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Diesel Engine Emissions and Their Control

AN OVERVIEW

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This review covers recent developments in regulations to limit diesel emissions, engine technology, and remediation of nitrogen oxides (NOx) and particulate matter (PM). The geographical focus of regulatory development is now the European Union (EU), where Euro V and Euro VI regulations for light-duty engines have been finalised for implementation in 2009 and 2014, respectively. The regulations are much more loosely drawn than those for the U.S., but options exist for adapting European vehicles to the U.S. market. Europe is just beginning to address heavy-duty regulations for 2013 and beyond. Engine technology is making very impressive progress, with clean combustion strategies in active development, mainly for U.S. light-duty application. Work with heavy-duty research engines is more focused on traditional approaches, and will provide numerous engine/aftertreatment options for complying with the stringent U.S. 2010 regulations. NOx control is focusing on selective catalytic reduction (SCR) for diverse applications. Zeolite catalysts will be the mainstay of this technology for Japan and the U.S., and perhaps even for some Euro V-compliant applications. The emphases are on low-temperature operation, secondary emissions and system optimisation. Lean NOx traps (LNTs) are effective up to about 60 to 70% deNOx efficiency, and are being considered for light-duty applications. There is growing interest in supplementing LNT performance with integrated SCR, which utilises ammonia generated in the LNT during rich regenerations. Diesel particulate filter (DPF) technology is at a stage of optimisation and cost reduction. Very sophisticated management strategies are being utilised, which open up options for the use of new filter materials and alternative system architectures. Issues with secondary emissions are emerging and are being addressed.

Light-Duty Regulatory Developments

Although regulatory initiatives for diesel tailpipe emissions have already been established for the foreseeable future in Japan and the U.S., the EU is still in the process of finalising the technical details of the light-duty regulations for the next 10 years. Concerning carbon dioxide emissions, the EU and automotive manufacturers came to a voluntary agreement a few years ago. California finalised similar regulations in 2005, which are currently undergoing judicial review.

At the time of writing this review, the European Union had approved the Euro V (2009) and Euro VI (2014) regulations. Figure 1 shows how the control requirements of the new proposed NOx regulations compare with those in the U.S., not taking into account test cycle differences (within the range 10 to 20%). Also shown in Figure 1 are the approximate NOx reductions that would be required in order for Euro V- and Euro VI-compliant vehicles to be sold in the U.S. The requirements of the Japanese 2009 regulations are similar to those of Euro VI.

It is expected that compliance with the Euro V NOx regulations will largely be possible without resort to NOx aftertreatment (1), but significant NOx controls will be needed if Euro V-compliant vehicles are to be saleable in all 50 states of the U.S. It is more likely that Euro VI-compliant vehicles will be developed in 2009/10, leveraging early incentive

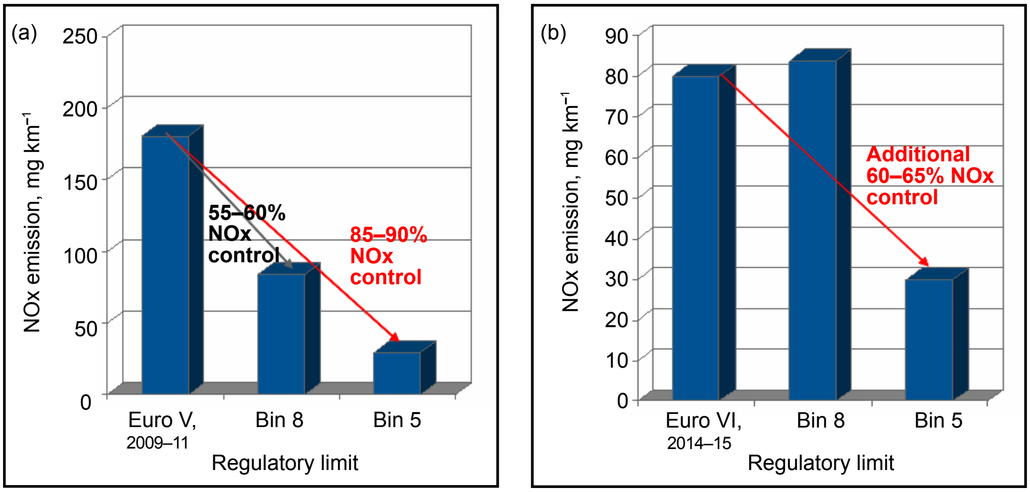

Fig. 1 Euro V and Euro VI light-duty NOx regulatory limits compared to the U.S.: (a) About 55 to 60% NOx control will be needed for a Euro V (2009) diesel to hit the U.S. Bin 8 maximum allowable emission (45 states). For Bin 5 (50 states) nominally 85 to 90% NOx control is needed; (b) For Euro VI (2014), the requirement is 65 to 70% additional NOx reduction

programmes. Some NOx aftertreatment will be required within that timeframe on the larger vehicles. Either LNT or SCR will need to be applied to the lighter vehicles to achieve the 60 to 65% NOx reduction required for sales to all the states in the U.S. Indeed, some European manufacturers have announced the introduction of Bin 5-compliant diesels for the U.S. in this timeframe using these two NOx control technologies.

The European Commission is considering adjusting the PM limit from 5 to 3 mg km^{-1} to reflect a new measurement protocol, and is determining an appropriate number-based PM emission limit (in number of particles per km). The technical protocol for this is being developed and is close to approval. Testing and monitoring of Euro V-compliant vehicles for particulate number is being considered. German manufacturers have agreed to use diesel particulate filters on all cars by 2009.

Figure 2 shows how the European market is faring in terms of carbon dioxide (CO_2) emissions (2). In the light of increasing vehicle size and capacity, and a consumer desire for more power, the targets were missed for the first time in 2005, and the trend does not look favourable. As a result, the European Commission and Council of Ministers are formally considering mandatory CO_2 limit values. California's regulations are mandatory and similar in restriction, but lag behind the European commitment by three to four years.

To meet the CO_2 targets, Thom (2) showed that significant effort will be needed concerning gasoline vehicles heavier than about 1000 kg and on diesel vehicles heavier than about 1500 kg.

