Cleaner Air, Better Performance:

Strategies for Upgrading and Modernizing Diesel Engines

May 2003

Diesel Technology Forum
www.dieselforum.org
Cleaner Air, Better Performance: Strategies for Upgrading and Modernizing Diesel Engines

The Diesel Technology Forum is the nation’s leading information resource on and promoter of clean diesel technology, its value, economic importance, environmental progress and promise for the future. The Forum promotes clean diesel solutions for new diesel engines (on/off road), conducts technology demonstrations and works with stakeholders to modernize and upgrade existing diesel engines. Members include leaders in diesel engine, vehicle and component manufacturing, fuel refining, and emissions treatment systems.
# Table of Contents

EXECUTIVE SUMMARY ........................................................................................................... i

THE ISSUE: NEW VERSUS EXISTING DIESEL ENGINES ............................................... 1
  Reducing Emissions from New Diesel Engines................................................. 1
  Air Quality Impact from Existing Diesel Engines................................. 2
  Reducing Emissions from Existing Diesel Engines................................. 2

EMISSIONS PERFORMANCE ENHANCEMENT OPTIONS ........................................ 4
  Repair/Rebuild: Tune-up for Emission and Fuel Economy Benefits .................................................. 4
  Refuel ......................................................................................................................... 6
  Retrofit: Exhaust Aftertreatment and Engine Modification Technologies .................................................................................................................. 9
  Engine Repower and Vehicle Replacement: Advanced New Engine Technologies for Existing Equipment... 12

IMPLEMENTING EMISSION PERFORMANCE ENHANCEMENTS ...................... 13
  Feasibility Analysis and Start-up Issues............................................................ 13
  Technical Resources .......................................................................................... 14
  Incentives and Funding Resources .................................................................. 14
  Cost Effectiveness .............................................................................................. 20

EXPERIENCE IN THE FIELD: CASE STUDIES ......................................................... 21
  Urban Buses: New York City Transit ................................................................. 21
  Construction Equipment: Boston's Big Dig ..................................................... 23
  Freight Trucks: ARCO/BP & Ralph's Grocery .............................................. 24

ENDNOTES ......................................................................................................................... 28
Executive Summary

America needs diesel engines and cleaner air; advanced clean diesel technology offers both. Diesel power drives the economy by building our nation's infrastructure of roads and bridges, taking crops from the field to food on the table and providing vital transportation of people and goods in the most efficient and cost effective manner possible. Clean diesel is the result of tremendous advancements in diesel engine emissions control technology, as engines manufactured today are dramatically cleaner than those built just a few years ago.

The future looks even cleaner. Industry is committed to developing a new generation of truck and bus engines that will virtually eliminate regulated emissions by 2007. The technologies and advancements to meet new engine standards in 2007 are creating opportunities to address emissions from existing diesel engines used both in on- and off-road equipment. This Diesel Technology Forum (DTF) white paper provides a primer on potential strategies for upgrading and modernizing existing diesel engines and off-road equipment. It covers four main topics:

(1) the difference between new and existing diesel engines in terms of emission reduction potential;

(2) opportunities for upgrading emissions performance – rebuilding, refueling, repowering, retrofitting and replacing;

(3) key project start-up issues and an outline of technical and financial resources that are available to facilitate retrofit projects; and,

(4) specific examples of successful diesel engine emission reduction projects involving a variety of vehicle categories.

New versus existing diesel engines. Heavy-duty diesel engines manufactured today for trucks and buses produce one-eighth the emissions than those built a dozen years ago. New clean diesel technology offers significant air quality benefits.

Due to the inherent durability of diesel engines, however, existing older diesel vehicles will be in service for many more years. Therefore, there is increasing interest in the air quality and performance benefits from modernizing and upgrading existing engines. These enhancements may serve to reduce emissions of PM (particulate matter) and NOx (oxides of nitrogen) by targeting these older vehicles' emissions. Modernizing and upgrading existing engines and equipment is a creative alternative to traditional regulatory approaches which have focused exclusively on new engine standards, and in some cases, can achieve significant, cost-effective emissions reductions.

Emissions performance enhancement options. Emissions performance enhancement options include:

- **Repair/Rebuild** - regular engine maintenance plays a critical role in maintaining emissions performance while engine rebuilding can upgrade emissions performance of older engines.

- **Refuel** - use of advanced diesel fuels such as Ultra-low Sulfur Diesel (ULSD) can lower emissions; some other fuel products such as emulsifications and renewable alternative fuels are being explored for similar potential.
• **Retrofit** - the installation of exhaust aftertreatment technologies such as particulate filters, oxidation catalysts, exhaust gas recirculation (EGR), selective catalytic reduction (SCR) devices, and NO\textsubscript{x} catalysts;

• **Repower** - replacing the older engine in diesel-powered equipment with a new clean diesel engine, which can dramatically reduce emissions while using currently available diesel fuel; and,

• **Replace** - replacing entire vehicles or equipment may be the best option for some of the oldest, heaviest emitting vehicles. State-of-the-art diesel technology can greatly reduce the overall emissions of a vehicle or equipment fleet.

Each of the approaches to modernizing and upgrading has its own advantages and disadvantages which are unique to each type of vehicle or piece of equipment and the desired air quality improvement goals and budgets.

**Implementing emissions performance enhancements.** Identifying the best candidates for upgrading in a diesel fleet—namely, matching the right engines with the appropriate enhancement technology—is crucial to a successful project. Technical resources and funding sources for emissions control and prevention projects are included on the DTF website, the U.S. Environmental Protection Agency’s (EPA’s) retrofit website and other state and federal government programs (information for these and other programs can be found on pages 14-17). Information about emissions credit trading programs are also available.

**Experience in the field.** Success with a number of high profile diesel emission reductions projects, such as the retrofit of construction equipment at Boston’s Big Dig Project, has encouraged efforts in other states. Several large-scale diesel engine emission reduction demonstration programs currently being completed are proving the effectiveness of these emission control mechanisms.

The Diesel Technology Forum maintains a searchable database of current and completed diesel emission reduction projects across the U.S. The final section to this white paper discusses three of the programs in detail, providing specific examples of projects that involve a variety of vehicle categories, including urban transit buses, off-road construction equipment and highway freight trucks.

Heavy-duty diesel engines manufactured today are significantly cleaner than those built just a short time ago. The EPA has adopted very stringent regulations for on-highway and off-highway diesel engines. These rules for highway trucks will require significant NO\textsubscript{x} reductions starting in 2004, and will virtually eliminate emissions of concern from new on-highway heavy-duty diesel engines by 2010. Similarly, more stringent emissions standards for off-road construction, agriculture, marine and locomotive equipment have been adopted since 1996, with additional reductions to be proposed in 2003.

This paper explores the potential to achieve emissions reductions by modernizing and upgrading existing diesel vehicles. These enhancements include the installation of exhaust aftertreatment technologies like particulate filters and oxidation catalysts (Retrofit), and other strategies such as proper engine maintenance (Repair/Rebuild), use of lower sulfur diesel fuel (Refuel), replacing engines (Repower), and replacing entire vehicles with new clean diesel technology (Replace).
The Issue: New Versus Existing Diesel Engines

Reducing Emissions from New Diesel Engines

Diesel engines constitute the primary source of power used in heavy-duty applications throughout the nation. The widespread use of diesel engines in industries such as truck, bus, rail and marine transportation, agriculture, construction, mining, and electric power generation can be attributed to the inherent performance advantages of diesel technology – powerful output, excellent fuel efficiency, better safety, low operating temperatures and superior durability.

Less recognized are the inherent environmental advantages of diesel engines. Compared to gasoline engines, diesels emit less carbon monoxide (CO), hydrocarbon (HC) and carbon dioxide (CO₂). The perception of the diesel engine as “dirty” is based on the comparatively higher levels of particulate matter (PM) and nitrogen oxides (NOₓ) emitted by older diesel engines.

In recent years, however, the diesel industry has made significant progress in developing technologies to greatly reduce PM and NOₓ emissions from new diesel engines. Diesel engines manufactured today emit 83 percent less particulate matter and 63 percent less NOₓ than they did in 1988. Moreover, the EPA’s new regulations will require even further reductions of PM and NOₓ emissions from these engines. For on-highway heavy-duty diesel engines built beginning in model year 2007, the new regulations will require reduction of both PM and NOₓ emissions by 98 percent from their 1988 levels – constituting virtual elimination of these emissions. Figures 1 and 2 show the significant progress made over the years in reducing PM and NOₓ emissions from new on-highway heavy-duty diesel engines.

By 2007, ultra-clean diesel technology will be widely available, and the environmental trade-off of using diesel engines will no longer exist. Diesels will be the obvious choice not only for inherently high performance and inherently low emissions of CO, HC and CO₂, but also for the low PM and NOₓ emissions made possible by the latest diesel technologies.

