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Potentials for NO_x and CO_2 reduction of combined NSC + passive SCR system in Diesel passenger car application

The stringent pollutant and CO_2 emission limitation in upcoming legislation norms for Diesel passenger car applications force the introduction of exhaust aftertreatment systems with maximum purification and energetic efficiency. The state-off-the-art technologies for NO_x reduction, NO_x storage and reduction catalyst (NSC) and selective catalytic reduction catalyst (SCR), show challenges for robust performance under strongly extended emission relevant operation conditions from cold start to high engine load and speed. One technical solution is the combination of NSC and passive SCR.

This paper presents the experimental results obtained in the EU project "Powerful". On engine test bench and demonstrator vehicle, an exhaust aftertreatment system combining NSC, passive SCR and fuel reformer technology was developed and experimentally investigated steady-state and on road. The engine independent NSC operation offers potentials for lowered fuel consumption penalty by avoiding engine rich operation. The intrinsic NH_3 formation during the NSC regeneration is used for additional NO_x conversion on the passive SCR and reduces NO_x and CO_2 emission.

Key words: *exhaust aftertreatment, NSC, SCR, fuel reformer*

1. Introduction

The upcoming worldwide more stringent emission legislation and CO_2 restriction are highly challenging for modern Diesel engine and aftertreatment technology. Beside the more restrictive worldwide exhaust emission standards and the lowering of Greenhouse Gas (GHG) emissions, new emission evaluation test procedures, like WLTC (*Worldwide harmonized Light vehicles Test Cycle*), RDE (*Real Driving Emissions*) and PEMS (*Portable Emissions Measurement System*) result in enlarged emission relevant engine operation area. Additionally, the higher dynamic profiles increase the demands to the DeNOx catalysts as NO_x concentrations and mass flows typically rise under these operational conditions. Thus either in case of SCR systems (*Selective Catalytic Reduction*) higher urea consumption or in the case of NSC systems (*NO_x storage and reduction catalyst*), more frequent purging intervals are required. Beside the increased coverage of engine load and speed also the emission testing including cold start and high temperature cycles demands an extended active temperature range of aftertreatment systems. On the one hand, moving to lower absolute emission levels by engine internal measures progressively cause drawbacks in CO_2 emission and system cost and complexity. On the other hand, increased combustion efficiency, decreased friction losses by improved engine technologies, low pressure EGR, refined boosting or electrification lead to lowered exhaust gas temperatures and raise the kinetic based challenges of exhaust aftertreatment functionalities. Increased exhaust purification activity requires sufficiently high exhaust gas temperature. Under these conditions, the cold start is especially challenging. However, an active heating strategy to overcome the cold start problem is facing a trade-off with fuel consumption penalty and thus CO_2 emissions. The optimization of the trade-off between emission minimization and fuel economy is very complex. Furthermore, OBD regulations request expanded durability over lifetime on high catalysis activity and selectivity level. For meeting all, partly contrary, emission requirements, an optimum interaction of advanced engine internal and exhaust aftertreatment functionalities is demanded.

On the aftertreatment side, advanced combined systems offer the best overall performance by the benefit of synergistic effects. Besides the well-established and mandatory DPF-technology, Diesel engines demand also the installation of high efficient NO_x reduction technologies for the forecasted EU-6 norms, at least for the majority of vehicles. However, neither the SCR nor the NSC technology offers optimum performance and consumer acceptance at the same time throughout the broad real driving operation window. Merits of the SCR technology are the continuous high NO_x performance at temperatures above 200 °C. However, increased urea consumption for high NO_x conversion under real driving and the consequently necessary urea refilling by the customer, urea crystallization constraints and the limited activity and high dependency on the NO_2/NO_x-ratio at low temperature with necessary heating measures are demerits of an SCR only system. In contrary, the NSC offers potential at low temperature by pure NO_x adsorption and does not rely on additional working media. However, the NSC´s demerits are the additional fuel consumption by regular exhaust enrichment and the small operation window with limited NO_x reduction at low temperature and limited NO_x adsorption capacity at high temperature. Combined NSC and SCR systems offer various potentials. As schematically shown in Fig. 1, NSC and SCR combination systems can generally be classified in 3 types:

1. NSC + SCR based system: active NSC + active SCR
   Both systems are independently and actively operated. The active SCR is based on a second working fluid as reducing agent, i.e. NH_3-carrier (e.g. liquid urea).
2. SCR based system: passive NO_x adsorber (PNA) + active SCR
   The active SCR is supplemented by an upstream positioned PNA, which only adsorbs and desorbs NO_x
3. NSC based system: NSC + passive SCR

Only the NSC is operated actively. The passive SCR is based on the NH_3 emission during the NSC enrichment and does not rely on a second working media.

The highest degree of freedom regarding NO_x conversion potential offers the combination type 1. Beside the extended active temperature coverage towards low temperature by NSC and towards high temperature by SCR, this combination provides an improved robustness of the DeNOx control strategy, since the required efficiencies of both components (NSC and SCR) are lower than for NSC or SCR only systems. Furthermore, the urea consumption can be reduced by NO_x conversion of the NSC operation as well as additionally by NH_3 formation during the NSC regeneration. However, this concept features the highest packaging, costs and system complexity and is also dependent on a second working fluid. Furthermore, to avoid high NSC NO_x load at engine start, that might cause NSC NO_x desorption without conversion at the cold SCR, comparably to the later described PNA difficulty, the NSC NO_x load has to be kept always below a certain controlled level. This mostly permanent active NSC operation causes CO_2 emission increase due to the required periodic rich engine operation. A multiplicity of control interactions between the active NSC and the active SCR need to be taken into account but also offer optimization potentials beyond the solely addition of two active systems. The NSC regeneration demand can be defined depending on the current SCR activity. At high SCR activity, the NSC can be operated at higher NO_x load. Hence, fuel consumption penalty can be reduced by less frequent NSC enrichment and higher reductant consumption efficiency due to higher NO_x-OSC ratio (OSC: *Oxygen Storage Capacity*, described later). At higher NO_x load, even the on-board NH_3 formation might be increased. In parallel, the urea consumption can be reduced on the one hand by NO_x reduction on the NSC and on the other hand by partial replacement of urea by on-board generated NH_3.

