ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1136262

NO_X-REDUCTION ON HD-VEHICLES-LOW COST QUALITY CHECK

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Abstract

The NO_x reduction of recent HD-vehicle is performed mostly by means of the selective catalytic reduction SCR. There are some manufactures and some applications of SCR as retrofit systems (mostly for the low emission zones LEZ and in combination with a DPF). In charge of Swiss authorities AFHB investigated several SCR-systems, or (DPF+SCR)-systems on HD-vehicles and proposed a simplified quality test procedure of those systems. This procedure can especially be useful for the admission of retrofit systems but it can also be helpful for the quality check of OEM-systems. In the present paper the test procedures will be described and some examples of specific results will be presented. As general conclusions it can be stated:

- *the foundations for the quality verification procedures of SCR-systems are established,*

– *the SCR-systems are not active at lower temperatures < 200°C,*
– *SCR-testing on vehicle is a simple & low-cost tool for quality check,*
– *the overall average NO_x reduction rate depends on the operating profile of the vehicle – for low-load, for cold operation and for interrupted operation (HEV) there are lower NO_x reduction efficiencies.*

Keywords*: Diesel particle filter, regeneration of DPF, non-legislated emissions, selective catalytic reduction SCR, NO_x-reduction, SCR-quality testing, on vehicle testing*

1. Introduction and objectives

The use of deNO_x (especially SCR) systems and the combinations with DPF's offers a large number of variants and technical complexity representing new challenges not only for the manufacturers, but also for the users and for the responsible authorities.

Retofitting with those combined systems is quite challenging and it is possible, in general opinion, mostly through incentives, or restrictions with respect to low emission zones LEZ, [1] and regulations of the respective authorities.

The need of testing the SCR-systems together with vehicle became stronger and the supporting Federal Offices accorded a supplementary project TeVeNO_x (Testing of Vehicles with NO_x reduction systems). In this project 2012–2013 several HD vehicles with SCR (OEM and retrofit) were tested and the test methods on HD chassis dynamometer and on-road were confirmed.

There is an intense research and development of SCR systems and their implementation, [2–6]. As effect significant reduction of the target emission parameters is possible.

The objectives of the present paper are to inform about the testing procedures of the TeVeNO_x project and to show some interesting results from vehicle testing, like:
– steptest with different feed factors,
– urea switch on & off in steptest,
– filtration efficiency of a retrofitted DPF,
– transient operation on chassis dyno and on-road,
– influence of tamb on K_{NOx},
– SCR in HEV operation,
– simple SCR function test on-road.

2. Testing on vehicle and TeVeNO_x procedures

Testing on vehicle in VERT for DPF-systems has the main objective to verify the durability and first of all the reliability of the system regeneration. The filtration efficiency of DPF is independent on vehicle, of the working profile, of position in the exhaust system etc.

For the SCR-systems the influences on the deNO_x-efficiency are much more complex: the temperature profile in exhaust system influences the urea dosing and the efficiency. The multiple chemical reactions in the SCR-system can be influenced by the urea mixture preparation by the position and geometry of the SCR-system in the vehicle exhaust line.

Beside the long-life functionality there is sometimes a need to check the efficiency and some unregulated emission components of a new system.

HD chassis dyno (VPNT2 & VPNT3, TeVeNO_x test Type 1)

The tests on HD chassis dyno shall enable application of more extended analytics and deeper control than the testing on the road. The tests on HD chassis dyno shall be performed with a combined system (DPF+SCR) within the framework of product quality testing twice:
– at the beginning of the field test VPNT2, and
– at the end of the field test as VPNT3.

The testing procedure is at steady state operating points with registering of data during the load transitions. The test objectives are:

– filtration efficiency of the DPF (based on nanoparticle counts),
– quality of the original NO_x-sensors of the SCR system,
– data logging of (p, T) before and after system,
– switch-on/off of urea dosing at different operating points,
– NO_x reduction efficiency (conversion rate K_{NOx}),
– Unregulated components: NO_2, NH_3, HNCO.

After the HD chassis dyno test it is possible to state, that the system and the datalogger control are well prepared for the field test. The results of NO_x reduction in a simple, repetitive operation collective enable the statements about the ageing and functionality after the field trial.

Field control (VPNT2, TeVeNO$_x$ test Type 2)

In this test of 1000h the durability of the system (DPF+SCR) has to be indicated by means of datalogging (p, T, NO_x before/after). The control has to be performed and documented by the user (log book).

The VERT inspections with field measuring apparatus have to take place at the beginning and at the end of the field test period.

