

Investigation of In-cylinder NO_x and PM Reduction with Delphi E3 Flexible Unit Injectors on a Heavy-duty Diesel Engine

Yiqun Huang and Jeffrey Leet*

Southwest Research Institute®

*Currently with Caterpillar Inc.

Copyright © 2008 SAE International

ABSTRACT

In-cylinder emission controls were the focus for diesel engines for many decades before the emergence of diesel aftertreatment. Even with modern aftertreatment, control of in-cylinder processes remains a key issue for developing diesel vehicles with low tailpipe emissions. A reduction in in-cylinder emissions makes aftertreatment more effective at lower cost with superior fuel economy. This paper describes a study focused on an in-cylinder combustion control approach using a Delphi E3 flexible fuel system to achieve low engine-out NO_x and PM emissions. A 2003 model year Detroit Diesel Corporation Series 60 14L heavy-duty diesel engine, modified to accept the Delphi E3 unit injectors, and ultra low sulfur fuel were used throughout this study. The process of achieving premixed low temperature combustion within the limited range of parameters of the stock ECU was investigated. Effects of fueling, EGR and needle open pressure on engine-out emissions were demonstrated over the 13 modes of the ESC cycle.

INTRODUCTION

Diesel manufacturers in the USA and Europe are facing very stringent emissions regulations. With the 2010 heavy-duty regulations in the USA, heavy-duty diesels have to achieve near 10 fold reduction in both NO_x and PM emissions compared with the 2004 U.S. emission levels. In order to achieve the required NO_x and PM emission levels required by the 2010 standards, both engine control systems and aftertreatment devices will need to improve. A Urea-SCR catalyst is the exhaust treatment device for NO_x control for heavy-duty diesels in Europe and likely in the USA. Diesel particulate filters (DPF) are a certainty for PM control in both Europe and the US [1,2], while Lean NO_x Trap (LNT) technology is a feasible solution for light duty diesel engines [3].

However, currently, dedicatedly lean burn diesel NO_x aftertreatment could not meet the requirements for both NO_x conversion efficiency and cost at the same time. LNT has the disadvantages of precious metal (cost) and durability (thermal deterioration during desulfation), while

urea-SCR has the disadvantages of additional hardware, dosing control and infrastructure [4]. At the same time, NO_x aftertreatment has limitations of a low carrying capacity and a narrow temperature range in which it is efficient. Therefore, it is important to improve combustion and reduce engine-out NO_x and PM emissions to increase the exhaust treatment feasibility.

Engine-out emission reduction using EGR and injection strategies have been studied by many researchers over the past several decades by experimental work and CFD simulation on both heavy-duty and light-duty diesels [5, 6, 7]. EGR has been proven to be the most effective in NO_x reduction over all engine speeds and loads, but increasing smoke significantly at higher loads. Unlike common rail fuel systems, unit injection systems typically do not have the flexibility of adjusting needle open pressure and injection patterns. However, Delphi had developed a flexible unit injection system, the E3 unit injector, which allowed the control of needle open pressure and double injections [8].

Alternative combustion modes, combining high EGR rates, high injection pressures, low temperature combustion and controlled auto-ignition, have been extensively studied to meet the new emission standards. Some advanced combustion modes are already used in new engine applications [9, 10, 11].

The goals of this study were to assess the effects of EGR, high needle pressure and injection strategies on the engine out NO_x and PM emissions of standard and low temperature combustion in the Detroit Diesel Corporation Series 60 engine.

EXPERIMENTAL SYSTEM

The test setups of engine, control system and aftertreatment are discussed in the following sections.

TEST ENGINE AND TEST FUEL

The test engine used for this study was a 2003 production Detroit Diesel Corporation Series 60 14L engine with a high-pressure cooled EGR system, a

conventional electronic unit injector (EUI) injection system, and a variable geometry turbocharger, as shown in Figure 1. The main engine specification parameters are listed in Table 1. Ultra-low sulfur diesel fuel was used throughout this program. The specifications of the fuel are summarized in Table 3.1.