Apart from the CO_2 targets, there are market and political pressures on the auto companies to improve fuel economy. The combination of more stringent tailpipe emission regulations and necessary improvements in fuel economy is driving significant technological progress in the industry.

Heavy-Duty Regulatory Developments

On the heavy-duty front, the picture is similar. Japan and the U.S. have finalised their regulations for the next five to ten years, but Europe is just beginning the process. In that regard, the European Commission recently asked key stakeholders to comment on six regulatory scenarios for the Euro VI standard in the timeframe 2012 to 2014, ranging from no or minor tightening from Euro V to full adoption

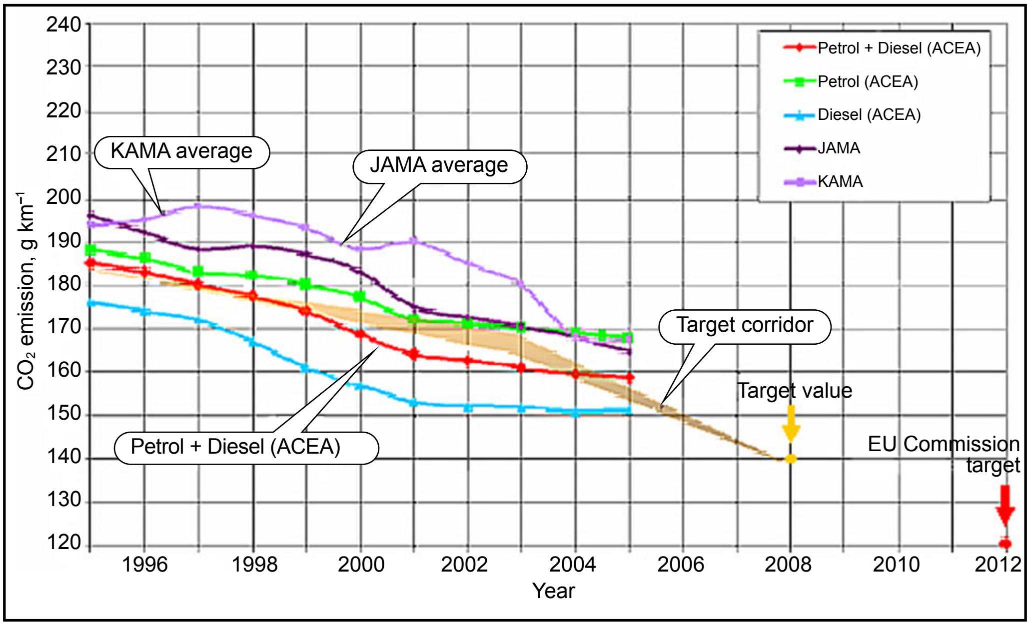

Fig. 2 Progress towards meeting the EU voluntary CO_2 limits (2). ACEA = European Automobile Manufacturers Association; JAMA = Japan Automobile Manufacturers Association; KAMA = Korea Automobile Manufacturers Association (Courtesy of DaimlerChrysler)

of U.S. 2010-type regulations with nominal limits of 0.20 g kWh^{-1} NOx and 0.010 g kWh^{-1} PM. For reference, the U.S. 2010 limits will be at 0.26 g kWh^{-1} NOx and 0.013 g kWh^{-1} PM, and the Japanese 2009 limits are 0.7 g kWh^{-1} NOx and 0.010 g kWh^{-1} PM. However, each has a different transient test cycle from Europe. To help address that disparity, the European Commission adopted a new World Harmonised Transient Cycle (WHTC), one that uses a higher load and speed than the Japanese cycle, but a speed only slightly lower than for the current European Transient Cycle. Also under serious consideration are a number-based particulate standard and a heavier in-use compliance measure. The Commission aims to have a formal proposal ready for the Parliament by early 2008.

Light-Duty Engine Developments

Regulatory, market, and fuel economy requirements are making great demands on diesel engine technology. Further, advanced gasoline concepts and hybrid electric vehicles are exerting competitive technology pressures. Diesel engine developers are responding by using advanced fuel injection technologies, exhaust gas recirculation (EGR) control, advanced and two-stage turbocharging, variable valve actuation, closed-loop combustion control, and advanced model-based control. Advanced diesel engines (3) are now approaching a specific power output of 70 kW l^{-1} and a brake mean effective pressure (BMEP) of 24 bar. Some of these developments are allowing diesel engines to approach Euro VI-compliant engine-out emissions levels (4, 5).

More sophisticated engine technologies could lead to the adoption of economical light-duty diesels in the U.S. The fundamental characteristics of these – the ‘advanced combustion, mixed mode’ engines – are illustrated in Figure 3 (6, 7).

In early injection strategies, much of the fuel charge is mixed with gas before ignition. This helps to avoid the conditions for soot formation. The NOx formation regime is avoided with high levels of EGR that keep the flame cooler.

With late injection strategies, the charge is mixed and simultaneously burned using, for example, high swirl. The combination of good

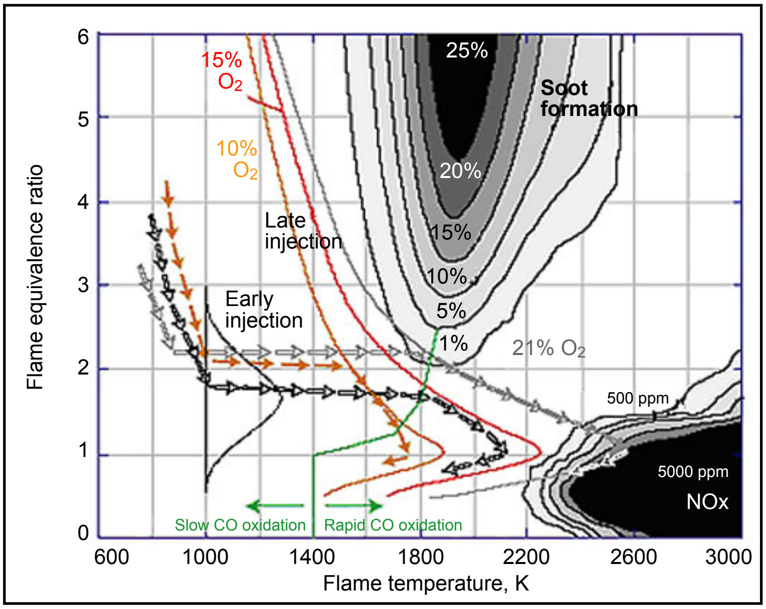

Fig. 3 Principles of advanced combustion (6) (Courtesy of Sandia National Laboratory). Regimes of soot and NOx formation expressed in terms of flame equivalence ratio (fuel:air ratio) and flame temperature. Soot and NOx are inhibited using high exhaust gas recirculation (EGR) levels with either early (highly premixed) fuel injection or late injection. CO oxidation zones from Reference (7)

mixing and high EGR helps the charge avoid soot and NOx formation regimes.

