DNO_x™

Taking the Diesel Engine
into the Future

DNO_x™

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Areskoog Reklam AB

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STT has been involved in engine development and analysis since 1980. During these years, STT has obtained a strong market position characterised by a synergistic relationship with the international automotive industry.

STT, among other things, develops its own turbosystems for diesel engines. The company has facilities for design, testing, manufacturing and certification of systems.

For STT's clients, which include manufacturers like Volvo, Mazda, SsangYong, Toyota and Shell, we offer everything from analysis work to full turnkey solutions.

STT is certified by the Vehicle Certification Agency (VCA) in England which enables STT to take responsibility for the development, manufacturing and distribution of engine systems. STT is also ISO 9001 certified.

STT is now introducing DNO_x™ – a system aimed at reducing the amount of nitrogen oxides emitted from diesel engines.

Introduction

During 1997, road traffic and construction equipment combined were responsible for more than 50% of the total nitrogen oxide emissions in Sweden. Emissions have a negative impact on human health – in particular very young people, old people and groups with cardiopulmonary problems. Particulates containing adsorbed hydrocarbons can penetrate deep into the lungs and can be cancerogenic. Nitrogen oxides contribute to smog, acid rain and ground level ozone.

Tighter emission regulations are gradually being introduced worldwide. In Sweden, vehicles and industrial equipment are classified according to their environmental properties. Certain cities have established 'Environmental Zones' to encourage the development of more environment-friendly engines.

Current emission systems reduce carbon monoxide, hydrocarbons and particulates. However, nitrogen oxides are not affected due to the fact that the diesel engine is run with a large excess of air. Systems for the reduction of nitrogen oxide emissions that have been tested so far, involve the injection of a reducing agent into the exhaust gases.

The technology that is considered to have the greatest potential for the reduction of nitrogen oxide emissions is EGR, which involves recirculating exhaust gases to the engine intake. EGR has not yet been used on heavy-duty diesel engines due to the unfavourable pressure conditions in the inlet and exhaust manifold.

The system now developed by STT is a so called low pressure system for recirculation of cooled and particulate free exhaust gases. The system contains an EGR throttle along with an electronic control unit, an EGR cooler and a particulate filter. The amount of recirculated exhaust gases is controlled as a function of engine speed and load.

Compared to traditional EGR systems this new technology opens up new reduction possibilities and has excellent EGR rate controllability under transient conditions. The system has good durability and can be used even if the engine is run on alternative fuels.

The system has been evaluated according to the European test cycle ECE R49 and the results show a 50 % decrease in nitrogen oxide emissions with only marginal effect on engine power. Also, diagnosis functions can be incorporated into the system.

Today there is no other commercial system for the reduction of nitrogen oxide emissions. An EGR system which can be retrofitted and decreases nitrogen oxide emissions by 50 % helps the diesel engine to meet the legislation of the 21st century.

Background

The diesel engine has high efficiency making it interesting for future engine systems

The main advantage of the diesel engine is its high efficiency resulting in a low specific fuel consumption and low carbon dioxide emissions. The low energy requirement makes the diesel engine an interesting alternative for future engine systems (1). It is viewed today as the only alternative for heavy-duty vehicles and construction machinery. Another advantage of the diesel engine is that it can be adjusted to run on alternative fuels.

Diesel engine combustion forms nitrogen oxides and particulates

Engines are developed by engine manufacturers all over the world and much of the work focuses on the reduction of nitrogen oxides and particulate emissions.

Emissions

Ignition of the air/fuel mixture in a diesel engine results in the formation of mainly carbon dioxide and water (Fig.1). At the pressure and temperature conditions in the combustion chamber, part of the nitrogen in the air is oxidised to nitrogen oxide. Nitrogen oxide usually refers to nitrogen monoxide and nitrogen dioxide. The nitrogen monoxide concentration is typically ten times that of the nitrogen dioxide concentration. Nitrogen monoxide is easily oxidised to nitrogen dioxide which is important for smog formation and acid rain.

Road traffic and construction equipment produce over 50% of nitrogen oxide-emissions

In 1997, 35% of the total nitrogen oxide emissions were attributed to road transportation while 22 % were attributed to construction machinery (ref 2). As more and more petrol engine cars are equipped with three-way catalytic converters, an increasing share of road traffic emissions will be caused by diesel engines.