At the end a test on chassis dyno (VPNT3) as described above has to be performed.

Short acceptance test (TeVeNO$_x$ test Type 3)

The short acceptance test belongs to each retrofit system (retrofitter quality control). It consists of following procedures:
– installation by the retrofitter,
– standstill measurement of particle filtration and noise (like VERT DPF),
– approx. 10 km test route with 2 NO_x -sensors upstream/downstream (original sensors),
– urea switch off at idling,
– control system, mal function indication, tampering,
– documentation of start of operation signed by retrofitter and owner,
– documentation for submission to the local authority.

3. Test vehicles

Two busses and seven trucks with SCR-systems or with combined (DPF+SCR) - systems were investigated during the project. Results of three vehicles are presented in this paper. Tab. 1 gives the overview of the vehicles, of the used exhaust after treatment systems and the short indications (A, B, E) used in the representation of results.

There was little information about the used SCR-systems. All of them used Vanadium-based SCR-catalysts and AdBlue as reduction agent.

Tab. 1. Investigated vehicles and exhaust after treatment systems

Vehicles		Exhaust system
A	Bus Volvo, 180 kW	DINEX, DPF+SCR, retrofit
B	Bus Volvo Hybrid, 158 kW	OEM, DPF+SCR
E	MAN TGS, 397 kW, 220 km	OEM SCR + DPF retrofit

4. Results

4.1. Stepstests

<u>SWON, SWOFF & different feed factors</u>

Figure 1 shows the time-plots of emissions and exhaust gas temperatures in the steps-cycle:

idling – 2 constant speeds – idling. The steps-cycle was repeated exactly in the same way for tests with RAI and with different feed factors $\alpha = 0.75$ and $\alpha = 0.85$. The exhaust gas temperatures show the warm-up of the exhaust system by passing to the higher engine loads and the thermal inertia of the exhaust system by passing back to the idling.

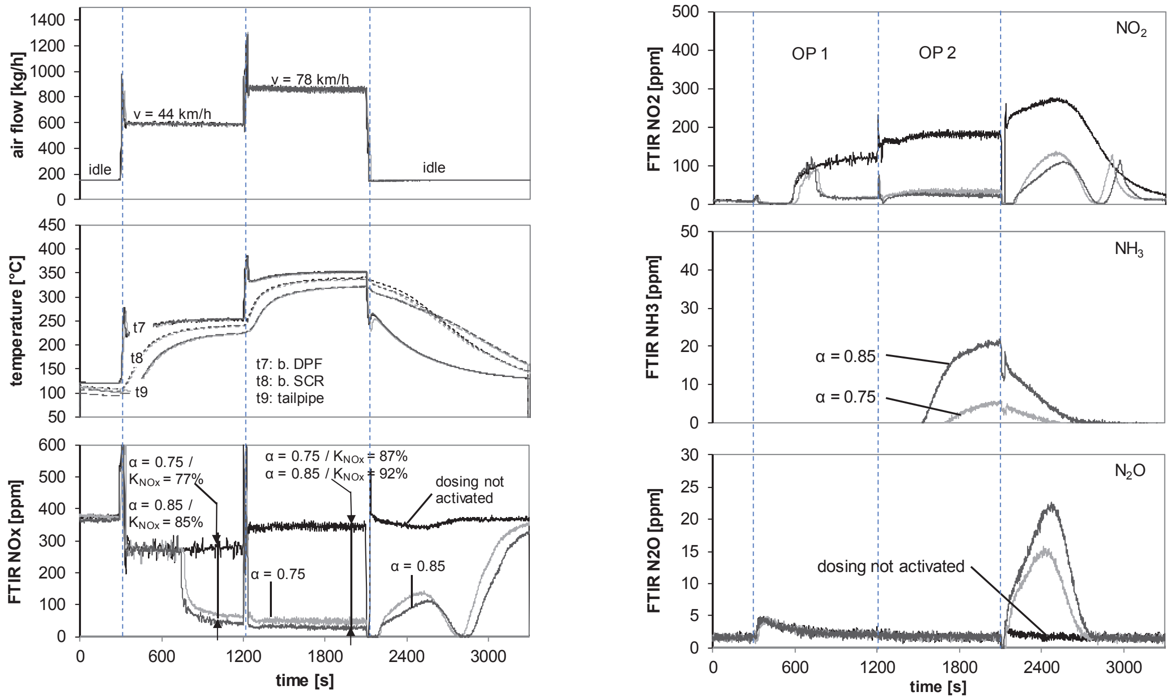

Fig. 1. Step test with different dosing rate after 1000h, retrofit system cDPF and SCR, dosing: not activated / 0.75 / 0.85 vehicle A, ULSD, chassis dyno

The urea switch-on (SWON) is visible after approximately 8 min operation at $v = 44$ km/h – there is a jump-down of NO_x and NO_2. Before that the NO_2 started to increase, because of the cDPF warming up.

