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Urea–SCR Technology for deNOx After Treatment of Diesel Exhausts

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Editors

Urea-SCR Technology for deNOx After Treatment of Diesel Exhausts

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Preface

It is widely recognized that Diesel vehicles are sure to significantly increase their worldwide penetration, particularly in countries like the United States where the present market share is not remarkable in comparison to that of vehicles with gasoline engines. This is mainly due to Diesel engines being inherently more thermodynamically efficient than spark-ignition engines, thus offering the prospect of reducing emissions of carbon dioxide.

Diesels produce, however, higher emissions of nitrogen oxides (NOx) and particulate matter (PM). The emissions levels which can be achieved depend on both the engine-out emissions and the performance of the emissions control system. For the engine-out emissions, there is a well-known trade-off between PM and NOx. Such a trade-off is not, however, a constant relationship between the two pollutants. Developments in combustion systems, fuel injection equipment, turbocharging, and associated control systems have allowed and continue to allow the trade-off curve to move to lower values of both NOx and PM. The trade-off thus gives engine developers the opportunity to combine the optimization of 'raw' emissions and fuel economy with the optimization of the emissions control system.

Improvements in combustion and/or alternative fuels can lead to lower NOx emissions, but it is generally recognized by now that, in order to meet the current and forthcoming legislative emissions standards both in Europe and in the USA, the application of after treatment systems is required. Indeed, Diesel particulate filters (DPFs) are needed to achieve the PM emission levels regardless of the system used to reduce NOx. But, most importantly, the significant CO_2 reduction (i.e., the improved fuel consumptions), that is also dictated by the upcoming regulations, are forcing a drastic decrease in the average temperature profile of the exhaust gases; in such conditions, the catalytic removal of NOx becomes extremely challenging. In fact, a significant portion of the present test cycles (e.g., the NEDC, New European Driving Cycle, and the WHTC, World Harmonized Transient Cycle) is characterized by very low exhaust temperatures. This makes very difficult the fulfillment of NOx emission limits.

Currently, the major deNOx after-treatment technologies under consideration include the so-called Lean-NOx Traps (LNT), which are used with direct injection gasoline and Diesel engines, and the Selective Catalytic Reduction (urea-SCR) process.

Urea-SCR was the European motor industry's technology of choice to meet Euro 4 and Euro 5 emissions requirements for heavy-duty Diesel engines and more recently was also applied to light-duty vehicles and passenger cars in the USA and in Europe, as well. An SCR system is designed to catalytically reduce NOx emissions in the oxygen-rich environment of Diesel exhausts. To this purpose, the SCR system needs a chemical reagent, or reductant, to help convert the NOx to nitrogen: in mobile applications, the preferred reductant is typically an aqueous solution of nontoxic urea, which is used as an ammonia source. In fact, the so-called Adblue® solution (or DEF, Diesel Emission Fluid) is injected into the exhaust system where it is decomposed to NH_3.

Usually, a Diesel Oxidation Catalyst is also present in the system configuration, upstream of the SCR converter, to partially convert NO to NO_2; this enriches the stream entering the SCR reactor with significant amounts of NO_2 in addition to NO, and thus enables the onset of the SCR deNOx reactions at lower temperature in comparison to the case where most of the NOx is composed of NO alone.

Urea-SCR was first brought to the market in 2005 for heavy-duty vehicle applications by Daimler AG (DaimlerChrysler at the time) under the trade mark BLUETEC®, based on the use of extruded honeycomb monolith catalysts consisting of V_2O_5–WO_3–TiO_2, similar to those extensively used worldwide for the control of NOx emissions from power stations and other stationary sources. Subsequently, we have seen a trend in the automobile industry to replace Vanadium-based SCR catalysts with a new generation of metal-exchanged zeolite-based systems in order to expand the operating temperature window and to solve the high temperature deactivation problems typical of the anatase-rutile TiO_2 transition. A variety of zeolites have been proposed for this purpose (e.g., ZSM-5, mordenite, beta, ferrierite, Y-zeolite, and more recently chabazite). Zeolites are generally promoted by transition metals, such as iron and copper: the resulting catalytic systems are associated with an excellent deNOx activity, particularly in the case of the Cu-zeolites. Indeed, metal-promoted zeolites have rapidly become the class of automotive SCR catalysts of choice, making urea-SCR the leading deNOx technology nowadays. In the last few years, the improvement of the critical low-temperature deNOx activity has been impressive, primarily due to the development of a new generation of Cu-promoted catalysts based on small pore zeolites, which also exhibit unparalleled stability with time-on-stream. The fundamental reasons for such enhanced performance, however, are not fully understood yet: they currently represent the objective of many academic and industrial research efforts.

