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TeVeNOx – Testing of SCR-Systems on HD-Vehicles

TeVeNOx - Testen von SCR-Systemen an schweren Motorfahrzeugen

TeVeNOx - Investigations des systèmes SCR sur les véhicules automobiles lourds

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Zusammenfassung

Die selektive katalytische Reduktion (SCR) ist breit angewendet, um die NOx Emissionen der Nutzfahrzeuge zu mindern. Es gibt manche Hersteller und manche Anwendungen von SCR als Nachrüstsysteme (meistens für die „Low Emission Zones“ LEZ und in Verbindung mit einem DPF).

Im Auftrag der Schweizer Behörden hat AFHB einige SCR-Systeme, oder (DPF+SCR)-Systeme auf Nutzfahrzeugen untersucht und einfache Qualitätsprüfprozeduren dieser Systeme vorgeschlagen. Diese Prozeduren können insbesondere für die Zulassung der Retrofit Systeme gebraucht, jedoch auch für die Qualitätsprüfung der OEM-Systeme nützlich werden.

Der Kurzname des Projektes ist TeVeNOx „Testing of Vehicles with NOx reduction systems“.

Alle untersuchten und auch am Markt verfügbaren Systeme nutzten Urea-Wasser-Lösung (Ad-Blue) als Reduktionsmittel.

Die Tests wurden am Nutzfahrzeug-Rollenprüfstand bei Stationären Betriebspunkten und auf einer wiederholbaren Fahrstecke auf der Strasse durchgeführt. Die Messungen wurden gemäss der Testprozeduren durchgeführt, welche in dem internationalen Netzwerk-Projekt VERT*)dePN (de-activation, decontamination, disposal of particles & NOx) entwickelt und in dem vorliegenden Projekt TeVeNOx angewendet wurden.

Während der Tests wurde für CO, CO_2, HC, NOx und NO_2 das AFHB-Feld Messgerät gebraucht.

Für NOx wurden der Doppelreaktor-CLD, der elektrochemische Sensor Horiba MEXA 120 und die NOx-Sensoren (CPK) verwendet.

Es gab einige DPF-Systeme an den untersuchten Fahrzeugen und die Nanopartikel-Abscheide-grade wurden getestet.

In manchen Fällen wurden die Nutzfahrzeug-Rollenprüfstände der Projektpartner (DINEX, EC-JRC) gebraucht.

Als allgemeine Schlussfolgerungen kann gesagt werden:

- die Grundlage der Prozeduren zur Qualitätsüberprüfung der SCR-Systeme sind erarbeitet,
- die SCR-Systeme sind bei tieferen Temperaturen < 200°C nicht aktiv,
- Testen der SCR-Systeme am Fahrzeug ist wichtiger, als das Testen der DPF-Systeme am Fahrzeug und dies ist eine einfache und kostengünstige Möglichkeit der Qualitätsüberprüfung,
- die durchschnittliche NOx-Reduktionsrate hängt von dem Arbeitskollektiv des Fahrzeuges ab – beim Niederlast –, Kalt – und unterbrochenen Betrieb (HEV) gibt es tiefere NOx-Reduktion, oder keine NOx-Minderung,
- Probenahme mit Impingers mit der anschliessenden Spurenanalytik sind geeignete Werkzeuge, um spezifische nichtlimitierte Emissionskomponenten nachzuweisen; für schnelle und einfache Überprüfung ist diese Methode nicht geeignet.

Zusammenfassend darf bemerkt werden, dass die Forschungsarbeiten das TeVeNOx Projektes verschiedene neue Aspekte gezeigt haben.

Die Qualität und die Funktionalität der SCR-Systeme für Nachrüstung können problemlos überprüft werden.

Beim Testen der OEM-SCR Systeme gibt es manchmal etwas Schwierigkeiten mit: physischer, oder elektronischer Zugänglichkeit, mit verschiedenen Programstrategien der OBD, Unmöglichkeit der Einflussnahme auf Urea „cut-off“ und mit der Temperaturschwelle der NOx-Sensoren.

Trotzdem, mit Rücksicht auf diese Beschränkungen kann die SCR Qualitätskontrolle mit den erarbeiteten Methoden durchgeführt werden.

Die Qualität der geprüften (DPF+SCR)-Systeme war meistens sehr gut.

Der vorliegende 12te Bericht zeigt die ausgewählten, wichtigsten Resultate vonTeVeNOx. Alle Resultate und detaillierte Informationen über jeden Arbeitsabschnitt sind in den 11 vorherigen Arbeits-berichten gegeben, siehe Literatur, [38-48].

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*) Abkürzungen: siehe am Ende dieses Berichtes, S. 59

Résumé

La réduction catalytique sélective (SCR) est largement utilisée pour la réduction des émissions de NOx des véhicules utilitaires.

Il y a des fabricants et des applications de systèmes SCR pour l'équipement ultérieur (retrofitting) – le plus souvent pour les zones de protection de l'air (ZAPAS) et en combinaison avec le FAP (filtre à particules).

Sur mandat des autorités suisses, l'AFHB a testé différents systèmes SCR, ou (DPF+SCR) sur les véhicules lourds et a proposé des procédures simplifiées de tests de qualité de ces systèmes. Ces procédures peuvent être utiles pour l'admission des systèmes de traitement des gaz « retrofit », mais aussi pour le contrôle de qualité des systèmes OEM (original equipment manufacturers).

Le nom abrégé du projet est TeVeNOx « Testing of Vehicules with NOx reduction systems ».

Tous les systèmes testés, et commercialement disponibles sur le marché, ont utili-sé une solution acqueuse d'uréa (Ad-Blue) comme agent de réduction. Les tests ont été exécutés sur le banc à rouleaux pour véhicules lourds aux modes d'opération station-naires, ainsi que sur un tronçon routier répété plusieurs fois. Les investigations ont été exécutées selon les procédures établies dans un projet-réseau international VERTdePN*) (deactivation, de-contamination, disposal of particles & NOx) et appliquées dans le pré-sent projet TeVeNOx.

Pour les composants gazeux CO, CO_2, HC, NOx et NOx l'appareillage de l'AFHB pour les mesures sur le terrain était utilisé.

Pour les NOx les analyseurs : CLD à double réacteurs, le capteur électronique Ho-riba MEXA 120 et les capteurs NOx (CPK) ont été utilisés.

Il y avait quelques systèmes FAP installés sur les véhicules testés et le taux de filtration des nanoparticules (granulométrie) a été examiné.

Dans certains cas, les bancs à rouleaux des partenaires du projet (DINEX, EC-JRC) ont été utilisés.

Nous pouvons donc tirer les conclusions générales suivantes :

- les bases des procédures du contrôle de qualité des systèmes SCR sont éta-blies,
- à température plus basse < 200°C les systèmes SCR ne sont pas actifs,
- le contrôle des systèmes SCR sur le véhicule est plus important que le con-trôle des systèmes FAP sur le véhicule et il offre une méthode de surveillance de qualité simple et peu coûteuse.
- le taux de réduction moyen des NOx dépend du collectif de charge du véhicule – à basse charge, aux modes d'opération à froid et opération intermittente (HEV), il y a une réduction limitiée des NOx ou pas de réduction,
- la prise d'échantillon par « impinger » avec l'analyse des traces est un outil pour détecter les émissions des composants spécifiques non-limités; pour un contrôle simple et rapide néanmoins cette méthode n'est pas appropriée.

En résumé, nous constatons que les travaux de recherche TeVeNOx ont montré différents nouveaux aspects.

La qualité et la fonctionnalité des systèmes SCR pour « retrofitting » peuvent être facilement contrôlées.

En testant les systèmes SCR OEM, on peut rencontrer certaines difficultés comme : accessibilité physique et électrique restreinte, différentes stratégies des programmes OBD, impossibilité d'influencer le cut-off de l'uréa et des seuils de température des capteurs NOx. Néanmoins, avec considération et adaptation à ces limites, le contrôle de qualité des systèmes SCR peut être exécuté avec les méthodes établies.

La qualité des systèmes testés (FAP + SCR) était dans la majorité des cas très bonne.

Le présent rapport, 12ème du nom, montre les résultats choisis les plus importants. Tous les résultats et les informations détaillées de chaque étape du travail sont donnés dans les 11 rapports précédents, voir litérature, [38-48].

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*) abréviations: voir page 59 à la fin du rapport

Summary

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

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.

The project short name is TeVeNOx “Testing of Vehicles with NOx reduction systems”.

All investigated and commercially available systems used urea-water solution (Ad-Blue) as reduc-tion agent (Exception was one special system for retrofitting NOxOFF).

The tests were performed on HD chassis dynamometers at constant operating points and on a road circuit. The investigations were performed according to the procedures established in the international network project VERT*)dePN (de-activation, de-contamination, disposal of particles & NOx) and applied in the present project TeVeNOx.

During the tests the AFHB field measuring technics was used for CO, CO_2, HC, NOx and NO2.

For NOx the double-reactor CLD, the electrochemical sensor Horiba MEXA 120 and the NOx sensors (CPK) were used.

There were some DPF systems on the investigated vehicles and the nanoparticle filtration efficiency was tested.

In some cases the HD chassis dynamometers and the measuring systems of project partners (DINEX, EC-JRC) were used.

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 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, or there is no reduction at all,
- Sampling with impingers with the following analytics of traces is approximately 1 order of magnitude more sensitive for Ammonia and 3 orders of magnitude more sensitive for Isocynic Acid. This method is an appropriate tool to detect specific non-legislated emission components; for a “quick-check” nevertheless it is not applicable.

Summarizing it has to be stated that the research works of the project TeVeNOx have shown several new aspects.

The quality and functionality of a retrofit SCR system can be easily tested.

Testing of the OEM-SCR system is a little more difficult, due to less physical and electronical ac-cess, different program strategies of the OBD-system, impossible urea cut-off

and activation tem-perature threshold of the NOx-sensors. Nevertheless a quality check of SCR is possible with the applied test procedures.

The quality of the investigated DPF+SCR systems was in most cases very good.

The present 12th report represents the chosen, most important results of TeVeNOx. All results and detailed information about each working package are given in the 11 preceding working reports, see literature, [38-48].

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*) Abbreviations: see at the end of this report, page 59

1 INTRODUCTION AND PRELIMINARY INFORMATION

1.1 Combined systems DPF+SCR

DPF+SCR

The combination of particle filtration (DPF) and of the most efficient deNO$_x$ technology (SCR) is widely considered as the best solution, up to date, to minimize the emissions of Diesel engines. Intense developments are on the way by the OEM's and a lot of research is performed, [1-14].
Several authorities worldwide try to promote the clean technologies by incentives, or creating low emission zones (LEZ). Due to that also the retrofitting market of combined systems (DPF+SCR) is developing.

The removal of NO$_x$ from the lean exhaust gases of Diesel engines (also lean-burn gasoline engines) is an important challenge. Selective catalytic reduction (SCR) uses a supplementary substance – reduction agent – which in presence of catalysts produces useful reactions transforming NO$_x$ in N_2 and H_2O.

The preferred reduction agent for toxicological and safety reasons is the water solution of urea (AdBlue), which due to reaction with water (hydrolysis) and due to thermal decomposition (thermolysis) produces ammonia NH_3, which is the real reduction substance.

A classical SCR deNO$_x$ system consists of 4 catalytic parts:

- precatalyst converting NO to NO_2 (with the aim of 50/50 proportion)
- injection of AdBlue (with the intention of best distribution and evaporation in the exhaust gas flow)
- hydrolysis catalyst (production of NH_3)
- selective catalyst (several deNO$_x$ reactions)
- oxidation catalyst (minimizing of NH_3 slip).

The main deNO$_x$-reactions between NH_3, NO and NO_2 are widely mentioned in the literature [12, 14, 15, 16, 17], see annex A1. They have different speeds according to the temperatures of gas and catalysts, space velocity and stoichiometry. All these influences cause a complex situation of reactions during the transient engine operation.

Additionally to that there are temperature windows for catalysts and cut off the AdBlue-injection at low exhaust gas temperatures to prevent the deposits of residues.

Several side reactions and secondary substances are present. An objective is to minimize the tail pipe emissions of: ammonia NH_3, nitrous oxide N_2O, isocyanic acid HNCO and ammonium nitrate NH_4 NO_3 (also known as secondary nanoparticles).

Intense further research about the solutions of problems of the present systems and about new developments is going on. To mention are:
- deposits of urea related substances (urea, cyanuric acid, ammonium nitrate), [16, 17, 18],
- measuring accuracy of NO$_x$ in presence of NH_3, [19, 20, 21],
- other reduction agents, [22, 23],
- AdBlue dosing and homogenous distribution [24],
- construction variants of DPF+SCR and their influences on functionality, warm-up, durability etc., [11, 12, 13].

Very rapid and extensive activities about deNOx and SCR take place actually in academia, in research & development and in industry, this is well demonstrated by the numerous technical conferences, which are organized about this topic in the last years.

1.2 VERT quality test procedures for DPF – former research work

(The present tests were with approved DPF, chap. for information only)

VERT verification procedure of DPF systems for retrofitting was developed in Switzerland since beginning of 90-ties.

It was a joint project of occupational insurance agencies from Switzerland (SUVA), from Austria (AUVA) and from Germany (TBG) concerning reduction of emissions of real (actual present) machines in tunnel construction, [25, 26, 27].

The objectives of VERT were to create a communication and understanding between industry, authorities and customers and to guarantee the technical quality and efficiency of products, to protect health and environment.

