Diesel-Powered Machines and Equipment:

Essential Uses, Economic Importance and Environmental Performance

Harvesting Food * Building Communities * Transporting Goods
Protecting Public Safety * Mining Resources

Diesel Technology Forum

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Diesel-Powered Machines and Equipment: Essential Uses, Economic Importance and Environmental Performance

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.

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Executive Summary

Diesel: Technology of Choice for Non-Road Equipment

Diesel offers an unmatched range of performance and economic advantages over other forms of power, including better durability, greater energy efficiency, increased engine safety, more low speed torque and suitability for very large applications. Thanks to this combination of attributes, the diesel engine is a mainstay for non-road equipment that serves a variety of industry sectors.

Non-road equipment powered by diesel engines puts food on our tables; builds our homes, schools, factories and infrastructure; mines our natural resources; delivers our goods and products on trains, ships and barges; propels the armed services that protect the nation; and keeps our air transportation system on the move by powering airport ground support equipment.

For many of these industry sectors, diesel is the predominant, and in some cases, exclusive, source of power. The following facts offer a glimpse of the extent of diesel's importance as an energy source:

- **Agriculture**: Farms and ranches use diesel to power two-thirds of all agricultural equipment — almost $19 billion worth of tractors, combines, irrigation pumps and other farm equipment.
- **Construction**: Nearly 100 percent of off-road construction equipment — nearly $17 billion worth — is diesel-powered.
- **Mining**: Diesel power accounts for 72 percent of the power used in mining.
- **Freight Transport**: Ninety percent of the nation's freight tonnage and 94 percent of its total freight ton-miles are moved by diesel power. While trucks move much of this cargo, diesel-powered non-road equipment powers rail, shipping and intermodal movements.
- **Public Safety & Homeland Security**: Diesel equipment is essential to the operation of the nation's utilities and also helps in rescue, recovery and clean up operations after natural disasters. And, when primary power systems fail, emergency back-up diesel generators are the only source that can provide immediate, reliable and full strength power.
- **Military**: Diesel engines propel a wide variety of weapons systems and power auxiliary equipment used by the military such as generators, compressors, pumps and cranes.
- **Airport Operations**: Approximately one-third of all pieces of airport ground support equipment are diesel-powered.

Many Applications, Many Engine Types

Non-road diesel engines are unparalleled in their versatility and range of applications. Serving so many different functions requires a wide array of engine types and sizes, from 10 horsepower engines that run lawn tractors and portable electric generators to massive 100,000 horsepower engines with cylinders more than three feet in diameter, used in ocean-going container ships. Just as non-road applications require many sizes, they also call for a diverse mix of engine designs and configurations to power different types of equipment.
The variety of engine types makes manufacturing diesel engines for the non-road sector complex and highly specialized. This is an important difference from on-highway truck and bus engines. Most on-highway engines are produced in larger quantities and in a more narrow range of sizes and designs than their non-road counterparts. This distinction means many on-highway emissions technologies are not readily transferable to off-road equipment, and certain types of on-highway technologies will not be adaptable to off-road applications at all.

A Decade of Environmental Progress
The U.S. Environmental Protection Agency (EPA) first implemented emissions standards for off-road equipment in 1996. Although off-road emissions regulations are relatively recent in comparison to on-highway diesel standards, which were first established in 1974, the rate of off-road emission reduction has been much more dramatic.

For engines used in backhoes, excavators and larger farm tractors (175-750 horsepower), particulate matter (PM) emissions from new engines have been reduced by 85 percent since 1996. Nitrogen oxides (NO$_x$) emissions have been reduced by 70 percent in that same timeframe, and will be reduced by another 40 percent by 2006 under current regulations, resulting in a total NO$_x$ reduction of 82 percent. These non-road emissions reductions will be achieved in a period of only 10 years between 1996 and 2006. In contrast, comparable reduction percentages from on-highway engines will have been achieved over the thirty-year period from 1974-2004.

Upgrading the Existing Fleet
The non-road diesel industry is also vigorously pursuing opportunities to upgrade existing engines and equipment. While non-road retrofits can be technically more difficult than on-highway projects, under the right circumstances, non-road emissions upgrades can be cost-effective emission control measures that don’t sacrifice equipment performance.

