Lean, mean and green

Patrick Swan on emissions legislation and diesel engines

Competitive pressure has traditionally driven engine development; however the direction this development now takes is controlled by exhaust emissions legislation aimed at reducing health concerns and climate change.

Although tailpipe emissions and their consequences are equally present in Europe and the USA, the 'not invented here' syndrome has ensured that legislation evolved independently on each side of the Atlantic.

The major controlled emissions are particulate matter (PM) and nitrogen oxides (NOx), and there is a direct link between the two: an engine can be optimised for either at the expense of the other, but not for both. The development choice taken by the engine builder then dictates the hardware, control systems and engine after treatment required.

US Federal Tier II and Euro 4 legislation, which take effect in 2004 and 2006 respectively, both require engine after treatment to meet the standards. Most US engine builders have opted to use exhaust gas recirculation (EGR) to meet this new standard while most European engine builders will use selective catalytic reduction (SCR).

South Africa will introduce diesel with a sulphur content of 0.05% in January 2006 to enable engine builders to meet the Euro II emissions standards, which will be implemented at the same time.

Competitive pressure has always been the driving factor for engine development, emphasis being on greater economy, either in fuel consumption or owning and operating costs. Emissions legislation has changed all that.

Diesel Engine Emissions

All engines burning petrol or diesel emit carbon dioxide and water vapour as the bulk of their tailpipe emissions. Relatively minor components of a diesel engine's exhaust emissions, which are controlled, include the following:

NOx Oxides of Nitrogen

This is the major cause of brown haze, usually visible over

FIGURE 1

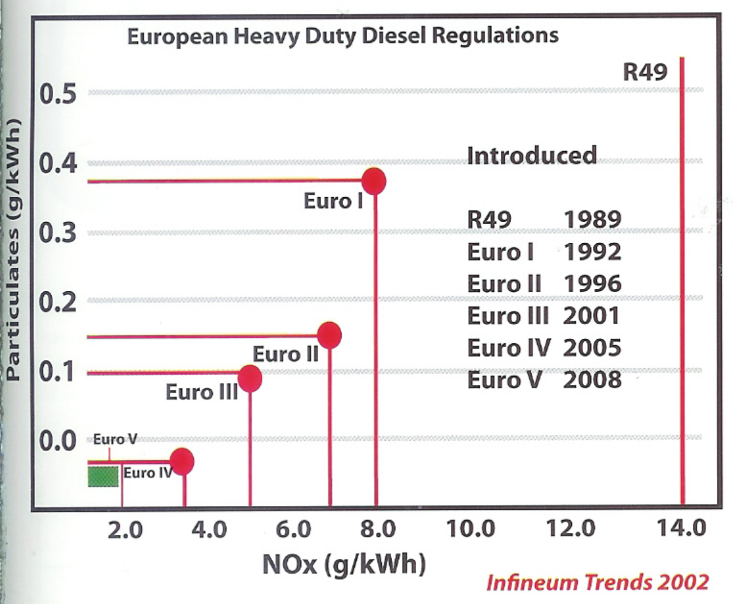
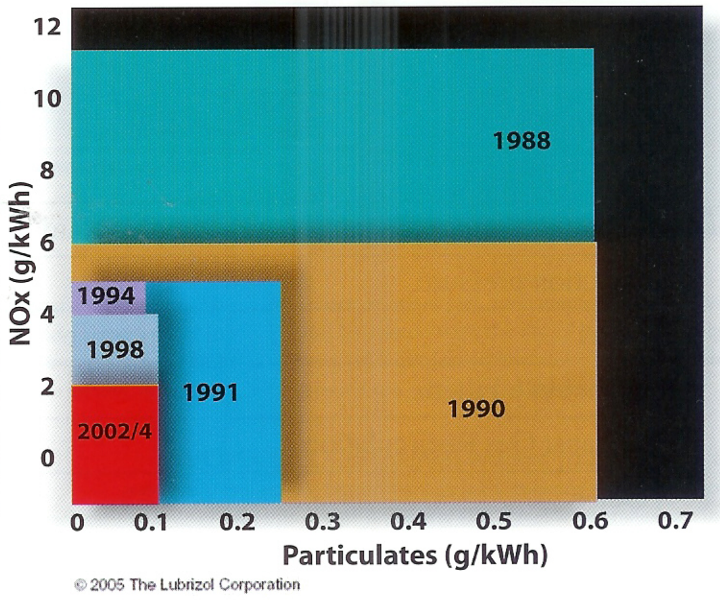