Figure 1: Continuous Improvement of On-Highway Heavy-Duty Diesel Engine PM Emissions Standards
(measured in grams/brake horsepower-hour)

<table>
<thead>
<tr>
<th>Model Year</th>
<th>PM (g/bhp-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>0.6</td>
</tr>
<tr>
<td>1991</td>
<td>0.5</td>
</tr>
<tr>
<td>1994</td>
<td>0.4</td>
</tr>
<tr>
<td>2007</td>
<td>0</td>
</tr>
</tbody>
</table>

98% Reduction

Source: The U.S. Environmental Protection Agency
Air Quality Impact from Existing Diesel Engines

Air quality will surely benefit from the clean diesel engines that will soon enter the marketplace. As noted above, diesel engines are well known for their superior durability. In fact, a well-maintained diesel engine can be operated for 20-30 years and power its vehicle for more than one million miles in many applications. Although new diesel engines built after 2007 will be ultra-clean, there remains an opportunity to address existing equipment and the nation’s current fleet of more than five million diesel trucks. As a demonstration of the continuing impact of today’s existing diesel fleet, Figure 3 depicts EPA’s projection into the future of total Vehicle Miles Traveled (VMT) by heavy-duty on-highway diesel engines built before 2007, and therefore not subject to the Agency’s stringent standards for post 2007 engines.

As shown in Figure 3, engines manufactured prior to 2007 will continue to power the economy until 2036. The benefits of recent regulations, improved technologies and reduced emissions will be realized as older diesels reach the end of their useful lives. New engines introduced during this time will be cleaner. Emissions standards for 2004 will cut NOx emissions in half for on-highway diesel engines. Even though the newer diesel engines will help reduce emissions significantly, the potential for additional emissions reductions from older existing engines is great.

Reducing Emissions from Existing Diesel Engines

Given the prevalence and longevity of older diesel engines on the road today, there is increasing interest in reducing emissions from this equipment. As explained in the next section, several different aspects of the latest clean diesel technology can be applied to some older diesel engines, resulting in lower emissions of PM and NOx (an ozone precursor). These changes can in some cases bring the emissions profile of existing engines closer to those clean diesel engines under development to meet 2007 new engine standards.

The cost of diesel engine enhancements is highly variable based on the age of the engine and the equipment or vehicle, as well as the nature of the enhancements. They typically range from several hundred dollars to tens of thousands of dollars. Therefore, large numbers of fleet owners cannot
be expected to undertake these projects without some type of outside incentive. In this case, however, the traditional mandatory approach to environmental regulation is not the appropriate mechanism to achieve the desired outcome.

Although EPA sets and enforces emissions standards for new diesel engines, EPA lacks the statutory authority to retroactively strengthen the standards for existing engines. Congress limited the Agency’s authority in this regard, because it would cause extreme hardship to require either vehicle owners/operators or engine manufacturers to conduct engine enhancements on millions of in-use vehicles across the nation – not to mention the huge logistical burdens that would result from attempting to enforce such a retroactive requirement.

While EPA cannot require owners and operators of diesel fleets to reduce emissions from their existing engines, there are several strategies that can be used to encourage voluntary emission reduction projects. These strategies include targeted subsidies, tax credits, emission credit trading programs and encouraging such projects to improve community relations or serve as air quality mitigation measures. These strategies are discussed in further detail later in this paper.

The concept of “retrofit” has typically been defined narrowly. The term is most often used as a label describing various exhaust aftertreatment devices. While exhaust aftertreatment technology represents a very promising category of solutions for in-use emissions reduction, it is only one of a number of options available for fleet owners. In addition to the retrofitting of aftertreatment devices, there is a full range of other options, including repairing/rebuilding, refueling, repowering and replacing existing equipment.

There is a wide range of options available for modernizing and upgrading existing diesel engines and equipment. Each of the “Five Rs” has its own advantages and strengths that can be tapped to tailor an emissions reduction program to specific air quality improvement goals, budgets and equipment owners’ needs.
**Emissions Performance Enhancement Options**

*Repair/Rebuild: Tune-up for Emissions and Fuel Economy Benefits*

The simplest and least expensive way to reduce PM emissions from existing diesel engines is to ensure that they are properly tuned and maintained. Proper maintenance and tuning can significantly improve emissions by ensuring that fuel is completely burned during combustion, rather than being emitted as exhaust PM. Proper maintenance and tuning, performed regularly, can also reduce operating costs by improving fuel economy, eliminating unnecessary maintenance, and extending engine life.

There are many engine maintenance items that can have a dramatic impact on emissions, fuel economy and engine life. The most common maintenance issues include: restricted air filters, improper injection timing, clogged, worn or mismatched fuel injectors, faulty fuel injection pumps, defective or misadjusted puff limiters, low air box pressure, improperly adjusted valve lash or governors, malfunctioning turbochargers and aftercoolers, maladjusted fuel racks, defective air fuel controllers, poor fuel quality, improper driving gear and air manifold leaks.

---

**THE FIVE R’S OF DIESEL EMISSIONS REDUCTION**

- **REPOWER:** NEW ENGINE
- **REBUILD:** ENGINETUNE-UPS
- **REFUEL:** CLEANER DIESEL FUELS
- **RETROFIT:** EMISSIONS FILTERS/ CATALYSTS
- **REPLACE:** NEW EQUIPMENT
Modern diesel maintenance has become a high-technology proposition, which has brought increasingly sophisticated technologies to bear on the task of maintaining diesel engine performance. Engine and vehicle manufacturers are utilizing the latest in computer and video technology in their maintenance programs. Personal Digital Assistants (PDAs), streaming video and wireless technology are now available to help monitor and maintain today’s heavy-duty vehicle fleet. Support networks are now applying these sophisticated diagnostic tools to increase the emissions and performance gains that can be generated from proper maintenance. 15

A recent study co-sponsored by the EPA has begun to quantify the emissions reductions that can be derived from repair and maintenance of “gross smoke emitters” identified through in-use smoke opacity testing. 16 This study identified smoking in-use vehicles and tested them on a chas-

<table>
<thead>
<tr>
<th>Figure 4: Emissions Performance Enhancement Options*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate Matter</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td><strong>REPAIR/REBUILD</strong></td>
</tr>
<tr>
<td>Basic Emissions Tune-up4</td>
</tr>
<tr>
<td><strong>REFUEL</strong></td>
</tr>
<tr>
<td>Refueling 5</td>
</tr>
<tr>
<td><strong>RETROFIT - EXHAUST AFTERTREATMENT AND ENGINE MODIFICATION</strong></td>
</tr>
<tr>
<td>Diesel Oxidation Catalysts 7</td>
</tr>
<tr>
<td>Diesel Particulate Filters 8</td>
</tr>
<tr>
<td>Exhaust Gas Recirculation (EGR) 9</td>
</tr>
<tr>
<td>Selective Catalytic Reduction 10</td>
</tr>
<tr>
<td>Nox Catalysts</td>
</tr>
<tr>
<td><strong>REPOWER &amp; REPLACEMENT</strong></td>
</tr>
<tr>
<td>2002 Model Year Engine 11</td>
</tr>
<tr>
<td>2004 Model Year Engine 13</td>
</tr>
<tr>
<td>2007 Model Year Engine 14</td>
</tr>
</tbody>
</table>

* Not all technologies apply to both on- and off-road.
** Unit cost range estimates are provided to show the relative cost differences between technology options. The actual technology costs will vary depending on the unique circumstances of a particular installation. These estimates have been collected from the sources cited in the endnotes for each technology category.
sis dynamometer for various regulated emissions before and after conducting repairs that were intended to reduce opacity. The study included 20 vehicles that were tested both before and after repair. Engine model years ranged from 1986-1999 and gross vehicle weights ranged from 11,000 to 80,000 pounds. Most repairs involved fuel injectors, fuel pumps, fuel pump calibration, throttle control and injection timing. Repair costs ranged between $699 and $2,035 and the average repair cost was $1,088. The study found that on average, HC emissions were reduced 78 percent, CO was reduced 17 percent, and PM was reduced 40 percent. The study also found that repair of high opacity vehicles also tended to increase NO\textsubscript{x} emissions. This was expected because engine operating strategies that lower PM generally increase combustion efficiency and temperatures, and thus increase NO\textsubscript{x} emissions while decreasing PM. Conversely, deterioration of injectors, pumps, and other components lowers combustion temperature, reduce engine efficiency and also lowers NO\textsubscript{x} while increasing PM. While NO\textsubscript{x} emissions were increased after repair, they were elevated only to levels close to the original emissions standards.

**Refuel**

While repair and maintenance represent the simplest way to enhance emissions performance for individual vehicles, the use of advanced diesel fuels is another option that can deliver emissions reductions broadly throughout a centrally fueled fleet. There are a number of proven and emerging fueling alternatives.

