

A Study on Operation Fluid Consumption for Heavy Duty Diesel Engine Application using both, EGR and SCR

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ABSTRACT

This paper describes a method for optimization of engine settings in view of best total cost of operation fluids. Under specific legal NO_x tailpipe emissions requirements the engine out NO_x can be matched to the current achievable SCR NO_x conversion efficiency. In view of a heavy duty long haul truck application various specific engine operation modes are defined. A heavy duty diesel engine was calibrated for all operation modes in an engine test cell. The characteristics of engine operation are demonstrated in different transient test cycles. Optimum engine operation mode (EOM) selection strategies between individual engine operation modes are discussed in view of legal test cycles and real world driving cycles which have been derived from on-road tests.

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INTRODUCTION

The development of diesel engine concepts is primarily governed by the emission legislation which motivates engine producers to introduce specific technologies such as EGR and exhaust gas after treatment concepts [1], [2]. However in practice the NO_x reduction only by EGR or SCR are partially limited, caused by technical as well economic reasons [3]. Beside of the limitation of harmful exhaust gas species also a legal limitation of CO₂ and other greenhouse gases will be introduced in some industrial nations within the next years. The CO₂ emission is directly linked to the fuel consumption of an engine. The basis for high overall performance is well dimensioned and matched hardware components for both engine and SCR system [4]. However, in spite of that its operating point at minimum CO₂ is not necessarily the optimum operating state from an economical point of view

because SCR systems are required to achieve NO_x emission targets. The latter require Diesel exhaust fluid (DEF) as reducing agent which is proportional to the amount of reduced nitrogen oxides. In contrast to that the fuel consumption of an engine usually falls with an increasing production of nitrogen oxides. Thus, any fuel savings are usually linked to an increase of DEF consumption which means that the sum of both operating fluids must be minimized on the basis of their cost. The characteristics of both the fuel and DEF consumption depend on the applied hardware and the engine operating point. Furthermore, it can be decisively influenced by the operating strategies of engine and SCR system. This is demonstrated by [Figure 1](#) for two different markets (Europe and USA).

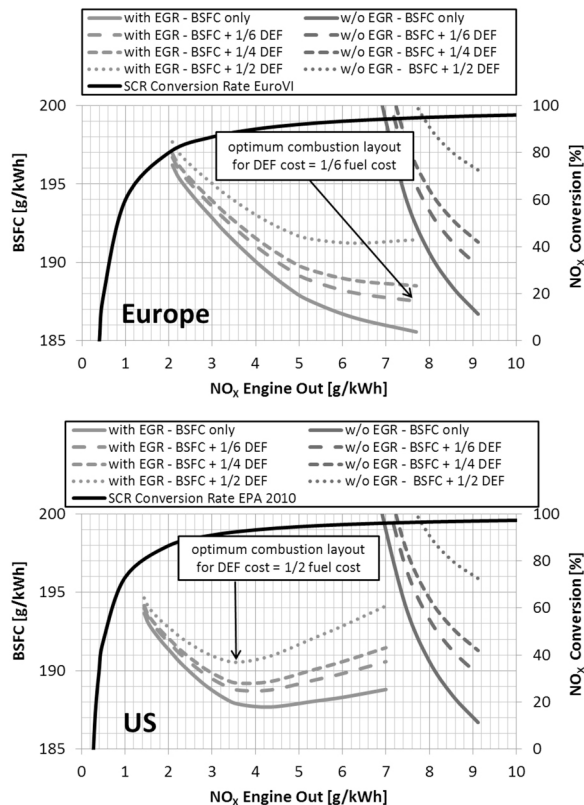


Figure 1. Cost equivalent operating fluid consumption for European and US market - benchmark engines with EGR/SCR combination and SCR only 50% engine speed / 100% engine load

The diagrams plot the following characteristics as function of the NO_x engine out emissions (abscissa) at one engine operating point (50% speed/100% load):

