Testing of SCR-Systems on HD-Vehicles-TeVeNO_x

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Abstract

The selective catalytic reduction SCR is extensively used for NO_x reduction of recent HD-vehicles.

There are some manufacturers 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.

The project name was TeVeNO_x - Testing of Vehicles with NO_x reduction systems.

In the present paper the test procedures will be described and some specific results will be discussed.

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 has more importance than DPF testing on vehicle and 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.

Introduction & 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.

Retrofitting 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 Swiss Federal Office of Environment BAFU and the Swiss Federal Roads Office ASTRA decided to support the activities of VERT to develop appropriate testing procedures and to define the quality criteria of dePN systems.

Laboratories for IC-Engines and Exhaust Emission Control of the University of Applied Sciences Biel, Switzerland (AFHB) participate since 1992 at the Swiss activities about nanoparticle analytics and DPF verification and since 2006 about the quality of SCR- and (DPF+SCR) - systems.

The need of testing the SCR-systems together with vehicle became stronger and the supporting Federal Offices accorded a supplementary project TeVeNOx. 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, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. As effect significant reduction of NOx-emission is possible.

The objectives of the present paper are to inform about the testing procedures of the TeVeNOx project and to show some interesting results from vehicle testing, like:

- steptest with different feed factors,
- urea switch on & off in steptest,
- estimate of NOx reduction rate with different analyzers,
- filtration efficiency of a retrofitted DPF,
- transient operation on chassis dynamometer and on-road,
 - influence of ambient temperature on NOx-reduction rate K_{NOx} ,
 - SCR in HEV operation,
 - estimate of KNOx with 1, or with 2 sensors,
 - SCR in Diesel-CNG operation,
- simple SCR function test on-road.

Testing on Vehicle & TeVeNOx 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 deNOx-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.

The ageing of SCR-catalysts can lower the conversion rates (this in opposite to DPF-materials, which increase the filtration efficiency with ageing). The reliability of urea injection, dosing and mixing, as well as the limitation of production of deposits are other important objectives of the long-life-testing.

In this situation the vehicle testing gains much more importance.

Vehicle testing of the combined systems was started in the VERTdePN project together with the manufacturers and users of those systems. In [14] it was proposed as Swiss NO Retrofit Benchmark (SNORB).

In the project TeVeNOx the vehicle testing was continued on several vehicles. Three types of test procedures are used to fulfil the objectives, which were elaborated in the VERTdePN project. These test procedures are to be performed on HD-chassis dynamometer and on the road.

Following sections describe briefly the actually used procedures.

HD Chassis Dynamometer (VPNT2 & VPNT3, TeVeNOx Test Type 1)

The tests on HD chassis dynamometer shall enable application of more extended analytics and deeper control than the testing on the road. The tests on HD chassis dynamometer 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 and measuring parameters are:

- filtration efficiency of the DPF:
 - apparatus (alternatively): CPC, SMPS, PAS, DC, or DiSC.

The filtration efficiency does not need to be investigated for the VERT/LRV-approved DPF's

- quality of the original NO_x-sensors of the SCR:
 - apparatus: NO, NO₂, NO_x external CLD, access to the original NO_x-signals,
- datalogging of (p, T) before system:
 - apparatus: datalogger installed and operative as for field test, remote control (if available),
- switch-on/off of urea dosing:
 - SW-procedure: warm up at low load and transition to the higher load with all necessary data acquisition; after stabilisation at high load go back to the low load. This procedure should be repeated 1 or 2 times, documented and be a reference for the control after field test (VPNT3),
- NO_x reduction efficiency:

calculated from the results at higher operating point with urea dosing (other operating points with the required range of exhaust gas temperature can be used, according to the necessity).

The NO_x reduction efficiency (RE), called also NO_x-conversion rate K_{NOx} , or deNO_x rate, is calculated:

$$RE_{NOx} = \frac{NO_x \text{ before} - NO_x \text{ after}}{NO_x \text{ before}} \cdot 100\%$$

before, after SCR (or system)

Instead of measuring "before" system the results "without" system as reference can be used.

