



EMISSIONS CONTROL TECHNOLOGIES TO MEET CURRENT AND FUTURE EUROPEAN VEHICLE EMISSIONS LEGISLATION

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ABSTRACT

The paper reviews the technologies available to meet the exhaust emissions regulations for passenger cars, light-duty and heavy-duty vehicles, non-road mobile machinery and motorcycles adopted by the European Union for implementation by 2016. This includes fast light-off catalysts, more thermally durable catalysts, improved substrate technology, diesel particulate filters, selective catalytic reduction, NOx adsorbers and lean DeNOx catalysts.

1. INTRODUCTION

AECC is an international association of European companies engaged in the development, production and testing of catalyst and filter based technologies for engine exhaust emissions control. This includes the development, testing and manufacture of autocatalysts, ceramic and metallic substrates, filters and catalyst based technologies to control diesel engine emissions (especially particulates and nitrogen oxides) and specialty materials incorporated into the catalytic converters and filters.

Catalyst-equipped cars were first introduced in the USA in 1974 but only appeared on European roads in 1985. It was 1993 before the European Union set new car emission standards that effectively mandated the installation of emission control catalysts on gasoline fuelled cars.

Nowadays, AECC members' technologies are incorporated in the exhaust emission control systems on all new cars and an increasing number of commercial vehicles, buses, non-road mobile machineries and motorcycles in Europe. They are used as part of an integrated approach to emissions control which includes the combustion system, fuel quality and electronic control systems.

2. EUROPEAN EMISSIONS AND FUEL LEGISLATION

The European Union (EU) emissions limits for passenger cars and heavy-duty vehicles have continuously been lowered since 1993 with the Euro 1 to 6 consecutive stages (1) and the Euro I to Euro VI stages (2) respectively. Not only have HC, CO, NOx and PM limits been dramatically reduced but also cold starts, particle number and CO₂ measurement have been added into emissions driving cycles. For engines intended for heavy-duty vehicles and non-road mobile machinery (NRMM), transient operation has also been added. Motorcycles and non-road mobile machinery have lagged behind but their environmental performance keeps improving nevertheless with Euro 1 to 3 stages for motorcycles (3) and Stages I to IV for NRMM (4).

3. THE IMPORTANCE OF FUEL QUALITY

Fuel and lubricant quality affects the performance of emissions control systems either by preventing the use of a technology unless the fuel quality is improved (the improved fuel is 'enabling' the use of that technology) or by 'enhancing' the performance of emissions control systems. In this case both the existing fleet and new vehicle registrations benefit. The motor industry has published information on the effects of fuel quality, with recommendations, in the 'Worldwide Fuel Charter' (5).

Examples of enabling fuels are unleaded petrol that allows three-way catalysts to be used and ultra-low sulfur fuels required so that NOx adsorbers can be used and which ease the use of catalyst-based Diesel Particulate Filters (DPF). Lead has long been recognized as a catalyst poison as well as having impacts on human health,

and is no longer permitted in European fuels. The ban on the sale of leaded petrol in EU and elsewhere, provides an example to influence other regions

Examples of enhancing fuels are the further reductions in the levels of lead, phosphorus and alkali metals that improve the performance and life of three-way catalysts and the introduction of ultra-low sulfur gasoline and diesel fuels. Reducing sulfur levels all the way down to near-zero delivers improved performance of catalysts.

The negative impact on catalyst performance of sulfur in gasoline and diesel fuels has been reported by AECC as part of the stakeholders input to the European Commission's review on fuel quality. A technical summary on EU fuel quality is available on the AECC website (6).

The sulfate storage and release process was minimized by the introduction of the <10 ppm sulfur diesel fuel being progressively introduced across the EU since 2005. This fuel quality is necessary for the full potential of emissions control systems to be realized. Ultra-low sulfur fuels, already widely available, will be mandatory in the EU for passenger cars and heavy-duty applications by 2011. Non-road mobile machinery will also require the use of ultra low sulfur diesel (10 ppm S) as of 1 January 2011.