There are several additional complications in using urea-SCR, including for example. The need for efficient ammonia release from the urea solution, and the related risks of deposits in the exhaust system due to by-products formation. Another issue is the accurate ammonia dosage: there should be enough ammonia present on the catalyst to reduce all NOx, but at the same time there must be no excess of ammonia, to prevent its slippage from the vehicle. In order to realize this balance, a deep understanding of the influence of the operating conditions on the amount of ammonia stored on the catalyst, and on the rates of ammonia

adsorption/desorption, is crucial for the design and particularly for the control of SCR catalytic converters for vehicles. Ammonia slip catalysts represent a recent development in this area. Another area of current development is related to the fact that the SCR catalyst is often placed downstream of the Diesel Particulate Filter (DPF), in order to meet the requirements on soot particle emissions. On one hand, this configuration exposes the SCR catalyst to very high temperatures during DPF regeneration, so that its hydrothermal stability is a major concern. On the other hand, the multifunctional combination of DPF and SCR in a single device (SCR catalyst coated onto the DPF) presents several advantages, and is receiving considerable attention.

Finally, mathematical modeling has been recognized since the early days as a critical tool for timely and cost-effective development of urea-SCR technology for vehicles. This has resulted in a significant evolution, wherein the initial simple empirical models have been progressively replaced by the present sophisticated, chemically and physically consistent models, used in many companies to generate reliable simulations of NOx emissions in highly transient test cycles for a wide range of conditions and parameters. Further efforts are being devoted to incorporate more details of the SCR catalytic chemistry, and to relate them to the catalyst features.

Several years after its first commercial applications, the development of urea-SCR has now clearly turned into a success story, with positive and promising perspectives and still many opportunities for further improvements and breakthroughs in a number of areas. So now, it is probably a good time to review the status of the technology, and highlight the next challenges.

This book provides a complete overview of the selective catalytic reduction of NOx by ammonia/urea (urea-SCR), drawing from the know-how of many leading experts in the field. The book begins with a discussion of the technology in the framework of the current context (legislation, market, system configurations), covers the fundamental aspects of the SCR process (catalysts, chemistry, mechanism, and kinetics) and eventually analyses its application to the real scale (modeling of full scale monolith catalysts, control aspects, ammonia/urea delivery systems and strategies, integration with other devices for combined removal of pollutants). The book concludes with case histories presented by two companies which have greatly and creatively contributed to make urea-SCR a well-established and crucial technology for the automotive industry.

The book is aimed primarily at researchers in industry and academia working on exhaust gas aftertreatment systems. Several chapters however provide reference material that will be useful for teaching general courses on catalytic processes for environmental protection, or dedicated courses on the Selective Catalytic Reduction of NOx.

Finally, this book is the result of the work of a number of industrial and academic experts: all of these persons are to be congratulated for devoting their time and effort to the present volume.

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Part I
Selective Catalytic Reduction Technology

Chapter 1
Review of Selective Catalytic Reduction (SCR) and Related Technologies for Mobile Applications

Timothy V. Johnson

1.1 Introduction

NOx is formed when air is heated to very high temperatures, and is thus emitted from combustion and engines. The most prevalent NOx species from engines is NO. It will oxidize in the atmosphere to form NO_2, and also react with many hydrocarbons (HCs) to form ozone; both ozone and NO_2 are toxic and strong oxidants. Thus, NOx is a criteria pollutant and is regulated. NOx is very effectively controlled from gasoline engines with three-way catalysts (TWCs) (CO, HCs, NOx), but they only operate under stoichiometric conditions. For lean diesel conditions, selective catalytic reduction (SCR) is the leading method of remediation. The reductant, ammonia (NH_3), which needs to be added to the exhaust, selectively reduces the NOx rather than being oxidized by the excess oxygen, as do the innate exhaust reductants, CO and HCs.

