Diesel Deadlines

With only three years before diesel engine manufacturers are required to meet new emissions standards, engineers are using innovative technologies to expedite efficient solutions.

By Charles T. Hare and Magdi K. Khair

The October 1998 consent decree involving the major heavy-duty diesel engine manufacturers, the Environmental Protection Agency (EPA), and the U.S. Department of Justice has forced an accelerated timeline to achieve the tightest emission goals in history for on-road diesel vehicles.

As recently as early 1998, diesel engine companies producing for the U.S. market were carrying out the long-term research needed to meet new emissions requirements that were anticipated for the 2004 model year, some five years away. Overnight, however, long-term research became short-term development as the decree called for the new standards to become effective in 2002 — a brief three years over the horizon.* Meeting these standards will only be possible with a concerted effort to finalize some of the diesel emissions reduction technology currently under development.

The diesel engine is the most efficient of the internal combustion powerplants. Highway trucks, urban buses, and industrial equipment are powered almost exclusively by diesel engines. However, heavy-duty diesel emissions have been increasingly identified as a major source of smog and acid rain precursors in the northeastern United States and in California. Estimates of the contribution of on-highway diesel engines to total oxides of nitrogen (NO_x) emissions nationally range from 12 to 18 percent. The EPA indicates that this fraction is increasing as commercial traffic activity rises and emissions attributable to other sources, such as passenger cars, decline. As for particulate matter (PM), highway diesels are estimated to contribute between 20 and 30 percent of the national loading. Diesel trucks and buses make up four to five percent of all vehicles on the road, but they are estimated to account for up to 40 percent of all vehicle miles

** The 1998 consent decree stipulates that, by the year 2002, heavy-duty diesel engines can emit no more than 2.5 grams of oxides of nitrogen (NO_x) + hydrocarbons (HC) and 0.10 grams of particulate matter (PM) per horsepower hour (g/hp-hr).*

Staff Engineer Magdi Khair (left) and Director Charles Hare utilize equipment for the control and monitoring of diesel engine test cell operation in their investigations within the SwRI Emissions Research Department. Khair specializes in reducing emissions from diesels using engine controls and aftertreatment concepts. He also provides an educational seminar on diesel engine technology through the Society of Automotive Engineers. Hare oversees a broad range of emissions research and development programs covering engines used in all types of mobile equipment, from lawnmowers to locomotives.

traveled, and operate at comparatively high power levels, proportional to the heavy loads they transport.

The Emissions Research Department at Southwest Research Institute (SwRI) has developed long-standing technical relationships with the diesel manufacturers affected by the EPA consent decree, either through dedicated project work or through a number of cooperative industry research projects (see related discussion, page 16). In the effort to control and reduce diesel emissions, Institute staff have contributed to engine design and development, tuning of emission control systems, quality audits, emissions certification, development and comparative study of testing methods, lubricant evaluation and qualification, and research into the effects of fuels on engine performance. As a result of the accelerated schedule for lower diesel emission standards, the Institute's work has taken on an increased sense of urgency.

In diesel engines such as those used in trucks and buses, only NO_x and PM emissions (among the criteria pollutants) are considered problematic. The levels of carbon monoxide (CO) and nonmethane hydrocarbons (NMHC) these engines produce are not thought to be major contributors to national air pollution levels. The inclusion of HC emissions in the combined NMHC + NO_x standards for the industry only serves to place a cap on such emissions, to ensure that HC levels would not markedly increase as a result of any new technologies that might be implemented. Emissions of the greenhouse gas carbon dioxide (CO_2) are somewhat lower from diesels than from most spark-ignited engines — perhaps by as much as 20 percent for equivalent power output.

Achieving the mandated EPA requirements within this abbreviated time frame will require combining technical solutions. No single technology may be capable of achieving the desired goals. A combination of fuel improvement, enhancements of in-engine performance, and exhaust aftertreatment will probably be necessary.