- Unregulated components:

NO₂ ... CLD
 NH₃ ... double reactor CLD, or other measuring devices, like FTIR, or impingers with integral sampling over a defined operational profile (sporadic measurement for special requirements).
 HNCO FTIR, or impingers with integral sampling over a defined operational profile (sporadic measurement for special requirements).

After the HD chassis dynamometer 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, TeVeNOx 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 dynamometer (VPNT3) as described above has to be performed.

Short Acceptance Test (TeVeNOx 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.

Road Benchmarking (TeVeNOx Test Type 2)

The real world road benchmarking was previously proposed and was performed with several vehicles during the TeVeNOx project.

The test can be performed with a given vehicle (truck) on a similar test loop in identical traffic situation and in similar atmospheric conditions with/without urea dosing. The NO_x-measurement can be performed by means of a portable on-board apparatus with on-line storage of the data. The driving speed and the exhaust temperature of vehicle can also be registered to give the information about the performed operating profile and about active or inactive SCR.

This method is not very exact in the strict sense, but it yields very useful average information about the deNO_x rates.

The road benchmarking is easy to perform and can be used by the authorities to verify and to classify the real efficiencies of deNO_x systems in the given conditions. Road benchmarking is not required in the VERTdePN quality procedures.

Test Vehicles, Instrumentation & Procedures

Two buses and seven trucks with SCR-systems or with combined (DPF+SCR) - systems were investigated during the project. [Table 1](#) gives the overview of the vehicles, of the used exhaust aftertreatment systems and the short indications (A, B, C...) 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. One exception is the NOxOFF retrofit system, which uses Ammonium Hydroxide (10% NH₃ in H₂O) as reduction agent - system no more in production.

Table 1. Investigated vehicles & exhaust aftertreatment systems

Vehicles		Exhaust system
A	Bus Volvo 180 kW	DINEX DPF+SCR retrofit
B	Bus volvo Hybrid 158 kW	OEM DPF+SCR
C	Mercedes Actros 300 kW 570 km	OEM SCR
D	Mercedes Actros 300 kW 500520 km	OEM SCR
E	MAN TGS 397 kW 220 km	OEM SCR + DPF retrofit
F	Mercedes Actros Blutech 6	OEM CRT+SCR
G	DAF Truck 340 kW	OEM SCR
H	MAN TGS 400 kW	OEM SCR 00KM
I		OEM SCR 84.9 T km
J	Mercedes Actros 260 kW	NOxOFF DPF+SCR retrofit

[Fig. 1](#) gives an example of an investigated truck on HD chassis dynamometer.

At each tested vehicle different sampling positions were prepared to enable the measurements with different analyzers and sensors.

[Fig. 2](#) shows an example of sampling arrangements on vehicle F at "engine-out" and "tailpipe".

In some cases, because of little space it was not possible to apply the sampling position before the system.

Figure 1. Vehicle E on the MAN HD chassis dynamometer with OEM SCR & retrofitted DPF.

Figure 2. Sampling positions on vehicle F

tailpipe

Figure 2. Sampling positions on vehicle F

Test Equipment for Exhaust Gas Emissions

The Laboratory for Exhaust Emissions Control (AFHB) of the Berne University of Applied Sciences Biel-Bienne, Switzerland is charged by the Federal Office for Environment (BAFU) to perform the field control of machines and vehicles, which are retrofitted with the DPF's.

For the control of gaseous emissions an Anapol EU-5000 portable exhaust gas analyzer with heated line is used. Following components are measured:

CO, CO ₂	... infrared detector NDIR
HC _{IR}	... infrared detector (HC 6), NDIR
NO, NO ₂ , O ₂	... electrochemical cells.

Other NO_x-measuring instruments were selectively used for comparison:

- Eco Physics CLD 822 ht with heated line, (abbreviation 2 CLD; double reactor CLD),
- Horiba MEXA 120 electrochemical NO_x-sensor up- and downstream of the DPF-system,
- CPK NO_x-sensors up- and downstream of the SCR-system.

