Diesels come Clean

Improved engines and exhaust scrubbers, combined with a new fuel, will make energy-efficient diesels nearly as green as hybrids

By Steven Ashley

Swinging his truck door open, the driver obligingly steps onto the cab seat and reaches for the roof. Extending himself upward, he slings a handkerchief over the exhaust stack of his late-model diesel rig. In mere moments, black fumes begrime a section of the white square with soot. "This good?" he asks, handing down the fluttering fabric. Nodding, I thank the man and retrieve the hankie. A short stroll away from his idling truck and its fellow 18-wheelers parked in this New Jersey Turnpike rest area sits their newborn brother, a Mercedes-Benz E320 Bluetec sedan. With a turn of the key, its diesel engine springs to life. Moments later, I kneel behind the car and cover its tailpipe with an unsoiled patch of cloth. It remains nearly spotless, even after a full minute.

As the so-called handkerchief test shows, the words "clean diesel" are no longer a contradiction in terms. Diesels have long been regarded as among the dirtiest of power plants, a reputation that lingers because so many decades-old examples of this durable technology still work the roads today. But the E320 is the vanguard of a new wave of diesel cars, SUVs and pickups that release far fewer air pollutants

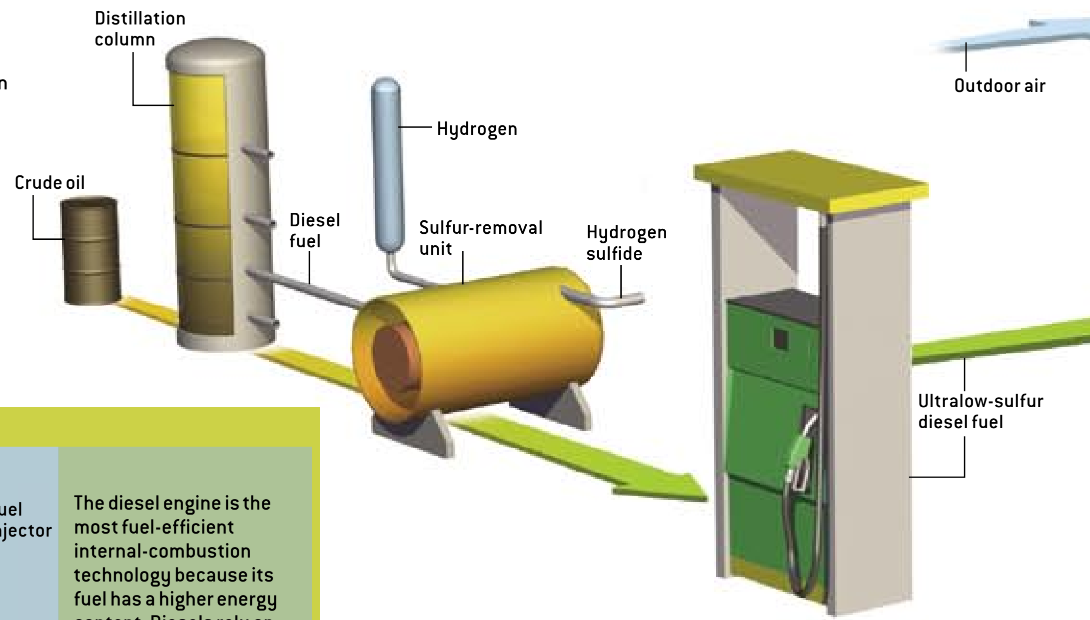
ILLUSTRATION BY MATT VINCENT; AMERICAN HONDA MOTOR CO. (engine)

NOT EXACTLY GREEN, perhaps, but diesel engines are cleaner than ever before. Near-term technologies will further reduce their emissions of nitrogen oxide, soot and carbon dioxide.