Upgrades such as oxidation catalysts and particulate filters can reduce key emissions by up to 90 percent when combined with low-sulfur fuel. More and more air quality planners and diesel fleet operators are conducting these and other performance upgrades on existing non-road diesel engines in order to achieve immediate local and regional air quality improvements.

Meeting the Challenge of Future Emissions Reductions
EPA is currently drafting a fourth round of emissions regulations for off-road equipment. These standards, known as “Tier 4,” are expected to be modeled after the proposed 2007 on-highway standards using a systems approach that will not only include engines, but also diesel fuel and exhaust aftertreatment devices. Transferring this approach from the on-highway to off-road sector could present some significant technical and commercial challenges.

These unique challenges involve addressing the diversity of non-road engines and equipment, the extreme duty-cycles compared to on-highway engines, the wide range of engine and exhaust temperatures, the significant space constraints, and the high sulfur content of non-road diesel fuel. To overcome these obstacles, off-road engine and equipment manufacturers, fuel refiners and aftertreatment manufacturers are working together to develop systems-based emissions reduction strategies for the next generation of non-road clean diesel engines.
Introduction

The diesel engine is the backbone of the global economy. The diesel's unique status as the world's most efficient internal combustion engine – producing more power and utilizing less fuel than other comparably sized engines – has led to its nearly universal use in heavy-duty mobile equipment applications that provide the principal source of power for a wide variety of critical economic sectors.

The critical role of diesel power is relatively well understood in on-highway applications, where it powers nearly all of America's long-haul highway trucks, and all of the nation's intercity buses. In contrast, the role of diesel in non-road applications is not well understood. While typically operating behind the scenes, diesel power makes a critical contribution to a very wide variety of activities including agriculture, construction, mining, logging, petroleum exploration, portable and back-up electric power generation, most forms of non-road transportation, and numerous military applications.

Non-road diesel power is increasingly becoming a subject of public interest. Investors, economists and policy makers have become re-focused on the sources of value and productivity in the traditional economy where diesel power is critical. At the same time, as new on-highway vehicles approach virtual elimination of regulated emissions, diesel emissions in the non-road sector are drawing increased attention.

This paper contributes to that discussion by exploring the role of diesel power in non-road applications. This inquiry embraces an extraordinarily diverse category of engines, and that diversity adds a layer of complexity to this issue that is absent in the on-highway diesel debate. This paper will discuss a number of key aspects of non-road diesel engines and equipment including:

• The critical role of non-road diesel in the economy;
• The diversity of non-road diesel engines and equipment;
• The progress to date in reducing non-road diesel emissions;
• The technical and commercial challenges associated with future non-road diesel emissions reductions; and
• The opportunity for more immediate emissions reductions through voluntary equipment upgrades.
Non-road diesel engines power an extremely wide range of equipment applications that provide the predominant source of power in a large number of economic sectors. Non-road diesel powered equipment includes railroad locomotives, ocean-going container ships, and stationary engines used for agricultural pumps and back-up electric power generators. Non-road diesel is also used in a wide range of off-road mobile equipment applications, which are the dominant source of power for most mobile equipment used in: agriculture, construction, mining, electric power generation, logging, petroleum exploration and production, and numerous military applications.*

**Diesel Technology’s Essential Role in Non-Road Applications**

The broad and diverse use of diesel stems from the inherent advantages of diesel power. Each of the industries that rely on diesel demands a source of heavy-duty mechanical power that is either mobile or portable. Other sources of industrial power, such as the electricity grid and steam boilers, are simply not adaptable to mobile applications or are not portable to remote locations. Only internal combustion engines can meet this demand for efficient mobile/portable heavy-duty power.

Diesel engines hold a number of inherent performance advantages over other internal combustion engines, which make them essentially irreplaceable in these heavy-duty non-road applications. Diesel’s nearly universal use in these sectors reflects the combination of all of its performance advantages over other internal combustion engines. These advantages include: more power, greater energy efficiency, increased safety, and better durability and suitability for very large applications.

> **More Power.** Diesels produce more drive force at lower engine speeds. This superior drive force is the result of the diesel engine combustion process, known as “compression ignition.” Compression ignition produces superior combustion force in the cylinder, which in turn provides more power or “torque.”