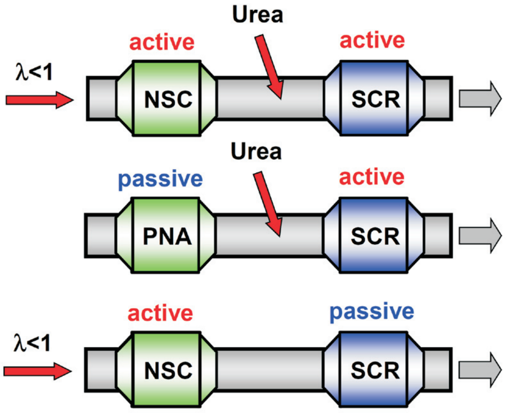


Fig. 1. NSC and SCR combination types

In type 2 the active NSC is replaced by a PNA with the target of intermediate NO_x storage during cold start and NO_x release after SCR light-off. However, this intended task of the PNA requires specific adsorber components with NO_x storage capability up to 200 °C and thermal desorption at an air-to-fuel-ratio (λ) > 1 in the temperature range of 180 °C to max. 250 °C. Such NO_x adsorber is not commercially available today. Additionally, the PNA functionality is only sufficiently applicable in case of low initial NO_x load. High initial NO_x load negatively influences the adsorption efficiency or even the total NO_x conversion by thermal NO_x desorption at cold SCR. Therefore, somehow active operation of the PNA might still be required for keeping the NO_x load on low levels resulting in increased control logic algorithms and CO_2 emission [1].

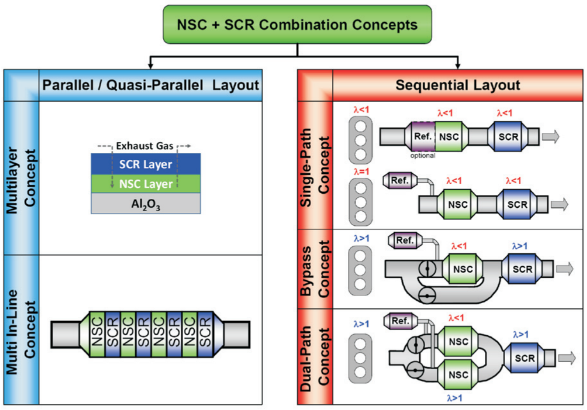
The third combination type is primarily an NSC system. In contrary to conventional NSC applications, the intrinsic ammonia (NH_3) formation during the NSC regeneration is not intended to be avoided but is desired. By this on-board formed NH_3, the NO_x conversion can be enhanced by a downstream positioned SCR. The SCR is passively operated and does not require a second working fluid without the disadvantages of a urea dosing system and additional hardware costs or urea refilling efforts.

In this paper, the exhaust purification and CO_2 emission potentials of a combined NSC and passive SCR system are investigated and discussed. The concept is in line with the requirement specification of the 7th Framework Program of the European Union, demonstrating emissions of 10 % below EU6 legislation (e.g. NO_x emission of 72 mg/km) without urea dosing system at total CO_2 emission of 98 g/km and and fuel consumption penalty of less than 2 %. Additionally, the system performance needs to be demonstrated in real driving conditions, too. To fulfil the requirements especially with strong focus on CO_2 emission, the concept is based on engine independent NSC regeneration by integrated on-board exhaust fuel reforming, with the potential of higher reductant generation efficiency than conventional Diesel engine internal enrichment. The investigated aftertreatment system is described in more detail in the next chapter.

2. Description of aftertreatment concept

2.1. Overall concept

One main functionality of the combined concept of NSC and passive SCR is the NH_3 formation on the NSC during the rich NSC regeneration. According to the state of knowledge [2–6], inside the reaction front, which axially propagates through the NSC during the rich regeneration, NH_3 is intermediately formed by over-reduction of NO_x. The formed NH_3 re-oxidizes by reaction with surface NO_x or oxygen (OSC: *oxygen storage capacity*) downstream the reaction front. At the end of the NSC regeneration, when the rich reaction front reaches the catalyst outlet, the intermediate NH_3 cannot be re-oxidized anymore and gets typically emitted as NH_3 spike. Based on this NH_3 formation process, the concepts for NSC and passive SCR combination systems can be generally differentiated between parallel or quasi-parallel layouts and sequential layouts. Figure 2 gives a general and schematic overview.



*Comment: DPF functionality is not displayed, only focus on NSC and SCR functionality

Fig. 2. Schematic overview of general layout concepts for NSC and passive SCR combination systems

The intention of a parallel layout in a multilayer design [7] resp. of a quasi-parallel layout in a multi in-line design is the in-situ utilization by storage and conversion of the axial NH_3 formation during the LNT regeneration. By this layout the intermediate NH_3 does not get re-oxidized but stored on the SCR layer resp. slice. Thereby, high NH_3 amounts might be used for NO_x conversion on the SCR. Nevertheless, the impact of the acid SCR on the alkaline NSC surface and its storage performance of acid NO_x on the one hand as well as the SCR poisoning by hydrocarbons (HC) and the absence of O_2 during the rich operation on the other hand is still open.