Managing these strategies becomes very difficult as the amount of charge increases. Therefore, they are limited today to the lower-left-hand quadrant of the engine's load-speed characteristic, up to perhaps 30 to 50% load and perhaps 50% speed. Traditional diesel combustion strategies will still be used at higher load, hence the term 'mixed mode'. Low-load advanced combustion operation might be sufficient, as most of the points of the certification test cycle fall within this region. This minimises the amount of NOx aftertreatment that might be required to meet the regulation, and probably results in cost savings. Indeed, some authors are projecting that, for a properly designed vehicle, it might be possible to meet the U.S. 50-state NOx requirements with no NOx aftertreatment by the end of the decade (4). Even so, some NOx treatment will still be used to prevent 'off-cycle' emissions.

Heavy-Duty Engine Developments

Heavy-duty (HD) diesel engine developments are primarily aimed at improved fuel economy, reliability, cost and durability. As such, advances tend to be conservative and incremental. The U.S. 2004 regulations were generally addressed using advanced EGR and turbocharging measures. U.S. 2007 and Japanese 2005 technologies added diesel particulate filters, whereas Euro IV (2005) and now Euro V (2008) regulations are largely addressed by using more conventional engine technologies and SCR.

Moving on to Japanese 2009 and U.S. 2010 requirements, incremental advances on the earlier compliant technologies will be seen. However, as with light-duty engines, advanced combustion strategies may emerge to address low-load emissions issues. Because most of the fuel in heavy-duty applications is spent under higher load regimes, engine researchers are focusing more on traditional diesel combustion hardware and strategies, and they are making significant progress.

Figure 4 summarises results for high-load emissions from research engines (8–12) with respect to the U.S. 2010 Not-to-Exceed (NTE) in-use emissions limits. U.S. NTE is the most difficult standard to meet under high load conditions in many applications. Figure 4 illustrates the range of possibilities for HD engines using 'cutting edge' hardware and control under laboratory conditions. These results are cited as representing the best results that technology

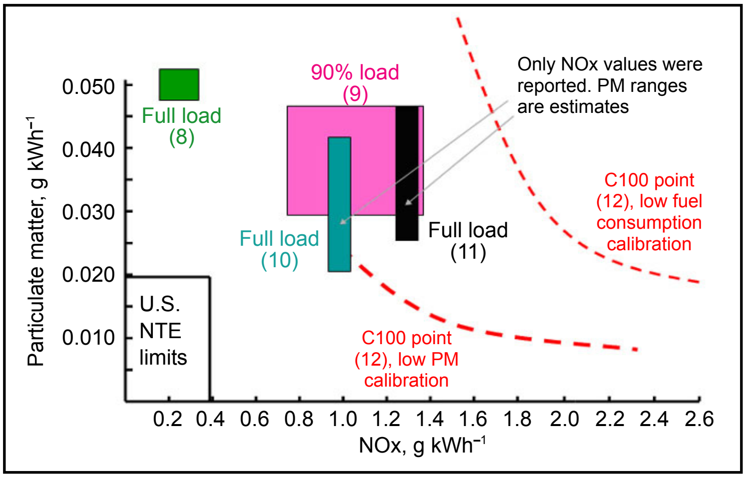

Fig. 4 High load test steady-state test results on heavy-duty research engines relative to the challenging U.S. Not-to-Exceed (NTE) in-use regulatory requirement (8–12)

might deliver in the next five years. With 75 to 80% NOx control from SCR systems under high load conditions, allowable engine-out NOx emissions of 1.6 to 2.0 g kWh^{-1} (without engineering margin) are commensurate with PM emissions at about 0.025 to 0.050 g kWh^{-1}, placing PM NTE requirements well within the capability of filters.

In the U.S., 2007 engines were required to meet NOx NTE limits of about 2.3 g kWh^{-1}. Without improvements, these engines need about 85% NOx control to meet the U.S. 2010 NTE requirements. With 90% efficient filters, meeting NTE PM limits is not a problem. A typical 2007 high load point would be well off the graph in Figure 4. It is reasonable to believe that actual 2010 engines may incorporate nominal 20% incremental improvements in engine-out NOx abatement relative to 2007 technology.

NOx Control Technologies

SCR is emerging as a key NOx control strategy for both light-duty and heavy-duty applications. It was first commercially available in 2005 for European and Japanese HD applications. The high NOx removal efficiency and robust performance of SCR allow fuel sensitive applications to be run at maximum efficiency (high engine-out NOx, low PM).

SCR is expected to be used in many 2010 U.S. HD applications. In addition, several light-duty Tier 2 Bin 5 (50-state) applications have been announced. For successful application of SCR in the U.S., the Environmental Protection Agency (EPA) requires a plentiful, readily available supply of urea, and that vehicle drivers keep urea on board. The key stakeholders in the industry and the EPA developed a framework that is incorporated in EPA guidelines (13).

On the light-duty side, the urea strategy (‘Bluetec II’) proposed by DaimlerChrysler (now Daimler) and licensed to Volkswagen and BMW requires that enough urea be kept on board to allow for filling at lubrication oil changes. This is perhaps up to 28 litres, assuming a 2% consumption rate relative to fuel for an 11,000 mile (17,600 km) range, according to Jackson *et al.* (14). The authors estimate that about half of U.S. drivers would utilise lubrication shops for this service. They also anticipate that 5- to 18-litre bottles of urea will also be available at fuelling stations and retail outlets at a cost of U.S.$5.30 to U.S.$4.30 per litre, respectively.