In research laboratories, which have at their disposal other measuring systems, like FTIR, Horiba, AVL etc. These systems are used and are considered as excellent and sufficient alternatives for the quality testing.

The validation of the DPF filtration efficiency was not a primary objective of this project, but nevertheless some controls were performed.

Particle Size Analysis

The particle size and counts distributions were analysed with following apparatus:

- SMPS - Scanning Mobility Particle Sizer, TSI (DMA TSI 3081, CPC TSI 3010 S)
- NanoMet - System consisting of:

- DC - Diffusion Charging Sensor (Matter Eng. LQ1-DC)
- MD19 tunable minidiluter (Matter Eng. MD19-2E).

Thermoconditioner (TC) (i.e. MD19 + postdilution sample heating up to 300°C).

Procedures

The vehicles were tested on HD chassis dynamometers and on the road.

The concept of the testing procedures was set to enable the use of simpler chassis dynamometers, which are able to perform a power braking only at constant operation. In case of a dynamic chassis dynamometer was available; the dynamic cycles on chassis dynamometer could replace the road-driving.

On the HD chassis dynamometer at least 3 operating points of the engine were performed. The injection of reduction agent was switched on and off by means of changing the operating points of the engine.

On the road the same route was driven once with active and once with inactive urea injection according to the possibility. The driving speed was registered by means of GPS and NO_x and tailpipe temperature were measured on-line.

For the retrofit systems it is possible to deactivate the reduction agent injection (RAI) by means of the system-ECU. By the OEM-SCR-systems this access is not given and to obtain the reference values on-road without active SCR sometimes the urea injector was removed from the exhaust/pipe and the Ad-Blue was injected to an external recipient - an intervention, which is no more possible with the last generation of OBD.

Results

Stepstests

SWON, SWOFF & Different Feed Factors

Fig. 3 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.

Figure 3a. Step test with different dosing rate after 1000h; retrofit system cDPF & SCR; dosing: not activated / 0.75 / 0.85 vehicle A; ULSD; chassis dynamometer

Figure 3b. Step test with different dosing rate after 1000h; retrofit system cDPF & SCR; dosing: not activated / 0.75 / 0.85 vehicle A; ULSD; chassis dynamometer

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 & 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 .

Figure 4. Switching back to idle; retrofit system cDPF & SCR; $\alpha = 0.75$ vehicle A; ULSD; chassis dynamometer

Summarizing the most important results from Fig. 3 it can be stated, that:

- the active RAI reduces significantly NO_x and NO_2 ,
- the reduction rates of NO_x (K_{NO_x}) 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 N_2O , during the first 3 steps of the test.

The extended running time in idling at the end of the test showed an interesting superposition of following effects, Fig. 4:

- by switching down the engine power the urea dosing system (UDS) adapts the injected urea quantity according to the reduced engine air consumption; there is in the 1st period of approx. 1.5 min a total elimination of NOx & NO_2 because of: lowering the engine-out emissions and abundant presence of reducing agent;
- cooling-down of the cDPF to the temperature range of the maximum NO_2 -production causes a significant production of NO_2 and with it also an increase of NOx ; this period takes approx 7.5 min and also causes an increased emission of N_2O - up to 20 ppm;
- after this period there is still urea dosing and abundance of reducing agent for the next 2.5 min, NOx & NO_2 are shortly eliminated, but due to the switching-off urea, they again start to increase;
- NOx increases (from the time 2800s) up to the value of "cool" idling before the test; NO_2 increases first together with NOx , but the catalytic activity of the cDPF cooled down stops (from the time 2900s) and NO_2 decreases back to the very low value of "cool" idling.

It has to be remarked, that these observed effects are connected with: the given SCR-system, the control of UDS and quality of urea homogenization, engine operation and thermal inertia of the exhaust system.

Different NO_x -Analyzers

For measurements of NO_x and for the estimate of K_{NOx} different analyzers and sensors can be used. If the urea SW-on is used, it is sufficient to apply only one sampling point at tailpipe.