This chapter will set the stage for the other chapters in the book by providing a representative review of the regulations, general engine trends, and key developments in SCR catalyst technology. It is not intended to be all-encompassing and comprehensive. Representative papers and presentations were chosen here that provide examples of new, key developments, and direction. For a more detailed review of SCR technologies, and diesel emission control technology trends and developments in general, the reader is referred to Johnson [1–3].

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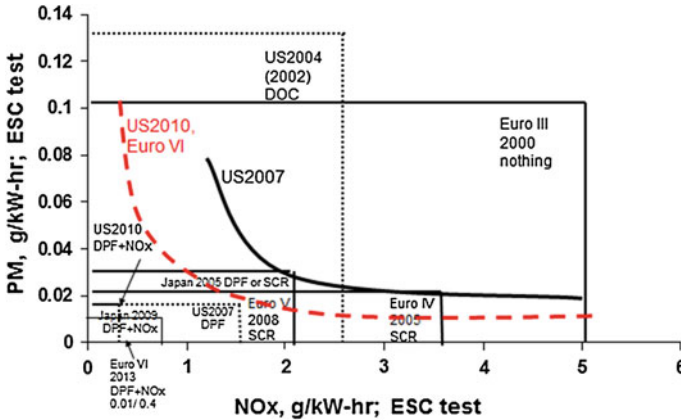
Fig. 1.1 Overview of key HD tailpipe regulations as measured on the ESC. The *dashed* and *solid lines* represent an estimate of the best commercially viable engine-out emissions for engines in 2007 and 2010

1.2 Regulatory Overview

Although the first commercial lean deNOx system was a lean NOx trap (LNT) on the European Toyota Avensis in the early 2000s, and then on the US Dodge Ram truck (Cummins engine) in 2007, the first wide-scale use of deNOx was the implementation of SCR for heavy-duty (HD) truck applications in Europe in 2005. The US Tier 2 and California Low Emission Vehicle (LEVII) regulations were the first to force SCR on light-duty (LD) applications in 2007. SCR did not make its way into NR applications until 2011 in both the US and Europe.

Following is a general overview of the HD, LD, and NR regulations pertinent to understanding the main drivers for SCR systems.

1.2.1 Heavy-Duty Truck Regulations

Figure 1.1 shows a summary of the key HD truck regulations in the world, along with estimates of the best commercially viable engine-out NOx and particulate matter (PM) capabilities, as measured on the European Steady-State Cycle (ESC). The first vehicle regulation in the world that was attained with SCR systems was the Japan 2005 HD truck regulation in October 2004, shortly followed by Euro IV in January 2005. Although Euro IV was only a 30 % NOx tightening from Euro III (2000), the PM regulation dropped $\sim$80 %, and truck manufacturers generally elected to tune their engines for higher NOx and lower PM and fuel consumption, and then use SCR to drop the tailpipe levels to within the NOx (and PM) requirements. It is interesting to note that although the US2007 NOx regulations

Fig. 1.2 Leading light-duty
diesel NOx and non-methane
hydrocarbon emissions
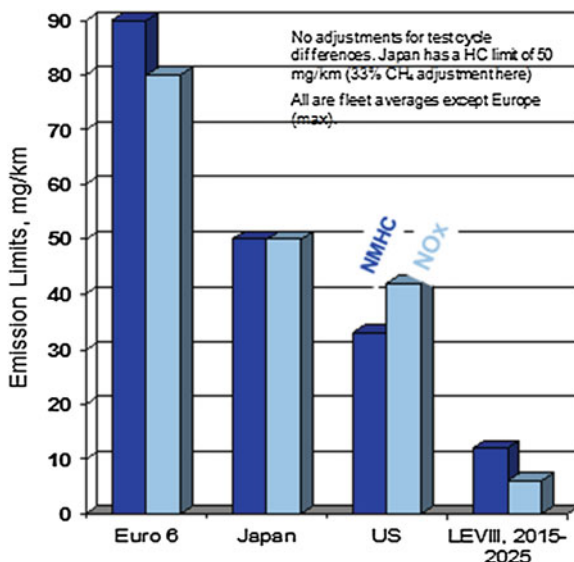
were 60 % lower than for Euro IV, and the PM regulations were about 35–55 %
tighter (steady state and transient testing, respectively), the US manufacturers
chose to meet the NOx regulations with engine technology (mainly exhaust gas
recirculation (EGR)), and the PM regulations with diesel particulate filters (DPFs).
The Japan 2005 regulation is intermediate between Europe and the US for both
NOx and PM, and there was a split of approaches used in Japan, with trucks in
high fuel consumption applications generally using a European SCR-only
approach, and all others using a EGR + DPF approach.

