

Achieving Ultra Low NO_x Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine - Comparison of Advanced Technology Approaches

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ABSTRACT

The 2010 emissions standards for heavy-duty engines have established a limit of oxides of nitrogen (NO_x) emissions of 0.20 g/bhp-hr. However, the California Air Resource Board (ARB) projects that even when the entire on-road fleet of heavy-duty vehicles operating in California is compliant with 2010 emission standards, the National Ambient Air Quality Standards (NAAQS) requirement for ambient particulate matter (PM) and Ozone will not be achieved without further reduction in NO_x emissions. The California Air Resources Board (CARB) funded a research program to explore the feasibility of achieving 0.02 g/bhp-hr NO_x emissions. This paper details the work performed on a heavy-duty diesel engine to explore the feasibility of various configurations of Traditional Technology (diesel oxidation catalyst-diesel particulate filter-selective catalytic reduction (SCR)) and Advanced Technology (passive NO_x adsorber or diesel oxidation catalyst - SCR on Filter - SCR) to demonstrate ultra-low NO_x emissions. Active and passive performance modifiers were also evaluated to demonstrate low NO_x emissions, including heated dosing, gaseous dosing, and supplemental heat addition devices. The proposed Ultra Low NO_x emission levels of 0.02 g/bhp-hr require a significant shift in technology application to address cold start NO_x emissions. Data are presented showing comparison in NO_x reduction capability of the various configurations. All testing was conducted on the FOCAS-HGTR® system, which is a full flow, transient gas reactor bench for testing full sized catalyst systems.

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INTRODUCTION

The 2010 emission standards for heavy-duty engines have established a limit for oxides of nitrogen (NO_x) emissions of 0.20 g/bhp-hr, a 90% reduction from the previous emission standards. However, ARB projects that even when the entire on-road fleet of heavy-duty vehicles operating in California is compliant with the 2010 emission standards, the upcoming National Ambient Air Quality Standards (NAAQS) requirements for ambient particulate matter (PM) and Ozone will not be achieved in California without further significant reductions in NO_x emissions from the heavy duty vehicle fleet. There is currently little incentive for manufacturers to pursue emission reductions beyond the current standards, and so the potential for further reductions is unclear.

To address this lack of information, ARB funded a research program to explore and investigate the feasibility of significantly reducing NO_x emissions below today's standard.

The study involved evaluating improved engine emission control calibrations, enhanced aftertreatment technology choices and configurations, improved and more efficient catalysts, improved aftertreatment thermal management, urea dosing strategies, and engine management practices for two heavy-duty engines: one natural gas engine with a three-way catalyst (TWC); and one diesel engine with a diesel particulate filter (DPF) and selective catalytic reduction (SCR). The target NO_x emission rate for this project over the heavy-duty Federal Test Procedure (FTP) was 0.02 g/bhp-hr. This paper covers the screening of an array of diesel aftertreatment

components and optional equipment to assess the feasibility of various configurations to reach ultra-low NO_x (ULN) levels on a target diesel test engine.

TEST ENGINE

The test engine used as the target for this program was a 2014 model year Volvo MD13TC engine with a 361 kW rating and included a turbo-compounder located after the fixed geometry turbocharger. At the time of selection, the engine was representative of the direction that the OEM intended to pursue for future greenhouse gas standards. A picture of the exhaust side of the engine is provided in [Figure 1](#).



Figure 1. Volvo MD13TC Diesel Engine

Table 1. Volvo MD13TC Engine Specifications

Displacement	12.8 L
Bore x Stroke	131 x 158 mm
Rated Power	361 kW
Rated Speed	1477 RPM
Peak Torque	3050 Nm
Peak Torque Speed	1050 RPM
Fuel System	F2 Common Rail
Turbocharger	Fixed Geometry
Turbo-compounder	Mechanical
EGR System	Cooled, high pressure
Emission Certification	Euro VI
Emission AT System	DOC+cDPF+SCR
Application	Line-haul

Although the engine was certified to Euro VI emission standards, emission testing conducted with the baseline aftertreatment system found that it was also US 2010 emissions compliant. The engine specifications are listed in [Table 1](#).