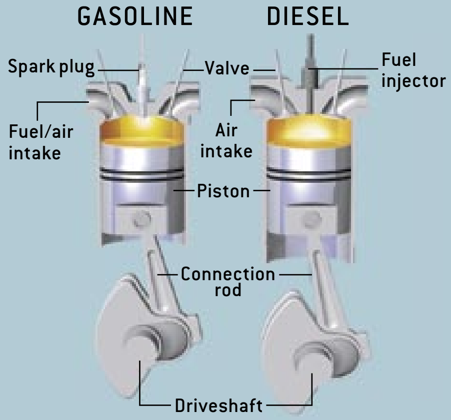
Elements of Clean Diesel Cars

ULTRALOW-SULFUR DIESEL FUEL

The fuel contains 97 percent less sulfur than previous diesel grades. Sulfur, a natural component of crude oil, would otherwise pollute the air and degrade the exhaust-treatment systems. Refiners add hydrogen to diesel distilled from crude, which bonds with the sulfur, allowing the resulting hydrogen sulfide to be separated out.



SPARK VS. COMPRESSION



The diesel engine is the most fuel-efficient internal-combustion technology because its fuel has a higher energy content. Diesels rely on compression rather than igniting fuel with spark plugs, as gasoline power plants do. The piston stroke in a diesel compresses the air so intensely that injected fuel explodes spontaneously.

without compromising the engine's traditionally excellent fuel economy. Powered by a 3.0-liter V-6 engine, the E320, for instance, gets 36 miles per gallon (combined) and can travel as much as 780 miles between fill-ups.

Overview/*Greener Diesels*

- Diesels have a bad reputation as dirty engines, but modern diesel automotive power plants put out significantly less pollution—principally carbon soot and nitrogen oxides—than their predecessors and get good gas mileage as well. Add cleaner fuel grades and new exhaust after-treatment systems, and diesel cars, sport utility vehicles and trucks can approach the environmental acceptability of hybrid vehicles.
- Ultralow-sulfur fuel, which recently became available in the U.S., is one key to the prospects of clean diesel technology. Sulfur otherwise would degrade the operation of exhaust-control systems over time.
- Tailpipe systems that scrub much of the soot and nitrogen oxide emissions from diesel exhaust are starting to appear in new models.

To bring about this transformation, modern diesels take advantage of advanced power plants that produce fewer pollutants, new exhaust systems that remove soot and convert tailpipe emissions into harmless gases, and cleaner low-sulfur fuels that just became available in North American markets this past fall. What is more, the improvements do not come with an exorbitant price tag. "The E320 Bluetec diesel costs only $1,000 more than the gasoline version," says Thomas Weber, the board member in charge of research and development at DaimlerChrysler (manufacturer of the Mercedes).

Volkswagen, Audi, BMW, Honda, General Motors, Ford, PSA Peugeot Citroën and others are also planning to introduce cleaner diesels in the next few years. These vehicles will be almost as green as gasoline-electric hybrids but without much of the added cost and complexity of their extra drive systems. Automakers intend the new diesels, together with hybrids and advanced gasoline-powered vehicles, to bridge the gap between today's cars and the hydrogen fuel cell machines of the future [see "Hybrid Vehicles Gain Traction," by Joseph J. Romm and Andrew A. Frank; Scientific American, April 2006, and "On the Road to Fuel-Cell Cars," by Steven Ashley; Scientific American, March 2005].