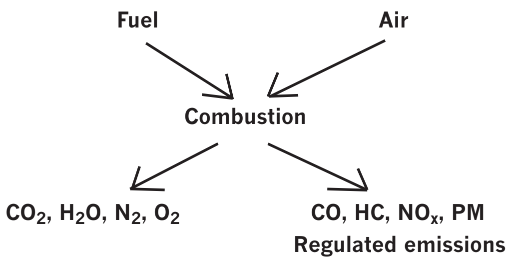

Figure 1 Emissions from a diesel engine

Diesel exhaust gas has low carbon monoxide- and hydrocarbon-contents

Incomplete combustion leads to the formation of carbon monoxide, hydrocarbons and particulates. Carbon monoxide and hydrocarbon contents are low compared to the contents in exhaust gases from petrol engines without catalyst. The difference in nitrogen oxide content is much less, whereas the content of particulates is higher in diesel exhaust gases.

Particulates are porous and contain heavy hydrocarbons

The particulates are porous and consist of a number of smaller particles and lube oil ash. The porosity promotes the adsorption of heavy hydrocarbons and sulphuric acid. Hydrocarbons from both fuel and lube oil are adsorbed on the particulates.

Hydrocarbons are present both as gases and as condensates on the particulates. Some of these hydrocarbons are carcinogenic.

Health effects

Engine emissions have a negative effect on human health

The direct effect of road transport on human health is relatively local. Because part of the air pollutants are adsorbed on vegetation and buildings close to the roads and streets, the dispersion is limited. The pollutants that are not adsorbed are spread over larger areas and contribute among other things to the formation of ground level ozone.

Recently, more and more interest has been focused on particulates and particulates in combination with other air pollutants. Particulates in cities stem mostly from diesel engines.

Particulates in diesel exhaust gases are small and penetrate deep into the lungs

The particulates vary in size between 10 nanometer to several microns – allowing them to penetrate deep into the lungs. Apart from the negative effect attributed to size alone the particulates also contain some carcinogenic hydrocarbons.

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Nitrogen oxides contribute to formation of smog and acid rain

Environmental effects

Photochemical smog is formed under certain conditions. Nitrogen oxides, hydrocarbons, oxygen and sunlight participate in the process. When nitrogen oxide is dispersed into the atmosphere, a number of chemical and photochemical reactions take place and lead to – among other things – the formation of acid rain.

Legislation

For new engines and vehicles, Swedish legislation coincides with EU regulation. In order to speed up the reduction of road traffic impact on the environment, regional deviations with even stricter standards apply.

Heavy-Duty diesel vehicles

Regulated emissions are carbon monoxide, hydrocarbon, nitrogen oxides and particulates

The EU-regulated emissions are carbon monoxide, hydrocarbons, nitrogen oxides and particulates. Limit values are given in grams per kilowatt-hour. The European test cycle presently in use for engine certification is the ECE R49 cycle, also referred to as the 13-step cycle.

Table 1 is a summary of current and proposed EU-legislation and shows that the regulation will be much more stringent during the next decade.

Table 1 Legislation development for heavy-duty diesel vehicles within the EU

			Limit value (g/kWh)			
Legislation	**Test cycle**	**Year**	**NOx**	**HC**	**CO**	**Particulates**
Euro 0	ECE R49		14,4	2,4	11,2	–
Euro 1	ECE R49	1992-93	8,0	1,1	4,5	0,36
Euro 2	ECE R49	1995-96	7,0	1,1	4,0	0,15
Euro 3	ESC, ELR (ETC)	2000	5,0	0,66	2,1	0,10
Euro 4	ETC, ESC/ELR	2005	3,5	0,46	1,5	0,02
Euro 5	ETC, ESC/ELR		2,0	0,46	1,5	0,02

Construction machinery

Legislation includes new construction machinery

Emission regulations for construction machinery with diesel engines have been in force in the United States since January 1996. Sweden followed an EU-directive and introduced such regulations during 1998.

The introduction of these regulations is a two-step process. Step 1 limit values will be enforced during 1998-2000 and step 2 values during 2001-2004. The regulation applies to new machinery and is summarised in tables 2 and 3.

