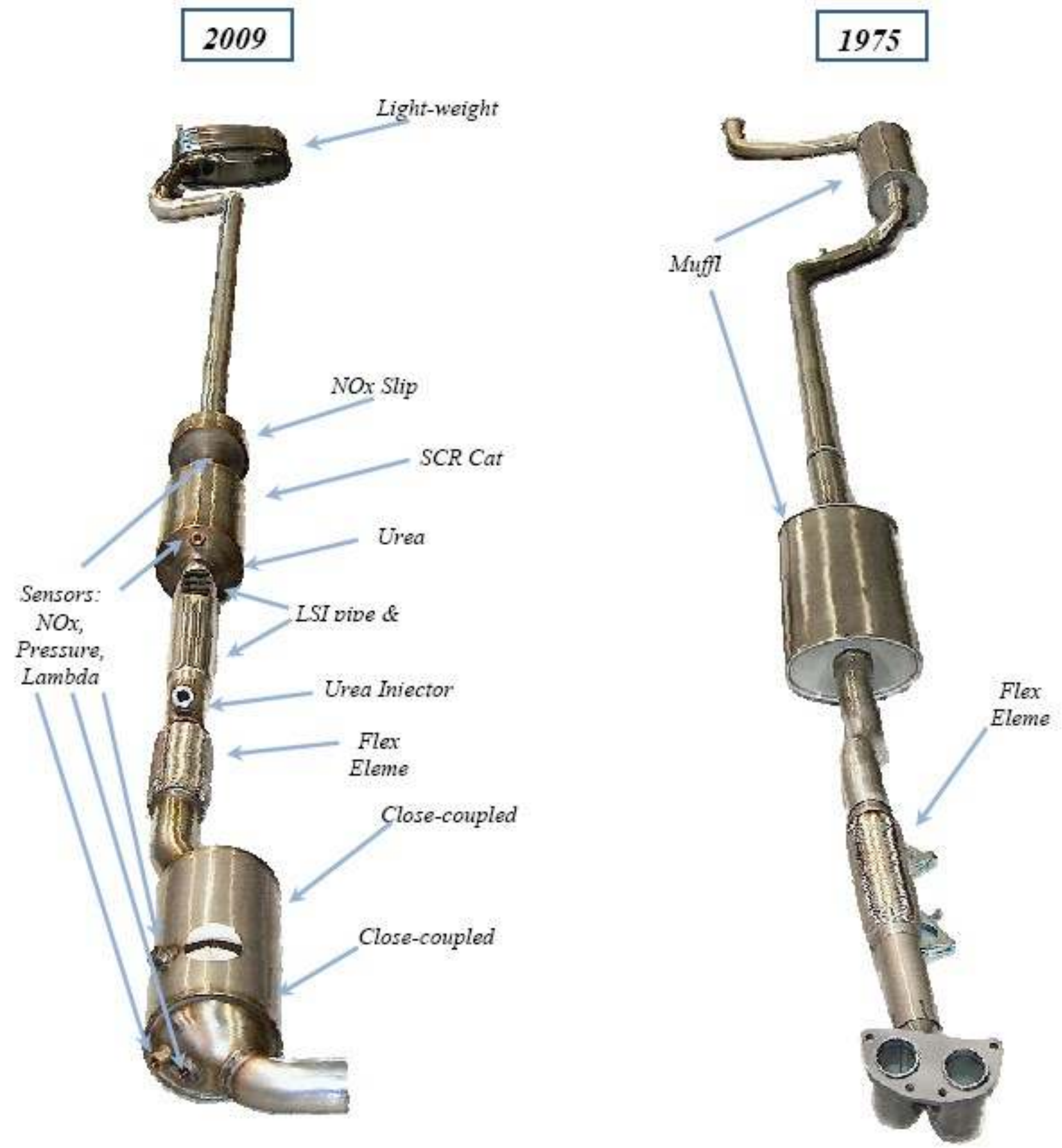
A BIG ROLE TO PLAY FOR THE HUMBLE MUFFLER

Two decades ago the humble muffler or exhaust was really only a noise control device, but today it is at the forefront of the ongoing battle to meet ever more exacting emissions requirements around the world.