High torque and power at low speeds is particularly critical in non-road applications. For example, non-road engines in off-road equipment like tractors, bulldozers and backhoes must possess the power to both perform the work of lifting, pushing, pulling and dumping while simultaneously propelling these heavy-weight machines across typically rough, unpaved surfaces and grades.

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*In this paper, the term “non-road diesel” is used to refer to the broad category of all diesels not certified for use in on-highway vehicles, such as: locomotives, ships, stationary power units and mobile off-road equipment. The term “off-road diesel” is used to refer more narrowly to the specific subcategory of non-road diesels that are used in land-based mobile equipment like tractors and bulldozers.*
> **Better Energy Efficiency.** Diesel engines are also irreplaceable in non-road applications because of their superior energy efficiency. Where both diesel engines and spark-ignition engines have reasonably equivalent power output characteristics, the diesel will consume significantly less fuel in performing the same work. How much less fuel the diesel engine will use varies with the application, but typical estimates range between 25 percent and 35 percent. These advantages come from both the greater efficiency of compression ignition and the higher energy content of diesel fuel (see side bar). Superior energy efficiency allows for longer operating between refueling. This can be critical in remote locations or in emergency back-up power applications where the use may be occasional but must remain uninterrupted for extended periods of time.

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### Diesel Efficiency: Combustion Cycle and Fuel Energy Density

Diesel's compression ignition process results in greater thermal efficiency – more of the fuel's chemical energy is harnessed as mechanical energy. Diesel holds this advantage over any spark-ignited engine, including not only gasoline, but also CNG, LNG, and propane ("LPG"). Like gasoline engines, these other spark ignition engines are less fuel-efficient because they burn fuel at lower temperatures under lower compression.

Diesel's combustion cycle is also more efficient than a spark ignition engine's because it does not rely on a throttle plate to control power. The use of a throttle plate results in increased "pumping losses," which reduce efficiency. At lower power the throttle plate in a spark ignition engine's air intake is partially or completely closed, creating a vacuum in the intake manifold. The cylinders must pump against the vacuum to draw air. Considerable work can be expended by the engine just to draw in air for combustion at low/closed throttle positions.

A gasoline engine is accordingly at its highest efficiency at high power with open throttle; unfortunately, however much of its life is spent at low throttle. In contrast, a diesel engine has no throttle plate. The power output is controlled by the amount of fuel injected and pumping losses are therefore much lower.

Diesel’s superior fuel efficiency is also a result of diesel fuel’s higher energy content or “energy density.” A gallon of diesel fuel produces roughly 11 percent more energy than a gallon of gasoline, 67 percent more than a gallon of LNG and 250 percent more than a gallon of CNG (at 3600 psi). The relatively low energy density of natural gas can be addressed in part by using larger fuel tanks, but the added weight of the tanks imposes an additional fuel economy penalty, and the size of the tanks may be entirely impractical in many types of non-road equipment.

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> **Suitability for Very Large Applications.** Spark ignition engines are not a viable alternative to diesel engines for applications requiring very high power output at low speeds. Generally speaking, spark ignition engines do not exceed ten liters (600 cu. in.) in displacement and are not used in applications where power requirements exceed about 400 horsepower. All internal combustion engines produce high temperatures inside their cylinders, but spark ignition engines generally run hotter than diesel compression ignition engines and, therefore, require more cooling. The high cylinder temperatures of spark ignition engines limit engine size because larger spark ignition engines suffer from “detonation” or “knock,” which is the spontaneous ignition of fuel in the cylinder due to high cylinder temperatures.

The fact that diesels produce less wasted heat makes them ideally suited for very large applications, like ocean-going ships, railroad locomotives and earthmovers. One of the biggest issues in designing large engines is the need to provide cooling systems to prevent overheating. This is a major challenge when dealing with the heat produced in very large combustion chambers. Because diesels waste less energy as heat,
they place lesser demands on cooling systems than spark ignition engines. This permits diesels to be scaled up to very large sizes — diesel engines in some applications have cylinders as large as three feet in diameter.

> Durability and Reliability. Diesel engines are legendary for their durability and reliability. Diesels both operate more miles before rebuilding is necessary, and also are more easily rebuilt to original specifications. It is not uncommon for heavy-duty engines to power off-road equipment such as tractors and bulldozers for 20 to 30 years, and to power other non-road equipment such as rail locomotives for more than 50 years, conserving valuable resources.

