FUEL FOR THE LONG HAUL?

DIESEL IN AMERICA

Brawny diesel engines have helped drive the world economy for more than a century. From an economic and operational perspective, there's little reason to expect that will change anytime soon. Diesel's big draws are power, durability, and an inherent advantage over gasoline: higher energy content and resulting fuel efficiency.

But studies beginning nearly 50 years ago and continuing today increasingly point to adverse health effects from diesel exhaust, especially the particulates that pour from the tailpipe or form later in the atmosphere. Exposure to ambient diesel particulate matter (DPM) containing such contaminants as sulfur oxides, volatile organic compounds, and aromatic hydrocarbons occurs in nearly every county in the eastern half of the United States and in many western counties, says the U.S. Environmental Protection Agency (EPA) in its National-Scale Air Toxics Assessment (NATA), released in May 2002 [see "U.S. Air Only Fair," p. A452 this issue].

To help stem the adverse health effects of diesel emissions, which some public health agencies now consider the source of at least 70% of the total toxic risk posed by air pollutants, U.S. regulators have been requiring cleaner diesel engines for several decades. As a result, the total mass of particulate emissions from a new or retrofitted engine has been sharply reduced.

But millions of older diesel engines that haven't been cleaned up are still running in the United States. And many questions remain about exactly what other tiny pollutants the new fuels and emission control methods may be creating. Researchers at

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several private and public facilities are scouring the data and designing new experiments, looking for answers.

While the results of their probes trickle in, sometimes with contradictory findings, new rounds of regulations for on-road diesel engines will take effect in the United States in 2002, 2004, 2007, and 2010, following recent court decisions and settlements. Other regulations, including those for off-road uses such as irrigation pumps and marine vessels, are still in the formative stages, but may play just as big a role in reducing diesel particulates as on-road engine regulations. "That's the next big bite of the apple," says Paul Billings, the American Lung Association's assistant vice president for government relations. About two-thirds of DPM comes from off-road sources, according to the EPA's 1999 *National Air Quality and Emissions Trends Report*.

While many people are pushing for and developing cleaner diesel engines, alternative energy sources such as hydrogen-powered fuel cells may prove to be a healthier long-term solution if they can match up in power, durability, and efficiency. Manufacturers are creeping closer to success with automobiles, light trucks, and even buses. But the diesel industry isn't about to wither away. "I don't think there will ever be a technology that replaces diesel," says Allen Schaeffer, executive director of the Diesel Technology Forum, a Frederick, Maryland–based organization that advocates for more than a dozen major diesel engine, fuel, and technology companies.

Durable Power and Particulates

The diesel engine is edging into its second century; German engineer Rudolf Diesel patented his design in 1892. Diesel experimented with many fuel types, including powdered coal, but an engine explosion helped convince him that liquid fuels might be a bit safer. Peanut oil was one of his early choices, but petroleum products soon dominated the diesel engine market.

Diesel engines are similar to gasoline engines in many ways. Both depend on internal combustion of a fuel to drive pistons, which then transmit their energy to a crankshaft and eventually to wheels, pulleys, or other power outlets. But the heat for diesel combustion comes from compression of the fuel, not ignition as in a gasoline engine. Diesel is less refined than gasoline, with a higher energy content.

For nearly a century, diesel combustion was controlled mechanically, through engine design and with relatively crude compression timing. Although such engines were powerful, they also were inefficient, resulting in incomplete combustion and high exhaust emissions. To help cut emissions, the EPA implemented its first DPM standard for light-duty cars and trucks in 1982, and for heavy-duty vehicles in 1988, after setting individual standards in earlier years for nitrogen oxides and hydrocarbons. As a result, newer vehicle engines have been designed with computer-controlled fuel injection systems, which result in more complete fuel combustion and fewer emissions. According to the U.S. Department of Energy's (DOE) Office of Transportation Technologies, the fuel efficiency of diesel is 45% versus 30% for gasoline. With improvements, diesel efficiency could rise still further, to the 55–63% range, the DOE says.