Also, there are concerns over the use of some metallic additives, with suggestions that their use in gasoline may, under some driving conditions, lead to deposits on exhaust system components such as the oxygen sensor and catalyst. Metallic or other ash-forming materials in diesel fuel will also add to the amount of ash captured by particulate filters and may require the system to be designed so as to allow for the additional ash. Detergent additives, on the other hand offer positive benefits. Their use helps keep the fuel injection system and combustion system clean, so helping to prolong optimum operating conditions for the emissions control technology.

4. EXHAUST EMISSIONS FROM INTERNAL COMBUSTION ENGINES

Exhaust emissions can be lowered by reducing engine-out emissions through improvements to the combustion process and fuel management, or by changes to the type of fuel or its composition.

Emissions control systems – autocatalysts, adsorbers and particulate filters – in combination with good quality fuel (low sulfur content) and enhanced engine management reduce emissions to very low levels. As well as their application in new vehicles and machinery, many emissions control systems can also be applied in retrofit applications to good effect.

5. CATALYST TECHNOLOGIES FOR EMISSIONS CONTROL

5.1 Substrate and Coating Technologies

The technology of the substrates, on which the active catalyst is supported, has seen great progress. In 1974, ceramic substrates had a cell density of 200 cells per square inch (cpsi) of cross section (31 cells/cm²) and a wall thickness of 0.012 inch or 12 mil (0.305 mm). By the end of the 70's the cell density had increased through 300 to 400 cpsi and wall thickness had been reduced by 50% to 6 mil. Now 400, 600 and 900 and even 1200 cpsi substrates are available and wall thickness can be reduced to 2 mil - almost 0.05 mm (7), (8), (9), (10) and (11).



Figure 1: Ceramic substrates.

In parallel, in the late 1970's, substrates derived from ultra-thin foils of corrosion-resistant steels came on to the market. From the beginning, the foils could be made from material only 0.05 mm thick allowing high cell densities to be achieved. Complex internal structures can now be developed; 800 and 1000 cpsi metallic substrates are available and their wall thickness is down to 0.025 mm (12) and (13).

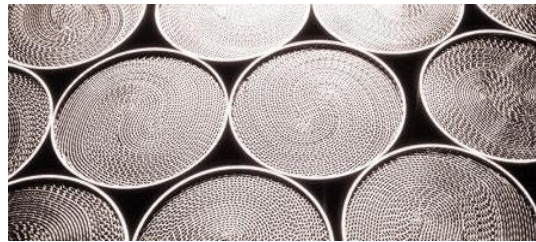


Figure 2: Metallic substrates.

This progress in ceramic and metal substrate technology has major benefits. A larger catalyst surface area can be incorporated into a given converter volume and this allows better conversion efficiency and durability. The thin walls reduce thermal capacity and limit pressure losses. Alternatively, the same performance can be incorporated into a smaller converter volume, making the catalyst easier to fit close to the engine as cars are made more compact.

Optimized systems incorporating these new technologies are in production. The use of additional catalytic converters close to the exhaust manifold reduces the time to light-off in the cold start and, therefore, the total emissions. Light-off times have been reduced from as long as one to two minutes to a few seconds (14). Improved substrate technology, combined with highly thermally stable catalysts and oxygen storage components, allows the close-coupled catalyst approach to meet the Euro 4, 5 and 6 standards.

In the original automotive catalyst it was only possible to apply the active coating to the whole substrate. Precision coating technologies now allow different active material compositions to be applied to different areas of the substrate to optimize the performance or, in some cases, to allow different functions. This includes, for instance, coating the inlet end of a particulate filter to act as an oxidation catalyst.

A further option that can be used for some types of catalyst is to incorporate the active materials directly into the ceramic substrate, so that the extruded ceramic matrix provides catalytic activity without further coating. Such 'homogeneous' catalysts are primarily used in the Selective Catalytic Reduction of NO_x emissions.