- The NO_x conversion efficiency of the SCR system which is required to reduce the engine out NO_x (abscissa) to the legal value (EURO VI = 0.4 g/kWh; US2010 = 0.27 g/kWh).
- Caused by the lower NO_x tailpipe limit and the higher DEF/Diesel price ratio, a lower NO_x engine out level was preferred for EGR engine applications at US market. Therefore the layout of the charging systems is different, which leads to a different BSFC- NO_x trade off.
- Additionally the fuel consumption characteristics of engines without EGR systems are shown.
- For engines without EGR the NO_x emissions are relatively high. There are only limited ways to reduce the engine-out NO_x emissions which in addition have a strong impact on the fuel consumption.
- For engines with EGR NO_x emissions fall with increasing EGR rate. However, an increasing EGR rate is disadvantageous because it increases scavenging losses and thus lowers the engine cycle efficiency.

• The fuel consumption characteristics with additional DEF consumption. The latter is converted to a “fuel equivalent” on the basis of its relative cost compared to diesel fuel. E.g., $\frac{1}{2}$ DEF means that the DEF cost amounts to $\frac{1}{2}$ of the diesel fuel cost.

It can be seen that the minimum diesel fuel consumption is achieved without EGR at an engine out NO_x emission of > 9 g/kWh. For the reduction of this NO_x emission to the legal levels, conversion efficiencies of $> 95\%$ (EURO VI) respectively $> 97\%$ (US2010) are required. This high NO_x conversion rate implies high DEF consumption.

If the DEF costs are added as “fuel equivalents”, the economic optimum for fuel and DEF consumption shifts towards lower engine out NO_x emission levels (3-8 g/kWh) which reduces the required NO_x conversion efficiency to a range of 91-97%.

Next, the NO_x conversion characteristic in SCR systems is elaborated in more detail. The most dominant parameter for the characterization of the NO_x conversion efficiency is the temperature. Figure 2 shows the NO_x reduction characteristics as function of temperature for a copper zeolite SCR catalyst, a constant NO_2/NO_x ratio of zero and a constant space velocity (SV) of 50000 1/h.

The solid line refers to an admixture of aqueous DEF solution which corresponds to the stoichiometric ratio of the chemical reactions for NO_x reduction ($\text{DEF solution}/\text{NO}_x = 2.06$ g/g). This stoichiometric ratio is denominated as Feed Ratio (FR = 1).

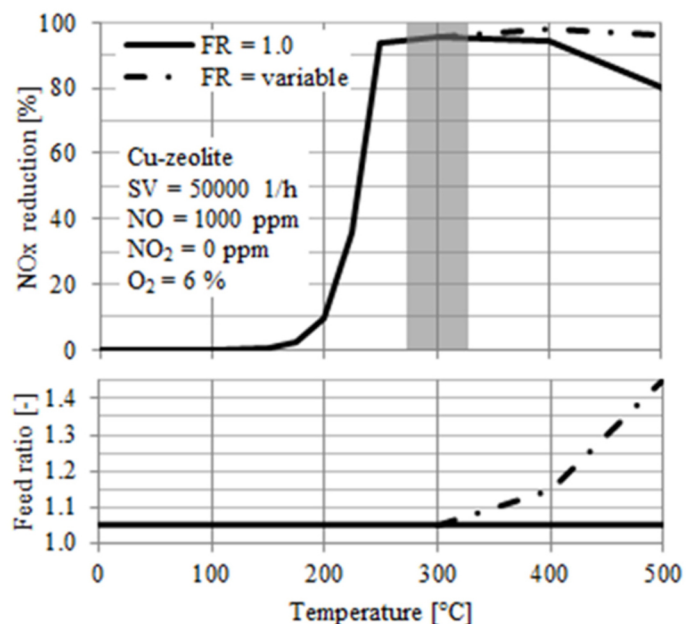


Figure 2. NO_x reduction copper zeolite depending on temperature and feed ratio for constant space velocity

The maximum NO_x reduction is achieved at approximately 300°C. At lower temperatures the chemical

reactions are inhibited which also affects the conversion of urea-solution into ammonia. Below 200°C deposits may be formed [5], thus the dosing of DEF-solution is usually switched off at temperatures below 200°C.

