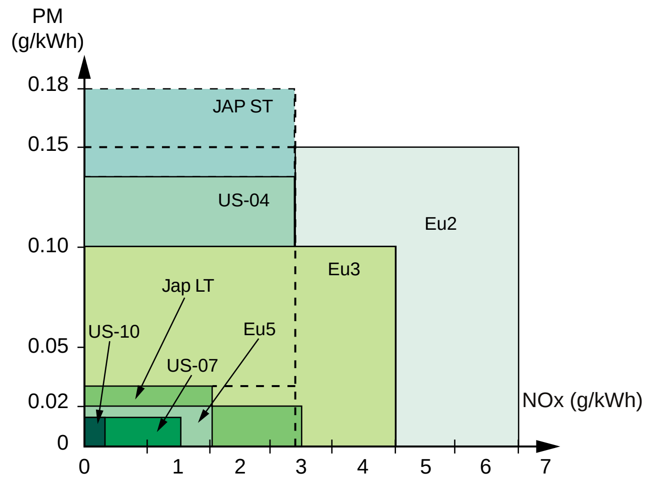
Emissions Control Techniques Applied to Industrial Vehicles

As emission standards for industrial vehicles become increasingly stringent, many research projects are seeking to develop aftertreatment systems. These systems will have to combine efficiency, durability and low operating cost.

Introduction

In the last few years, industrial vehicles (buses, heavy trucks), like passenger cars, have been subjected to increasingly stringent emissions control standards, particularly as far as NOx emissions and particulate matter are concerned. Figure 1 charts this trend for Europe (Euro 2, 1996 to Euro 5, 2008), the United States (US04 to US10) and Japan.

Fig. 1 Emissions standards for heavy-duty vehicles



The first step towards compliance with these very low emissions levels is to improve engine technologies. To reach the targets set for 2005 and beyond, it will also be necessary to install tailpipe emissions aftertreatment systems to reduce nitrogen oxides and particulate emissions (cf. Figure 2).

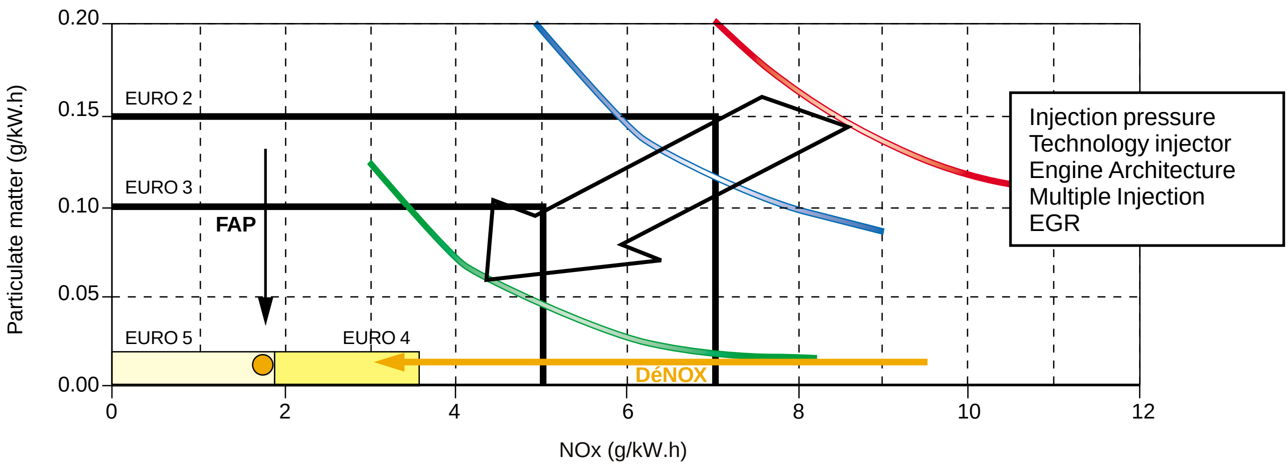
Engine Technology Trends

The improvement of injection systems and supercharging, the introduction of exhaust gas recirculation and the emergence of new combustion processes have led to a substantial reduction of the base emissions generated by diesel engines, especially those equipping heavy-duty diesel vehicles, with hopes of obtaining further reductions.

