

Cost and Fuel Efficient SCR-only Solution for Post-2010 HD Emission Standards

Robert Cloudt, Frank Willems and Peter van der Heijden
TNO Automotive

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ABSTRACT

A promising SCR-only solution is presented to meet post-2010 NO_x emission targets for heavy duty applications. The proposed concept is based on an engine from a EURO IV SCR application, which is considered optimal with respect to fuel economy and costs. The addition of advanced SCR after treatment comprising a standard and a close-coupled SCR catalyst offers a feasible emission solution, especially suited for EURO VI.

In this paper, results of a simulation study are presented. This study concentrates on optimizing SCR deNO_x performance. Simulation results of cold start FTP and WHTC test cycles are presented to demonstrate the potential of the close-coupled SCR concept. Comparison with measured engine out emissions of an EGR engine shows that a close-coupled SCR catalyst potentially has NO_x reduction performance as good as EGR. Practical issues regarding the use of an SCR catalyst in close-coupled position will be addressed, as well as engine and exhaust layout.

For comparison, the requirements of a US 2010/EURO VI compliant high EGR engine are discussed: base engine design, heat rejection, fuel injection equipment, turbo charging and fuel economy. From this study, it is concluded that the SCR-only approach leads to a less expensive engine design with better fuel economy and lower PM emissions.

INTRODUCTION

During the past decade, heavy duty truck and engine manufacturers have been facing challenges in complying with more and more stringent emission standards, culminating in the US EPA 2010 standard and EURO VI

in Europe. Table 1 gives an overview of the current and future NO_x and Particulate Matter (PM) limits for the US and Europe.

Table 1. US and European Heavy Duty emission targets

Emission legislation	Year	Test cycle	NO _x limit (g/kWh)	PM limit (g/kWh)
US 2007	2007	FTP / SET	(1.5) ¹	0.013
US 2010	2010	FTP / SET	0.27	0.013
EURO V	2008	ESC	2.0	0.020
		ETC	2.0	0.030
EURO VI ²	2013	ESC / ETC	0.40	0.010
		WHSC	0.40	0.010
		WHTC	0.50-0.70	0.010

¹ There is no crisp NO_x limit for US 2007. The 2010 NO_x limit is phased in from 2007 to 2009 on a 50% of sale basis. The EPA Averaging, Banking and Trading scheme further allows postponing and compensation of emission reduction, based on other engine families or saved credits. According to [1], most 2007 model year HD truck engines have been certified at a NO_x level of 1.6 to 2.0 g/kWh. 1.5 g/kWh is based on the mean of 2004 and 2010 targets.

² Expected values, legislation is not fixed yet

Details of the EURO VI legislation have not been consolidated yet, though emission targets based on ETC and ESC cycles have been published. Correlation factors for emissions on the WHTC are being determined. The European Automobile Manufacturers Association suggests a WHTC offset of +0.3 g/kWh relative to the ETC, for NO_x emissions only [2]. An expected WHTC NO_x target of 0.5 g/kWh has also been reported. The

WHTC will be tested twice in a cold start - soak - hot start order. The expected weights for the cold and hot start cycles are 10% and 90% respectively.

To further reduce the impact of heavy duty vehicles on health and air quality in densely populated areas, the final EURO VI legislation may include limits on the particle number emission and NO₂ emission. By limiting the particle numbers instead of particulate mass, the emission of fine particulates is more heavily penalized. EURO VI may also include a limit on NH₃ slip for after treatment systems using urea Selective Catalytic Reduction (SCR). Besides emission targets for test cycles, requirements for real-world performance will be introduced during the next stages: On-Board Diagnostics (OBD) and In-Use Compliance (IUC).

Figure 1 gives an overview of the applied and expected emission reduction technologies during the different emission legislation stages. With the introduction of EURO IV and V emission limits, urea SCR after treatment systems were introduced to the heavy duty truck market to reduce NO_x emissions. A few European truck brands have opted for a solution which does not require an additional reagent to be carried on board. These non-SCR solutions generally apply Exhaust Gas Recirculation (EGR) and a Diesel Particulate Filter (DPF) to reduce the increased raw PM emission.