Despite diesel's efficiency advantage, the emissions from a diesel engine still tend to be far higher than those from an equivalent gasoline engine. That's especially true for particulates and nitrogen oxides, despite cuts in vehicle engine emissions that the DOE says exceed 90% compared to 1980 designs. Without additional actions to control those two emission products, health and environmental concerns remain in some quarters, especially given the trends in diesel use. The DOE says diesel fuel consumption has risen steadily in recent years—from a little over 29 billion gallons in 1996 to about 35.5 billion gallons in 2000—and is expected to continue rising about 2% per year for the next few decades.

Any reversal of that trend likely won't come from extensive engine breakdowns. Diesel engines tend to last a long time, in

The diesel dilemma. The strength and durability of diesel engines makes them perfect for heavy-duty applications such as manufacturing, construction, marine vessels, and agriculture. The dirty emissions such engines produce, however, are now thought to make up 70% of the total toxic risk from air pollutants.

part due to the strength of the materials required to contain the fuel compression. The 6 million U.S. vehicles already on the road could last for 400,000 miles, or conceivably even a million miles. About 6 million more off-road diesel engines in the United States—in tractors, irrigation pumps, forklifts, locomotives, bulldozers, construction cranes, portable generators in underground mines, refrigeration units on trucks, marine engines, and elsewhere—can run for years and years.

Exhaust and Health Effects

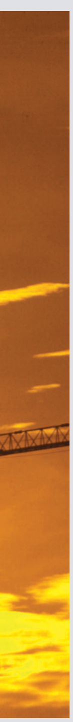
The swirling fumes coming out of a diesel engine exhaust pipe are composed of thousands of substances, including carbon monoxide, sulfur oxides, nitrogen oxides, volatile organic compounds, alkenes, aromatic hydrocarbons, and aldehydes. Health effects of most of the individual substances often are poorly understood, as are most of the interactions that occur among the exhaust chemicals and those already in the atmosphere. However, more than 40 of the individual exhaust chemicals are known to be carcinogens and hazardous air pollutants.

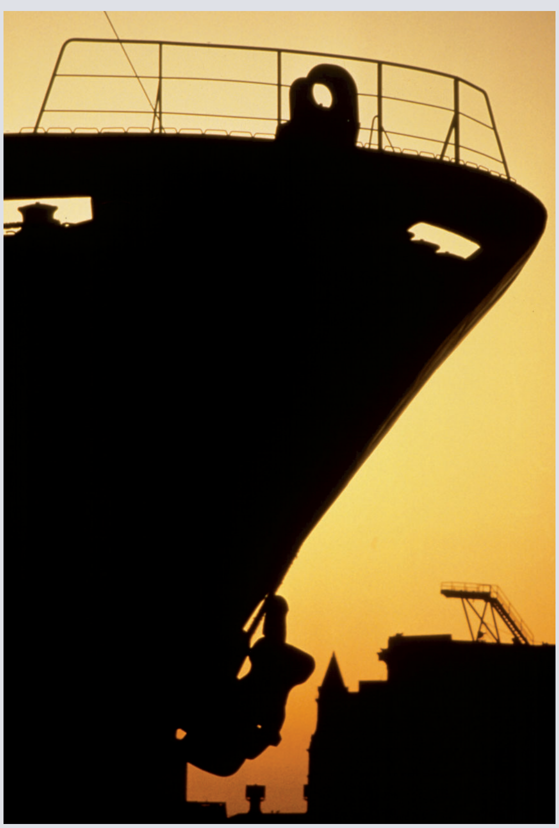
Many researchers and officials, including those who developed NATA, are concluding that whole diesel exhaust as measured by DPM can cause a variety of health problems other than cancer, including increased airway inflammation and susceptibility to infection and allergens, and decreased pulmonary function. Research on particulate matter smaller than 2.5 µm ($PM_{2.5}$) from all sources, including diesel exhaust, is finding that the tiny pollutants are linked with a variety of cardiovascular and reproductive problems, as well as diabetes. This is the finding of an April 2002 report, *Understanding the Health Effects of Components of the Particulate Matter Mix: Progress and Next Steps*, by the Health Effects Institute (HEI), a Boston-based research organization supported by both the EPA and a consortium of motor vehicle and engine manufacturers. A January 2002 report from the EPA's Particulate Matter Health Effects Research Centers Program titled *A Mid-Course (2 1/2 year) Report of Status, Progress, and Plans* states that fine particulates also can cause neurological problems and can increase the severity and number of asthma attacks.

