

Diesel Cold-Start Emission Control Research for 2015-2025 LEV III Emissions

Gary D. Neely, Jayant V. Sarlashkar and Darius Mehta
Southwest Research Institute

ABSTRACT

The diesel engine can be an effective solution to meet future greenhouse gas and fuel economy standards, especially for larger segment vehicles. However, a key challenge facing the diesel is the upcoming LEV III emissions standard which will require significant reductions of hydrocarbon (HC) and oxides of nitrogen (NO_x) from current levels. The challenge stems from the fact that diesel exhaust temperatures are much lower than gasoline engines so the time required to achieve effective emissions control with current aftertreatment devices is considerably longer.

The objective of this study was to determine the potential of a novel diesel cold-start emissions control strategy for achieving LEV III emissions. The strategy combines several technologies to reduce HC and NO_x emissions before the start of the second hill of the FTP75. The technologies include: 1) intake throttling, 2) high temperature glow plugs with model-based temperature control, 3) multiple fuel injections, 4) high EGR idle operation after the first hill, 5) improved diesel particulate filter (DPF) catalyst formulation, and 6) a small close-coupled LNT with improved an formulation. For the overall emissions control strategy, an underfloor SCR would provide the main NO_x control starting in the second hill.

This paper describes the benefits of the engine tuning technologies (1-4) and evaluates the strategy during transient engine dynamometer investigations that simulate the first 162 seconds of the FTP75. Using the combined engine tuning technologies, HC emission reduction of over 80% relative to the baseline calibration was achieved at the tailpipe (or more correctly, at the entrance to the underfloor NO_x control device) with the baseline aftertreatment system. This level of HC reduction is in the range required for LEV III compliance; however, part of the reduction was obtained by moving to higher NO_x on the HC versus NO_x trade-off curve. Additional tests with a closed-coupled LNT and DPF with improved catalyst formulations are planned to investigate if the right balance of engine-out HC and NO_x can be obtained with this strategy for LEV III.

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INTRODUCTION

The United States is now placing strong emphasis on reducing greenhouse gas emissions from mobile sources as outlined in the finalized 2017-2025 U.S. EPA greenhouse gas and NHTSA fuel economy standards [1]. The diesel engine can be an effective solution for automakers to meet these standards, especially for larger segment vehicles where highly fuel-efficient hybrid vehicles may be cost prohibitive. However, a key challenge facing the diesel is the upcoming LEV III emissions standard which phase-in from 2015 to 2025. The LEV III standard stipulates a fleet average non-methane organic gas (NMOG) + NO_x level of 0.03 g/mi in 2025, which is equivalent to the current SULEV or EPA Tier 2 Bin 2 and represents an 81% reduction from the current LEV or Tier 2 Bin 5 level.

The emissions challenge stems from the fact that the majority of tailpipe emissions from diesel passenger cars occur during the first 250 seconds of the FTP75 cycle when the aftertreatment catalysts are cold. To illustrate this point, FTP75-weighted cumulative tailpipe HC + NO_x emissions from a production Bin 5 diesel car are shown in [Figure 1](#). Total HC emissions were used to compute the cumulative emissions shown in the figure due to the difficulty in obtaining continuous NMOG emissions; however, the difference between total HC and NMOG emissions is generally small for diesel engines. The figure shows that the cumulative NO_x + HC emissions exceed the SULEV limit after 180 seconds. The total FTP75 NO_x + NMOG emissions were included in the figure to demonstrate the excellent emissions control obtained after all aftertreatment systems

have reached normal operating temperatures. From this result, it is clear that meeting the upcoming LEV III standard will require significant cold-phase emission reductions.

