

Meeting the US Heavy-Duty EPA 2010 Standards and Providing Increased Value for the Customer

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ABSTRACT

The paper will discuss the design and development of heavy-duty diesel engines to meet the US EPA 2010 on-highway standards - 0.2g/HP-hr NO_x and 0.01g/HP-hr particulate matter (PM). In meeting these standards a combination of in-cylinder control and aftertreatment control for both NO_x and particulate has been used.

For NO_x control, a combination of cooled exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) is used. The SCR catalyst uses copper zeolite to achieve high levels of NO_x conversion efficiency with minimal ammonia slip and unparalleled thermal durability.

For particulate control, a diesel particulate filter (DPF) with upstream oxidation catalyst (DOC) is used. While the DPF may be actively regenerated when required, it operates predominantly with passive regeneration -enabled by the high NO_x levels between the engine and the DPF, associated with high efficiency SCR systems and NO₂ production across the DOC.

The engine features a proprietary high pressure common rail fuel system (HPCR), developed jointly by Cummins and Scania. This HPCR system was developed for medium- and heavy-duty engines and is known as XPI. The XPI system was developed for very high pressure injection required by heavy-duty engines at US EPA 2010, EURO 5 and EURO 6 exhaust emission levels. Together with the variable geometry turbocharger (VGT), the HPCR provides flexibility for thermal management of the aftertreatment system. Thermal management is used extensively to provide fast warm-up and optimum DPF and SCR performance in use.

This system architecture is designed to minimize both fuel and DEF consumption characteristics. With the adoption of

copper zeolite SCR, it has been possible to achieve the near-zero US EPA 2010 emission standards, while reducing overall operating costs significantly (4-5%) when compared with the EPA 2007 engine it replaces.

On-board diagnostics (OBD) has been fully implemented in these HD engines for 2010. This has required that all emission control systems be monitored for performance against emission thresholds, and that all related actuators and sensors be monitored for correct functionality

INTRODUCTION

The modern Heavy-Duty diesel engine is used around the world to power applications as varied as heavy-duty trucks - see [Figure 1](#), electrical power generators, ships, locomotives, agricultural and industrial equipment. The success of the HD diesel engine results from its unique combination of low operating costs, 1 million mile durability, reliability and affordability - which drive the lowest total cost of ownership.

The exhaust emission standards introduced in the US in 2010 - see [Table 1](#), have required the development and introduction of new technologies in order to achieve the near-zero emissions of oxides of nitrogen (NO_x) and particulate (PM), while retaining the customer values outlined above. Progress toward near-zero emissions has required:

- Engines incorporating new technologies - e.g. Cooled EGR, VG Turbochargers and HPCR Fuel Systems
- NO_x and PM aftertreatment systems
- Ultra-low sulfur diesel fuels
- Next generation controls and on-board diagnostics (OBD)
- System Integration using System Engineering Principles

The paper documents the design and development of 11.9 liter and 15 liter HD engine systems. The 11.9L engine is a

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truly clean sheet design which will be used in a wide range of applications from 300 to 500HP -including: RV, fire truck, urban bus, and other vocational applications. The 15L engine is an evolution of the 2007 ISX used predominantly in class 8 line-haul applications at ratings between 400 and 600HP [1,2,3].

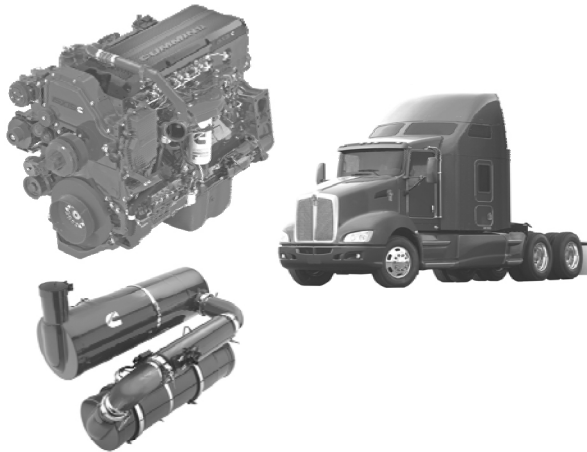


Figure 1. US Conventional Truck, 2010 15L HD Diesel Engine used in Long-Haul Applications and Combined SCR and Diesel Particulate Filter.