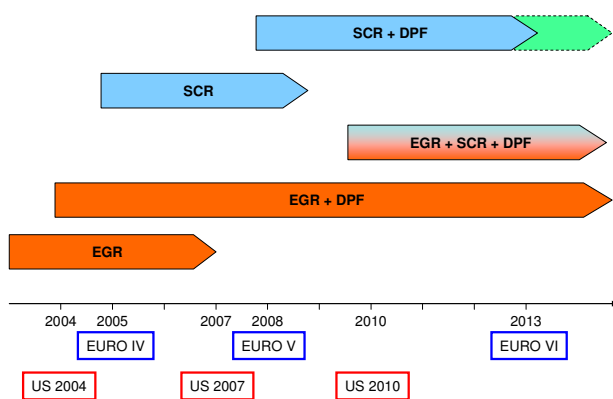


Figure 1. Overview of emission reduction technologies for HD applications

In Europe, the urea distribution network is gradually becoming mature. In North America on the other hand, the urea infrastructure is still rather sparse. Concerns about the availability of AdBlue, lower fuel prices and advances in EGR, turbocharging and fuel injection equipment technology, have caused 2007 model year heavy duty engines for the US market to be equipped with EGR and DPF systems.

US 2007 engine platforms can be made US 2010 or EURO VI compliant, by either adding urea-SCR after treatment, or by further developing EGR technology. Some parties announced that they will pursue in

developing an EGR based engine solution for the US 2010 emission target [3, 4]. However, growing concerns about CO₂ emission contributing to the greenhouse effect, energy security and especially fuel prices, have caused a shift in attention towards fuel efficiency. EGR is well known to cause an increase in fuel consumption, and clearly is not the favourable solution when fuel economy is of concern [5].

In this paper, the potential of an alternative SCR-only solution is examined. Starting from a basic non-EGR engine, SCR after treatment with a close-coupled SCR catalyst is added to comply with post-2010 emission standards. This approach will result in an inexpensive engine design with better fuel economy and lower PM emissions, especially suited for EURO VI.

This paper starts with a comprehensive discussion on design and performance considerations for the high EGR engine concept. Secondly, the SCR-only approach is introduced. This approach requires very high NO_x conversion efficiencies of the after treatment system. For this concept, issues and trade-offs in achieving optimal SCR performance are discussed. Focus is on low temperature and cold start performance. Finally, possible after treatment configurations for EURO VI will be discussed.

HIGH EGR ENGINE CONCEPT

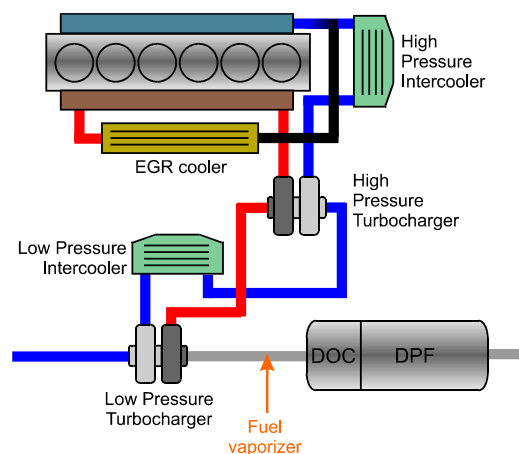


Figure 2. High EGR engine concept

Figure 2 shows the general layout of a high EGR engine concept. Such an engine can accomplish low engine-out NO_x emission (well below 2 g/kWh) by applying high EGR rates: over 20% at full load and over 40% at some partial load conditions. A DPF is incorporated in the exhaust line to reduce the PM emissions. A fuel vaporizer and Diesel Oxidation Catalyst (DOC) facilitate active regeneration of the DPF.

An already performed study [6] into EGR trade-offs on a two-stage turbocharged 12 litre heavy duty diesel engine provides general trends for NO_x and PM emission and

Break Specific Fuel Consumption (BSFC) as a function of the EGR percentage. Figure 3 depicts the NO_x, PM and BSFC trade-offs for the A25 and C100 ESC modes.