Injection Systems

Maximum injection pressures have reached 1600 to 1800 bar using common-rail diesel injection and exceeded 2000 bar using the unit injector technique. This improves fuel atomization, thus considerably reducing soot emissions. These

Fig. 2 Technology trends and the NOx/particulate trade-off



Emissions Control Techniques Applied to Industrial Vehicles

injection systems also implement new control technologies to distribute the quantity injected into multiple injections (up to 5 to 7 for common rail) during the thermodynamic cycle. By modulating the combustion process, this technique very substantially reduces emissions at the source (CO, NOx and particulate matter) while bringing down the noise level.

Exhaust Gas Recirculation (EGR)

By recirculating exhaust gases to engine intake, it is possible to limit the formation of nitrogen oxides, bringing combustion temperatures down by diluting the ait/fuel mixture. This technique is commonly applied to heavy-duty vehicles with moderate EGR rates compatible with maintaining fuel efficiency targets and engine durability. EGR is the NOx emissions control technique used in the United States where SCR-type aftertreatment systems have not yet gained acceptance.

Supercharging

Advances in supercharging — variable gemetry turbine and compressor, two-stage supercharging — have made it possible to augment and improve the management and use of intake air; improve engine performance (higher torque over the entire power range), increase power density while reducing consumption and polluting emissions (especially NOx emissions, by raising the EGR rates).

Combustion Chamber Design

To exploit the advances made in injection and supercharging while using EGR technology to best effect, the design of the combustion chamber must be optimized to improve combustion quality and reduce polluting emissions. Increasingly, 3D modeling is being used for this purpose because of continuous progress made on calculation codes.

New Combustion Processes

The idea is to distribute the fuel-air mixture much more evenly throughout the combustion chamber. By lowering the combustion temperature and avoiding excessively fuel-rich areas, NOx and soot formation can be very substantially reduced while minimizing the effects on consumption and noise. Most of the engine manufacturers and many research institutes are working to adapt these new processes to heavy-duty diesels (*e.g.* Caterpillar, IFP and Lund).

By way of an example, the IFP has developed a process known as Narrow Angle Direct Injection (NADI™). The combustion system consists of an injector with a cone angle smaller than usual (60° versus 150° in conventional systems) and an adapted combustion chamber design. Fuel is injected very early in the engine cycle: fuel impingement on the cylinder wall is limited, so oil dilution by the fuel is prevented. This means there is more time to ensure an homogeneous air-fuel mixture before auto ignition. The compression ratio and the EGR rate are adapted to ensure quasi-optimal combustion timing, by adjusting the rate of auto-ignition reactions. The disadvantages of this type of approach reside in a tendency to increase noise, CO and unburned hydrocarbon emissions. Again, these problems can be solved by using suitable multi-stage injection strategies to control the noise level as well as an oxidation catalyst to eliminate the HCs and CO.

Today, when applied to heavy-duty diesels, the NADI™ process can reduce NOx emissions by a factor of 10 to 50 while keeping soot emissions very low over half of the operating range. Work is being done to extend this zone to full power.

The Treatment of Particulate Matter

Diesel Particulate Filters (DPF) using ceramic monoliths (silicon carbide or cordierite) offer a filtration efficiency of well over 90%, including for ultrafine particles. The main difficulty lies in the regeneration of the filter, which involves burning the soot that accumulates in the filter periodically. Various regeneration management concepts are applied to heavy-duty engines.

The Continuously Regenerating Trap (CRT)

This particulate filter, marketed by Johnson Matthey, uses NO_2 to oxidize soot and does not require any specific procedure for regeneration, which takes place on a continuous basis. An oxidation catalyst placed upstream from the filter converts NO to NO_2, which is used to oxidize the soot in the filter as it accumulates. Efficient from 260°C, this system necessitates a NOx/particulates ratio higher than 8; ideally, it would be between 20 and 25. However, the CRT must be used with a low-sulfur fuel (< 50 ppm).