Fig. 5 represents the results at SWON with 3 analyzers.

In the 1st step ($P_{wheel} = 30kW$) there is a start of the AdBlue injection, which is visible by means of all NOx -measuring devices (2CLD, MEXA & Anapol) indicating a drop of NOx (pt. 3).

The step duration was too short to obtain a stationary NOx -value with RAI in the 1st step. The NOx value with RAI in the 2nd step is supposed to be very close to this one in the 1st step, so it was used for estimate of K_{NOx} . This K_{NOx} (84% for Anapol and 86% for 2CLD) is very close to the average result from previous measurement (83.9%).

The confidence ranges of K_{NOx} estimate were for Anapol $\pm 1\%$ and for 2CLD $\pm 0.5\%$

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 5. K_{NOx} at SWON in step test with different analyzers. OEM SCR; dosing activated; vehicle E; ULSD; chassis dynamometer MAN

Fig. 6 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.

Transient Operation on Chassis Dynamometer and On-Road

Influence of Ambient Temperature on K_{NOx}

Fig. 7 gives the overview of average emission values in the FIGE test cycles performed on the HD chassis dynamometer.

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 NOx , NO_2 & K_{NOx} . NH_3 was only slightly visible at the last test with the highest temperature.

Figure 6. SMPS size spectra at OP2 and NP-filtration of a retrofitted DPF. OEM SCR; dosing activated; vehicle E; chassis dynamometer MAN

Figure 7. Emissions in FIGE transient cycle & sensitivity to t_{amb} ; retrofit system cDPF & SCR; $\alpha = 0.75$ vehicle A; ULSD; chassis dynamometer

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

SCR in HEV Operation

CPK-dataloggers and CPK- NOx -sensors up- & 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 NOx -sensors below $140^{\circ}C$, 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 NOx conversion levels between 30% and 67% depending on the operating profile and on the average temperatures of the exhaust system.

- 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

Figure 8. Hybrid on road trip - switching off the engine. Vehicle B CRT & SCR; ULSD; AdBlue

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”.

Fig. 8 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,
- NOx-sensors signals (CPK) up- and downstream.

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} & NOx.

At engine switch-off the NOx-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 dynamometer. It was remarked, that after engine stop and ventilation system still going on, the signal of the NOx-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 ($t_{\text{sensors}} < 140^{\circ}\text{C}$). This inactive phase is much shorter with the “warm” started engine and exhaust system.

Estimate of K_{NOX} On-Road with 1, or with 2 Sensors

For the on-road testing of vehicle F the CPK sensors before/ after system and 2 CLD with heated line were used. First 3 trips (trips 1, 2, 3) were performed with the CLD at “engine out” position (EO, before DPF+SCR system) and 3 further trips (trips 4, 5, 6) were performed with CLD at tailpipe (TP, after system).

The NOx-traces with CPK sensors are interrupted, when the sensor temperature is falling below 140°C . This is a protection measure of the sensors and as consequence there is only partial information about the measured NOx-emissions. This information is given in working periods with warmer exhaust and consequently with higher K_{NOX} .

To study the question, how reliable would be the estimate of K_{NOX} with 1 sensor only, the CLD results were also considered in the limited periods of active SCR and active CPK sensors.

The estimate of K_{NOX} with 1 sensor only means to drive a circuit with active RAI and with time-measurement of NOx at TP and afterwards to drive the same circuit with deactivated RAI. This is applicable for the SCR-systems, having only 1 NOx-sensor downstream.

The present results from 6 trips were used to estimate the K_{NOX} -values in the active periods of CPK & SCR in two ways:

- measurement only with 1 sensor (CLD) EO, or TP: use of one reference value (EO) for more results (TP) from other trips (here: trips 4, 5, 6) see Fig.9,
- simultaneous measurement with 2 sensors (CPK) EO & TP, in all trips.