The paper underlines the importance of selecting the right technology and system architecture for the application, executing the design of hardware and controls software using the principles of systems engineering, and optimizing the performance, fuel economy and emissions through controls calibration using the best available tools.

US EPA 2010 STANDARDS

The US EPA 2010 standards for HD diesel engines have been met by almost all engine manufacturers by a combination of cooled EGR and SCR for NO_x control and an actively regenerated DPF for particulate control. The European EURO 4/5 HD vehicle standards have been met with either cooled EGR or SCR technologies, without the use of a DPF. It is anticipated that meeting EURO 6 standards will require system architectures similar to those presented here for meeting US EPA 2010 - namely cooled EGR, SCR and DPF with high pressure common rail fuel systems. A summary of the US and European standards for HD engines is shown in [Table 1](#).

Table 1. Summary of US EPA and European (EURO) Emission Standards for HD Diesel Engines

	NO_x	Particulate
US EPA 2007*	1.20 g/HP-hr	0.01 g/HP-hr
US EPA 2010	0.20 g/HP-hr (0.27 g/kW-hr)	0.01 g/HP-hr (0.013 g/kW-hr)
EURO 4	3.50 g/kW-hr (2.61 g/HP-hr)	0.030 g/kW-hr (0.022 g/HP-hr)
EURO 5	2.00 g/kW-hr (1.50 g/HP-hr)	0.030 g/kW-hr (0.022 g/HP-hr)
EURO 6[§]	0.40 g/kW-hr (0.3 g/HP-hr)	0.01 g/kW-hr (0.0075 g/HP-hr)

**The US 2007 NO_x shown in [Table 1](#) is not itself a standard. It is an average of the phase-in standard of 0.2g/HP-hr and the phase-out standard of 2.5g/HP-hr, in accordance with the EPA NO_x phase-in provisions.*

§Regulation 595/2009 published on 18 July 2009 & 31 July 2009

PERFORMANCE & EMISSIONS ARCHITECTURE FOR US EPA 2010

Meeting the near-zero NO_x levels associated with the US EPA 2010 emission standards requires significant in-cylinder control and high performing NO_x aftertreatment. Similarly, control of tailpipe particulate matter (PM) requires both an optimized combustion system, in order to limit engine-out smoke levels, and an efficient diesel particulate filter. Furthermore, efficient operation of the NO_x and PM aftertreatment requires thermal management by the engine - which includes a degree of control over exhaust mass flow rate, exhaust temperature and exhaust oxygen. Thermal management is an essential element in the integration of engine and aftertreatment, and allows both the DPF and the SCR to operate at peak efficiency over a wide range of duty-cycles. The system architecture chosen to meet US EPA 2010 emissions is shown in [Figure 2](#).

In the development of the 2010 HD engines it was found that an optimum balance exists between in-cylinder control of NO_x and PM and aftertreatment control of NO_x and PM. The primary parameter determining this optimum balance is the operating cost - driven by both fuel consumption and urea (DEF) consumption. The optimum engine-out NO_x level depends on the relative price of DEF and diesel fuel. The automotive grade urea used in DEF is produced from natural gas and therefore its pricing is largely indexed to the price of natural gas. At the time of writing, the relative prices of DEF and diesel fuel range from (DEF/Diesel Fuel) 45% to 70%, when purchased in bulk quantities of 300 gallons or more. Higher prices exist for smaller quantities such as 2.5 gallon containers, where the ratio is closer to 100%). In the analysis

shown in Figure 3 we have assumed DEF is available at 70% of the price of diesel fuel in order to illustrate the trade-offs, which is a conservative assumption for those buying in bulk quantities. Figure 3 shows clearly how SCR can be leveraged to allow an increase in engine-out NO_x in order to dramatically reduce fuel consumption, net of DEF consumption.

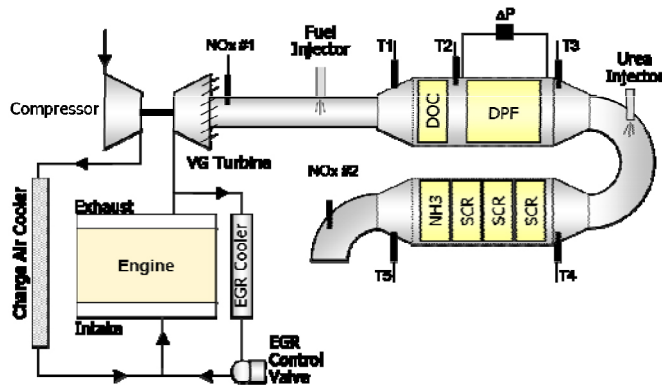


Figure 2. Engine and Aftertreatment system architecture, showing temperature sensors (T1-T5), differential pressure sensor (ΔP) and exhaust fuel doser for on-demand active DPF regeneration. Also shown are engine-out and tailpipe NO_x sensors used for both OBD and system control and ammonia slip catalyst.