In the initial phase VERT activities were sponsored by the occupational insurances from Switzerland, Austria and Germany and after that it became self-supporting.

The quality testing of DPF system consists not only of testing the filtration efficiency, but checking all necessary subsystems, like regeneration systems, control systems, sensors and fulfilment of several general requirements of quality and security.

Additionally to the engine dynamometer tests very important points of the testing procedure are:

- 2000 hours filed test,
- analytics of secondary emissions in justified cases.

It was recognized very quickly in the VERT project, that the retrofitting with DPF is a most efficient measure to eliminate radically the particle emissions of Diesel engines in underground. To introduce the DPF-systems for retrofitting it was necessary to establish: the quality criteria and quality test procedure, field control and appropriate support to the users.

One of the most important statements of VERT is, that the validation of filtration efficiency of a DPF by means of particle mass PM (legal parameter up to date) is not sufficient and sometimes misleading.

In several cases, particularly with a presence of some catalytic substances in the DPF, sulfates can be produced (only the sulfur from lube oil can be sufficient for that), which pass the DPF as vapor and condensate afterwards on the PM-measuring filter. In an extreme case this can cause, that the DPF, which filters perfectly the solid particles (NP, EC e.g. 98%) seems to double or triple the particle mass (PM).

The filtration efficiency of a DPF can be properly judged only for the solid particles. In this context the nanoparticles are considered in VERT as the most important criterion, [28, 29]. A complementary information is given by a coulometric analysis of elemental carbon (EC) from the collected PM of the filter residuum.

The nanoparticulates can be measured with different methods and due to the aptitude of penetrating very easily into the living organisms they are regarded as very dangerous for health, [30, 31, 32].

Since 2001 there are discussions in the international legislative expert groups about possibilities of introducing the NPs as a legally limited parameter – Particulate Measurement

Program (PMP) of the UN Working Party on Pollution and Energy (GRPE), [33, 34, 35, 36].

These efforts allowed the introduction of nanoparticles as a supplementary limited parameter into the European legislation for passenger cars with Diesel- and with DI-Otto engines, starting in 2011.

For some systems, which use catalytic coatings, or fuel additives, or combinations of both of them a VERT secondary emission test (VSET) has to be performed.

For retrofitting with combined systems (DPF+SCR) quality testing and fulfilment of certain criteria are necessary both: for the user and for the authority.

The Swiss VERT Network performed and is continuing the works to include the deNOx-systems (SCR, EGR, storage catalysts) in the VERT verification procedures (VERTdePN Programm).

1.3 TeVeNOx-testing (VERTdePN) for DPF+SCR

Research subjects and objectives

A general objective of VERTdePN is to include the combined systems DPF+SCR in the test procedure, which was previously developed for DPF only.

Since the stationary testing of SCR for on road application is not sufficient any more, a simplified dynamic test procedure, which nevertheless is representative for the real world operation, has been found.

Different variants of catalyst and/or their sequences used for different types of SCR systems, different sequences of DPF and SCR, different possibilities of introduction, homogenization and control of urea and finally different applications offer a large multitude of cases. This was considered during the tests according to the given systems.

For the VERT DPF quality procedure the research objectives were:

- filtration quality
- durability
- control - & auxiliary systems
- secondary emissions.

The new objectives for a SCR system in the VERTdePN tests are:

- NO_x reduction
- NO_2- and / or NH_3- slip
- temperature window
- dynamic operation
- field application & durability
- auxiliary systems
- further secondary emissions.

The main structure of VERTdePN tests for SCR is similar, as the preceding VERT activities for DPF:

- Quality test and basic investigation on dynamic engine dynamometer, or on a representative HD-chassis dynamometer,
- Supervised field test 1000h,
- Analytics of unlimited- and secondary emissions (if required).

When the DPF of the combined system is already approved by VERT, only simplified tests for the SCR-part will be necessary.

1.4 TeVeNOx-testing procedures on vehicles

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 re-actions in the SCR-system can be influenced by the urea mixture preparation by the position and ge-ometry 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 unregu-lated emission components of a new system.

The ageing of SCR-catalysts lowers 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 another 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 man-ufacturers and users of those systems.

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

Following sections describe briefly the actually used procedures, [37].

<u>HD chassis dyno (VPNT2 & VPNT3, TeVeNOx test Type 1)</u>

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) in the frame 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 NOx-sensors of the SCR:
  - apparatus: NO, NO_2, NOx external CLD, access to the original NOx-signals,

- datalogging of (p, T) before system:
  - apparatus: datalogger installed and operative as for field test, remote control (if available),
- switch-on/off temperature of urea dosing:
  - SW-procedure: warm up at low load and transition to the higher load with all necessary data acquisition; after approx. 30s 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).
- NOx 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 NOx reduction efficiency (RE) is calculated:

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

before, after SCR (or system)

Instead of measuring “before” system the results “without” systems as reference can be used.

- Unregulated components:

  NO_2 ... CLD

  NH_3 ... double reactor CLD & impingers with integral sampling over a defined operational profile (sporadic measurement for special requirements).

  HNCO ... impingers with integral sampling over a defined operational profile (sporadic measurement for special requirements).

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 NOx reduction in a simple, repetitive operation collective enable the statements about the ageing and functionality after the field trial.

<u>Field control (VPNT2, TeVeNOx test Type 2)</u>

In this test of 1000h the durability of the system (DPF+SCR) has to be indicated by means of datalogging (p, T, NOx 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.

<u>Short acceptance test (TeVeNOx test Type 3)</u>

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 NOx -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.

<u>Road benchmarking (SNORB, TeVeNOx test Type 2)</u>

The real world road benchmarking was proposed to find the correlations of de NOx reduction efficiency between:

- laboratory results on engine or chassis dyno and real world results of a given (DPF+SCR) system,
- OEM vehicles with SCR and similar retrofitted vehicles in identical driving profiles on road,
- low load operation, high load operation and legal limit values for OEM vehicles with SCR.

The tests can be performed with a given vehicle (truck) on a similar test loop in identical traffic situation with/without urea dosing. The NOx-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 mathematical sense, but it yields very useful average information about the deNOx rates.

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

<u>Fig. 01</u> represents the scheme of both testing procedures: VERTdePN and TeVeNOx

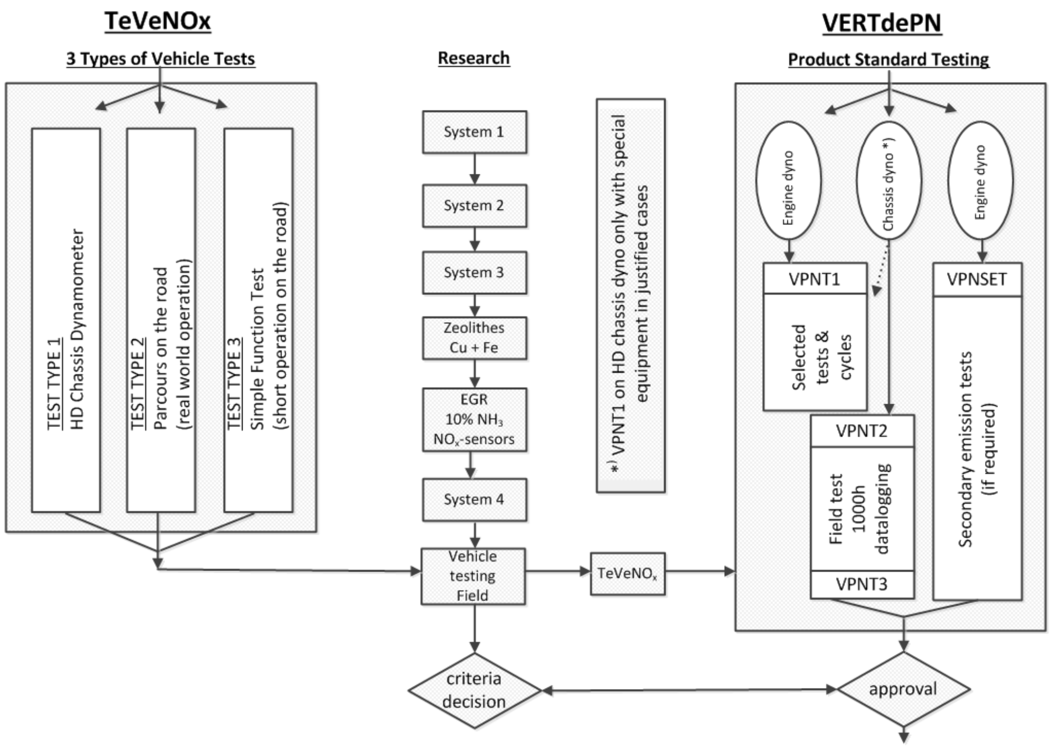


Fig. 01: VERTdePN and TeVeNOx testing procedures for (DPF+SCR) combisystems

2 OBJECTIVES

The functionality of exhaust aftertreatment systems consisting of DPF and urea SCR has to be tested on HD-vehicles.

The tests have to be performed on vehicle on a HD chassis dynamometer and on the road.

A special attention has to be paid to the NOx measurement and to the resulting NOx reduction rate.

For some of the applied DPF systems the nanoparticle count filtration efficiency has to be tested.

3 TEST-VEHICLES, FUELS AND LUBRICANTS

3.1 Test vehicles

Two busses 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 aftertreat-ment 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% NH_3 in H_2O 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 Blutec 6 330 kW 12000km	OEM CRT+SCR
G	DAF Truck 340 kW	OEM SCR
H	MAN TGS 400 kW	OEM SCR 0 KM
I		OEM SCR 84.9 T km
J	Mercedes Actros 260 kW	NOxOFF DPF+SCR retrofit

The data and some details of measuring set-up for all investigated vehicles are represented in annex A2.

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

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

3.2 Fuels and Lubricants

As fuel the market Diesel according to EN 590, with sulfur content < 10 ppm was used. In one case (vehicle G) a part of tests was performed at bi-fuel operation Diesel-GNG.

Engine lube oils were applied according to the requirements of engine manufacturers.

4 TEST EQUIPMENT

4.1 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
HCIR	…	infrared detector (HC 6), NDIR
NO, NO_2, O_2	…	electrochemical cells.

Other NOx-measuring instruments were used for comparison:

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

4.2 Particle Size Analysis

The particle size and counts distributions are 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 until 300°C)

Particle measuring system was used, to check and confirm the filtration efficiency of the used DPF systems.

5 TEST 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 dyno was available; the dynamic cycles on chassis dyno could replace the road-driving.

On the HD chassis dynamometer at least 3 operating points of the engine were performed. The injec-tion 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 accord-ing to the possibility. The driving speed was registered by means of GPS and NOx and tailpipe tem-perature 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.

An example of a road circuit is given in annex A3.

6 TEST OBJECTS

All investigated SCR systems were with Vanadium-based SCR-catalyst and with urea injection. A ret-rofit system NOxOFF used 10% NH_3 solution in water (Ammonium Hydroxide), see chap. 4.1.

Generally it was little information given about the SCR systems. There was also no access to the ECU of the OEM-systems and the urea switch-off could not be realized by electronic control.

7 RESULTS

In present report only the examples of mostet important results are represented. All detailed results and information are given in the reports of each working package, [38-48].

7.1 NOx reduction all vehicles

Table 2 summarizes the average NOx reduction rates of all investigated vehicles. (Vehicle J, NOxOFF is no market-deNOx-system).

The most important experience is that the average NOx reduction efficiency in on-road transient operation is lower, than in the constant operating points (on chassis dyno). This is due to:

- low load periods with no urea dosing,
- low load periods with urea dosing, but with colder SCR catalyst,
- cold and warm-up periods with no urea dosing.

An extreme example is low-load, often interrupted operation of a hybrid bus, where over whole day there is no registered work of the SCR-system (winter period, undefined trips).

Several remarks concerning the tests or experience are given in Table 2 for each vehicle.

To mention are:

- the NOx sensors (UDS, CPK, OEM) are a useful tool in warm operation to control the deNOx efficiency,
- if the RAI is placed close to the turbocharger (in OEM application) it is not useful to place a CPK-NOx sensor for datalogging downstream of the RAI-point (no useful signal from the sensor possible),
- in OEM SCR when the wheels of vehicle stop, the urea dosing is also stopped automatically,
- the higher load of truck increases also the engine load in on-road operation; empty trucks have lower KNOx,
- the controlled OEM DPF's had excellent filtration quality PCFE > 99.5%,
- the investigated CNG retrofit system for bi-fuel operation "Diesel-CNG" showed increased emissions of CO, HC, aldehydes and SO_2 and relatively low NOx-conversion rates.

Further details of results are given in the following sections.

In general: the quality of a SCR system concerning the maxiumum NOx reduction potential is visible in the present tests at stationary warm operation (here in average 85%).

In the performed transient road operation the temperature level in the exhaust system is lower as well as the average deNOx-efficiency. Eliminating the results with very low operating collectives the average deNOx rate of 60% results.