5.2 Three-Way Catalysts (TWC)

Three-Way Catalysts are the main autocatalyst technology used to control emissions from gasoline engines. The catalyst uses a ceramic or metallic substrate with an active coating incorporating alumina, ceria and other oxides and combinations of the precious metals - platinum, palladium and rhodium. Three-way catalysts operate in a closed-loop system including a lambda or oxygen sensor to regulate the air:fuel ratio on gasoline engines. The catalyst can then simultaneously oxidize CO and HC to CO₂ and water while reducing NO_x to nitrogen.

Fast light-off catalysts allow the catalytic converter to work sooner by decreasing the exhaust temperature required for operation. Untreated exhaust emitted at the start of the legislated emissions test and on short journeys in the real world is curtailed. Changes to the thermal capacity of substrates and type and composition of the active precious metal catalyst have together resulted in big improvements (15).

More thermally durable catalysts with increased stability at high temperature allow the catalytic converter to be mounted closer to the engine and increase the life of the catalyst, particularly during demanding driving conditions (16). Precious metal catalysts with stabilized crystallites and washcoat materials that maintain high surface area at temperatures around 1000°C are needed for this. Improved oxygen storage components stabilize the surface area of the washcoat, maximize the air:fuel 'window' for three-way operation and help the oxygen sensors to indicate the 'health' of the catalyst for On Board Diagnostic (OBD) systems. "Close-coupled" catalysts mounted immediately after the engine exhaust manifold allow the catalyst to start working within seconds (17).

Electrically heated catalyst systems use a small catalyst ahead of the main catalyst. The substrate, onto which the catalyst is deposited, is made from metal so that, when an electric current is passed, it will heat up quickly. This brings the catalyst to its full operating temperature in a few seconds (18).

5.3 Oxidation Catalysts

Oxidation catalysts are the original type of autocatalysts and were used from the mid-1970's for petrol-engined cars until superseded by three-way catalysts. They look much the same as three-way catalysts and their construction and composition is similar but slightly less complex. Oxidation catalysts convert carbon monoxide (CO) and hydrocarbons (HC) to carbon dioxide (CO₂) and water but have little effect on nitrogen oxides (NO_x). They are now rarely used on gasoline cars in Europe because of the advantages of three-way catalysts, but they are still used in some parts of the world where emissions legislation is less stringent. They may also be

used on some buses running on Compressed Natural Gas (CNG), motorcycles and for applications such as small petrol engines for hand-held equipment such as strimmers and recreational boats.

Diesel Oxidation Catalysts (DOC) remain a key technology for diesel engines where the high oxygen content of the exhaust precludes the use of three-way catalysts. These Diesel Oxidation Catalysts (DOC) convert CO and HC but also decrease the mass of diesel particulate emissions by oxidizing some of the hydrocarbons that are adsorbed onto the carbon particles (19). All new diesel engines mounted in passenger cars, light-duty and heavy-duty trucks and busses are now equipped with DOCs.

DOCs may also be used in conjunction with NO_x adsorbers, DPFs or SCR catalysts to increase the NO₂:NO_x ratio or to minimize any residual injected reductant used for NO_x reduction (hydrocarbons or ammonia).

5.4 Control Technologies for Particulate Matter

Particulate filters are generally used with diesel engines to remove diesel particulate matter (PM), but in principle can be used with other types of engine/fuel combinations, although these produce less particulate matter. Based on engine technology and application specificities, different filter technologies may be used to reduce particles emissions.

Diesel Particulate Filters (DPFs) have been applied to production vehicles since 2000 and are now standard equipment on most new diesel cars in Europe. Some buses and trucks meeting the Euro IV, V and EEV (Enhanced Environmentally-friendly Vehicle) emissions standards are equipped with DPFs and most Euro VI heavy-duty vehicles are expected to be equipped with them so as to meet the PM mass and particle number emissions requirements. There is, as a result, quite an active field of development in regeneration optimization, substrates materials and catalyst improvements plus developments in related On-Board Diagnostics.