Traditional solutions under investigation

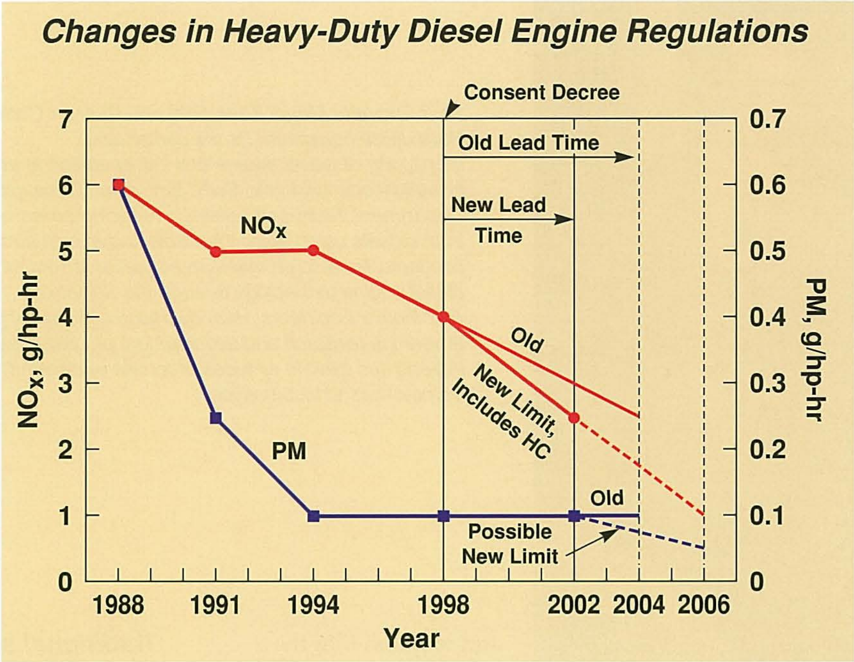
Fortunately, the Institute already has considerable experience with many of these technologies and their effectiveness in reducing emissions. A grouping of past and present research projects includes design changes to the engine itself, combined with improvements in the characteristics of the fuel and lubricants now in use. Researchers can, for example:

Improve fuel injection systems, including the placement, hole size, and design of the injector, as well as the timing and rate shaping of injection and metering, aided by electronic controls. These techniques promote fuel/air mixing, control the rate of combustion and pressure rise, decrease noise, and reduce the "white smoke" emitted by cold engines at startup.

Redesign the combustion chamber and combine it with an improved intake port design to allow better air flow and fuel mixing, and to provide more complete combustion. More complete combustion reduces HC and CO emissions and improves engine efficiency.

Augment air boost and motion, and control charge air temperature together with better fuel/air mixture preparation to reduce black smoke or "soot," as well as CO and the total mass of PM emissions.

Manipulate fuel characteristics, such as sulfur content, viscosity, lubricity, and molecular structure, as well as inves-



tigate the use of synthetic fuels. Reducing sulfur content and optimizing the molecular structure of a fuel can lead to less sulfate formation, lower emissions of "toxics" such as polynuclear aromatic hydrocarbons, and to some extent, lower NO_x. Viscosity and lubricity control are important in improving fuel spray characteristics to lower HC emissions, maintain fuel injector and fuel pump life, and ensure good cold-weather operation.

Finally, **alter oil properties** that can affect volatility, soot tolerance, and dispersion, and take advantage of performance improvements available using the latest additive packages. Improved oil characteristics can reduce the soluble fraction of PM, keep deposits to a minimum, and protect against wear caused by the presence of soot derived from the combustion process.

Using these five areas of technology in various combinations, the in-engine solutions have, so far, generally been adequate to meet emission standards through the current model year. The advantages of this approach include the ability to keep technology completely under the control of the manufacturer and to minimize complexity and potential impact on the consumer. In addition, manufacturers retain the sole responsibility for certifying and tracking the in-use performance of their engines.