Figure 1 Test Engine, Detroit Diesel Corporation, Series 60

Table 1 Test Engine Specification

Bore	133 mm
Stroke	168 mm
Displacement	14.0L
Rated Power	373 kW
Rated Power Speed	2100 rpm
Peak Torque	2500 N-m
Peak Torque Speed	1200 rpm
Turbocharger	Garrett VNT (production)
EGR System	High-pressure loop and Cooled (production)

Table 2 Specifications of the Ultra-Low Sulfur Test Fuel

Parameter	ASTM Method	Value
Gravity API	D 4052	38.2
Density (kg/L) @ 15°C	D 4052	0.834
Viscosity @ 40°C (cST)	D 445	2.3
Distillation (°C)		
IBP	D 86	194
50%		251
90%		312
Net Heat of Combustion (MJ/kg)	D 3338	43.0
Carbon (wt. %)	D 3343	0.8664
Hydrogen (wt. %)	D 3343	0.1336
Hydrogen-Carbon Ratio		1.837
Sulfur (ppm)	D 4045	5
Cetane Number	D 613	42.3
Aromatics (% volume)	D 1319	28.8
SFC Aromatics (% volume)	D 5186	26.4
Polynuclear Aromatics (% volume)		7.2

CONTROL SYSTEM

The OEM ECU did not have the flexibility of controlling additional hardware, sensors or actuators. In order to

have full authority control of the engine and aftertreatment system, the original OEM ECU was not used. Instead, the Rapid Prototyping Engine Control System (RPECS) from Southwest Research Institute was used for both engine and additional actuator control.

RPECS has the capability to meet various needs for mapping engine control parameters, developing advanced engine control algorithms, steady-state and transient engine controls, as well as data acquisition, etc. The RPECS engine control system is shown in Figure 2.

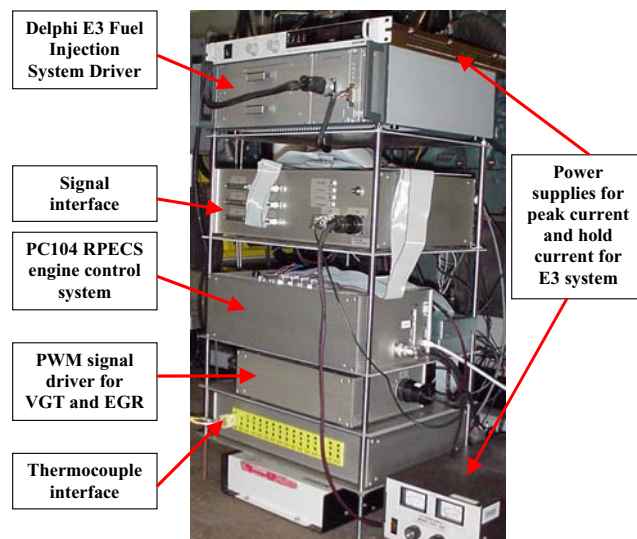


Figure 2 RPECS Hardware Configuration

The functional module structures of RPECS are shown in Figure 3. The controller is based on a Pentium processor based PC/104 form factor mother board and associated analog and digital I/O cards. A one-million gate FPGA card performed all engine position tracking, fueling control and PWM related actuator controls. The RPECS control program was operated under QNX real time operation system.