A comparison between 1975 and 2009 passenger car exhaust system

To comply with national and international regulations, Exhaust and After-treatment Systems (EAS) have become complex computer-controlled units. Temperature, pressure, flow and oxygen/fuel mixture are all carefully monitored and managed by sophisticated real-time electronics.

To achieve this level of control, the ECU generally uses a sophisticated digital model of the entire operating envelope of the engine and its EAS. This model is derived from a detailed process of mathematical prediction and bench testing to verify these predictions and confirm the parameters required for designed performance.

Each engine has a different digital model, and the system components required to clean up diesel exhaust are different from those in a gasoline unit. There is some convergence between the two when Gasoline Direct Injection (GDI) engines are taken into account because GDI produces particulates requiring filtering similar to those from a diesel engine. This sophistication is the engineering response to 30 years of ever-tighter emissions regulation outlined above. For comparison, The illustration above shows a 1975 passenger car diesel exhaust and a new-generation passenger car after-treatment system showing the components required to achieve the mandated reduction in emissions. The increase in complexity is obvious.

Gasoline (Petrol) Engine Emissions

Assuming that the engine is running with an ideal air/fuel mixture (known as Lambda1) a gasoline engine emits NOx, HC and CO.

Three-Way Catalytic converter (TWC)

The TWC contains precious metal chemicals held in a substrate so that the gases can flow over them. These chemicals are the ‘catalysts’ which promote and enable the reactions necessary for cleaning up the exhaust gases. There are two types of catalyst, one each for the chemical reactions required: ‘reduction’ and ‘oxidation’. In each case, a substrate – metal or ceramic – is coated with the catalyst in such a way as to ensure that the reaction happens but with the minimum of catalytic material. This is because the materials involved are very expensive, usually platinum, rhodium and/or palladium.

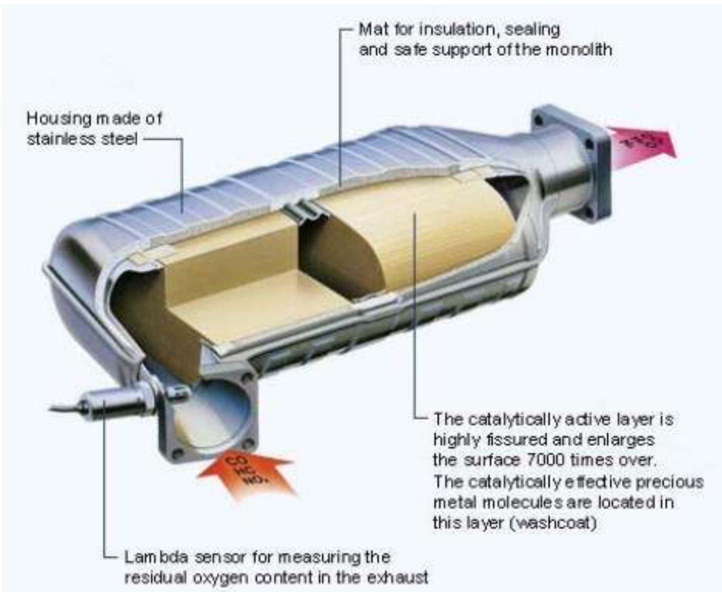


Figure 1: A Three-way catalytic converter

Source: Eberspächer

The first type of reaction in a TWC is *reduction*. This reaction cleans up the NOx. The NO or NO_2 molecules in the NOx are broken down so that nitrogen (N_2), oxygen (O_2), carbon dioxide (CO2) and water (H_2O) are released. One chemical reaction uses the carbon monoxide (CO) already present in the exhaust as a reducing agent. Another reaction uses the exhaust’s hydrocarbons (HC) for the same purpose. The catalyst promoting the reactions is rhodium.

The second type of reaction is *oxidation* – burning. This cleans up the CO and HC by converting them into CO_2, and H_2O. The catalysts for the reactions are platinum and/or palladium, depending upon raw material prices. This same reaction is used in a Diesel Oxidation Catalyst (DOC), which is the same as a TWC but has no reducing capability.