TRANSIENT REACTOR ENGINE SIMULATION

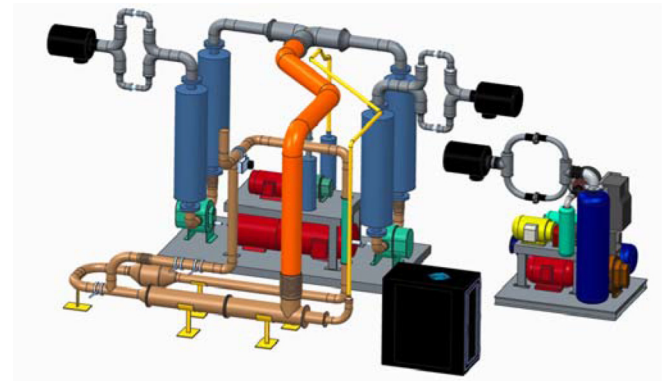


Figure 2. Schematic of Hot Gas Transient Reactor (HGTR) Test System

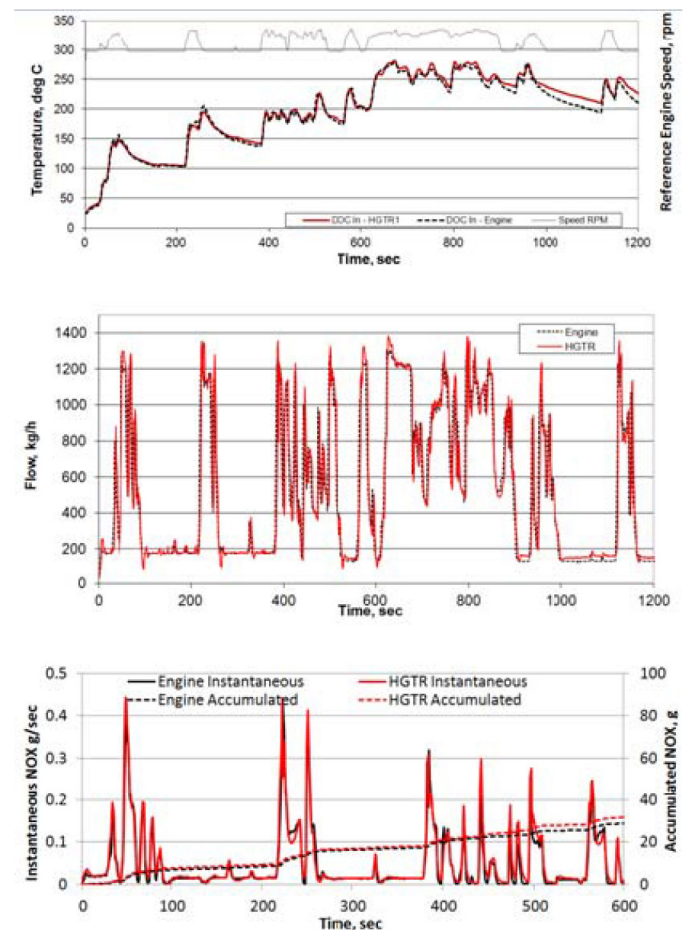


Figure 3. Comparison of Baseline Exhaust Gas Conditions Between the Engine and the HGTR