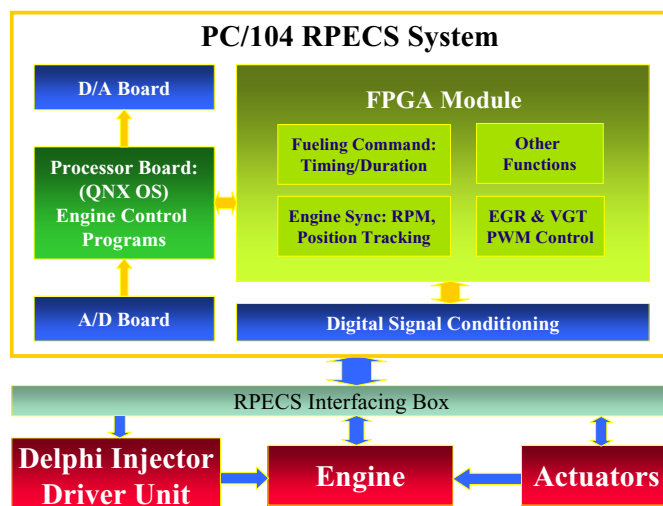


Figure 3 RPECS Functional Module Structures

DELPHI E3 INJECTION SYSTEM COMPONENT

The E3 unit injection system features two valves inside the injector body, as illustrated in Figure 4 [8]. The spill control valve (SCV) determines when the bypass of fuel through injector ceases as with traditional unit injectors. The needle control valve (NCV) determines the movement of the needle and, therefore, the nozzle opening and closing pressures. Together these two valves allow for multiple injections per cycle within the limitations of the camshaft.

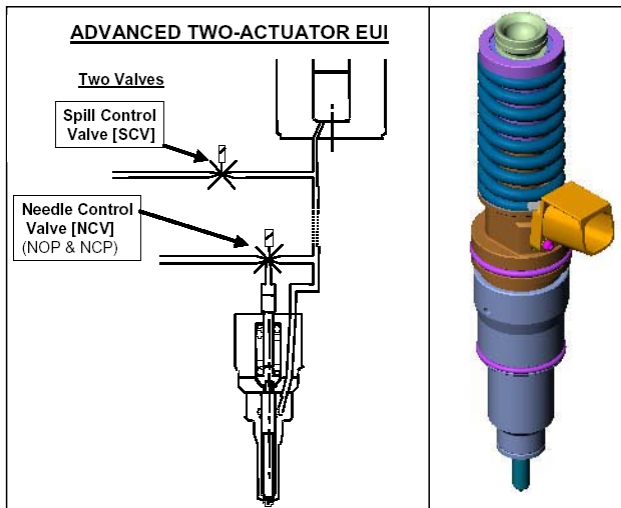


Figure 4 Principle of Operation for the E3 Injector and Example E3 Injector System [8]

The following components were changed on the Series 60 engine to accommodate the E3 injection system and are shown in the collage of Figure 5.

- Cylinder head compatible with the E3 injector design, which have adapters for cylinder pressure measurement
- Camshaft
- E3 injectors
- E3 wiring harness
- E3 injector driver
- Low pressure supply pump

EXHAUST AFTERTREATMENT COMPONENTS

The exhaust treatment system was installed including a 11L oxidation catalyst before the catalyzed DPF (cDPF), as shown in Figure 6. The purposes of the oxidation catalyst were to help protect the cDPF from excessive soot and unburned fuel, help achieve a temperature increase in the catalyst (an exotherm) to warm the cDPF and passive regeneration of the cDPF. Exhaust gas temperatures were measured at the inlet and outlet of each exhaust treatment device and substrate locations. In order to minimize the heat transfer from the exhaust system, the exhaust pipe was wrapped with fiberglass insulation from the turbine outlet to the oxidation catalyst inlet and between the cDPF outlets as shown in Figure 6. It is understood that the installation demonstrated would not be suitable for production.