Diesels used in rail locomotives are an excellent illustration of the durability, reliability and repairability of these engines. Locomotive engines have one of the highest operation and utilization rates in the industry, and are overhauled only every six to eight years. Between overhauls, a typical 4,000 horsepower locomotive engine will produce about 30,000 megawatt hours of work.

> Fuel Safety. Diesel fuels generally are less volatile and, therefore, safer to store and handle than the fuels used in spark ignition engines. In addition, diesel fuel ignites at a much higher temperature than gasoline or natural gas. For these reasons, diesel fuel is far less likely to ignite if spilled or released as a result of an accident. Diesel is also safer because it need not be handled in pressurized vessels, like CNG, which is stored in pressurized cylinders (up to 3600 psi). High pressure greatly increases the risk of leaks during loading, unloading and storage. Military vehicles, marine vessels and engines used in certain stationary applications rely on diesel power, in part for safety reasons.

Economic Value of the Non-Road Diesel Industry
Non-road diesel technology is widely applicable in numerous industries and adds significant value to the U.S. economy. Non-road diesel applications can be found in many industries that are heavily, if not entirely, reliant on the power provided by diesel engines.

Industries with High Reliance on Diesel

Agriculture
Diesel technology is the workhorse for the world’s farms and ranches, powering two-thirds of all farm equipment. Diesel’s unique combination of power, efficiency and reliability has played a central role in increasing the productivity of America’s farms. In the U.S., the agricultural sector contributed $80.6 billion to the GDP in 2001. Agriculture uses diesel engines as the source to power almost $19 billion worth of tractors, combines, irrigation pumps and other farm equipment.

A mere 3.4 million individuals (about 2.5 percent of the labor force), farming 310 million cultivated acres of land, manage not only to feed and clothe our citizens but also export a significant share of what they produce. This productivity makes food inexpensive. The typical American family spends only about 8.3 percent of its budget on food prepared and consumed in the home.
The period since World War II has witnessed two revolutionary events in American agriculture: the completion of the transition from animal to tractor power, and the intensive application of science to farming. In 1945, America had 5.9 million farms; each averaged 195 acres. Nearly 25 million people—17.5 percent of the country’s population—lived on farms. America’s farmers used only 2.3 million tractors, an average of 0.39 per farm. The total power output of these 2.3 million tractors was 61 million horsepower, an average of just over 25 horsepower per tractor. Just after the war, wheat yields averaged 17 bushels per acre; corn, about 36 bushels per acre; and cotton, 273 pounds per acre.

By 1997, America had fewer than two million farms and less than a million individuals who identified farming as their principal occupation. The average size of a farm had grown to 487 acres. The number of tractors had grown to 3.9 million—an average of about 2 per farm. Seven hundred thousand farms had either two or three tractors, and almost 300,000 farms had four tractors or more. These tractors were much larger. In 1983, the last year for which these particular data are available, each tractor averaged 66 horsepower. By 1997 nearly one million of the 3.9 million tractors had a power output of greater than 100 horsepower. Wheat yields in 1998 averaged 43 bushels per acre; corn averaged 134 bushels per acre; and cotton, 618 pounds per acre.

While farming had become much more mechanized, the agriculture sector overall was using less energy. Indeed, agricultural energy use peaked in the late 1970s and declined throughout most of the 1980s (Figure 1). During the mid-1990s it was only slightly higher than it had been in 1974. Yet between 1974 and 1994, food crop output rose by nearly 80 percent.

The U.S. Department of Agriculture attributes this dramatic 80 percent increase in food crop output between 1974 and 1994, with no corresponding increase in agricultural energy use, in substantial part to increased use of efficient diesel-powered machinery rather than gasoline-powered machinery.\(^5\) In 1974, gasoline accounted for 49 percent of the energy supplied by fuels purchased by farms; diesel accounted for 38 percent. By 1994, gasoline’s share had fallen to 24 percent; diesel’s had risen to 66 percent.