**1. Ultra-low Sulfur Diesel:** Fuel with reduced sulfur content is the most popular refueling option. Fifteen ppm Ultra-low Sulfur Diesel (“ULSD”) has been adopted by the EPA as part of its heavy-duty on-highway regulatory program, which will begin implementation in 2006. In a number of regions of the country, ULSD is available today for use by centrally fueled fleets in voluntary emissions reduction programs. The primary purpose of lower sulfur fuel is to enable or improve the performance of aftertreatment technologies. Fuel sulfur tends to degrade the effectiveness and longevity of aftertreatment devices by inhibiting the function of catalysts and filters. However, reduced sulfur will also provide a small emissions benefit without additional aftertreatment, because a portion of PM emissions is comprised of sulfates, the formation of which is a direct function of the level of sulfur in the fuel. The quantity of emissions reduction from the use of ULSD alone will vary depending on the application, level of sulfur reduction, and other fuel characteristics of the replacement fuel (e.g., cetane number, aromatics, PNA).

In off-road equipment, significant fuel sulfur reductions can be achieved by simply switching from off-road fuel to today’s highway diesel fuel. Typical off-road diesel meets American Society for Testing and Materials (ASTM) specification D975, which sets a maximum sulfur level of 5,000 ppm. Fuel meeting this standard typically has a sulfur level of up to 3,000 ppm. Highway diesel fuel is regulated and has a maximum sulfur content of 500 ppm, with a typical average sulfur level of 300 ppm. Because highway diesel fuel is readily available, and because the baseline emissions from off-road equipment are relatively high, PM reductions from just switching from off-road fuel to current 500 ppm highway diesel can be very cost effective on a per-ton basis.

While ULSD-only emissions reductions for PM are relatively modest on a per-vehicle basis compared to aftertreatment retrofit,
ULSD emissions reductions can add up to greater fleet-wide savings because this strategy can be implemented across large numbers of fleet vehicles. While refuel-only emissions reduction programs may be desirable in some cases, the cost effectiveness of the refuel-only option should be carefully compared to programs that match both ULSD and aftertreatment.

The following are answers to some common questions about the impact of ULSD on engine performance and longevity.

**Will ULSD hurt my fuel economy?**

Some operators have questioned whether use of ULSD will result in reduced fuel economy. In general, as refiners remove sulfur from diesel, the fuel can have a slightly lower energy content. Fuel energy content in today’s diesel varies from refinery to refinery, and it varies between blend to blend within the same refinery. Accordingly, precise measurement of any potential fuel economy impacts requires carefully analyzing the vehicles’ fuel economy before and after a fuel change is challenging. The impact, if any, will vary from refinery to refinery and tank to tank based on refinery operating conditions, equipment, feedstocks and blend stocks.

In the Ralph’s Grocery pilot program, discussed later in the case studies section, the fuel economy of the class 8 tractor-trailers using ULSD (and catalyzed diesel particulate filters) was 3 percent lower than trucks running on ordinary highway diesel without aftertreatment. This was consistent with the reduced energy content of the ULSD, which ranged between 2.4 percent and 2.8 percent lower than the ordinary highway diesel. The energy content of recent ULSD formulations is closer to that of regular highway diesel. Even under the controlled conditions of this pilot program, the study sponsors were careful to note that the differences in fuel economy observed could have been due to other factors such as route, driver variability, trailer loads or other causes.

**Will ULSD hurt my engine?**

As refiners remove sulfur from diesel the lubricating properties tend to degrade. This is a well-known issue that the refining industry has been successfully addressing over the past decade through the use of lubricity additives. As refiners produce ULSD they may need to use more or slightly reformulated additives to ensure their finished diesel products meet engine lubricity requirements. ASTM is currently working to develop a lubricity standard for diesel fuels.

**Will ULSD cause fuel system seal leakage?**

In 1993, when the sulfur content of on-highway diesel fuel was reduced to 500 ppm, certain types of fuel system seals experienced leaks when run on some formulations of the new fuels. Certain properties of the new fuel formulation were incompatible with the rubber and elastomer seals and hoses used in older engines. The causes of this problem are now well understood by the refining industry, fuel injection manufacturers and engine manufacturers. The combined efforts of the refining industry (fuel formulation), and engine and fuel injection manufacturing industries (seal materials) have addressed the causes of the problems experienced in 1993, and these problems have been eliminated for new engines built since 1993. However, users should contact their original equipment manufacturers before using ULSD in older, pre-1994 engines to ensure that the fuel is compatible with certain engine components.

As with any aftermarket product or new fuel
specification, operators should consult with their original equipment manufacturer before switching to ULSD or switching from off-road to highway diesel in off-road equipment.

2. **Biodiesel:** Biodiesel is a term used to describe fuel derived from vegetable oils or animal fat that can be used in compression ignition engines. It is typically made from renewable agricultural products like soybeans. Biodiesel itself contains no petroleum, but it is commonly mixed with ordinary petroleum diesel to make biodiesel blends like B20. B20 is a blend of 20 percent biodiesel and 80 percent petroleum diesel. Straight non-mixed biodiesel (B100) can also be burned as fuel in diesel engines, but some biodiesel properties differ from standard diesel, and greater precautions need to be taken to ensure that the fuel is suitable for use.

Biodiesel proponents, like the National Biodiesel Board, claim that biodiesel provides significant environmental benefits although at an increased cost for fleet operators and consumers. Straight biodiesel is considerably more expensive than ordinary highway diesel, so total fuel costs will increase depending on the quantity of biodiesel in the blend used. Compared to today’s conventional diesel, the Biodiesel Board studies indicate that B20 blends reduced unburned hydrocarbons by 14 percent, carbon monoxide by 9 percent, and PM by 8 percent. Various studies report that NO\(_x\) emissions can actually be increased slightly, depending on the duty-cycle and blend used. Studies show that NO\(_x\) increases for B100 can range between 0-13 percent, and NO\(_x\) increases for B20 can range between 0-4 percent. Biodiesel has slightly lower energy content than typical petroleum diesel, so some reduction in fuel economy can also be expected depending on the ratio of the biodiesel blend.

Biodiesel proponents recommend that new users take precautions to ensure that fuel filters and systems do not become clogged during initial use. Biodiesel has a solvent effect that may release deposits that have accumulated on tank walls and pipes from previous petroleum fuel storage. The release of deposits may initially clog filters, but special precautions can be taken to deal with this issue. Over time, the solvent effect of biodiesel may also tend to soften and degrade certain types of elastomers and natural rubber compounds used in some diesel engines.

Fuel injection equipment manufacturers have also identified a number of potential performance and durability problems that can be associated with the use of biodiesel. The potential for such problems will depend on the precise composition, base stock, blend ratio and quality control of the biodiesel, as well as the type of equipment and application the fuel is used in. As with all aftermarket products and consumables, operators should also consult with their original equipment manufacturers to ensure that use of biodiesel is appropriate for their equipment and application.

The “World-Wide Fuel Charter,” published by auto and engine manufacturers, recommends against the use of diesel fuel that contains more than 5 percent biodiesel by volume. The recommendation is based on concerns about the effects of biodiesel on fuel viscosity, corrosion, and the compatibility of biodiesel with seals and fuel system materials.

3. **Other Fuel Products and Additives:** A number of other promising fuel products and additives are currently at the research and development stage. Additional research is needed to ensure compatibility with engines and engine components.
Fuel Emulsions: A number of companies are now developing fuel additives that are designed to reduce emissions without major engine modifications. A number of these products are “fuel emulsions” which allow normal diesel fuel to be blended with purified water to produce a stable homogeneous fuel emulsion. These products are continuing to be developed through field demonstration projects. Emulsion proponents claim that their products can reduce NO\textsubscript{x} emissions by 30 percent or more, depending on test-loads, and PM by up to 50 percent. The addition of water to diesel fuel can significantly reduce the energy content of the fuel, so a reduction in power and fuel economy can be expected from the use of these types of products.

E-Diesel and Oxydiesel: Research is also being done on mixtures of ethanol and petroleum diesel fuel. Ethanol is a bio-fuel produced from corn or other biomass. The blends, typically 10 percent ethanol, are known as “E-diesel” or “Oxydiesel.” E-Diesel proponents hope to demonstrate significant emissions reductions in addition to the other environmental and economic advantages linked to the use of renewable energy sources. These fuels are not likely to be commercially available in the near future due to performance and safety issues that have not been resolved.

As with all aftermarket products and consumables, users should consult with their original equipment manufacturers before using fuel emulsions, or experimental fuel alternatives.

Retrofit: Exhaust Aftertreatment and Engine Modification Technologies

Advanced exhaust aftertreatment and engine modification technologies, combined with ULSD, are the emissions reduction strategies with the potential for the most dramatic per-vehicle emissions reductions. As discussed below, these technologies can reduce key vehicle emissions by as much as 90 percent or more in some cases. The principal types of exhaust aftertreatment and engine modification are described below.

