

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

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ABSTRACT

The most recent 2010 emissions standards for heavy-duty engines have established a tailpipe limit of oxides of nitrogen (NO_x) emissions of 0.20 g/bhp-hr. However, it is 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 (CARB) funded a research program to explore the feasibility of achieving 0.02 g/bhp-hr NO_x emissions. This paper details the thermal management strategies employed by the engine and supplemental exhaust heat addition device as was needed to achieve Ultra-Low NO_x levels on a heavy-duty diesel engine with an advanced technology aftertreatment solution. 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 tailpipe 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](#).

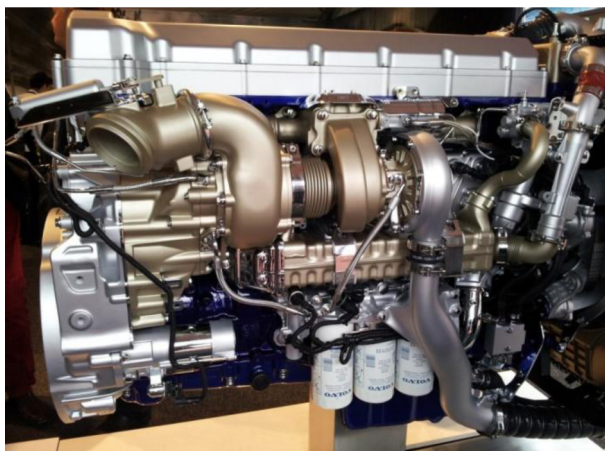


Figure 1. Volvo MD13TC Diesel Engine

Although the baseline engine and aftertreatment system were 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.

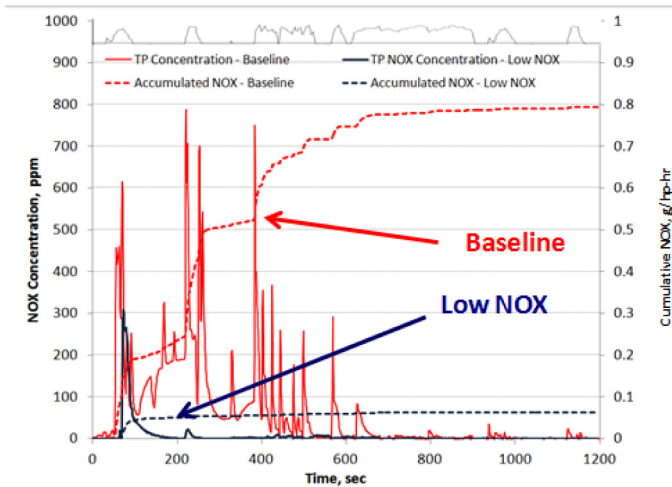


Figure 2. Baseline Cold-Start FTP Tailpipe NO_x Emissions Compared to an Ultra-Low NO_x System

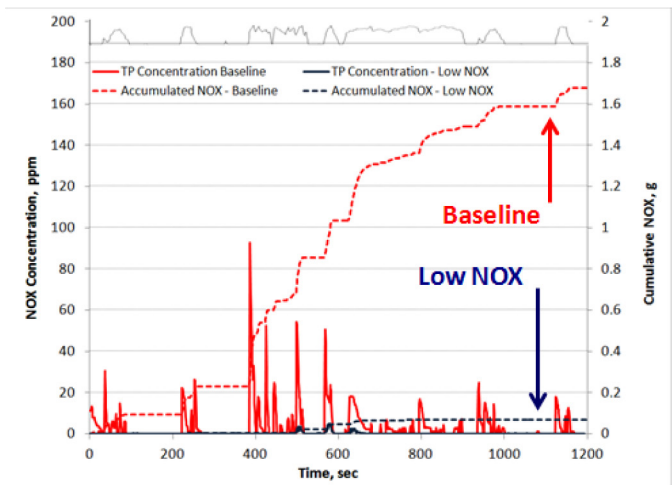


Figure 3. Baseline Hot-Start FTP Tailpipe NO_x Emissions Compared to an Ultra-Low NO_x System

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	
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
 - Improved NO_x conversion at lower temperature
 - Reduced temperature for introduction of reductant to SCR
 - Improved thermal management/reduced heat losses
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

FINAL AFTERTREATMENT SYSTEM CONFIGURATION

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.

