

Achieving Ultra Low NO_x Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine and an Advanced Technology Emissions System - NO_x Management Strategies

Christopher Sharp
 Southwest Research Institute

Cynthia C. Webb
 Low Emission Technology Solutions

Gary Neely, Jayant V. Sarlashkar, and Sankar B. Rengarajan
 Southwest Research Institute

Seungju Yoon
 ARB

Cary Henry and Bryan Zavala
 Southwest Research Institute

ABSTRACT

Recent 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, CARB has projected 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 and Ozone will not be achieved without further reduction in NO_x emissions. The California Air Resources Board (ARB) funded a research program to explore the feasibility of achieving 0.02 g/bhp-hr NO_x emissions. This paper details engine and aftertreatment NO_x management requirements and model based control considerations for achieving Ultra-Low NO_x (ULN) levels with a heavy-duty diesel engine. Data are presented for several Advanced Technology aftertreatment solutions and the integration of these solutions with the engine calibration. Further development is necessary for optimizing vocational test cycle emissions, but the results presented here demonstrate a potential pathway to achieving ultra-low NO_x emissions on future heavy duty vehicles.

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INTRODUCTION

Recently introduced 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, it is projected 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 and ozone will not be achieved in California without further significant reductions in NO_x emissions from the heavy duty vehicle fleet [1]. 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 is funding a research program to explore and investigate the feasibility of significantly reducing NO_x emissions below today's standard.

CARB commissioned a study to investigate the feasibility of achieving NO_x emissions significantly lower than the current engine standard. The study involved evaluating improved engine emission control calibration, enhanced aftertreatment technology choices and configurations, improved and more efficient catalyst, 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) is 0.02 g/bhp-hr. This paper details the selected diesel engine and NO_x mass emission control strategies.

TEST ENGINE

The test engine used for the diesel engine demonstration 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 compliance with future greenhouse gas standards. A picture of the exhaust side of the engine is provided in [Figure 1](#).

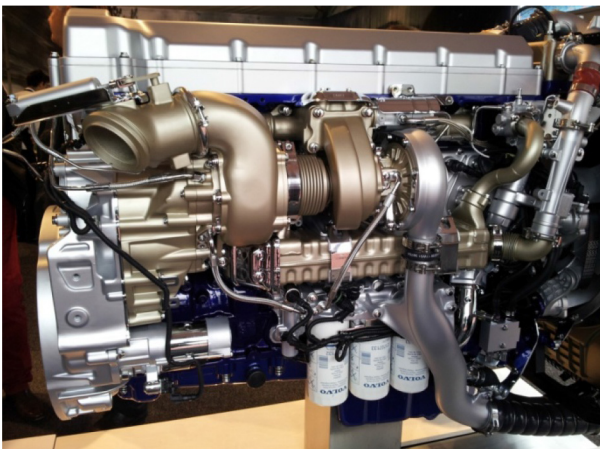


Figure 1. Volvo MD13TC Diesel Engine

Although the baseline engine and aftertreatment system was calibrated for Euro VI emission standards, emission testing conducted with the baseline aftertreatment system found it was also US 2010 emissions compliant as shown in the next section. The engine and aftertreatment specifications are listed in [Table 1](#).

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 Tractor

The engine was equipped with an open ECU which was interfaced with commercially available ECU calibration development software. This interface enabled manual control of fueling and air-handling actuators through an override function as well as access to various calibration tables. In addition, the engine was provided with provisions to allow installation of a cylinder pressure transducer in one cylinder. Therefore, a Kistler 6045A pressure sensor was installed and crank-angle-based cylinder pressure was monitored during both steady-state and transient engine testing. Unless otherwise stated, engine emissions testing was performed in accordance with 40 CFR Part 1065 procedures in a 1065 certified engine test cell, with dilute tailpipe engine emissions sampled via a CVS dilution tunnel and Horiba MEXA-7200D, and raw engine-out emissions sampled via a Horiba MEXA-7100DEGR analyzer. In addition, certification grade ULSD fuel was used for all testing.