Exhaust emission control using aftertreatment technologies

In-engine solutions are still being developed and improved by manufacturers and engineers at SwRI in the effort to meet future standards. A variety of other technologies may also be needed and are considered increasingly likely to meet the new 2002 standards. These methods are exhaust aftertreatment techniques and include:

Exhaust gas recirculation (EGR), which pipes a small fraction of the exhaust back to the inlet duct, replacing some of the intake air with exhaust gas. This gas contains less oxygen than fresh air, but also has more water and carbon dioxide, all of which reduce or absorb heat from the combustion process, lowering the temperature and reducing NO_x formation. With or without the use of EGR, diesels produce a certain amount of solid PM. One technique to control this is to use a **diesel particulate filter** that, with either a passive or active regeneration system, can continuously remove soot from the exhaust without becoming clogged.

Oxidation catalysts, which can reduce PM by helping to control the volatile organic fraction. They adsorb organic material, including gaseous hydrocarbons, on their high surface areas where the precious metal catalysts they contain can facilitate oxidation.

Lean NO_x catalysts operate in a different way, bringing NO_x molecules into contact with hydrocarbon reductants to cause a reduction reaction. The

Equipment for monitoring gas concentrations in three or four streams simultaneously is needed during the development of diesel exhaust aftertreatment schemes. Taken in order, sample locations include the fresh air intake, the inlet manifold (when EGR is used), the exhaust manifold, and the tailpipe (following the aftertreatment device).

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Diesel particulate filter cores made of specialty ceramics such as cordierite and silicon carbide (shown) are studied for particle collection efficiency, resistance to exhaust heat, buildup of backpressure, and completeness of regeneration (cleaning).

hydrocarbon reductants are generally in the form of fuel injected into the exhaust, upstream from the catalyst itself.

Yet another option, called the **lean NO_x trap,** is a two-stage device that converts exhaust nitric oxide (NO) to nitrogen dioxide (NO_2) in a first stage. The second stage acts as storage for the NO_2, and also acts as a reducing element when a hydrocarbon reductant (again, generally fuel) is injected upstream from the device.

The operation of **catalytically regenerated particulate filters** bears some resemblance to that of lean NO_x traps, in that they contain a first-stage precious metal catalyst to generate NO_2 from NO. From that point on, however, they differ because the NO_2 is used to oxidize the trapped carbon particulate directly, and no reducing agent is added.

Another particulate control method is the **catalytically assisted passively regenerated diesel particulate filter**, which uses a catalytic coating to reduce volatiles and provide some heat assist. Regeneration is further enhanced by the presence of a fuel-borne catalyst (sometimes used independently to control emissions), which reduces the ignition temperature of the collected particulate to the point that it burns off more frequently and keeps the filter flowing freely.

Plasma reactors and plasma-assisted catalysis form a relatively new field of interest for diesel engineers. This is a technology in which a single reactor has been observed to control both the NO_x and PM simultaneously. The high potential payoff of plasma technology is tempered, however, by the unknown developmental risks and costs of the device. The system is also fairly complex as currently designed.

Plasma reactors generally consist of a packed bed or a central-wire chamber in which a nonthermal plasma is electrically generated, producing a stream of ions that cause reactions to accelerate in the exhaust passing through the device. Plasma-assisted catalysts add another element, a lean-NO_x catalyst. A synergy has been observed between the actions of the plasma and the catalyst that may prove to enhance conversion of pollutants, reduce plasma energy requirements, or both.