On the heavy-duty side, a 1% urea consumption rate is expected. A 75-litre tank might last 13,000 to 17,000 miles (21,000 to 27,000 km) for Class 8 and Class 6-7 vehicles respectively. The Class 8 vehicles would need one urea fill between major services (i.e. lubrication oil changes), whereas the smaller classes will not. Approximately 5000 truck stops pump about half the on-road fuel. These vendors would use 3000- to 15,000-litre urea stillages in the early years, until urea demand reaches about 9500 litres per month. After that point, underground tanks become more economic.

European SCR catalysts are based on vanadia, whereas those in Japan are zeolite-based. Given that zeolites have better high-temperature durability, and that the SCR will be receiving very hot gas from the upstream filter system during regenerations, zeolites are expected also to be used in the U.S. As Figure 5 shows, the new zeolite formulations perform better at the extreme temperatures and are less sensitive to non-ideal NO_2/NOx ratios (15).

SCR work is now being directed toward improving low-temperature performance *via* more accurate NO_2/NOx control (a 50% ratio provides the fastest reduction reaction), minimising secondary emissions, and improving on-board urea delivery systems. Given improving catalyst and system performance, low-temperature SCR systems are becoming viable at urea decomposition temperatures. If urea can be thermally decomposed, for example with a bypass heater, system efficiency can be improved from 75 to 95% (16). Slip catalysts are generally thought to remove most of the secondary emissions from SCR systems, such as ammonia, isocyanic acid (originating from incomplete urea decomposition), nitrous oxide and nitrohydrocarbons (17). New slip catalysts are emerging that will convert ammonia all the way to nitrogen, and will probably abate hydrocarbon-based emissions as well (18). On-board urea systems are now largely of the airless type (19, 20). Modelling of the urea-exhaust wall interaction demonstrates enhanced mass and heat transfer for better urea distribution when

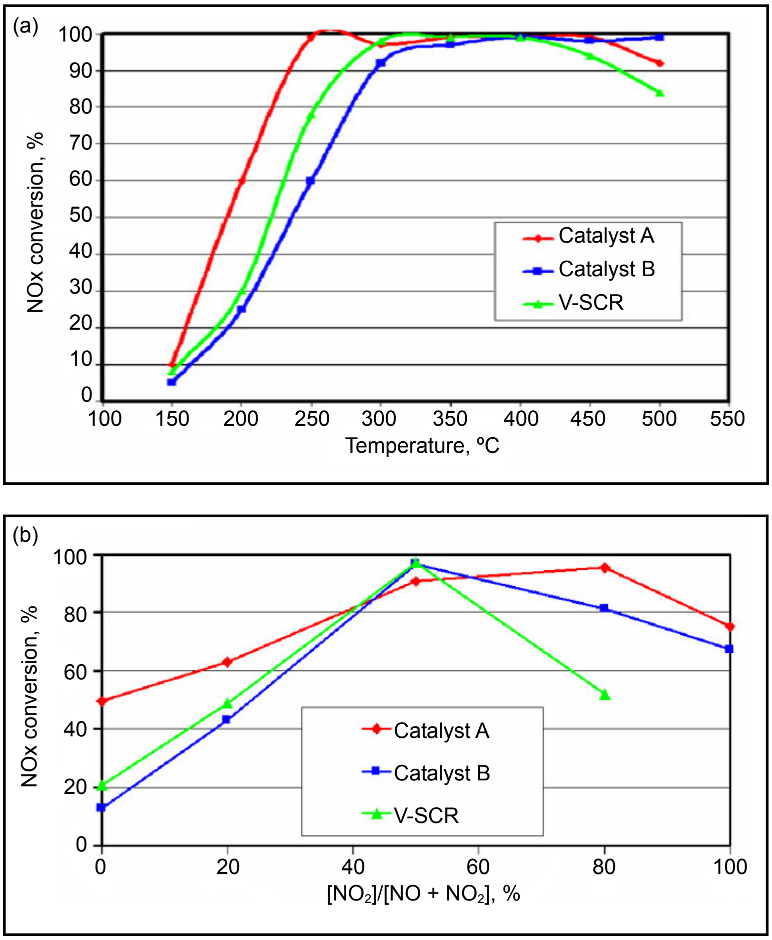

Fig. 5 Performance of zeolite selective catalytic reduction (SCR) catalysts ('Catalyst A' and 'Catalyst B') relative to a standard wash coated vanadia catalyst (V-SCR). Zeolites exhibit:
(a) better low temperature and high temperature performance; and
(b) less sensitivity to NO_2 inlet levels (15)
(Temperature = 200°C)
(Courtesy of Johnson Matthey)

the spray is impinged on the pipe; however, thin films can form if the pipe temperature is less than about 280°C (21). There is also much interest in urea systems affording a higher capacity by employing solid urea or magnesium chloride ($MgCl_2$) as the storage medium. Solid urea lasts more than twice as long as liquid urea for a given volume, but needs to be heated to about 180 to 200°C in the presence of water vapour to decompose to ammonia (22). $MgCl_2$ stores ammonia, and cartridges can readily be handled, replaced, recharged and recycled (23). It also has three times the volume-specific ammonia capacity and half the weight of Adblue®. Theoretically, a 28-litre tank will last 150,000 miles (240,000 km) of testing under the Federal Test Procedure (FTP) when abating the emission from a Bin 8-compliant light-duty engine to a Bin 5 tailpipe limit.

SCR is not always the preferred NOx abatement technology. Some vehicle manufacturers consider that their customers will resist urea-SCR if other options exist. Also, mainly because of the relatively fixed cost of an on-board urea system, small LNTs are cheaper for engines of less than about 2.0 to 2.5 litres capacity (24). Finally, since mixed-mode engines greatly reduce low-load NOx, allowing LNT deployment to focus on NOx entering at temperatures greater than about 300°C, about 70% of the platinum group metals (pgms) might be removed (25). This could make LNT more economically attractive than SCR for cars with engines of up to 5 or 6 litres capacity (24, 26).