At temperatures above 300°C the conversion efficiency also decreases. At these temperatures NH_3 may directly oxidize which thus lacks for the SCR reactions. However, the loss of NH_3 can be compensated by an overdosage of DEF solution, see lower diagram of Figure 2 - characteristics for a variable feed ratio ($\text{FR} > 1$; dash-dotted line). This operating state must be carefully controlled in order to avoid NH_3 break through and it means a progressive increase in DEF consumption [6]. At 400°C a feed ratio of approximately 1.15 is required in order to keep the high conversion efficiency.

This elaboration clearly indicates that an SCR system has one optimum state of operation. However, it must be evaluated under which conditions this state is optimum from the economic point of view. It is obvious that the production and maintenance of optimum conditions in the aftertreatment system usually requires additional fuel input on the engine side. Consequently, it is often favorable to move away from optimum SCR system conditions and compensate for the lowered NO_x conversion efficiency by a reduction of engine-out NO_x emissions.

The paper describes the definition of frequently used engine operation modes, the development of optimum conditions for each of these modes and optimum switching strategies between individual modes.

TEST SETUP

All results within this paper have been achieved with one test setup. This consisted of a modified production engine, a prototype exhaust after treatment system and an ECU with a bypass to a rapid prototyping control system. Table 1 shows the specifications of the research engine.

Table 1. Data of research engine

Number of cylinders	6
Cylinder arrangement	in-line
Displacement	10500 cc
Compression ratio	17.0:1
Number of valves per cylinder	4
Peak firing pressure	200 bar
Common rail pressure	1800 bar
Charging system	1 stage / VGT
Charge air cooling	air to air
High pressure EGR	cooled – w/o reed valves
Rated speed	1900 rpm
Rated power	297 kW

The following modifications of the production engine were carried out:

- The two stage turbocharging system was replaced by a single stage turbocharger with variable geometry turbine.
- For an active temperature management an intake throttle was installed between charge air cooler and intake manifold

(electrically actuated) and an exhaust flap was installed downstream the turbocharger (electro-pneumatically actuated).

- The high pressure exhaust gas recirculation system was modified and thus laid out for a maximum EGR temperature of 150°C at rated conditions.
- The fuel injection system (Common Rail system; max.1800 bar), the compression ratio and the shape of the combustion bowl were not changed.

The exhaust gas after treatment system is given in Table 2.

Table 2. Exhaust gas after treatment system; sequence of components in exhaust gas flow direction

Diesel oxidation catalyst	8.5 litre – Pt/Pd
Diesel particulate filter	22.2 litre – Pt/Pd
DEF dosing unit	Air supported
Hydrolyses catalyst	8.0 litre
SCR catalyst	25.5 litre - Cu zeolite
Ammonia Slip catalyst	-
Exhaust gas back pressure	20kPa (total aftertreatment system) @ rated point

The production engine control unit (ECU) was extended by a rapid control prototyping system. This contained:

- Closed loop controllers for VGT actuator and EGR valve
- Open loop controllers for exhaust flap and throttle
- Additional functions and algorithms were added for an adaptive engine control strategy which was based on the state of the after treatment system

DESCRIPTION OF ENGINE OPERATION MODES

The engine tests focused on EURO VI legislation. The certification procedure includes the following test cycles:

- WHSC (World harmonized stationary cycle)
- WHTC (World harmonized transient cycle)
- WNTE (Off cycle emissions)
- ISC (In service conformity)

To consider also economic aspects for real world conditions of a long haul truck application an additional cycle was introduced. The origin of this cycle is an on-road vehicle test which was performed on a representative test route.

Different modes of engine operating conditions were defined to fulfill the legal emission limits under consideration of the specific state characteristics of the EAS. They also take into account the economic aspects.

Each EOM has different control mappings for injection timing, EGR rates, VGT position, exhaust flap and throttle