At the higher speed $v = 78$ km/h there is a slight emission of NH_3, which decreases after switching down to idling. This emission is much higher with $\alpha = 0.85$ and it suggests an eventual short overdosing during the load jump from 44 km/h to 78 km/h. This can become a source of some residues in the system, which in turn produce a supplementary emission of NH_3 at increasing temperature until being consumed (or until the temperature has been lowered). This mechanism of overdosing and residues is confirmed for both feed factors α.

Summarizing the most important results from Fig. 1 it can be stated, that:

– the active RAI reduces significantly NO_x and NO_2,
– the reduction rates of NO_x (K_{NOx}) are at the lower vehicle speed in the range of 77% and at the higher vehicle speed in the range of 87% (with $\alpha = 0.75$),
– the higher feed factor ($\alpha = 0.85$) increases slightly K_{NOx}, but also increases significantly the NH_3-discharge at higher vehicle speed.

There were no significant emissions of N2O, during the first 3 steps of the test.

DPF filtration quality

Some trucks with OEM-SCR system were refitted in Switzerland with cDPF for air protection reasons. One of the retrofitted DPF's was tested and an excellent filtration quality was found.

Figure 2 represents the nanoparticles size distribution spectra measured before and after DPF with the SMPS-system. In the lowest part of this figure there is the penetration (ratio of particle count passing through the filter to the particle count before filter). The penetration in all investigated OP's varied between 0.03 and 0.0001, which represents a very high filtration quality of the tested DPF.

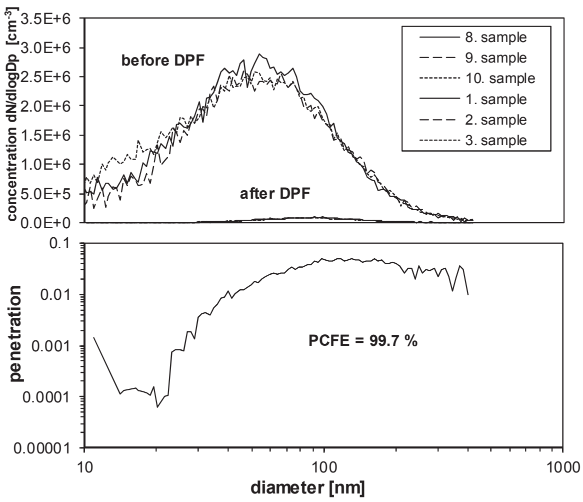

Fig. 2. SMPS size spectra at OP2 and NP-filtration of a retrofitted DPF. OEM SCR, dosing activated, vehicle E, chassis dyno MAN

4.2. Transient operation on chassis dyno and on-road

Influence of ambient temperature on K_{NOx}

Figure 3 gives the overview of average emission values in the FIGE test cycles performed on the HD chassis dyno.

The differences of average temperature during the tests result from the fact, that the hall with the HD-chassis dynamometer was irregularly opened, or closed for other purposes of transport and due to the cold ambient air (winter time) strong dispersion of the air temperature in the measuring hall resulted. This influenced the temperature before SCR and provoked the dispersion of results: integral NO_x, NO_2 and K_{NOx}. NH_3 was only slightly visible at the last test with the highest temperature.

It is clear, that with the lowest ambient temperature there is a lower NO_x reduction rate and the comparative testing on vehicle e.g. before and after field durability period, should be realized at similar ambient conditions.

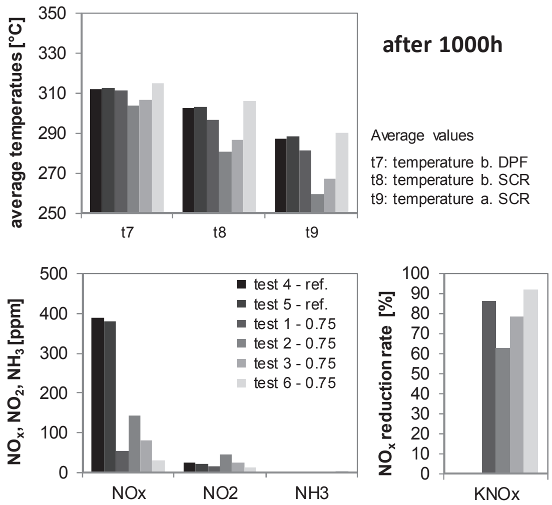

Fig. 3. Emissions in FIGE transcient cycle and sensitivity to t_{amb}, retrofit system cDPF and SCR, α = 0.75 vehicle A, ULSD, chassis dynoSCR in HEV operation

CPK-dataloggers and CPK-NO_x-sensors up- and downstream of the system were installed on a hybrid bus (veh. B) for some months. A complete registration of data could be performed during 48 days.