Some of the populations typically found to be vulnerable to particulates from all sources include pregnant women, children, the elderly, those with weakened immune systems, and those already suffering from chronic health problems such as respiratory conditions or diabetes. But much of the detail about who can be affected, and how, remains unclear.

Studies over past decades have shown that ambient $PM_{2.5}$ (the upper threshold of the EPA's standard for ambient fine particulate concentrations, which supplements its standard for particulates less than 10 µm in diameter) comprises the vast majority of particulates near roadways. Of those fine particulates, the great majority in number are nanoparticulates in the range of 5–50 nm, or 50–500 times smaller than $PM_{2.5}$. DPM tends to dominate the particulate numbers in a roadside setting, says David Kittelson, a professor in the University of Minnesota's Department of Mechanical Engineering, although gasoline engines tend to produce even tinier particulates than diesel engines.

The core carbon of DPM, however, may not be the primary culprit for any adverse health effects, according to a number of studies. Instead, the attached pollutants may be of the most concern. Those hitchhikers, when bonded to the tiniest carbon particulates, penetrate deeply into the lungs and are increasingly suspected of triggering a cascade of effects in many body systems. The high numbers of the tiniest particulates are causing significant concern in some circles, because a 1 g mass of nanoparticulates has a far greater surface area than the same mass of, say, $PM_{2.5}$. That allows far more chemical contaminants to bond to nanoparticulates. In addition to the nanoparticulates coming out of tailpipes, Kittelson has found that a large number are formed through variable chemical reactions after the exhaust spreads into the atmosphere.





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Questions and Answers

As research continues on many fronts, one critical focus should be on filling a basic void: "It seems like a very important step to be able to tell how much diesel particulate is in the air," says HEI senior scientist Debra Kaden. Methods for approximating DPM exist, but they can go awry fairly easily, she adds.

That's typical of much of the research on DPM. Even two apparently identical vehicles can result in widely different emissions. Variables include engine age and load, fuel type, lubricating oil composition, type of emission control system, atmospheric conditions, altitude, and the presence of other substances, such as ozone.

And the testing and measuring procedures are still very much in flux, says Mridul Gautam, an associate professor in West Virginia University's Department of Mechanical and Aerospace Engineering who is devising new diesel testing methods for clients such as the DOE and the South Coast Air Quality Management District in California.

Researchers at the Puget Sound Clean Air Agency think they already may have a fairly good tool for measuring diesel exhaust. Naydene Maykut, a senior air quality scientist with the Washington state agency, says that a process called positive matrix factorization (PMF) is looking good as a means of closely estimating particulate sources, in lieu of the EPA's current chemical mass balance method. She and her colleagues used PMF to evaluate the Seattle area's air after they learned the results of the NATA study, which found that the Puget Sound area was among the worst 5% in the country for air toxics. That analysis, plus concurrent evaluation of emission inventories and pollutant monitoring, all confirmed the same apportionment range for DPM. "Either we're awfully lucky or we're right," she says.

She is leaning toward the latter, as are other researchers, after working with the method, which was developed about five years ago in Finland. But PMF still depends on accurate input and would be improved with a better chemical fingerprint of diesel to plug in to the calculations, Kaden cautions.

Regulations and Reductions

The regulatory actions for diesel emissions that officials in the United States and around the world have taken so far have been based on an increasing body of research that began in the 1950s, just a few years after diesel trucks and locomotives were introduced in large numbers in the United States. Interest in diesel emissions increased in the late 1970s, following reports that diesel soot extracts were mutagenic to bacteria.