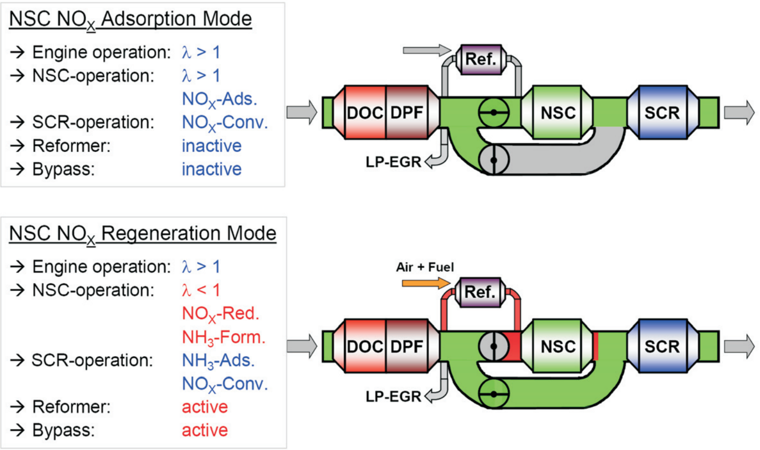
In the sequential layout, the passive SCR is operated only by the NH_3, which is being emitted from the NSC at the end of the NSC regeneration. The design can be set up as single-path [8], bypass [9] or dual-path concept. The single-path concept requests in any case a specific engine operating mode for NSC regeneration. Comparable to conventional NSC application, the NSC regeneration can be done by engine internal enrichment. Optionally, an in-line reformer catalyst might be installed upstream NSC for increasing H_2 and CO and decreasing HC concentrations and thereby improving especially the regeneration efficiency at low temperature. However, due to the necessity of high reformer operation temperatures usually in the range of 800 – 950°C for sufficient reforming activity, the capability of an in-line reformer is limited. In case of reductant breakthrough, the SCR is operated at an air-to-fuel-ratio below 1 with the risk of HC poisoning. Alternatively, an out-line reformer might be controlled in optimum operation range, resulting in enhanced reformate composition regarding H_2 and CO concentration. Nevertheless, the engine still has to be at least operated at $\lambda = 1$ to minimize excess O_2 and high exothermic reactions on the NSC during the regeneration. In contrary to the single-path concept, both bypass and dual-path concepts do not require any engine internal operation mode change. The engine can be operated independently at $\lambda > 1$ due to the local enrichment only of the NSC. In the dual-path concept the two NSC are operated alternatively by switching the exhaust gas flaps. The NSC bypass in the bypass concept is only activated during the NSC regeneration.

As best compromise between NO_x reduction performance at cold and high temperature, CO_2 emission, system modularity for application of various operation strategies and system complexity the bypass concept is chosen. Main target is the investigation of the interaction of an NSC and a passively operated SCR fulfilling the required specification of none additional working fluid.

Figure 3 shows the simplified method of operation of the investigated exhaust aftertreatment system combining on-board fuel reformer assisted under-floor NSC with exhaust bypass and passive SCR. The complete hardware design and system integration as well as the software functional development and control algorithms have been developed. Basically, the system is discontinuously operated in two operation modes. During NO_x adsorption mode, the total system is operated under lean condition. The NSC path is opened, the NSC bypass is closed. NO_x treatment takes place either by NO_x adsorption on the NSC or continuous reduction on the SCR by previously stored NH_3. The integrated on-board fuel reformer is inactive. For the regularly necessary NSC regeneration, the NSC is locally enriched by opening the bypass path, closing the NSC path and feeding H_2 and CO containing reformate gas at low space velocity via the activated fuel reformer. The exhaust paths are actuated by two serial exhaust flaps. The on-board exhaust fuel reformer is described in more detail in the next chapter.

2.2. Reformer concept

The integrated on-board fuel reformer is predominantly operated by exhaust gas, which is taken downstream DPF. Diesel is injected by an air-assisted, low-pressure injector at a significant under-stoichiometric air/fuel ratio ($\lambda_{Ref} = 0.35 – 0.80$) and is catalysed to a H_2- and CO-rich synthesis gas. The completely new developed on-board fuel reformer is a coaxial design and shown in more detail in Fig. 2.



NSC NO_X Adsorption Mode

→ Engine operation: λ > 1
→ NSC-operation: λ > 1
NO_X-Ads.
→ SCR-operation: NO_X-Conv.
→ Reformer: inactive
→ Bypass: inactive

NSC NO_X Regeneration Mode

→ Engine operation: λ > 1
→ NSC-operation: λ < 1
NO_X-Red.
NH_3-Form.
→ SCR-operation: NH_3-Ads.
NO_X-Conv.
→ Reformer: active
→ Bypass: active

Fig. 3. Simplified method of operation of final layout of NSC based combination system, with under-floor NSC plus exhaust bypass, passive SCR and integrated exhaust gas fuel reformer

The reaction enthalpy, which is released in the ring-shaped reformer catalyst, supports fuel vaporisation via internal heat transfer. The reforming reaction process can be described by superposition of exothermic partial oxidation (POx) by the residual oxygen in the exhaust gas as well as the secondary air, and endothermic steam (SR) and CO_2 reforming (DR) which occurs via H_2O and CO_2 introduced by the exhaust gas. Additionally, the reforming products are temperature-dependently in chemical equilibrium, among others mainly according to the water-gas shift (WGS) and methanation reaction. In comparison to pure POx, exhaust gas reforming exhibits favourable thermal behaviour as well as benefits regarding H_2 and CO yield, due to the endothermic part of the reaction. The reformer operation is strongly dependent on the exhaust gas composition. Fuel is injected by feed-forward control of λ_{Ref} depending on the fraction of molar oxygen to the total amount of reactant oxygen sources (O_2, H_2O and CO_2) and space velocity. Additionally, fuel supply is corrected by closed-loop control of reformer temperature in terms of maximizing H_2 and CO as well as minimizing HC concentration in the reformate, while complying with temperature limits.