During the evaluation it was stated, that there was at several days no operation, or very short operation or operation in short intervals with temperature of the NO_x-sensors below 140°C, when they did not register any data.

Finally the data from 14 days were selected as complete and representative for a full-day-operation with warm engine and warmed-up exhaust aftertreatment system. These data showed average NO_x conversion levels between 30% and 67% depending on the operating profile and on the average temperatures of the exhaust system.

The test vehicle was also given for a specific test of AFHB on a defined road circuit. This circuit was chosen in the manner to obtain possibly different traffic situations, as "non-urban" and "motorway".

Figure 4 represents the time-plots of results from one of the trips on the same road circuit. The results are: vehicle speed, altitude, distance, exhaust temperature up- and downstream, NO_x-sensors signals (CPK) up- and downstream.

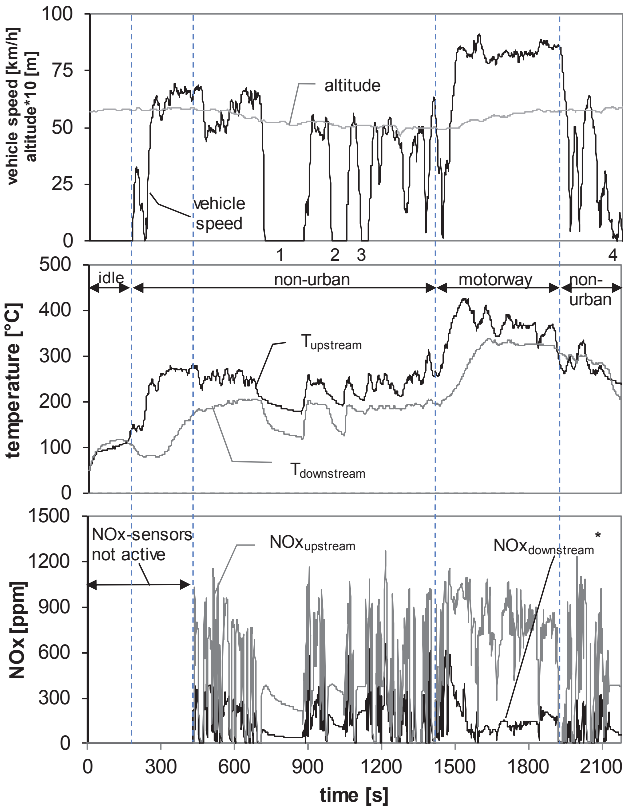

*Fig. 4. Hybrid on road trip – switching off the engine. Vehicle B CRT & SCR, ULSD, AdBlue. 1) railroad crossing – combustion engine off, 2) traffic light – combustion engine off, 3) traffic light – combustion engine on, 4) reverse – combustion engine off. * $NOx_{downstream}$ values from NOx-sensor, without consideration of the cross-sensitivity*

Different traffic situations are marked with numbers. During the stop of vehicle there is mostly a stop of the engine, which is visible by lowering of t_{exh} and NO_x.

At engine switch-off the NO_x-values are first falling down to zero, but after approx. 5–15 seconds they jump up to a certain value and decline slowly during the rest of the engine-stop time.

This effect was repeated and confirmed on engine dyno. It was remarked, that after engine stop and ventilation system still going on, the signal of the NO_x-sensor upstream drops the first. It must be supposed, that there is a stored exhaust gas volume in the exhaust system near to the sensor, or in the sensor, which gives reason for this indication.

In the initial phase of the driving cycle the sensors are not active ($t_{sensors}$ < 140°C). This inactive phase is much shorter with the "warm" started engine and exhaust system.