In 1988, the National Institute for Occupational Safety and Health (NIOSH) determined that diesel exhaust as a whole was a potential occupational carcinogen. In 1990, the state of California concluded that diesel exhaust was known to cause cancer. By the mid-1990s, the American Conference of Governmental Industrial Hygienists had designated diesel exhaust a suspected human carcinogen. Back in California, the state's Air Resources Board (CARB) determined in 1998 that DPM is a toxic air contaminant. CARB also has concluded that DPM accounts for about 70% of the total toxic air pollutant risk for Californians. In its 2001 *Ninth Report on Carcinogens*, the National Toxicology Program classified DPM as "reasonably anticipated to be a human carcinogen."

The EPA labels diesel exhaust as "likely to be carcinogenic to humans" and an air toxic. However, the agency is waiting on results from ongoing studies before it assigns a numerical value to the risk posed by DPM. "EPA hasn't chosen to adopt [CARB's] values," says Charles Ris, deputy director of the EPA's National Center for Environmental Assessment in Washington, D.C. "We don't feel as comfortable about the data as they apparently do." However, in its 2000 rules for heavy-duty highway engines and the recently released NATA, the EPA concluded that the average lifetime cancer risk from diesel exhaust may fall into the range of 1 in 100,000 to 1 in 1,000, far higher than its goal of 1 in 1 million.

The Puget Sound Clean Air Agency came to a conclusion similar to CARB's in its *Puget Sound Air Toxics Evaluation*, released in May 2002, finding that 70–85% of the Seattle area's air toxics risk comes from diesel exhaust. "We feel pretty comfortable about the results," says executive director Dennis McLerran. But the findings themselves are disconcerting, he adds, in part because diesel exhaust "crosses the boundary between cancer and noncancer risk."

The EPA first established a standard for DPM in 1982, limiting emissions to 0.60 g/mi for cars and light-duty trucks. That was ratcheted down in 1987 to 0.20 g/mi for cars and 0.26 g/mi for light-duty trucks. In 1988, the EPA added a standard for heavy-duty trucks of 0.60 g per brake horsepower-hour (bhp-hr; a measure of emissions based on the size of the engine and how long it runs). A 1991 standard of 0.25 g/bhp-hr for heavy-duty trucks and 0.10 g/bhp-hr for buses followed. By 1994, that standard had been cut to 0.10 g/bhp-hr for regular engines and 0.07 g/bhp-hr for urban buses. It will drop to 0.01 g/bhp-hr by 2007, following a series of court battles ending in May 2002. Reduced standards for nitrogen oxides and nonmethane hydro-

On the road—and under it. Regulators are looking to limit the health effects of diesel from both transportation sources and uses in activities such as mining, where workers are exposed to dangerous levels of particulates.

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carbons also will be phased in through 2010.

