The influence of engine warm up phase on nitrogen oxides emission for heavy-duty Euro VI diesel engine

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Abstract. This article presents test results achieved under World Harmonized Transient Driving Cycle (WHTC) run on heavy-duty diesel engine compliant with Euro VI standard. The emission cycle was performed both for cold and hot engine start up conditions. Modal analysis of emission compounds was carried out with the focus on nitro-gen oxides (NOx) emission. The scope of the work was to assess the influence of cold start effect on selective catalytic reduction (SCR) system operation efficiency. Due to the fact that the urea injection strategy in SCR system can be activated only after certain exhaust gas temperature threshold is achieved, the NOx emission on WHTC cold start cycle is significantly greater than for the hot start one. Result analysis included also determination of time period needed for achieving the readiness of SCR system to work efficiently. The occurrence of ammonia slip emissions downstream SCR was also monitored.

1 Introduction

Current legislative emission limits of passenger and heavy duty vehicles further tighten requirements of emitted NOx. Certification procedures of both vehicle groups include cold start condition as a part of a test cycle. Nevertheless there is a significant difference of cold start influence at test overall outcome between passenger cars and heavy duty engines. The chassis dyno cycle of light vehicles e.g. WLTC comprises cold start as one of the most crucial and influential phase of the test. On the other hand the World Harmonized Heavy Duty Certification Procedure minimalizes the meaning of cold start emission. This procedure incorporates world harmonized steady-state test cycle (WHSC) and transient cold and hot test cycles (WHTC). Regardless presence of cold cycle, its importance at final WHTC result is relatively low giving it only approx. 10% of total value. Consequently, the heavy duty engines after-treatment systems (ATS) do not focus on cold start emissions as much as of light vehicles. Nowadays the most common solution for reducing NOx emission of HD diesel engines is an introduction of Selective Catalytic Reduction to ATS. This, as all catalyst-based cleaning up devices, starts to work effectively only when proper level of exhaust temperature is achieved. This technology meets legislation limits of Euro VI ensuring low NOx emission for rare cold start engine operation. However when a cold start occurs the emission is significantly greater. The investigation of engine out and tailpipe NOx concentration traces clearly outlines engine operation periods practically without NOx after-treatment.

2 SCR operation under engine warm up conditions

Improving the vehicle fuel economy that basically means decreasing of CO₂ emission, is a real technical challenge when it comes to simultaneous reduction of NOx emissions to meet tight legislative limits. Introduction of advanced fuel combustion strategies leads to an improvement of engine efficiency and decreases CO₂ emission, but at the same time causes an increase of raw NOx emission [1]. This in turn requires an application of highly efficient NOx removal systems. Additionally, optimized combustion processes result in dropping exhaust temperature even further and that has an adverse effect on after-treatment system operation, especially in a warm up phase.

Considering the lean NOx after-treatment methods, the selective catalytic reduction (SCR) system provides the highest NOx reduction efficiency and it is the most reliable over entire engine operation range. This basic features make the SCR a dominant technology in the light of current and upcoming stringent NOx emission limits [2, 3]. Further advantages of SCR are durable performance, width of performance window, reasonable cost and also available infrastructure. In order to meet current Euro VI regulations, the average NOx conversion efficiency calculated from cold and hot cycles often needs to exceed the 95% [4-6].

The process of selective catalytic reduction relies on dosing the NOx reduction agent, which is water urea solution, upstream of the SCR catalyst. The atomized into the hot exhaust gas stream urea decomposes in three steps that are physically separated in time and space: evaporation, the thermal decomposition of finely sprayed

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urea into ammonia (NH_3) and isocyanic acid (HNCO), hydrolysis, which would occur along the exhaust pipe prior to the catalyst, and the hydrolysis of isocyanic acid, which would occur on the catalyst surface [7, 8]. When sprayed into the exhaust line, the evaporation of the water decreases the exhaust gas temperature by some 10-15 °C [9]. This cooling effect has an influence on activity, especially in the low temperature region where the conversion is limited. Moreover, there is solid deposit formation in the exhaust and difficulties in dosing at exhaust temperatures below 200 °C.