The durability of LNTs under sulfur contamination has always been a major problem. The sulfur is removed by passing a rich, hot stream (700°C) for a total of about 10 minutes every 3000 to 6000 miles (5000 to 10,000 km). Although earlier LNTs lost perhaps 50% of their capacity over 15 to 20 desulfation cycles, newer versions now lose only about 25% of the fresh NOx capacity. Further, in the past it was difficult to control desulfation temperature to within 700 to 800°C. Newer control strategies now allow this degree of control (27), and perhaps even better. Given this, LNTs are effective to about 60 to 70% NOx efficiency in 'real-world' light-duty systems (28), as shown in Figure 6. This is sufficient to bring a Euro V-compliant engine to Bin 8 compliance, or a Euro VI-compliant engine to Bin 5 compliance, as shown in Figure 1.

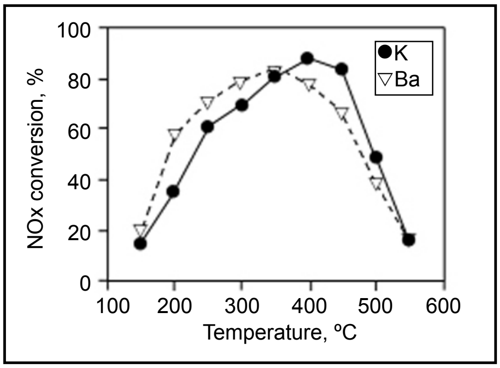

Fig. 6 NOx performance curves for heavily-aged potassium- and barium-based lean NOx traps (LNTs). U.S. Federal Test Procedure (FTP) efficiency is 63%. Swept volume ratio (SVR) = 0.94; 3.9 g l^{-1} pgm loading (28) (Courtesy of SAE and Umicore)

For the medium- and heavy-duty applications, high-temperature LNT formulations are being developed to address the challenge of meeting the difficult high-load requirements of the U.S. NTE regulation (29). As LNTs need a periodically rich stream to regenerate NOx and to desulfate, minimising the amount of rich gas used in the LNT saves fuel and helps control. As such, bypassing most of the lean exhaust past the LNT (29) or into an adjacent LNT system (30) can deliver good NOx reductions at reasonable fuel penalties – 75 to 80% efficiency at full load, at 1.2 to 2.0% fuel penalty, with an LNT sized at 1.4 times the swept volume of the engine (swept volume ratio (SVR)). These results, however, do not reflect deterioration due to significant ageing.

Finally, there has been much recent interest in combining LNTs with SCR. In this case, a downstream SCR catalyst stores ammonia that is generated in the LNT during rich operation. The ammonia can react with slipped rich NOx or lean NOx, increasing system efficiency, or decreasing pgm loading, and hence cost at constant efficiency. A recent variant of this method employs a NOx adsorber/SCR double layer configuration (31). Figure 7 shows the concept. The system exhibits excellent low-temperature NOx conversion in the 200°C range, but poor high-temperature conversion over 350°C. Another feature is that desulfation occurs at 500°C, as compared with 700 to 750°C for conventional LNT systems.

Particulate Matter Control Technologies

Platinum-based diesel particulate filters (DPFs) are now as integral to the diesel engine as fuel injectors. Within a couple of years, virtually all new diesel cars in Europe, the U.S. and Japan will deploy DPFs. They have a high penetration in new Japanese trucks, and all new U.S. truck engines have used them since January 2007.

Peugeot opened up this field with the announcement of their system in April 1999, and a subsequent literature report (32). The system comprised a flexible common rail fuel injection system, enabling late or post injections of hydrocarbons into a platinum-based diesel oxidation catalyst (DOC) for burning to start DPF regeneration, a cerium-based fuel-borne catalyst (FBC) to help burn the soot, and an uncatalysed silicon carbide (SiC) DPF. In subsequent development, other automotive manufacturers chose to catalyse the filter instead of using FBC, and in the latest variant the DOC function is incorporated into the filter (33). For medium-duty applications, approaches are similar to those for light duty, but for the larger engines in the U.S., auxiliary injectors or burners are deployed in the exhaust to impart DPF regeneration. Concerns in this regard are oil dilution by fuel from late injections, and the desire to decouple DPF injection events from engine management requirements.

DPF management is becoming quite sophisticated. A platinum-catalysed filter system will 'passively' regenerate from the reaction of NO_2 with carbon under medium- and high-load conditions (34). Passive regeneration is limited by temperature and by NOx:C ratios. Successful long-term passive operation of filter systems (35) has been achieved with exhaust gas temperature profiles of 40% > 210°C and NOx:soot ratios less than 15. In extended operating conditions under which passive regeneration is not enough to keep the filter clean, 'active' regeneration is needed. Zink *et al.* (36) reviewed the approaches in the European light-duty sector, and identified common features:

- Estimation of DPF soot loading using engine and back pressure models, and fuel consumption;
- Preheating the system to ensure that injected

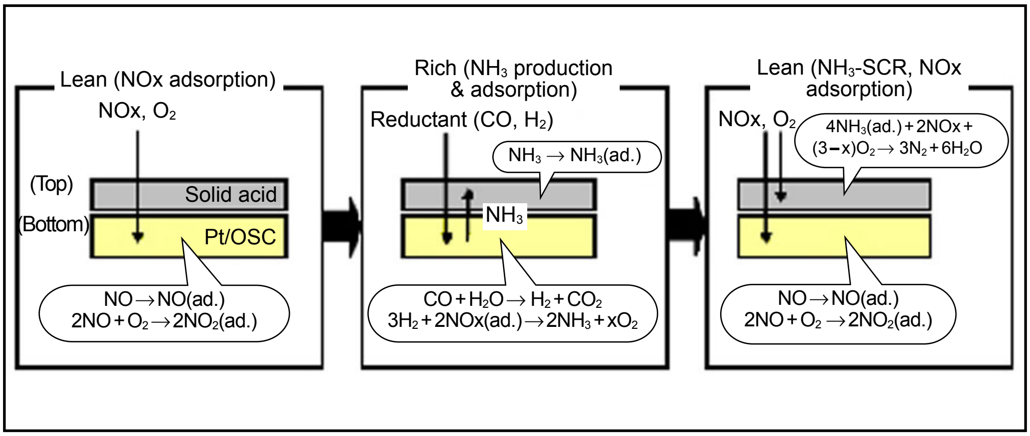

Fig. 7 In the NOx adsorber/selective catalytic reduction (SCR) combination double layer system, lean NOx is adsorbed on a ceria material. During rich operation some of the NOx is converted to ammonia which is stored and used during lean operation on an upper platinum SCR catalyst (31) (Courtesy of ika and VKA Aachen Kolloquium; and Honda); OSC = oxygen storage capacity; ad. = adsorbed

hydrocarbons can ignite and heat up the filter;