Table 2: Average NO_x-reduction rates of investigated vehicles

	Vehicle	Exh. Syst.	KNOx			Remarks
			OP1 50 km/h	OP2 70 km/h	transient	
A	Bus Volvo 180 kW	DINEX DPF + SCR retrofit	80%	88%	FIGE 80% road UDS 88%	UDS sensors useful
B	Bus Volvo Hybrid 158 kW	OEM DPF+SCR	- not measured *)	- not measured *)	road circuit 62%-70%	undefined trips KNOX= 30-67% no chassis dyno tests
C	Mercedes Actros 300 kW 570 km	OEM SCR	95%	88%	- *)	• no CPK sensor downstream RAI-injection point • wheels-stop-RAI stop • tractor only – no circuit with RAI
D	Mercedes Actros 300 kW 500520 km	OEM SCR	78%	88%	road circuit average 42%	• wheels-stop-RAI stop • circuit with RAI, with trailer
E	MAN TGS 397 kW 220 km	OEM SCR + DPF retrofit	84%	- *)	- *)	• cDPF PCFE 99.5% • steps: NO_2/NO_x↑ 70% part load • wheels-stop-RAI stop • no SWOFF • no circuit • impingers
F	Mercedes Actros Blutec 6 330 kW 12000 km	OEM CRT+SCR	94%	91%	road circuit 63%-89%	• CRT PCFE 99.9% • impingers • CLD on road • 6 trips estimate of KNOX
G	DAF Truck 340 kW	OEM SCR	<u>Diesel</u> – (no RAI) <u>Diesel/CNG</u> 27%	<u>Diesel</u> 28% <u>Diesel/CNG</u> 55%	<u>FIGE, Diesel</u> 55%-70% FIGE D/CNG 19%-50%	retrofit CNG system → CO ↑↑, HC↑↑, Aldeh ↑, SO_2↑
H	MAN TGS 400 kW 84970 km	OEM SCR used	84%	69%	road trip average 20%	road circuit: low operating collective wheels stop – RAI stop • CLD on road
I	MAN TGS 400 kW	OEM SCR new	92%	75%	road trip average 20%	road circuit: low operating collective wheels stop – RAI stop • CLD on road
J	Mercedes Actros 260 kW 112'000 km	NOxOFF DPF+SCR retrofit	- *)	- *)	50%	10% NH_3 in H_2O; system no more in production
average of present KNOx values (without vehicle G) without vehicles H & I all results			86.7	83.2	 60% 51%	in mixte on-road driving there are lower average temperatures of exhaust system

7.2 Stationary operation

7.2.1 Urea switch on/off & different feed factors

Fig. 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 α = 0.75 and α = 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.

The urea switch-on (SWON) is visible after approximately 8 min operation at v = 44 km/h – there is a jump-down of NOx & 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 α = 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 produces a supplementary emission of NH3 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 NOx and NO_2,
- the reduction rates of NOx (KNOx) are at the lower vehicle speed in the range of 77% and at the higher vehicle speed in the range of 87% (with α = 0.75),
- the higher feed factor (α = 0.85) increases slightly KNOx, but also increases significantly the NH_3-discharge at higher vehicle speed.

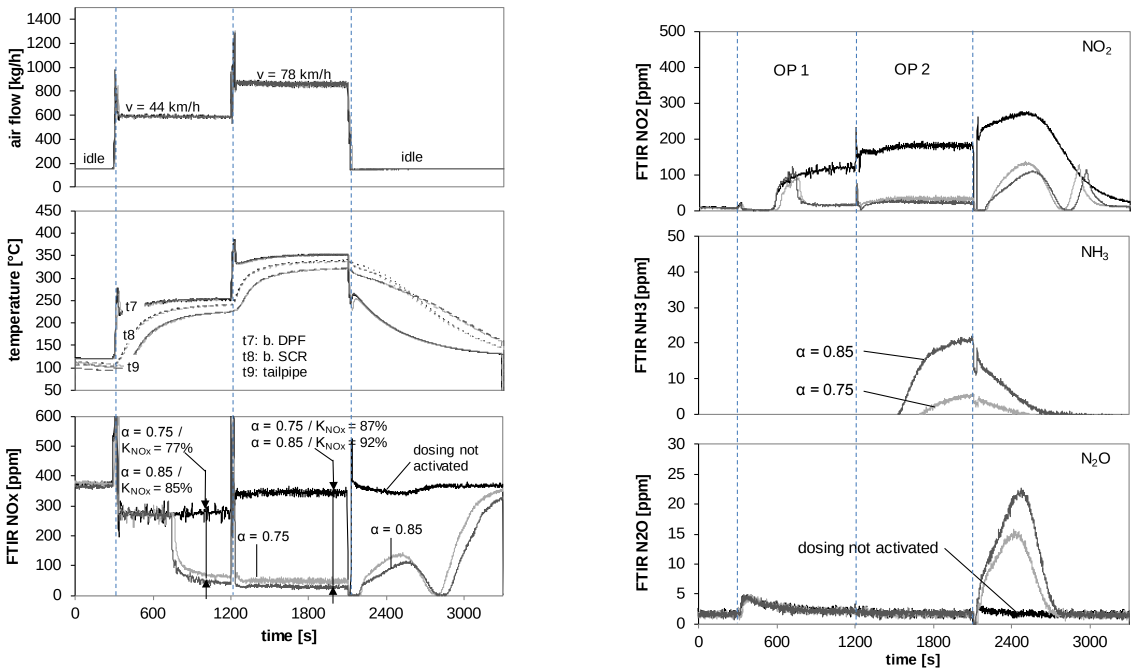


Fig. 1: Step test with different dosing rate after 1000h; retrofit system cDPF & SCR; dosing: not activated / 0.75 / 0.85; vehicle A; ULSD; chassis dyno DINEX

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. 2:

a) 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;
b) 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;
c) 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;
d) 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.

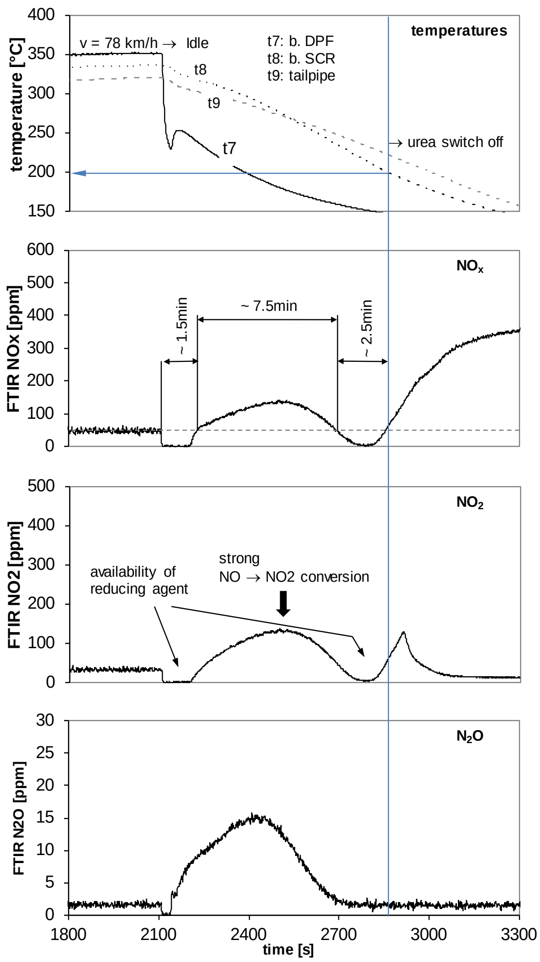


Fig. 2: Switching back to idle; retrofit system cDPF & SCR; α = 0.75; vehicle A; ULSD; chassis dyno DINEX

7.2.2 Different NOx-analyzers

For measurements of NOx and for the estimate of KNOx 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. 3 represents the results at SWON with 3 analyzers.

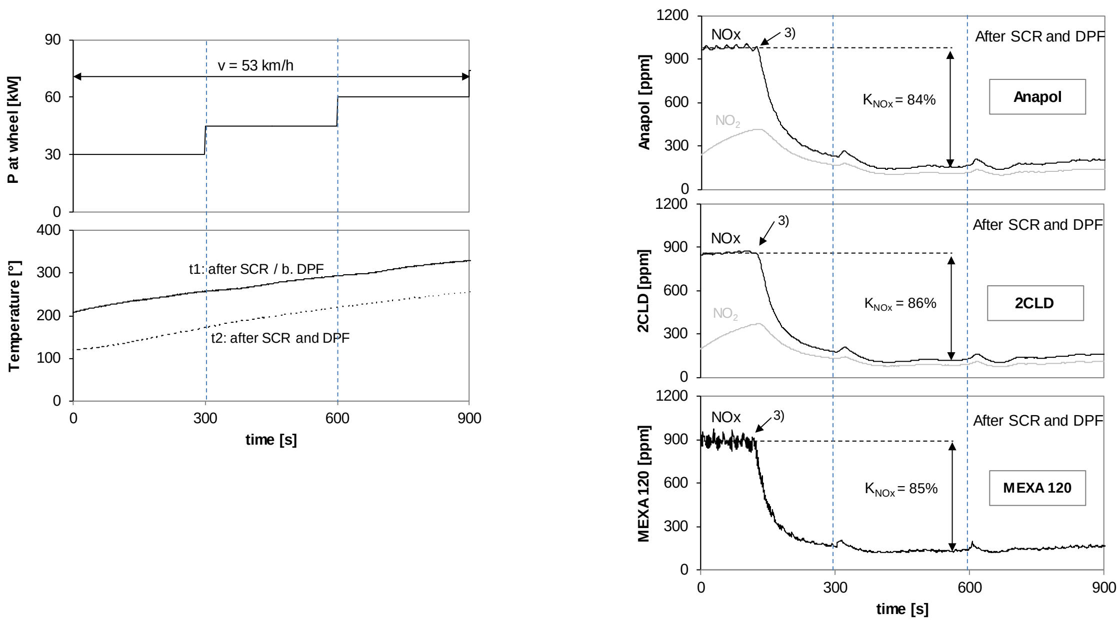


Fig. 3: KNOx at SWON in steptest with different analyzers. OEM SCR; dosing activated; vehicle E; ULSD; chassis dyno MAN

In the 1st step (Pwheel = 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.

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 KNOX OP1-OP2. This KNOx (84% for Anapol and 86% for 2CLD) is very close to the aver-age result from previous measurement (83.9%).

7.2.3 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 4 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.

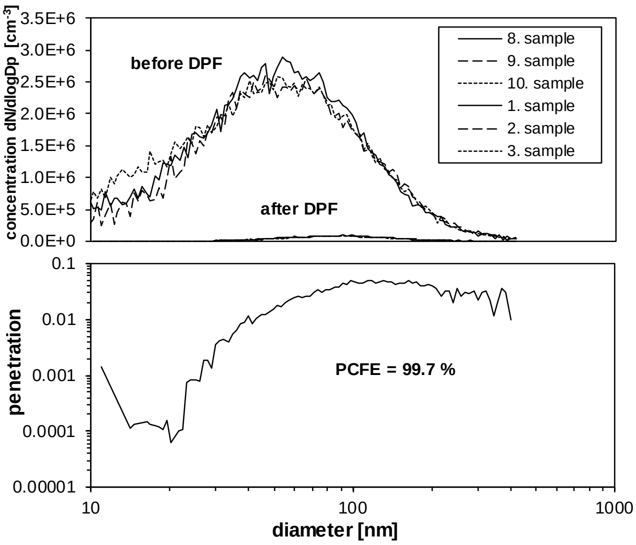


Fig. 4: SMPS size spectra at OP2 and NP-filtration of a retrofitted DPF. OEM SCR; dosing activated; vehicle E; chassis dyno MAN

7.2.4 Increased backpressure

Diesel exhaust gas aftertreatment systems, which are extensively used in the heavy duty (HD) vehicles often as retrofit systems can increase the backpressure of the engine.

Tests with increased backpressure, in the range, which is probable for the exhaust after-treatment systems, were performed on engine dynamometer, [45] and on a modern truck on chassis dynamometer, [46].

The Iveco F1C engine on engine dynamometer could be operated with & without EGR and also in dynamic cycle (ETC). Some non-legislated emissions could be additionally measured by FTIR.

The MAN Truck Euro V could be operated on chassis dynamometer at some chosen constant oper-ating points.

The most important results from Iveco engine, [45], are:

- The increased backpressure without EGR causes at stationary operation: slight reduction of HC, slight increase of CO and no significant influence on NOx,
- with EGR and at lower part load operation (at stationary working conditions) there is no
- influence of increased backpressure (in the investigated range) on emissions,
- the nanoparticles emissions without EGR are at lower level and increase slightly with in-creasing backpressure; with EGR there is a higher emission level, but no influence of backpressure,
- at dynamic operation in ETC there are no significant influences of increased backpressure on CO and HC; nevertheless, there is an increase of NOx in the range of 2% w/o EGR and 7% with EGR,
- the increased backpressure lowers the engine air consumption and increases the fuel consumption,
- there are no increases of the non-legislated emission components measured with FTIR.

The results from Man truck, [46], are:

- at high engine load the increased backpressure (Δp) provokes the increase of CO, CO_2 and NOx, there are no HC to be measured,
- at low engine load there is only a slight increase of CO_2, but reduction of CO & NOx with increased Δp.

To sum up, it can be stated, that the increased backpressure, in some situations has, and in other situations, has no influences on engine-out emissions. The question: "if the emissions can be deteriorated by higher Δp to be significantly beyond the legal limits?" – cannot be strictly answered for all application cases.

There are experiences of trucks Euro V with OEM-SCR, which were retrofitted with DPF and showed no significant deterioration of the limited gaseous components. AFHB can offer such tests.