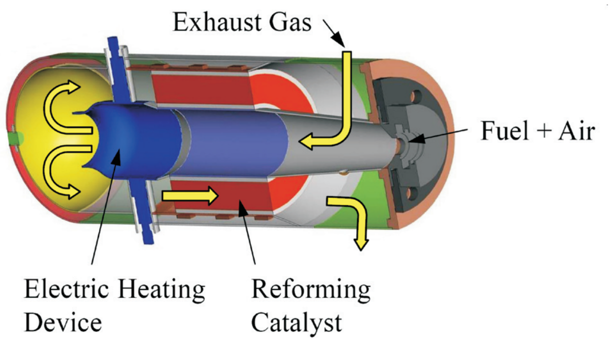


Fig. 4. CAD design of the fuel reformer

3. Experimental

3.1. Test bench

The full-scale experiments for investigating the NO_x purification behavior of the combination system as well as the performance of the fuel reformer were conducted with a high efficient 1.4 L 3-cylinder Diesel engine on a transient engine test bench. The investigated systems (NSC+SCR, fuel reformer) were placed under-floor downstream the serial close-coupled DOC+DPF unit and low-pressure EGR branch. The catalysts were thermally conditioned by several hours of DPF regeneration operation. The control logic of the EATS, which was completely new developed, was running on a rapid control system independently from the engine. A few necessary informations were transferred between engine and EATS control via ECU bypass. For steady-state investigations, the engine operation (speed, load, operation mode) was set in order to adjust target conditions at the NSC (temperature, NO_x concentration, exhaust mass flow, air-to-fuel-ratio). Additionally, transient test cycles (NEDC, WLTC, FTP75, CADC, highway, ADAC) were conducted in order to evaluate and calibrate the system performance and operation strategy. The emissions were measured by different analyzers (CLD: NO_x, NO; NDIR: CO, CO_2; Magnos: O_2; FID: THC; FTIR: NO, NO_2, CO, CO_2, H_2O, NH_3, N_2O, CH_4; LDS: in-situ NH_3; mass spectrometer: H_2) and sensors (NO_x, λ) at various positions (engine out, downstream DPF, upstream and downstream SCR). The gas composition of the out-line exhaust gas fuel reformer was calculated based on emission measurements in the full exhaust gas flow and the dilution factor. Based on the achieved on-board reformate gas composition, a reformate substitute gas was applied in parallel, containing molar fractions of 20 % H_2, 20 % CO and 60 % N_2.

Two different NSC formulations ("NSC A" and "NSC B") were tested, with 1.4 l volume each. The PGM loading was 85 ("PGM low") or 130 g/cft ("PGM high"). The SCR catalyst was copper zeolite based with a volume of 2.9 l in engine and vehicle experiments.

3.2. Vehicle

In parallel to the test bench investigations, the system was also integrated into a Volkswagen Golf Variant for investigating cycle (NEDC, WLTC) and off-cycle (RDE) performance. The same catalytic converters were used as for the test bench activities. Figure 5 shows the final integration of the aftertreatment system into the demonstrator vehicle.

4. Steady-state test bench results

4.1. Exhaust gas fuel reformer

The following Fig. 6 shows the reformer performance as summary achieved under steady-state conditions. Fig.

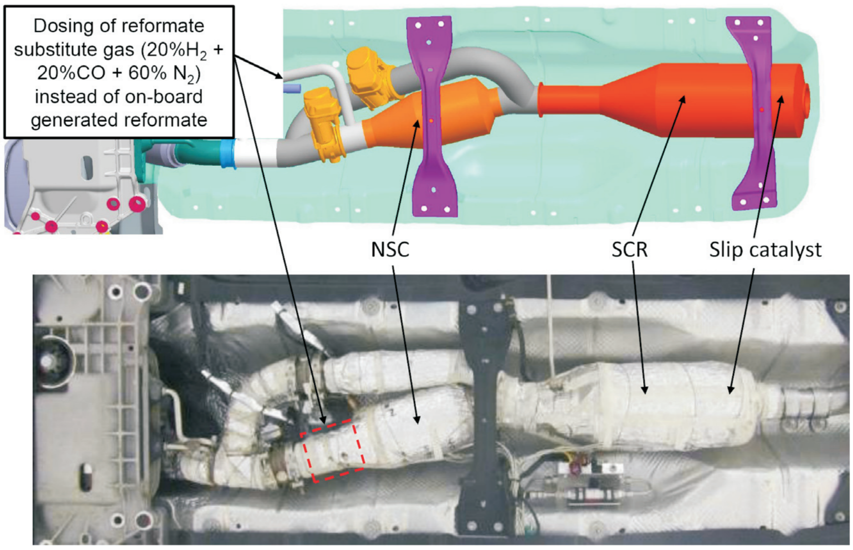


Fig. 5. Final integration of the aftertreatment system into the vehicle

6a shows a comparison of the realized H_2 and CO molar concentrations with those attainable under stoichiometric conditions as function of λ_{Ref}. The concentrations are close to the maximum yield and demonstrate high fuel conversion. Compared to rich diesel engine operation, substantially higher concentrations can be achieved. Fig. 6b shows a comparison of the achieved ratio of heating values (HVR) as well as the reductant yield Y_{Red} (ratio of oxygen consumption potential of the reducing agent generated in the exhaust gas relative to the additional fuel introduced to reach rich operation) in contrast to corresponding theoretically attainable pure POx values. At lean engine operation and consequently predominantly exothermic reactant composition, due to thermal reasons a low λ_{Ref} must be set. With decreasing engine lambda and consequently increasing endothermic reactant composition, λ_{Ref} must on one hand be enleaned to support endothermic reaction enthalpy. On the other hand, it offers high reformate quality. In contrast to HVR, Y_{Red} is an important indicator for NSC regeneration in terms of CO_2 emissions.

In addition, Fig. 7 shows Y_{Red} by fuel reforming in comparison to diesel engine enrichment of various engine calibrations as function of brake mean effective pressure (BMEP). The theoretical optimum reductant yield is represented by the direct use of fuel for the NSC regeneration, e.g. by fuel injection upstream NSC with closed exhaust flap. In this case, the reductant yield is 100 %. Compared to actual engine calibrations for rich operation, the reformer generally exhibits considerably higher efficiency and thus represents a potential decrease in CO_2 emissions for NSC regeneration. The reductant loss of the reformer is based on partial oxidation of fuel by molar oxygen. The reductant loss of engine enrichment is caused by internal combustion efficiency loss at $\lambda_{Engine} = 1$ due to intake throttling and post injection. Furthermore, by use of a reformer instead of the engine, the NSC regeneration can in principle even be conducted during idle or start-stop operation. In contrary, rich engine operation is limited to BMEP above a certain level, depending on combustion stability and acoustic behaviour.