1. Oxidation Catalysts: Diesel oxidation catalysts have been used for more than 30 years, and are perhaps the most proven of the aftertreatment options. Over 1.5 million units have been installed on heavy-duty highway trucks built since 1994 and have operated successfully for hundreds of thousands of miles. The catalysts also have been used in off-road diesels around the world for over 20 years, with more than 250,000 units installed in the mining and materials handling industries. They have also been used extensively in retrofit applications on U.S. urban buses and on European highway trucks, with over 10,000 units installed over the last two years. Oxidation catalysts can be used with a wide variety of fuels, including conventional diesel fuel (without reduced sulfur), biodiesel, emulsified diesel and ethanol/diesel blends.

Manufacturers report that flow-through oxidation catalysts can reduce total PM by 20-50 percent. (Reductions of carbon monoxide and hydrocarbons in the range of 60-90 percent can also be achieved.) Oxidation catalysts have been used for more than 30 years, and are perhaps the most proven of the aftertreatment options. Over 1.5 million units have been installed on heavy-duty highway trucks built since 1994 and have operated successfully for hundreds of thousands of miles. The catalysts also have been used in off-road diesels around the world for over 20 years, with more than 250,000 units installed in the mining and materials handling industries. They have also been used extensively in retrofit applications on U.S. urban buses and on European highway trucks, with over 10,000 units installed over the last two years. Oxidation catalysts can be used with a wide variety of fuels, including conventional diesel fuel (without reduced sulfur), biodiesel, emulsified diesel and ethanol/diesel blends.

Manufacturers report that flow-through oxidation catalysts can reduce total PM by 20-50 percent. (Reductions of carbon monoxide and hydrocarbons in the range of 60-90 percent can also be achieved.) Oxidation catalysts have been used for more than 30 years, and are perhaps the most proven of the aftertreatment options. Over 1.5 million units have been installed on heavy-duty highway trucks built since 1994 and have operated successfully for hundreds of thousands of miles. The catalysts also have been used in off-road diesels around the world for over 20 years, with more than 250,000 units installed in the mining and materials handling industries. They have also been used extensively in retrofit applications on U.S. urban buses and on European highway trucks, with over 10,000 units installed over the last two years. Oxidation catalysts can be used with a wide variety of fuels, including conventional diesel fuel (without reduced sulfur), biodiesel, emulsified diesel and ethanol/diesel blends.

Manufacturers report that flow-through oxidation catalysts can reduce total PM by 20-50 percent. (Reductions of carbon monoxide and hydrocarbons in the range of 60-90 percent can also be achieved.) Oxidation catalysts have been used for more than 30 years, and are perhaps the most proven of the aftertreatment options. Over 1.5 million units have been installed on heavy-duty highway trucks built since 1994 and have operated successfully for hundreds of thousands of miles. The catalysts also have been used in off-road diesels around the world for over 20 years, with more than 250,000 units installed in the mining and materials handling industries. They have also been used extensively in retrofit applications on U.S. urban buses and on European highway trucks, with over 10,000 units installed over the last two years. Oxidation catalysts can be used with a wide variety of fuels, including conventional diesel fuel (without reduced sulfur), biodiesel, emulsified diesel and ethanol/diesel blends.
efficiency and filter regeneration units, but units are commercially available and currently being used in a number of retrofit projects in the U.S.

3. Exhaust Gas Recirculation: Retrofitting exhaust gas recirculation on diesel engines can produce significant NO\textsubscript{x} reductions. Over 400 EGR systems have been installed on in-use bus engines in Europe. EGR retrofit systems are now being installed in the U.S. on solid waste collection vehicles, buses and some city-owned vehicles. Technology demonstration programs have been conducted in Houston and Los Angeles, and additional demonstration programs are being planned in California. EGR reduces NO\textsubscript{x} by reducing the temperature at which fuel burns in the combustion chamber. Engines employing EGR recycle a portion of engine exhaust back to the engine air intake. The oxygen-depleted exhaust gas is mixed into the fresh air that enters the combustion chamber, which dilutes the oxygen content of the air in the combustion chamber. The reduction in oxygen produces a lower temperature burn, and hence reduces NO\textsubscript{x} emissions by as much as 40 percent. The recycled exhaust gas can also be cooled, which further reduces NO\textsubscript{x} emissions.

4. Selective Catalytic Reduction Devices: Selective catalytic reduction (“SCR”) is an-
other technology being developed that may have potential for vehicle retrofit application. SCR has been used to reduce NOₓ emissions from stationary sources for over 15 years. More recently it has been applied in retrofit projects on mobile sources including trucks and marine vessels.

SCR has been found to produce simultaneous reductions of NOₓ (75-90 percent), hydrocarbons (80 percent) and PM (20-30 percent). SCR is similar to an oxidation catalyst in that it initiates chemical reactions to eliminate pollutants without itself being changed or consumed. SCR goes beyond catalytic activity, however, by adding a reducing agent to the exhaust stream that converts NOₓ to nitrogen and oxygen. As the exhaust gases, along with the reducing agent (usually ammonia or urea), pass over a catalyst-coated substrate, NOₓ, HC and PM are converted to harmless emissions.

5. NOₓ Catalysts: A limited number of vehicles have been retrofitted with NOₓ catalyst systems on a pilot basis in the U.S. Currently, peak conversion efficiency is around 10-20 percent, but two catalyst technologies are being developed to reduce NOₓ emissions by up to 70 percent. The first, so-called “lean NOₓ catalyst” works like SCR in that it adds a reducing agent to the exhaust stream to facilitate catalytic conversion. Systems using lean NOₓ catalysts inject diesel fuel into the exhaust gas to add hydrocarbons. The hydrocarbons act as a reducing agent to facilitate the conversion of NOₓ to nitrogen and water vapor in the catalyst.

The second technology, known as “NOₓ Adsorber,” operates in two stages. First, the NOₓ is converted and adsorbed into a chemical storage site within the system. Then when the NOₓ adsorber becomes saturated, it is regenerated by adding extra diesel fuel to the exhaust stream. The addition of the fuel causes the NOₓ adsorber to work like a lean NOₓ catalyst – it converts the collected NOₓ into simple nitrogen and oxygen that is emitted from the system.

Aftertreatment may not be cost effective in some cases, and in others it may
not be technologically feasible. As with all aftermarket products, users should consult with their original equipment manufacturers before selecting and installing aftertreatment devices.

**Engine Repower and Vehicle Replacement: Advanced New Engine Technologies For Existing Equipment**

In some cases, the retirement and replacement of older diesel equipment and engines may provide the most practical and cost effective emissions improvements for a particular fleet. Replacement enables fleet operators to replace the emissions profile of their oldest and worst emissions performers with state of the art technology. This approach has been successfully applied in large municipal vehicle fleets with regular replacement programs and urban transit bus programs that have already implemented first generation aftertreatment under the EPA’s mandatory urban bus retrofit program.

Replacement of just the engine in diesel powered equipment, “repowering,” may be appropriate where a fleet operator has diesel powered equipment, like certain off-road equipment, with a useful life that is longer than the useful life of the engine itself. Engine and vehicle replacements may also be an appropriate alternative where ULSD is not available, because new engines have been engineered to dramatically reduce emissions while using the currently available diesel fuel. In some cases, however, engine replacement may not be cost effective. In all cases, equipment owners should consult original equipment manufacturers to ensure that the torque and horsepower of replacement engines are properly matched to the original application to prevent damage to the vehicle or equipment.

Significant emissions reductions can be achieved through the use of new diesel engines and equipment. Particulate matter emissions from new on-highway diesel engines have been reduced 83 percent since 1988. Emissions of nitrogen oxides have been reduced by 63 percent during the same time period.

These reductions have been accomplished largely through improvements in fuel delivery, the design of combustion chambers and turbocharging. Electronic fuel injection has permitted engine manufacturers to control fuel injection independently of engine speed, allowing injection to be optimized for emissions performance. In today’s engines, fuel is injected at very high pressures to ensure a more complete burn, and the timing of fuel injection can be varied to meet emissions goals under different operating conditions. Combustion chamber design has also been enhanced in a variety of ways. Turbocharging has also been widely adopted, and has been refined by the development of air-to-air charge cooling to reduce combustion temperatures.

New engines will continue to get cleaner. Emissions standards for 2004 will cut NOx emissions in half for on-highway diesel engines, effecting an 83 percent total reduction since 1988. By 2007, new engines will provide 98 percent reductions in both NOx and PM emissions over 1988 engines. Similarly, additional new engine emission standards for off-road equipment will be implemented in 2003, and will lower NOx and PM by 30-50 percent depending on engine category. Thus, aggressive engine and vehicle replacement programs will continue to provide increasingly significant air quality benefits over the next decade.
Implementing Emission Performance Enhancements

Feasibility Analysis and Start-up Issues

Creating a successful retrofit project begins with careful selection of engine candidates. Some engines and vehicle applications make much better retrofit candidates than others, and certain engines and vehicles may simply be inappropriate for investment in an upgrade. In other cases, retrofit may be technologically infeasible. Once appropriate candidates are identified, it is equally important to match those engines with the right enhancement technology. Proper technology matching helps ensure that emissions performance meets a project’s air quality improvement goals, and ensures that vehicle reliability is not negatively impacted.