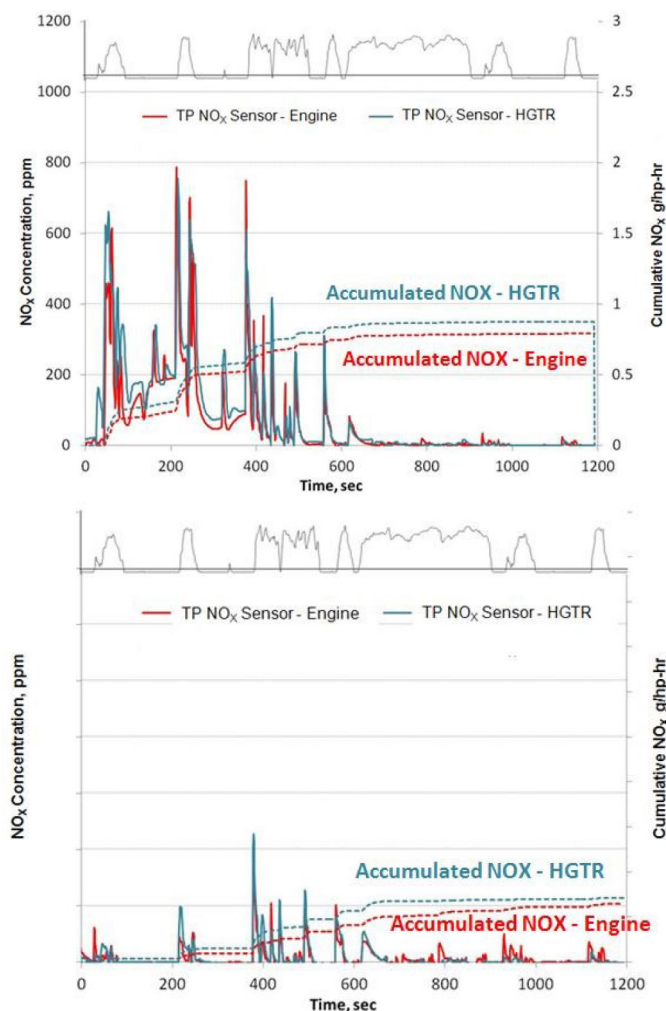


Figure 4. Baseline Tailpipe NO_x Emissions From the Stock ATS; Top Shows the Cold-Start Cycle, Bottom Shows the Hot-Start Cycle

The screening experiments were conducted using a full size transient gas reactor (FOCAS® Hot Gas Transient Reactor® (HGTR®)) to enable precise control over the input cycle enabling accurate comparisons between the various emissions system configurations. The work focused on the cold- and hot-FTP test cycles.

The HGTR is a computer-controlled multi-fueled, burner-based flow reactor system designed to replicate the lean exhaust conditions of internal combustion engines. The HGTR is a transient, full size reactor type system. Unlike typical small core gas reactor benches, which use bottled gas to simulate exhaust conditions, the HGTR produces an exhaust gas stream through combustion of fuels and compounds, producing an exhaust gas composition that more closely replicates the array of gaseous and particulate species created from the combustion of hydrocarbon fuel in an engine. The exhaust gas conditions are generated through independent, model-based control and allow any combination of mass flow, temperature, NO_x, HC, H₂O, O₂, and PM emission within the window of operation. The details of the exhaust component simulation are discussed in more detail in SAE 2013-01-1301. The HGTR is predominantly used for catalyst performance evaluation and screening, multi-dimensional

mapping, control model calibration, engine/catalyst calibration integration, and engine cycle simulation and can be applied to individual catalysts or complete exhaust aftertreatment systems. A model of the system is provided in Figure 2.

The first task in the screening exercise was to use the reactor to simulate the baseline FTP cycle from the Volvo Engine. During this task, the engine out exhaust gas temperature, flow and NO_x concentration were simulated. Figure 3 shows a comparison of these parameters measured over the cold-start FTP cycle between the engine and the HGTR system. The tailpipe NO_x mass emissions between the engine and the HGTR are shown in Figure 4.

NO_x EMISSION GOALS: REDUCTION AND EFFICIENCY

The baseline engine provided a good example of current technology control using a typical aftertreatment emissions configuration consisting of a diesel oxidation catalyst-diesel particulate filter-selective catalytic reduction (DOC-DPF-SCR). The baseline engine emissions and overall catalyst efficiency on each cycle are listed in Table 2.

Table 2. Baseline NO_x Engine Emissions and Conversion Efficiencies

Test	BSNO _x [g/bhp-hr]		NO _x Conv. Eff. [%]
	Engine-out	Tailpipe	
Cold	2.82	0.715	74.7
Hot	2.98	0.047	98.4
Composite	2.94	0.140	95.2

Under an Ultra-Low NO_x (ULN) emissions control strategy, the cold-start emissions must be aggressively addressed, as well as making improvements to hot start and high space velocity control. Figure 5 and Figure 6 show examples of measured tailpipe NO_x emissions from the baseline engine compared to those of an Ultra-Low NO_x example.