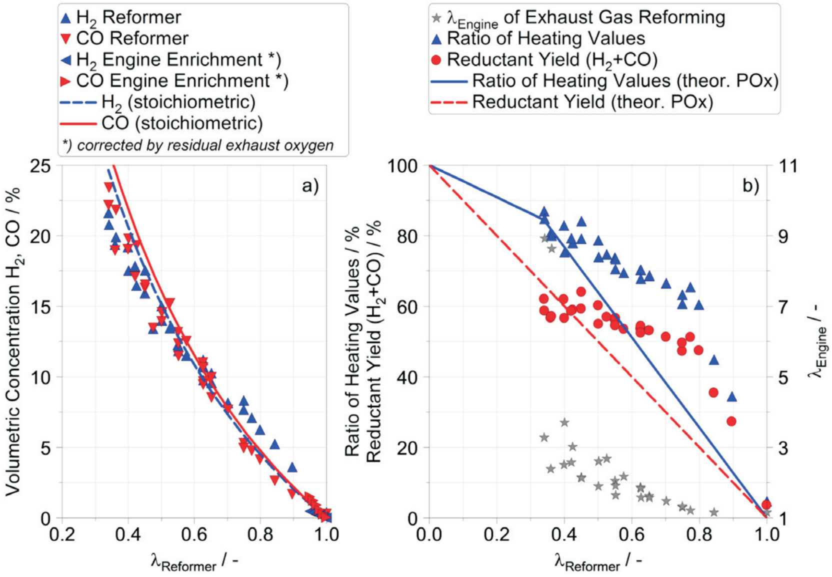


Fig. 6. Reformer output as function of relative reformer air/fuel ratio: a) measured and stoichiometric H_2 and CO molar concentrations in reformate; b) measured and theoretical POx values for ratio of heating values (HVR) and reductant yield (Y_{Red}, only H_2 + CO are considered) of the reformer, engine relative air/fuel ratio of the exhaust gas supply to the reformer

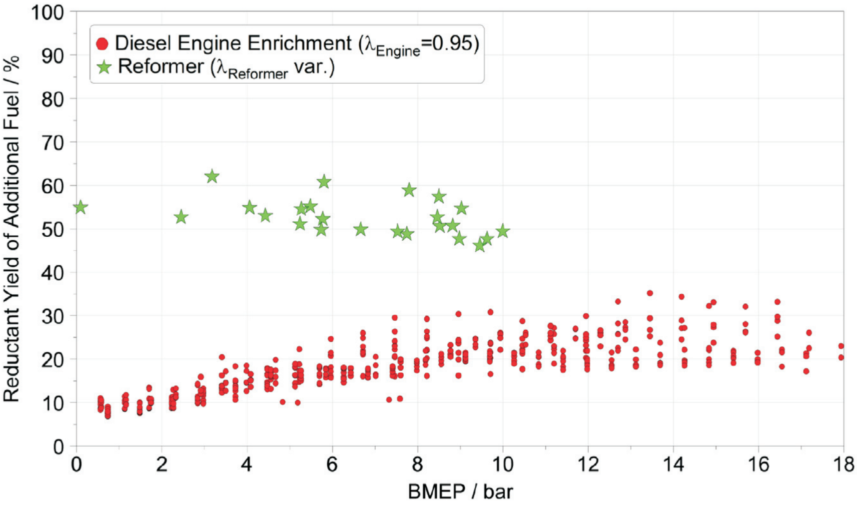


Fig. 7. Reductant yield of additional fuel for NSC enrichment by fuel reforming in comparison to Diesel engine enrichment of various engine calibrations as function of brake mean effective pressure (BMEP)

4.2. Base investigation of NSC

The NSC base experiments were performed in order to screen two full-scale NSC variants (NSC A with high PGM and NSC B with high PGM). The NH_3 formation yield (molar ratio of cumulated NH_3 amount during NSC regeneration to initial NSC NO_x load at NSC regeneration start) is an important parameter for operating the combined system. The NSC regeneration strategy has a high impact on NH_3 formation and emission. Figure 8 shows an exemplary NSC regeneration.

The bypass system offers high degree of freedom for NSC regeneration strategy by flexible adjustment of reformate gas dosing and exhaust flap actuation, Fig. 8b). The regeneration period is divided in 3 phases. In phase I, the NSC reduction takes place (typical $\lambda_{downstream\ NSC} = 1$). The completion of

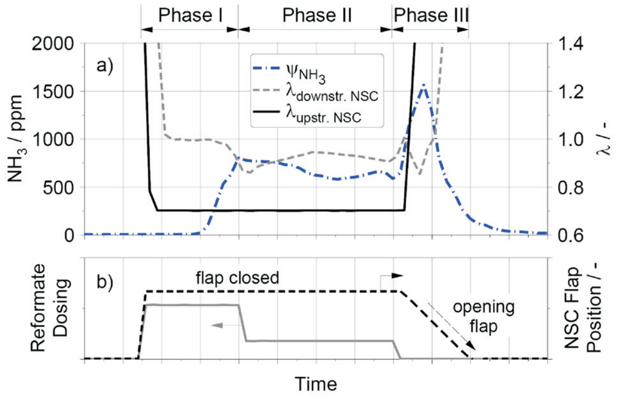


Fig. 8. Exemplary NSC regeneration as function of time at 250 °C: a) NH_3 concentration upstream SCR and l upstream and downstream NSC, b) reformate gas flow and NSC flap actuation; Phase I: time till λ-breakthrough ($\lambda_{downstream\ LNT} < 0.95$), Phase II: regeneration duration after λ-breakthrough, Phase III: time between end of reformate dosing and NSC flap opening (various flap opening strategies possible)

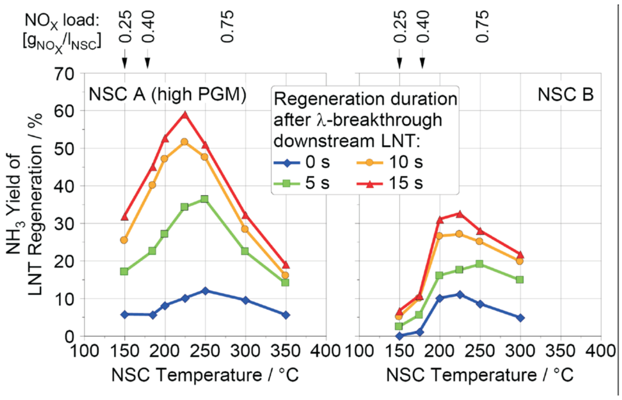


Fig. 9. NH_3 yield of NSC regeneration as function of NSC temperature for various regeneration durations after λ-breakthrough downstream NSC (operation by reformate substitute). NSC A (high PGM) and NSC B in comparison

enrichment is identifiable by λ-breakthrough ($\lambda_{downstream\ NSC} < 0.95$). Phase II defines the regeneration duration after λ-breakthrough. Specific to the bypass system, in phase III after end of dosing the NSC exhaust flap opening can be actuated by various strategies. As shown in Figure 8a), in line with the literature, the NH_3 emission occurs at the end of phase I. The NSC enrichment in conventional application is stopped at the end of phase I in order to avoid reductant and NH_3 slip. However, the lean exhaust gas downstream SCR due to the bypass system offers reductant slip oxidation and hence elongated rich duration, which results in enlarged NH_3 emission. Figure 9 shows the NH_3 yield as function of temperature for various regeneration durations after λ-breakthrough in comparison for NSC A (high PGM) and NSC B.