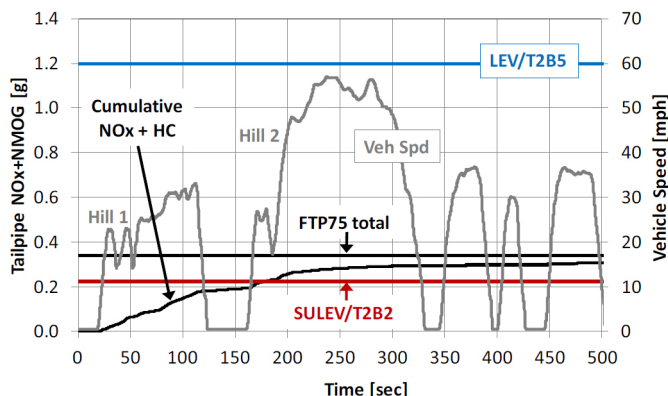


Figure 1. Cumulative tailpipe $\text{NO}_x + \text{HC}$ emissions during Bag 1 of FTP75 for a Bin 5 production diesel car

Previous SULEV Research

Several innovative approaches have been investigated to address the cold-phase emissions for potential SULEV compliance. Nissan demonstrated SULEV emissions using a HC- NO_x trap which combined a HC trap layer with an improved LNT catalyst layer in a single device [2]. The HC trap was effective in trapping the large molecule HCs formed during the cold-phase and the improved LNT catalyst increased NO_x conversion efficiencies at lower inlet temperatures. The aftertreatment device layout was a close-coupled diesel oxidation catalyst (DOC), HC- NO_x trap and an underfloor catalyzed DPF. This arrangement has benefits and challenges. For the FTP75, having the HC-LNT just after the DOC reduces the heat up time required for NO_x control compared to an underfloor location. However, during the US06 test cycle, it is possible that the exhaust temperatures at this location are too high to maintain high LNT NO_x conversion efficiency. In general, LNT NO_x conversion efficiency decreases above 400°C [3]. Another issue associated with this arrangement is the high temperature exposure of the LNT and increased fuel consumption during DPF regenerations.

Cummins et al. is addressing the cold-phase NO_x emissions on a Bin 2 light-duty truck development program by using a combination of passive NO_x storage, improved low temperature selective catalytic reduction (SCR) performance, and gaseous ammonia (NH_3) injection [4, 5]. In principle, a passive NO_x adsorber (PNA) stores NO_x at low temperature until the SCR is able to provide effective NO_x control. After a critical temperature is reached, the stored NO_x begins to release from the PNA and is converted by the SCR. Since the NO_x release from the PNA starts at a relatively low temperature of 150°C, significant improvement

in the low temperature performance of the SCR was required and achieved with SCR catalyst formulation improvement and direct NH_3 gas delivery. Even with the low temperature performance improvement, the SCR must be located just after the PNA so it is hot enough to convert the released NO_x . To avoid the increased fuel consumption associated with the regeneration of an underfloor DPF, the SCR is implemented in a SCR-on-filter which combines SCR and DPF functionality in a single device. A second underfloor SCR is also needed to meet the NO_x target. One challenge of this approach is that it requires the use of gaseous ammonia, which is not currently available in the market.

A new SULEV emissions control strategy was also presented by Honda et al. that used special engine tuning to achieve rapid DOC light-off during hill 1 of the FTP75 and various NO_x control strategies including high EGR, urea-SCR and stoichiometric operation for NO_x reduction over a DOC [6]. The use of all three NO_x control strategies early in hill 2 was found to be more effective in terms of NO_x reduction than a fast SCR heat up strategy. The aftertreatment device layout consisted of a more common closed-coupled DOC, DPF and an underfloor SCR. Hills 1 and 2 correspond to the first and second non-zero vehicle speed portions of the FTP75 cycle, which are labeled in Figure 1.