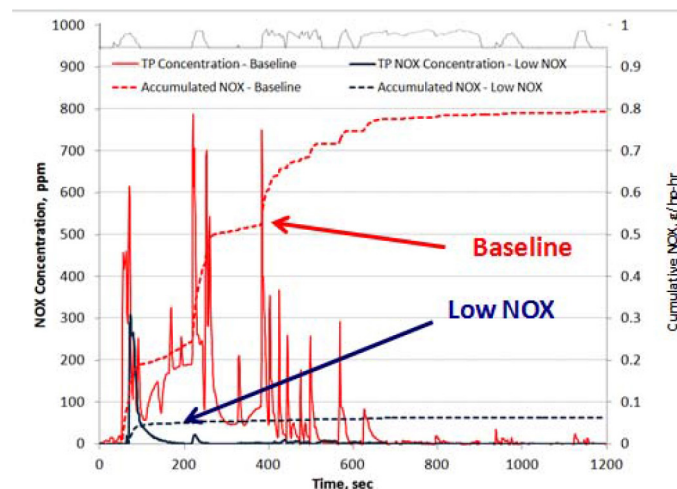


Figure 5. Baseline Cold-Start FTP Tailpipe NO_x Emissions Compared to an Ultra-Low NO_x Example

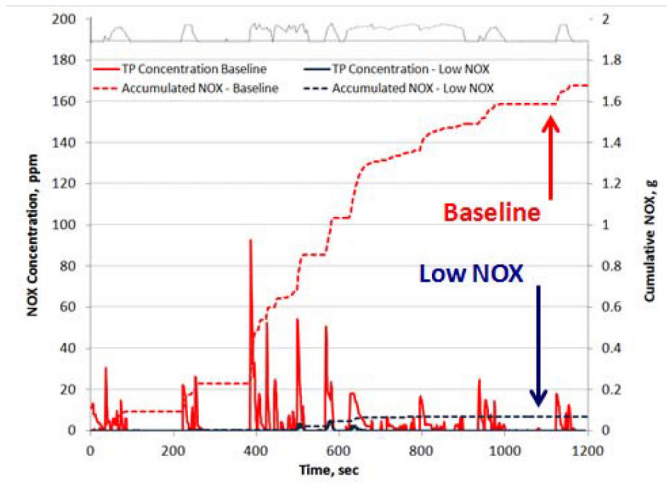


Figure 6. Baseline Hot-Start FTP Tailpipe NO_x Emissions Compared to an Ultra-Low NO_x Example

Achieving composite ULN mass emissions of 0.02 g/bhp-hr requires a more than 90% reduction from the current regulated level. Figure 7 illustrates the allowable hot-start to cold-start NO_x tradeoff that must be met to achieve levels below ULN.

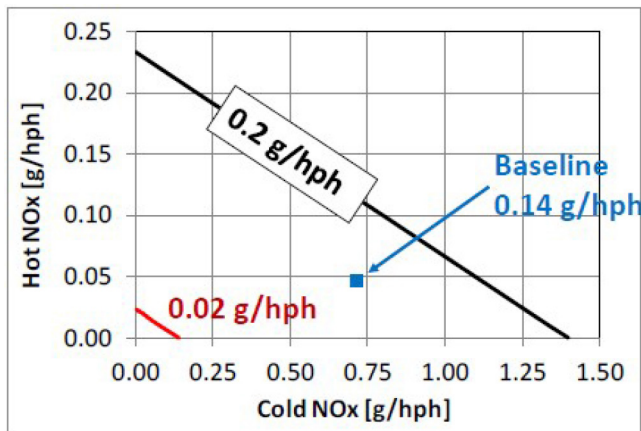


Figure 7. Hot-Start to Cold-Start Tailpipe NO_x Mass Emission Trade-Off to Reach Various Targeted Composite Emissions Levels