For both NSC, the NH_3 yield strongly increases by prolonged NSC enrichment after λ-breakthrough and saturates at higher durations. However, it must be mentioned that the NH_3 emission occurs roughly in parallel to reductant breakthrough. Therefore, high NH_3 formation causes increased reductant slip. For both NSC, the NH_3 yield shows a maximum at medium temperature (200–250 °C). NSC A shows significantly higher NH_3 yield compared to NSC B. For the further investigations, NSC A was used due to the higher NH_3 formation compared to NSC B and also due to the better NO_x adsorption (not shown).

4.3. Investigation of NSC + passive SCR combination

The NSC + SCR experiments are conducted for investigating the interaction of NSC and passive SCR and its impact on the total NO_x purification behavior. Additional focus is the definition of the optimum operation strategy and a pre-calibration of the aftertreatment control for later implementation into the demonstrator vehicle.

Figure 10 shows the correlation of NO_x conversion, fuel consumption penalty and NO_x raw emission level for NSC only and NSC + SCR exemplarily at 230 °C.

Generally, increasing NO_x conversion progressively causes the drawback of increasing fuel consumption penalty. The NO_x conversion converges asymptotically against a maximum. Furthermore, higher NO_x raw emission shows significantly negative impact on NO_x conversion for certain fuel consumption and maximum achievable NO_x conversion. Hence, for achieving high NO_x conversion at reasonable fuel consumption, the NO_x raw emission must be limited. In comparison to NSC-only, NSC + SCR shows high benefits regarding fuel consumption and NO_x conversion. For the given example, high maximum total NO_x conversion of up to > 95 % is achievable at low fuel consumption penalty of ≈ 1 % for reasonable NO_x raw emissions. At high NO_x

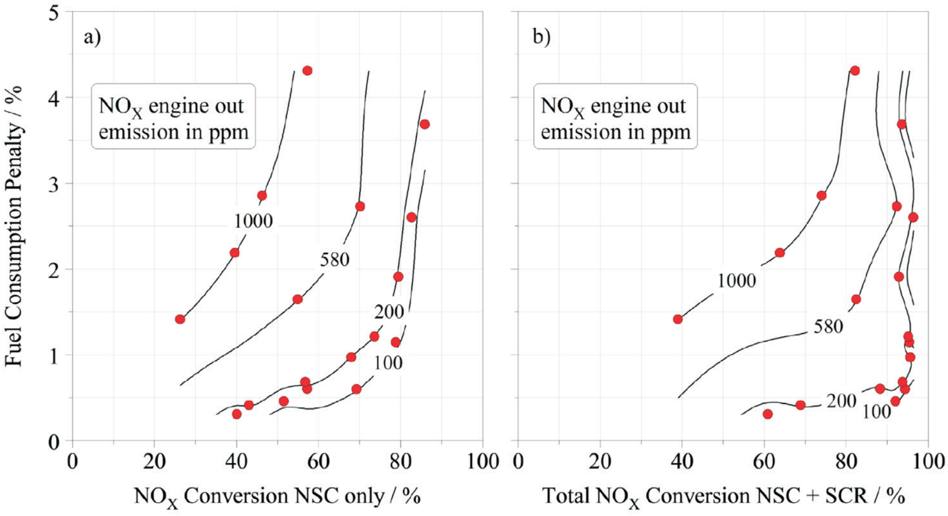


Fig. 10. Correlation between NO_x conversion and fuel consumption penalty as function of NO_x raw emission level: a) NSC only, b) NSC + passive SCR; T_{NSC} = 230 °C, operation by reformate substitute, NSC A

raw emission level, the total NO_x conversion decreases but is significantly higher than for NSC-only. At certain NO_x conversion, significant lower fuel consumption is attainable by the NSC + SCR.

Significant influence on the total NO_x performance and especially on the conversion share between NSC and SCR is given by the NSC NO_x load. Figure 11 shows the NO_x conversion efficiencies, NO_x conversion shares of NSC with bypass and passive SCR and the related fuel consumption penalty as function of NSC NO_x load exemplarily at 250 °C.

In contrary to conventional NSC application, the NSC NO_x slip caused by decreased adsorption efficiency at increased NO_x load level does not automatically drop the system NO_x conversion but can be converted by the passive SCR up to a certain NO_x load due to the increasing NSC NH_3 yield. The passive SCR achieves a maximum of 40 % conversion. The cycle integrated NH_3-NO_x-ratio upstream SCR (α) is ≥ 1 for NSC NO_x load below 1.1 g/l. For higher NO_x loads, α is dropping below the stoichiometry of 1, which results in corresponding decrease of SCR and therefore also of total NO_x conversion. With elongating NO_x adsorption duration resp. higher NO_x load, the NO_x conversion distribution is significantly shifted from NSC to SCR (75 % / 25 % at 0.25 g/l NO_x load to 60 % / 40 % at 1.2 g/l NO_x load). A great potential of the conversion shifting between NSC and SCR is the impact on the fuel consumption penalty. By expanding the NO_x adsorption duration towards higher NSC NO_x loads, the fuel consumption penalty can almost be halved. This benefit is mainly based on three effects. First, higher NO_x load enables lower regeneration frequency. Second, the higher the NO_x load, the more reductant is relatively consumed for NO_x reduction instead of OSC reduction [10], which takes place in parallel. Third, NH_3 as reductant carrier is highly efficient utilized for further NO_x conversion on the passive SCR.