- Figure 9. Measurements with 2 CLD in 6 trips & estimate of K_{NOX} with 1 sensor only
- 2 sensors simultaneously

In Fig. 10, the method of estimate “1 sensor only” was applied to the CPK-results and compared with the CLD-results. There are represented:

- K_{NOX} in trips 4, 5, 6 with reference values from trips 1, 2, 3 - estimate “1 sensor only” with CLD and with CPK,
- K_{NOX} in all trips -estimate “2 sensors simultaneously” with CPK.

It has to be remarked that trip 1 was with a cold start and trip 3 was started after longer cooling period.

With consideration of “cold” trips 1 & 3 of the simultaneous measuring method (2 CPK sensors) the dispersion (COV) of K_{NOX} is higher. In opposite to that the method of “1 sensor” shows less dispersion of results and does not recognize the K_{NOX} -differences between “cold” and “warm”.

It can be summarized that: the “1 sensor” method offers at warm operation of the exhaust system the same information about the average K_{NOX} -values, as the “2-sensors” method. For “cold” cycles the “1 sensor” method is less selective and does not indicate the K_{NOX} -differences between “cold” and “warm”.

Fig. 11 shows the estimates of K_{NOx} -values over whole trip (CLD) or over active time (of CPK + SCR). The logic of evaluations in this figure is the same as in the previous considerations.

Figure 10. Comparison of K_{NOx} -dispersion between 2 measurement types: with 1 sensor only and with 2 sensors simultaneously. Periods of active SCR & CPK sensors; vehicle F; ULSD; AdBlue; dosing activated.

The most important statement is: as colder is the exhaust aftertreatment system during a part of the trip, as lower is the average K_{NOx} -value in this period. The CPK-sensors are less active and cannot indicate all emissions. In the active periods the CPK-sensors show 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".

Figure 11. Comparison of K_{NOx} -values from different periods of the trip ① 2CLD whole trip → ② CPK & SCR active time. Vehicle F; ULSD; AdBlue; dosing activated.

SCR in Diesel-CNG Operation

Research on vehicle G has been performed on the HD chassis dynamometer at bi-fuel operation: Diesel fuel and Diesel/CNG. The vehicle was equipped with an OEM-SCR-system and retrofitted with a system, which interacts with the electronic control of the engine and can replace a part of the Diesel fuel by a gaseous fuel CNG, LNG, LPG or other gaseous fuels.

This system yields an electronically controlled multipoint gas injection in the intake channels of individual cylinders. In the case of the present DAF truck there is no Lambda regulation and no 3-way-catalyst attached. The Diesel substitution rate at transient operation is 40-50% - according to the external information.

Fig. 12 shows the results of following FIGE-cycles, which were performed in this time sequence:

- FIGE 1, engine cold, high load, Diesel,
- FIGE 2, engine warm, high load, Diesel,
- FIGE 3, engine cold, low load bi-fuel,
- FIGE 4, engine warm, high load, bi-fuel,
- FIGE 5, engine cold, low load, Diesel.

The last part of FIGE 4 was performed with Diesel fuel only, since the CNG-reserve was finished and FIGES 5 was a repetition with Diesel fuel.

It can be remarked that there is a very high emission of HC with CNG-addition and for the cold cycle HC are much higher, than for the warm cycle. In Diesel-fuel operation there is a

slight Ammonia slip originating from the deposits, which were previously accumulated. The CNG operation enabled the elimination of these deposits and there are no more traces of NH₃ in the last cycle with Diesel-fuel (FIGE 5).

The NO_x-traces with CPK sensors are interrupted, when the sensor temperature is falling below 140°C. This is a protection measure of the sensors and as consequence there is only partial information about the measured NO_x-emissions.

Except of the period, when the CPK-sensors are not active, there also is a period, when SCR is not active due to low temperature and no RAI activated.