TWCs store O_2 using cerium. The reason for this is that oxygen is needed for oxidation of CO and HC. This O_2 is usually found in the exhaust gas itself as a product of NOx reduction. But sometimes this is not available because the engine is running rich due to acceleration or other factors. At these times the O_2 stored in the cerium is released and used for oxidation. This is only true in gasoline engines because diesel exhaust has sufficient oxygen.

Inevitably, there are some real-world problems associated with this theory. The two biggest problems are mixture and temperature control.

Mixture control is needed to flip the gases flowing through the TWC between oxygen-rich and oxygen-lean states. A rich mixture is need for the oxidation phase of the cleansing process – and a lean mixture ensures that reduction happens.

A heated TWC

The timing of this process is crucial to ensure the proper function of the TWC. But it must also happen without the driver noticing any change in the response and performance of his car. Oxygen (lambda) sensors provide information to the ECU to enable this to happen. As for the need to control temperature, this is important because the catalyst is only effective when in its optimum working temperature range. And since a large proportion of total pollutants are emitted when the engine makes a cold start, this is a problem because the TWC is also cold and the necessary chemical reactions to clean up the emissions cannot take place.

To address this problem, some systems use a pre-catalyst to reduce start-up emissions and burn off the HCs which are present when a cold engine is running rich. Another approach is to ensure that the TWC is 'close coupled' – as near to the warm engine as possible. This helps the catalyst achieve early 'light off' so that emissions treatment begins as soon as possible after the engine has started.

Some OEMs have tried pre-heating the catalyst in various ways – for example with an electrical heater - so that the operating temperature of the TWC is reached quickly (as illustrate above).

All this heating of the TWC needs to be tightly controlled however, because over-heating can permanently damage the converter. A number of sensors of various kinds control this process by passing information to the ECU which manages and monitors the EAS. Upstream and downstream parts of the TWC may also be separated to ensure an optimum working temperature and to allow space for the various lambda sensors necessary to provide information to the ECU.

Finally, as with all systems, the TWC can age and become less effective. For this reason all modern vehicles have on-board diagnostics to tell the driver that the TWC needs to be checked, and around the world standard stipulate the minimum useful life of EAS equipment.

Diesel Engine Emissions

As with gasoline, diesel engine exhaust emissions have to be cleansed of CO, HC and NOx. Diesels emit Particulate Matter (PM) and so need additional technology to remove this pollutant.

With NOx, the difference between diesel and gasoline engines is that the ratio of NO to NO_2 favours the NO_2 because of the greater availability of O_2 in the exhaust gas. There is also a trade-off between NOx and PM production. Reduce PM and NOx increases; reduce NOx and more PMs are produce. These facts guide the design of diesel engines and their emissions systems.

Diesel Oxidation Catalyst (DOC)

As in a gasoline engine, removing CO and HC involves an oxidation process. This takes place in a Diesel Oxidation Catalyst (DOC) which operates in a similar manner to a TWC. Precious metal catalysts held on a substrate are used to oxidise the CO and HC, producing water and carbon dioxide. Being an oxidiser, a DOC needs an oxygen rich atmosphere to operate effectively. Diesel exhaust contains up to 15% O_2 and so easily meets this requirement.

Like a TWC, a DOC operates within an optimum temperature range – usually around 200 to 400° centigrade. They can be 90% efficient in removing these pollutants and can also reduce PMs by 10-15%.

NOx Removal Equipment

Tightening standards mean that more complete removal of NOx from diesel emissions is emerging as the focus for much of the development in EAS. Engine management alone can reduce NOx emissions. But the link between NOx and PM production means that if NOx reduction is favoured, the engine's efficiency is reduced, fuel consumption increases and PM emissions become a problem. Consequently, a balance has to be struck, reducing both to the minimum and then filtering out the PM and removing the NOx.