With urea solution dosed as a reductant, there exists an additional constraint in the lower temperature range, because the conversion of urea to NH_3 in the exhaust line does not take place completely below 200 °C. The limited conversion of isocyanic acid by hydrolysis is perhaps the biggest obstacle facing the use of urea-SCR for achieving high NO_x conversion in urban areas [10, 11] due to low exhaust temperatures. While the SCR catalyst still has activity down to at least 150°C, the urea dosing has to be stopped to avoid formation of deposits and undesired by-products.

A lot of effort is being made to reduce the cold-start emissions, which has become critical in the practical applications and also to improve de NO_x performance in urban driving or other low load conditions. As a result, higher activity of SCR catalysts at low temperatures is desired to effectively reduce real-world NO_x emission while fuel economy requirement has to be simultaneously met. One of the main obstacles is that during low-speed urban driving, the efficient combustion engines generate exhaust gas temperatures below 200 °C, which is insufficient for the conventional urea-SCR based systems [12, 13]

Further development focuses on high-efficiency SCR catalysts with broad temperature windows, with superb thermal durability, with precise control algorithm incorporating ammonia storage capacity, and with the entire after-treatment system optimized to meet the current and emerging NO_x regulations [14-16].

There are already existing solutions and ongoing research works on solid materials delivering already volatile ammonia into exhaust gas. This kind of methods help to faster initialize the SCR system during engine warm up phase and to improve the mixing process in exhaust.

Currently, the-state-of-art de NO_x technology is urea-SCR over primarily CuZ SCR, with relatively wide temperature window, better durability, and low NH_3 slip [17]. In many applications to reduce the NH_3 slip, the additional oxidation clean-up catalyst (CUC) is installed downstream of SCR.

3 Test methodology description

3.1 Test stand

The procedure chosen for testing was the World Harmonized Transient Cycle (WHTC), part of world-wide harmonized heavy-duty certification (WHDC) procedure for engine exhaust emissions. The WHTC is a

transient test cycle with both cold and hot start requirements that lasts 1800 s, with several motoring segments. The execution of certification procedures obligate a test stand capable to fulfill all legislative requirements. BOSMAL's Engine Development Laboratory incorporates highly automated fully dynamic dynamometer with up to date emission measurement instruments.

Fig. 1. Aftertreatment system equipped with selective catalytic reduction system.

The undiluted exhaust gas is measured by two independent sets of analyzers allowing continuous acquisition of engine out and tailpipe emissions. The direct concentration measurement of the following compounds is carried out: total hydrocarbons (THC), methane (CH_4), carbon monoxide (CO), nitrogen oxides (NO_x), nitrogen oxide (NO), oxygen (O_2) and carbon dioxide (CO_2). The results obtained allow to calculate the concentration of non-methane hydrocarbons (NMHC) and nitrogen dioxide (NO_2). Since ammonia (NH_3) emission is expected solely downstream SCR, the NH_3 measurement by laser diode detection instrument is done only at the tailpipe. For the particulate mass (PM) measurement the partial dilution tunnel is applied. The diluted sample is transferred through fine fiber filter which is weighed after test execution. The secondary sample dilution is carried out in order to measure particulate number (PN). The acquired results of gas compounds concentration and particulates are calculated accordingly to legislative formulas and specific values of emission and fuel consumption are obtained [18-20].

3.2 Engine and aftertreatment system

The engine assigned to the testing was a Euro VI compliant heavy duty six cylinder engine of 6.7 L displacement and rated power of 235 kW. The basic features of the engine includes single stage turbocharging and common rail system with maximum fuel injection pressure of 1800 bar. The advanced aftertreatment system allows no-EGR architecture decreasing soot formation and consequently lowering the particulate filter load. The duty of NO_x emission reduction is shifted to the aftertreatment system. The fulfilment of Euro VI limits requires the ATS of high complexity. The system incorporates DOC, DPF, SCR technologies and NH_3 clean-up reactor to minimize

ammonia slip. The SCR functionality is based upon exhaust mass flow and readings of number of sensors: NO_x upstream and downstream ATS, NH₃ at tailpipe and exhaust temperature.

4 Test results and discussion

The WHTC cycle lasts 1800 seconds and it is run from cold and hot engine start. Presented below are total emission results calculated from cold and hot WHTC cycles, compared to Euro VI limits (Table 1).

The profile of NO_x conversion efficiency and basic exhaust and engine parameters of cold and hot WHTC cycles are presented on the Fig. 3 and Fig. 4.