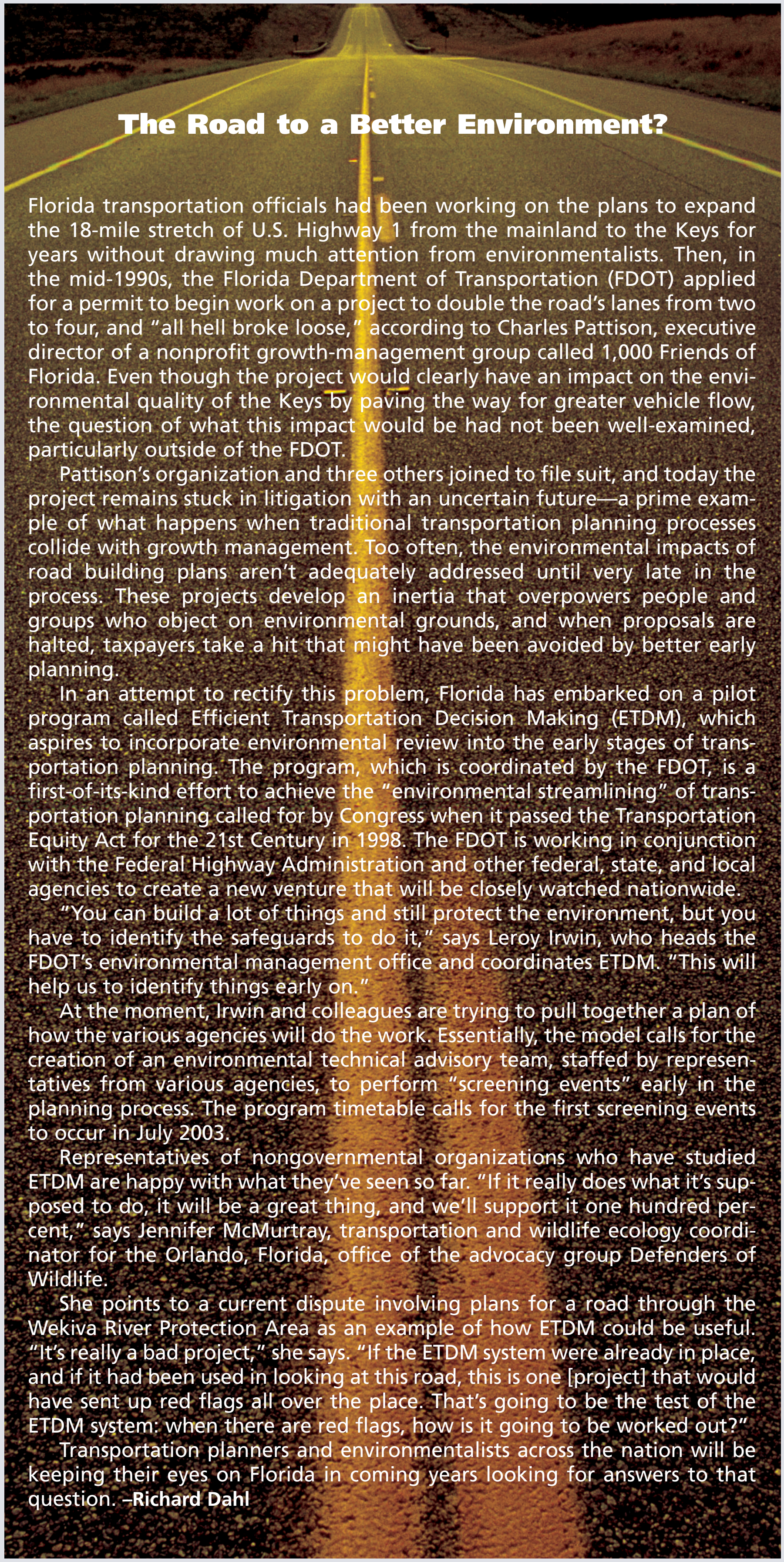
According to the EPA, when all of these standards are fully implemented and when most older engines are phased out, roughly 25–30 years from now, emission reductions should lead to the annual prevention of 8,300 premature deaths, 386,000 episodes of respiratory symptoms in asthmatic children, 360,000 asthma attacks, 2,400 emergency room visits for asthma, 17,600 cases of acute bronchitis, 5,500 cases of chronic bronchitis, 7,100 hospitalizations, and 1.5 million lost workdays.

Much of the fine particulate matter causing nonattainment of EPA standards (25–32% in metro areas such as Denver and Los Angeles) comes from heavy-duty diesel trucks and buses, says the National Research Council in its April 2002 report *The Congestion Mitigation and Air Quality Improvement Program: Assessing 10 Years of Experience*. As a result, the report states, counties, and cities likely will be motivated to force diesel engine operators to cut their particulate emissions to help jurisdictions comply with a state implementation plan required by the Clean Air Act.

In addition, as part of the same series of EPA proposals and court battles, the sulfur content of diesel fuel will drop from its current maximum of 500 parts per million (ppm) to 15 ppm by 1 June 2006. Low sulfur content is a key component in reducing DPM, says Kittelson, because sulfur plays an important role in the formation of many of the nanoparticulates that coalesce after they are emitted. At the same time, low sulfur content is mandatory for the new generation of emission control devices now under development to work effectively.

A smattering of low-sulfur fuel already is available, and a May 2001 study by the DOE's Energy Information Administration titled *The Transition to Ultra-Low-Sulfur Diesel Fuel: Effects on Prices and Supply* suggests that adequate supplies should be available by 2006 when the new standards begin to kick in. However, Jim Williams, products issues manager for the Washington, D.C.–based American Petroleum Institute, says the issue is still in doubt, and may be significantly influenced by any new rules for off-road engines.