Current SULEV Approach

The focus of the current research was on evaluating an emissions control strategy during the cold-phase portion of the FTP75 test cycle (first 162 seconds) as an enabler for meeting LEV III emissions. This portion of the FTP75 test cycle includes hill 1 and the idle period prior to the start of hill 2. This strategy leverages several technologies to control HC and NO_x emissions. The technologies include:

- Intake throttling to reduce in-cylinder charge mass and increase exhaust gas temperature.
- High temperature glow plugs with model-based temperature control to maintain good ignition quality at low compression pressure.
- Multiple pilot injections to achieve an ignitable mixture near the glow plug and after Top-Dead-Center (TDC) injections to increase exhaust gas temperature without increasing HC emissions.
- High EGR idle operation after the first hill to minimize engine-out NO_x and to maintain catalyst temperatures by providing HC and CO for exothermic reactions while limiting exhaust flow rates.
- Improved DPF catalyst formulation for additional HC conversion.
- Replacement of the baseline close-coupled DOC with a LNT with metal substrate for fast heat up and with an

advanced low temperature formulation to obtain NO_x storage and HC conversion early in hill 1.

EXPERIMENTAL SETUP

The test engine used for this study was a 2-liter class diesel with low compression ratio, single-stage variable nozzle turbocharger (VNT) and a dual-loop EGR system. The vehicle for this engine has an inertia weight of approximately 4000 pounds. The engine, vehicle and test fuel specifications are listed in Table 1.

Table 1. Test engine and vehicle specifications

Engine Displacement	2L class
Compression Ratio	15:1
Injection System	Common Rail Solenoid Injectors
Max. Rail Pressure	200 MPa
Boost System	Single-stage VNT
EGR System	Dual-loop EGR
Vehicle Inertia Weight	~4000 lbs
Transmission	6-speed Manual
Fuel	US 2007 emissions cert. fuel Cetane number = 42.2 Sulfur content = 14 ppm

The engine was installed in a test cell with an open ECU and rapid prototyping tool that allowed custom engine control logic to be used. Standard gaseous emissions analyzers were used to sample emissions after the turbocharger for engine-out samples and after the DPF for DPF-out samples. All HC results in this report correspond to total HCs unless otherwise stated. Glow plugs were installed in each cylinder so a separate hole was machined for a Kistler 6052C pressure transducer in one cylinder to allow cylinder pressure measurement.

The engine had a developmental Tier 2 Bin 5 calibration that used a closed-coupled DOC and DPF and an underfloor LNT. However, the aftertreatment system layout that is proposed for this LEV III emissions strategy is a closed-coupled LNT and DPF and an underfloor SCR as shown in Figure 2. The underfloor SCR is proposed for the main NO_x control instead of the LNT for several of reasons. One reason is to avoid HC breakthrough during the periodic rich operations for LNT de-NO_x which is difficult to avoid and could impede achieving the very stringent HC level. Also, SCR provides the best opportunity for maximizing fuel economy especially when very high NO_x conversion efficiency is required. Another reason is an underfloor SCR removes the complication of achieving sufficient underfloor LNT temperature during desulfation without thermally damaging the close-coupled LNT.