Another important agriculture-related use of diesel power is to drive irrigation pumps. As last reported in 1997, diesel-powered pumps were used to provide the water that irrigated over 10 million acres—over one-quarter of all irrigated land. This represented a 25 percent increase in the number of acres irrigated using diesel-powered pumps since 1994, a period when total acres irrigated increased by only about 7 percent. The reason for diesel’s growth in this application is fuel efficiency.\(^6\)
Construction

Diesel is used to power a significant amount of off-road construction equipment because of its power, fuel efficiency and safety advantages over gasoline. The construction industry is dependent on almost $17 billion worth of diesel-powered equipment. The latest economic census data show that almost 656,000 entities were engaged in construction in 1997; they employed 5.7 million persons and paid $174 billion in wages and benefits; and they purchased $241 billion in materials, components, supplies and fuels, $2.5 billion of which was for fuel for off-highway use (at least half of which is estimated to have been for diesel fuel). Overall, the construction industry contributed $480 billion to the U.S. GDP in 2001.

Much of the diesel-powered equipment used in construction is classified as “off-road.” Although data is limited on the number and power characteristics of this equipment, the EPA reported that 440,000 pieces of diesel-powered off-road equipment used primarily in construction were produced in this country between 1991 and 1995. This EPA study reported that in Canada, all of the concrete pavers, scrapers, asphalt pavers, rollers, trenchers, bore/drill rigs and excavators over 100 horsepower were diesel-powered.

Diesel is used to power construction equipment for the same reasons it is used elsewhere in the economy. It provides more power per unit of fuel—an important consideration when fuel must be hauled to distant and sometimes remote construction sites. It provides higher power output at low engine speeds and its lower volatility makes it safer to handle than gasoline.

<table>
<thead>
<tr>
<th>Equipment Application</th>
<th>Examples of Equipment</th>
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<tbody>
<tr>
<td>Tractors</td>
<td>Wheel Tractor-Scrapers</td>
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<tr>
<td></td>
<td>Rotary Cutters</td>
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<tr>
<td></td>
<td>Skid Steer Loaders</td>
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<td></td>
<td>Loaders</td>
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<td></td>
<td>Sprayers</td>
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<tr>
<td></td>
<td>Utility Tractors</td>
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<td></td>
<td>Row Crop Tractors</td>
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<tr>
<td>Bale Handlers</td>
<td>Mowers</td>
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<tr>
<td>Round/Square Balers</td>
<td>Forage Harvesters</td>
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<tr>
<td>Choppers</td>
<td>Shredders</td>
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<td></td>
<td>Windrowers</td>
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<tr>
<td>Air Seeder</td>
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<tr>
<td>Drills</td>
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<tr>
<td>Unit Planter</td>
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<tr>
<td>Hoes</td>
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<tr>
<td>Plows</td>
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<td>Generators</td>
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<tr>
<td>Milking Machines</td>
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<tr>
<td>Grinders</td>
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<tr>
<td>Cotton Pickers/Strippers</td>
<td></td>
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<tr>
<td>Combines</td>
<td></td>
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<tr>
<td>Irrigation Sets/Pumps</td>
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<td></td>
<td></td>
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<tr>
<td>Log Loaders</td>
<td></td>
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<tr>
<td>Knuckleboom Loader</td>
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<td>Track Harvester</td>
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<tr>
<td>Wheel Skidders</td>
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<td>Track Skidders</td>
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<tr>
<td>Track Feller Bunchers</td>
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<tr>
<td>Wheel Feller</td>
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<tr>
<td>Bunchers Felling Heads</td>
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<tr>
<td>Cut-to-Length</td>
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<tr>
<td>Harvesters and Forwarders</td>
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</tbody>
</table>

TABLE 1: Examples of Diesel Agricultural Applications
Diesel power is essential to the mining industry, which uses almost $7 billion worth of diesel-powered equipment. The bituminous coal and lignite surface mining segment of the industry, for example, relies on off-road trucks and heavy earth-moving equipment powered by diesel. The oil and gas production segment of the industry requires diesel power for 85 percent of its drilling operations and more than half of its support operations. The latest economic census data show that almost 26,000 entities engaged in mining in 1997, employing 550,000 persons and paying $22 billion in wages and benefits. Overall, mining contributed $139 billion to the U.S. GDP in 2001.

Mining, especially “open pit” or “surface” mining, shares many characteristics of heavy construction in its use of diesel power. Indeed, the largest rubber-tired, diesel-powered equipment is to be found in mining—off-road trucks with engines of over 2,500 horsepower, capable of hauling over 300 tons per load. Different sectors of mining depend on diesel to different degrees, but overall, diesel accounts for 72 percent of the energy used by the sector (excluding gas and coal used in the same facility in which it is produced).

