

Diesel Cold-Start Emission Control Research for 2015-2025 LEV III Emissions - Part 2

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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 and Tier 3 emission standards which will require significant reductions in hydrocarbon (HC) and oxides of nitrogen (NO_x) emissions. 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 after a cold-start with typical aftertreatment devices is considerably longer.

To address this challenge, a novel diesel cold-start emission control strategy was investigated on a 2L class diesel engine. This strategy combines several technologies to reduce tailpipe HC and NO_x emissions before the start of the second hill of the FTP75. The technologies include both engine tuning and aftertreatment changes. The benefits of the engine tuning changes were presented in detail in a previous publication. This paper expands the discussion to include test results obtained with the modified aftertreatment device: namely, a close-coupled LNT with a low-temperature formulation.

Using this strategy, effective NO_x and HC control was achieved within 50 seconds after the start of the FTP75. Compared to a production Tier 2 Bin 5 diesel vehicle, a 57% reduction in cumulative tailpipe NO_x + HC emissions was obtained after the first hill of the FTP75. This level of cold-start emission reduction along with modern NO_x aftertreatment performance during hot operation confirms that this strategy is a viable LEV III option.

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INTRODUCTION

The United States continues to place strong emphasis on reducing greenhouse gas emissions from mobile sources as outlined in the 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 hybrid/electric powertrains may be cost prohibitive. However, a key challenge facing the diesel is the upcoming CARB LEV III and EPA Tier 3 emission standards which are posed to phase-in starting in 2015 and 2017, respectively. Both emission standards require fleet average non-methane organic gas (NMOG) + NO_x levels of 0.03 g/mi in 2025, which is equivalent to the current SULEV or 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.

An overview of several innovative approaches for reducing the cold-phase emissions from diesels for potential SULEV compliance was provided in the first part of this publication [2]. Since then, a notable technology advancement involving the passive NO_x storage device has been made. An improved passive NO_x storage device, called the Cold Start Concept (CSC™) catalyst, has been developed and the details were recently presented [3]. Compared to the previous Passive NO_x

Adsorber (PNA), the CSC has several improvements including increased low temperature NO_x storage capacity, reduced N_2O formation, and a lower cost formulation. However, the challenge of preventing stored NO_x release from the CSC before the downstream NO_x converter temperature is up to sufficient temperature remains. As such, a temperature gap in NO_x control still exists.

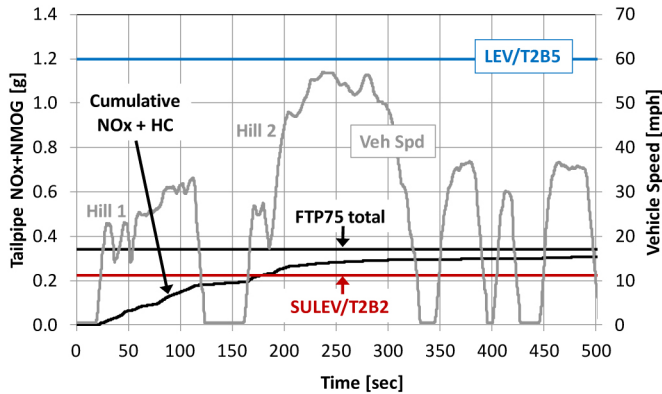


Figure 1. Cumulative tailpipe NO_x +HC emissions during Bag 1 of FTP75 for a Bin 5 production diesel car.

The emission control strategy investigated in this study combined several technologies to reduce HC and NO_x emissions emitted during the cold-phase portion of the FTP75 test cycle. The individual elements that comprise this cold-start emission control strategy include:

- High temperature glow plugs with model-based temperature control to maintain good ignition quality at low compression pressure
- Intake throttling to reduce in-cylinder charge mass and increase exhaust gas temperature
- Multiple pilot injections to achieve an ignitable mixture near the glow plug along with post injections to increase exhaust gas temperature without increasing HC emissions
- Revised cold engine calibration that prioritizes low HC emissions and high exhaust temperature over NO_x
- Replacement of the baseline close-coupled DOC with a LNT with an advanced low temperature formulation to obtain NO_x storage and HC conversion early in hill 1

The close-coupled LNT size and formulation can be optimized to provide effective NO_x storage during hill 1 and potentially into hill 2, depending on the application. After sufficient LNT temperature is achieved, this catalyst arrangement allows LNT de- NO_x during hill 1 or early in hill 2 so that additional NO_x storage would be available during hill 2. Additional LNT NO_x storage in hill 2 would allow more time for the underfloor SCR to reach sufficient operating temperature. Once the underfloor SCR is up to temperature, LNT regeneration would cease and full NO_x control would be provided by the SCR.