Considering the engine and ATS warm up phase during WHTC cold cycle (Fig. 3) there are three characteristic sub phases that can be distinguished:

Table 1. WHTC total results and EU Emission Standards for Heavy-Duty Diesel.

Stage	WHTC	CO	NMHC	CH ₄	NO _x	PM	PN	NH ₃
		g/kWh					1/kWh	ppm
Euro IV	Euro VI limits	4,0	0,16	0,5	0,46	0,01	6,0·10 ¹¹	10
	WHTC result	0,01	0,0	0,02	0,33	0,0017	2,53·10 ¹¹	0,0

Fig. 2. Aftertreatment system layout with sampling points.

Fig. 3. NO_x conversion efficiency and base operating parameters over WHTC cycle – warm up phases.

Phase I – starts just after engine cranking up and lasts until urea dosing is switched on. During that phase the exhaust gas temperature is too low to start the dispensing of the reducing agent. The catalyst light-off temperature was not yet reached therefore efficiency of catalytic reduction and oxidation processes are very poor. In this phase the lowering of NO_x emission greatly relies on in-cylinder measures such as retarded fuel injection process or post injection. The last aims to increase the pace of catalyst warm up. The duration of phase I is about 470 seconds.

Phase II – extends from the point when desired exhaust temperature is reached and the urea injection starts. The phase lasts until the moment when the SCR system achieves its nominal NO_x conversion efficiency. In this phase the exhaust gas temperatures measured pre SCR for cold and hot cycles converge (Fig. 3) but the NO_x reduction efficiency for the cold cycle is still lower than for the hot one. The response time of the SCR system in NO_x reduction from the start of urea dosing is 60 seconds. The reason for this phenomena can be explained by different thermal state of catalyst substrate and lower SCR saturation with ammonia. The duration time of phase II is approximately 200 seconds.

Phase III – is considered from the time when the traces of NO_x conversion efficiency for both cold and hot cycles are inline and the SCR system efficiency reaches 98% or more. This phase lasts to the end of WHTC cycle with the duration time of 1130 seconds (Fig. 4).

Fig. 4. NO_x conversion efficiency and base operating parameters over WHTC cycle – after warm up.

The length of phases I and II determines the exhaust system warm up. The length of both phases is 670 seconds which is 30% of cold cycle duration. During this period the NO_x emission is noticeably high. There are many technical efforts undertaken to decrease this critical warm up phase. Frequent usage of the vehicle with SCR system on a short distances with cold start events considerably increases the real NO_x emission level.

The effect of engine thermal state on harmful emission components and CO₂ is presented on Fig. 5. It can be seen that the NO_x emission on hot cycle is 65%

lower comparing to the cold one. There is also a great impact of engine warm up on CO and PM emission, as well as on THC and CO₂ compounds.

Fig. 5. Emission components of cold end hot WHTC cycle.

5 Conclusions

A major challenge in the development was the control of cold start NO_x emissions, making thermal management strategies a key component of the project. The engine initial calibration for the cold start portion has been modified, including EGR modifications, multiple injections, intake throttling, and elevated idle speed. The engine reverted to the original, high fuel economy calibration when hot.

Passive NO_x absorbers remain a promising technology for the control of cold start emissions in future low NO_x engines. The formulation stores NO_x below 200 °C and has a peak NO_x release 250 °C. The NO_x storage capacity becomes fully regenerated after exposure to temperatures above 300 °C.

The development of a high-efficiency SCR system for future engines targets at developing SCR formulation capable to achieve 90% of NO_x reduction at 150°C with favourable range of NO/NO_x in exhaust gas, provided by the DOC. Further the urea droplet sizes should be decreased below 10 micron in order to minimize deposits formation at low gas temperature level.

While NO_x emission standards for heavy-duty engines have not changed since 2010, the real world SCR performance has been continuously improving since the launch of SCR equipped engines. In particular, newer SCR equipped engines achieve higher NO_x conversions at low temperature conditions – an important issue identified with many early SCR implementations. Also, the control strategy changes have improved system response and tightened the range of dosing to achieve closer to stoichiometric NO_x/NH₃ conditions.

Further design optimisation is taken into account to minimize NO_x emission at low exhaust temperature. It includes thermal insulation improvement, lowering dosing onset temperature, improved catalysts, and optimized fluid dynamics during urea injection.

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