In the 2009+ time frame, Japan 2009, US2010, and Euro VI (2013) all require
both SCR and DPF solutions. These regulations range from 0.26 to 0.7 g NOx/
kW-h and 0.010 to 0.013 g PM/kW-h.

1.2.2 Light-Duty Regulations

The leading LD diesel non-methane HC and NOx regulations are graphically
shown in Fig. 1.2. Only the US (Federal and California LEVIII) has the test-cycle
and limit value combination to force NOx aftertreatment. All require a DPF
(regulations not shown). By 2013, perhaps a dozen diesel models will be on the US
market. However, the majority of Euro 6 applications will have NOx aftertreat-
ment to minimize NO_2 emissions and fuel consumption.

One regulatory development that will drive SCR system design in Europe and
elsewhere is emerging now in Europe: Real-World Driving Emissions (RDE).
Investigators have found that NOx emissions from LD diesels can be 3–4X higher

Fig. 1.3 EGR can have fuel consumption benefits at low engine-out NOx levels (<4 g/bhp-h or 5.2 g/kW-h), but at higher levels there is a fuel penalty versus SCR approaches with high deNOx efficiency [4]
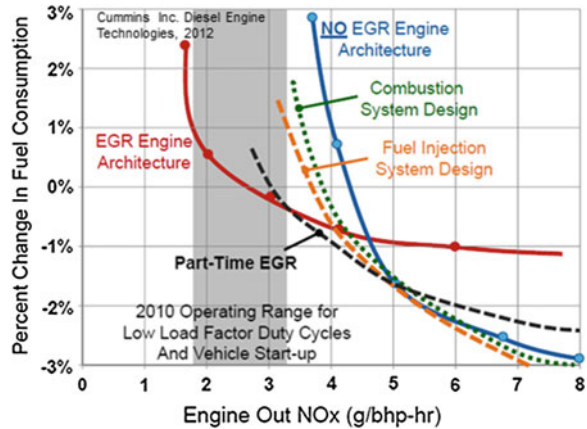
than the laboratory certification level. It is too early to note the details of these regulations, but they are likely to include portable emissions monitoring systems (PEMS) and require advance controls for cold start, high speed, and load conditions.

The regulatory trend in the US, Europe, and Japan is for very low-NOx emissions. All HD trucks in these markets will have SCR systems by early 2014. These regulations are migrating into the NR machine sector, wherein most engines >70 kW will have SCR systems in 2014+. For passenger cars, all but the smaller diesels will have SCR systems in the three markets. Tighter regulations are foreseen for the developing markets, with Brazil leading the way, followed by China and India.

1.3 Engine Developments

This section will summarize HD and LD diesel engine technologies. We may see lean-burn gasoline engines in the market, and SCR is a viable option for these engines, but this is beyond the scope of this summary.

1.3.1 Heavy-Duty Engines

HD engine technology is in development to meet the next round of OBD (onboard diagnostics) tightening in the US for 2013 and the new CO_2 regulations in 2014. Concurrent with this, the Euro VI regulations come into play in 2013–2014.

Stanton [4] shows in Fig. 1.3 that the most effective engine means for reducing NOx, EGR is an efficient approach and can have fuel consumption benefits if SCR
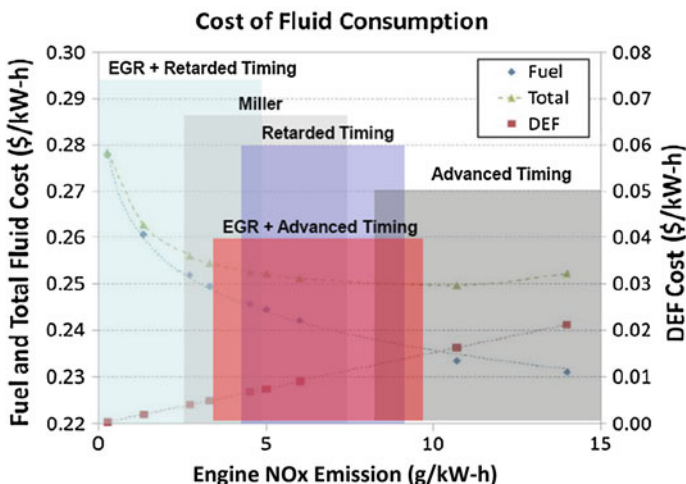
Fig. 1.4 General advance HD engine technologies and the resultant urea (DEF) and fuel cost curves, assuming DEF costs $2.56 per gallon ($0.69/l) and diesel fuel cost $3.89/gallon ($1.05/l). Fluid costs are minimized at 8–11 g/kW-h NOx [5]