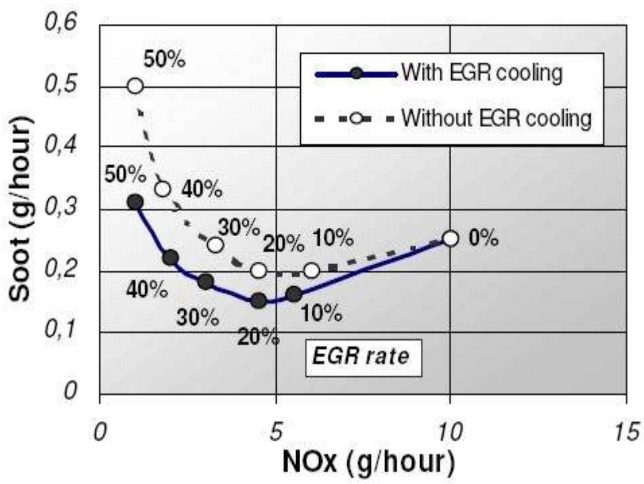
Three approaches can be used to remove NOx from emissions: Exhaust Gas Re-circulation (EGR); NOx Trap, and Selective Catalytic Reduction (SCR).

Exhaust Gas Recirculation (EGR)

EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. Intermixing the incoming air with recirculated exhaust gas dilutes the mix with inert gas, lowering the adiabatic flame temperature and (in diesel engines) reducing the amount of excess oxygen. The exhaust gas also increases the specific heat capacity of the mix lowering the peak combustion temperature. Because NOx formation progresses much faster at high temperatures, EGR serves to limit the generation of NOx. NOx is primarily formed when a mix of nitrogen and oxygen is subjected to high temperatures.

In modern diesel engines, the EGR gas is cooled through a heat exchanger to allow the introduction of a greater mass of recirculated gas. Unlike spark ignition (SI) engine, diesels are not limited by the need for a contiguous flame front; furthermore, since diesels always operate with excess air, they benefit from EGR rates as high as 50% (at idle, where there is otherwise a very large amount of excess air) in controlling NOx emissions.

EGR does not lower throttling losses in the way that it does for SI engines. However, exhaust gas (largely carbon dioxide and water vapour) has a higher specific heat than air, and so it still serves to lower peak combustion temperatures; this aids the diesel engine's efficiency by reduced heat rejection and dissociation. There are trade-offs however. Adding EGR to a diesel reduces the specific heat ratio of the combustion gases in the power stroke. This reduces the amount of power that can be extracted by the piston. EGR also tends to reduce the amount of fuel burned in the power stroke. This is evident by the increase in particulate emissions that corresponds to an increase in EGR. Particulate matter (mainly carbon) that is not burned in the power stroke is wasted energy. Stricter regulations on particulate matter (PM) mean that further emission controls are required to compensate for the PM emissions introduced by EGR. The most common is particulate filters in the exhaust system that results in reduced fuel efficiency. Since EGR increases the amount of PM that must be dealt with and reduces the exhaust gas temperatures and available oxygen, these filters need to function properly to burn off soot.



NOx /particulates trade-off in cooled and non-cooled EGR systems

A disadvantage of EGR is that it increases the heat rejected to coolant. Some manufacturers are estimating that as much as 50% additional heat will need to be dissipated by improved and larger cooling systems in future.

Two EGR systems are available: high pressure (HP) and low pressure (LP). The HP EGR system has the disadvantage that the re-circulated, un-processed exhaust gases can have an adverse effect on intake and turbocharger components, whereas the LP EGR system, which re-circulates exhaust gases downstream from the aftertreatment system reduces this problem.

Cooled EGR

The Exhaust Gas Recirculation (EGR) technique appears today at the most favoured method to lower NOx production in automotive diesel engines. Since exhaust gas is an inert gas (it's already been through the combustion process and therefore is non-reactive), mixing intake air with re-circulated exhaust gases decreases the mixture oxygen content, while reducing its heat capacity. This decreases the maximum combustion temperature and less amount of NOx is formed. However, dilution of intake air with an inert gas means that less oxygen is available in the combustion process, incrementing the particulate emissions. By cooling the re-circulated exhaust gases, EGR density increases, therefore minimising the volumetric conflict between intake air and exhaust gas.