The DTF recommends that potential project sponsors work closely with engine and equipment manufacturers to ensure that proper candidate selection and technology matching is achieved. Early and frequent consultation with engine and equipment manufacturers ensures that projects can benefit from the knowledge and resources that only original equipment manufacturers (OEMs) can provide relating to engine/equipment design parameters and field experience on similar projects.

Certain enhancement technologies require special prerequisites like ULSD or enhanced maintenance and monitoring requirements. Project sponsors should work with engine makers and technology vendors to identify these issues early in the process to ensure a successful program. The following are examples of the types of start-up issues that need to be addressed early in the planning stages of a project:

On-Board Backpressure Monitoring: Where exhaust aftertreatment technology is used, the user of the filters/catalysts will be responsible for servicing the filters/catalysts and therefore should consider using on-board monitoring of backpressure to protect the filter and the engine. The fact that aftertreatment has been installed on an engine will not void the engine maker’s warranty for factory defects in workmanship or materials; however, engine or exhaust system damage caused by improper servicing or sizing of the filters will generally not be covered by the warranty of the filter or engine maker.

Duty-Cycle and Service Intervals: Understanding the actual duty-cycle to which the filter will be exposed is critical for proper operation. Project sponsors should also work with the filter suppliers to determine service intervals and filter maintenance procedures for the fleet. The service interval is determined by considering the engine duty cycle, ash content of the lube oil, typical engine oil consumption and service environment.

Proper Installation of Aftertreatment: Many aftertreatment devices are intended to replace the original exhaust muffler, but are larger and heavier than most OEM mufflers.
Therefore, engineering may be required for proper installation and support of the filters when replacing the muffler for a specific truck and engine model. For example, the clamps and supports should be well engineered for long-term installation. Clearance between the filter system and the cab of the truck is also an issue. Depending on the age and configuration of the vehicles, customized installation hardware may be required. Experienced professional service technicians should always be used for the installation of hardware.

**Ultra Low Sulfur Diesel:** Where ULSD is required, it is important to ensure that only ULSD is used so that aftertreatment performance will not be inhibited. The use of higher sulfur diesel (greater than 15 ppm) in many catalyzed filters for a short period of time may not permanently damage the filters, but it will temporarily reduce the effectiveness of the catalyst in the filter. Therefore, maintaining fuel segregation is important. The most effective way to avoid misfueling would be to convert the entire fleet fueling facility to ULSD. Where that is not feasible, the use of segregated fuel storage tanks and lockable fuel caps has been proven effective in reducing misfueling. Additional planning must be undertaken where the trucks are not centrally fueled and there is a risk of offsite fueling with higher sulfur diesel. Education of drivers and fuelers is also very important.

**Technical Resources**

The EPA maintains an active retrofit website at [http://www.epa.gov/otaq/retrofit/index.htm](http://www.epa.gov/otaq/retrofit/index.htm). This site is a comprehensive source of information for retrofit project sponsors and includes summaries of technical resources available from both government and commercial sources. In addition, this site includes a full description of the EPA’s voluntary diesel retrofit program and retrofit technology verification process, as well as contact information for all sectors of the diesel industry, including engine makers, fuel refiners and aftertreatment makers.

**Incentives and Funding Resources**

State and local governments may use a number of different strategies to provide fleet owners/operators with incentives to undertake diesel engine emission reduction projects. In addition, different federal funding sources exist that states may use to help pay for such programs. Before turning to the specifics of such strategies, however, it will be helpful to understand how these programs can fit into the context of state government obligations under the Clean Air Act.

**1. State Obligations Under the Clean Air Act:** Diesel engine emission reduction strategies may be used by state and local governments to help meet their obligations under the Clean Air Act. Specifically, the EPA has set health-based National Ambient Air Quality Standards (NAAQS) for several common pollutants—including PM, NO\textsubscript{x} and ozone—but the individual states are tasked with developing and implementing strategies to meet these NAAQS. To this end, States must submit State Implementation Plans (SIPs) to the EPA that detail the specific measures they will use to attain and maintain compliance with the ambient standards. If the SIP does not provide for sufficient emission reductions, the EPA can step into the state’s role and impose its own wide-ranging restrictions on sources within the state. Moreover, if the state does not actually attain the air quality standards within a specified time period, it risks becoming ineligible for millions of dollars in federal highway funds.
There are many different emission reduction strategies that EPA will accept in a state’s SIP, and each of the strategies a state selects is assigned a specific “SIP Credit” that is put toward meeting the state’s air quality obligations. EPA policy allows 3 percent of the total emission reductions needed by a state to come from a category of clean air programs known as voluntary mobile source emission reduction programs.\textsuperscript{23} In certain situations, States may work with their Regional EPA Office to obtain credit for such programs that account for even more than 3 percent of the required reductions. In any case, voluntary mobile source programs can be an important aspect of a state’s overall air quality strategy. Such programs include diesel emission performance enhancements, which the EPA specifically encourages through its Voluntary Diesel Retrofit Program\textsuperscript{24} and its Guidelines for States on Establishing SIP Credits From Heavy-Duty Engine Retrofit Projects.\textsuperscript{25}

2. Federal Funds for State Programs:
Not only does the EPA provide a specific mechanism by which states can claim SIP Credit for their diesel engine emission reduction programs, but the federal government also provides several large sources of funds that state and local governments may use to implement these projects. The following selection of federal grant programs is not an exhaustive list of potential federal funding sources, and the availability of funds from these particular programs may vary from year to year, but it demonstrates that the federal government provides several sources of funds that can be used by state/local governments to implement diesel engine emission reduction programs. For additional grant program listings and updates, visit EPA’s Environmental Finance Program at http://www.epa.gov/efinpage/. Another resource is the DTF website, www.dieselforum.org, which includes a funding directory.

- **Congestion Mitigation & Air Quality (CMAQ) Improvement Program**

  The CMAQ Improvement Program provides approximately $1.5 billion per year in federal transportation funds to support state and local projects that reduce ozone, carbon monoxide, or PM-10 emissions from transportation sources. The program is administered by the U.S. Department of Transportation (USDOT) in consultation with the EPA, and is coordinated through each urban area’s lead transportation planning organization. Funding levels are determined by a legislative formula, and a state or local match of funds is required.

- **Office of Transportation and Air Quality (OTAQ) Program Funds and Mobile Source Outreach Assistance Grants**
  [www.epa.gov/OMSWWW/rfp.htm]

  EPA’s Office of Transportation and Air Quality is charged with reducing air pollution from mobile sources. OTAQ administers various grant programs from year to year that assist state and local governments in developing and implementing mobile source emission control programs. Eligibility and funding will depend on the specifics of the OTAQ Projects currently available.

- **Air Pollution Control Program Grants**
  [http://aspe.os.dhhs.gov/cfda/p66001.htm]

  Clean Air Act Section 105 establishes a federal grant program to assist state and local air pollution control agencies in developing, establishing, improving and maintaining air pollution control programs. The federal grant program is administered through the various EPA
Regional Offices, and can fund up to 60 percent of the specific state/local air pollution control program’s budget. Grants have ranged from $7,500 to $7 million per recipient, with an average of about $900,000.

- **Environmental Justice Through Pollution Prevention (EJP2) Program**
  [www.epa.gov/opptintr/ejp2/]

This program provides funds to non-profit organizations, tribes and local governments to encourage pollution prevention projects in minority and low-income communities. Among the 2001 grants awarded by this program, EJP2 funded a community business/government coalition that encouraged small public and private bus companies to reduce diesel emissions by using alternative fuel vehicles or conducting diesel engine retrofits. The program also funded efforts to reduce heavy-duty diesel engine emissions in another community by creating a Best Diesel Practices Program to educate fleet operators about cost-effective fuel and maintenance alternatives.

- **Regional Grants**
  [www.epa.gov/epahome/locate2.htm]

Each of EPA’s 10 regional offices administers a wide variety of grant programs for pollution control projects within the regional area. Eligibility and funding levels depend on the specifics of the grant programs currently available in each region.

3. **Funds Directly Available to Owners and Operators:** Government programs that provide direct funding subsidies or tax credits for voluntary diesel engine emission reduction enhancements are being developed and implemented by various state and local governments across the nation. Some of these programs take advantage of the federal funding sources described above; some are funded entirely by state sources such as the general budget or vehicle registration fees; and still others are funded through unique compliance programs that allow other sources of air pollution to pay into a funding pool for such projects in lieu of making their own emission reductions. No matter how they are funded, these programs assist diesel vehicle owners/operators in certain geographic areas undertake emission reduction projects. A few examples of these programs are listed below. The Diesel Technology Forum maintains a Retrofit Funding Directory of these programs at www.dieselforum.org/retrofit/funding.html. Please refer to the Retrofit Funding Directory for additional programs, program updates, and more detail regarding the programs discussed herein.