Table 2 Limit values for new construction machinery during step 1

		Limit value (g/kWh)			
Power (kW)	**Date**	**NOx**	**HC**	**CO**	**Particulates**
130-560	1998-10-01	9,2	1,3	5,0	0,54
75-130	1998-10-01	9,2	1,3	5,0	0,70
37-75	1999-04-01	9,2	1,3	5,0	0,85

Table 3 Limit values for new construction machinery during step 2

		Limit value (g/kWh)			
Power (kW)	**Date**	**NOx**	**HC**	**CO**	**Particulates**
130-560	2002-01-01	6,0	1,0	3,5	0,2
75-130	2003-01-01	6,0	1,0	5,0	0,3
37-75	2004-01-01	7,0	1,3	5,0	0,4
18-37	2001-01-01	8,0	1,5	5,5	0,8

Sweden at the environmental forefront

Environmental zones are used to accelerate replacement/upgrade of old equipment

The reduction of exhaust gas emissions as a consequence of new and tighter regulations is marginal initially, since the regulations apply to new construction machinery and new vehicles only. As these constitute only a few percent of the total number of machines and vehicles, faster improvement in air quality can be achieved if exhaust gas emissions are reduced also on engines already in use.

The cities of Stockholm, Gothenburg, Malmoe and Lund have introduced environmental zones to speed up the exchange of old equipment and increase the number of engines equipped with exhaust gas aftertreatment systems. Construction machinery was not affected until January 1 1999, when both old and new construction machinery were included in the system. This means that in order for a company to get a public contract, its construction machinery has to fulfill the emission regulations.

Fuel

The fuel has a great impact on emissions and fuel sulphur levels are decreasing. Future EU directives indicate a sulphur content of no more than 50 ppm.

Nitrogen oxide and particulate emissions are influenced by the fuel

Alternative fuels are tested as one way of decreasing the emissions of mostly nitrogen oxides and particulates. Ethanol and dimethyleter are used as diesel engine fuels where the engines have been made compatible with the respective fuel.

Exhaust gas aftertreatment

Carbon monoxide, hydrocarbons and particulates

Engine development focuses on cleaner and more efficient engines. Where engine modifications are insufficient to meet given targets, exhaust gas aftertreatment can be used (3).

The available systems for the aftertreatment of diesel engine exhaust gases can be divided into two types: oxidation catalysts and particulate filters.

An oxidation catalyst converts carbon monoxide and hydrocarbons

The oxidation catalyst converts carbon monoxide and hydrocarbon to carbon dioxide and water. It also affects the heavy hydrocarbons adsorbed on particulates at lower temperatures. The catalyst's working temperature should exceed 250°C. The conversion is often higher than 80%. At high sulphur levels in diesel fuel there is a risk of sulphuric acid formation if the temperature is higher than 400°C. Total nitrogen oxide emission is not affected, but part of the nitrogen monoxide may be oxidised to nitrogen dioxide.

A particulate filter reduces particulate emissions

The filtration efficiency of different types of particulate filters may vary from 30-40% to close to 100%. The trapped particulates have to be burned off continuously or after a predetermined time period. In a passive filter system, the particulates are burnt off continuously without any additional energy. In an active system additional energy is used to temporarily increase the exhaust gas temperature and to burn off the particulates. Different kinds of fuel additives

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A particulate filter must be regenerated

are tested to lower the soot ignition temperature and faciliate the continous burn-off of particulates.

Filters have no impact on nitrogen oxide emissions.

Nitrogen oxides

Excess oxygen in diesel exhaust gases makes catalyst systems complicated

Diesel exhaust gases always contain considerable amounts of oxygen making three way catalysts used in light-duty petrol cars in-effective. Thermodynamically, the dissociation of nitrogen monoxide/-nitrogen dioxide to nitrogen and oxygen in the presence of excess oxygen is possible. However, in reality this reaction has been difficult to achieve.

Until now, there have been no commercially available after-treatment systems for the reduction of nitrogen oxides in diesel engine exhaust gases.

Reduction of nitrogen oxide emissions by recirculation of exhaust gases

Exhaust gas recirculation can be implemented in different ways

The technology that is considered to have the greatest potential for the reduction of nitrogen oxide emissions from diesel engines (4) is called Exhaust Gas Recirculation, EGR. It involves the recirculation of part of the exhaust gases to the engine air intake.

This can either be accomplished conventionally through so called high pressure EGR (Fig 2), which involves the exhaust gas recirculation from the engines exhaust side to the charge air pipe, or through so called low pressure EGR (Fig 3). Here, exhaust gases are recirculated from the exhaust side to the engine intake system upstream of the turbocharger.