To achieve ULN composite emissions levels, the cold-start FTP NO_x emissions must be very low (targeted less than 2.7 g accumulated NO_x for this engine over the cold-start portion of the HD FTP), on the order of current technology hot-start emissions. The Hot-Start control strategy must achieve very high catalyst efficiency for the whole cycle, (emitting less than about 0.2 g accumulated over the hot-start portion of the HD-FTP). The calibrations and elements employed in an ULN strategy can be grouped into two basic approaches:

1. Reduce time to catalyst light-off

- Modified catalyst configurations
- Supplemental heat and/or distributed heat
- Engine calibration for increased exhaust temperature
- Potential consideration to Phase II GHG approaches

2. Reduce engine-out NO_x until catalyst NO_x control is achieved

- More aggressive engine-out NO_x reduction at low coolant temperature
- NO_x control catalyst systems

To increase throughput for streamlined catalyst system evaluation, engine and aftertreatment development were conducted in parallel using a developmental engine test cell and HGTR, respectively. This enabled more catalyst configurations and systems to be evaluated while the engine calibration was developed. However, since it was known that the ULN engine calibration would be very different than the baseline engine control; producing more heat and less NO_x during the Aftertreatment System (ATS) warm-up period, an initial ULN engine calibration was developed prior to screening and the same cold-calibration (CC1) was used throughout screening.

Figure 8 and Figure 9 show the baseline and the cold-start engine strategies developed to assist with cold-start NO_x control and accelerated catalyst light-off. The calibration approach utilized to increase exhaust temperature included increased idle speed, intake throttling, EGR, and late in-cylinder post injection. NO_x control also leveraged EGR and post injection fueling. No modifications were made to the engine calibration during hot-start. The engine calibration is described in separate publications [1] [2].

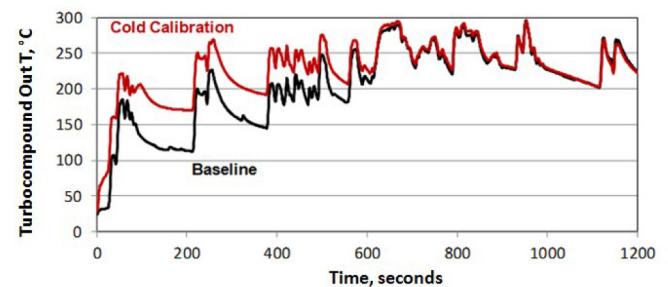


Figure 8. Baseline and ULN Engine Calibration for Increased Exhaust Energy

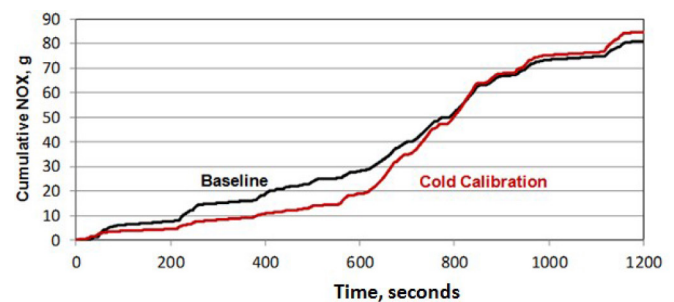


Figure 9. Baseline and ULN Engine Calibration for NO_x Control During Catalyst Warm Up Period

Figure 10 shows the tailpipe NO_x for the production catalyst system operating over the baseline and ULN CC1 for the cold-start FTP cycle. This figure shows that cold-start FTP tailpipe NO_x was reduced by approximately 50% for CC1. This was predominantly attributed to the nearly 50% reduction in engine-out NO_x during the warm up period of the ATS. Figure 11 provides a comparison of

dosing between the two tests. During screening, a simple temperature activated real-time ammonia (NH_3) to NO_x ratio (ANR) with mid-bed NH_3 compensation was employed[1]. This strategy provided more consistency in dosing for more applicable comparisons. The impact of the elevated exhaust temperature and flow (increased energy calibration) of CC1 can be seen as a slight advantage in earlier DEF dosing compared to the baseline (exceeding dosing temperatures about 75 seconds sooner). This earlier dosing also provided a reduction in tailpipe NO_x .