Finally, **selective catalytic reduction,** using urea or ammonia reagents, is another technique with high potential for diesel engine NO_x control. As the name implies, this method selectively promotes the reduction of NO_x to N_2 over proprietary catalysts when specific reducing agents are mixed with the exhaust stream. The basic forms of these reactions are:

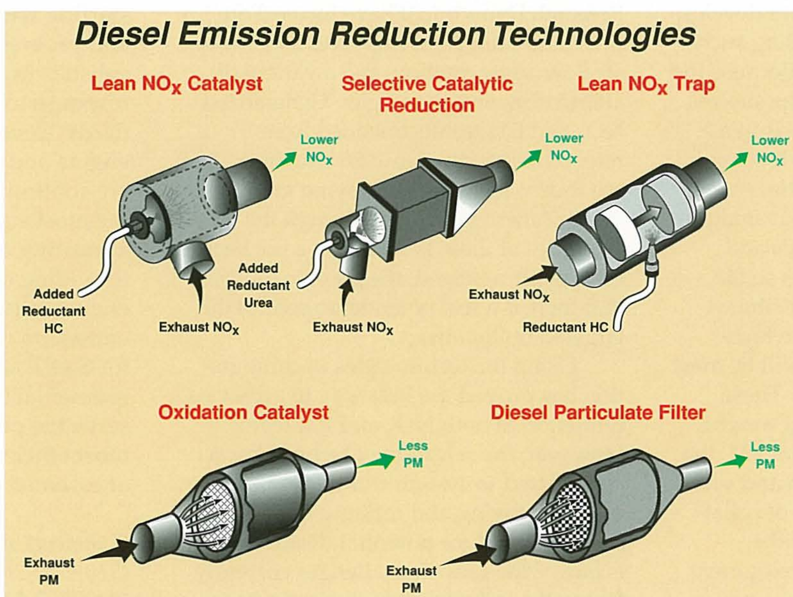
$$4NO + 4NH_3 \text{ (ammonia)} + O_2 \rightarrow 4N_2 + 6H_2O$$

$$\textit{or } 6NO + 2(NH_2)_2CO \text{ (urea)} \rightarrow 5N_2 + 4H_2O + 2CO_2$$

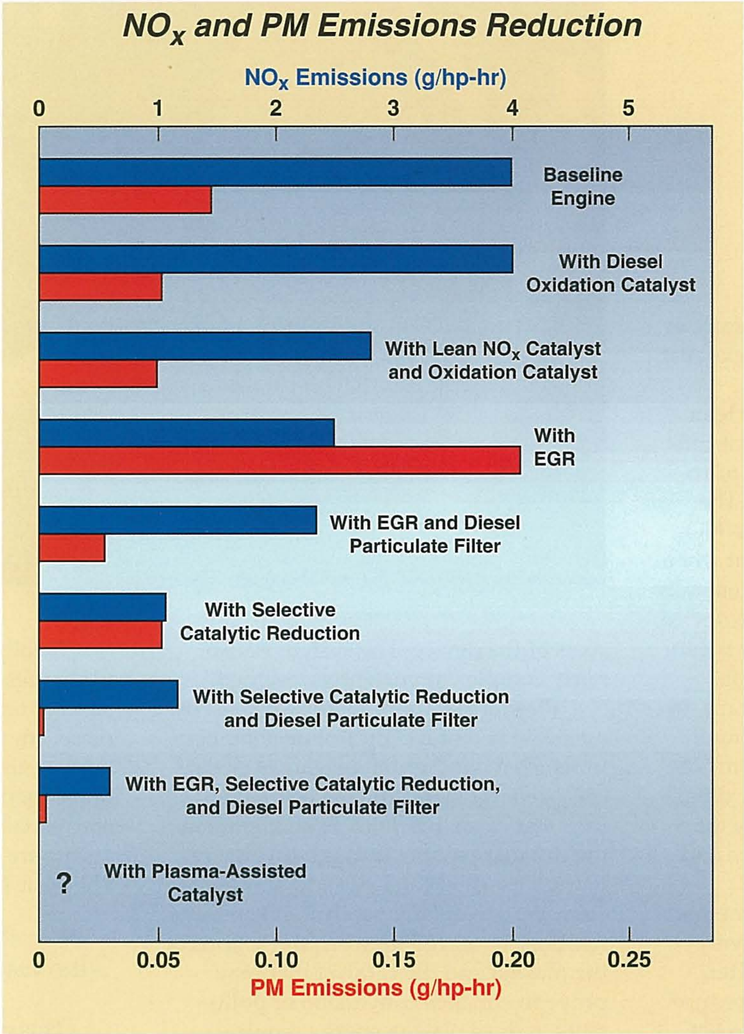
This can produce an NO_x conversion efficiency of 80 percent or more. However, while the complications this technology introduces are understood, the engineering solutions needed to minimize the problems have not been completed.