NO_x EMISSION GOALS: REDUCTION AND EFFICIENCY

Ultra-Low NO_x (ULN) is defined as a composite FTP NO_x mass emission rate below 0.02 g/bhp-hr. This represents a 90% reduction from the current 2010 heavy-duty composite NO_x emission limit of 0.20 g/bhp-hr. The composite emission is a weighted sum comprised of 1/7 from the cold-start FTP and 6/7 from the hot-start. Under the current emission regulation, it is possible to achieve the composite emission target of 0.02 g/bhp-hr by primarily focusing on high space velocity NO_x control and good catalytic control of NO_x from the beginning of the hot start cycle. A typical 2010 and later emission system does not achieve substantial NO_x conversion rate until approximately one-third of the way (400 s) into the cold-start FTP, and does not reach high rates of reduction (i.e. better than 95%) until the half-way (600 s) point of the cycle.

The baseline engine provides a very good example of current technology control using a typical aftertreatment emissions control configuration consisting of a diesel oxidation catalyst-diesel particulate filter-and a selective catalyst reduction catalyst (DOC-DPF-SCR). The baseline engine NO_x emissions and catalyst conversion efficiencies over the FTP cycle are shown in [Table 2](#).

Table 2. Baseline NO_x Engine Emissions and Conversion Efficiencies

Test Type	BSNO _x [g/bhp-hr]		NO _x Conv. Eff.[%]
	Engine-out	Tailpipe	
Cold	2.8	0.715	75 %
Hot	3.0	0.047	98 %
Composite	3.0	0.140	95 %

Under an ULN emissions control strategy, the cold-start emissions must be aggressively reduced, and the emission control system must provide superior hot start and high space velocity NO_x control. [Figures 2](#) and [3](#) show examples of measured tailpipe NO_x emissions from the baseline engine compared to those of an ULN system.

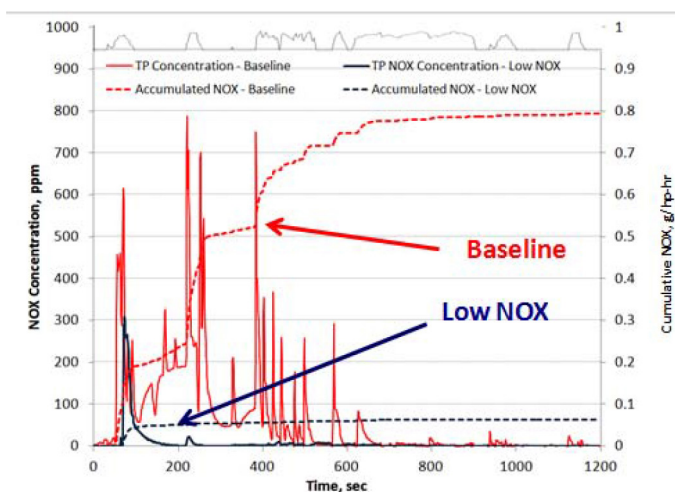


Figure 2. Baseline Cold-Start FTP Tailpipe NO_x Emissions Compared to an Ultra-Low NO_x System

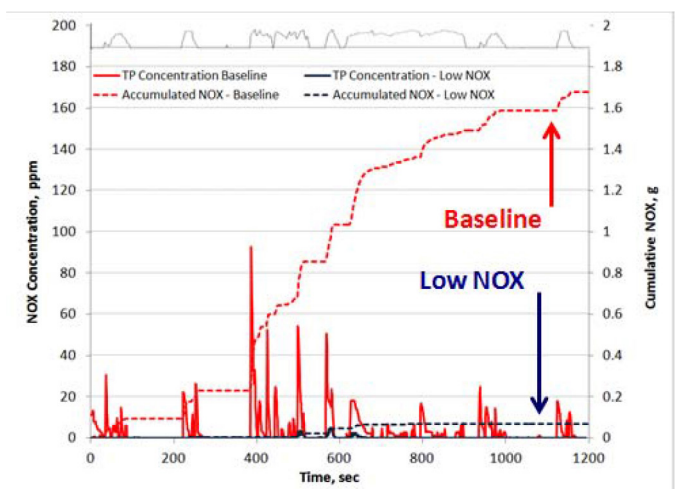


Figure 3. Baseline Hot-Start FTP Tailpipe NO_x Emissions Compared to an Ultra-Low NO_x System

An example of the cycle specific emissions that are needed for an ULN level are shown in Table 3.