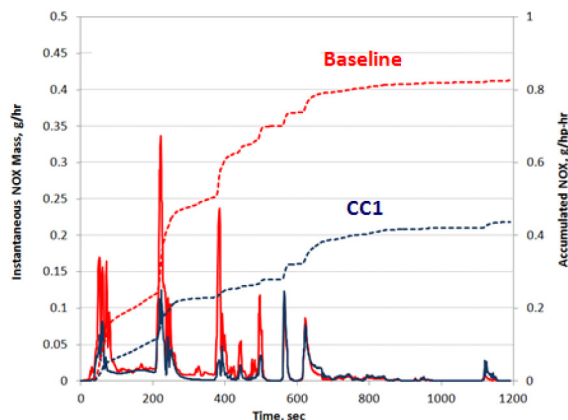


Figure 10. Tailpipe NO_x Emission Comparison between the Baseline Engine Calibration and CC1 for the Stock Emissions System

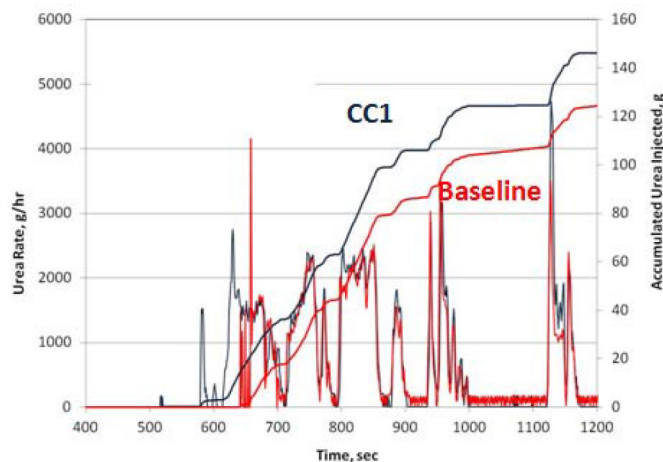


Figure 11. Measured Instantaneous and Accumulated DEF During the Baseline and CC1 Cold-Start FTP Cycles

AFTERTREATMENT SYSTEMS AND OPTIONS

Many different aftertreatment catalysts and low emission enabling components were provided for this program. The preliminary goal of this part of the study was to evaluate the NO_x reduction capability of various combinations of aftertreatment components and the potential impact of alternative dosing and supplemental energy options to assess the feasibility of achieving ultra-low NO_x emissions levels using production and near-production technologies. Some of the components and options that were evaluated during the study included:

Low Thermal Loss/Mass Components

- Air gap exhaust manifolds
- Air gap transfer pipes
- Catalyst packaging
- Catalyst positioning
- Thin wall substrates

Advanced Technology Components

- SCR on Filter (SCRF)
- Passive NO_x Adsorber (PNA)
- Light-Off SCR (LO-SCR)
- Advanced technology formulations

Traditional Technology Components

- Diesel Oxidation Catalyst (DOC)
- Diesel Particulate Filter (DPF)
- Selective Catalytic Reduction(SCR)

Dosing Options

- Compact mixer/doser
- Full flow heated dosing
- Partial flow heated dosing
- Gaseous NH_3 Injection

Supplemental Energy Options

- Electrical Heated Catalyst (EHC) (2-6 kW)
- Diesel fueled mini-burner (5-20 kW)
- EHC assisted catalytic oxidation

The catalysts and components were provided by Manufacturers of Emission Control Association (MECA) member companies. Each component was canned and flanged to allow modular construction enabling various configurations and options to be evaluated. The systems were classified into two basic subsets; advanced technology systems or traditional technology systems. The traditional technology systems consisted of a DOC-DPF-SCR and the performance was modified using alternate dosing options or the addition of supplemental heat. The advanced technology systems contained catalyst components that varied from the traditional technologies, such as PNA and SCRF. There were over 500 different possible combinations of catalysts, options, and cold and hot cycles from the components that were received. The screening exercise was limited to a 20-week period of time, so the number of approaches selected for screening was 33. These selections were designed to encompass a wide array of combinations to enable a broad picture of technology trends to achieve ULN. Figure 12 depicts the advanced technology configurations with options that could have been tested.