7.3 Transient operation on chassis dyno and on-road

7.3.1 Influence of ambient temperature on KNOx

Fig. 5 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 NOx, NO_2 & KNOx. 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 NOx reduction rate and the comparative testing on vehicle e.g. before and after field durability period, should be realized at similar ambient conditions.

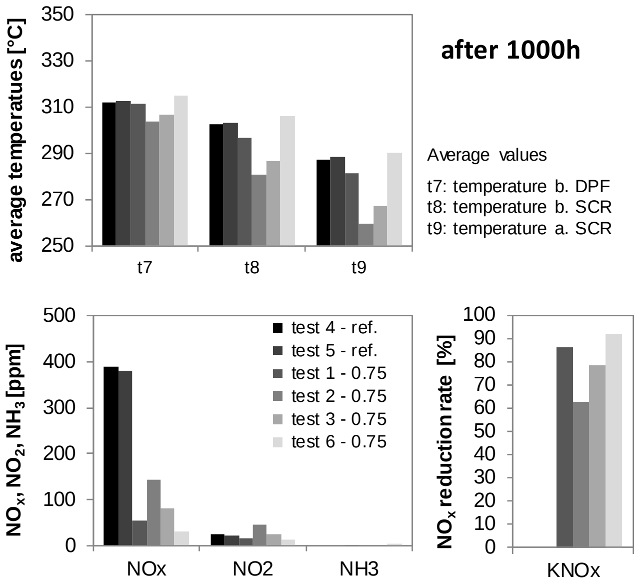


Fig. 5: Emissions in FIGE transcient cycle & sensitivity to tamb; retrofit system cDPF &

SCR; α = 0.75; vehicle A; ULSD; chassis dyno DINEX

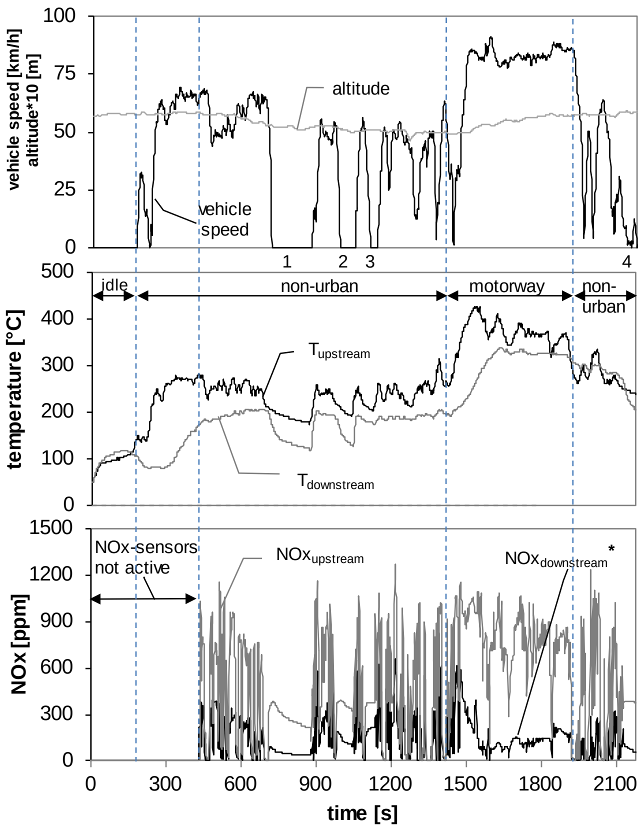
7.3.2 SCR in hybrid vehicle (HEV) operation

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°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.

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".



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

Fig. 6: Hybrid on road trip – switching off the engine. Vehicle B; CRT & SCR; ULSD; AdBlue

Fig. 6 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 dyno. 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 ($t_{sensors}$ < 140°C). This inactive phase is much shorter with the “warm” started engine and exhaust system.

7.3.3 Estimate of KNOx 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 KNOx.

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

The estimate of KNOx 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 KNO_X-values in the active periods of CPK & SCR in two ways:

a) 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.7,
b) simultaneous measurement with 2 sensors (CPK) EO & TP, in all trips.

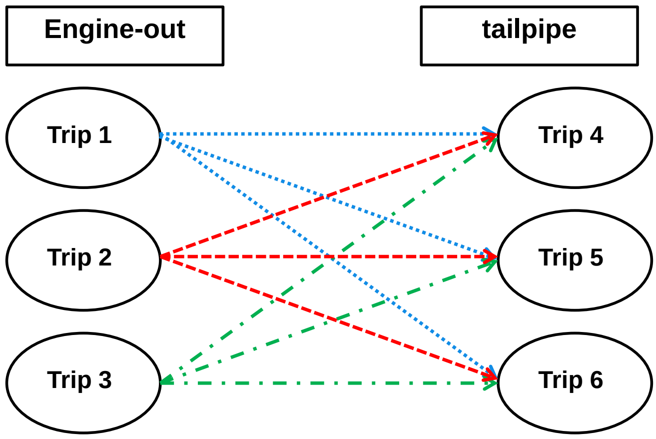


Fig. 7: Measurements with 2 CLD in 6 trips & estimate of KNOx with

→ 1 sensor only
→ 2 sensors simultaneously

In Fig. 8, the method of estimate "1 sensor only" was applied to the CPK-results and compared with the CLD-results. There are represented:

- KNOx in trips 4, 5, 6 with reference values from trips 1, 2, 3 – estimate "1 sensor only " with CLD and with CPK,
- KNOx 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 KNOx is higher. In opposite to that the method of "1 sensor" shows less dispersion of results and does not recognize the KNOx-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 KNOx-values, as the "2-sensors" meth-od. For "cold" cycles the "1 sensor" method is less selective and does not indicate the KNOx-differences between "cold" and "warm".

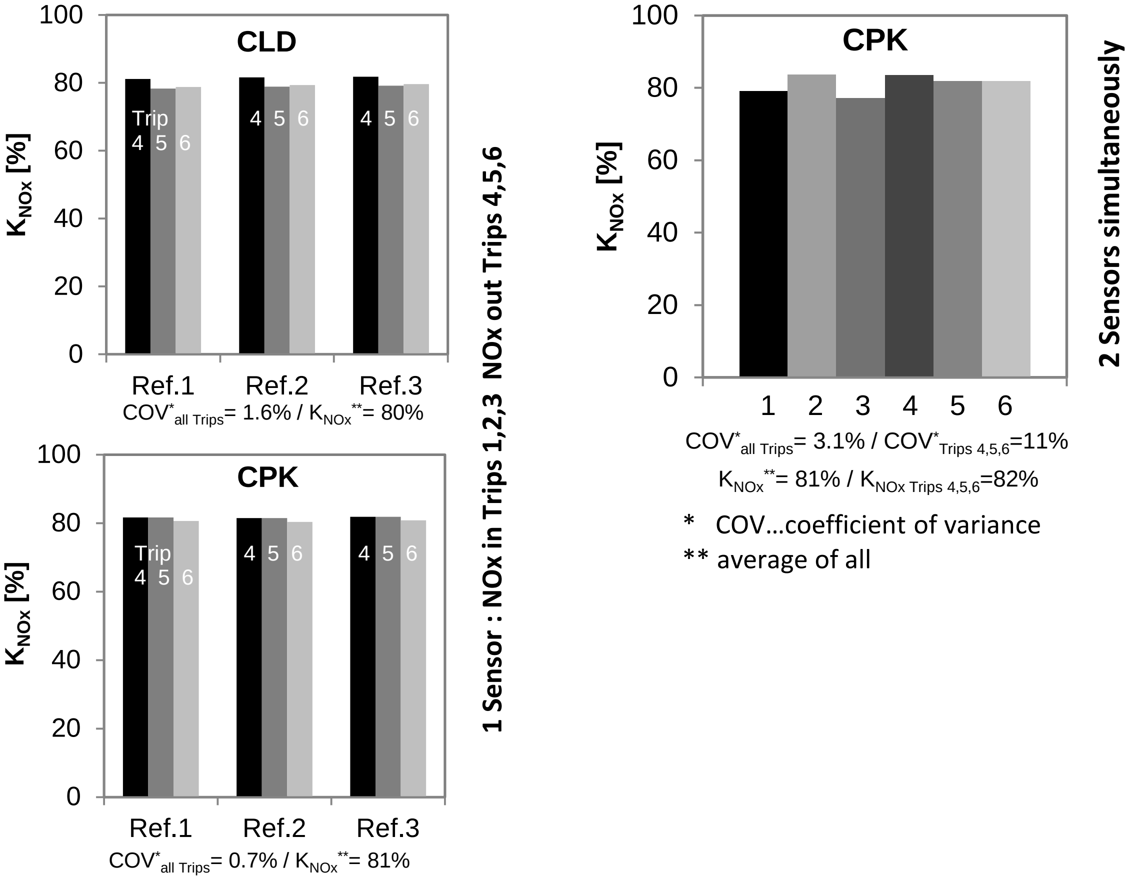


Fig. 8: Comparison of KNOx-dispersion between 2 measurement types: with 1 sensor only and with 2 sensors simultaneously. Periods of active SCR & CPK sensors; vehicle F; ULSD; AdBlue; dosing activated.

Fig. 9 shows the estimates of KNOx-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.

The most important statement is: as colder is the exhaust aftertreatment system during a part of the trip, as lower is the average KNOx-value in this period. The CPK-sensors are less active and cannot indicate all emissions. In the active periods the CPK-sensors show higher KNOx-values, than the average of the colder cycle part. For the hot exhaust aftertreatment system there are no differences of KNOx between “whole trip CLD” and “active time CPK”.

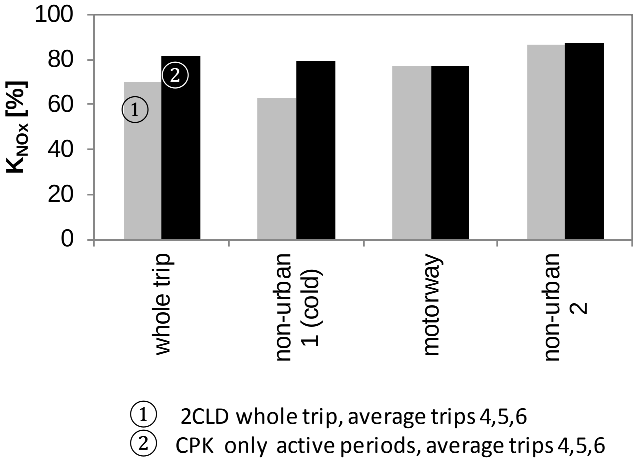


Fig. 9:Comparison of KNOx-values from different periods of the trip ① 2CLD whole trip → ② CPK & SCR active time. Vehicle F; ULSD; AdBlue; dosing activated.

7.3.4 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. 10 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 FIGE 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 NH_3 in the last cycle with Diesel-fuel (FIGE 5).

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.

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 3 summarizes the average KNOX-values obtained in the FIGE cycles:

Diesel

KNOx %	FIGE1		FIGE2		FIGE5	
fuel	ULSD		ULSD		ULSD	
load dyno	high		high		low	
engine	cold*		warm		cold**	
integral	whole test	SCR on	whole test	SCR on	whole test	SCR on
AMA	57	71	68	72	55	66
CPK***	62	70	69	71	58	65

* Longer cooling period

** Very short cooling period

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

Bi-fuel

KNOx %	FIGE3		FIGE4 1)	
fuel	ULSD		ULSD	
load dyno	high		high	
engine	cold*		warm	
integral	whole test	SCR on	whole test	SCR on
AMA	17	29	50	60
CPK***	19	32	50	60

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

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

Table 3: Average values of KNOX in FIGE-cycle; OEM SCR; dosing activated; CNG retro-fit; Vehicle G; Euro V; ULSD; chassis dyno JRC

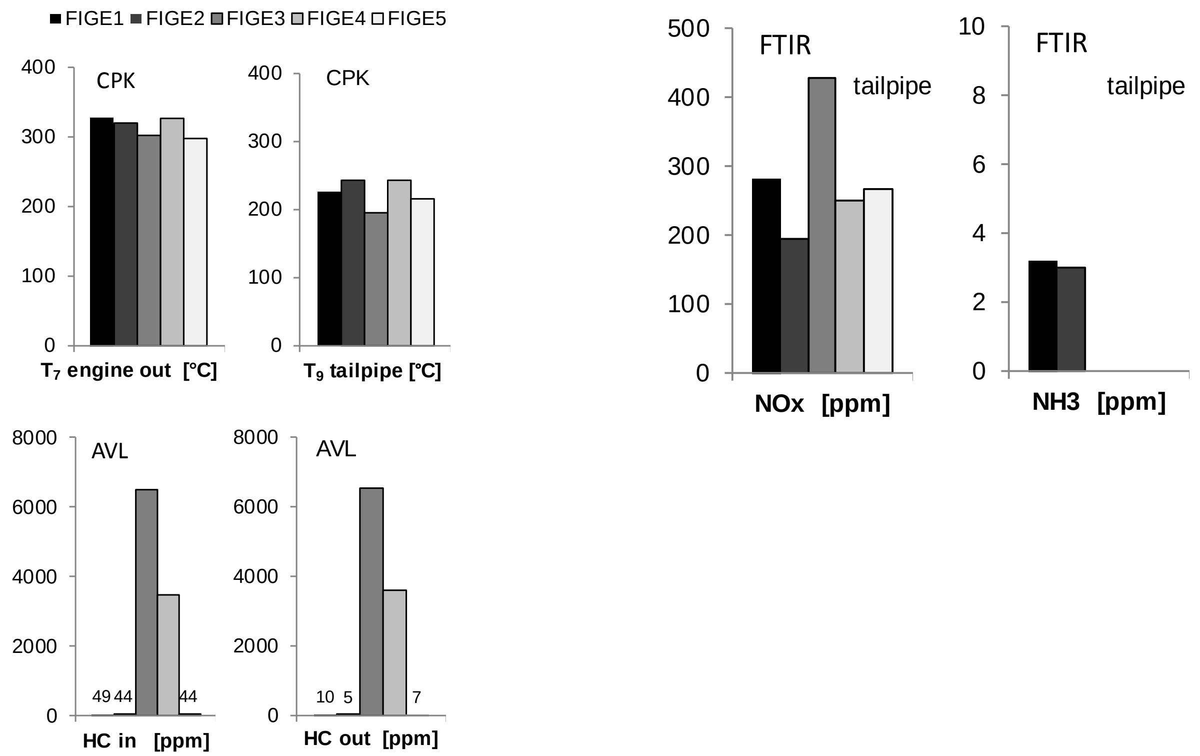


Fig. 10: Average emission in FIGE with ULSD & Bi-Fuel. OEM SCR; dosing activated; Vehicle G; Euro V; chassis dyno JRC

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

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

An important parameter, which influences the NOx-reduction is the average exhaust tem-per-ature. At stationary operation texh is higher for bi-fuel-operation, at dynamic operation texh-average is lower. So are the relationships of KNOX-values too. Obviously these rela-tionships 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 HCHO and Acetyladehyde MECHO
- 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.