Combining emissions reduction technologies

An important question that remains is, which technologies can logically be combined? In general, improving fuel quality helps all the other techniques to function as intended, so progressing from high sulfur to low sulfur to essentially zero sulfur fuel would be helpful.



SwRI engineers are investigating a variety of aftertreatment technologies to meet 2002 heavy-duty diesel emission standards. The diagram shows NO_x and PM emissions levels using technologies singly and in combination. Note that combined device performance and test variability for all technologies is approximately ± 0.15 for NO_x and ± 0.002 for PM.



However, these changes involve costs to the refiner, which would be passed along to the consumer. Likewise, progress from today's fuel composition to a low-aromatic fuel, and possibly progressing to synthetic fuels containing no aromatic compounds at all, would be advantageous. However, this would also entail *substantial* additional costs for NO_x and PM reductions of approximately 10–20 percent for advanced engines. Reductions of this magnitude may be helpful, but they are not even close to the 50–75 percent control efficiencies needed for the year 2002 and beyond.

Several SwRI programs have been in progress throughout the 1990s to develop low-emission diesel systems using such combinations of technologies. Because the Institute has equal interest in the success of all candidate technologies, it is in a good position to evaluate and develop a variety of combinations. Doubtless some systems may have particular advantages for individual engine companies and engine applications, and results so far show a large variation in the attributes that will ultimately determine which combinations of technologies will be most widely used on future engines. These attributes include cost, size and weight, efficiency of control for NO_x and PM, the amount of power consumption and subsequent fuel penalty, difficulty of collateral problems, the reliability of the technology, and its current development status and future potential.

Recent efforts in the Emissions Research Department have focused on EGR adaptation and improvements, intake air flow augmentation, and a variety of aftertreatment technologies. Generalized NO_x and PM results obtained from research carried out in 1998 and early 1999 are shown in an accompanying graphic for some of these systems. Although the attributes of these systems have not been completely assessed, the graphic shows that there is a real potential to control the targeted pollutants.

Using the technologies in combination has proved the best way to achieve a reduction in both NO_x and PM levels. However, the selection of technology is also related to system complexity and cost. Improving and refining the design process to reduce potential disadvantages is one of the serious challenges currently facing the industry. It is encouraging to note that results achieved so far in the laboratory have met the demonstration goals of 1.0 gram per horsepower-hour (g/hp-hr) for NO_x and 0.01 g/hp-hr for PM that the program stipulated.

Another technology, plasma-assisted catalysis, is not fully evaluated yet. Combined reductions in emission levels may be possible through this single technology, but many uncertainties concerning power requirements, efficiency, and by-product generation remain to be studied.

Conclusions

For more than 30 years, the Institute has been instrumental in reducing emission problems associated with diesel engines, starting with odor and smoke control, and progressively working on PM, toxic substances, and gaseous pollutants in response to ever more demanding standards. Development projects using in-engine and aftertreatment technologies are continuing, and within a few years, the most successful combinations will be appearing on production engines. Providing crucial assistance to the diesel engine industry as it strives to overcome emissions challenges is a rewarding role for SwRI, and one that will yield environmental benefits as well as help preserve the position of the diesel as the most efficient motive power for a range of essential applications. ❖

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