efficiency requires low engine-out NOx levels (<2.5–5 g/kW-h NOx) in low-load operating regimes. However, if increased SCR deNOx efficiency allows higher NOx levels, EGR results in a fuel penalty. Given this, Stanton estimates that if SCR can attain a 98 % cycle-average deNOx efficiency, EGR can be eliminated. Furthermore, as shown in Fig. 1.3, running at higher engine-out NOx can return substantial fuel consumption benefits. In the high-NOx regimes, about 1 % fuel can be saved for every 1.2–1.5 % urea consumed (relative to fuel) to drop the NOx. This is beneficial for both CO_2 reductions and fluid cost savings (urea plus fuel).

Roberts [5] described some HD technologies for both high- and low-engine-out NOx approaches. A summary is shown in Fig. 1.4, wherein each point represents an engine hardware configuration that is optimized for low fuel consumption. As with previous such descriptions of advance engine technology packages [6], fuel consumption decreases as NOx increases, even out at >5 g NOx/kW-h. Roberts shows minimum fluid operating costs (top line) at 8–11 g/kW-h engine-out NOx. He assumes here that the urea (Diesel Exhaust Fluid (DEF)) is 65 % the cost of fuel. Emission control technologies (like SCR) would be needed to achieve at least 97–98 % efficiency to achieve this minimum fluid-consumption-cost calibration range, to meet the US 2010 regulations.

Zybell [7] also described some HD technology packages for meeting low emissions and fuel consumption, but mainly in the context of fuel injection technology. His slopes of fuel consumption versus NOx are not as steep as shown in Figs. 1.3 and 1.4, so his minimum cost range is in the 3–5 g/kW-h NOx range. However, when fuel injection pressure is increased from 1,800 to 2,400 bar, the fluid consumption drops about 0.6 % and the minimum calibration shifts to

2.5–4.0 g/kW-h NOx. Continuing the trend, if injection pressure is increased to 3,000 bar, fluid consumption drops another 0.1 % and the minimum point shifts to 2.0–3.0 g/kW-h NOx.

Kobayashi et al. [8] gave a detailed account of their attempt to drop engine-out NOx to 0.2 g/kW-h on a 10.5 l engine with the following features: 2,000 bar common rail fuel injection system, low-pressure (LP) and high-pressure (HP) EGR, variable valve actuation, 300 bar peak cylinder pressure, variable swirl, and advanced combustion chamber design. With a DPF, the engine achieved 0.8 g/kW-h NOx on the JE05 Japanese HD transient cycle. At 1,200 RPM and 8 bar BMEP, substituting about 40–70 % LP-EGR instead of HP-EGR results in similar NOx levels, despite 5–10 % higher total EGR rates, but with greatly reduced PM and fuel consumption. Also striving for high-efficiency and low-NOx, Ojeda [9] reported that a prototype 13-l engine with 2-stage EGR cooling, 2-stage turbocharging, a 2,200 bar injection system, and optimized combustion system achieved 45 % BTE at road loads, with a 0.5 g/bhp-h NOx (0.65 g/kW-h) NOx level. This is higher efficiency than some 2,010 engines running with SCR at much higher NOx levels. Although impressive, these studies show that achieving the engine-out NOx levels required to meet the emerging tailpipe regulations, without NOx aftertreatment is quite difficult and could be very expensive.

Improved thermal management is increasing in importance, especially as it pertains to reducing urban NOx from engines with SCR. The first evidence that this issue is being addressed on Euro VI engines was reported by Vermeulen et al. [10]. The 13-l prototype Scania engine had cooled-EGR to reduce low-load NOx and intake throttling for thermal management. NOx in-service conformity (ISC) was well below the 1.5X limit after allowable calibration adjustments, and NOx emissions generally vary from 0.35 to 0.76 g/kW-h for most trips and segments. The SCR system was fully functional after 500 s of operation after a cold start at 3 °C.

