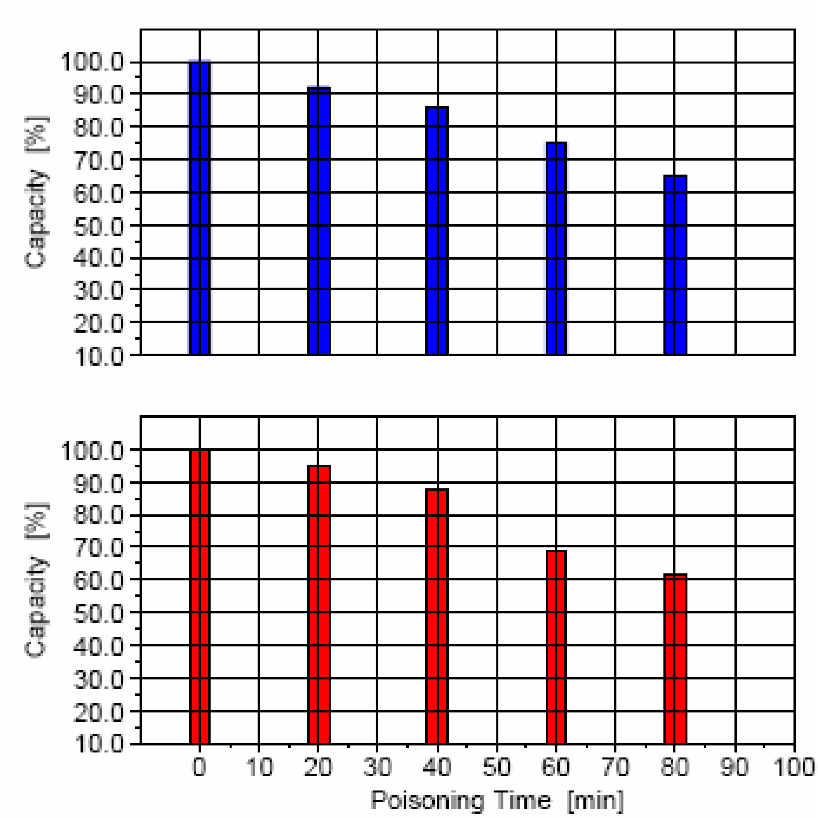

Figure 17: DNT relative NOx Storage Capacity during Poisoning

The comparison of the post DeSOx capacities resulted in a considerable loss in NOx storage as illustrated in Figure 18. The DNT inlet temperature for the two discussed DeSOx events is below 700°C and the lean-rich amplitude is 0.06 from lambda 0.98 to 1.04.

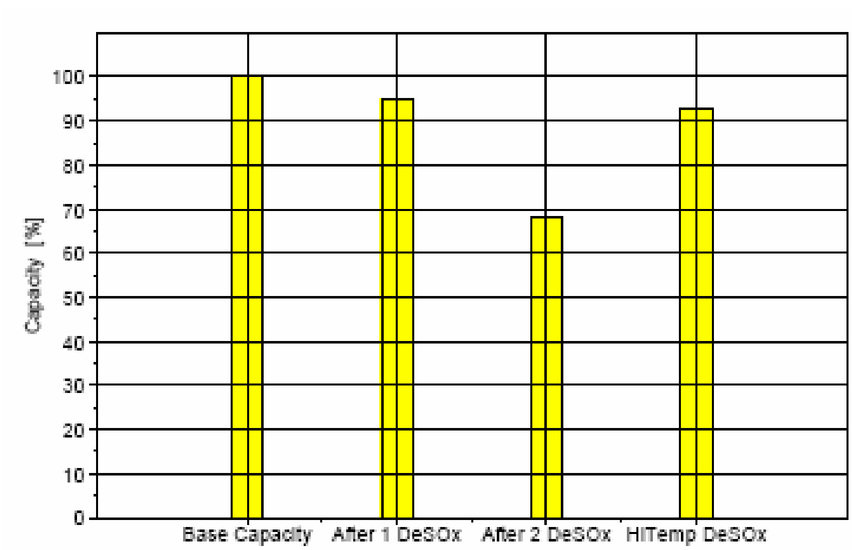

Figure 18: Comparison of DeSOx Efficiencies

In an attempt to regain the lost NOx storage capacity, a more aggressive DeSOx strategy is employed. This strategy utilizes a higher system inlet temperature as well as larger lambda amplitude results in lower lambda values. The differences in the temperature profile are shown in the following Figure 19.