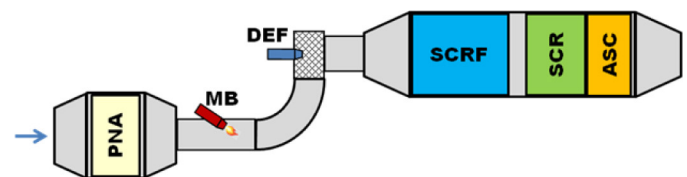


Figure 4. Final Low NO_x Aftertreatment System

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 limited

only for thermal management events such as cold start and low temperature operation.

- A dual-layer Ammonia Slip Catalyst (ASC).

SCR LIGHT-OFF TIME REDUCTION STRATEGIES FOR COLD-START AND LOW TEMPERATURE OPERATION

The cold-start example NO_x traces for both the baseline and ULN cases shown in Figure 2 illustrate the challenge in obtaining significant catalytic NO_x reduction with cold SCR systems. In the absence of any cold-start strategy, the temperature in front of the first SCR catalyst did not exceed 200°C for well over 500 seconds into the cold-start cycle (baseline). During this period of time, the engine emitted 19 grams of NO_x, which exceeds the target 2.8 g/bhp-hr for a cold-start cycle from an ULN application. For the ULN example, this time was significantly reduced to less than 200 seconds. As stated in the previous section, to achieve ULN requires both reduced SCR light-off time and NO_x emission management prior to SCR light-off. Reducing SCR light-off time for a cold-start is achieved by increasing the exhaust energy flow rate into the SCR.

There are many approaches that can be leveraged to increase the exhaust gas temperature at the inlet to the catalyst. However, each approach costs energy and has associated efficiency losses. The temperature management strategies are loosely classified into engine-based and emissions system-based approaches.

When high levels of supplemental energy are required for exhaust gas temperature management, transferring the supplemental energy efficiently to the catalyst system becomes the main priority in reducing the fuel economy penalty.

For example, if the desired input temperature for acceptable NO_x conversion is 200°C, then the required energy input is governed by the First Law of Thermodynamics, where the energy required is directly related to the total exhaust flow and the difference between the desired temperature and the actual input temperature. Figure 5 illustrates the theoretical amount of energy required to increase the SCR catalyst inlet temperature to the desired temperature of 200°C. The real energy required also includes the efficiency of generation of heat energy from fuel energy and the transfer of that energy to the catalyst.

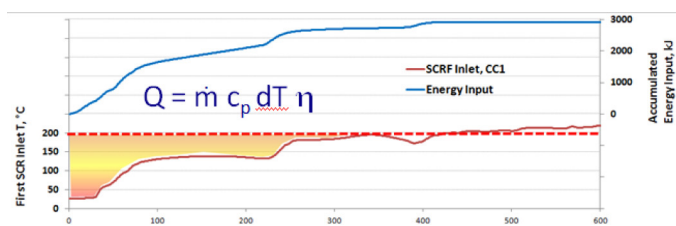


Figure 5. Illustration of the required energy to raise a given configuration to the desired temperature

The first Law can be utilized to categorize the thermal management options such as mass flow modifiers, heat generators, efficiency improvers, low temperature enablers, and energy requirement reducers. Figure 6 shows some of the engine and ATS management strategies and devices grouped by category.

Mass Modifiers	Heat Addition	Efficiency	Low T Enablers	Energy Reduction
•Intake throttle •RPM •EGR	•Burners •EHC •Plnj •7th → DOC	•Air Gap manifolds •TC Bypass •Energy loss path to SCR	•Gaseous NH3 •Heated dosing	•Low thermal mass substrates •Positioning •Distributed Heat •Distributed NH3 injection
NO _x Control	•EGR		•PNA	

Figure 6. Exhaust energy management options grouped by First Law category

Increased exhaust energy can be obtained from the engine by manipulating the fueling parameters and from in-exhaust heat addition devices such as electric heaters or burners. Both of these approaches were utilized in this ULN study.