Finally, US HD engine manufacturers described their future approaches to meeting the US Department of Energy (DOE) goal of demonstrating 50 % BTE (break thermal efficiency) on a HD engine [1]. All four US HD truck engine manufacturers get much of their efficiency improvements from combustion (chamber design, control, mixing, etc.), reduction of friction and parasitic losses, and Rankine cycle waste heat recovery (WHR). Improved SCR performance is also mentioned commonly (for higher NOx calibrations).

Although HD NOx regulations might be met by further advancements in engine technology, the best balance of low fuel consumption and low tailpipe NOx emissions requires about 98+ % efficient SCR.

1.3.2 Light-Duty Diesel Engines

LD diesel engines are also improving to keep the efficiency advantage over gasoline. Pischinger [11] described future technologies for both diesel and gasoline engines to achieve 35 % CO_2 reductions. Major improvements in both platforms

include 25 % downsizing (7 % reductions), stop–start system (6 %), LP-EGR (3 %), and down-speeding (3 %). The approach can result in lower exhaust temperatures due to more turbocharging, and higher NOx as the result of the same fuel amount burned in a smaller cylinder. However, for gasoline vehicles to meet the 95 g/km fleet average CO_2 emission requirement in Europe in 2020, Pischinger projects significant hybridization is needed. Diesel engines can meet the regulation with standard drivetrains.

In the US, to meet the tight LEVIII emissions, reduced cold start emissions are the key, requiring significant thermal management methods. Popuri et al. [12] use an intake throttle, bypass valves for the EGR, turbine, and LP-VGT (variable gate turbocharger), idle speed modulation, late cycle fuel injections, cylinder deactivation (fueling cut off), and an exhaust-manifold integrated diesel oxidation catalyst (DOC) to allow urea injection 125 s, earlier than for a baseline engine. Despite that the engine-out NOx increased 20 %, and fuel consumption increased 5–7 % when the methods are used, Federal Test Procedure (FTP) Bag 1 deNOx was an impressive 70 % and overall fuel efficiency increased 25 % compared to their baseline engine. A 4.5 l engine in a 5,000 pound (2,270 kg) vehicle achieved US Tier 2 Bin 5 standards at 25.5 MPG (9.1 l/100 km). Ruth [13] reported significant progress in the same program that reduces thermal management requirements and is now targeted to meet the LEVIII fleet average requirements (−70 % vs. Tier 2 Bin 5) by using a passive NOx adsorber (PNA) that adsorbs NOx at low temperature and releases it passively as temperature increases, a combination SCR + DPF (SCR catalyst coated onto a DPF), and gaseous NH_3 injection. The progress shows how critical advanced SCR technology is to improve feasibility of clean LD diesel engines.

Another LEVIII approach was reported by Balland et al. [14]. To address the challenge SCR and other deNOx systems have in reducing high-load NOx, the investigators report that a standard DOC can efficiently remove NOx at stoichiometry, and thus run the engine in that mode during accelerations. The approach requires tight control of EGR, the turbocharger, and other engine parameters, and uses an "air-based control" approach similar to that of gasoline engines, rather than a fuel-based approach typical of diesel engines. Exhaust temperatures also increase substantially in the accelerations and the strategy is part of cold start thermal management.

Diesel engine costs have been a problem in competing with modern gasoline engines. Regner et al. [15] are updating the opposed-piston diesel engine, solving the historic problems using new materials and modern analytical techniques. Because it has no head or valve train, compared to a standard diesel engine, it has 40 % fewer parts, is 30 % lighter, and costs about 10 % less. Fuel consumption is 15–20 % lower than a state of the art 6.7 l diesel engine, but lube oil consumption and NOx emissions are about double.

Contrary to HD applications, wherein deNOx improvements are used to reduce fuel consumption and 98 % deNOx is desired, modern LD diesel engines do not have as strong a relationship between NOx and fuel consumption at the higher NOx levels. In the US, all of the available deNOx efficiency will be used to meet

the LD NOx regulations. In Europe, deNOx efficiencies of 50–70 % are needed to meet the regulations in the most efficient means.
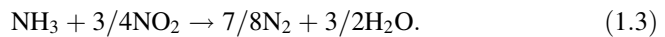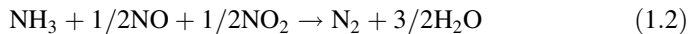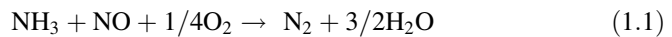
Lean NOx control (lean deNOx) technologies will be integral to meeting the emerging HD criteria pollutant regulations for diesel engines. Minimum removal efficiencies on the order of 85 % will be needed, but levels up to 97–98 % are desired to allow engines to operate in high-NOx low-fuel consumption regimes. For LD applications, the efficiency is as important in the US, but light-off or low-temperature performance characteristics are even more so.