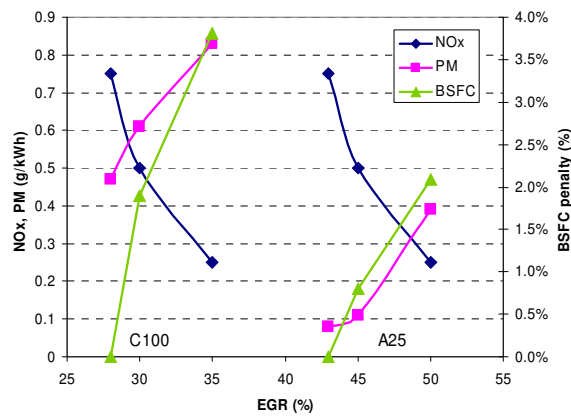


Figure 3. NO_x and PM emission and BSFC penalty as a function EGR percentage. BSFC penalty is relative to lowest EGR percentage.

The next sections will present a discussion on the subsystems of the high EGR engine concept.

TURBOCHARGING

The high EGR engine concept as described requires a high performance turbocharging system in order to establish the required in-cylinder Air Fuel Ratio (AFR) in combination with high EGR rates. The turbo charging system needs to deliver higher inlet manifold pressures compensating the increased in-cylinder mass flow demand. As a result of this, both pre-intercooler temperature and intake manifold temperature will increase significantly.

The pressure ratios required for a high EGR engine push the envelope for single-stage turbocharging compressor. Two-stage turbocharging can deliver the required boost pressure, but is more costly. Moreover, the additional pumping work will cause an increase in fuel consumption [7].

Achieving a US 2010 engine-out NO_x level of 0.27 g/kWh requires EGR rates of 35% at full load and 50% at partial load. For these EGR rates, it is expected that the required boost pressure causes the compressed air temperature at the outlet of the low pressure compressor to be too high for a standard material high pressure turbo compressor. Advanced materials like a Titanium compressor wheel and a die-cast compressor housing will be required to withstand the more severe conditions. Alternatively, a second intercooler can be placed between the low and high pressure compressors.

COOLING

The exhaust gas diverted back to the engine intake is cooled by an EGR cooler for lower NO_x emission and to prevent over heating of the engine. With increasing EGR rates, the amount of heat rejected to the cooling circuit gradually increases. For an EGR rate of 30% at full load on a 350 kW engine, the EGR cooler needs to have cooling capacity of 100 kW [6]! Taken into account the additional heat form the intercoolers, the total cooling capacity for a high EGR engine needs almost to be doubled in comparison with a conventional 350 kW class engine.

Recent improvements in (EGR) cooling technology may relieve the impact on the cooling system [8], but still EGR cooler design poses challenges with respect to performance, durability and sizing aspects. The EGR cooler is suspect to fouling and corrosion. Corrosion is promoted by condensation, which is of concern especially during low temperature load conditions. The cooling efficiency of the EGR cooler drops, once it is fouled. Catalysts and filters fitted upstream of the EGR cooler can alleviate this issue, but will also increase the cooler back pressure [9].

FUEL INJECTION EQUIPMENT

To comply with 2007 PM targets and beyond, the engine out PM emission needs to be below 0.2 g/kWh, when an overall DPF filtration efficiency of 95% is assumed. An even lower engine out PM level of about 0.1 g/kWh is desired to reduce the DPF regeneration frequency and according fuel penalty, prevent filter plugging, and reduce EGR cooler fouling.

When high EGR rates are applied to reduce engine out NO_x emission, low PM levels can only be accomplished by high pressure fuel injection equipment (up to 2400 bar) [7, 10]. These advanced high pressure diesel injection systems introduce additional costs and parasitic losses affecting the fuel economy.

BASE ENGINE DESIGN

Apart from all the requirements a high EGR engine is posing on the subsystems, the base engine design is also affected. Depending on how far one is pushing to lower NO_x emissions through EGR, requirements on the mechanical components tighten. If the engine power output is kept constant, engine Peak Firing Pressures (PFP) will increase, due to higher injection pressures and high EGR rates. High Peak Firing Pressures (up to 250 bar) are demanding for the cylinder head, gaskets and bearings, and may require different materials for the piston (steel). High boost pressures (up to 4 bar) challenges the intake manifold fastening, construction and seals.

Oil change intervals will have to be shortened due to interference of the high pressure fuel injection jet with the