Figure 2

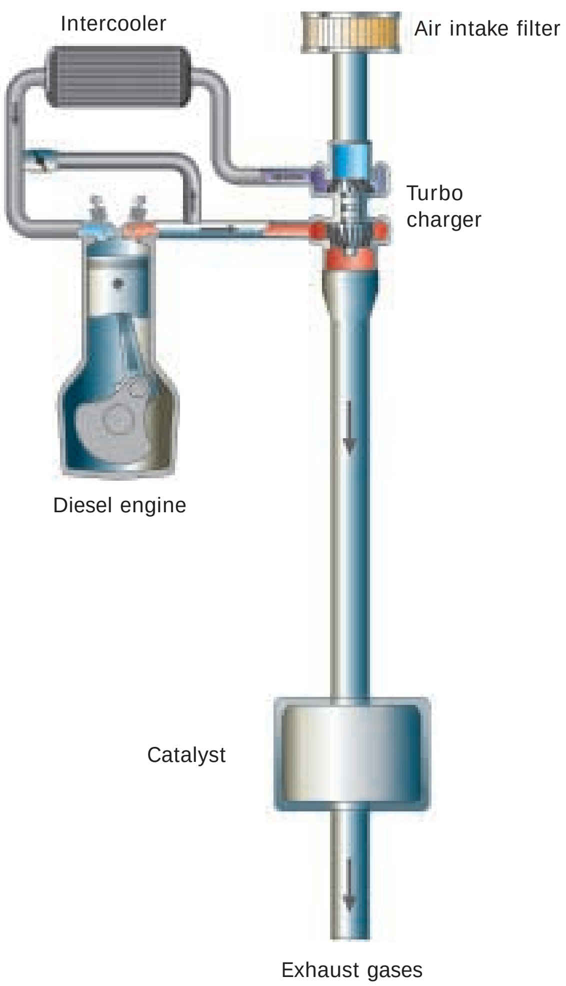
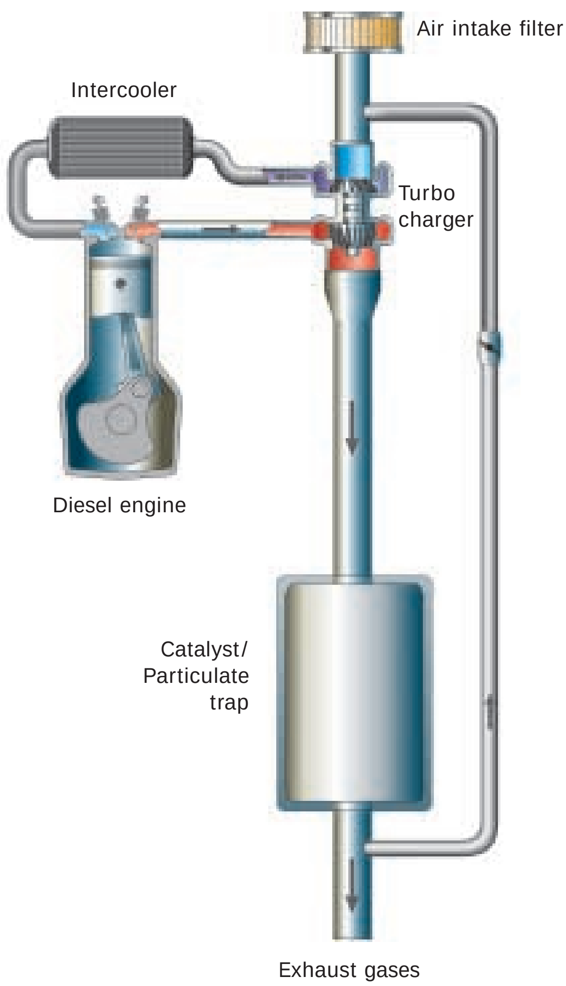


Figure 3



Impact of EGR on emissions

EGR affects the formation of nitrogen monoxide during combustion

When part of the exhaust gas is recirculated to the intake air the oxygen content is decreased and the heat capacitivity is increased. This lowers the maximum combustion temperature and less nitrogen monoxide is formed.

The decrease in oxygen content may cause an increase in the amount of particulates. It is therefore essential to control the EGR rate at different engine loads.

Technical solutions for EGR

A heavy-duty diesel engine has unfavourable pressure conditions in the inlet and exhaust manifolds

So far, conventional EGR has not been used on heavy-duty diesel engines because the pressure conditions in the inlet and exhaust manifolds are such that sufficient recirculation could not be reached by using just an EGR valve. Also, the exhaust gases contain particulates that may increase engine wear and change lube oil properties. There have also been concerns about the components of an EGR system and their long term durability.