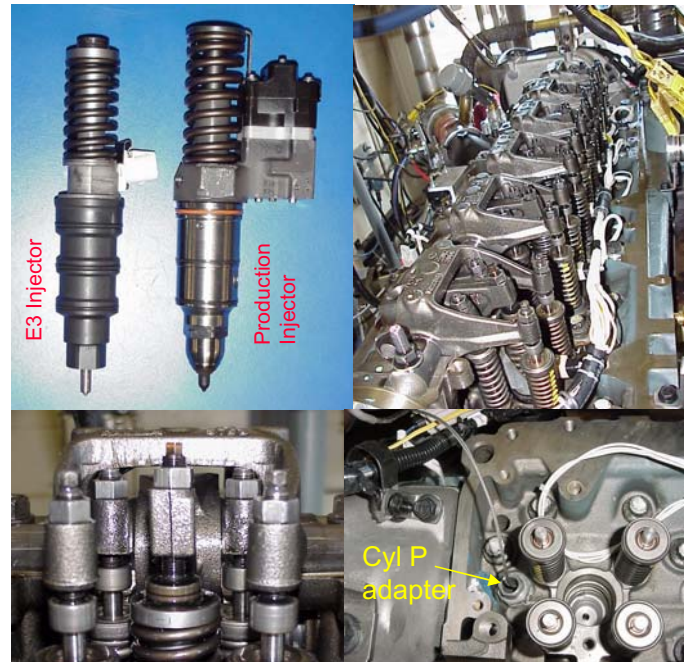


Figure 5 Components Changed to Accommodate the E3 Injection System

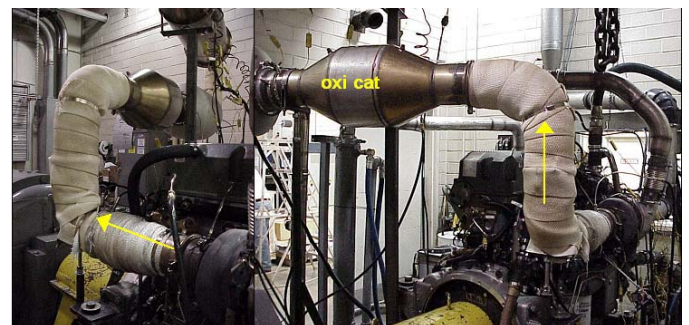


Figure 6 Oxidation Catalyst and Catalyzed DPF Installation In A Transient Dynamometer Test Cell

RESULTS AND DISCUSSIONS

The E3 injector control logic, combustion system tuning and engine-out emissions results will be discussed in the following sections. All injection timings denoted by positive numbers imply timing before TDC.

CONTROL OF DELPHI E3 UNIT INJECTION SYSTEM

Unlike traditional unit injector controllers, the E3 injection system needs two independent drivers, one for the spill control valve (SCV) and one for the needle control valve (NCV). The FPGA module in the RPECS is responsible for generating both control signals for the spill control valve and needle control valve.

The injector rocker arm in cylinder #1 was instrumented with strain gauges to measure the rocker arm load as a surrogate for injection pressure. As shown in Figure 7, the spill control valve of the E3 injector was timed the same as the needle control valve (energizing and de-energizing), which made the E3 injector act as a traditional unit injector. The opening and closing of the

injector's needle were set, therefore, by the spring load of the injector.

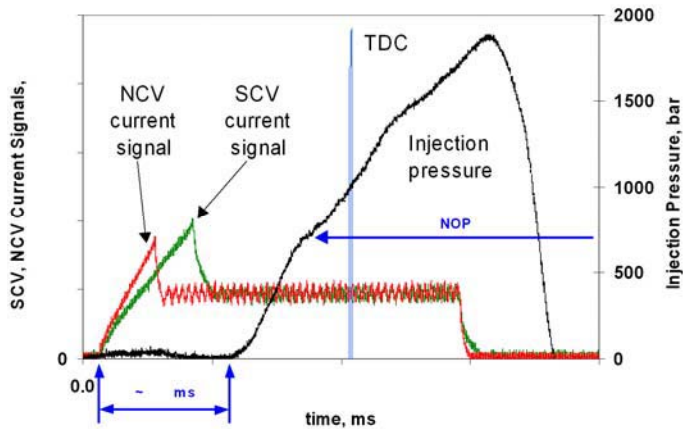


Figure 7 Timing of Spill Control Valve and Needle Control Valve and Injection Pressure at Mode 12 of ESC for the Delphi E3 Injection System

The delay time between the energizing of the spill control valve solenoid to the mechanical movement of the spill control valve is independent of engine speed. Knowledge of the spill control valve delay time is required to specify the start of the electrical event in order to achieve a desired physical start of injection. A traditional one-bump injector lobe camshaft was used to investigate engine-out NO_x reduction strategies, as discussed subsequently.

To control the needle opening pressure (NOP) of the E3 injector, the needle control valve and spill control valve timings were calculated according to the control logic shown in Figure 8. The algorithm was developed to account for the actuator response time and the speed effect on the SCV and NCV of the E3 injector.

At a given engine speed, the inputs to the algorithm are Physical SOI Desired, Physical Duration Desired (fuel mass) and NOP Desired. The outputs from the algorithm should be the commands to the injector drivers as SCV Electrical Timing, NCV Electrical Timing and Duration. The SCV de-energizing timing can be the same as NCV.