1.4 SCR Technologies

1.4.1 SCR System Introduction

The TWC is the most effective NOx reduction system on vehicles but requires the absence of oxygen. It has been in production for more than 30 years and is removing more than 99 % of the NOx from modern engines. In this system, unburned CO and HCs are used to reduce NOx on a rhodium catalyst. The key to this technology is the gas mixture control. It is critical to have a near-stoichiometric mixture, wherein the mixture of air and fuel are near-ideal and there is very little excess oxygen. If oxygen is present in the exhaust, the CO and HCs will react with it rather than with the NOx. Diesel engines are lean-burn with plenty of excess oxygen. Practical and effective catalysts for selectively reducing NOx with CO or HCs in a lean environment are not yet available, but selective catalysts using ammonia as the reductant have been commercialized in the stationary sector for decades.

The key SCR catalyst reactions are shown as

$$NH_3 + NO + 1/4O_2 \rightarrow N_2 + 3/2H_2O \tag{1.1}$$

$$NH_3 + 1/2NO + 1/2NO_2 \rightarrow N_2 + 3/2H_2O \tag{1.2}$$

$$NH_3 + 3/4NO_2 \rightarrow 7/8N_2 + 3/2H_2O. \tag{1.3}$$

Reaction (1.1) is generally the "standard SCR reaction". As NO_2 is always present in the exhaust to some extent (maybe 10 % of NOx), Reaction (1.2) is also pertinent, and is in fact the fastest and preferred NOx reduction reaction. To promote this "fast SCR reaction" a DOC is commonly used to form more NO_2 over platinum by the following reaction:

$$NO + {}^1\!/_2O_2 \rightarrow NO_2. \tag{1.4}$$

If too much NO_2 is produced in the DOC, more than 1:1 = NO:NO$_2$, then Reaction (1.3) becomes operative. This is undesirable because the "excess" NO_2 can yield N_2O, which is a strong greenhouse gas:
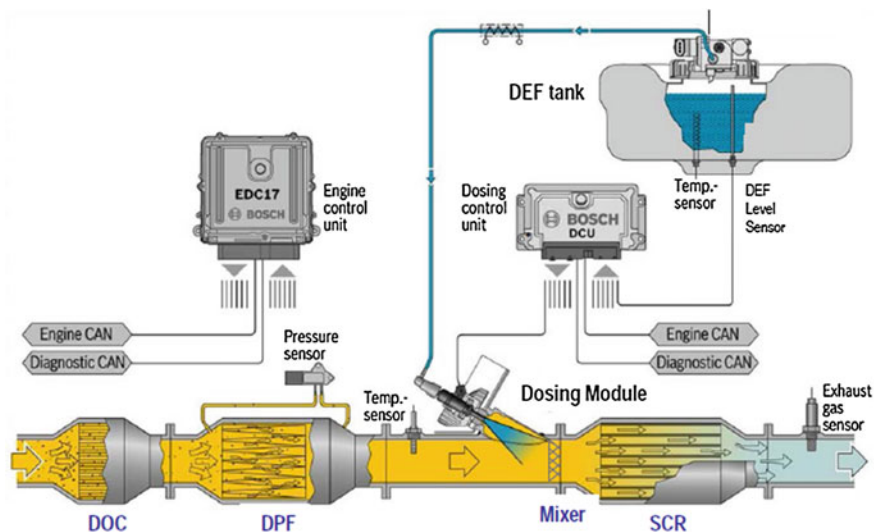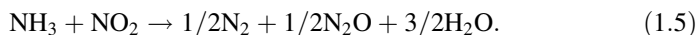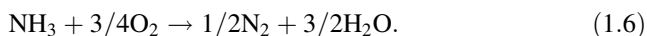
Fig. 1.5 Layout of a DPF + SCR system [16]