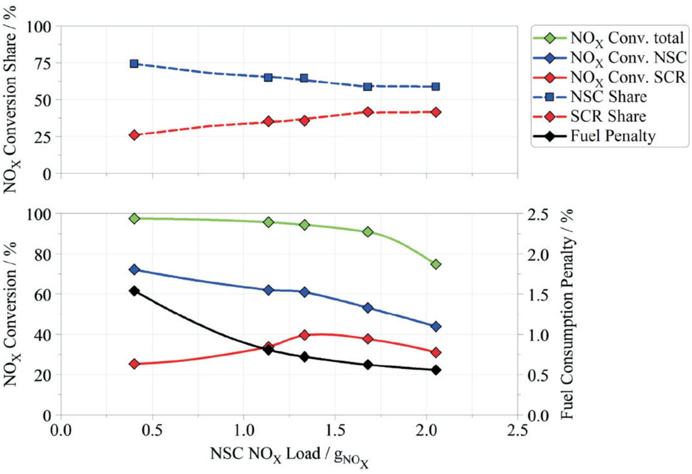


Fig. 11. NO_x conversion, related fuel consumption penalty and NO_x conversion share of NSC with bypass and passive SCR as function of NSC NO_x load; T_{NSC} = 250 °C, operation by reformate substitute, NSC A

Summarizing, Figure 12 shows the steady-state NO_x conversion and fuel consumption penalty of the NSC + SCR system for two system variants with on-board generated reformate and reformate substitute as function of NSC temperature.

The attained NO_x conversion is comparable for both, operation with the integrated on-board reformer as well as operation with reformate substitute. The system with the higher PGM loaded NSC achieves slight increase in conversion at T < 250 °C. At 250 °C almost complete conversion is achieved at fuel consumption penalty of ≈ 1.5 %. The operation strategy of NO_x adsorption and regeneration is optimized with regard to maximum total NO_x conversion and suitable fuel consumption penalty. The SCR significantly contributes to the total NO_x conversion. At T < 250 °C the total steady-state NO_x conversion drops due to reduced NSC activity as well as NH_3 yield. The fuel consumption penalty increases due to higher NSC regeneration frequency as well as lower engine fuel consumption due to lower engine load. Nevertheless, 65–70 % steady-state NO_x conversion at 185 °C resp. 30 % steady-state NO_x conversion at 150 °C are still achieved. In transient operation, higher conversion rates can be achieved due to pure NO_x adsorption at the NSC as well as SCR conversion with previously stored NH_3. At T > 350 °C the steady-state NO_x conversion drops due to decreasing (for thermodynamic reasons) NO_x adsorption capacity of the NSC as well as lower NH_3 yield of NSC regeneration. The decreased NSC NH_3 yield causes limited steady-state SCR conversion in contrast to urea based SCR operation. However, during transient operation, complete conversion can still be maintained by the SCR for short time, e.g. during DPF regeneration, by

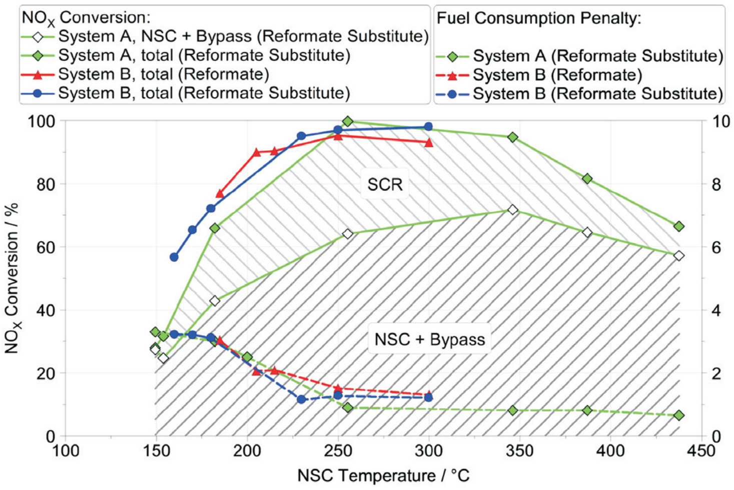


Fig. 12. Steady-state NO_x conversion and fuel consumption penalty of NSC + SCR system with reformate and reformate substitute as function of NSC temperature; EU4 NO_x raw emission level

consuming previously stored NH_3 depending on SCR NH_3 load and NO_x mass flow. This represents high NO_x performance benefits compared to conventional NSC application.

5. Transient investigation

Figure 13 compares NO_x conversion and exhaust temperatures in cold start and high load cycles measured on engine test bench. Diagram a) shows steady-state and cycle-integrated NO_x conversions of NSC + SCR as function of steady-state and cycle-integrated NO_x mass flow weighted NSC temperature. Diagram b) shows exhaust gas temperatures upstream DOC and downstream DPF representative for close-coupled and under-floor exhaust temperature level.

Positioning close to the engine is advantageous for cold cycles, resp. mainly cold operated applications. However, operation at high-load in real driving is critical for an NSC based system with only passive SCR, due to the NO_x conversion drop at high temperature. Additionally, low-pressure EGR increases exhaust mass flow and hence space velocity and NO_x mass flow over NSC. The highly transient temperature profile can cause risk of thermal NO_x desorption and NSC degradation. On the opposite, an under-floor positioned system is challenging at cold start and requires active heating measures with negative implications for CO_2 emission. However, in warm condition at 200–350 °C e.g. during real driving, the NSC based system shows optimum NO_x performance. Due to the requirement of demonstration of emission purification in cold start cycles and under real driving condition as well as for packaging reasons, the NSC + SCR system is placed under-floor.