Table 2 summarizes the average K_{NOx} -values obtained in the FIGE cycles:

Table 2. Average values of K_{NOx} in FIGE-cycle; OEM SCR; dosing activated; CNG retrofit; Vehicle G; Euro V; ULSD; chassis dynamometer JRC

Diesel

K_{NOx} %	FIGE1		FIGE2		FIGE5	
fuel	ULSD		ULSD		ULSD	
load dyno	high		high		low	
engine	cold*		warm		cold**	
integral	w hole test	SCR on	w hole test	SCR on	w hole test	SCR on
AMA	57	71	68	72	55	66
CPK***	62	70	69	71	58	65

* Longer cooling period

** Very short cooling period

*** NO_x sensors are not active during the first part of the test.

Bi-fuel

K_{NOx} %	FIGE3		FIGE4 ¹⁾	
fuel	ULSD		ULSD	
load dyno	high		high	
engine	cold*		warm	
integral	w hole test	SCR on	w hole test	SCR on
AMA	17	29	50	60
CPK***	19	32	50	60

*** NO_x sensors are not active during the first part of the test.

1) Last part of test only with diesel (no CNG)

¹⁾ Last part of FIGE4 only with diesel (no CNG)

Figure 12. Average emission in FIGE with ULSD & Bi-Fuel. OEM SCR; dosing activated; Vehicle G; Euro V; chassis dynamometer JRC

For the cold cycle the K_{NOx} over whole test is much lower, than the K_{NOx} during "SCR on". For the warm cycle this tendency is less pronounced. In the bi-fuel operation the investigated SCR-system attains the K_{NOx} -values over whole cycle between 19% for cold cycle and 50% for warm operation.

In the monofuel operation (ulsd) there are generally higher NO_x reduction rates - for whole cycles between 55% (cold) and 69% (warm).

An important parameter, which influences the NO_x-reduction is the average exhaust temperature. At stationary operation t_{exh} is higher for bi-fuel-operation, at dynamic operation t_{exh} -average is lower. So are the relationships of K_{NOx} -values too. Obviously these relationships are dependent on the choice of the operating conditions.

Other significant influences of the bi-fuel operation on the emissions are:

- much higher CO-values
- much higher HC-values (mostly Methane, Ethane & Ethene)
- increase of Formaldehyde and Acetylaldehyde
- increase of Sulfur Dioxide.

For the bi-fuel operation there is the same exhaust aftertreatment system (SCR). The lowest hydrocarbons are most stable and cannot be sufficiently oxidized in this system. The surplus of Sulfur is believed to originate from the used gaseous fuel.

Simple SCR Function Test On-Road

This SCR function test is a part of the short acceptance test (TeVeNO_x Type 3, see section 3 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. 3. In OEM-SCR applications there are different interventions of the ECU, which make necessary to modify the simple procedure. These are:

- 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 dynamometer, but it is hardly possible in the normal road traffic, as it needs a time of 10 to 15 minutes.
- Adaptation of the low load engine power to the needs of the on-board energy consumption - Fig. 13 shows the intervention of ECU after long idling and the results of NO_x during vehicle stop and urea cut-off. By the test "with dosing activated" the total elimination of "NO_xout" during approx. 45s after urea cut-off is a repetitive effect and can be regarded as a prove of the functionality of RAI. The estimate of K_{NOx} nevertheless is not possible.
- Engine switch off & on after vehicle stop in the hybrid application. Fig. 14 shows the traces of t_{exh} & NO_x up- and downstream in the period after vehicle stop (approx. 12 min).

After the 1st engine cut-off (period II) the NO_x-sensors show higher signals, than after the 2nd engine cut-off (period IV). This is a sign, that the temperature of the sensors plays an important role in indicating the NO_x-values at engine standstill.

During the engine switch-on (period III) there is a sudden change of NO_x-level. This indicates a change of engine load directed by the hybrid control system to satisfy the energy demand in the given situation (SOC, auxiliary aggregates etc).

In the engine run period III there are some periods of stabilized engine operation and stabilized NO_x-values up- & downstream. This enables to estimate the NO_x conversion ratios in this given thermal situation.

Figure 13. SWOFF - ECU intervention after long idling period. OEM SCR; dosing OP2 activated; Vehicle D; ULSD, chassis dynamometer LARAG

Figure 14. HEV: Engine switch off & on after vehicle stop, dependant on battery SOC. Vehicle B, CRT & SCR; ULSD; AdBlue

Similar results with nearly the same K_{NOx} -values were obtained from three performed trips. This suggests that there is a sufficient repeatability and this estimate could be used for quick quality control of the deNOx-systems.