7.3.5 Simple SCR function test on road

This SCR function test is a part of the short acceptance test (TeVeNOx Type 3, see sec-tion 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 NOx-measurement is represented in Fig. 3. In OEM-SCR applications there are different inter-ventions 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) Adaptation of the low load engine power to the needs of the on-board energy con-sumption – Fig. 11 shows the intervention of ECU after long idling and the results of NOx during vehicle stop and urea cut-off. By the test “with dosing acti-vated” the total elimination of “NOxout” 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 KNOx never-theless is not possible.
c) Engine switch off & on after vehicle stop in the hybrid application. Fig. 12 shows the traces of texh & NOx up-and downstream in the period after vehicle stop (ap-prox. 12 min).

After the 1st engine cut-off (period II) the NOx-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 im-portant role in indicating the NOx-values at engine standstill.

During the engine switch-on (period III) there is a sudden change of NOx-level. This indi-cates 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 sta-bi-lized NOx-values up- & downstream. This enables to estimate the NOx conversion ra-tios in this given thermal situation.

Similar results with nearly the same KNOX-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.

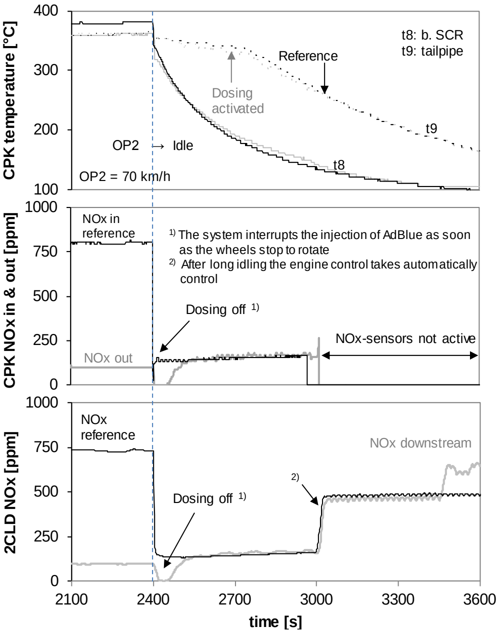


Fig. 11: SWOFF – ECU intervention after long idling period. OEM SCR; dosing OP2 activated; Vehicle D; ULSD, chassis dyno LARAG

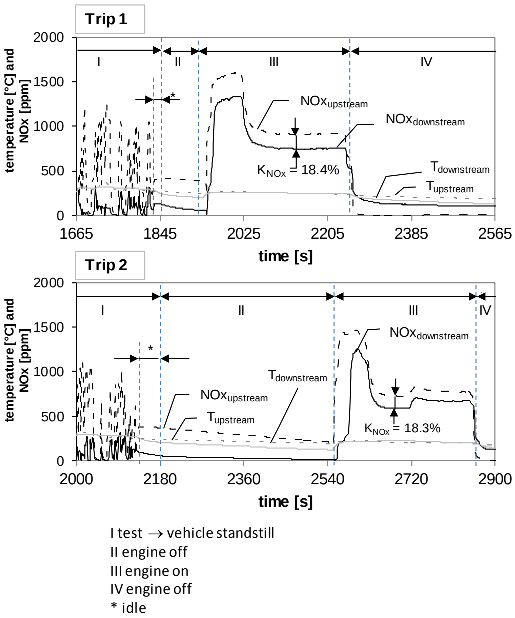


Fig. 12: HEV: Engine switch off & on after vehicle stop, dependant on battery SOC. Vehicle B, CRT & SCR; ULSD; AdBlue; on road

7.4 Use of impingers to dertermine the reactive nitrogen compounds (RNC) emissions

A special interest was given in TeVeNOx to emissions of reactive nitrogen compounds (RNC) such as NO, NO_2, NH_3 and HNCO, which are of toxicological relevance. These compounds are highly reactive, difficult to sample and analyse, but all involved in the deNOx chemistry of SCR catalysts. NH_3 and HNCO are formed in the catalyst during urea decomposition and if released, have to be considered as secondary emissions of the converter. FT-IR-based methods are currently not sensitive enough to monitor the release of these compounds at the ppb level. Therefore we applied two chemisorption methods to accumulate NH_3 and HNCO in impingers transforming them to chemically stable forms, which can be analyzed off-line. Ammonia is transformed in an ammonium salt and analyzed with ion chromatography, HNCO in an urea derivative, which is analyzed by LC-MS.

With sampling volumes of 10-30 L of exhaust could we obtain detection limits of 0.2 mg/m3 (260 ppb) for ammonia and 0.004 mg/m3 (2 ppb) for isocyanic acid, which is about one and three orders of magnitude below the sensitivity of the FT-IR method. Thus, both impinger methods are more sensitive and suitable to determine emission factors under steady-state conditions. These methods have been applied in the TeVeNOx project on HDV chassis dynamometers in the three-phase cycle and more widely on the engine test bench in the 8-phase ISO8178/4 C1 cycle.

As an example, HNCO emission factors (mg/h) of two HDV vehicles are shown Figure 13. One vehicle was equipped with a combined DPF-SCR system [41], the other had an OEM SCR system and was retrofitted with an efficient LRV-approved DPF downstream of the deNOx system [42]. HNCO emissions in the three-phase cycle are given for cold idle, at 50 km/h during SCR light-off, at 50 and 70 km/h with active SCR and during hot idle conditions. Emissions at the tail-pipe (lower diagrams), engine-out (upper left) and after the SCR (upper right) are reported. The applied LC-MS analysis was able to detect HNCO in all samples. Emissions after active SCR were increased, but retrofitting a DPF down-stream of the SCR lowered HNCO emissions to some degree.

We conclude that secondary emissions of isocyanic acid can be found in exhausts of the Euro-VI and the Euro-V HDVs in the same order of magnitude. As shown before, HNCO emissions of urea-based SCR systems vary considerably for different converter technologies and different operating points. Tail-pipe emissions of both HDVs varied by two orders of magnitude and reached about 200 mg/h. Both HDVs emit at the lower end compared to previous studies [49, 50].

Detailed results of EMPA research with impingers in the TeVeNOx project are given in [51].

EMPA
Materials Science & Technology

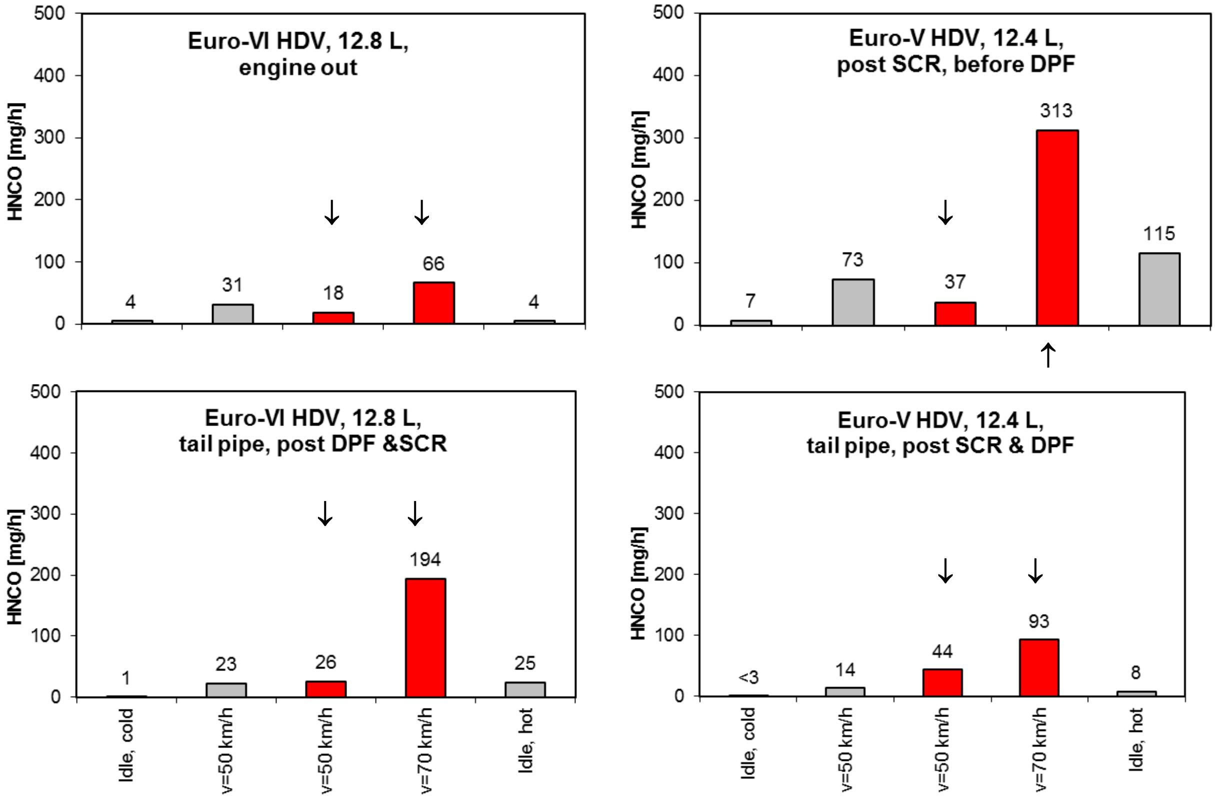


Fig. 13: HNCO emission factors in mg/h of Euro-VI (left) and Euro-V (right) heavy-duty vehicles operated in the 3-mode test cycle. Engine-out emissions (upper left) and tail-pipe emissions (lower left) are compared for the Euro-VI HDV and emissions after SCR (before DPF, upper right) and at the tail-pipe (lower right) are shown for the Euro-V truck. Conditions with fully active SCR are highlighted with ↓. The Euro-VI vehicle has an OEM DPF up-stream of the SCR, the Euro-V vehicle had an OEM SCR system and was retrofitted with a DPF.

8 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,
- Sampling with impingers with the following analytics of traces is approximately 1 order of magnitude more sensitive for Ammonia and 3 orders of magnitude more sensitive for Isocynic Acid. This method is an appropriate tool to detect specific non-legislated emission components; for a "quick-check" nevertheless it is not applicable.

Other remarkable technical points are:

- •higher feed factor α increases slightly KNOx, 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 KNOx – the comparative testing on vehicle e.g. before and after field durability period, should be realized at similar ambient conditions,
- for estimate of KNOx 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 KNOx-values, than the average of the colder cycle part. For the hot exhaust aftertreatment system there are no differences of KNOx between "whole trip CLD" and "active time CPK",
- the average KNOX-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 KNOX-values, as the "2 sensors" method. For "cold" cycles the "1 sensor" method is less selective and does not indicate the KNOx-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.

9 DOCUMENTATION

The original data are confidential. They are archived at the Exhaust Gas Laboratory of the University of Applied Sciences, Biel.

Information about the quality management of measuring systems and of data is available on request.

10 ACKNOWLEDGEMENT

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- Swiss Federal Roads Office ASTRA,
- Swiss Federal Office of Environment BAFU.