The drive to more efficient, cleaner vehicles has grown in

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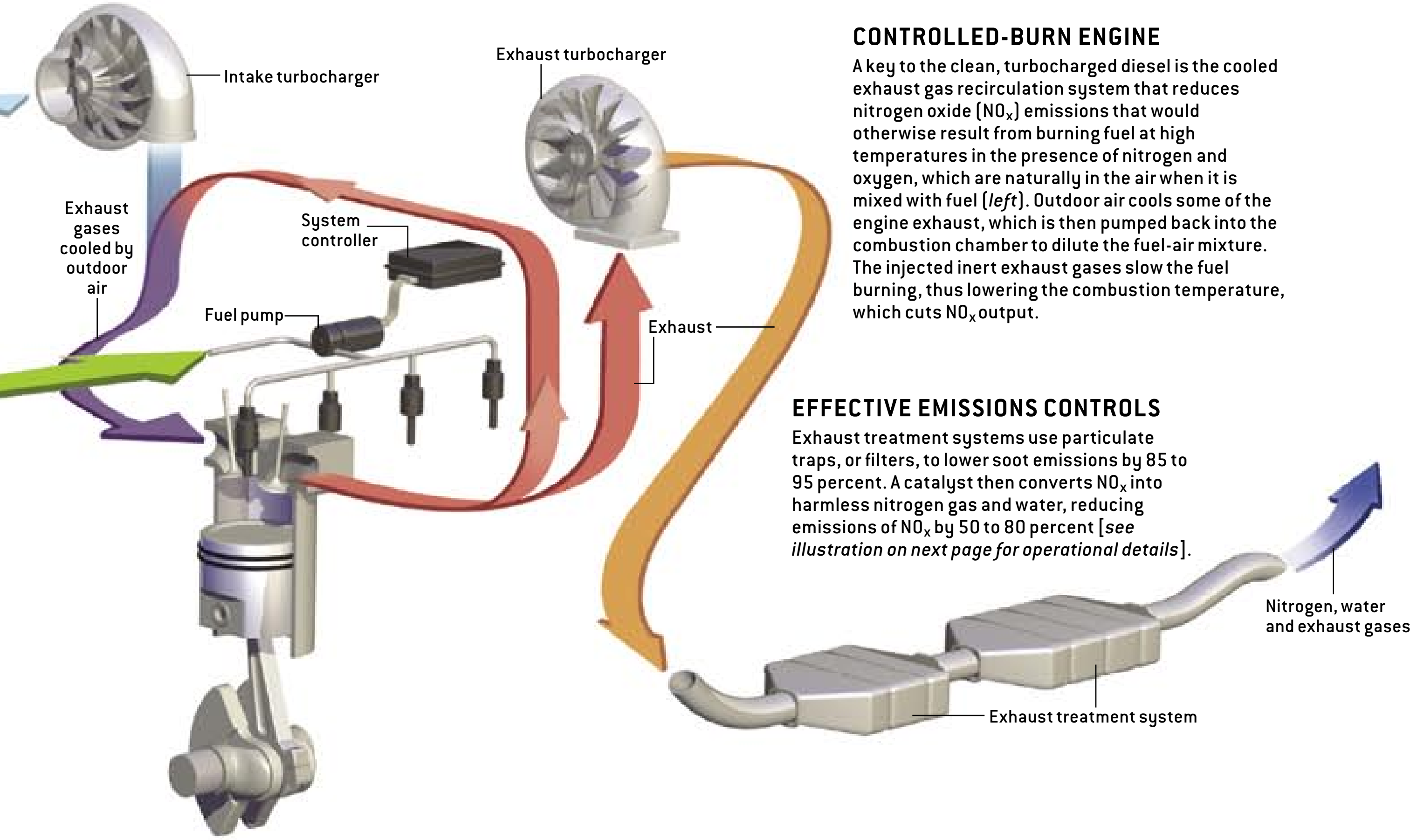


CONTROLLED-BURN ENGINE

A key to the clean, turbocharged diesel is the cooled exhaust gas recirculation system that reduces nitrogen oxide (NO_x) emissions that would otherwise result from burning fuel at high temperatures in the presence of nitrogen and oxygen, which are naturally in the air when it is mixed with fuel (*left*). Outdoor air cools some of the engine exhaust, which is then pumped back into the combustion chamber to dilute the fuel-air mixture. The injected inert exhaust gases slow the fuel burning, thus lowering the combustion temperature, which cuts NO_x output.

EFFECTIVE EMISSIONS CONTROLS

Exhaust treatment systems use particulate traps, or filters, to lower soot emissions by 85 to 95 percent. A catalyst then converts NO_x into harmless nitrogen gas and water, reducing emissions of NO_x by 50 to 80 percent [*see illustration on next page for operational details*].

significance because cutting fossil-fuel consumption (and therefore carbon dioxide output) has become central to fending off global climate change as well as reducing our dependence on foreign oil. According to the Environmental Protection Agency (EPA), if diesels were to power one third of all light-duty vehicles (comprising cars, SUVs and small trucks) in the U.S., the shift would save about 1.4 million barrels of oil a day—equal to the daily shipments from Saudi Arabia (from which this country imports about 7 percent of its oil supply).