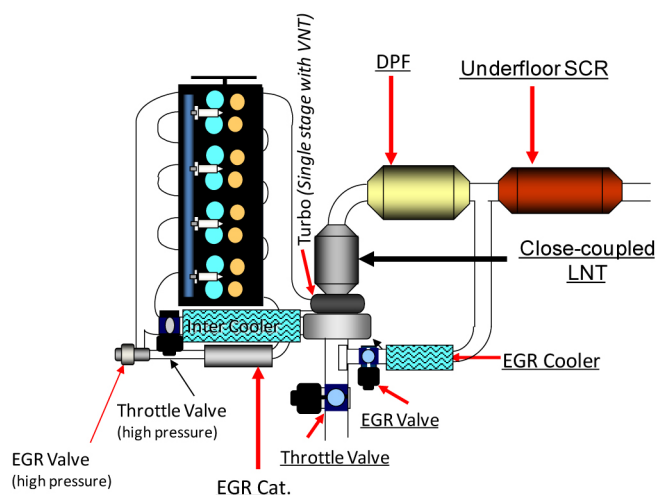


Figure 2. Proposed LEV III aftertreatment system layout

ENGINE TUNING TECHNOLOGIES

Intake Throttling to Increase Exhaust Gas Temperature

Intake throttling was used to increase the exhaust gas temperature by reducing the in-cylinder charge mass. To evaluate the effectiveness of this method, steady-state tests were conducted at 1200 rpm and 1.7 bar BMEP without EGR and with the stock glow plugs. The EGR valve was closed and the VNT was fully open during these tests. As shown in Figure 3, closing the intake throttle valve reduced the intake manifold absolute pressure (MAP) and airflow and increased the pumping work (more negative) which required increased fuel delivery to maintain the target engine load. However, since the airflow reduction was significantly greater than the fueling increase, the total exhaust flow rate was reduced with throttling. Therefore, the combination of lower in-cylinder trapped mass and increased fueling resulted in an increase in the turbine outlet temperature. The increase in fuel consumption is deemed acceptable in this case since the moderate throttling strategy is only used during the first hill of the FTP75.

Since catalyst heat up is affected by both exhaust gas temperature and flow rate, it is appropriate to examine the effect of intake throttling on the exhaust enthalpy. As shown in Figure 3, intake throttling reduces the exhaust enthalpy due to the large dependence on the exhaust flow rate. However, the enthalpy difference between the non-throttled and maximum throttled cases was only 0.3 kW (6.7%) for the 52°C exhaust temperature increase. Therefore, no significant effect of reduced exhaust enthalpy on the catalyst heat up time was expected with the level of intake throttling planned for this strategy.

The total engine-out HC mass flow rate increased by only 6.4% even though the concentration increased by 50% with throttling. This is due to the exhaust flow rate reduction

which exceeds the concentration increase. Throttling is limited by combustion stability so if more aggressive throttling was used, engine misfire would eventually occur which would result in extremely high HC emissions and poor engine operation. Technologies that can help control HC emissions during intake throttling are glow plugs and multiple injections as discussed in the next sections.