- Increase of exhaust hydrocarbon levels *via* in-cylinder or supplemental fuel injection, for burning on a catalyst;
- Control and monitoring of the regeneration as a function of operating point and conditions;
- Recalculation of pertinent models to take account of ash build-up.

Soot loading models have been in development for many years. Although contemporary pressure-drop models take account of filter and catalyst architecture, ash loading, PM characteristics, and completeness and nature of regeneration, they still generally serve as supplementary algorithms to soot loading determinations based on engine operating conditions.

If active regeneration is required, a catalyst temperature in the range of 220 to 250°C is necessary to burn injected hydrocarbons, sometimes calling for active system heat-up strategies. Common approaches are air intake and/or exhaust throttling, as well as appropriate late injection of fuel (37). These measures enable heat-up at ambient temperatures of –10°C with, in a medium-duty vehicle application, an average speed of 14 km h^{-1}. The use of increased electrical loads on the engine has also been described (38).

Once hot, fuel injection strategies will depend on operating conditions (34, 38); see Figure 8. To prevent lubricating oil ash from sintering to itself, and to protect the DPF catalyst, soot burning exotherms need to be controlled within suitable maxima. Some parameters required for achieving this are filter thermal mass and catalyst loading, exhaust temperature and flow rate, and soot loading and characteristics. Craig *et al.* (39) provide an excellent example of how, under worst-case 'drop-to-idle' (DTI) conditions (start soot combustion at high temperature and flow, and then drop to idle), maximum exothermic temperatures vary with soot load, and gas temperature and flow rate using cordierite filters. Karkkainen *et al.* (40) show how this information can be incorporated into a safe regeneration strategy, in which exhaust temperature is gradually increased from 550 to 600°C as soot burns, and if the engine drops to idle, engine speed is increased to remove heat from the filter. Additionally, managing oxygen through EGR control is being proposed (1).

An example of the level of sophistication of DPF soot loading models is offered by Muramatsu *et al.* (41). They found that the primary soot combustion characteristics, namely ignition temperature and oxidation rate, depend on how the soot was generated. They quantified these parameters and incorporated them into their control and monitoring model, part of which is illustrated in Figure 9.

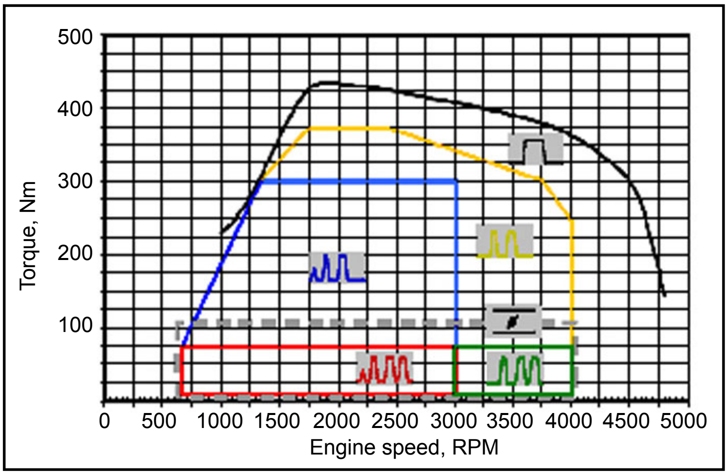

Fig. 8 Different fuel injection and throttling strategies are used to initiate and control diesel particulate filter (DPF) regeneration (38) (The inset boxes show the general fuel injection pattern (fuel quantity as a function of crank angle.) The colours represent the regimes on the engine map where these injection patterns are operative. The dotted lined box represents the operating regime within which intake throttling is used to increase exhaust temperature.)

Advances in material science are likewise facilitating developments in filter materials. For light-duty applications, SiC filters have been the standard. However, aluminium titanate (AT) (33) filters are now in series production, and, aided by better engine controls, the industry is beginning to move to the deployment of advanced cordierite (42) filters. Cordierite is the preferred filter material for heavy-duty applications.

The properties of the new AT filters are impressive in comparison with SiC materials. The low thermal expansion and high strength of AT mean that filter integrity is maintained without pasting smaller segments together to relieve thermal shock in a larger filter. No cracks in the filter material were observed even after a long run of severe regeneration cycles (with exotherms to 1150°C) (33). Further, tight control of pore size reduces back pressure for catalysed AT filters with soot, as shown in Figure 10.

Filter designers are also using cell geometry

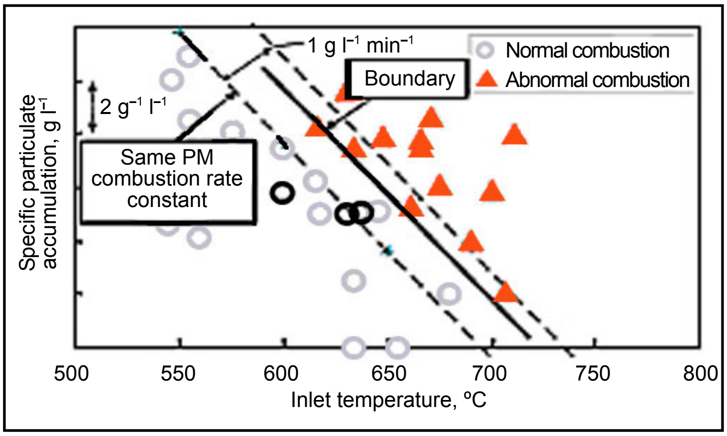

Fig. 9 Relationship between filter soot load and exhaust temperature to impart a normal regeneration event. The boundary changes depend on soot characteristics (41) (Courtesy of SAE)