In comparison with a 2007 engine using cooled EGR as the primary NO_x control, Figure 3 shows that an equivalent 2010 engine using EGR and SCR has a 6% fuel consumption improvement, and a 2.5% DEF consumption. With DEF priced at between 45% and 70% the price of diesel fuel, this gives a net improvement of 4% to 5% in the cost of consumables - i.e. diesel fuel plus DEF. This represents significantly greater customer value between 2007 and 2010, especially when considering that the NO_x is reduced by 84%, to near-zero levels.

With the introduction of cooled EGR it is necessary to raise the average exhaust pressure to allow exhaust gas to flow from exhaust manifold to intake manifold. In the 2010 engine this is achieved by modulating the VG turbine stage. This allows the turbine expansion ratio and pressure differential across the engine, to be controlled continuously and efficiently in response to the EGR delivery requirements at any given operating condition.

While the NO_x levels associated with EPA 2010 (0.2 g/HP-hr) and EURO 6 (0.4 g/kW-hr) can be achieved steady-state under controlled laboratory conditions with in-cylinder NO_x controls - in this work, it has been found that such solutions are impractical and unattractive to users of heavy-duty trucks. Such low NO_x levels require very high EGR rates - typically

greater than 40%. Some of the problems posed by such high EGR rates include excessive:

- Pumping work and fuel consumption
- Heat rejection
- Engine-out smoke and DPF regeneration
- Injection pressure requirement (≥ 3000 bar)
- Risk of corrosion from EGR condensation
- Cylinder pressure requirement

In addition, it is challenging to achieve both near-zero engine-out NO_x levels and acceptable transient response. This results from the low oxygen availability in the cylinder necessary to achieve very low NO_x levels.

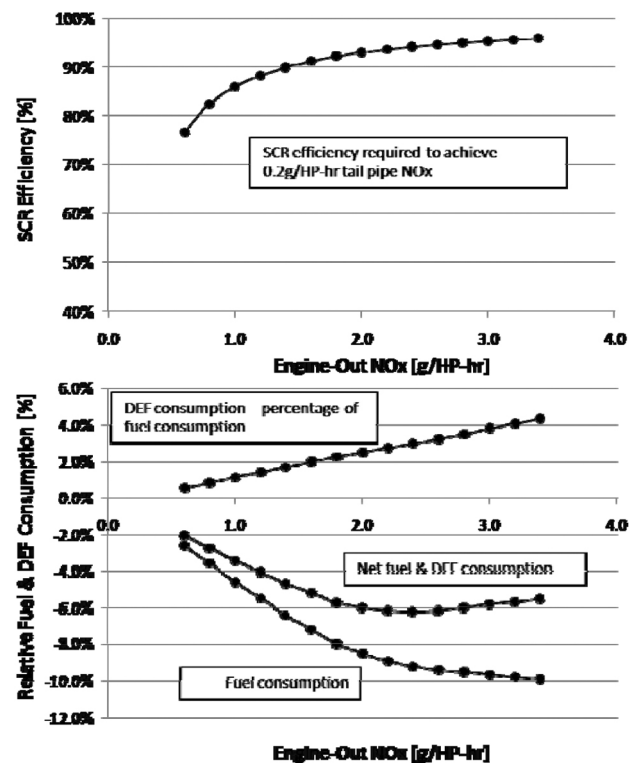


Figure 3. Trade-off between EGR and SCR at 2010 EPA emission levels. DEF consumption is fuel-equivalent at 70% price of fuel. Optimum engine-out NO_x under these assumptions is between 2.2 and 2.8 g/HP-hr. Further operating efficiencies are achieved through passive regeneration of the DPF with increasing engine-out NO_x. DPF regeneration fuel penalty is negligible when operating at engine-out NO_x levels above 2.0 g/HP-hr.