**Table 2: Examples of Diesel Construction Applications**

<table>
<thead>
<tr>
<th>Equipment Application</th>
<th>Examples of Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Construction</td>
<td></td>
</tr>
<tr>
<td>Dozers</td>
<td>Rubber-Tired Dozers</td>
</tr>
<tr>
<td></td>
<td>Wheel Dozers</td>
</tr>
<tr>
<td>Loaders</td>
<td>Rubber-Tired Loaders</td>
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<tr>
<td></td>
<td>Skid Steer Loaders</td>
</tr>
<tr>
<td></td>
<td>Track-Type Loaders</td>
</tr>
<tr>
<td>Excavation</td>
<td>Excavators</td>
</tr>
<tr>
<td></td>
<td>Backhoes</td>
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<tr>
<td></td>
<td>Mass Excavators</td>
</tr>
<tr>
<td>Pavers/Paving Equipment</td>
<td>Cold Planers</td>
</tr>
<tr>
<td>Compactors</td>
<td>Asphalt Compactors</td>
</tr>
<tr>
<td>Various</td>
<td>Road Reclaimers</td>
</tr>
<tr>
<td>Various</td>
<td>Bores/Drill Rigs</td>
</tr>
<tr>
<td></td>
<td>Cement Mixers</td>
</tr>
<tr>
<td></td>
<td>Off-Highway Trucks</td>
</tr>
<tr>
<td></td>
<td>Off-Highway Tractors</td>
</tr>
</tbody>
</table>

**Table 3: Examples of Diesel Mining Applications**

<table>
<thead>
<tr>
<th>Equipment Application</th>
<th>Examples of Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining</td>
<td></td>
</tr>
<tr>
<td>Underground Mining Equipment</td>
<td>Trucks – Articulated Load Haul Dump Trucks</td>
</tr>
<tr>
<td>Heavy Earth-Moving Equipment</td>
<td>Dozers Loaders Excavators</td>
</tr>
<tr>
<td>Various</td>
<td>Off-Road trucks</td>
</tr>
<tr>
<td></td>
<td>Generators</td>
</tr>
<tr>
<td></td>
<td>Pressure Washers</td>
</tr>
<tr>
<td></td>
<td>Cranes</td>
</tr>
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<td></td>
<td>Forklifts</td>
</tr>
</tbody>
</table>
**Freight Transport**

One of the economic sectors most heavily reliant on diesel engines is non-road freight transportation. Current estimates indicate that diesel power moves about 90 percent of the nation’s entire freight tonnage and 94 percent of its total freight ton-miles. While much of this freight is moved by diesel-powered highway trucks, non-road modes of transportation are also critical to freight transport. In these non-road modes, which include railroads, marine shipping, and intermodal movements, diesel power is either the exclusive or dominant source of power.

**Rail Freight**

All the 20,000 freight locomotives in the U.S. are powered by diesel. The latest economic census data show that U.S. freight trains, which are powered by diesel locomotives, hauled 1.5 billion tons of freight worth $320 billion in single-mode service in 1997, and moved another 134 million tons of freight worth $77.5 million in intermodal service (i.e., with other modes of transportation involved) in that year. As discussed in more detail below, U.S. freight railroads account for more than 40 percent of all freight transportation in the country. U.S. freight railroads employ almost 192,000 persons and contribute more than $14 billion annually to the U.S. economy in wages and benefits, along with billions of dollars more in purchases from suppliers. Overall, railroad transportation contributed $25.8 billion to the U.S. GDP in 2001.

**Marine Freight Transport**

The United States is the world’s largest importer and exporter of goods. The vast bulk of goods imported into or exported from this country move by ship. Virtually all of the bulk carriers that transport oil, ore, wheat and other goods are diesel-powered. So are the container ships that transport the majority of all manufactured imports and exports. The engines that power these bulk carriers and container ships are the largest diesels made. They can generate over 130,000 horsepower, have as many as 18 cylinders, and stand three to four stories high. The latest economic census data show that almost 2,000 entities were engaged in the transportation of freight by water in 1997 and moved 563 billion tons of freight worth $76 billion.