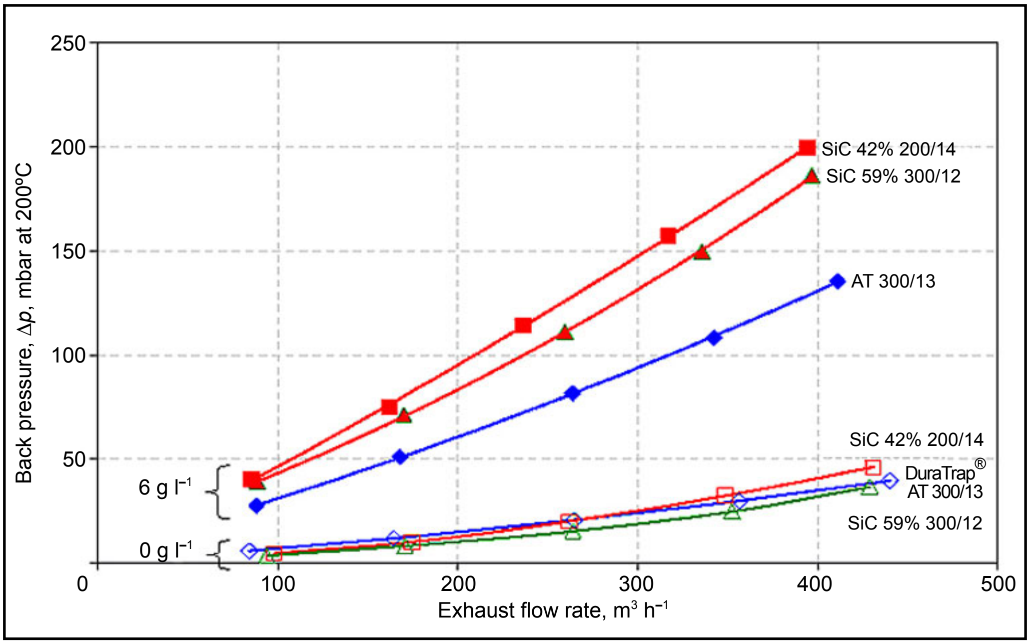

Fig. 10 Soot-loaded catalysed advanced aluminium titanate (AT) filters have 30% lower back pressure than comparable SiC filters (33) (Courtesy of Technical University Dresden and Volkswagen AG)

creatively to increase ash storage capacity. By increasing the size of the inlet cell relative to that of the exit cell, ash loading can increase by 50% while maintaining the same back pressure for soot-loaded filters; this is illustrated in Figure 11 (43).

Filter catalyst technology is advancing impressively. Recent reports show that pgm loadings may be reduced and performance improved if the DOC function is incorporated into the filter *via* new coating methods. Filter regeneration is more complete as compared with systems with a separate DOC or FBC (44). In addition, hydrocarbon and CO reductions are comparable to those with DOC systems, and NO_2 emissions are reduced (45).

As filter technology evolves and expands, more attention is being paid to secondary emissions. In some European cities, ambient NO_2 levels are increasing despite reduced or constant total NOx levels. Much of this increase is attributable to the large numbers of light-duty diesels that utilise DOCs (46), but some evidence suggests that catalysed filter systems are also contributors (47). Indeed, by 2009 California will require that diesel retrofit systems emit no more than 25% of the NOx as NO_2. In that regard, Goersmann *et al.* (48) demonstrated a new system (Figure 12) that abates more than 95% of the NO_2 emissions coming from catalysed DPFs.

Aerosol nanoparticles are another form of secondary emission under discussion. Epidemiological studies have correlated adverse health effects to particulate mass, and some physiological evidence suggests that solid ultrafines can cause biological effects. In this regard, filter systems remove over 90% of PM mass and over 99.9% of carbon and other solid ultrafine particles. Some operating conditions (mainly high load and/or low ambient temperature) may increase the emission of aerosol nanoparticles in the < 30 nm size range from catalysed filter systems (49). Although the nanoparticles are almost all sulfates, the use of ultra-low sulfur fuel and low sulfur lubricating oil has only a minimal effect. However, when a sulfur trap is applied after the catalysed DPF system (50), the concentration of aerosol ultrafine particles drops below ambient levels (49). Figure 13 shows some results.

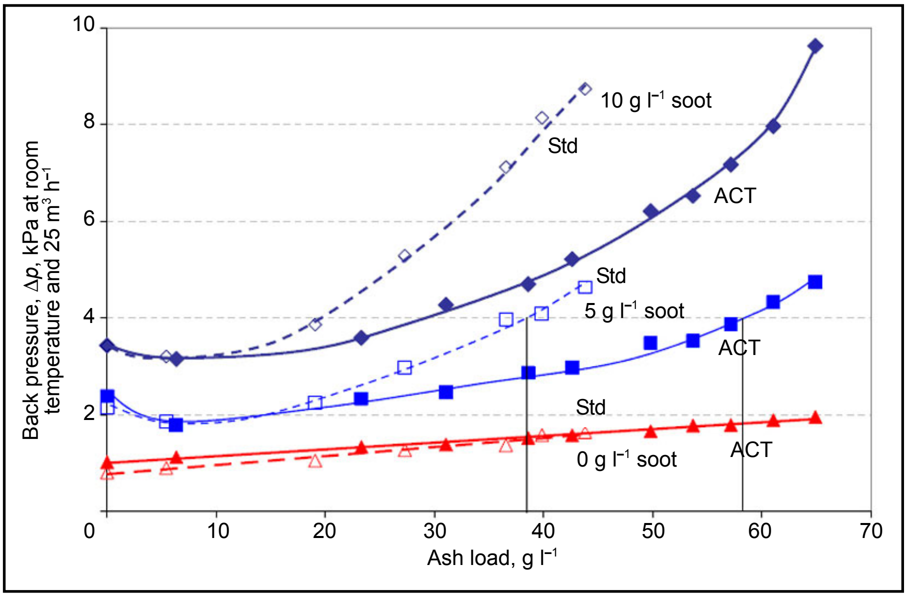

Fig. 11 Asymmetric cell technology (ACT), wherein inlet diesel particulate filter (DPF) cells are larger than exit cells, can give 50% more ash capacity while maintaining back pressure (43) (Courtesy of ika and VKA Aachen Kolloquium; and Corning Incorporated)