Compression Ignition

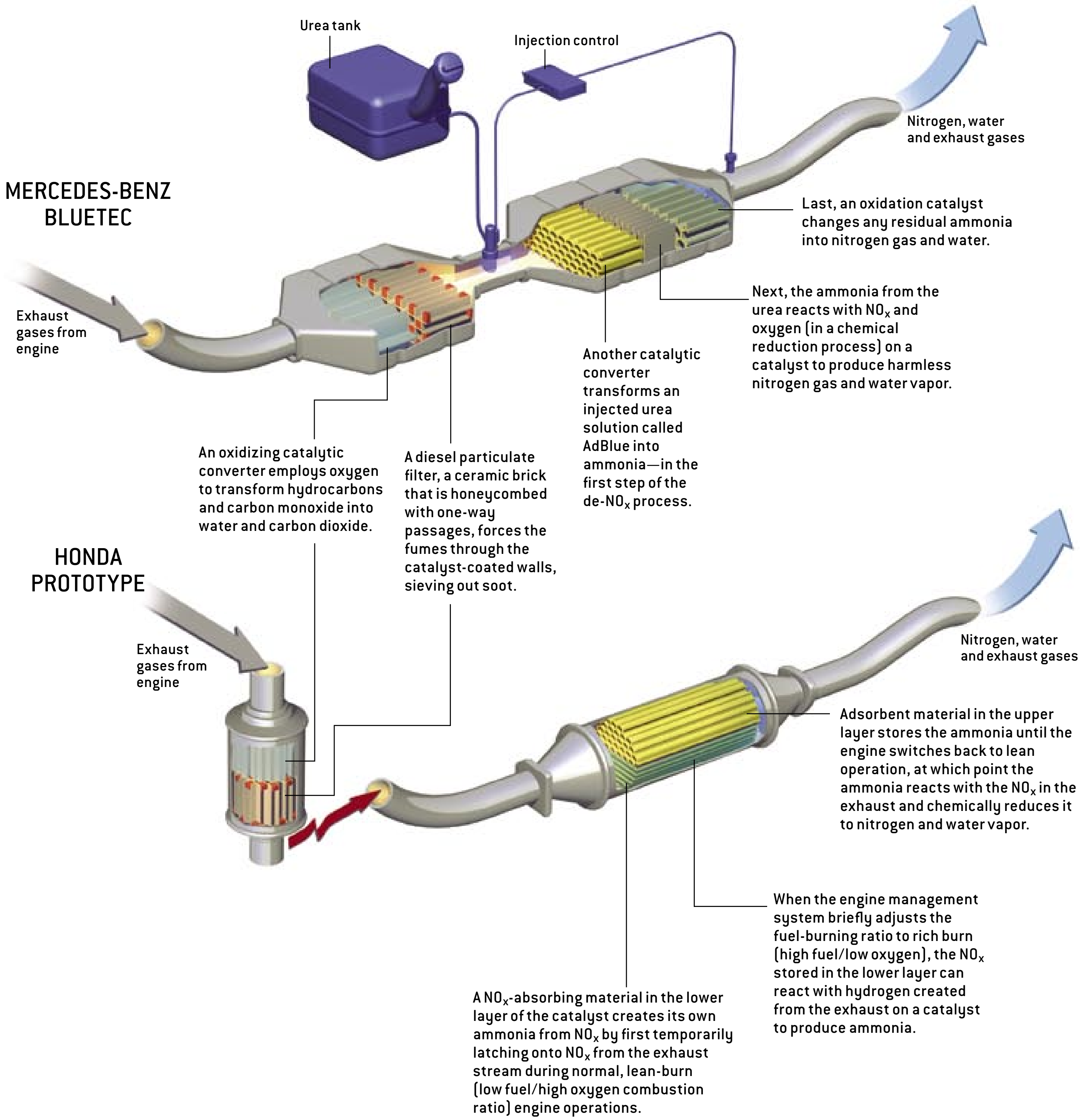
THE DIESEL ENGINE already has a long and storied past, having served as the backbone of modern heavy industry and transport since shortly after German engineer Rudolf Diesel invented it in the 1890s. Whereas the gasoline engine requires an electric spark to ignite a compressed mixture of fuel and air in a cylinder, a diesel relies on compression: the piston stroke squeezes the air in the cylinder more tightly, raising its temperature so that injected fuel explodes spontaneously. Today this so-called compression-ignition engine produces more energy per unit of fuel, and therefore 25 to 30 percent better mileage, than its gasoline-powered counterpart, explains Charles Freese, executive director of diesel engineering at GM Powertrain. Compact diesel cars can get 40 to 50 miles to the gallon, for instance, whereas comparably sized gasoline-fueled vehicles rarely surpass 35 mpg.