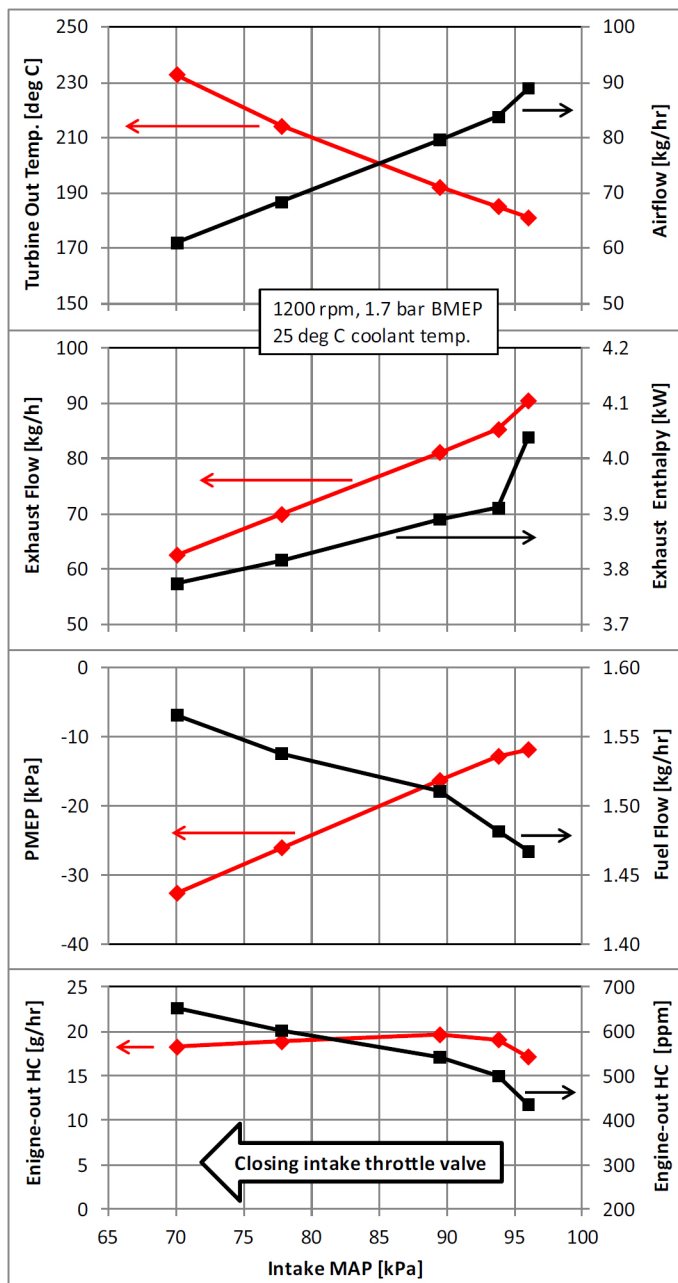


Figure 3. Intake throttling test results conducted at 1200 rpm, 1.7 bar BMEP

Glow Plugs

Glow plugs are traditionally associated with improving engine starting characteristics at low ambient conditions.

However, the role of glow plugs (GPs) in diesel engines has expanded to include providing smooth idle operation, reduced emissions, and is also a key enabler for reducing engine compression ratio with typical GP operating temperatures of up to 1300°C [7, 8, 9]. For this study, prototype GPs capable of 1350°C were used in addition to the stock GPs. The prototype GPs had the same external geometry as the stock GPs and some were instrumented with thermocouples to allow direct tip temperature measurement.

Steady-state engine tests were conducted at several engine speed and load conditions with the prototype GPs to evaluate the effect of GP temperature on engine-out HC emissions at low coolant temperatures. An instrumented GP was used in one cylinder (regular GPs in the other cylinders) so that the target GP temperatures could be achieved by varying the GP power. Tests were also conducted with the stock GPs and controller for comparison purposes only since direct temperature measurement of the stock GPs was not possible. Test results obtained at 1200 rpm, 4 bar BMEP are presented in Figure 4 and results obtained at 2000 rpm, 1.7 bar BMEP are shown in Figure 5. Note that the HC mass flow rates were normalized by the stock GP results so that HC emission changes relative to the stock GPs could be easily discerned.

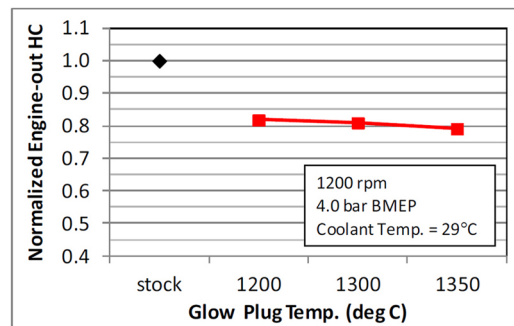


Figure 4. Effect of glow plug temperature on HC emissions for base engine calibration at 1200 rpm, 4.0 bar BMEP

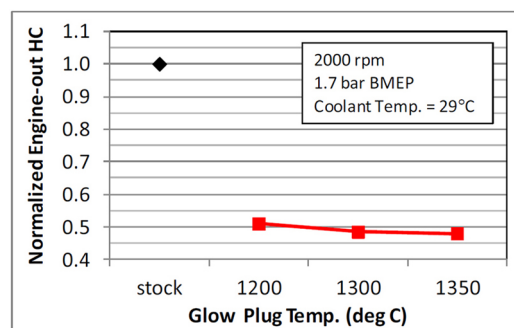


Figure 5. Effect of glow plug temperature on HC emissions for base engine calibration at 2000 rpm, 1.7 bar BMEP

The test results obtained with the prototype GPs indicate that HC emissions decrease with GP temperatures above