The EPA is planning to submit a proposed rule for off-road diesel engines to the Office of Management and Budget for interagency review by the end of 2002. Frank O'Donnell, executive director of the Clean Air Trust, a Washington, D.C.–based nonprofit organization, is looking forward to seeing the effort move forward. "We think the public health benefit will be even greater than for on-road engines," he says.



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The Road to a Better Environment?

Florida transportation officials had been working on the plans to expand the 18-mile stretch of U.S. Highway 1 from the mainland to the Keys for years without drawing much attention from environmentalists. Then, in the mid-1990s, the Florida Department of Transportation (FDOT) applied for a permit to begin work on a project to double the road's lanes from two to four, and "all hell broke loose," according to Charles Pattison, executive director of a nonprofit growth-management group called 1,000 Friends of Florida. Even though the project would clearly have an impact on the environmental quality of the Keys by paving the way for greater vehicle flow, the question of what this impact would be had not been well-examined, particularly outside of the FDOT.

Pattison's organization and three others joined to file suit, and today the project remains stuck in litigation with an uncertain future—a prime example of what happens when traditional transportation planning processes collide with growth management. Too often, the environmental impacts of road building plans aren't adequately addressed until very late in the process. These projects develop an inertia that overpowers people and groups who object on environmental grounds, and when proposals are halted, taxpayers take a hit that might have been avoided by better early planning.

In an attempt to rectify this problem, Florida has embarked on a pilot program called Efficient Transportation Decision Making (ETDM), which aspires to incorporate environmental review into the early stages of transportation planning. The program, which is coordinated by the FDOT, is a first-of-its-kind effort to achieve the "environmental streamlining" of transportation planning called for by Congress when it passed the Transportation Equity Act for the 21st Century in 1998. The FDOT is working in conjunction with the Federal Highway Administration and other federal, state, and local agencies to create a new venture that will be closely watched nationwide.

"You can build a lot of things and still protect the environment, but you have to identify the safeguards to do it," says Leroy Irwin, who heads the FDOT's environmental management office and coordinates ETDM. "This will help us to identify things early on."

At the moment, Irwin and colleagues are trying to pull together a plan of how the various agencies will do the work. Essentially, the model calls for the creation of an environmental technical advisory team, staffed by representatives from various agencies, to perform "screening events" early in the planning process. The program timetable calls for the first screening events to occur in July 2003.

Representatives of nongovernmental organizations who have studied ETDM are happy with what they've seen so far. "If it really does what it's supposed to do, it will be a great thing, and we'll support it one hundred percent," says Jennifer McMurtray, transportation and wildlife ecology coordinator for the Orlando, Florida, office of the advocacy group Defenders of Wildlife.

She points to a current dispute involving plans for a road through the Wekiva River Protection Area as an example of how ETDM could be useful. "It's really a bad project," she says. "If the ETDM system were already in place, and if it had been used in looking at this road, this is one [project] that would have sent up red flags all over the place. That's going to be the test of the ETDM system: when there are red flags, how is it going to be worked out?"

Transportation planners and environmentalists across the nation will be keeping their eyes on Florida in coming years looking for answers to that question. **–Richard Dahl**

"But we expect the usual resistance from some companies." Schaeffer says the topic "clearly will be important." But the range of engine types that may be covered is so huge—from riding lawn mowers to mining trucks—that he and the companies he helps represent are waiting to see the proposed rules before determining their course of action.

The U.S. Mine Safety and Health Administration (MSHA) says that about 34,000 subsurface workers are exposed to diesel exhaust from more than 10,000 engines, and about 200,000 surface miners are exposed to diesel exhaust from some 120,000 engines. Mean ambient DPM readings in subsurface mines have been as high as 830 μg/m^3, with peak concentrations up to 5,570 μg/m^3, MSHA reports in the latest edition (1997) of its publication *Practical Ways to Reduce Exposure to Diesel Exhaust in Mining—A Toolbox*. MSHA adopted new rules in 2001 that, while not specifically addressing the size of particulates, do set maximum total carbon concentrations at 400 μg/m^3 beginning in July 2002, dropping to 160 μg/m^3 in five years. Industry representatives are challenging portions of the rules in court.