The diesel provides "a lot of low-end torque [rotational force during starts], which, together with modern [power-boosting] turbochargers, gives diesels the good pickup and acceleration that makes them fun to drive," Freese says. But the technology's fuel characteristics and higher-temperature combustion conditions also yield more ultrafine carbon particulates (soot) and smog- and acid-rain-forming nitrogen oxide (NO_x) tailpipe pollutants than gasoline engines. Richard Kassel, director of the clean fuels and vehicles project at the Natural Resources Defense Council, estimates that diesel emissions from all sources—cars, trucks, locomotives and off-road equipment—annually cause as many as 25,000 premature deaths and 2.5 million lost workdays from cancer, asthma, bronchitis and other conditions in the U.S. Avoiding release of these aerial contaminants, he states, will save around $150 billion a year in nationwide health costs by 2030.

Despite certain advantages, the diesel automobile has remained stuck in neutral in the U.S.—accounting for just 3 to 4 percent of sales, according to the J.D. Power market research firm. (Diesel's worldwide share for cars and smaller

Exhaust Treatment Systems

Advanced diesel exhaust emissions-control systems from Mercedes-Benz and Honda can lower tailpipe output of hydrocarbons, carbon monoxide, nitrogen oxides (NO_x) and soot.



trucks is reportedly also relatively small: 13 percent are diesel-fueled, whereas 85 percent run on gasoline.) Diesels never sold well because of a poor reputation among U.S. buyers and unfavorable domestic environmental standards. Negative images conjured up by smoke-belching tractor-trailers and bad memories of American-made, diesel-powered lemons of the 1970s put most drivers off the engines. Meanwhile federal regulations placed harsher restrictions on the NO_x and soot emitted by diesels than on carbon monoxide and hydrocarbons, the principal air pollutants generated by gasoline engines. NO_x standards are particularly stringent in North America, where new rules require that diesels produce no more than one sixth the levels permitted in Europe.

The picture is quite different across the Atlantic, where somewhat lower-sulfur fuels have been available for several years because European refineries have incentives to produce more diesel than gasoline. In countries of that region, diesels make up more than 40 percent of the new cars purchased. European regulators, concerned more about fuel efficiency, have encouraged the use of diesels in recent decades with tax-based fuel-pricing strategies that make gasoline less attractive, and emissions standards that have deemphasized NO_x and soot output. For decades in Europe, these policies kept diesel cheaper than gasoline, although prices there have tended to level off in recent years—diesel currently costs about $5 a gallon and gasoline is priced at around $6, whereas in the U.S. they both go for $2.25 to $2.50. The tilt toward diesels in these countries has spurred auto engineers to develop smaller (2-liter) diesel engines that over the years have shed most of the technology's former undesirable characteristics, including loud engine noise and difficulty starting up in cold weather.