TEST RESULTS - ENGINE CALIBRATION FOR INCREASED THERMAL ENERGY

One approach to exhaust gas temperature management is to use various engine means to generate the supplemental heat needed for acceptable catalyst efficiency. A major consideration to engine-based approaches is that the supplemental heat generated by the engine has many potential heat loss pathways which can greatly reduce the efficiency of the transfer of that heat to the catalyst. A major source of the heat loss occurs in the engine during combustion of the supplemental fuel, and after the exhaust leaves the engine, heat loss can occur in the exhaust manifolds, the turbocharger, turbo-compounder, the downpipe, and any catalysts located upstream of the first SCR catalyst.

This task began by documenting the baseline engine operation at several steady-state engine conditions that were representative of engine operation during the first 500 seconds of the FTP cycle. This testing was performed at low coolant temperature by using a blocked open thermostat and lab heat exchangers to maintain engine coolant temperature around 30 °C. Three modes of baseline operation were available. The first mode corresponds to what is used for around the first 400 seconds of the cold start FTP and is referred to subsequently as the “Normal Cold Map.” No EGR is used in this mode to avoid potential condensation of the exhaust gas in the EGR cooler due to the low coolant temperature. The second baseline engine mode is an elevated exhaust temperature calibration and is used after the normal cold map during baseline cold-start FTP operation. For the purposes of this study, this mode is referred to as high exhaust temperature operation and uses the label “Hi Exh Temp Map” in the results. The baseline operation in this mode uses EGR since the coolant temperature is high enough to avoid condensation. However, engine tests were conducted both with and without EGR to examine the effect of EGR on NO_x at low engine coolant temperature. The third mode of baseline operation corresponds to what is used after SCR light-off is achieved and is characterized by higher engine-out NO_x and more fuel efficient operation.

Enabled by the common rail fuel system on the test engine, the injection pattern used by the baseline calibration in the high exhaust temperature mode for all of the test points consisted of three injections: 1) pilot, 2) main, and 3) close post. Adding an additional close post injection with appropriate spacing so that combustion is maintained has been shown to be effective on a light-duty diesel engine to increase exhaust gas temperature for cold-start [2-3]. Therefore, the effect of adding a second post injection to the high exhaust temperature calibration was also investigated at several test points. The cylinder pressure measurement was essential for verifying combustion quality for the post injections. The two injection patterns are illustrated in Figure 7. It should be noted that when a second post injection was added, the engine torque increased so the main injection quantity was reduced to maintain the target engine load.

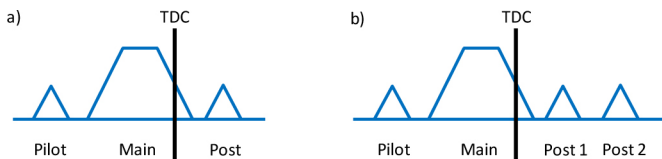


Figure 7. Injection Patterns used during Calibration Investigations: a) Single Post, b) Double Post

Based on the results obtained from the investigations described above, the production engine fueling and air-handling calibration tables used during high exhaust temperature operation were modified to create a new cold calibration referred to as “Cold Cal 1.” The resulting exhaust temperature, NO_x , and fuel consumption results from the modified calibration as well as the other modes of operation are presented in the next sections for three engine conditions: 1000 RPM, 0Nm, 1000 RPM, 500 Nm, and 1800 RPM, 500 Nm. The different operating conditions are labeled in the plots as:

1. “Normal Cold Map” - Baseline operation mode for first 300 seconds of cold-start FTP.
2. “Hi Exh Temp Map” - Baseline calibration for elevated exhaust temperature operation and used after normal cold map. Baseline operation is with EGR, however these tests were conducted without EGR so the impact of EGR on NO_x could be assessed.
3. “Hi Exh Temp Map+EGR” - Same as 2, but with baseline EGR settings plus additional levels of EGR.
4. “Adding 2nd Post Inj” - Same as 3, but a second post injection was added and the quantity was varied to assess the impact on exhaust temperature and fuel consumption.
5. “Cold Cal 1” - Resulting engine calibration developed for cold-start FTP which utilizes double post injections and increased EGR.