The Catalytic Filter

Applying an oxidation catalyst to the filter walls is another way to achieve continuous regeneration (starting at 300°C). If soot accumulates after prolonged engine running at low throttle, active regeneration can be triggered via engine control action on the fuel injection. Part of the motor fuel is used to reheat the filter in order to trigger combustion of the accumulated soot.

Retrofitting for Existing Engines

With the implementation of emissions control regulations, emissions control in new vehicles has been improved.

Emissions Control Techniques Applied to Industrial Vehicles

Retrofit systems have also been developed for installation on older vehicles, especially buses or refuse trucks. "Passive" systems generally rely on a fuel-borne additive to lower the soot ignition temperature and accelerate regeneration of the particulate filter. "Active" systems usually use a filter with an oxidation catalyst upstream. Filter regeneration requires a high temperature. One way to obtain a high temperature is to inject diesel fuel via an injector placed in the exhaust system: the injected hydrocarbons oxidize on the catalyst and generate the necessary heat. In France, a number of bus fleets are equipped with this type of system, often supplied by the company Airmeex (Fig. 3).

Fig. 3 View of a retrofit system for buses

The Treatment of Nitrogen Oxides

For the catalytic reduction of nitrogen oxides, there are two key technologies: selective catalytic reduction (SCR) and NOx traps.

Selective Catalytic Reduction (SCR)

At stationary combustion installations, the catalytic reduction of nitrogen oxides by ammonia has been used for many years. When the gases are situated in the temperature window of the catalyst (200-500°C), this method achieves an efficiency of 90%. For vehicle applications, the reducer employed is not ammonia but an aqueous solution of urea (NH_2CONH_2), which, injected into the exhaust system, releases ammonia by means of an hydrolysis reaction.

Figure 4 provides a schematic view of a SCR system. Placing an oxidation catalyst upstream raises the NO_2/NO ratio of the exhaust gases. This increases the conversion efficiency, especially at low temperature considering that NO_2 reacts with NH_3 more quickly than NO with NH_3.

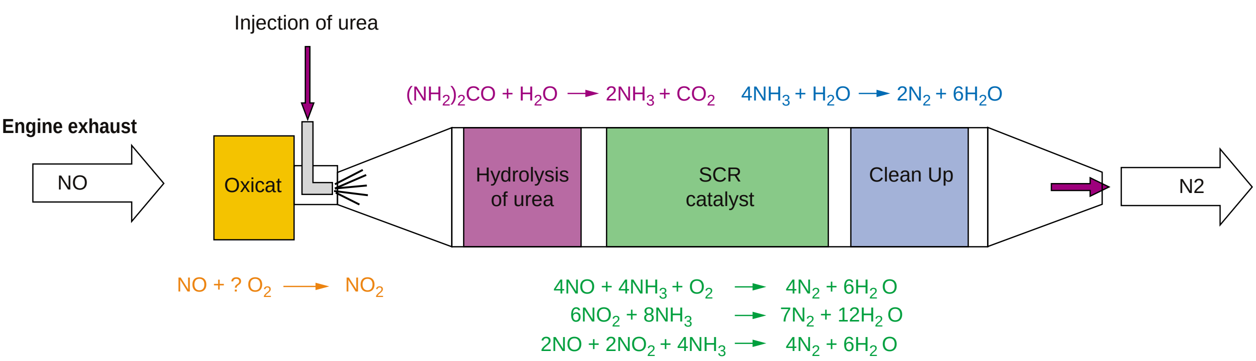
The so-called "clean-up" catalyst is installed downstream from the SCR to treat any excess ammonia that might be discharged, especially during transients.

The development of a SCR system for vehicle applications will require very precise calibration of the amount of urea injected as a function of the quantity of NOx emitted by the engine, exhaust temperature and catalyst characteristics. Installing a clean-up catalyst would provide more latitude and obtain higher NOx conversion ratios without the re-emission of ammonia into the atmosphere.