11 LIST OF FIGURES

Annexes

I ANNEXES

I.1 A1 Reactions in a SCR deNOx Systems

A 1-1

Reactions in a SCR deNO$_x$ system

Precatalyst

$$2\,NO + O_2 \leftrightarrow 2\,NO_2$$

After AdBlue injection

Thermolysis

$$(NH_2)_2\,CO \longrightarrow NH_3 + HNCO$$

t_{Exh} ~ 150-350°C

Hydrolysis catalyst

Hydrolysis

$$HNCO + H_2O \longrightarrow NH_3 + CO_2$$

SCR catalyst

$$4\,NH_3 + 4\,NO + O_2 \longrightarrow 4\,N_2 + 6\,H_2O \quad \text{(normal)}$$

$$4\,NH_3 + 2\,NO + 2\,NO_2 \longrightarrow 4\,N_2 + 6\,H_2O \quad \text{(rapid)}$$

$$8\,NH_3 + 6\,NO_2 \longrightarrow 7\,N_2 + 12\,H_2O \quad \text{(slow)}$$

Oxidation catalyst

$$4\,NH_3 + 3\,O_2 \longrightarrow 2\,N_2 + 6\,H_2O$$

undesired:

$$2\,NH_3 + 2\,O_2 \longrightarrow N_2O + 3\,H_2O$$

$$4\,NH_3 + 4\,NO + 3\,O_2 \longrightarrow 4\,N_2O + 6\,H_2O$$

$$4\,NH_3 + 5\,O_2 \longrightarrow 4\,NO + 6\,H_2O$$

$$2\,NH_3 + H_2SO_4 \longrightarrow (NH_4)_2\,SO_4$$

$$2\,NH_3 + 2\,NO_2 \longrightarrow NH_4NO_3 + N_2 + H_2O$$

$$NH_3 + HNO_3 \longrightarrow NH_4NO_3$$

B362_A1-1_Reactions in a SCR deNOx system AFHB

Glossary of principal nitric components

AdBlue: reduction agent, 32,5 mass % urea, rest water (-11°C)

NO	…	nitric oxide (nitrogen oxide)
NO_2	…	nitric dioxide (nitrogen dioxide)
N_2O	…	nitrous oxide (greenhouse potential ~ 300x CO2)
NH_3	…	ammonia (ammonia slip undesired)
NH_4	…	ammonium
$(NH_2)_2CO$	…	urea (bio-compatible)
$NH_4\ NO_3$	…	ammoniumnitrate
$(NH_4)_2SO_4$	…	ammoniumsulphate
HNCO	…	isocyanic acid (thermolysis of urea)
$(HNCO)_3$	…	cyanuric acid (temp. < 350°C solid)
HNO_3	…	nitric acid
HNO_2	…	nitrous acid
HCN	…	hydrogen cyanide

Denoxium:
reduction agent, urea + ammoniumformiat + water (-30°C)
Ammoniumformiat … $HCO_2\ NH_4$

Some problems:

- inclomplete urea decomposition at t_{Exh} < 300°C
- serious risks of solid deposits at t_{Exh} < 200°C
- urea related deposits (cyanuric acid up to 350°C)
  - deterioration of performance and structure of catalytic surfaces
  - deficit of NH_3 for the SCR downstream, [17]
- with ammonia slip possibilities of secondary reactions in the sampling line, interference with measuring accuracy, risk of deposits and / or damaging of measuring apparatus (particulary CLD), [20].

Reasons for NH_3 slip:

- incomplete SCR reaction
- release from SCR-cat. by temperature changes (store – release)
- incomplete urea conversion before SCR-cat → NH_3 production after SCR-cat.

I.2 A2 Data and measuring set-up of investigated vehicles

A 2-1

Vehicle A

Tested city bus on the HD chassis-dyno (Dinex A/S, Middelfart – Denmark)

Vehicle Data	
Type of vehicle	City Bus
Make and type	VOLVO B10 BLE
Chassis-Nr.	YV3R4A517XA004863
Matriculation number	PZ 95 492
Types approval	-
Overall displacement	9.603 dm^3
Power	180 kW @ 2000 rpm
Emission Code	Euro II
Exhaust aftertreatment	DPF + SCR (retrofitted)
Matriculation	05.1999

Measuring set-up with vehicle A

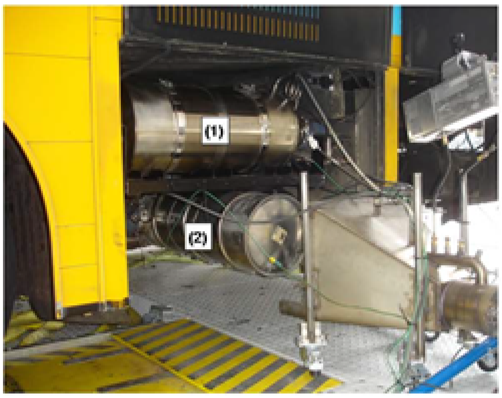


Fig.3a: Retroffited combined System.
DPF (1) & SCR (2)

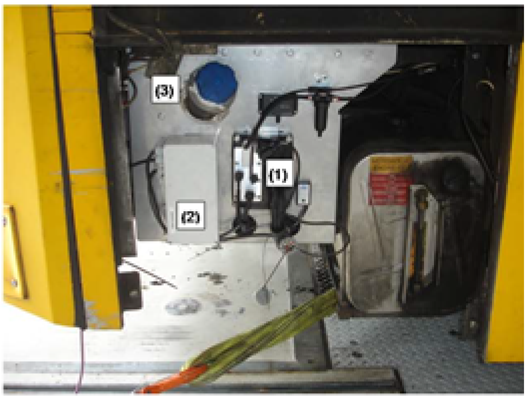


Fig.3b: Urea Dosing System UDS (1),
datalogger (2) & Adblue tank (3)

TeVeNO$_x$: Chassis Dyno @ Dinex/DK

Tested vehicle: VOLVO B10 BLE
Retrofitted system: DPF (DiSic Catalyzed) & DiNO$_x$ (Vanadium SCR)

Measurements:

1) Fige: Test preconditioning: (10 min. at 78 km/h, 2 min. idle)
   - at least 1 measurement with gain 0.75
   - run with UDS dosing off (reference, not done on 06.2011) ***

2) Stationary operating points:
   Time schedule:
   00:00 Idle
   05:00 OP1 / 44 km/h (Gear 3, 1500 rpm) -> SWON
   20:00 OP2 / 78 km/h (Gear 4, 1900 rpm)
   35:00 Idle
   40:00 test end (-> change to 50:00 to stabilize the NO$_x$-emissions at idle -> SWOFF)
   - at least 1 measurement with gain 0.75 & *gain 0.85*
   - if possible 1 repetition without dosing (vehicle influences 06.2011 -> 01.2012)

3) On-road measurements:
   + with NO$_x$-Sensor (up & downstream)
   + on-board NO$_x$ measurement (if available)
   - defined roadway:
   ~20 min. if possible with a highway part at the end.
   2 runs with dosing, 1 run without dosing.
   - after each hot run with UDS go on the side in idling and measure urea switch-off during the cooldown (see Fig10, B298)

Vehicle B

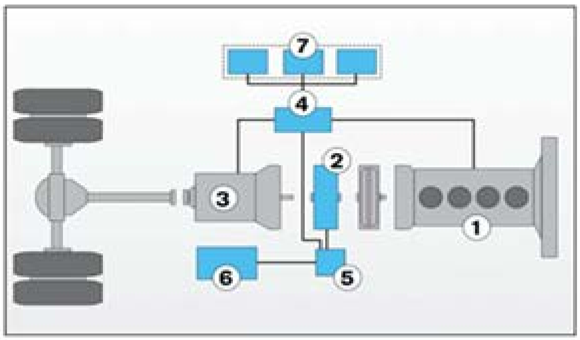
Tested city bus Volvo 7700 Hybrid

Vehicle Data	
Type of vehicle	City Bus
Make and type	VOLVO 7700 Hybrid
Chassis-Nr.	YV3T1S127C1152251
Matriculation number	BE 661644
Types approval	-
Diesel engine displacement	4.76 dm^3
Power Diesel	158 kW @ 2200 rpm
Elektric motor power	max 120 kW, continuous 70 kw
Emission Code	Euro V
Exhaust aftertreatment	DPF (CRT)+ SCR
Matriculation	2011

Measuring set-up with vehicle A

The hybrid bus's main components

1. Diesel engine
2. Electric motor/generator
3. Transmission
4. Electronic control unit
5. Energy converter DC/AC
6. Batteries
7. Electrical additional components



The drive-train of Volvo 7700 Hybrid Bus

VOLVO 7700 HYBRID 12M, 31+2

Lagerbus, VTS1105 (152251)

Dieselmotor (D5E215):
158 kW bei 2'200 U/min
800 Nm bei 1'200–1'700 U/min
Elekromotor (I-SAM):
120 kW max. / kontinuierlich 70 kW
800 Nm max. / kontinuierlich 400 Nm
I-Shift
3 Türen ISAF, T1 = IST, T2 – 3 = IST
Kneeling
Klimaanlage Spheros Citysphere 2 x 3.8 kW
Zusatzheizer Webasto
VDV Actia Armaturenbrett
RAG 2000+
2 Dachluken
Sitze Kiel Centra
Aussenanzeigen (Gorba LED):
Front 126x16-15
Seite 112x16-10
Hinten 112x16-10
1 x 19" LCD – Bildschirm
Behindertenrampe manuel Hübner HK174
Radio / CD

Engine SCR CRT

Combustion engine and CRT + SCR -System

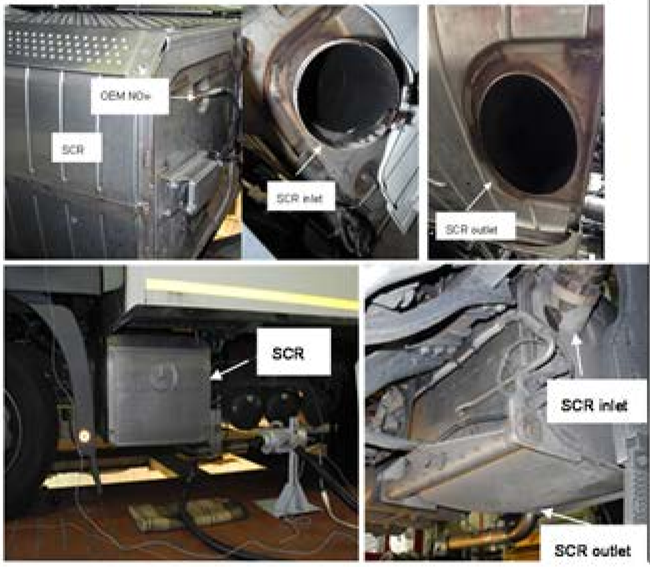
A 2-3

Vehicle C & D

The tested vehicles and some principal data

Vehicle Data		
Type of vehicle	Truck (**vehicle C**)	Truck (**vehicle D**)
Make and type	Mercedes-Benz Actros 1848	Mercedes-Benz Actros 1841
Chassis-Nr.	WDB 9340321L391662	WDB 9300361L098058
Matriculation number	-	SG 32240
Types approval	-	-
Overall displacement	11.95 dm^3	11.95 dm^3
Power	350 kW @ 1800 rpm	300 kW @ 1800 rpm
Emission Code	Euro V	Euro V
Exhaust aftertreatment	SCR (OEM)	SCR (OEM)
Matriculation	2012	2006
Odometer at start	573 km	500'523 km
Type of vehicle	Truck (vehicle C)	Truck (vehicle D)
Make and type	Mercedes-Benz Actros 1848	Mercedes-Benz Actros 1841
Chassis-Nr.	WDB 9340321L391662	WDB 9300361L098058
Matriculation number	-	SG 32240
Types approval	-	-

Measuring set-up with vehicle C & D



TeVeNOx : Chassis Dyno @ LARAG/Wil SG

Tested vehicles:
Mercedes- Benz Actros 1848 / 1841

OEM system: OEM SCR
Measurements:

1) Stationary operating points:
Time schedule:
00:00 Idle
05:00 OP1 / ≈ 50 km/h (1200 rpm) -> SWON
25:00 OP2 / ≈ 70 km/h (1600 rpm)
40:00 Idle
60:00 test end -> SWOFF

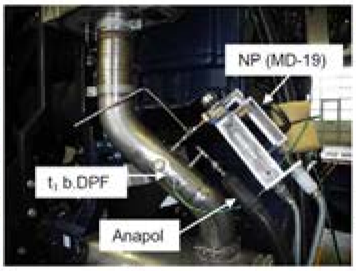
2) On-road measurements:
+ with NOx-Sensor (up & downstream)
+ on board NOx measurement (if available)
- defined roadway:
  ~30 min. if possible with a highway part at the end.
  2 runs with dosing, 2 runs without dosing.
- after each run with dosing go on the side in idling and measure urea switch-off during the cooldown.