EXPERIMENTAL SETUP

The effectiveness of this strategy was evaluated on a 2-liter class diesel engine with a low compression ratio, single-stage variable nozzle turbocharger (VNT) and a dual-loop EGR system. The intended vehicle has an inertia weight of approximately 1800 kilograms. The engine and test fuel specifications are listed in Table 1.

Table 1. Test engine specifications.

Engine Displacement	2L class
Compression Ratio	15:1
Injection System	Common Rail with Solenoid Injectors
Max. Rail Pressure	200 MPa
Boost System	Single-stage VNT
EGR System	Dual-loop EGR
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.

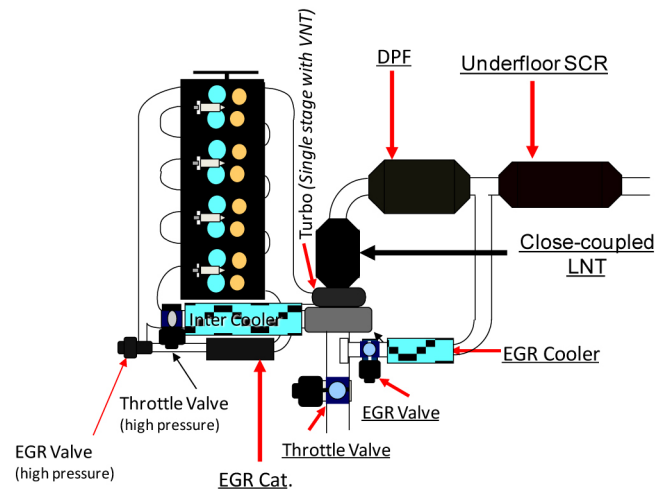


Figure 2. Proposed LEV III aftertreatment system layout.

The base engine had a developmental Tier 2 Bin 5 calibration that used a closed-coupled DOC and DPF and an underfloor LNT. For LEV III, the aftertreatment system layout that is proposed 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 underfloor LNT for several of reasons. One reason is to minimize HC breakthrough associated with the periodic LNT de- NO_x events, which could impede achieving LEV III. Also, SCR provides an opportunity for maximizing fuel economy especially when very

high NO_x conversion efficiency is required. Finally, an underfloor SCR removes the complication of achieving sufficient underfloor LNT temperature during desulfation without thermally damaging the close-coupled LNT.

The focus of this study was on the first 162 seconds of the FTP75 test cycle, which includes hill 1 and the idle period prior to the start of hill 2 (see Figure 1 for hill references). Transient tests were conducted in an engine test cell with a speed and load profile which simulated this portion of the FTP75 test cycle. The speed and load profile is shown in Figure 3 and was used for all transient evaluations during this study.

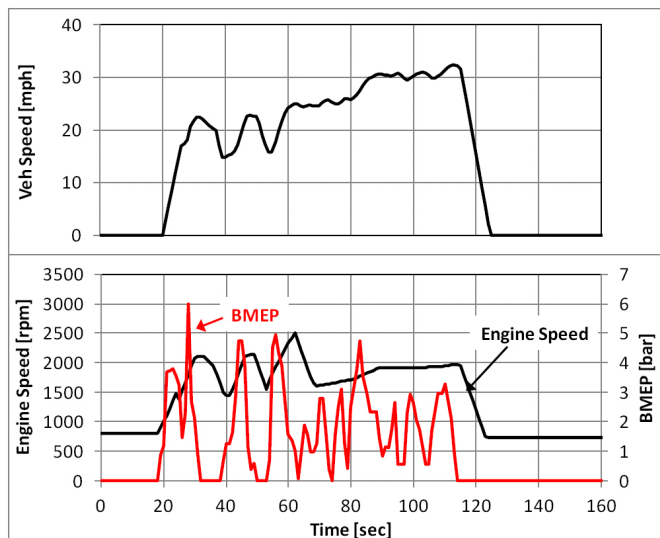


Figure 3. Transient test cycle used for test cell simulation of cold-phase portion of FTP75.

ENGINE TUNING TECHNOLOGIES

The engine tuning technologies were discussed in detail in the first publication, however a high level summary of the benefits of each technology is provided in this section.