Advancing the SCV timing relative to NCV can increase the NOP. The SCV advance must be greater than the mechanical delay time for the SCV in order to use the NCV to control the start of injection. Then the SCV Advancing Time relative to the physical SOI is determined with the correlation of pressure rise rate and speed before NCV opens. The Advancing Time of SCV is added to the Physical SOI of NCV to form the command of SCV timing.

The NCV Electrical Timing is determined from the Physical SOI Desired and the mechanical delay time of NCV. The NCV Electrical Duration is determined from the Physical Duration Desired and the mechanical delay time of NCV.

Other factors influencing the actuation of the injector can also be factored in the algorithm but not included in this paper.

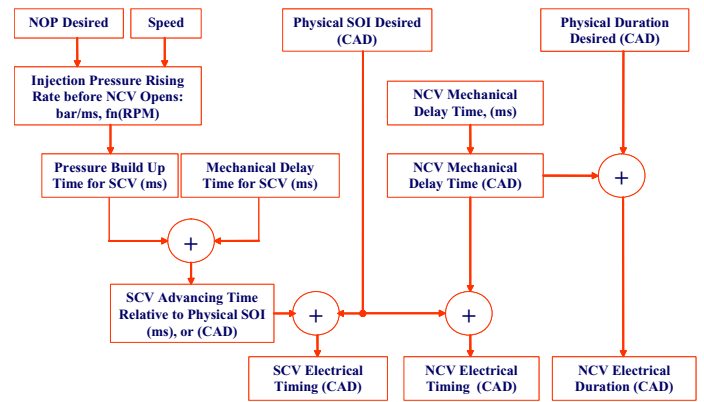


Figure 8 Logics for NOP and Fueling Control

As shown in Figure 9, the start of injection is fixed by the needle control valve timing and the spill control valve timing is advanced relative to the needle control valve timing to increase the needle opening pressure.

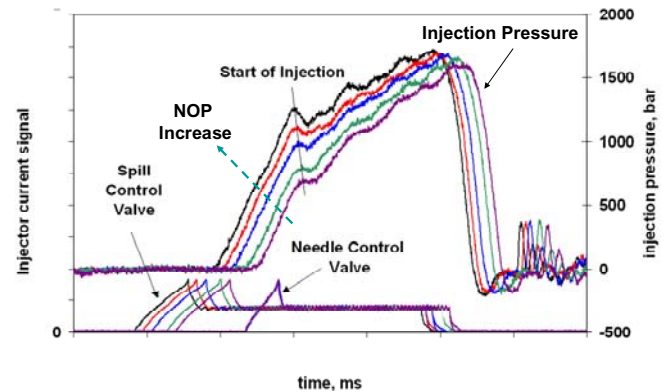


Figure 9 Injection Pressure and Timings of Spill and Needle Control Valves at ESC Mode 4

With the E3 injector, the rise rate of injection pressure before the needle opens changes with speed, as shown in Figure 10 for the camshaft used in this study. This correlation was the basis for controlling the spill control valve timing relative to the needle control valve. The pressure rise rate is higher at higher engine speed (less time for leakage).

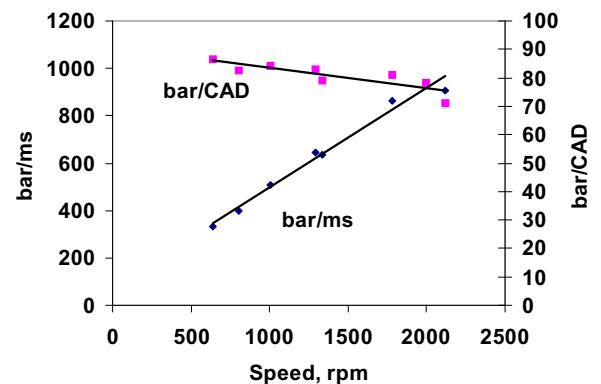


Figure 10 Correlation of the Injection Pressure Rise Rate before Needle Opens vs. Engine Speed for #1 CAM

Even though the static NOP is a constant determined by the spring load inside the injector, the dynamic NOP under the spill valve control mode (similar to the