Retrofitting and Looking Forward

Although the new standards are expected to reduce DPM significantly for highway-use engines, millions of older diesel engines, with the numbers boosted by a substantial rise in purchases before the 2002 standards take effect, will still be operating for decades. To help reduce those emissions somewhat, the EPA, as well as agencies in states such as California, Washington, New York, and New Jersey, are pushing voluntary retrofit programs. The EPA is about three-quarters of the way toward its goal of getting commitments for 100,000 vehicle retrofits. Participants are primarily public agencies, which are retrofitting buses, ferries, refuse haulers, and other vehicles.

Methods for retrofitting engines with emission control devices have not been standardized, but include installation of particulate filters or oxidation catalysts. For heavy-duty vehicles, the most promising devices for both new and retrofit applications appear to be catalytic particulate filters, says Scott Wayne, director of the Transportable Heavy-Duty Vehicle Emissions Testing Laboratory at the West Virginia University Department of Mechanical and Aerospace Engineering. They tend to cut the mass of particulates emitted by more than 95% while also slashing hydrocarbons and carbon monoxide. However, they still have problems knocking down nitrogen oxides, the bane of any remedy tested so far. And they produce a small amount of ash, which will qualify as hazardous waste under certain standards.

For light-duty diesel vehicles, officials at the DOE are coordinating research on a different system—a microwave-regenerated particulate exhaust filter. Typical catalytic methods don't work on light-duty engines, because the engines don't operate at high enough temperatures. The microwave filter uses a silicon carbide fiber that converts microwave energy to heat, allowing the filter to operate at high enough temperatures either while running or during unavoidable cold starts. The method is showing some promise, says Kathi Epping, manager of diesel combustion and emission control research and development in the DOE's Office of Advanced Automotive Technologies.

Although it's early in the process to fully understand how any of these devices will perform, many of the players like what they see so far. "The filters are very, very effective," says Kittelson. "I'm pretty optimistic." But some observers aren't sold yet. "There may be problems with finer particulates," says Billings. "There's an area that clearly needs some more attention. We need to be vigilant about what the potential impacts are."

The pace of retrofitting may pick up a little in a few years. With the EPA's $PM_{2.5}$ standard for ambient air that is now in effect—15 μg/m^3 annually and 65 μg/m^3 for 24 hours—the agency likely will designate about 120–170 counties for nonattainment when it completes its review process in 2004 or 2005, says John Bachmann, the EPA's associate director for science policy. General areas of concern are the East Coast, the upper Midwest, and California.

An alternative to retrofitting may be new engines that eat their grains and vegetables, as some of Rudolf Diesel's did more than a century ago. Biodiesel, which can be derived from soybeans, switchgrass, corn, and many other crops, can reduce particulate emissions by more than 55% compared to regular diesel, according to a February 2000 DOE report, *Biodiesel: Clean, Green Diesel Fuel*.

Even when just 20% of a blended fuel is biodiesel, as it often is to reduce costs, particulate emissions drop about 18%. Carbon monoxide, hydrocarbons, and air toxics also drop substantially with either 100% or 20% blends, although nitrogen oxide emissions rise a little with both. Switching to biodiesel can cause problems such as deterioration of gaskets and clogging, but the National Biodiesel Board, based in Jefferson City, Missouri, says those problems can be addressed fairly easily with proper maintenance and monitoring practices.

Despite all the recent and projected improvements to diesel engines, there still will be some emissions. Even these may be cut somewhat by using transitional power systems that are now starting to catch on. Prototypes of diesel–electric and natural gas–electric hybrids are under development and on the road. Also on the horizon are hydrogen-powered fuel cells, which are expected to have very low emissions of toxic substances.

But with so many diesel engines already in use, and the prospect that many more potentially cleaner ones will go out the door soon, diesel manufacturers are sticking with what they know. "There's very clearly a strong future for diesel," says Schaeffer. "It's really woven into the fabric of life here."

Bob Weinhold

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Better diesel? Biodiesel made from plant crops may be a clean and efficient alternative.