$$NH_3 + NO_2 \rightarrow 1/2N_2 + 1/2N_2O + 3/2H_2O. \tag{1.5}$$

If the reactants are not well-mixed, if excess ammonia is injected to obtain high deNOx efficiencies, or if ammonia stored on the SCR catalyst is released too fast, ammonia emissions can occur. To remediate this, an ASC is utilized:

$$NH_3 + 3/4O_2 \rightarrow 1/2N_2 + 3/2H_2O. \tag{1.6}$$

SCR technology is entering its third or fourth generation since commercial introduction in Europe in 2003. Then, systems were removing upwards of 75 % NOx over the European HD Transient Cycle to meet Euro IV regulations. To meet the US2010 and emerging Euro VI regulations in 2013, cycle-average deNOx efficiencies approaching 95 % is realized. Work is continuing in the US to go even higher in efficiency to meet the current and emerging LD NOx regulations. In both HD and LD applications, targets of 98 % test-cycle deNOx efficiency are in the scope for future systems.

To achieve this high level of efficiency, all aspects of the system need to be optimized. An SCR system will generally comprise an ammonia delivery system, and the catalyst system itself comprises the DOC (and typically DPF), SCR catalyst, and the ammonia slip catalyst.

Casarella [16] shows the layout of a typical diesel emission control system incorporating the DPF, Fig. 1.5. In the US, the urea solution is referred to as DEF. In Europe, it is referred to as "AdBlue".

In addition to the SCR catalyst system (DOC, SCR, ASC, mixer) and the DPF, the other main components of the system are the urea delivery system, comprising the storage tank (DEF tank) and sensors, the heated delivery line, pump, and
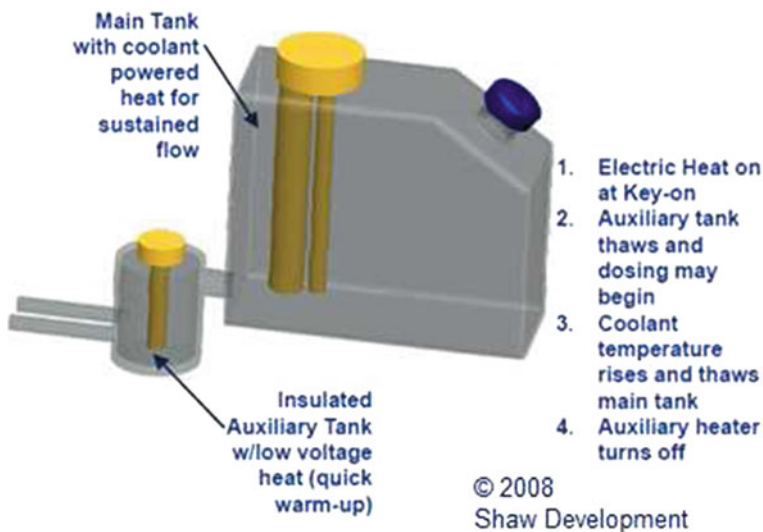
Fig. 1.6 Basic features of the heating system of a urea storage tank [17]

dosing module, including the injector and mixer; and the control system, comprising the sensors, dosing control module, engine control module, and controller area network (CAN) buses.

The following sections will provide more details on these subsystems.

1.4.2 Urea Delivery System

The urea tank, injector, controls, and mixer are significantly engineered systems. Ostertag [17] provides an example of the tank design alone. Figure 1.6 shows the heat-up features and basic designs. Urea is corrosive, so material selection is limited to stainless steel and plastic. Because urea solution (32.5 % urea, balance deionized water) will freeze at −11 °C, the design has to allow for the 7 % expansion upon freezing and for rapid thawing to enable prompt use of the system. Further, internal components like heaters, level and temperature sensors, and fill and extraction lines need to be designed to withstand impact by solids in partially thawed systems. The design shown in Fig. 1.6 has all these components integrated into one unit (in yellow). Finally, and especially for NR applications, the draw point for liquid urea needs to accommodate different vehicle angles of operation.

The urea pump, dosing module, and injectors play a critical role. Designs have migrated from separate pumps and dosing modules to integrated designs [18]; from air-assisted to airless injection; and to systems with no return line. Injectors are designed to disperse fine droplets (20–100 μm mean size) into the exhaust, while minimizing contact with the exhaust pipe to minimize solid by-product formation.