5.4.1 Wall-Flow Filters

In the most common type – wall-flow filters – particulate matter is removed from the exhaust by physical filtration using a honeycomb structure similar to an emissions catalyst substrate but with the channels blocked at alternate ends. The exhaust gas is thus forced to flow through the walls between the channels and the particulate matter is deposited as a soot cake on the walls. Such filters are made of ceramic (cordierite, silicon carbide or aluminium titanate (20)) honeycomb materials.

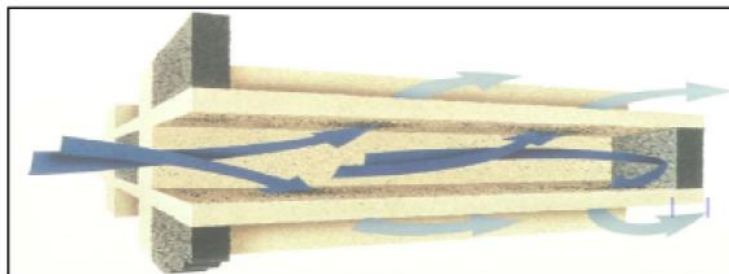


Figure 3: Exhaust gas flow through a wall-flow filter channel.

Ceramic wall-flow filters remove almost completely the carbonaceous and metallic particulates, including fine particulates of less than 100 nanometers (nm) diameter with an efficiency of >95% in mass and >99% in number of particles over a wide range of engine operating conditions (21). The latest European emissions limit values (i.e. Euro 5, 6 and VI) are set on the basis of both mass and number counts to ensure control of the ultrafine particles, which are thought to be more critical indicators of health impact.

Since the continuous flow of soot into the filter would eventually block it, it is necessary to 'regenerate' the filtration properties of the filter by burning-off the collected particulate on a regular basis. The most successful methods to achieve regeneration include:

- Incorporating an oxidation catalyst upstream of the filter that, as well as operating as a conventional oxidation catalyst, also increases the ratio of NO₂ to NO in the exhaust (22). NO₂ provides a more effective oxidant than oxygen and so provides optimum passive regeneration efficiency.
- Incorporating a catalytic coating on the filter to lower the temperature at which particulate burns. New formulations and process development intend to lower backpressure (23) and to substitute platinum by palladium where ultra-low sulfur fuels are available. In (24), Pt/Pd formulations at a 3:1 ratio had lower light-off temperature (the temperature at which the catalyst starts to work) than Pt-only catalysts (240°C vs. 295°C) in the aged state, generated as much NO₂ for passive soot oxidation, and were resistant to sulfur contamination. In one investigation (25), platinum was completely substituted for palladium with use of a base metal catalyst. New formulations are using ceria or zirconia to make the soot react directly with oxygen at the catalyst-soot interface. One paper (26) shows a new zirconia-based soot

catalyst that transfers oxygen from the gas to the soot-catalyst interface for 70% faster soot oxidation rates at 75°C lower temperatures. Enhanced versions based on ceria are showing potential to oxidize soot at temperatures as low as 260°C with very little precious metal (27).

- Using very small quantities of Fuel-Borne Catalyst (FBC), such as ceria (28) or iron additive compounds added to the fuel using an on-board dosing system. The FBC, when collected on the filter as an intimate mixture with the particulate, allows the particulate to burn at lower exhaust temperatures (around 350°C instead of 650°C) and increases the combustion kinetics (typically 2-3 minutes) while the solid residues of the catalyst are retained on the filter as ashes. The third generation of FBC (29) is based on 3 ppm iron allowing a 1.7 litre tank to last the life of the vehicle (240 000 km) and requiring no process for ash cleaning.



Figure 4: Fuel-borne catalyst dosing unit.