Engine and Fuel Upgrades

SO-CALLED CLEAN DIESELS get that way from engineers' efforts to improve the engines, fuels and exhaust systems. A series of engine innovations (most initially introduced in trucks) brought about the first category of improvements, Freese says. These upgrades include high-pressure fuel systems that reduce diesel injection time and boost cylinder compression, as well as optimized chamber and valve designs for good air-fuel mixing and hence uniform, stable and efficient combustion. Turbochargers—exhaust gas–driven compressors—boost power output by ramming air into the combustion chamber to raise the amount of oxygen available for burning. Meanwhile sophisticated control systems use sensors to monitor engine operations and adjust running parameters to fine-tune their workings.

Of particular importance to diesel emissions control was the development of an engine component called the exhaust gas recirculation system in the early 1970s. This component dilutes the flame-supporting oxygen in the cylinder with injected (inert) exhaust, which slows combustion and therefore avoids NO_x-creating temperature spikes. Since its introduction, it has already cut raw NO_x production by about three quarters, according to industry claims. A relatively recent advance in this area is the cooled exhaust gas recirculation system, which lowers the temperature of exhaust fumes (by mixing them with outside air or cooling them in a heat exchanger) before they are pumped into the combustion cylinder, further reducing NO_x output.

THE WORDS "CLEAN DIESEL" ARE NO LONGER A CONTRADICTION IN TERMS.

These improved technologies cut emissions production, but they were not enough by themselves to clean up diesel's act. Another key was the availibility of an ultralow-sulfur diesel fuel that made their operation possible. Sulfur, which is naturally present in crude oil, not only corrodes engine components but "poisons," or renders ineffective, catalytic converters because it bonds preferentially to catalytic compounds and clogs particulate traps, causing exhaust systems to back up. To extract sulfur, refineries process diesel with hydrogen, which bonds preferentially with the sulfur. The new federally mandated ultralow-sulfur fuel contains 97 percent less sulfur than prior grades; levels have dropped from 500 parts per million to 15, which is equivalent to just an ounce of sulfur in an entire tanker truck of diesel.

Cleansing the Tailpipe

THE LAST PIECES of the clean diesel puzzle are the superior exhaust-scrubbing techniques that are just now being introduced in cars. When exhaust emerges from a modern diesel engine, it typically enters the first stage of the emissions control system, the oxidizing catalytic converter, which strips it of a significant portion of its carbon monoxide and unburned hydrocarbon constituents by chemically binding some of these compounds to oxygen in the exhaust flow.

The gases then often run into a diesel particulate filter, or particle trap, which strains out their carbon soot. A trap usually contains a brick of heat-resistant ceramic (such as silicon carbide or cordierite) honeycombed with passages that are alternately blocked at opposite ends. Any exhaust that flows into a passage is forced to pass through substrate walls that are coated with a catalyst, which sieves out the ultrafine carbon particles. Such particle filters can reduce soot emissions by as much as 98 percent.

When clogged, some of these filters operate "something like a self-cleaning oven," says GM's Freese. If sensors indicate a slowdown in exhaust flow, the engine controls raise the amount of fuel injected into the cylinder for a short time, which increas-

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CLEANER DIESEL CAR, the 2007 Mercedes-Benz E320 sedan.

es hydrocarbon output. These chemicals get caught in the oxidation catalytic converter and then ignite, which elevates the exhaust temperature to around 650 degrees Celsius, enough to burn off the carbon and regenerate the filter's capabilities.

NO_x Removal

IN THE NEW CLEAN DIESEL vehicles, the exhaust next goes into a de-NO_x after-treatment system, which has been a main focus of recent engineering efforts in the diesel industry. Some of these components, called lean-NO_x traps or lean-NO_x catalysts, accomplish their functions during lean-engine operations. "Lean" refers to the concentration of fuel in the combustion mixture in the engine cylinder. An engine runs lean when fuel is injected sparingly, which means there is relatively more oxygen in the mix. "Rich" operation occurs when more fuel is burned. To maintain good fuel efficiency, engineers design diesels to run lean, but the consequent increased availability of oxygen promotes the formation of NO_x during fuel combustion.