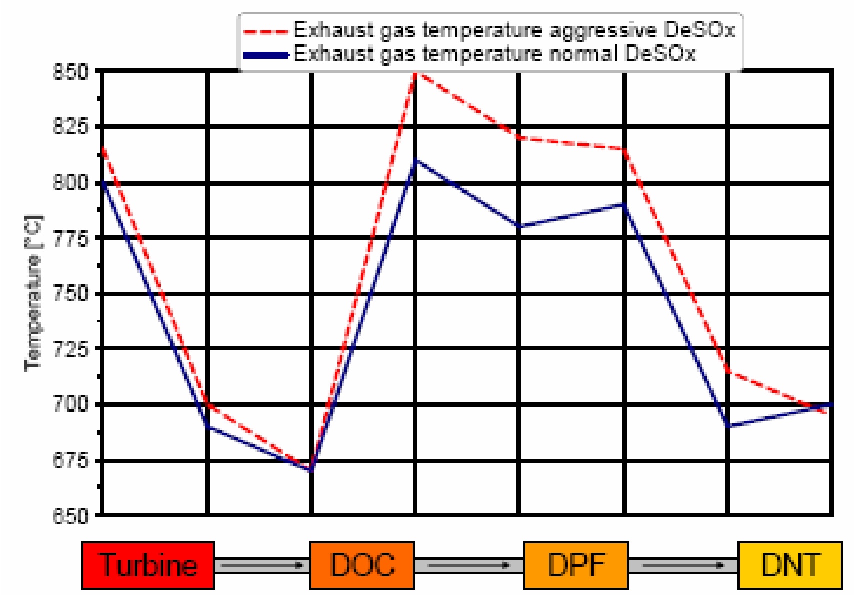

Figure 19: Temperature Profile during Desulfurization

13 MODE TEST (SET – SUPPLEMENTAL EMISSIONS TEST)

The result of the lean-rich modulation work results in a sustainable and repeatable tailpipe emission number for the SET. Figure 20 shows the final development results comparing test cell aged and fresh exhaust aftertreatment systems.

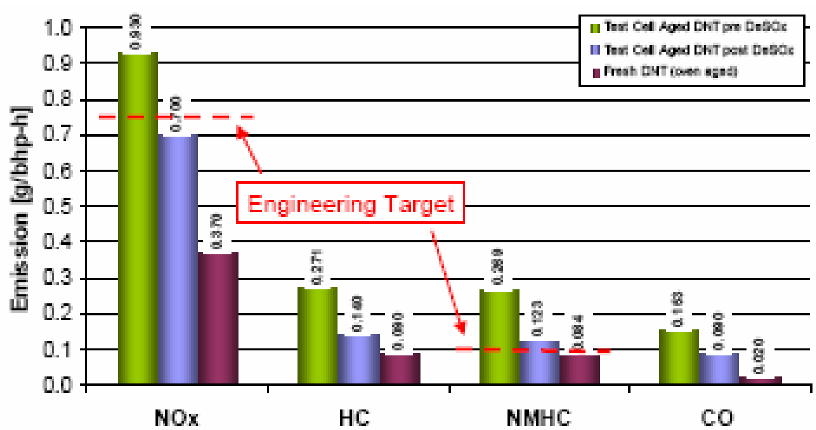

Figure 20: Emission Results for the SET

The test cell aged catalyst was exposed to about 300 hours of test cell development operation including DeNOx and DPF regeneration work and can be considered as moderately aged. The fresh catalyst was oven aged prior to the installation in the test cell. The oven aging is performed at 700°C for 10 hours.

For all the configurations NOx emissions are within the emission standard, while the fresh catalyst performance allows to significantly staying below the engineering target. As expected the NMHC are the largest portion of the total hydrocarbons (HC), with an average of less than 5% of Methane. With the aged catalyst the post desulfurization NMHC emissions are within the emission standard, close to the engineering target. The pre-desulfurization NMHC level exceeds the standard. The reason for this is the increase of required NOx adsorber regeneration events and associated hydrocarbon break-through resulting from each event.

HEAVY-DUTY FTP EMISSIONS TEST

With a sustainable level of control under steady-state conditions the control strategy is evaluated under transient conditions operating over the HD-FTP. The control strategy as well as the calibration is adjusted to the specific needs of the transient operation with frequent changes in engine speed and engine load.

Figure 21 shows the results of the strategy development and calibration efforts. With the calibration as used for the SET, the hydrocarbon emissions exceed the emission standards and the engineering target by 81% (154% over the engineering target). A hydrocarbon conscious calibration is the result of incremental development steps moving towards higher tailpipe NOx levels which are still within the engineering target.

With the final setup of hard- and software as well as controls calibration, the emission standards for all gaseous emissions as well as PM can be met.

The strategy and calibration provide stable hydrocarbon emissions over the cold and hot cycle with only minor performance differences between the starting conditions.