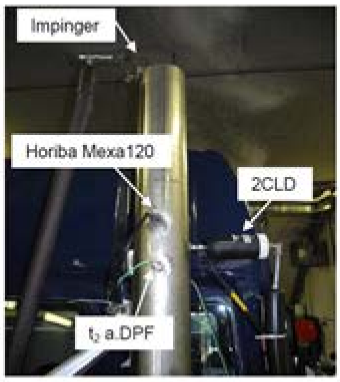
Vehicle E

Tested Truck on the HD chassis-dyno (Vehicle E, MAN Otelfingen)

Vehicle Data	
Type of vehicle	Truck (vehicle E)
Make and type	MAN TGS 41.540 10x4
Chassis-Nr.	WMA39SZZXCM600685
Matriculation number	-
Types approval	-
Overall displacement	12.419 dm^3
Power	397 kW @ 1700-1900 rpm
Emission Code	Euro V
Exhaust aftertreatment	SCR (OEM) + retrofitted DPF
Matriculation	2012
Odometer at start	225 km

Measuring set-up with vehicle E



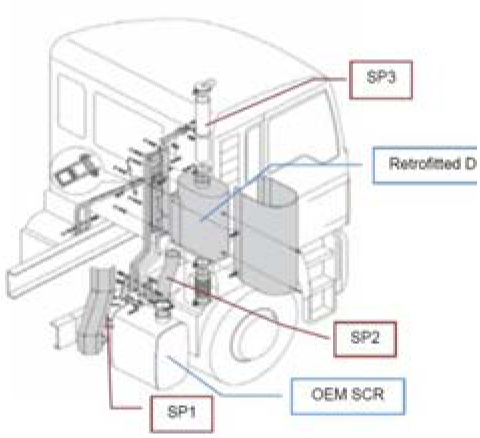


TeVeNOx : Chassis Dyno @ MAN/Otelfingen

Tested vehicles: MAN TGS 41.540
System: OEM SCR + retrofitted DPF
Measurements:

1) Stationary operating points:
Time schedule:
00:00 Idle
15:00 OP1 / ≈ 52 km/h (1240 rpm) -> SWON
40:00 OP2 / ≈ 73 km/h (1180 rpm)
55:00 Idle
75:00 test end -> SWOFF

2) NO_2-Steptest
Time schedule:
00:00 OP1 / ≈ 53 km/h (1250 rpm / P_{wheel} 30 kW)
00:05 OP2 / ≈ 53 km/h (1250 rpm / P_{wheel} 45 kW)
00:10 OP3 / ≈ 53 km/h (1250 rpm / P_{wheel} 60 kW)
00:15 OP4 / ≈ 53 km/h (1250 rpm / P_{wheel} 74 kW)
00:20 OP5 / ≈ 53 km/h (1250 rpm / P_{wheel} 90 kW)
00:25 idle / ≈ 0 km/h (600 rpm / P_{wheel} 0 kW)
00:30 test end



Vehicle F

Tested Truck on the HD chassis-dyno (Vehicle F, LARAG Wil SG)

Vehicle Data	
Type of vehicle	Truck
Make and type	Mercedes Actros 1845 Blutec 6
Chassis-Nr.	WDB9630031L626074
Matriculation number	SG 210 160
Types approval	-
Overall displacement	12.809 dm^3
Power	330 kW @ 1800 rpm
Emission Code	Euro VI
Exhaust aftertreatment	OEM CRT & SCR
Matriculation	2012
Odometer at start	11'919 km

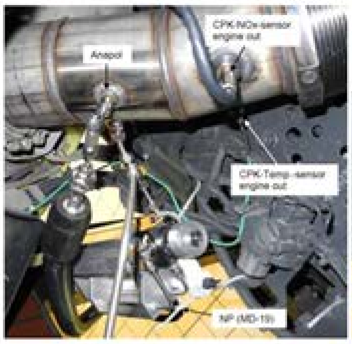
Measuring set-up with vehicle F

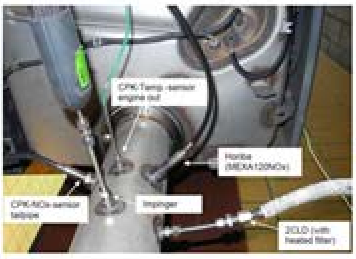
TeVeNOx : Chassis Dyno @ LARAG/Wil SG

Tested vehicles: Mercedes Actros 1845 Bluetec 6
System: OEM DOC, DPF + SCR

Measurements:
1) Stationary operating points:
Time schedule:
00:00 Idle
15:00 OP1 / ≈ 53 km/h (1200 rpm) -> SWON
40:00 OP2 / ≈ 71 km/h (1600 rpm)
55:00 OP3 / ≈ 9 km/h (670 rpm)
75:00 test end -> SWOFF

2) On-road measurements:
+ with NOx-Sensor (up & downstream; CPK-DL)
+ 2CLD measurement apparatus
+ Horiba Mexa 120NOx (tailpipe)
- defined roadway:
~30 min. if possible with a highway part at the end.
6 runs (3 runs 2CLD upstream, 3 runs 2CLD downstream)





A 2-6

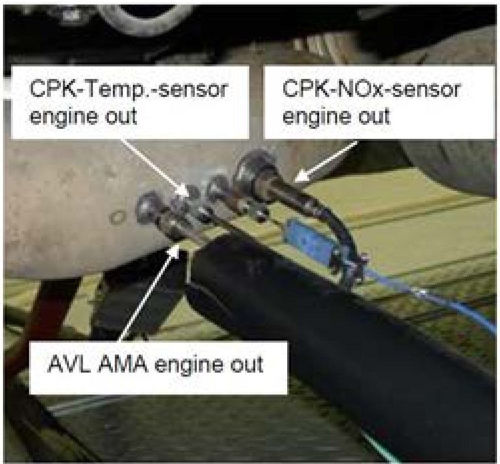
Vehicle G

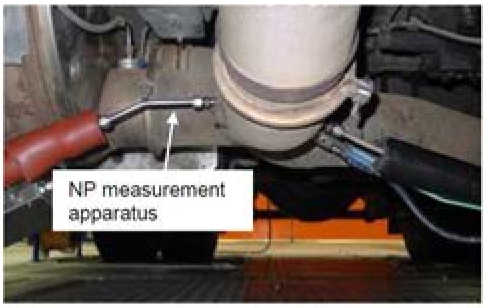
Tested Truck on the HD chassis-dyno (Vehicle G, JRC Ispra/Italy)

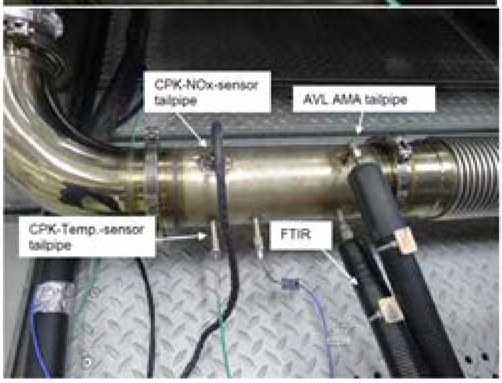
The vehicle is equipped with a retrofitted system for CNG, which enables the bi-fuel operation Diesel-CNG

Vehicle Data	
Type of vehicle	Truck
Make and type	Mercedes Actros 1845 Blutec 6
Chassis-Nr.	WDB9630031L626074
Matriculation number	SG 210 160
Types approval	-
Overall displacement	12.809 dm^3
Power	330 kW @ 1800 rpm
Emission Code	Euro VI
Exhaust aftertreatment	OEM CRT & SCR
Matriculation	2012
Odometer at start	11'919 km

Measuring set-up with vehicle G







TeVeNOx : Chassis Dyno at JRC Ispra / Italy

Tested vehicles: DAF XF 105
System: OEM SCR

Measurements:

1) Stationary operating points:
Time schedule:
00:00 Idle
05:00 OP1 / ≈ 50 km/h (960 rpm) -> SWON
20:00 OP2 / ≈ 78 km/h (1165 rpm)
30:00 OP3 / ≈ 10 km/h (875 rpm)
50:00 test end -> SWOFF

2) FIGE
+ with NOx-Sensor (up & downstream; CPK-Datalogger)
+ AVL AMA apparatus
+ AVL FTIR (tailpipe)
+ AVL NP apparatus (tailpipe)

Vehicle H & I

Tested Truck on the HD chassis-dyno (Vehicle H & I, MAN / Otelfingen)

Vehicle Data	
Type of vehicle	Truck
Make and type	MAN TGS 18.400 4x2
Chassis-Nr.	WMA06SZZ68M522408
Matriculation number	ZH 515909
Type approval	-
Overall displacement	10.520 dm^3
Power	400 kW / 1900 rpm
Emission Code	Euro V
Exhaust aftertreatment	OEM SCR
Matriculation	2008
Odometer at start	84'974 km

Measuring set-up with vehicle H & I

TeVeNOx / Chassis Dyno, MAN / Otelfingen / Test program

Vehicle:
(TeVeNOx Vehicle H, OEM SCR, no DPF)
MAN TGS 18.400 4x2 BL
ZH 515'909
VIN: WMA06SZZ68M522408
Radstand 5500mm
Aufbau Walde Courtain Sider
Fahrerhaus LX
1x original SCR used
1x new SCR

Measurements:
A) Chassis dyno -> 3 points test with original SCR
B) Chassis dyno -> 3 points test without dosing *
C) Chassis dyno -> 3 points test with new SCR
E) Road trip with new SCR 3x
F) Road trip without dosing * 3x
G) Road trip with original SCR 3x
* if possible
Chassis dyno test schedule for test A, B, C
Phase1: Idle 5min. -> stable temperature
Phase2: OP1 15min. -> switch-on (T>200°C)
Phase3: OP2 15min. -> higher temperature
Phase4: OP3 "Idle" (10km/h), no load 20min. -> cool down & Switch-off
If there is no possibility of running without AdBlue injection:
- cool down
- idle -> OP2 (switch-on on OP2 to define NOx level w/o injection)

Vehicle H&I fitted for on-road measurements with NOx sensor, CLD and 3000 kg load.

A 2-8

Vehicle J

Tested Truck on the HD chassis-dyno (Vehicle J, LARAG / Wil)

Vehicle Data	
Type of vehicle	Truck
Make and type	Mercedes-Benz Actros 2635
Chassis-Nr.	WDB 952 073 1K82 4466
Matriculation number	-
Type approval	3MF8 97 M
Engine	OM 501 LA
Overall displacement	11'946 cm^3
Power	260 kW
Emission Code	EURO III
Exhaust aftertreatment	DPF&SCR retrofit: HJS / CRT & Umtec / NO_xOFF
Matriculation	14.10.2003

Measuring set-up with vehicle J

Tested vehicle and measuring apparatus on the LARAG HD chassis dyno

2CLD and Anapol

Vehicle exhaust tailpipe equipped for chassis dyno measurements

Leistungsbereich	20 – 500 kW
Durchmesser Katalysator	163 – 496 mm (abhängig von Leistungsbereich)
Länge Katalysator	430 – 970 mm (abhängig von Leistungsbereich und ev. Kombination mit Partikelfilter)
Durchmesser Ein-/Auslass	42 – 168 mm (abhängig von Leistungsbereich)
Isolation Katalysator	Dicke 20 mm; 0.05 W/m/K Oberflächentemperatur aussen max. 80°C
Anordnung Ein/Austritt	jeweils axial und radial möglich
Gewicht Katalysator	15 – 110 kg
Aufhängung, Befestigung	variabel, in verschiedenen Positionen möglich
Spezifische Katalysatoren	Auf Wunsch sind verschiedene Beschichtungen möglich
Reduktionsmittel	Ammoniakwasser, Konzentration <10% (Salmiakgeist, verdünnt)
Einsatzbereich	-15°C bis +60°C Umgebungstemperatur (bei Einsatz von Ammoniakwasser mit 25% Konzentration bis -40°C möglich)
Verbrauch	Abhängig von Motorengrösse, ursprünglicher Emissionskategorie und Belastung
Material Katalysator	
Material Gehäuse	Sämtliche Komponenten sind aus hochwertigem Chromstahl gefertigt
Regelung	Speicherprogrammierbare Steuerung (SPS) Selectron 727/723, Möglichkeit zur Anbindung an CANopen, erfüllt EN 50 155 («Bahnnorm»)
Betankung	Tankstelle «RKtop», komplett geschlossenes System, einfachste Bedienung, Vorratsbehälter von 180 – 2000 Liter

Technischen Daten NO_xOFF system

I.3 A3 Example of a road test circuit

Restliche Formatierung wie normaler Text

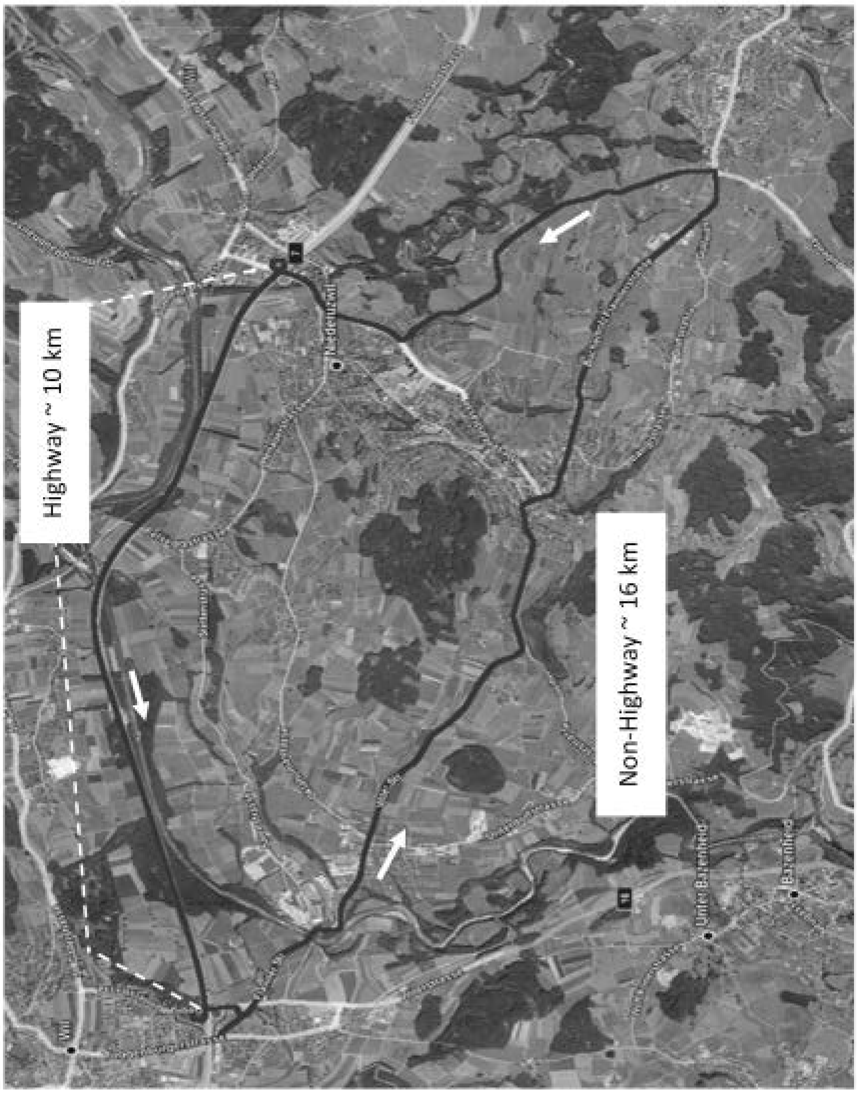
A 3

Example of Road Testing Circuit

Vehicle F; OEM DOC, DPF & SCR; ULSD; AdBlue

Trip

Beginning:	Toggenburgerstrasse 104, 9501 Wil SG
Ending:	Toggenburgerstrasse 104, 9501 Wil SG
Total length:	approximately 26 km
Duration of trip:	approximately 30 min