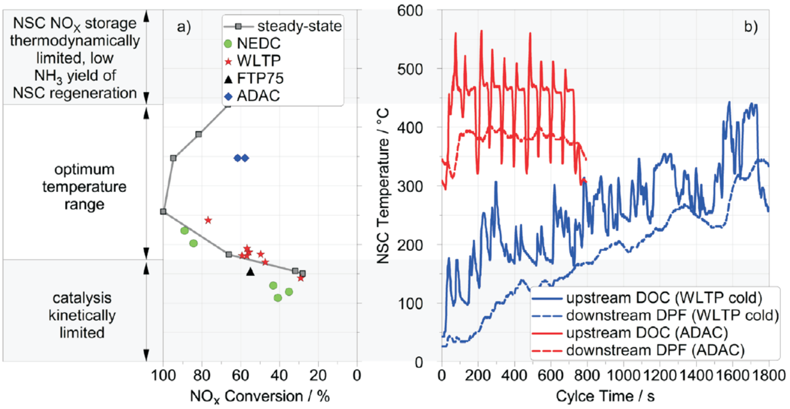


Fig. 13. Comparison of NO_x conversion and cycle exhaust temperature; a) steady-state and cycle-integrated NO_x conversion of NSC + SCR as function of steady-state and cycle-integrated NO_x mass flow weighted NSC temperature, b) Temperature close-coupled and under-floor for transient cycles; operation by reformate substitute on engine test bench

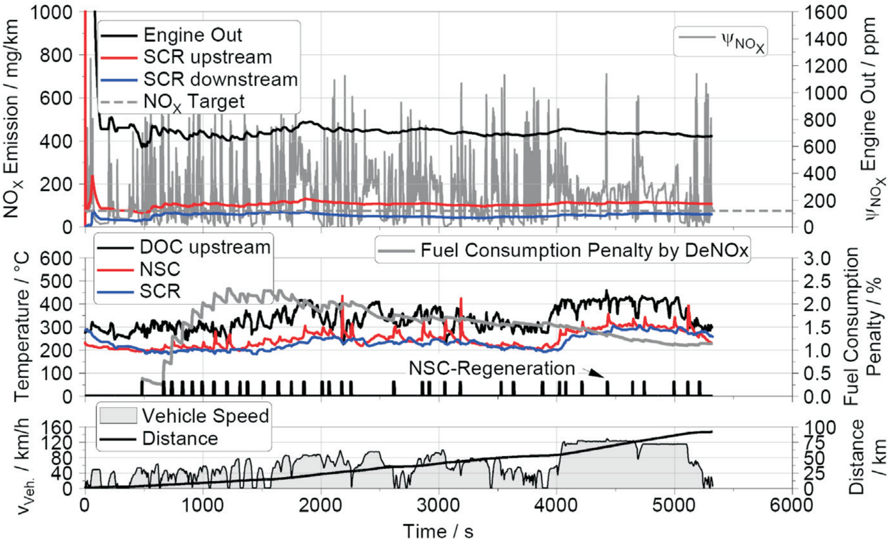


Fig. 14. Transient NO_x conversion and fuel consumption penalty of NSC + SCR system with reformate substitute in RDE (*Real Driving Emissions*) "normal vehicle driving"

The final results measured in the demonstrator vehicle are shown exemplarily for RDE operation in "normal" vehicle driving in Figure 14 and summarized in Figure 15. The under-floor positioned aftertreatment system requires in cold start cycles significant fuel consumption penalty by heating but only minor by NSC enrichment. However, in real driving warm operation the system performance show high NO_x conversion and realizes low NO_x emission at low fuel consumption penalty of less than 2 %.

6. Summary

For the specific requirements of the EU project "Powerful" with focus on NO_x and CO_2 emission, a combined aftertreatment system comprising NSC, NSC-bypass, passive SCR and exhaust gas fuel reformer was chosen and studied. The position of the NSC is crucial for the NO_x conversion in cold started cycles on the one hand and high engine load operation and high exhaust gas temperature on the other hand. Due to the focus on real driving emissions, the aftertreatment system is placed under-floor. The undertaken investigations on the engine test bench and vehicle testing confirm the challenge of the NO_x-CO_2 trade-off. For the mostly NSC based system, the under-floor position is critical in short cold start operation, like NEDC and requests heating measures. It is less critical and even advantageous for more dynamic and longer test cycles like WLTC and especially real driving. Once the system is heated up, the NO_x conversion is sufficient and the engine can run in the most efficient mode. This is highly beneficial for NO_x and CO_2 emission in real world driving, where the new aftertreatment concept can show full potential also in combination with highly efficient Diesel-engines.

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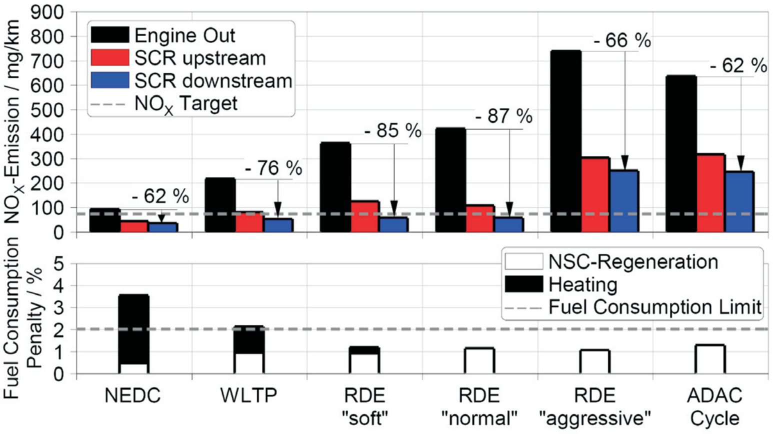

Fig. 15. Summary of transient NO_x conversion and fuel consumption penalty of NSC + SCR system with reformate substitute

Abbreviations

ADAC	Allgemeiner Deutscher Automobilclub (*German Automobile Club*)
BMEP	Brake Mean Effective Pressure
CADC	Common Artemis Driving Cycle
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
FEP	Fuel Economy/Consumption Penalty
FTP75	Federal Test Procedure
HC	Hydrocarbon
NSC	NO_x Storage and Reduction Catalyst
NEDC	New European Driving Cycle
OSC	Oxygen Storage Capacity
PEMS	Portable Emissions Measurement System
PNA	Passive NO_x Adsorber
POx	Partial Oxidation
RDE	Real Driving Emissions
SCR	Selective Catalytic Reduction
SV	Space Velocity
WLTC	Worldwide Harmonized Light-duty Test Cycle
λ	Air-to-Fuel-Ratio
α	NH_3-NO_x-Ratio
ψ	Volumetric Concentration

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