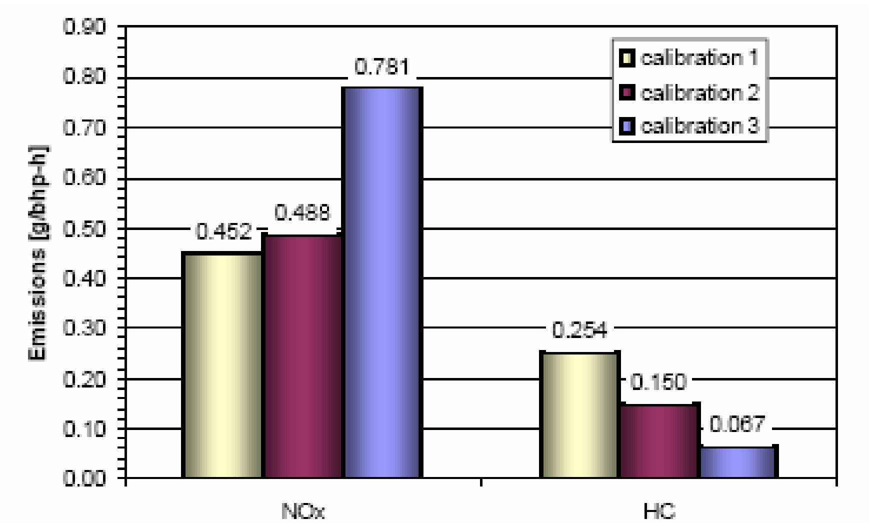

Figure 21: HD-FTP Emission Results

CONCLUSION

This development program has demonstrated is the potential to integrate an inexpensive base engine with an aftertreatment system and sophisticated controls to meet the 2007 heavy-duty emission standards. Optimizing the control unit's memory leads to an alternative aftertreatment control structure using a multi-input, multi-output controller for temperature and lambda control. Demonstrating successful emission control system performance for both the HD-FTP as well as SET will be followed by certification for the engine – aftertreatment system. The certification process entails extensive aftertreatment durability testing, which will be outlined in future publications.

REFERENCES

1. 40CFR §86.1333-90 Transient test cycle generation
2. Dieselnet: www.dieselnet.com
3. Tomazic D., Tatur M., Thornton M. "Development of a Diesel Passenger Car Meeting Tier 2 Emissions Levels," SAE Paper 2004-01-0581, March 2004, Detroit, Michigan.
4. Tomazic D., Tatur M., Thornton M. "APBF-DEC NOx Adsorber/DPF Project: Light-Duty Passenger Car Platform," DEER Paper, August 2003, Newport, Rhode Island.
5. Geckler S., Tomazic D., et al. "Development of a Desulfurization Strategy for a NOx Adsorber Catalyst System," SAE Paper 2001-01-0510, March 2001, Detroit, Michigan.
6. McDonald, J. "Progress in the Development of Tier 2 Light-Duty Diesel Vehicles," SAE Paper 2004-01-1791, March 2004, Detroit, Michigan.

7. Webb, C., et al. “Achieving Tier 2 Bin 5 Emission Levels With a Medium-Duty Diesel Pick-Up and a NoDx Adsorber, Diesel Particulate Filter Emissions System-Exhaust Gas Temperature Management” SAE Paper 2004-01-0584.
8. Whitacre, S., et al. “Systems Approach to Meeting EPA 2010 Heavy-Duty Emission Standards Using a NoDx Adsorber Catalyst and Diesel Particle Filter on a 15l Engine” SAE Paper 2004-01-0587.
9. Tatur M., Tyrer H., Tomazic D., Thornton M., McDonald, J. “Tier 2 Intermediate Useful Life (50,000 miles) and 4000 Mile Supplemental Federal Test Procedure (SFTP) Exhaust Emission Results for a NOx Adsorber and Diesel Particle Filter Equipped Light-Duty Diesel Vehicle,” SAE Paper 2005-01-1755.
10. Thornton M., Tatur M., Tyrer H., Tomazic D. “Full Useful Life (120,000 miles) Exhaust Emission Performance of a NOx Adsorber and Diesel Particle Filter Equipped Passenger Car and Medium-Duty Engine in Conjunction with Ultra Low Sulfur Fuel,” DEER 2005.