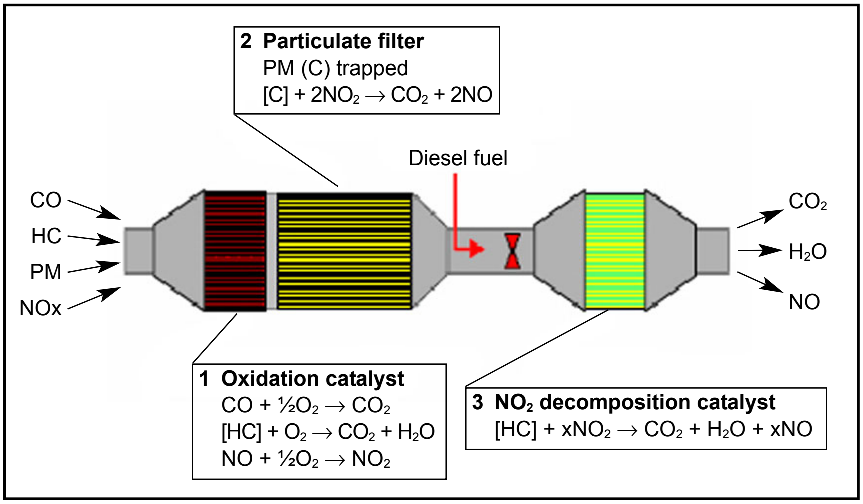

Fig. 12 A new NO_2 remediation system reduces 95% of the NO_2 emissions from catalysed filter systems (48) (Courtesy of Technical University Dresden and Johnson Matthey)

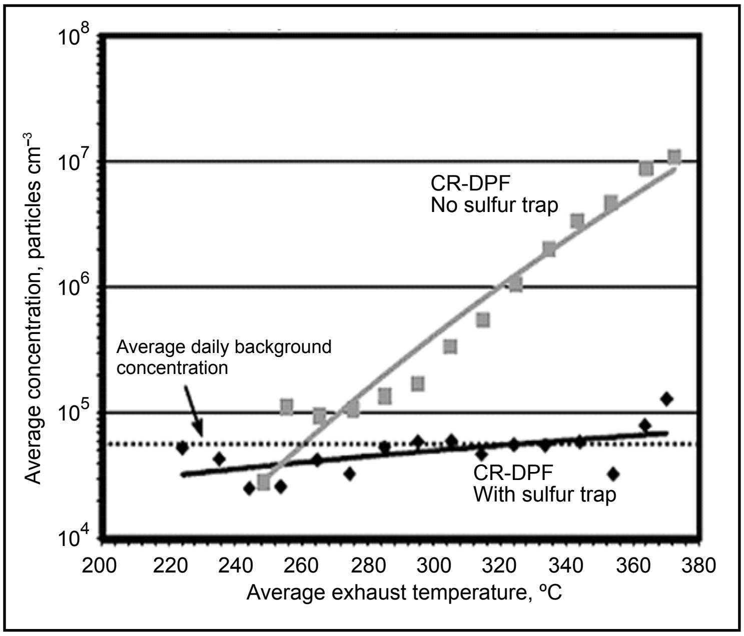

Fig. 13 Sulfur-based aerosol ultrafine particulates can be generated in catalysed filter systems. Sulfur traps reduce these emissions to below ambient levels (49). (CR-DPF = continuously regenerating diesel particulate filter) (Courtesy of SAE and University of Minnesota)

Integrated NOx/Particulate Matter Systems

The first integrated NOx and PM systems are expected to enter service in 2008 in the U.S. light-duty market and in 2009 in the Japanese heavy-duty market, formally three months ahead of the U.S. 2010 heavy-duty market.

It is greatly preferable to position the NOx system after the filter system to allow as much passive NO_2-based regeneration of the filter as possible. Using only active regenerations for the filter can result in a net fuel penalty of up to 3%, depending on the drive cycle. However, for chassis-certified light-duty applications, fast light-off of the NOx system is critical, so locating the NOx system in front is being considered for those applications (51). For most heavy-duty applications, in which passive filter regenerations dominate and low fuel consumption is critical, NOx systems are located behind the filter.

Management of integrated NOx/PM systems presents a unique set of challenges and synergies. For LNT-based systems, there are synergies, such as coordinating desulfation with active DPF regenerations, and utilising the periodic rich LNT regenerations to burn soot on catalysed DPFs that contain oxygen storage washcoats. For both SCR and LNT systems, the upstream DPF may provide NO_2 to facilitate the deNOx reactions. On the liability side, active DPF regeneration could send hot gas into the NOx system, raising durability concerns. Also, management of the fuel injection for DPF or LNT management and urea injection steps is more difficult.

Moving into the future, we expect to see innovative component and system integration, with plenty of choice between engine, DOC, filter and deNOx options.

Recommendations for Future Work

As the automotive industry progresses with advanced combustion mixed-mode engines, especially in the light-duty sector, cold-start hydrocarbon and CO emissions in advanced mode, and/or NOx emissions in traditional combustion mode will become critical. Light-off should be at temperatures lower than 175°C. Further development is needed in the LNT and SCR systems, especially on the mechanisms of ammonia formation on LNT materials when run in the rich mode. Zeolite SCR catalysts also need improvement to their performance in the low-temperature regimes, and better models are needed to understand ammonia storage dynamics. Low-temperature (< 200°C) urea decomposition is a limiting factor for many systems, and advanced hydrolysis catalysts might help here. Lean NOx catalysts, using fuel instead of ammonia for the SCR reaction, show promise for providing effective, low-cost NOx reduction. Much more work is needed on these catalyst systems.

For PM control, limiting NO_2 emissions is critical; here mathematical modelling, better catalysts and improved management methods are all needed. A better understanding of the catalyst-support-soot-gas interaction might lead to more effective DPF catalysts.

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