Several basic approaches to de-NO_x systems exist, says Ben Knight, vice president of R&D for American Honda. One is known as continuous hydrocarbon selective catalytic reduction. This method involves running the diesel engine rich to place hydrocarbons in the exhaust stream, where they work with a catalyst to chemically reduce NO_x—that is, to ready the NO_x for conversion into nitrogen gas by adding an electron in a partial reaction. The method has cut NO_x output by as much as 40 percent during certain European test driving cycles but also adds a 5 percent fuel penalty, which is not considered cost-effective. In addition, it yields lower conversion efficiency at low temperatures.

Another de-NO_x technique is NO_x storage and conversion, which is currently used in vehicles with gasoline direct-injection engines. This so-called discontinuous technology stores NO_x on a barium-containing catalyst under normal lean-burn conditions; it then releases and chemically reduces the stored NO_x during the interval when the cylinder mixture is temporarily enriched with fuel, which leads to a dearth of oxygen in the exhaust. Applying this approach to diesel power plants requires major alterations in their design as well as in how they are run. Like the hydrocarbon selective catalytic reduction technique, it exhibits reduced NO_x conversion efficiencies at low temperatures.

A third, more common method is urea-injection selective catalytic reduction. It employs a reducing agent, usually an ammonia-containing fluid called urea, to transform NO_x into nitrogen on a catalytic substrate. (Chemists formulate the usually strong-smelling additive to have a relatively benign aroma.) The principal drawbacks to this technique are that it uses a urea-injection system, needs a new commercial distribution infrastructure for the liquid and requires maintenance to keep the onboard reservoir filled.

The next generation of Bluetec technology (which will be used by DaimlerChrysler, Volkswagen and others) will rely on injecting a urea solution, which makers have dubbed AdBlue [*see box on page 84*]. Weber says that DaimlerChrysler engineers worked with researchers at Bosch to develop the system, which can cut NO_x emissions by as much as 80 percent. And when fitted with this next-generation exhaust after-treatment technology, the next version of the E320 has every prospect of satisfying the strict federal Tier 2, Bin 5 levels (which in part mandate 0.07 gram of NO_x and 0.01 gram of particulate per mile). These standards constitute more than a 10-fold reduction for soot and a twofold cut for NO_x over the previous regulations. Standards almost identical to Bin 5 levels are due to come into effect this year in California (whose huge auto market tends to set de facto national standards), whereas Bin 5 itself will be applied countrywide in 2009. Both are expected to continue to be enforced for the foreseeable future. The new E320 sedan, he notes, uses an average of 0.1 liter of the urea reducing agent per 100 kilometers traveled. The urea tank is to be sized large enough that it can span the standard oil change interval.

Solid-State Catalyst

HONDA RECENTLY announced an elegant new approach to de-NO_x technology, a lean-NO_x catalyst that demonstrates NO_x conversion rates of 90 percent yet requires no added reducing agents [*see box on page 84*]. This innovative technique converts some NO_x into ammonia and then recombines it with the remaining NO_x to make nitrogen gas. The prototype process, which was developed by a team led by chief engineer Hiroshi Ohno, is expected to first appear in a diesel-powered 2009 Honda Accord, according to news reports.

The Honda system centers around a compact dual-layer catalyst, Knight says. The top layer contains zeolites, microporous materials that act as high-surface-area, solid-state acid substrates that facilitate chemical reactions. The bottom layer incorporates two other common catalysts, cerium oxide and platinum.

"During normal lean engine operations," Knight explains, "the top layer simultaneously absorbs incoming NO_x and converts part of it into nitrogen. In the brief periods when the diesel is set to run rich, the bottom catalytic layer generates ammonia from the exhaust gases. But rather than passing this

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ammonia directly back into the flow, it is stored in the upper layer's zeolite substrate until the engine flips back over to lean-burn, at which point the ammonia reduces the NO_x into nitrogen gas." The lower layer forms ammonia in two ways: it chemically combines ambient NO_x and hydrogen to yield the compound ammonia, and it also performs what chemists call a water-gas shift reaction with carbon monoxide and water vapor to form ammonia. Because the NO_x storage burden is lessened (compared with other methods), he says, there is less NO_x to trap during lean operation, which keeps the system compact and cuts down on rich operation time, thereby lowering the fuel penalty.