CONTACT

Marek Tatur, FEV Engine Technology, Senior Engineer Diesel Combustion Systems. E-Mail: tatur@fev-et.com

Taylor Holland, AM General, Program Manager – General Engine Products. E-Mail: taylor.holland@amgeneral.com

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BTDC: Before Top Dead Center
CA: Crank Angle
CO: Carbon Monoxide
CO2: Carbon Dioxide
DOE U.S. Department of Energy
DPF: Diesel Particle Filter
DNT: DeNOx Trap
ECM: Electronic Control Module
ECS: Emission Control System
ECU: Engine Control Unit
EGR: Exhaust Gas Recirculation
EPA: Environmental Protection Agency
FSN: Filter Smoke Number
FTP: Federal Test Procedure
HC: Hydrocarbon
HD: Heavy-Duty
HSDI: High-Speed Direct Injection
IDI: Indirect Injection
NAC: NOx Adsorber Catalyst
NMHC: Non-Methane Hydrocarbon
NO: Nitric Oxide
NO2: Nitrogen Dioxide
NOx: Oxides of Nitrogen
O2 Oxygen
OEM: Original Equipment Manufacturer
PM: Particulate Matter
PCR: (Boost) Pressure Control Regulator
RPM: Revolutions per Minute (engine speed)
SCR: Selective Catalytic Reduction
SET: Supplemental Emissions Test
SFI: Secondary Fuel Injector
THC: Total Hydrocarbon
TV: Throttle Valve

APPENDIX A

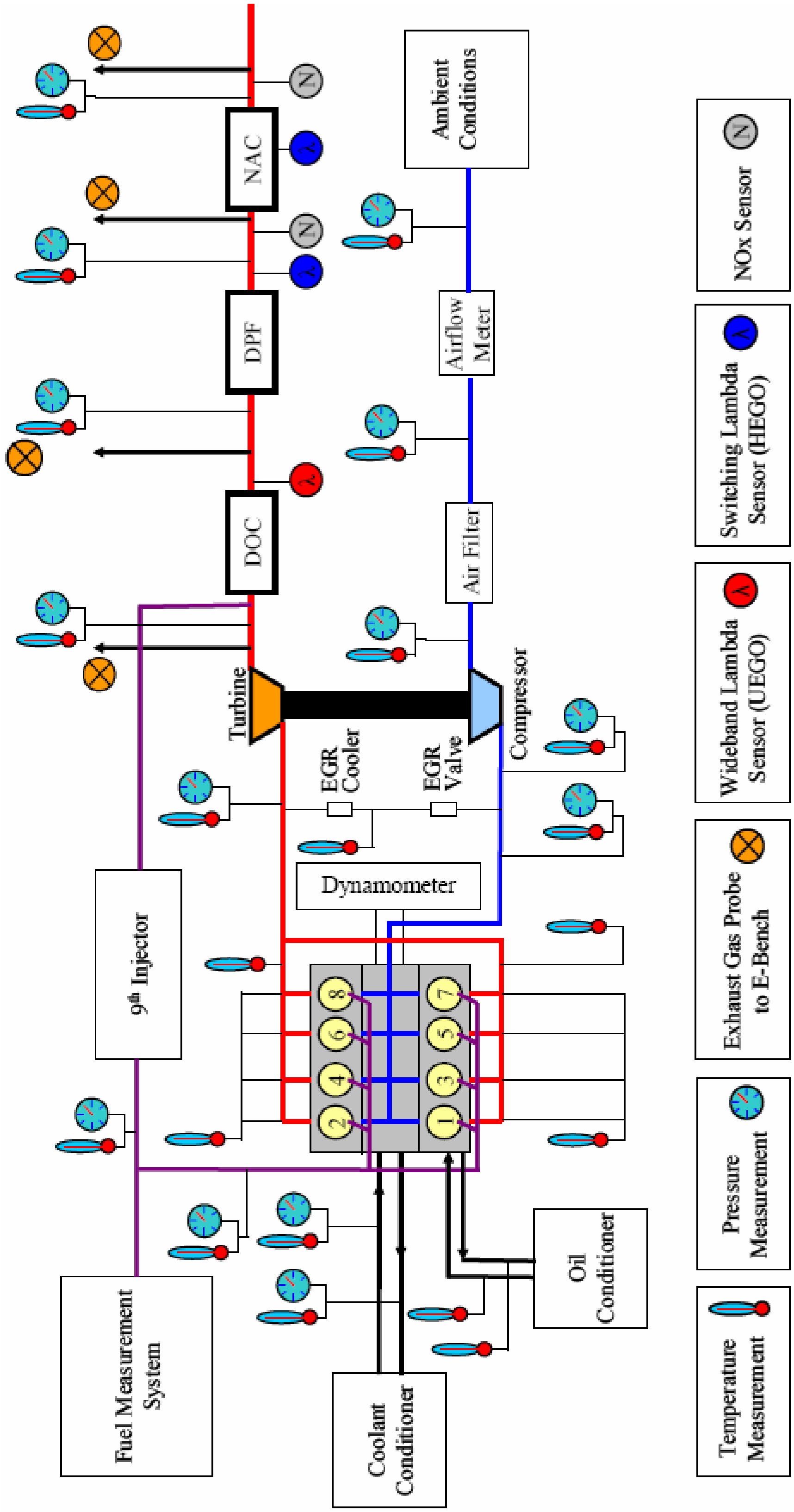

Figure 26: Test Cell Instrumentation Setup