Simple SCR function test on-road

This SCR function test is a part of the short acceptance test (TeVeNOx Type 3, see section 2 of this paper). This test consisting essentially of warm-up of the system on-road (until urea SWON) and cooling down at idling (until urea SWOFF), with on-line NO_x-measurement is represented in Fig. 1. In OEM-SCR applications there are different interventions of the ECU, which make necessary to modify the simple procedure. These are:

a) Cut-off urea dosing, when the vehicle wheels stop – in this case the SWOFF can be performed, if the vehicle is rolling slowly with near-to-idling engine operation. This has been done on the chassis dyno, but it is hardly possible in the normal road traffic, as it needs a time of 10 to 15 minutes.
b) Engine switch off and on after vehicle stop in the hybrid application. There is a change of engine load directed by the hybrid control system to satisfy the energy demand in the given situation (SOC, auxiliary aggregates etc).

There are nevertheless some periods of stabilized engine operation and stabilized NO_x-values up- and downstream. This enables to estimate the NO_x conversion ratios in this given thermal situation.

After these examples it can be stated that the simple SCR function test on road is possible, but especially for the OEM-applications the procedure has to be adapted to the conditions given by the electronic control system of the vehicle.

5. Conclusions

As general conclusions it can be stated:

– the foundations for the quality verification procedures of SCR-systems are established,
– the SCR-systems are not active at lower temperatures < 200°C,
– SCR-testing on vehicle is a simple & low-cost tool for quality check,
– the overall average NO_x reduction rate depends on the operating profile of the vehicle – for low-load, for cold operation and for interrupted operation (HEV) there are lower NO_x reduction efficiencies.

Other remarkable technical points are:

– higher feed factor α increases slightly K_{NOx}, but also increases significantly the NH3-slip,
– the retrofitted DPF's confirmed their excellent filtration quality (according to VERT/OAPC),
– the ambient temperature influences the average K_{NOx} – the comparative testing on vehicle e.g. before and after field durability period, should be realized at similar ambient conditions,
– for estimate of K_{NOx} different analyzers and sensors can be used,
– the CPK-sensors do not indicate the emissions in the colder parts of driving cycles (at sensor temperature < 140°C); for this reason the CPK-sensors show in their active periods higher K_{NOx}-values, than the average of the colder cycle part. For the hot exhaust aftertreatment system there are no differences of K_{NOx} between "whole trip CLD" and "active time CPK",
– the simple SCR function test on road is possible, but especially for the OEM-applications the procedure has to be adapted to the conditions given by the electronic control system of the vehicle.

Acknowledgements

The authors want to express their gratitude for the financial support and realisation of the project to the Swiss Federal Office for Roads ASTRA and the Swiss Federal Office of Environment BAFU.

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Abbreviations

AFHB	Abgasprüfstelle FH Biel, CH
ASTRA	Amt für Strassen, CH, Swiss Road Authority
BAFU	Bundesamt für Umwelt, CH (Swiss EPA)
cDPF	catalyzed DPF
CPC	condensation particle counter
CPK	supplier of datalogging equipment
dePN	de Particles + deNO_x
DMA	differential mobility analyzer
DPF	Diesel Particle Filter
ECU	electronic control unit
EMPA	Eidgenössische Material Prüf- und Forschungsanstalt
ETC	European Transient Cycle
FIGE	a non-standardized vehicle version of ETC
FOEN	Federal Office of Environment (BAFU)
HD	heavy duty
HEV	hybrid electric vehicle
ICE	internal combustion engines
K_{NOx}	conversion rate of NO_x
LEZ	low emission zones
LRV	Luftreinhalteverordnung
NP	Nanoparticles <999nm (SMPS range)
OAPC	Swiss Ordinance on Air Pollution Control
OEM	original equipment manufacturer
OP	operating point
PC	particle counts
PCFE	particle counts filtration efficiency
PM	particulate matter, particle mass
PMFE	particle mass filtration efficiency
PSD	particle size distribution
RAI	reduction agent injection
SCR	selective catalytic reduction
SMPS	Scanning Mobility Particle Sizer
SOC	state of charge
SP	sampling position
SW	urea switch
SWON	urea switch on
SWOFF	urea switch off
TeVeNO_x	Testing of Vehicles with NO_x reduction systems
TTM	Technik Thermische Maschinen
UDS	urea dosing system
ULSD	ultra low sulfur Diesel
VERT	Verminderung der Emissionen von Realmaschinen in Tunelbau
VERTdePN	VERT DPF + VERT deNO_x
VPNT1, 2, 3	VERTdePN Test 1, 2, 3 – engine dyno
VPNTSET	VERTdePN secondary emissions test - engine dyno
α	feed factor of urea dosing; ratio: urea injected / urea stoichio-metric; calculated by the ECU.