FIGURE 2



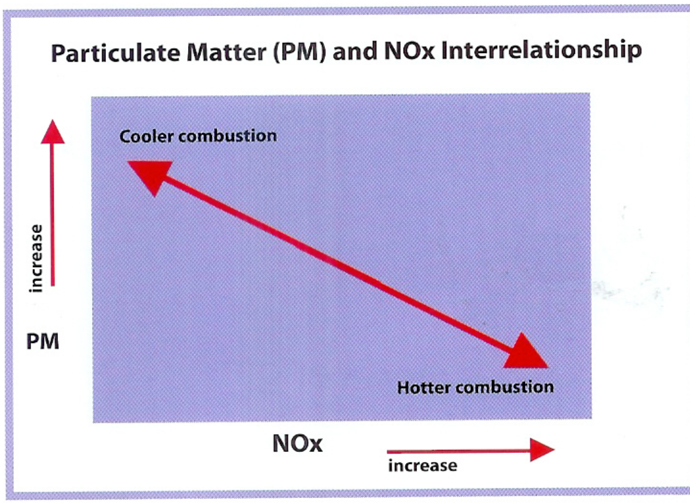


FIGURE 3

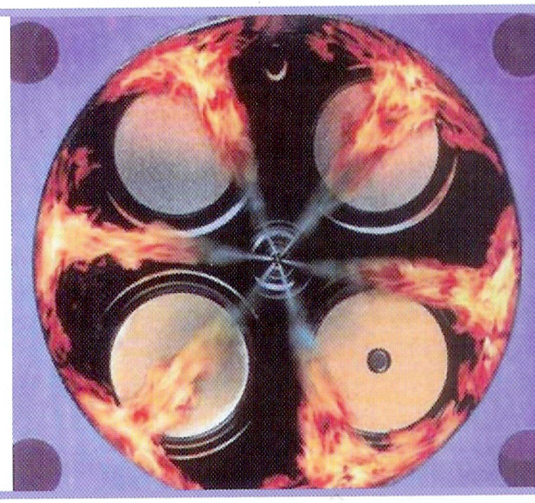


FIGURE 4

large cities, but today to a great extent absent over European cities. It is also a precursor for ozone depletion, and thus enlarges the hole in the ozone layer, allowing more UV rays to enter our atmosphere. Under normal temperatures oxygen and nitrogen do not react together, but under increasing temperature and pressures will eventually react together. The rate of NOx formation is temperature dependant: higher temperatures produce more NOx.

SOx Oxides of Sulphur

SOx in the atmosphere react with water vapour to form sulphur acids, commonly called acid rain, which has killed a significant portion of Europe's forests over the past few decades. Sulphur in both the fuel and crankcase lubricant burn in the combustion chamber to form SOx, however lubricant based sulphur has a minor effect on engine SOx emissions. Most exhaust catalytic converter systems are also poisoned by SOx in the exhaust stream.

M Particulate Matter

These are minute particles of carbon rich, partly burned fuel; the usual size range of 0.1 to 0.5 microns is well below what is considered to be the normal respirable limit of 2.5 microns (1). PM is the leading cause of pollution related mortality. The US Environmental Protection Agency and Harvard School of Public Health found in a study that 50 000 to 60 000 deaths per annum are caused by particle pollution, and that no other form of pollution causes as many deaths (2). Further, the World Health Organisation has concluded that diesel PM is a probable human carcinogen (3).

HC Unburned Hydrocarbon remnants

These are often attached to the PM.

CO Carbon Monoxide

TABLE 1

Technology	Euro 1	Euro 2	Euro 3	Euro 4
Fuel Sulphur	0.3%	0.3%	0.035%	0.005%
Injection timing	Slight retard	Retard	0 to -2°	+8°
Injection pressure	Increase	1600 bar	2050 bar	2400 bar
Swirl	Optimise	Optimise	Optimise	Optimise
Particulate Filters		x	x	x
Exhaust Gas Recirculation		x	x	x
Other				SCR[1]

Diesel engines always have an excess of air, however CO is formed in localised pockets rich in fuel, during the combustion process,

Although tailpipe emissions and brown haze were equally present on both sides of the Atlantic, national arrogance ensured that emissions legislation evolved independently in Europe and the USA, which favoured the development of separate engine technology. Figures 1 and 2 show the emissions standards established for Europe and the USA respectively.

Interrelation between emissions components

Since all tailpipe emissions come from the combustion chamber there is a great synergistic interdependence between the fuel, fuel injection system and chamber geometry, and between the emitted components. The major controlled emitted components are PM and NOx; their interdependence is shown in figure 3. Essentially hotter combustion is more complete but produces NOx, while cooler combustion produces PM while limiting NOx.

Engines can be optimised for either minimum NOx or for minimum PM mission, but not both. Whichever approach is chosen determines the hardware, management system, and mapping of the management system.