- **Diesel Particulate Trap Retrofit Program** (California’s South Coast Air Quality Management District)

A $1 million program that offers to fund 100 percent of the cost of purchasing and installing a particulate trap on heavy-duty on-road diesel vehicles (up to $8,000 per vehicle) plus an up-front contribution of $500 per vehicle to offset the incremental cost of low-sulfur diesel fuel.

![One example of a diesel particulate trap. (Photo courtesy of Johnson Matthey.)](Image)
• **Air Quality Investment Program**  
(California’s South Coast Air Quality Management District)

An alternative compliance program for large employers in the District that are subject to local Emission Reduction Targets. Rather than directly sponsoring initiatives to achieve their targets, employers may contribute money to a funding pool managed by the Air Quality Management District and made available for other mobile source emission reduction projects that demonstrate cost-effective emission control.

• **Heavy-Duty Engine Emission Reduction Incentive Program**  
(California’s San Joaquin Valley Air Pollution Control District)

A grant program that pays for the differential cost of purchasing, repowering or retrofitting heavy-duty diesel engines to reduce NO\(_x\) and/or PM emissions. Eligible funding categories include heavy-duty on-road vehicles, off-road equipment, locomotives, marine vessels and stationary agricultural irrigation pump engines.

• **Clean Diesel Initiative**  
(Oregon)

Provides a three-year state income tax credit worth up to 35 percent of the cost to conduct a diesel engine emission reduction project.

• **Emissions Reduction Incentive Grants Program**  
(Nonattainment areas in Texas)

Provides grants for the incremental cost of repowering or retrofitting heavy-duty on-road or off-road engines to reduce NO\(_x\) by at least 30 percent below the applicable federal standard.

• **Clean Vehicle Program**  
(Houston-Galveston Area – Texas)

Although focused primarily on encouraging the use of alternative fuel vehicles, this program is also open to funding 75 percent of the cost of diesel engine NO\(_x\) emission reduction projects. Eligible projects are selected on a competitive basis, considering cost-effectiveness.

• **Diesel Solutions Program**  
(Puget Sound Area – Washington)

A public/private coalition dedicated to retrofitting existing diesel engines in the region and increasing the availability of ULSD. Fleet owners/operators work with other coalition partners to secure retrofit funding from various sources.

In addition to these types of established programs that generally seek broad participation from area fleets, fleet owners/operators can work on an individual basis with federal or state government agencies and/or private entities that are interested in funding diesel emission pilot or demonstration programs.

Specifically, state agencies that are considering a diesel engine emission reduction program usually gain experience through a smaller pilot program, and fleet owners can offer to work with the agencies in this regard. Furthermore, the EPA sponsors several grant programs that fund pollution control development and demonstration projects. With the rapidly evolving nature of diesel engine retrofits, there are opportunities for fleet managers to become involved. For more information regarding pilot or demonstration programs, contact your state air...
4. Mobile Source Emission Reduction Credits: Several jurisdictions across the country have established a unique strategy to provide funding for mobile source emission reduction projects, while decreasing compliance costs for stationary sources such as power plants and manufacturing facilities. These states/localities have adopted emission credit trading programs that allow the voluntary participation of mobile source fleet managers who wish to generate and sell Mobile Source Emission Reduction Credits (MERCs). Such programs are a logical extension of the new-generation, market-based approaches to stationary source regulation that EPA has incorporated into several Clean Air Act Programs. The concept is to create a market in emission credits that stationary sources may purchase in lieu of meeting their own emission reduction obligations. Under such programs, sources that reduce their emissions beyond legal requirements generate emission credits that they may sell to other sources. These programs provide extra incentives to develop innovative emission control measures, and they encourage emission control where it is most cost-effective. In addition, some programs require stationary sources to purchase emission credits at more than a 1:1 ratio to satisfy their emission reduction obligations, thereby ensuring that the trade improves overall air quality even beyond the primary emission reduction requirement.

In implementing these programs, some states allow trading only among regulated stationary sources. However, EPA guidance allows states to include mobile sources in their trading programs. In states that adopt such a program, mobile source fleet managers can enter agreements to undertake emission reduction projects, and thereby generate MERCs that they can sell to stationary sources in need of emission credits. Effectively, stationary sources thereby pay fleet managers to conduct mobile source emission reduction projects. Depending on the market conditions and the cost of the mobile source project, fleet managers participating in such programs can make a profit simply by reducing their own emissions and selling the credits. Even if market conditions are less favorable, MERC programs offer a way to help pay for new equipment while improving a company’s environmental credentials.

MERC programs have been established in Arizona, California, Colorado, Delaware, Idaho, Louisiana, Massachusetts, Michigan, New Hampshire, New Jersey, New York, Pennsylvania, Texas and West Virginia. Although these programs have the potential to allow fleet managers to reduce emissions and improve public image while making money on the projects, the programs are still relatively new and the rules can seem quite complex. Therefore, due
either to unfamiliarity or uncertainty, there has yet to be significant participation by fleet managers in almost any of the MERC programs across the nation.

The major exception to this statement—where significant experience with MERCs has been gained—concerns the Otay Mesa Power Plant near San Diego. In order to obtain a New Source Review (NSR) pre-construction permit for this state-of-the-art 510 megawatt power plant, project planners were required to offset the projected NOx emissions with emission reduction credits (ERCs) obtained from other nearby sources. However, there were insufficient ERCs available from nearby stationary sources, so the electric utility took advantage of the San Diego County Air Pollution Control District’s MERC Program and secured the required credits from mobile source emission reduction projects. Specifically, the electric utility agreed to pay for the replacement of 120 existing heavy-duty diesel vehicles in a local refuse collection fleet with new natural gas or propane/diesel vehicles, and also agreed to pay for the repowering of certain San Diego Harbor marine vessels with natural gas or clean diesel engines. Using the MERCs generated by these diesel engine emission reduction projects, the electric utility was able to obtain its NSR permit, and southern California will receive a much-needed new source of power. Moreover, the project’s mobile source partners have received new equipment courtesy of the electric utility, and the project has received favorable publicity for improving air quality.

Working off of the experiences gained at the Otay Mesa Power Plant project, other major stationary sources across the country are now considering use of their state MERC programs. For instance, in New York City, Consolidated Edison is currently contemplating retrofitting the diesel engines on Staten Island ferries to earn NOx emissions reduction credits.

5. Contract Bidding Incentives: As just mentioned, the public’s perception of the diesel industry can greatly benefit from diesel engine emission reduction projects. In fact, the Massachusetts Department of Environmental Protection (DEP) has turned the positive publicity generated by diesel retrofits into the driving force behind its Clean Air Construction Initiative (CACI). The CACI was initiated as part of the Massachusetts Turnpike Authority’s Central Artery/Tunnel (“Big Dig”) Project, as discussed in the following case studies. Under the CACI, the Massachusetts DEP encourages public or private sponsors of large infrastructure and development projects to require construction contractors to retrofit their heavy-duty equipment before working on the project. It has been the DEP’s experience that project planners find the retrofits to be an effective mechanism to mitigate the air quality impacts of large-scale construction projects, thereby improving relations with project neighbors, environmental groups, and regulatory agencies. By making the retrofits part of the up-front contracting requirements, contractors can add the cost of the retrofits to their project bids. In this way, retrofit costs can be factored into the overall project budget as an environmental mitigation measure. Where project planners may otherwise face strong public opposition or government permitting hurdles, the air quality benefits of diesel retrofits can help allay the public’s concerns and assist applicants in obtaining government permits.

As explained in the next section, the CACI has had its greatest success in retrofitting construction equipment at Boston’s Big Dig Project. The retrofit initiative, however, is now expanding into several other large
infrastructure and development projects throughout the Commonwealth. In fact, as part of its role in reviewing the environmental impacts of large projects under the Massachusetts Environmental Policy Act, the Massachusetts DEP now “strongly encourages” participation in the CACI whenever construction projects call for a large concentration of diesel-powered equipment. The initiative has also sparked interest beyond the borders of Massachusetts. State governments and project planners across the nation have contacted the Massachusetts DEP to discuss the success of its program. The concept has been adopted into projects like the construction of an additional runway at Hartsfield International Airport in Atlanta. In addition, state officials have recently indicated that New York will require the use of ULSD and will retrofit certain construction and support equipment at the World Trade Center site.30

Diesel engine emission reduction programs are expected to grow quite quickly across the nation, as several large-scale demonstration programs are currently reaching maturity and proving to be very effective emission control mechanisms. In order to track the increasing number of such projects, the Diesel Technology Forum maintains a searchable database of current and completed diesel engine emission reduction projects across the United States (see “Retrofit Activity Matrix” at http://www.dieselforum.org/retrofit/activitymatrix.asp). Following are three of those programs described in detail, with specific examples of successful diesel engine emission reduction demonstration/pilot projects involving a variety of vehicle categories, including urban transit buses, off-road construction equipment and highway freight trucks.