B362_A3_Road testing circuit Trip1-6

Abbreviations

Begriff	Bedeutung
AFHB	Abgasprüfstelle FH Biel, CH
ASTRA	Bundesamt für Strassen, (Swiss Federal Roads Office)
AUVA	Austria Unfall Versicherung-Anstalt
BAFU	Bundesamt für Umwelt, (Swiss Federal Office of Environment)
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 analyser
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
FTIR	Fourrier Transform Infrared Spectrometer
GPS	global positioning system
GRPE	UN Groupe of Rapporteurs Pollution & Energie
HD HDV	heavy duty heavy duty vehicle
HEV	hybrid electric vehicle
HNCO	isocyanic acid
ICE	internal combustion engines
JRC	EC Joint Research Center
KNOX	conversion rate of NO$_x$
LC-MS	liquid chromatography & mass spectrometry
LEZ	low emission zones
LRV	Luftreinhalteverordnung
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
OEM	original equipment manufacturer

Begriff	Bedeutung
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
PMP	Particulate Measurement Program of GRPE
PSD	particle size distribution
RAI	reduction agent injection
RE	reduction efficiency
RNC	reactive nitrogen compounds
SCR	selective catalytic reduction
SMPS	Scanning Mobility Particle Sizer
SNORB	Swiss NO Retrofit Benchmark
SOC	state of charge
SP	sampling position
SUVA	Schweiz. Unfallversicherungs-Anstalt
SW	urea switch
SWON	urea switch on
SWOFF	urea switch off
TBG	Tiefbaugenossenschaft
TC	thermoconditioner. Total Carbon
TeVeNO$_x$	Testing of Vehicles with NO$_x$ reduction systems
TP	Tailpipe
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	VERTdePN Test 1 - engine dyno
VPNT2	VERTdePN Test 2 - field durability 1000h
VPNT3	VERTdePN Test 3 - check after field test chassis dyno
VPNTSET	VERTdePN secondary emissions test - engine dyno
VSET	VERT Secondary Emissions Test
	feed factor of urea dosing; ratio: urea injected / urea stoichiometric; calculated by the ECU.

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Final Report

Schweizerische Eidgenossenschaft
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Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK
Bundesamt für Strassen ASTRA

FORSCHUNG IM STRASSENWESEN DES UVEK
Formular Nr. 3: Projektabschluss

erstellt / geändert am: 26. August 2013 / 9. Sept. 2013

Grunddaten

Projekt-Nr.:	ASTRA 2011/015
Projekttitel:	TeVeNOx - Testing of SCR-Systems on HD-Vehicles
Enddatum:	30. Juni 2013

Texte

Zusammenfassung der Projektresultate:

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,
- Sampling with impingers with the following analytics of traces is approximately 1 order of magnitude more sensitive for Ammonia and 3 orders of magnitude more sensitive for Isocynic Acid. This method is an appropriate tool to detect specific non-legislated emission components; for a "quick-check" nevertheless it is not applicable.

Other remarkable technical points are:

- higher feed factor α increases slightly KNOX, 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 KNOX – the comparative testing on vehicle e.g. before and after field durability period, should be realized at similar ambient conditions,
- for estimate of KNOX 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 KNOX-values, than the average of the colder cycle part. For the hot exhaust aftertreatment sys-tem there are no differences of KNOX between "whole trip CLD" and "active time CPK",
- the average KNOX-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 KNOX-values, as the "2 sensors" method. For "cold" cycles the "1 sensor" method is less selective and does not indicate the KNOX-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.

Forschung im Strassenwesen des UVEK: Formular 3 — Seite 1 / 3

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Bundesamt für Strassen ASTRA

Zielerreichung:

Die Ziele des Projektes wurden erreicht: es wurden die geplanten Fahrzeuge getestet und es wurden alle vorgenommenen Testmethoden angewendet.
Es wurden auch Zusatzschwerpunkte, wie Gegendrucksteigerung, Bi-fuel-Betrieb (CNG), erweiterte Tests mit CPK-Sensoren, sowie erweiterte Tests mit Impingers am Motorprüfstand realisiert.
Das Wissen über die Qualitätsprüfung der SCR-Systeme an Fahrzeugen wurde erarbeitet und die Grundlagen für mögliche weitere Schritte der Behörden wurden geliefert.

Folgerungen und Empfehlungen:

Um die erarbeiteten Resultate zu nützen empfehlen wir:

- die Erkenntnisse dem Weltforum zur Harmonisierung fahrzeugtechnischer Vorschriften (WP.29) im Rahmen der UNECE zur Verfügung zu stellen, im Speziellen der Arbeitsgruppe WP.29-GRPE, welche sich mit der weltweiten Harmonisierung der Abgasvorschriften befasst;
- eine geeignete Information weiterer internationaler Fachkreise ins Auge zu fassen;
- sofern notwendig eine Informationsveranstaltung in Schweizer Fachkreisen vorzusehen.

Publikationen:

- Es wurde ein SAE Paper erstellt und für den SAE World Congress, Detroit 2014 angeboten
Authoren: J. Czerwinski, Y. Zimmerli/AFHB*), A. Mayer/TTM*), N. Heeb/EMPA*), H. Berger/ASTRA*), G. D'Urbano/BAFU*)
Titel: Testing of SCR-Systems on HD-Vehicles-TeVeNOx
(die formelle Abgabe des Papers an SAE ist für Januar 2014 vorgesehen).
- Es wird vorgeschlagen, eine Präsentation des Projektes beim nächsten VERT-Forum an der EMPA, im März 2014, durchzuführen.

Der Projektleiter/die Projektleiterin:

Name: Prof. Dr. Czerwinski Vorname: Jan

Amt, Firma, Institut: AFHB Abgasprüfstelle und Motorenlabors der BFH-TI, Biel

Unterschrift des Projektleiters/der Projektleiterin:

J. Czerwinski

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Bundesamt für Strassen ASTRA

FORSCHUNG IM STRASSENWESEN DES UVEK

Formular Nr. 3: Projektabschluss

Beurteilung der Begleitkommission:

Beurteilung:

Das Projekt wurde speditiv an die Hand genommen, mit den Untersuchungen wurde bei Projektbewilligung unverzüglich begonnen. Die untersuchten Fahrzeuge und Systeme (zwei Busse, sieben Lastwagen und ein Lastwagen-Motor, dazu drei Untersuchungen bezüglich Sekundäremissionen) zeigen eine breite Palette der heute im Strassenverkehr anzutreffenden Fahrzeuge und deren Verhalten in Bezug auf NOx- und Sekundäremissionen. Gleichzeitig konnte eine grosse Anzahl SCR-Systeme, seien es Original- oder Nachrüstsysteme unter verschiedenen Fahr- und Messbedingungen auf ihre Wirksamkeit überprüft werden. Das Projektziel wurde erreicht. Das Projekt darf als gelungen und die daraus gewonnenen Erkenntnisse als wertvoll bezeichnet werden.

Umsetzung:

Die aus diesem Projekt gewonnenen Erkenntnisse dienen der weiteren Entwicklung der Abgasvorschriften, speziell was die Reduktion von Stickoxidemissionen anbelangt aber u. U. auch in Bezug auf heute noch nicht reglementierte Sekundäremissionen. Die Umsetzung erfolgt auf internationaler Ebene im Rahmen der Europäischen Wirtschaftskommission der Vereinten Nationen (UNECE) im Weltforum zur Harmonisierung fahrzeugtechnischer Vorschriften (WP.29), auf nationaler Ebene durch die Fachämter in der entsprechenden Gesetzgebung.

weitergehender Forschungsbedarf:

Der weitergehende Forschungsbedarf wird laufend überprüft und entsprechend den Erfordernissen der Vorschriftenentwicklung (national und international) festgelegt.

Einfluss auf Normenwerk:

Die WP.29 erarbeitet, u. a. auf Basis der hier gewonnenen Erkenntnisse, verfeinerte Testmethoden und Vorschriften zur Reglementierung von Fahrzeugabgasen (sog. UNECE-Reglemente).

Der Präsident/die Präsidentin der Begleitkommission:

Name: Berger Vorname: Heinz

Amt, Firma, Institut: Bundesamt für Strassen ASTRA

Unterschrift des Präsidenten/der Präsidentin der Begleitkommission:

H. Berger

Catalogue of the reports of the research about roads

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1365	SVI 2004/014	Neue Erkenntnisse zum Mobilitätsverhalten dank Data Mining?	2011
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1328	VSS 2005/302	Grundlagen zur Quantifizierung der Auswirkungen von Sicherheitsdefiziten	2011
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1322	SVI 2005/007	Zeitwerte im Personenverkehr: Wahrnehmungs- und Distanzabhängigkeit	2008
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1313	VSS 2001/201	Kosten-/Nutzenbetrachtung von Strassenentwässerungssystemen, Ökobilanzierung	2010
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1308	VSS 2008/201	Hindernisfreier Verkehrsraum- Anforderungen aus Sicht von Menschen mit Behinderung	2010
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1301	SVI 2007/006	Optimierung der Strassenverkehrs- unfallstatistik durch Berücksichtigung von Daten aus dem Gesundheitswesen	2009
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1298	ASTRA 2007/012	Griffigkeit auf winterlichen Fahrbahnen	2010
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1290	VSS 1999/209	Conception et aménagement de passages inférieurs et supérieurs pour piétons et deux-roues légers	2008
1289	VSS 2005/505	Affinität von Gesteinskörnungen und Bitumen, nationale Umsetzung der EN	2010
1288	ASTRA 2006/020	Footprint II- Long Term Pavement Performance and Environmental Monitoring on A1	2010
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1286	VSS 2000/338	Verkehrssqualität und Leistungsfähigkeit auf Strassen ohne Richtungstrennung	2010
1285	VSS 2002/202	In-situ Messung der akustischen Leistungsfähigkeit von Schallschirmen	2009
1284	VSS 2004/203	Evacuation des eaux de chaussée par les bas-cotés	2010
1283	VSS 2000/339	Grundlagen für eine differenzierte Bemessung von Verkehrsanlagen	2008
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1281	SVI 2004/002	Systematische Wirkungsanalysen von kleinen und mittleren Verkehrsvorhaben	2009
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1278	ASTRA 2004/016	Auswirkungen von fahrzeuginternen Informationssystemen auf das Fahrverhalten und die Verkehrssicherheit - Verkehrstechnischer Teilbericht	2009
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1268	ASTRA 2005/007	PM10-Emissionsfaktoren von Abriedspartikeln des Strassenverkehrs (APART)	2009
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644	AGB 2005/004	Hochleistungsfähiger Faserfeinkornbeton zur Effizienzsteigerung bei der Erhaltung von Kunstbauten aus Stahlbeton	2010
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632	AGB 2008/201	Sicherheit des Verkehrssystem Strasse und dessen Kunstbauten Testregion - Methoden zur Risikobeurteilung Schlussbericht	2010
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627	AGB 2002/002	Eigenschaften von normalbreiten und überbreiten Fahrbahnübergängen aus Polymerbitumen nach starker Verkehrsbelastung	2008
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625	AGB 2005/109	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Effektivität und Effizienz von Massnahmen bei Kunstbauten	2009
624	AGB 2005/108	Sicherheit des Verkehrssystems / Strasse und dessen Kunstbauten / Risikobeurteilung für Kunstbauten	2010
623	AGB 2005/107	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Tragsicherheit der bestehenden Kunstbauten	2009
622	AGB 2005/106	Rechtliche Aspekte eines risiko- und effizienzbasierten Sicherheitskonzepts	2009
621	AGB 2005/105	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten Szenarien der Gefahrenentwicklung	2009
620	AGB 2005/104	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Effektivität und Effizienz von Massnahmen	2009
619	AGB 2005/103	Sicherheit des Verkehrssystems / Strasse und dessen Kunstbauten / Ermittlung des Netzrisikos	2010
618	AGB 2005/102	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Methodik zur vergleichenden Risikobeurteilung	2009
617	AGB 2005/100	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten Synthesebericht	2010
616	AGB 2002/020	Beurteilung von Risiken und Kriterien zur Festlegung akzeptierter Risiken in Folge aussergewöhnlicher Einwirkungen bei Kunstbauten	2009