Figure 5 shows an example of a system implemented on an HD vehicle. For Euro 4 applications, urea consumption (in volume) represents about 4 to 8% of the diesel fuel consumption.

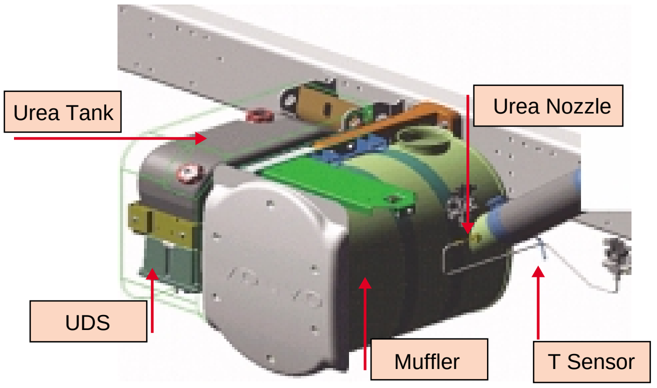
As we can see, the SCR is a very efficient technique for NOx treatment. Starting in 2005, several manufacturers will be installing it on series vehicles (DaimlerChrysler, DAF, Volvo, Iveco and Renault Trucks). Key advantage: it has no major impact on engine operation, which further optimizes its energy efficiency and thus lowers CO_2 emissions. It has a disadvantage in that the vehicle needs urea on board to operate, which means that urea must be delivered through appropriate distribution networks.

Fig. 4 Principle of a SCR system



Emissions Control Techniques Applied to Industrial Vehicles

Fig. 5 Installation of a SCR system on vehicle



The NOx Trap

The NOx trap offers efficiency ratios comparable to those obtained by the SCR, but without the disadvantage of having to carry another reducer on board. A number of development projects are focused on this alternative nitrogen oxide treatment.

In principle, it operates by alternating two stages:

- the engine runs normally on a lean mixture. During this stage, the nitrogen oxides (after being oxidized to NO_2) are stored in nitrate form on an adsorbant mass;
- the engine is run on a rich mixture. The NOx are released then reduced by the reducers (CO, HC) present in the exhaust gases.

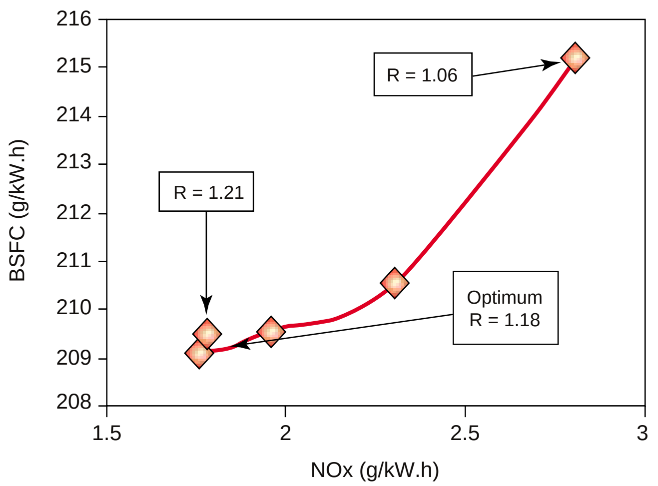
To release and reduce the nitrogen oxides, the air/fuel ratio must exceed or be equal to 1, which is unusual for a diesel engine. This is done by tuning the engine (air flow, injection phasing and duration, EGR ratio). One priority of current development projects is to optimize these alternations (lean versus rich) to obtain the best trade-off between NOx emissions and over fuel consumption.

The conditions under which regeneration occurs (fuel/air ratio, tuning) affect the duration and efficiency of release. For instance, it takes less time when the mixture is richer (> 1.15) and is better when tuning adjustments favor CO emissions over HCs. Regeneration also causes a substantial rise in the temperature of the trap, which could exceed its storage window and thereby limit the efficiency of the subsequent storage phase.