Inland waterways are also a critical mode of non-road transport within the United States. All freight barges on U.S. waterways are powered by diesel engine towboats. In 1997, approximately 650 million tons of freight – about 8 percent of the total freight tonnage transported by all modes – moved through the nation’s 12,000 miles of commercially navigable channels. This network moved 60 percent of the nation’s grain exports, 24 percent of its chemical and petroleum shipments, and 20 percent of its domestic coal tonnage. All of this traffic was propelled by diesel-powered towboats, which in essence are hulls wrapped around one or more extremely powerful diesel engines. According to the U.S. Army Corps of Engineers, there are over 5,000 towboats in the U.S. towboat fleet. These towboats range between 1,800 and 10,500 horsepower, and generate a total of 9.4 million horsepower.

**Public Safety & Homeland Security**

Diesel powered machines and construction equipment play a vital role in many aspects of public safety and homeland security. For example, construction equipment (backhoes, trenchers, excavators, loaders) is required to assure safe operation of the nation’s utilities, install public drinking water and sewer systems as well as fiber optic and telecommunications cables. And when disaster strikes, this same equipment plays a vital role in rescue, recovery and clean-up efforts, helping to rescue trapped victims, and remove debris after hurricanes, tornadoes, ice storms and other natural disasters. In the case of
firefighting, diesel-powered machines (bulldozers, backhoes) are a key tool involved in suppression and fighting of forest fires in the nation’s national forests. Diesel-powered vehicles play an increasingly vital role in homeland security, from U.S. Coast Guard port and harbor patrol vessels to National Guard and military vehicles. And, when primary power systems fail during natural disasters, emergency back-up diesel generators provide a unique service in immediate, reliable and full strength power to rapidly restore a wide variety of mission-critical systems, such as water pumps, national security telecommunications systems, nuclear power plant back-ups, and hospitals and emergency operations centers, helping to restore public safety.

Military
The U.S. military relies heavily on diesel power. Diesel engines are used to propel weapons systems and to power all kinds of auxiliary mobile and stationary equipment, including generators, compressors, pumps and cranes. Diesel engines reported in the Defense Logistics Service’s Federal Supply Schedule range in size from a one-cylinder, 180-pound engine to a 16-cylinder engine weighing more than 17 tons.

The military uses diesels for many of the same reasons as civilian enterprises. The diesel engine’s superior fuel economy means that a diesel-powered piece of equipment can travel farther on the same amount of fuel. The military must transport large amounts of fuel, so the greater fuel efficiency of diesels cuts down on logistical support costs. It also extends the military’s striking range. In addition, the lower volatility of diesel fuel provides a safety advantage by reducing the risk of explosion if vehicles and equipment are hit during combat. Finally, compression ignition engines are much more “fuel tolerant” than spark-ignition engines. This means that they can burn a wide range of fuels, depending on what is available, thus increasing the military’s flexibility in adverse conditions.

<table>
<thead>
<tr>
<th>Vehicle / Equipment Application</th>
<th>Examples of Vehicles / Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most of the amphibious force vessels</td>
<td>Vehicles transporting troops, equipment, material to mission sites</td>
</tr>
<tr>
<td>Auxiliary ships</td>
<td>E.g., combat support vessels</td>
</tr>
<tr>
<td>Not used as propulsion system in main combatant surface ships; however, some classes have diesel engines to provide emergency propulsion if needed</td>
<td>E.g., Nimitz and Enterprise Class Ships have four diesel engines capable of generating 10,000 hp</td>
</tr>
<tr>
<td>Military Sealift Command</td>
<td>All oilers and fleet ocean tugs, 50 percent of dry cargo ships, combat stores, etc.</td>
</tr>
<tr>
<td>Navy Sealift Force</td>
<td>Tanker and Roll-on Roll-off ships</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>U.S. Navy</th>
<th>U.S. Coast Guard</th>
<th>U.S. Army and Marine Forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>All high-endurance cutters are also powered by diesel engines; all non-high-endurance cutters are propelled solely by diesel</td>
<td>Workhorse icebreakers</td>
<td>Most armor and self-propelled artillery are diesel powered, with a wide range of uses and functions</td>
</tr>
<tr>
<td>Ice-breakers propelled by diesel-electric systems</td>
<td></td>
<td>Tank destroyers, self-propelled guns and howitzers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amphibious assault vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Almost all military vehicles and logistics systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E.g., prime movers, heavy-equipment transporters, special attack vehicles, “Humvee” vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E.g., M2/M3 Bradley armored personnel carriers, ambulances, mortar carriers, anti-aircraft gun carriers, missile launchers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M901, M109, M110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LFTP7A1</td>
</tr>
</tbody>
</table>
Airport Operations
The country’s air transportation system also depends heavily on diesel engines. The EPA estimates that approximately one-third of all pieces of airport ground support equipment—15,000 out of a total of 45,000—are diesel-powered.