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.

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 has more importance and is a simple & low-cost tool for quality check,
- The overall average NOx reduction rate depends on the operating profile of the vehicle - for low-load, for cold operation and for interrupted operation (HEV) there are lower NOx reduction efficiencies.

Other remarkable technical points are:

- higher feed factor α increases slightly K_{NOx} , but also increases significantly the NH_3 -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 average K_{NOx} -values in a road trip can be estimated with "1 sensor only" (2 trips with/without RAI), or with "2 sensors" (simultaneous measurements during 1 trip) - the "1 sensor" method offers at warm operation of the exhaust system the same information about the average K_{NOx} -values, as the "2 sensors" method. For "cold" cycles the "1 sensor" method is less selective and does not indicate the K_{NOx} -differences between "cold" and "warm",
- a bi-fuel operation Diesel-CNG with a retrofitted CNG system showed a significant lowering of the NOx reduction rate and a significant increase of the CO- and HC-values,

- 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.

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Abbreviations

AFHB - Abgasprüfstelle FH Biel, CH
ASTRA - Amt für Strassen, CH, Swiss Road Authority
BAFU - Bundesamt für Umwelt, CH (FOEN)
cDPF - catalyzed DPF
CLD - chemoluminescence detector
CNC - condensation nuclei counter
CNG - compressed natural gas
COV - coefficient of variance
CPC - condensation particle counter
CPK - supplier of datalogging equipment
CRT - continuously regenerating trap
DC - diffusion Charging Sensor
dePN - de Particles + deNO_x
DI - Direct Injection
DiSC - diffusion size classifier
DMA - differential mobility analyzer
DPF - Diesel Particle Filter
ECU - electronic control unit
EMPA - Eidgenössische Material Prüf- und Forschungsanstalt
ETC - European Transient Cycle
EO - engine out
FE - filtration efficiency
FID - flame ionization detector
FIGE - a non-standardized vehicle version of ETC
FL - full load
FOEN - Federal Office of Environment (BAFU)
FTIR - Fourier Transform Infrared Spectrometer
HD - heavy duty
HEV - hybrid electric vehicle
ICE - internal combustion engines
K_{NOx} - conversion rate of NO_x (see p. 2)

LEZ - low emission zones
LRV - Luftreinhalteverordnung (OAPC)
ME - Matter Engineering
MD19 - heated minidiluter
NanoMet - NanoMetnanoparticle summary surface analyser (PAS + DC + MD19) PAS + DC + sampling & dilution unit
NP - nanoparticles < 999 nm (SMPS range)
OAPC - Swiss Ordinance on Air Pollution Control (LRV)
OEM - original equipment manufacturer
OP - operating point
PAS - Photoelectric Aerosol Sensor
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
RE - reduction efficiency
SCR - selective catalytic reduction
SMPS - Scanning Mobility Particle Sizer
SNORB - Swiss NO Retrofit Benchmark
SOC - state of charge
SP - sampling position
SW - urea switch
SWON - urea switch on
SWOFF - urea switch off
TC - thermoconditioner. Total Carbon
TeV_{NOx} - Testing of Vehicles with NO_x reduction systems
TP - tailpipe
TTM - Technik Thermische Maschinen
UDS - urea dosing system
ULSD - ultra low sulfur Diesel
VERT - Verification of Emission Reduction Technologies, www.vert-dpf.eu
VERTdePN - VERT DPF + VERT deNO_x
VPNT1 - VERTdePN Test 1 - engine dynamometer
VPNT2 - VERTdePN Test 2 - field durability 1000h
VPNT3 - VERTdePN Test 3 - check after field test chassis dynamometer
VPNTSET - VERTdePN secondary emissions test - engine dynamometer
VSET - VERT Secondary Emissions Test
α - feed factor of urea dosing; ratio: urea injected / urea stoichio-metric; calculated by the ECU.

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