- Fuel injector placed in the exhaust line upstream of the DPF (30). This provides a source of hydrocarbons to initiate the temperature rise for regeneration.
- Electrical heating of the trap either on or off the vehicle (31) and (32).

Trapped particulate burns off at normal exhaust temperatures using the powerful oxidative properties of NO₂ and can burn in oxygen when the temperature of the exhaust gas is periodically increased through post-combustion. Maximum exothermic temperatures must be controlled, especially in worst-case 'drop-to-idle' conditions when the soot combustion starts at high temperature and flow and then the engine drops to idle (33).

One study suggests that a Diesel Oxidation Catalyst is needed to get higher temperatures at the inlet face of DPF to assist the first centimeters to regenerate (34).

As the understanding of DPF fundamentals has moved forward, a porous membrane can now be added to the inlet wall so that soot is kept out of the wall (35). This improves filtration efficiency and back-pressure, as well as the correlation between back-pressure and soot loading. This correlation can be used for OBD purpose and for example, soot models using wall permeability algorithms have been developed (36). Soot sensors may also be needed in the future. Sensor concepts are being tested and compared (37). Concepts include using charge transfer by soot from one charged plate to another and using PM film electrical property measurement.



Figure 5: wall-flow particulate filters.

5.4.2 Partial-Flow Filters

Diesel Partial-Flow Filters normally use a metallic substrate. The metallic partial-flow filter uses a special perforated metal foil substrate with a metal 'fleece' layer so that the exhaust gas flow is diverted into adjacent channels and the particles are temporarily retained in the fleece before being burnt by a continuous reaction with the NO₂ generated by an oxidation catalyst located upstream in the exhaust. It offers an option for reducing PM emissions by 30-80% depending on filter size and operating conditions (38) and (39).

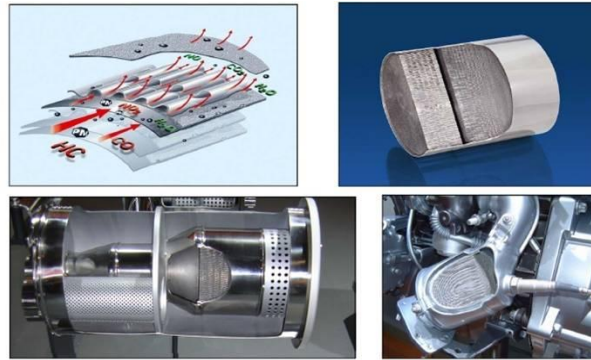


Figure 6: Diesel partial-flow filters.

5.4.3 “Open Filters”

So-called open filters are available in various materials from fibre-based to metallic ‘foams’. ‘Open’ filters do not have a storage function. Their efficiency is normally limited and they are usually used in some retrofit applications (40).

5.5 NOx Control Technologies

With the development of lean burn direct injection gasoline engines and the increased use of diesel engines in passenger cars, there is an increasing need for the control of NOx in lean combustion systems. Lean burn systems limit CO₂ emissions and reduce fuel consumption and so are key technologies for the future.

5.5.1 Selective Catalytic Reduction (SCR)

SCR was originally developed and used to reduce nitrogen oxide emissions from coal, oil and gas fired power stations, marine vessels and stationary diesel engines. SCR technology permits the NOx reduction reaction to take place in an oxidizing atmosphere. It is called “selective” because the catalytic reduction of NOx with ammonia (NH₃) as a reductant occurs preferentially to the oxidation of NH₃ with oxygen.

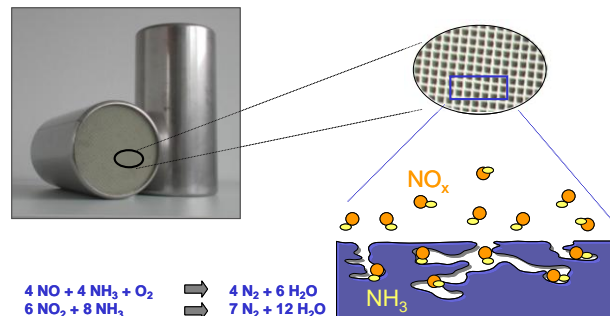


Figure 7: Selective Catalytic Reduction.