Cost Effectiveness

The cost effectiveness of the various diesel emissions reduction options can vary significantly depending on the elements of a particular project. A wide range of factors will affect both the costs and benefits of a particular project, including: choice of technology, economies of scale, cost of capital, estimated equipment life, equipment usage rates and duty cycle.31

Although cost effectiveness is best evaluated on a case-by-case basis, the California Air Resources Board (CARB) has developed a significant amount of data on the cost effectiveness of engine replacements in reducing NOx emissions. Evaluating CARB’s experience may be instructive. CARB administers one of the country’s largest diesel engine improvement programs, and has attempted to quantify the costs and benefits of its three-year experience. Since 1999, the CARB’s “Carl Moyer Program” has distributed nearly $100 million in incentive grants to lower NOx emissions from heavy-duty diesel engines.

Regulatory agencies for severe or extreme ozone non-attainment areas would likely consider any NOx emissions reduction strategy costing less than $10,000 per ton to be cost effective.32 When measured against that criterion, the types of equipment upgrades funded by CARB’s program are found to be extremely cost effective. Using data from over 2,000 diesel applications, CARB judged the cost effectiveness of upgrading the engines on long-haul trucks to be $2,570 per ton of NOx reduced. For off-road equipment, CARB found that NOx reductions from farm equipment cost $4,179 per ton, and for construction equipment, the cost was $3,627 per ton.33
Urban Buses: New York City Transit

In February 2000, New York City Transit (NYCT) began a demonstration project to test the in-use performance of diesel engine retrofit technology and ULSD fuel in New York City urban transit buses. The demonstration program involved twenty-five Orion V model-year 1999 buses powered by Detroit Diesel Series 50 engines, retrofitted with Johnson Matthey PM filters, fueled with Equilon ULSD (< 30 ppm) and operated in rigorous transit service for 9-12 months. The objectives of the program were to test emissions performance of both retrofit and control-group buses, and to identify any effect that the retrofit technology may have on operational performance and vehicle reliability.

For its PM filters, NYCT chose the patented Continuously Regenerating Trap (CRT™) technology manufactured by Johnson Matthey, Inc. This retrofit device has no moving parts, requires no external energy source, and simply mounts in place of the original muffler/catalyst system. CRTs contain a platinum-coated oxidation catalyst followed by a ceramic PM filter. The catalyst oxidizes nitrogen monoxide (NO) into nitrogen dioxide (NO₂), which is then used to combust soot in the filter while staying within temperatures that are typical of standard diesel exhaust systems. In addition to reducing PM emissions, CRTs also reduce hydrocarbon (HC) and carbon monoxide (CO) emissions without increasing NOₓ or CO₂ emissions. As with other catalyzed particulate filters, CRTs must be used in combination with reduced sulfur fuel in order to minimize sulfate formation.

During one year of operating the 25 retrofitted buses over some of the most punishing urban service routes in the City, and accumulating up to 40,000 miles on any single bus, NYCT found that all of the CRTs continued to work properly throughout the entire period—causing no failures, no adverse effect on vehicle reliability and no measurable loss of fuel economy. Moreover, NYCT’s emissions testing showed that the CRTs achieved dramatic emission reductions.

![Figure 5: NYC Transit Bus Average Hydrocarbon Emissions (Central Business District Testing Cycle)](image)

**Source:** New York City Transit
reduction. For this emissions analysis, NYCT conducted a series of dynamometer tests on two buses—first with the original mufflers/catalysts and fueled with standard 350 ppm diesel (“baseline fuel”), then with the original mufflers/catalysts but fueled with 30 ppm low sulfur diesel, and finally retrofitted with the CRT and fueled with ULSD. Figures 5-7 show the results of this testing for average CO, HC, and PM levels emitted by the two buses under each of the three different testing parameters and operated over the Central Business District testing cycle (one bus was also tested over the New York Bus Cycle and showed even greater reductions). NYCT also tested for NOx and CO2, confirming that the CRTs caused no significant changes in these emissions.

Compared to original equipment buses fueled with standard diesel, the retrofitted buses fueled with ULSD produced an average 93 percent reduction in total HC, 94 percent...
reduction in CO, and 88 percent reduction in PM emissions. More detailed analysis of the PM reductions showed that particulate counts were reduced evenly across all size ranges, and that total PM emission levels from the retrofitted diesels were essentially equivalent to PM emissions from natural gas buses.\textsuperscript{36} NYCT also analyzed emissions of air toxics, and found that the CRT/ULSD combination reduced emissions of toxics by 70-99 percent, with emissions of several toxic substances reduced even below detection limits.\textsuperscript{37}

NYCT operates over 4,000 urban transit buses, constituting the largest bus fleet in North America.\textsuperscript{38} Its goal is to make this fleet the cleanest in the country, while improving passenger service and keeping within a limited budget. NYCT’s demonstration project has convinced transit managers that diesel engine retrofits and ULSD fuel will play critical roles in achieving those objectives. To begin implementing this plan, NYCT has already switched its entire diesel fleet to ULSD, thereby obtaining immediate air quality benefits. Moreover, NYCT has already installed catalyzed filters on more than 500 additional diesel buses, and plans to retrofit more than 3,500 buses with filters by the end of 2003.\textsuperscript{39}

(For additional information and links, see the DTF website at www.dieselforum.org/retrofit/nyctransit.html)

**Construction Equipment: Boston’s Big Dig**

The Massachusetts Department of Environmental Protection (DEP) developed its voluntary diesel retrofit program – known as the Clean Air Construction Initiative (CACI) – in response to the need to mitigate air quality impacts from construction activities at the massive Central Artery/Tunnel Project (otherwise known as the “Big Dig”) in central Boston. While the CACI has now expanded into several other large construction projects throughout Massachusetts, the diesel engine retrofit experience at the Big Dig will continue to serve as the program’s model.

The $14 billion Big Dig highway construction project constitutes the nation’s largest public works initiative. Its location through the heart of central Boston not only presented enormous engineering challenges, but also raised significant concern regarding localized air quality impacts. In order to mitigate these air quality concerns, the Massachusetts Turnpike Authority (MTA) agreed to enter a cost sharing agreement with its contractors to pay for the retrofit of on-site heavy-duty construction equipment.

The program began in September 1998 with the initial retrofit of ten pieces of construction equipment, soon followed by an additional 60 retrofits. The retrofit technology consisted of oxidation catalysts and/or particulate filters installed on equipment such as front-end loaders, backhoes, cranes, and excavators. Contractors at the Big Dig have found that the retrofitted equipment does not experience any significant loss of power, does not contribute to adverse operational problems and does not increase maintenance costs. Furthermore, engine manufacturers are continuing to honor engine warranties on the retrofitted equipment.

Project managers and regulatory agencies have also been very pleased with the retrofit experience. Preliminary estimates indicate that the 70 initial retrofits have decreased emissions by about 36 tons/year of CO, 12 tons/year of HC, and three tons/year of PM. In addition, the retrofit technology is also reducing odor and noise levels generated from the construction equipment. Estimating that
the equipment will be used on the site for five years after retrofit, project managers expect to reduce total construction emissions by approximately 200 tons—which is equal to eliminating 96 million diesel truck miles or removing 1,300 urban diesel buses for one full year. Furthermore, because the retrofit technology will stay with the equipment after the Big Dig is completed, additional air quality benefits will be achieved at subsequent construction projects.

Retrofit costs have ranged from about $1,000 – 3,000/vehicle, with an average cost of about $2,500/vehicle. Even at the higher end of $3,000/vehicle, these retrofits have resulted in a cost-effectiveness ratio of about $1,000 per ton of pollution removed. Not only does $1,000/ton represent a relatively low cost for pollution control, but because many of the construction vehicles themselves cost around $250,000, an extra $3,000 for the retrofit device is not a significant additional expense.

Encouraged by the reduction in emissions, reduced odor and noise, good equipment performance, and low cost, project officials have now decided that all major construction equipment at the Big Dig—about 250 pieces—will be retrofitted with aftertreatment emission control devices. In implementing these plans, state officials plan to take advantage of recent advances in retrofit technology that enable significant reduction not only in CO, HC and PM emissions, but will significantly reduce NO\textsubscript{x} emissions as well. After these retrofits have taken place and the state can demonstrate significant NO\textsubscript{x} reductions, the Massachusetts DEP plans to apply for SIP credits during its next ozone SIP review.