The combined impact of these different parameters, on both storage and destorage, shows that the best NOx/consumption trade-off is obtained when regeneration occurs at high levels of richness (see Figure 6).

By optimizing the system as a whole, it is possible to obtain reduction efficiencies of about 80% for over diesel fuel consumption of 2 to 5%. To avoid discharge of CO and HCs, which can happen when running a richer fuel mixture, an oxidation catalyst is installed downstream from the trap to treat these emissions (a bit like the clean-up catalyst in the SCR).

Fig. 6 NOx trap: NOx/fuel consumption trade-off



The NOx trap also requires the use of a low-sulfur fuel (< 10 ppm). In the presence of sulfur, the trap becomes progressively saturated with sulfates, more stable than nitrates, which quickly reduces its efficiency. In addition, it requires periodic desulfation by running a richer fuel mixture at high temperature.

Unlike the SCR, the NOx trap works closely with the engine in managing rich-mixture running. In order to optimize strategies, any impact on engine operation and its durability (lubricant dilution, thermal stresses, etc.) should be taken into account, along with the thermal aging of the trap. Rich-mixture running, especially at high engine loads, generates smoke emissions that would necessitate the use of a particulate filter.

The Combined Treatment of NOx and Particulates

NOx Trap + Particulate Filter

In order to develop a system of this type, it will be necessary to decide which filter technology is best suited for combined treatment (CRT, catalytic filter, regeneration with fuel-borne additive), define the respective position of each system and combine the engine control strategies needed to ensure that both systems operate properly (nitrate storage/destorage, desulfation of the NOx trap, regeneration of the particulate

Emissions Control Techniques Applied to Industrial Vehicles

filter) to optimize the overall NOx/particulates/fuel consumption trade-off.

Thermal management of the entire system will be key to optimization. Many factors must be taken into account: efficiency window for the trap; efficiency window for the CRT or catalytic filter (depending on which is used); and the impact of regeneration on trap durability if the NOx trap is located downstream from the DPF.

The optimum solution will depend on the target application: base engine emissions, exhaust temperatures, conditions of use (city or highway driving).

SCR + Particulate Filter

Similarly, the SCR and particulate filter can be configured into one system. Here again, respective positioning will depend on respective requirements (efficiency window, regeneration strategies and durability).

Four-Way Catalysis

The "ultimate" emissions control solution is four-way catalysis eliminating the four pollutants simultaneously (CO, HC, NOx and particulate matter). This involves applying an CO, HC and NOx adsorber catalyst to a filtering medium to treat these emissions.

There is a difficulty inherent to this approach: active NOx treatment sites must be left accessible at the filter surface and excessive soot accumulations must not be allowed to cover them up. In developing the ceramic material, special attention is paid to porosity to limit accumulation and to avoiding an excessive increase in pressure loss due to the presence of the adsorbant catalyst.

As far as passenger cars are concerned, Toyota has brought out its DPNR system for light-duty vehicles. This is a diesel particulate filter onto which a NOx adsorber catalyst is applied. Similar applications are under development for heavy-duty vehicles. Four-way concepts based on SCR technology are also under study.

Conclusion

Mandatory compliance with anti-pollution standards for heavy-duty vehicles has and will continue to generate major technology changes in engines and complex tailpipe emissions treatment systems. Driven by fuel efficiency and durability constraints specific to these applications, these changes will impact vehicle cost.

For the two solutions that could be implemented in the short term to achieve compliance with standards of the US07 type (EGR + particulate filter or SCR + particulate filter), the added cost of the powertrain would be about 25 to 30%, according to estimates. As for impact on consumption, the SCR technology, which makes it possible to tune the engine for a better efficiency, outperforms EGR by 3 to 5%, after correcting fuel consumption for urea consumption. This translates into well to wheel CO_2 emissions gains of about 6%. The added annual cost of use (including fuel, urea, maintenance, etc.) is about $50 for SCR versus $500 for EGR. The annual impact of added investment (*e.g.* cost of the system, cost of use, impact on the load hauled) has been estimated at $1,500 for SCR and $2,000 for EGR.

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