SCR technology is now fitted to most new heavy-duty (i.e. truck and bus) diesel engines in Europe. Systems are also being introduced on light-duty diesel vehicles and on non-road mobile machinery such as construction equipment. The efficiency of SCR for NOx reduction also offers a benefit for fuel consumption. It allows diesel engine developers to take advantage of the trade-off between NOx, PM and fuel consumption and calibrate the engine in a lower area of fuel consumption than if they had to reduce NOx by engine measures alone. Particulate emissions are also lowered and SCR catalytic converters can be used alone or in combination with a particulate filter.

For mobile source applications ammonia is used as a selective reductant, in the presence of excess oxygen, to convert over 70% (up to 95%) of NO and NO₂ to nitrogen over a special catalyst system. Different precursors of ammonia can be used; but for vehicles the most common option is a solution of urea in water (e.g. AdBlue[®]) carefully metered from a separate tank and sprayed into the exhaust system where it hydrolyses into ammonia ahead of the SCR catalyst. AdBlue[®] is a stable, non-flammable, colorless fluid containing 32.5% urea which is not classified as hazardous to health and does not require any special handling precautions. It is made to internationally-recognized standards. Urea is used as an artificial fertilizer and is found in products such as cosmetics. The consumption of AdBlue[®] is typically 3-4% of fuel consumption for a Euro IV engine, and 5-7% for a Euro V engine, depending on driving, load and road conditions. A truck can have an AdBlue[®] tank which will hold enough urea solution to last for up to 10 000 km. On-board systems alert the driver when it is time to fill

up the urea tank. An AdBlue® infrastructure was put in place over Europe and a dedicated website www.findadblue.com is available to show facilities where AdBlue® is available.

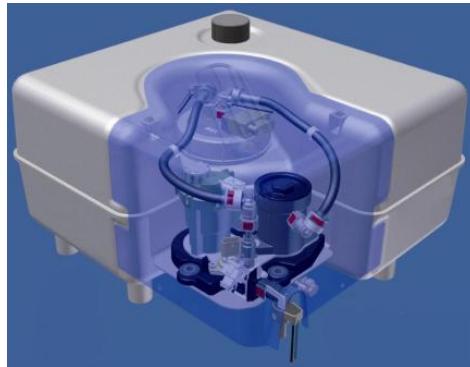


Figure 8: Urea dosing system.

SCR technology is relatively dynamic and improvements are being made in low temperature performance, urea delivery systems, system design, and alternatives to liquid urea. Indeed, SCR is emerging in the light-duty sector and further NO_x reductions are also desired in the heavy-duty sector in urban driving or other low load conditions.

Urea injection quality and mixing are complex and critically important. A study shows (41) that the urea droplet quality from various nozzle designs can impact the deNO_x system efficiency by up to 10% while the urea distribution across the catalyst can result in efficiency variations from 60 to 95%.

Modeling studies to improve urea injection and mixing using a variety of devices are numerous (42), (43) and (44). About 10-20% deNO_x efficiency improvements can come from good injection practice, with nominally 5-10% coming from using a variety of mixers. Ammonia storage models also help with cold start deNO_x (45).

Airless injectors (46), without a urea return line, simplify the urea delivery system and allow accurate delivery of lower volumes. The injector cooling is performed by raising off the exhaust pipe and using convection air and fins cooling rather than by using an excess of urea. Also, upon shut-off, the urea line drains to eliminate freezing issues and the need for line heaters.