An EGR-system can be evaluated using the following criteria:
- EGR rate at high load
- ability to control the EGR rate both under steady-state and transient conditions
- packaging
- contamination of intake system
- complexity and cost.

DNO_X™ – an EGR-based emission system

The system developed by STT reduces nitrogen oxide emissions by recirculation of exhaust gases. Other regulated emissions are reduced through exhaust gas aftertreatment. The system is based on known technology and uses known components.

Description of the DNOx system

Exhaust gases are mixed with intake air before the turbo

The DNOx system is a low pressure system, that is, recirculated exhaust gases are mixed with intake air before the turbo. The recirculated gases are made particulate free and cooled. The former is accomplished by recirculating exhaust gases that have passed through a diesel particulate filter. Figure 4 is a schematic diagram of the system and the different components.

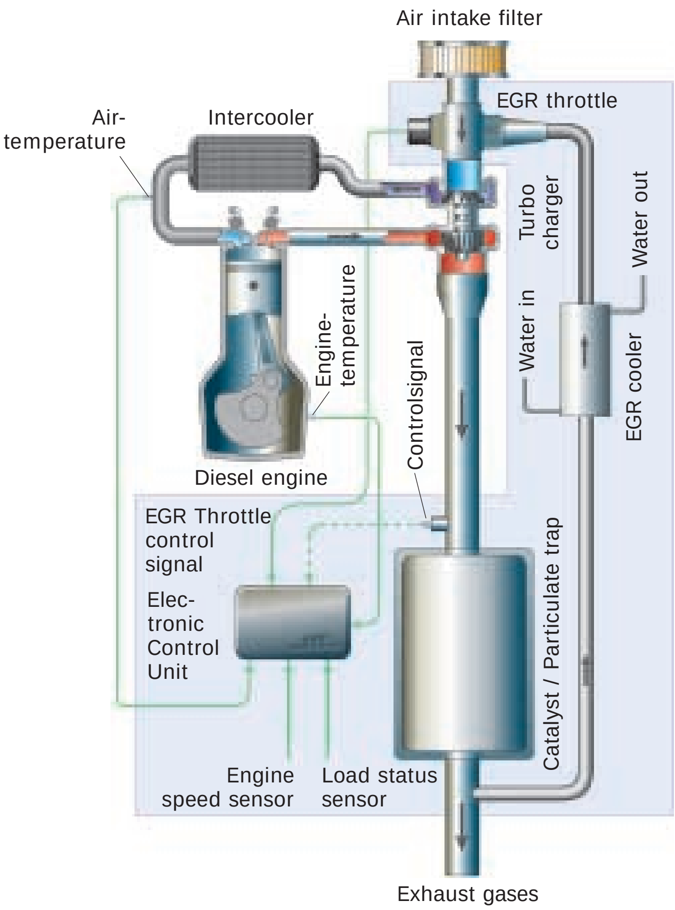
EGR-throttle

The EGR-throttle controls the EGR rate

The EGR throttle controls the rate at which exhaust gases are recirculated . The throttle consists of a throttle body with two valves.

The valves are controlled by an electronic control unit (ECU). Controlling the two valves makes it possible to quickly and accurately adjust the EGR rate according to operating conditions within the engines entire speed and load range.

Figure 4 DNO$_x$™-system layout and components



The ECU uses speed and load to control the EGR rate

ECU

The electronic control unit contains a map of valve positions which corresponds to predetermined EGR rates at different speed and load conditions.

Other components

EGR cooler and lambda sensor. The EGR coolers purpose is to decrease the emission of carbon monoxide, hydrocarbons and particulates at high EGR rates. The cooling has to be chosen carefully for optimum reduction of nitrogen oxide emissions. Aftertreatment gives particulate free exhaust gases. A lambda sensor is used for system monitoring.

DNO$_x$™-system highlights

The DNO$_x$™-system meets the requirements

The DNOx system is characterised by:

- high EGR rates at high loads and good controllability under transient conditions
- small space requirements
- intake path contamination eliminated as the recirculated exhaust gases are particulate free

- EGR cooling by use of engine coolant
- mechanical design based on proven technology combining cost effectiveness with good durability
- fuel choice independancy. Fuels such as ethanol and dimethyl ether give very low particulate emissions making a particulate filter unnecessary

The DNO_x™ system can be used independently of the fuel

Results

Results in urban buses

A bus equipped with the DNOx-system has been tested by Svensk Bilprovning. The engine was equipped with EDC and Euro-2 certified. The test performed was the ECE R49 test cycle.