Elevated Idle - 1000 RPM, 0 Nm

In addition to the initial 24-second idle period at the beginning of the heavy-duty FTP, there are two prolonged periods of idle of nearly 2 minutes each within the selected 525-second window (see the FTP cycle on the top portion of Figure 2). Therefore, it was of interest to investigate the potential exhaust temperature and energy flow improvements available by simply increasing the engine idle speed from the baseline value of 550 RPM to 1000 RPM. Engine data was recorded at the baseline idle (referred to by “BI”) and elevated idle

speed (referred to as “EI”) while in the normal cold map mode. At the elevated idle speed, additional data was acquired after changing to the elevated exhaust temperature mode with EGR and then after adding a second post injection (which corresponds to the final cold cal 1 map). All testing was conducted with low coolant temperatures (between 25 and 30 °C). The resulting steady-state exhaust flow rates, turbo-compounder out temperature, and exhaust energy increase over the baseline case are shown in Figure 8.

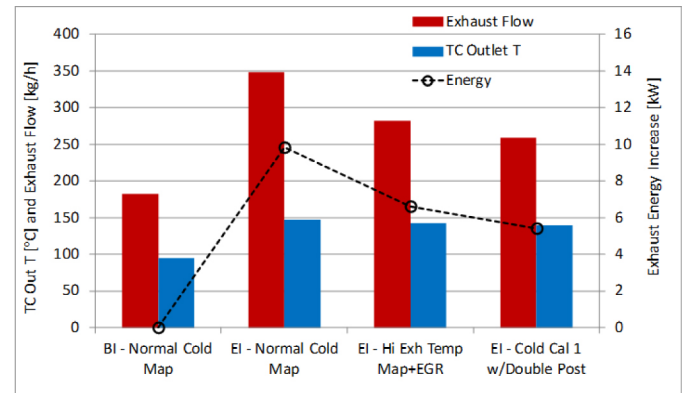


Figure 8. Temperature, Exhaust Flow and Energy Results at Idle

A simple increase of the idle speed under base normal cold map operation resulted in a significant increase in the exhaust energy (10 kW over the baseline idle condition) due to the combined effect of increased exhaust gas flow rate and temperature. However, changing to the baseline high exhaust temperature mode or Cold Cal 1 operation did not result in further increases in exhaust gas temperature and resulted in a reduction in exhaust flow rate and corresponding energy flow. However, compared to the base idle case, the Cold Cal 1 resulted in an energy increase of nearly 6 kW.

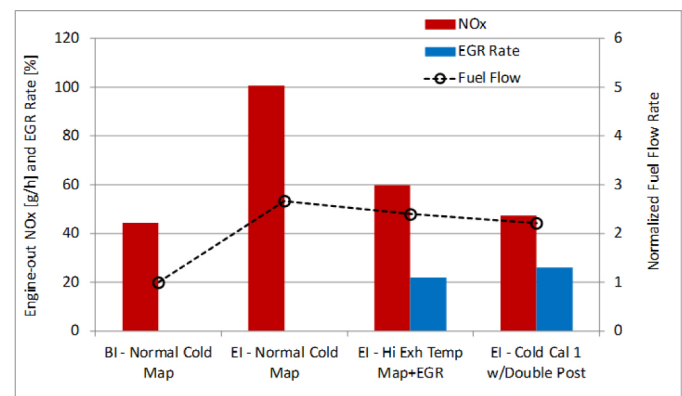


Figure 9. Engine-out NO_x , EGR Rate and Fuel Flow Rate Results at Idle

The corresponding engine-out NO_x , EGR rate, and fuel flow results are presented in Figure 9. The exhaust flow reduction for the high exhaust temperature mode was due to the addition of EGR and the final Cold Cal 1 map had slightly increased EGR compared to that of the baseline high exhaust temperature mode. A higher level of EGR was necessary to mitigate the increase in NO_x mass flow rate resulting from the elevated idle speed operation. Final Cold Cal 1 tuning resulted in a similar NO_x mass flow rate as the baseline idle