Table 3. Example of Cycle Specific NO_x Emissions in an Ultra-low NO_x Application

Test Type	BSNO _x [g/bhp-hr]		NO _x Conv. Eff. [%]
	Engine-out	Tailpipe	
Program Targets			
FTP Composite	n/a	0.02	n/a
Example ULN Emissions Requirements			
Cold	2.8	0.06	98 %
Hot	3.0	0.01	99.7 %
Composite	3.0	0.017	99.4 %

As with the 2010 standards, the primary de-NO_x technology that will be utilized for an ULN diesel application will be urea-SCR. However, the ULN target will require significant improvements in SCR NO_x reduction performance, and other NO_x reduction technologies may be needed as well to reach a final level of 0.02 g/bhp-hr.

As can be seen from the values in the Table 3, there are two key targets an emission control system must reach to realize ULN levels. The first is to achieve the maximum possible conversion on the cold-start FTP as early as possible. This will involve a combination of strategies to heat up the system and reduce SCR inlet NO_x until the aftertreatment system has exceeded light-off temperature. The second target is to achieve very high sustained NO_x reduction rates, in excess of 99.5% over the SCR, in a stable fashion after the system has exceeded light-off temperature. Both cold-start and hot-start FTP cycles will likely require thermal management to heat the catalyst system up to levels required to obtain high conversion efficiency quickly.

The cold-start elements of an ULN application include two basic components:

1. **Reduced time to exceed catalyst light-off temperature**
 - Modified catalyst configurations
 - Supplemental heat and/or distributed heat
 - Engine calibration for increased exhaust temperature/enthalpy
2. **Reduced SCR system inlet NO_x until light-off achieved**
 - Engine-out NO_x reduction at low aftertreatment temperatures
 - NO_x storage catalyst systems

It should be noted that a similar challenge is present for light-duty diesel vehicles when attempting to reach SULEV targets on the light-duty FTP. Previous efforts have detailed strategies involving a combination of low temperature NO_x storage transitioning to higher temperature SCR-based control [2].

This cold-start approach must also be paired with high precision control during warmed-up operation. The catalysts must have sufficient capacity to convert all of the NO_x emitted by the engine when it is operating at peak fuel efficiency. Given that urea-SCR is the primary NO_x mitigation strategy when the engine system is at operating temperature, the dosing control approach must be able to accurately maintain ammonia coverage on the SCR catalyst(s) to sustain very high NO_x conversion rates. As a result of this demand, an advanced, model-based control approach is needed, and that control must be augmented by real-time feedback to maintain system performance. The SCR dosing controller approach is described later in this paper.

FINAL AFTERTREATMENT SYSTEM CONFIGURATION

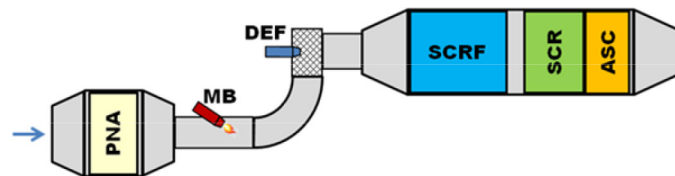


Figure 4. Final Low NO_x Aftertreatment System

A diagram of the final ULN aftertreatment system that was utilized for the Volvo MD13TC engine is shown in Figure 4. As discussed in the previous paper [3], a wide variety of different arrangements and components were examined before the final system configuration was

determined. This configuration was selected, in large part, due to the low exhaust temperatures that were produced with the turbocompound waste heat recovery system that was on the MD13TC engine.

The final configuration has several primary components:

- A multi-bed SCR system consisting of an SCR-on-Filter (SCRF) followed by a flow-thru SCR catalyst
- A passive NO_x Adsorber (PNA) for low temperature NO_x storage. The PNA also serves the functions of a traditional DOC in this system, including generation of the exotherm needed for regeneration of the filter (via supplemental fuel injection using in the exhaust).
- Supplemental Heat for additional thermal management in the form of a Mini-burner (MB). It should be noted that the mini-burner is not sized for regeneration of the filter, and is intended only for thermal management events such as cold start and low temperature operation.
- A dual-layer Ammonia Slip Catalyst (ASC).

The thermal management function via the mini-burner is described in the companion paper on that topic [4]. The function of the NO_x control components is discussed below. Unless otherwise noted, all catalysts described in this paper were hydrothermally aged for 100 hours at a temperature of 650°C.