Figure 9: Urea injector, mixing device and SCR catalyst

Several types of catalysts are used, the choice of which is determined by the temperature of the exhaust environment. Originally in Europe, China and India, SCR catalysts were based on vanadia. However, if DPFs are used in combination with SCR systems, zeolites are preferred due to the better high temperature durability needed when exotherms associated with DPF regeneration can expose SCR catalysts to temperatures up to 800°C. Currently copper-zeolites have the best low temperature performance and iron-zeolites have the best high temperature performance.

Optimized operation of SCR catalysts depends on control of adsorbed urea and use of oxidation catalysts to deliver the appropriate NO₂/NO_x ratio. In fact, the 'fast SCR reaction' uses both NO and NO₂ at an optimum ratio of 1:1 and this is critical for good performance below 200°C. However, excess NO may be needed to oxidize ammonium nitrate (NH₄NO₃) which can condense and block catalytic sites. The reduction mechanism for the SCR reactions over zeolite catalysts are described in (47). It shows that with NO_x present only as NO, the oxidation to NO₂ to promote the 'fast SCR reaction' is the limiting step.

Copper and iron can be used together for a balanced performance over a broad range of temperatures (48), (49). Vanadia is cheaper and more tolerant to sulfur, but deteriorates at temperatures greater than 600°C whereas zeolites are very little affected with long exposure at 800°C (50). Like vanadia, Fe-zeolites are quite tolerant to sulfur but Cu-zeolite performance deteriorates and can be restored with a desulfation cycle (51). New zeolite are being developed for low temperature conversion without copper (49) and new catalyst families based on acidic zirconia are also emerging (52).

Emerging systems now incorporate the catalyst onto the Diesel Particulate Filter (51), (53) and (54) with a slightly lower deNO_x performance (5-10% lower NO_x conversion) than using separate substrates. Results are

mixed on the impact of soot blocking SCR performance; and backpressure is higher for the combined system due to high catalyst loading on the DPF.

On-Board Diagnostic (OBD) and closed loop SCR control are using either the reputable NO_x sensors (55) or a new ammonia sensor (56) which has a ± 5 ppm ammonia detection accuracy up to about 30 ppm ammonia, and has negligible interference from NO_x, HC and CO.

Finally, alternative SCR reductants are being developed as solid urea (57) and magnesium dichloride ammonia storage media (58). Both have three times more ammonia per liter than liquid urea.

5.5.2 NO_x adsorbers or Lean NO_x Traps (LNT)

Lean NO_x traps adsorb and store NO_x under lean conditions. A typical approach is to speed up the conversion of nitric oxide (NO) to nitrogen dioxide (NO₂) using an oxidation or three-way catalyst mounted close to the engine so that NO₂ can rapidly be stored as nitrate. The function of the NO_x storage element can be fulfilled by materials that are able to form sufficiently stable nitrates within the temperature range determined by lean operating engine points. Thus especially alkaline, alkaline earth and to a certain extent also rare-earth compounds can be used.

When this storage media reaches its capacity, it must be regenerated. This is accomplished in a NO_x regeneration step. Unfortunately, alkaline and alkaline earth compounds have a strong affinity for sulfation. As a consequence, alkaline and alkaline earth compounds are almost irreversibly poisoned by the sulfur contained in the fuel during the NO_x storage operation mode, leading to a decrease in NO_x adsorption efficiency.

The stored NO_x is released by creating a rich atmosphere with injection of small amounts of fuel. The rich running portion is of short duration and can be accomplished in a number of ways, but usually includes some combination of intake air throttling, EGR, late ignition timing and post-combustion fuel injection.

The released NO_x is quickly reduced to N₂ by reaction with CO (the same reaction that occurs in three-way catalysts for spark-ignited engines) on a rhodium catalyst site or another precious metal that is incorporated into this unique single catalyst layer.