The retrofit experience at the Big Dig has been very positive for all involved. Project managers have benefited from improved public relations and fewer regulatory hurdles. Project contractors have found that the retrofits improve working conditions and cause no adverse effects on equipment performance. Project neighbors and construction workers have benefited from dramatically reduced localized emissions, and everyone in the area has benefited from reduced concentrations of carbon monoxide, hydrocarbons and particulate matter in the ambient air.

**Freight Trucks: ARCO/BP & Ralph’s Grocery**

ARCO, a BP company, recently completed a large-scale demonstration program to analyze the performance of heavy-duty diesel vehicles fueled with ARCO’s new ultra-low sulfur Emission Control Diesel (ECD or EC-Diesel) and retrofitted with continuously regenerating particulate filters. This initiative, known as the EC-Diesel Technology Validation Program, was a one-year program that gathered data on eight different diesel fleets in southern California. The program received significant contributions from a number of government and industry partners. The purpose of the program was to analyze whether EC-Diesel would enable the retrofitted vehicles to achieve significant emission reductions over the course of a year, while also studying any effects on fuel...
economy and maintenance requirements. The wide variety of diesel fleets involved in ARCO’s program included grocery trucks, fuel tankers, sanitation trucks, transit buses and school buses. The results showed dramatic emission reductions in all of these categories. This discussion, however, will focus on that aspect of the demonstration program that studied the ECD/retrofit experience of large freight trucks owned and operated by Ralph’s Grocery. Not only are these tractor/trailers representative of a large population of similar trucks across the country, but ARCO chose to test more vehicles and run more extensive tests on this particular fleet.

The Ralph’s Grocery test fleet included 20 identical Class 8 Sterling L-Line tractor/trailers with an 80,000 lb. gross vehicle weight rating, powered by 1998 Detroit Diesel Series 60 engines. The trucks all made very similar daily trips between distribution centers and grocery stores, traveling over city, suburban, and highway routes. At the beginning of the testing period in January 2000, all 20 of the trucks had accumulated similar mileage of around 150,000 miles.

The trucks were evenly divided into four testing groups. The control group consisted of five trucks that retained their original muffler systems and were fueled with standard CARB diesel (about 120 ppm sulfur). Five other trucks also retained their original muffler systems, but were fueled with ECD (less than 15 ppm sulfur). Five of the trucks were retrofitted with Engelhard catalytic soot filters (DPX™) and fueled with ECD. Finally, five trucks were retrofitted with Johnson Matthey Continuously Regenerating Traps (CRT™) and also fueled with ECD.

Both the DPX and the CRT retrofit devices are catalytic particulate filters that form NO₂ in order to combust filtered exhaust pollutants under the relatively low temperatures that are typical of diesel exhaust systems. Both filters should be used with low sulfur (< 50 ppm) diesel fuel in order to minimize sulfate formation and maximize filter regeneration. Both devices are “passive,” meaning there is no need for engine modification or an active control system. The DPX contains a platinum and base metal oxide catalyst coating impregnated into the porous walls of a ceramic filter. As described previously in the New York City Transit Bus section, the CRT is a two-stage system containing an oxidation catalyst followed by a ceramic wall-flow particulate filter.

The filters and assemblies were custom-designed for the fleet, taking into account the engine model, power rating and duty cycle. Excluding installation labor, the cost of each retrofit device was about $6,000—and would have been substantially lower if large numbers of the units had been ordered. The average installation time was about three hours for the DPX, and about six hours for the CRT. In addition to replacing the original muffler with the filter units, insulation wrap was added to a portion of the exhaust pipe to reduce heat rejection, and special consideration was given to mounting bracket design and clearance issues in order to accommodate the heavier and somewhat larger filter units.

After the retrofit, the trucks returned to normal operation for a one-year period. During this time, ARCO conducted two rounds of emission testing, and they also tracked fuel economy and maintenance issues. The fuel economy data showed a 2-3 percent decrease in miles per gallon for all three test groups fueled with ECD, attributable to the somewhat lower energy content of this fuel. There was essentially
no difference in fuel economy between the retrofitted and non-retrofitted trucks fueled with ECD, demonstrating that despite causing some increased back-pressure, the particulate filters themselves caused no measurable fuel economy penalty.

Over the entire 12-month period—during which each truck accumulated over 100,000 miles—the filter units experienced no failures, and no truck required roadside assistance related in any way to the ECD fuel or the particulate filters. Exhaust system repair costs did average $0.002/mile higher for the retrofitted trucks, due to additional labor needed to check and adjust the filter systems. Both Engelhard and Johnson Matthey recommend periodic maintenance on the filter units to remove inorganic lube oil ash that accumulates on the filter, suggesting that the filter should be removed and back-flushed with compressed air at the earlier of once a year or every 60,000 miles. However, the rate of lube oil ash accumulation varies with vehicle age, application, lube oil consumption and the oil’s ash content. Therefore, as an alternative to regularly scheduled periodic maintenance, a vehicle operator can monitor back-pressure and exhaust temperature to determine when the particular filter is in need of flushing. In this case, although the retrofitted trucks were driven well over 60,000 miles, back-pressure and exhaust temperature testing demonstrated good filter performance throughout the entire testing period, so conducting the periodic maintenance was not necessary.

ARCO’s two rounds of emissions testing not only enabled comparisons between testing groups, but also allowed an analysis of

![Figure 8: Freight Truck Average Emissions (City-Suburban Heavy Vehicle Route Cycle)](source: Society of Automotive Engineers)
each group’s emissions performance over time. The first round of emissions testing occurred just a few weeks after the trucks had been retrofitted, and the second round occurred after the one-year demonstration period. To better account for vehicle-to-vehicle variability, all 20 of the Ralph’s Grocery demonstration vehicles were emission tested. Each test involved triplicate runs over appropriate duty cycles. Results are presented in Figure 8, with each bar representing the average emissions value obtained for all five trucks in each group.

As demonstrated by these graphs, ARCO’s testing showed consistently dramatic emission reductions from the ECD-fueled vehicles equipped with both aftertreatment particulate filters. Moreover, a comparison of the first and second round emission results demonstrates that neither retrofit device experienced significant deterioration after 100,000 miles. Compared to the control vehicles fueled with CARB Diesel, the retrofitted vehicles fueled with ECD reduced PM emissions by 98–99 percent in both rounds, reduced CO emissions by 96–98 percent in the first round and 62–89 percent in the second round, and practically eliminated HC emissions to undetectable levels (shown as “0” on the HC graph in Figure 8) during both rounds of testing. Consistent with NYCT’s testing of the CRT retrofit device, ARCO found that NOx emissions were basically unaffected by the ULSD/retrofit. Although the graphs show a small decrease in NOx emissions between CARB Diesel and the ECD-fueled test groups in the first round of emissions testing, this decrease was not statistically significant.

Overall, ARCO’s testing showed that large tractor/trailers retrofitted with either a DPX or CRT catalytic particulate filter and fueled with ECD ultra-low sulfur diesel fuel will achieve dramatic reductions in PM, HC and CO emissions. ARCO’s second generation ECD-1 is already commercially available throughout California at 124 ARCO retail sites across the state.

(For additional information, see the DTF website at www.dieselforum.org/retrofit/tech_casestudy.html)
Endnotes


3 Id.


5 Estimate for switching from off-road diesel, averaging around 3,000 ppm sulfur to today’s federal highway diesel, which averages around 300 ppm sulfur. This value is based on analysis of emissions test data from eight off-road engines contained in “Exhaust Emission Factors for Non-Road Emission Modeling - Compression Ignition,” Meagan Beardsley and Chris Lindhjem, U.S. EPA Office of Mobile Sources, NR-009a, Table B2, June 1998.

6 Hart’s Diesel Fuel News (May 27, 2002). The marginal cost increase for switching to federal highway diesel will vary according to the supplier, delivery location, market price for petroleum and any applicable pre-negotiated pricing contracts.


8 Id.

9 Id.

10 Id.


19 Id. At 7

20 http://www.biodiesel.org/


27 For example, see press release at http://www.wm.com/env_pge.asp.


29 “Massachusetts Diesel Retrofit Program,” Steven Lipman, P.E., MADEP,
Cleaner Air, Better Performance: Strategies for Upgrading and Modernizing Diesel Engines


31 Note: if both NOX and PM are reduced, the costs and effectiveness of each should be assigned properly.

32 In other areas of the country that are in attainment for ozone or in less severe non-attainment for ozone than California, stationary source NOx controls should be compared with mobile source controls as they may be a more cost-effective NOx reduction strategy.


35 Id.


37 Id.


40 More information on ARCO’s EC Diesel program is available at www.ecdiesel.com.

41 Partners with ARCO in this effort included: U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL); Detroit Diesel; Cummins Engine Company; International Truck and Engine Corporation; Ford Motor Company; Engelhard Corporation; Johnson Matthey International; California Air Resources Board; South Coast Air Quality Management District; California Energy Commission; Fleetguard/Nelson; NGK-Loke, Inc.; Corning Incorporated; West Virginia University; University of California at Riverside, Battelle.”

41