Raw fuel is atomised by the injector into the combustion chamber, as seen in figure 4, which contains only hot compressed air. This raw fuel must then mix with the air, vaporise and auto-ignite before combustion. To reduce PM therefore requires that the mixture of air and fuel is as homogenous as possible. PM is also influenced by the fuel's ignition and burning qualities. Increasing the injection pressure and number of nozzle holes improves fuel distribution, while creating swirl in the combustion chamber adds energy to mixing of the air and fuel. PM and HC are reduced by ensuring complete fuel combustion at the hottest practical temperature. CO is reduced by eliminating pockets in the combustion chamber rich in fuel; that is by ensuring a homogenous mixture of air and fuel.

NOx is controlled by reducing the combustion temperature; this is achieved by retarding the injection timing, at the expense of fuel economy. It 4 harmed by SOx, which is why most engine manufacturers lobby for low sulphur diesel. Further, removing fuel sulphur has a major effect on PM reduction: a reduction in sulphur from 0.4% to 0.05% resulted in a 36% decrease in PM emissions (4). Fuel sulphur is reduced at the refinery by reacting the fuel with hydrogen, which also reduces the

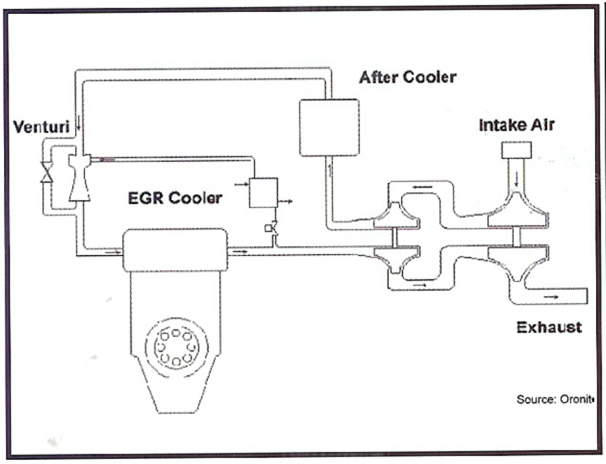


FIGURE 5

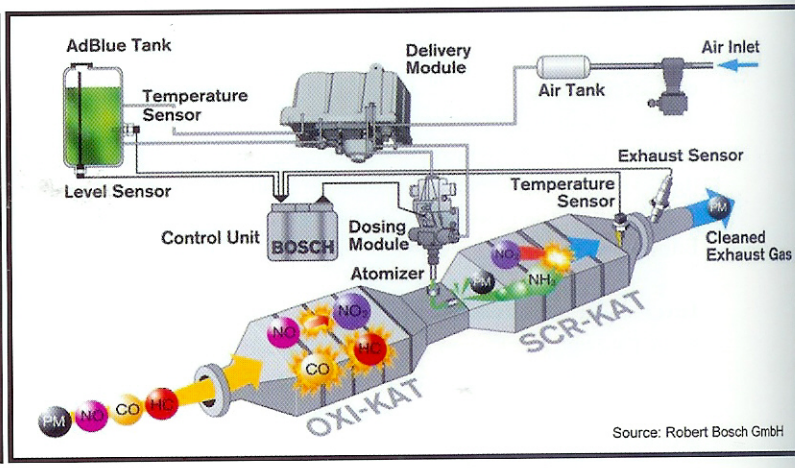


FIGURE 6

polyaromatic content of the fuel; a reduction from 30% to 10% resulted in an additional decrease in PM of 16% (4).

Emissions Standards

Lower level standards can be met simply by controlling fuel quality, specifically fuel sulphur, and combustion **chamber conditions through:**

- Higher injection pressure
- Increasing the number of injector holes
- Increasing combustion chamber swirl, both by piston crown design and induced swirl by using four valves with stepped timing and air flow paths
- Computer control of the injection cycle
- Retarding injection timing during transient and high load periods

Technologies used to achieve the emissions targets are shown in table 1.

Higher level standards, and particularly implementation of the US 2004 and Euro 4 specifications in 2005, create a major new challege to engine manufacturers: the need to reduce NOx. This emissions level has spit the manufacturers and continents like no previous requirement. The US has opted for EGR technology while most European manufacturers have embraced SCR. All manufacturers will use particulate filters.

Retarded injection timing

While PM can be controlled by using low sulphur diesel and the latest injection system technology, with computer control throughout the combustion cycle, NOx formation has been controlled by reducing combustion temperature, by retarding injection timing. In some cases timing only starts after top dead centre (TDC), and fuel is then atomised onto a receding piston, resulting in an excess of burning fuel at the end of the combustion cycle, which produces excessive soot. Retarded timing has a negative effect on fuel consumption, which is increased by as much as 8%. At the same time the excess soot produced by late combustion is captured by the crankcase lubricant, thus accelerating oil thickening and potentially reducing drain periods.