NO_x REDUCTION STRATEGIES FOR COLD-START PRIOR TO SCR LIGHT-OFF

The cold-start example NO_x traces for both the baseline and ULN cases shown in Figure 2 illustrate the challenge in achieving significant catalytic NO_x reduction quickly with cold SCR systems. For the baseline system, highly efficient catalytic NO_x control wasn't achieved until 600 seconds into the cycle, while 200 seconds was needed for the ULN example. As stated in the previous section, to achieve ULN requires both reduced SCR light-off time and early NO_x emission management prior to SCR light-off. Reducing the NO_x flux into the SCR may be achieved by a combination of more aggressive engine-out NO_x reduction measures and the use an upstream NO_x storage device, such as a PNA. Both of these strategies were investigated in this study.

Engine Calibration for Cold-Start NO_x Management

The basic approach to engine calibration was to reduce engine-out NO_x during the portion of the FTP wherein the SCR catalyst system was below light-off temperature for high efficiency. The primary SCR technology used for this program was a copper zeolite-based SCR catalyst. Generally it was desirable to exceed 200 °C for maximum conversion; however, it was not necessary to exceed this temperature over the entire catalyst bed

The main factor available on the diesel engine for engine-out NO_x reduction was EGR. Reviewing the characteristics of the baseline calibration for a cold-start FTP, it was discovered that high-pressure EGR was not activated until the coolant temperature exceeded approximately 50 °C, which corresponded to approximately 400

seconds into the cycle. This strategy was acceptable for the higher NO_x limits of the Euro VI and US 2010 emission standards, but not for the ULN target of this program. Therefore, ECU calibration parameters were modified to activate the production cooled high-pressure EGR system during the initial idle period prior to the first acceleration at 24 seconds. In addition, revised calibration maps for the EGR and intake throttle valves were developed from steady-state testing at several engine speed and load conditions which were representative of engine operation during the first 500 seconds of the FTP cycle. The resulting NO_x reduction is shown in Figure 5 where engine-out NO_x mass flow rates and cumulative mass are shown for the baseline and ULN engine calibrations. A scaled and shifted engine speed trace is included in the chart for cycle reference. Only the first 500 seconds of the FTP cycle are shown since that was the focus area of the engine calibration effort. This calibration was used only until the SCR catalysts reached sufficient temperature for high efficiency NO_x conversion, at which point the engine calibration could revert to the more fuel efficient and higher engine-out NO_x baseline calibration. As shown, the revised engine calibration reduced the cumulative engine-out NO_x by nearly 50% compared to the baseline calibration during these first 500 s.

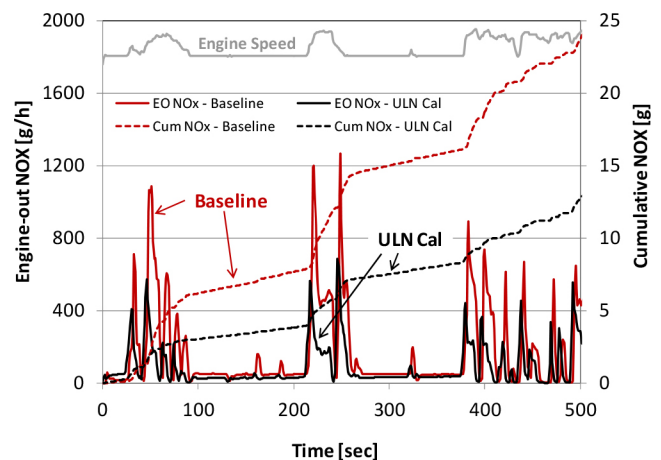


Figure 5. Engine-out NO_x Comparison between Baseline and ULN Calibration for first 500 seconds of Cold-Start FTP

It should be noted that utilizing cooled high-pressure EGR with room temperature coolant may be cause for concern in terms of long-term EGR cooler durability due to the possibility of condensation of the exhaust gas occurring in the cooler [5]. An EGR cooler by-pass system would alleviate this concern and examples of this hardware can be seen on several production light-duty diesel engines. However, an EGR cooler by-pass was not readily available for this engine and as such was not used for this testing. During the course of this project, no EGR cooler durability problems were encountered. It should be noted that the use of an EGR cooler bypass would also result in somewhat higher engine-out temperatures, which would also assist with catalyst light-off.

NO_x Storage Catalyst / Passive NO_x Adsorber (PNA)

In addition to the revised engine calibration, another key strategy for reducing the amount of NO_x flux into the SCR system prior to light-off was to employ a PNA. These devices store NO_x at low temperature, and thermally release the stored NO_x at higher