Gasoline Direct Injection (GDI)

GDI is a fuel injection method which enables a very lean burning gasoline engine. The system relies on very precise control of the combustion process by the ECU. GDI reduces fuel consumption, increases power output and lowers the level of some emissions. By combining GDI with advanced turbo charging, fuel consumption reduction of up to 15% is claimed for the system – which is beneficial for CO_2 emissions reduction.

The problem with GDI from an EAS point of view is that although some emissions are reduced, NOx (not necessarily) and PM levels are higher. This requires more sophisticated after-treatment of the exhaust gases similar to those required for a diesel unit and described below. Second generation GDI engines do seem to have lower PM emissions.

Lean NOx Trap (LNT) or NOx Absorber Catalyst (NAC)

A Lean NOx Trap (LNT) is a chemical means of controlling NOx emissions by capturing and retaining it. NOx is stored when the diesel engine is running under normal lean conditions. This is done by oxidising NO to NO_2 as it flows through the trap using a platinum catalyst and storing it in nitrate form. Periodically – when the trap is full and no more NOx can be stored – the engine is run rich for a short time and this releases the stored nitrates as nitrogen gas which is expelled along with CO_2. The LNT is thus regenerated and can be used again. The regeneration process uses fuel and may therefore reduce the overall fuel economy of the vehicle.

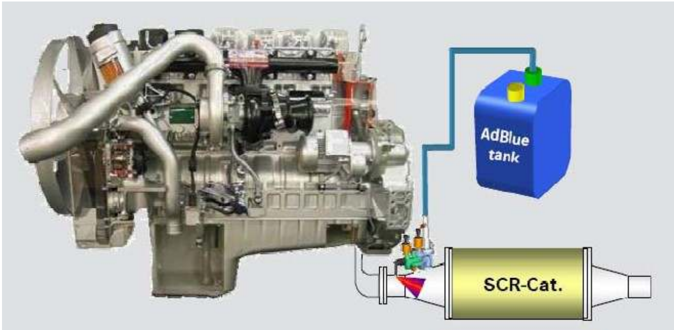
Selective Catalytic Reduction (SCR)

Currently, this is the prevailing solution in Europe for NOx emissions control in the future when standards are more stringent. As with other catalytic converters, SCR uses a catalyst to promote a chemical reaction. In this case it is the reduction of NOx into nitrogen and water. A range of catalysts can be used, factors to consider being resistance to high temperatures, price, availability and tendency to oxidise sulphur dioxide into damaging sulphur trioxide.

The most common reducing agent currently in use is urea. Urea is an organic chemical compound which is diluted about 2:1 with water for automotive SCR applications. The common name for this urea solution is AdBlue.

For example, AdBlue is used as part of Daimler's BlueTec NO_x reduction system for diesels. It is used in passenger cars such as the Mercedes E320. When sprayed into the exhaust stream, the heat causes the urea solution to release ammonia. This is called urea dosing. The ammonia then reacts with NOx to produce the nitrogen and water. Much research is underway to find the best way of spraying and mixing AdBlue with exhaust gases.

There are real-world issues with urea dosing: the AdBlue solution has to be carried on the vehicle in a tank which is topped up by the driver. If this is not done, NOx emissions climb. Consequently a network of AdBlue delivery pumps will have to be created at gas stations for this to be a viable diesel passenger car solution. AdBlue also freezes at temperatures less than -11°C, so in cold climates, pumps, AdBlue and SCR systems on vehicles have to be heated.