Results	
CO	**0,09 g/kWh**
HC	**0,00 g/kWh**
NO_x	**3,21 g/kWh**
PM	**0,014 g/kWh**

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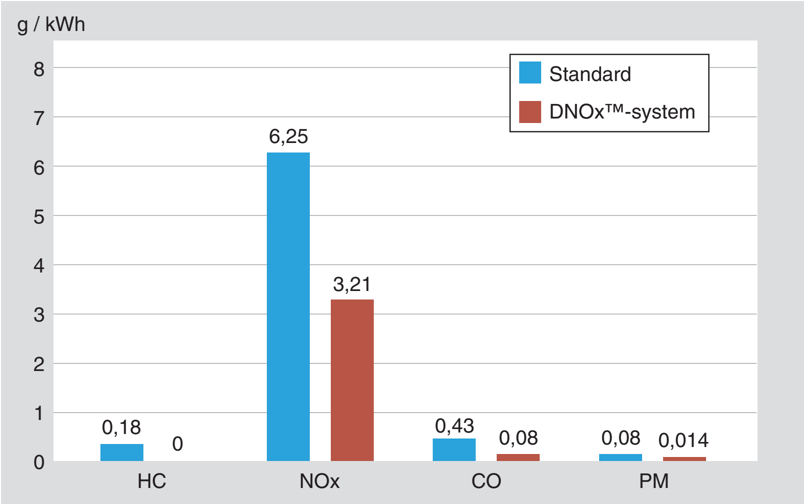

Figure 5 Results of bus tested according to simulated ECE R49 with a 10-litre bus engine of Euro 2-type

Nitrogen oxide emissions are reduced by approx. 55% in the Braunschweig-cycle

The same vehicle was also tested according to the Braunschweig-cycle – a transient test cycle closely emulating city driving conditions

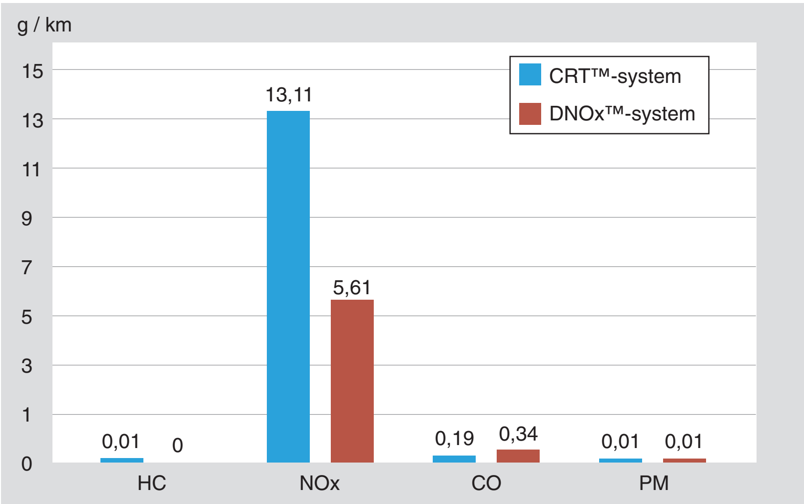

Figure 6 Results of bus tested according to the Braunschweig-cycle with a 10-litre bus engine of Euro 2-type

Conclusions

A total system solution to cut nitrogen oxide emissions in half

Resultats show that DNOx™ can reduce nitrogen oxide emissions by 50%.

The system can be applied to engines with negative exhaust gas/intake air pressure conditions with only marginal effect on specific fuel consumption.

The system adapts optimally under transient conditions similar to realistic conditions and future certification test cycles.

A commercially available system

The system is an add-on system and can be implemented both in the production of heavy-duty diesel engines and in the conversion of existing fleets.

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List of symbols

Description	Symbol
Exhaust Gas Recirculation	EGR
Electronic Control Unit	ECU
Kilowatthour	kWh
Carbon dioxide	CO_2
Carbon monoxide	CO
Hydrocarbon	HC
Nitrogen	N
Nitrogen dioxide	NO_2
Nitrogen monoxide	NO
Nitrogen oxides	NO_x
Ozone	O_3
Particulates	PM
Water	H_2O

Symbol	Description
CO	Carbon monoxide
CO_2	Carbon dioxide
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
H_2O	Water
HC	Hydrocarbon
kWh	Kilowatthour
N	Nitrogen
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_3	Ozone
PM	Particulates

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