Knight emphasizes that the lean-NO_x catalyst's advanced control system is important because it determines how much ammonia is made. The controls realize this goal by monitoring and modifying the engine operation to set the durations of its lean and rich periods. "The controls are adaptive and optimize the system even if the catalysts degrade over time," Knight says—a key to enabling future Honda diesels to achieve EPA Tier 2, Bin 5 output over the required 125,000 miles of driving.

NEW DIESELS WILL HELP BRIDGE THE GAP TO FUTURE FUEL-CELL VEHICLES.

A Diesel Future?

EXACTLY WHERE this new chapter in the diesel story will lead remains uncertain. Although companies including DaimlerChrysler, Honda and VW are bullish on the diesel's prospects in the North American market, others are less sanguine about its future there, particularly in smaller vehicles. Both GM and Ford, for example, believe that light-duty diesel engines are better suited, at least initially, to pickup trucks and larger SUVs, where their extra torque output and high fuel efficiency can clearly shine. Toyota is even gloomier regarding domestic diesels. Says company spokesman John Hanson: "Toyota is not looking to promote diesels soon in North America. Although we continue to develop advanced diesels for the European and Asian markets, we don't think that the U.S. market is receptive to the technology and won't be for some time." Toyota thinks of the latest generation as "cleaner diesels," Hanson adds, but "none of the new models will rank high with regard to the EPA and California criteria for environmental friendliness ... Even the cleanest among them will only barely qualify for use in California."

Questions about fuels also exist. Although ultralow-sulfur fuel is here, it typically has a lower and a wider range of cetane values than that available in Europe (cetane is the diesel equivalent of gasoline's octane). Better, more consistent fuel would help promote clean diesel technology. But because North American refineries are designed to produce gasoline rather than diesel, improved diesel fuel could require substantial capital investment in equipment.

In the meantime, despite the recent media buzz, industry observers expect that sulfur-free biodiesel (which can be derived domestically from crops such as soybeans) will remain a niche product. Says NRDC's Kassel: "biodiesel supplies will grow in the coming decades but will be a tiny piece of the entire diesel pie." He also cites "the need for national technical specifications for biodiesel grades" to ensure even performance when engines are fueled from different sources. Elsewhere, European diesel manufacturers and some energy companies say they are interested in recent efforts to produce sulfur-free diesel fuel from suitable coal and natural gas grades using variants of Fischer-Tropsch chemistry, a fuel-synthesis method first developed during World War II.

One issue that is clear is that most of today's diesel engines will stay on the road for another two and a half decades or more. That reality means that the gross benefits of clean diesel technology are unlikely to start to show up in the atmosphere for at least a decade or so. Nevertheless, it should have a positive impact before too long. The EPA estimates that by 2030, when the entire diesel-powered vehicle fleet (on- and off-highway equipment) in the U.S. will finally turn over as a result of retirement, NO_x emissions will be reduced by four million tons annually and cancer-causing particulates by 250,000 tons per year. The benefits in the fight against climate change should also be significant, although perhaps not as apparent.

"The recent availability of low-sulfur fuel is a sea change in the car world," Kassel says. "It resembles the period in the early 1970s when the government removed lead from gasoline." This action not only halted lead emissions but also permitted engineers to use the catalytic converter to deal with the other exhaust pollutants. "It took more than 30 years to go from leaded gas and no effective emissions controls to today's extremely clean and increasingly fuel-efficient cars," he states. "By next year, in less than a decade, the car world will have undergone a similar change with diesels." SA

Steven Ashley is a staff editor and writer.

MORE TO EXPLORE

Diesel Technology Forum discussion of clean diesels: **www.dieselforum.org/meet-clean-diesel/what-is-clean-diesel/**

U.S. Environmental Protection Agency's National Clean Diesel Campaign: **www.epa.gov/cleandiesel/**

Mercedes-Benz Bluetec technology: **www4.mercedes-benz.com/specials/scr/en/index_nocom_en.htm**

Honda clean diesel technology: **http://world.honda.com/news/2006/c060925DieselEngine/**