Euro 4 and US 2004 (Federal Tier II Legislation)

Retarded fuel injection timing has become the accepted means to restrict NOx emissions, which occurs at the expense of greater fuel consumption. Both Euro 4 and the US 2004 emissions legislation restrict NOx to levels which would unacceptable compromise fuel consumption, and thus open the doors for new technology.

The new technologies are either Exhaust Gas Re-Circulation (EGR) or Selective Catalytic Reduction (SCR). Both control NOx production and allow a more optimum injection timing, that is about 8O before TDC. Optimised injection timing reduces fuel consumption by up to 8% over previous generation engines which used retarded timing to control NOx. This saving is significant.

EGR

EGR cools and recycles a portion of the exhaust gas back into the combustion

chamber, as seen in figure 5, which cools and slows the combustion process because the major components are water and carbon dioxide which absorb energy from the combustion process. Both water and carbon dioxide have higher specific heats than air.

The effects of EGR are:

- Recirculated exhaust gas is generally below the dew point of

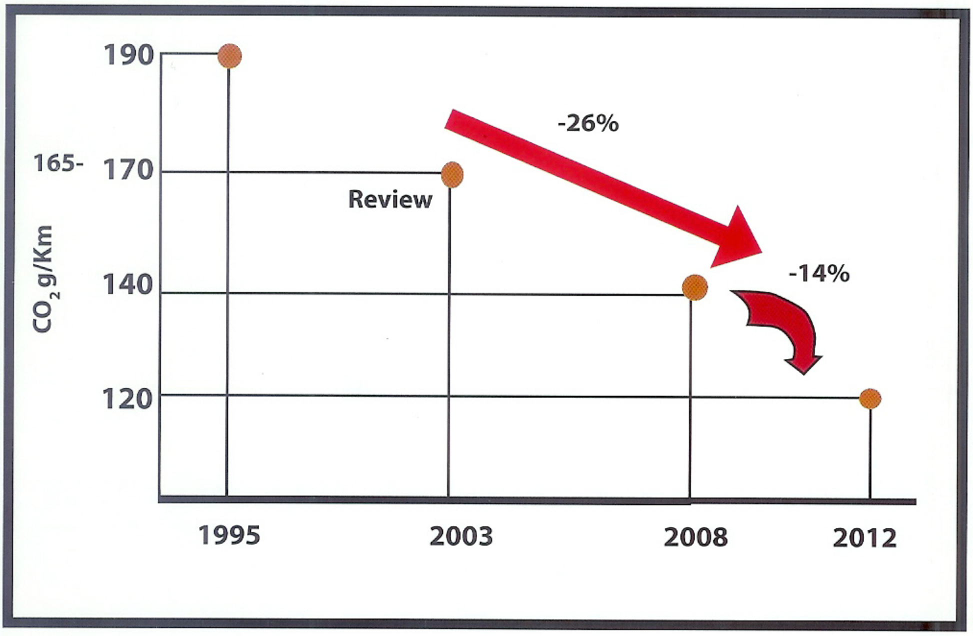


FIGURE 7

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water, thus NOx and SOx in the exhaust gas form strong nitrogen and sulphur acids, the worst being sulphuric and nitric

- Combustion chamber soot is recycled
- Crankcase lubricant life may be compromised relative to alternate technology
- Combustion chamber soot is softer than with alternate technologies (5)
- Engine cooling must be increased by as much as 30% (6)

SCR

The exhaust gas is treated with urea, as shown in figure 6, which reacts with NOx to form nitrogen and water vapour, which are harmless emissions. Using SRC the engine can be mapped for optimum efficiency, and the NOx produced is reduced in the exhaust by the SCR system.

The effects of SCR are:

- The vehicle must be equipped with a urea tank and injection and control system
- The cost of urea, in Europe, is set at about 90% of the cost of diesel
- Urea consumption is estimated at 0.5 l/100km
- Fuel consumption is about 5-6% lower than engines meeting the same emissions standards but using EGR (6, 7) .

South African Emissions Standards

South Africa will introduce the Euro 2 emissions standard from 1 January 2006. At the same time the new diesel specification of 0.05% (500 ppm) maximum sulphur will be introduced. Because the engine technology to achieve Euro 2 standards is well established, to meet Euro 2 with 0.05% sulphur fuel does not appear to be a major issue.

The major green house gas is carbon dioxide, which is also the major exhaust component from any engine. As a signatory to the Kyoto Protocol limiting greenhouse gases, South Africa will have to meet future limits in fuel consumption to control carbon dioxide emissions.

Figure 7 shows the carbon dioxide goals set for Europe.

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