A schematic illustrating SCR

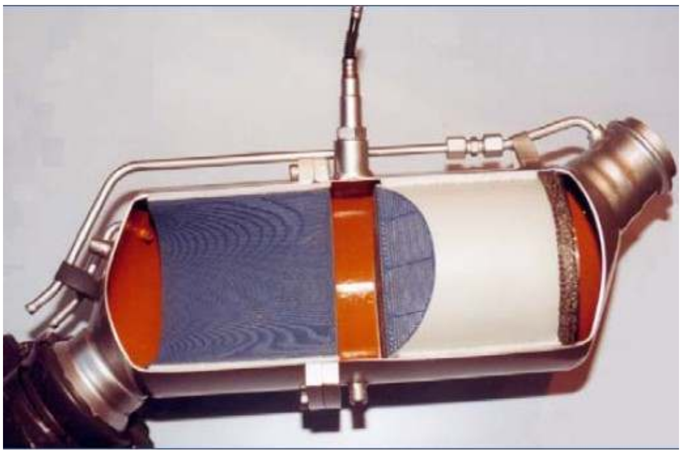
Urea pellets can also be used as a source of ammonia. This approach overcomes some of the above problems. But the pellets need to be stored and transported carefully to avoid their absorbing water in transit. If this happens, they stick together and clog the delivery mechanism on the vehicle. Also, the amount of water used to hydrate these pellets when in use needs to be carefully controlled.

Major OEMs and EAS suppliers including Audi, BMW, Bosch, Daimler, Ford and VW have been looking at urea dosing with pellets. The research has been done over the past few years by Professor Werner Müller of the Technical University of Kaiserslauten.

Other chemicals such as metal ammines can be used to generate the ammonia required for the SCR to work. They have the advantage of being high-density and easily-handled in cartridges. This approach is still not fully developed as a commercial proposition.

SCR systems have to be tuned to work effectively. Much testing is therefore done to create a data model which is then used by the ECU to manage the SCR process. Theoretically this delivers a 100% result. But this is unlikely because of excess ammonia production or un-reacted ammonia remaining.

This ‘ammonia slip’ means that some ammonia is released by the SCR into the exhaust stream. Previously this was not a problem, but in order to meet near-future regulations, this ammonia slip has to be dealt with. The usual solution is to fit another component into the line known as a Slip Catalyst which removes this excess ammonia.



Diesel Particulate Filter

Diesel Particulate Filter (DPF)

The main additional requirement for a diesel EAS is the removal of soot, usually known as particulate matter (PM). This is done using a Diesel Particulate Filter (DPF). An efficient DPF can remove in excess of 85% of PM from a diesel’s emissions.

DPFs sit in the exhaust stream and trap PM in a filter, usually made of cordierite, silicon carbide or metal fibres woven into the core. Every 500km or so the soot in the DPF is burnt and CO_2 is emitted. This is called regeneration because the PM in the DPF is cleaned out and the filter is once more able to collect PM from the exhaust. The temperature at which the PM is burnt has to be controlled very tightly because, just as in a TWC, the DPF filter material can be destroyed by too high a regeneration temperature.

This control is achieved by pressure and temperature sensors which pass data to the ECU which then uses an on-board map of pre-programmed trigger points to decide when to activate the regeneration cycle.

PMs require a minimum temperature of 600^{o}C to burn off. This is a high temperature to attain, especially given that diesel exhaust is at a lower temperature than that of gasoline units. However, diesel exhaust is more oxygen-rich than that of gasoline and so offers the opportunity for efficient burning and reaching this temperature. The downside of this is that there is also the potential for destructive run-away combustion.

A number of techniques are used by EAS designers to manage this balance in the combustion process and keep temperatures in a range around 350^{o}C to 450^{o}C. This preserves and lengthens the life of the DPF. Methods include adding fuel to the input gases and, in more recent designs, using a catalyst of precious metal such as platinum in the DPF. As in a TWC, various substrates can be employed. Depending upon the configuration, regeneration of the DPF can take up to 20 minutes.

The need to burn fuel or generate electrical power to heat the DPF may reduce fuel efficiency of the vehicle by a small amount, usually between one and five per cent.

Finally, the EU is moving away from a standard based on the weight of PM emitted per kilometre to one based on the number of PM particles in the exhaust. This is because although larger particulates are dangerous, they can be seen and are also trapped in the lungs. Smaller nano-sized particles are very dangerous because currently they are not controlled and can be absorbed directly into the blood stream rather than being trapped in the tissue of the lungs.

This requirement to filter very small particles from diesel exhaust emissions will lead to considerable development, so that methods of capturing these smaller, more dangerous, particles in the DPF can be found. Diagnostic equipment which can demonstrate that the system complies with the standard will also need to be developed.