High Temperature Glow Plugs with Improved Temperature Control

Significant HC reductions, ranging from 20 to 50% relative to the stock glow plugs (GPs) and controller, were obtained on the baseline Bin 5 engine calibration with high temperature capable GPs with improved temperature control targeting a tip temperature of 1200°C. As explained in the previous publication, the stock glow plugs were 1200°C capable. However, the controller available on this developmental Bin 5 calibration was not able to maintain this temperature during transient operation. HC emissions continued to decrease with increasing GP temperatures (up to 1350°C was tested); however the additional reductions were generally less than 5%.

Improved GP temperature control was obtained during transient testing with a model-based temperature controller that was developed during this study. Example test results obtained over the simulated cold-phase part of the FTP75 with the baseline Bin 5 engine calibration are shown in Figure 4.

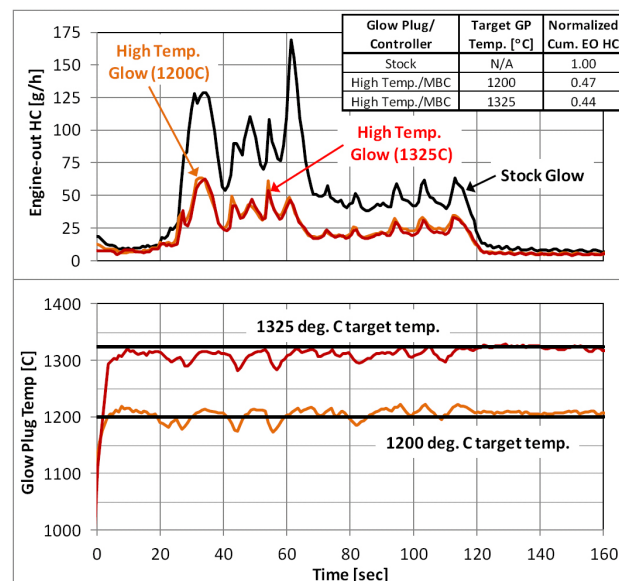


Figure 4. Effect of glow plug temperature and control on engine-out HC emissions for baseline Bin 5 engine calibration during cold-phase portion of FTP75 test cycle (engine test cell simulation).

Intake Throttling

Moderate intake throttling was used to increase exhaust gas temperature without significantly increasing HC emissions or decreasing the exhaust enthalpy. Engine testing was conducted at 1200 rpm and 1.7 bar BMEP at cold coolant conditions and without EGR to evaluate the effectiveness of intake throttling. EGR was not used during this testing to avoid confounding of the results by intake manifold temperature changes since the high-pressure EGR system on this engine was un-cooled. As shown in Figure 5, a 52°C turbine-out temperature increase was obtained for a 6.4% increase in engine-out HC mass emissions when using the stock GPs and controller. The corresponding enthalpy decrease was 6.7%. However, when the intake throttling was repeated with GPs with improved temperature control at 1200°C, a 70°C turbine-out temperature increase and 2.1% decrease in engine-out HC mass emissions was obtained for a 4.5% decrease in exhaust enthalpy. Clearly, improved GP temperature control enhances the effectiveness of intake throttling.

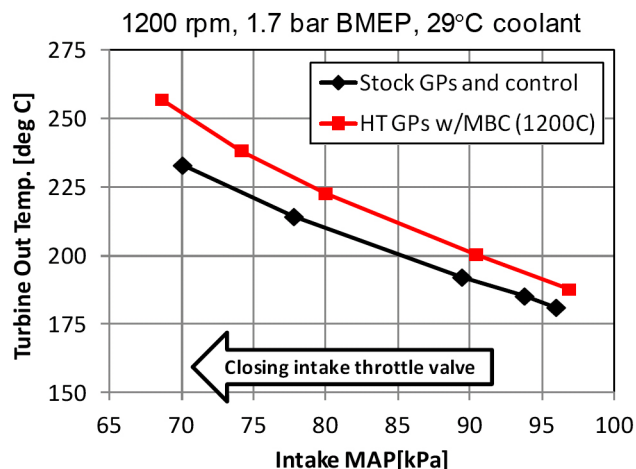


Figure 5. Turbine-out temperature from intake throttling tests conducted at 1200 rpm, 1.7 bar BMEP with stock and high temperature capable glow plugs controlled to 1200°C.