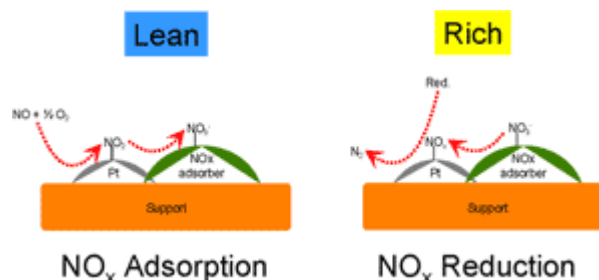


Figure 10: NO_x adsorber system.

Under oxygen rich conditions, the thermal dissociation of the alkaline and alkaline earth sulfates would require temperatures above 1000°C. Such temperatures cannot be achieved under realistic driving conditions. However, it has been demonstrated in various publications (59), (60) and (61) that it is in principle possible to decompose the corresponding alkaline earth sulfate under reducing exhaust gas conditions at elevated temperatures. In this way, the NO_x storage capacity can be restored.

For engines less than 2.0 to 2.5 liters, NO_x adsorbers may be more cost effective than SCR (62). Also, mixed-mode engines with reduced low-load NO_x allow NO_x adsorbers to focus on NO_x emitted at higher temperatures (> 350°C), more than half the precious metals might be removed (63) and (64), which may make them economically attractive for light-duty applications with mixed-mode engines of 5-6 liters. Also improved NO_x adsorber formulations with greatly improved precious metal dispersion, result in less PGM usage for better performance (65).

5.5.3 Lean deNO_x Catalysts

Lean De-NO_x catalysts, also known as hydrocarbon-SCR systems use advanced structural properties in the catalytic coating to create a rich 'microclimate' where hydrocarbons from the exhaust can reduce the nitrogen oxides to nitrogen, while the overall exhaust remains lean. The hydrocarbon may be that occurring in the exhaust gas ('native') or may be added to the exhaust gas through injection of a small amount of additional fuel. This has the advantage that no additional reductant source (i.e. urea) needs to be carried but these systems do not, at present, offer the same performance as ammonia-SCR systems.

A study (66) evaluated the influence of diesel fuel sulfur content on the performance of a passive deNO_x catalyst. The program used two specially prepared fuels with different sulfur contents, but with other fuel parameters unchanged. The NO_x conversion efficiency of the deNO_x catalyst increased from 14 to 26% over the European test cycle when the sulfur content was reduced from 49 to 6 ppm.

Recent developments on HC-SCR using hydrocarbons from the fuel are reported in the literature (67), (68) and a patent (69) specifies very low precious metal loadings (0.7 g/l) but the system needs temperature greater than 300°C to perform well.

A concept is reported (70) to combine an HC-trap and LNT, wherein the zeolite HC-adsorber is applied first on to the honeycomb substrate and the LNT material is placed on top. The HC-adsorber helps reducing cold start HC emissions and adsorbs HC during the lean periods. Upon release during the hotter rich periods, hydrogen and CO are formed to help LNT regeneration.

5.6 Combined PM and NOx Control Technologies

Diesel Particulate Filters combined with Selective Catalytic Reduction show significant reduction in both PM mass and number and NOx (see § 6) Such systems are already in use for some vehicles but are expected to be widely used to meet light-duty Euro 6 and heavy-duty Euro VI emissions requirements. An example of results from such a system is shown in the following section.

6. AECC DEMONSTRATION PROGRAMS

Throughout several test programs run over the last decade, AECC has consistently demonstrated technical feasibility of future and more stringent emissions limits, including durability aspects. Test programs results were published on passenger cars (71), (72), heavy-duty engine (73), (74), (75) and (21), non-road mobile machinery engine (76) and (77), and motorcycles (78) and (79).

7. CONCLUSIONS

Technologies exist for control of CO, HC, NOx, PM and PN, for stoichiometric and lean-burn gasoline engines and diesel engines. They are used and proven in many different applications. Continuous improvement in substrate and coating technologies, as part of an integrated system comprising electronic control and fuel quality, allows meeting more and more stringent combustion engines emissions legislations.

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