The use of diesel-powered aircraft ground support equipment varies widely by equipment type. Table 5 groups these types of equipment into three categories: those that are predominantly diesel-powered, those that are predominantly powered by gasoline or other fuels and those that are split roughly evenly between diesel and gasoline/other power. Generally speaking, the diesel-powered units are larger and, therefore, used in the jobs requiring greater power, such as towing jumbo jets like the Boeing 747 and 777. When fully fueled and loaded with passengers and cargo, these aircraft can weigh as much as 875,000 pounds. The tugs that maneuver these aircraft must be able to move them easily and precisely. The ability of diesel engines to generate great power in a compact space greatly facilitates this movement.

<table>
<thead>
<tr>
<th>Predominant Fuel Used by Type of Equipment</th>
<th>Type of Equipment</th>
<th>Number Using Diesels</th>
<th>Number Using Gasoline/Other</th>
<th>Diesel Share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesels</td>
<td>Aircraft Pushback Tractor</td>
<td>2,113</td>
<td>646</td>
<td>76.6%</td>
</tr>
<tr>
<td></td>
<td>Conditioned Air Unit</td>
<td>376</td>
<td>103</td>
<td>78.5%</td>
</tr>
<tr>
<td></td>
<td>Air Start Unit</td>
<td>771</td>
<td>110</td>
<td>87.5%</td>
</tr>
<tr>
<td></td>
<td>Cargo Loader</td>
<td>1,129</td>
<td>330</td>
<td>77.4%</td>
</tr>
<tr>
<td></td>
<td>Ground Power Unit</td>
<td>2,504</td>
<td>549</td>
<td>82.0%</td>
</tr>
<tr>
<td>Roughly Equal Split</td>
<td>Baggage Tug</td>
<td>4,399</td>
<td>6,106</td>
<td>41.9%</td>
</tr>
<tr>
<td></td>
<td>Belt Loader</td>
<td>2,429</td>
<td>2,725</td>
<td>47.1%</td>
</tr>
<tr>
<td></td>
<td>Bus</td>
<td>115</td>
<td>173</td>
<td>39.9%</td>
</tr>
<tr>
<td>Gasoline/Other</td>
<td>Various*</td>
<td>1,254</td>
<td>19,239</td>
<td>6.1%</td>
</tr>
</tbody>
</table>

*Includes belt loaders, bobtails, carts, deicers, forklifts, fuel trucks, lavatory carts, lavatory trucks, lifts, maintenance trucks, other GSE, service trucks, cars, pickup trucks, vans and water trucks.
Diversity of Non-Road Diesel Engines

As demonstrated by the previous discussion, the term “non-road diesel engine” embraces an extremely large family of engines employed in a diverse range of equipment applications. This diverse array of equipment in turn requires a broad range of engine sizes and mechanical capabilities. The range of engine sizes, power ratings, configurations and number of different non-road equipment applications dwarfs that of on-highway engine products.

Wide Range of Engine Sizes and Power Ratings

The largest non-road diesel engines have up to 18 cylinders, each of which can measure over three feet in diameter and generate over 100,000 horsepower. These massive engines are used to power container ships capable of hauling over 6,000 twenty-foot freight containers. Train locomotives also use extremely large diesel engines, rated at up to 6,000 horsepower. For comparison, the on-highway diesels used in Class 8 semi-tractors are typically rated between 350 and 600 horsepower.

At the other end of the spectrum, non-road diesel engines also power portable electricity generators and lawn tractors with less than 10 horsepower, which are some of the smallest pieces of mobile equipment regulated by the federal government. In recognition of this wide range of engine sizes and diversity of applications, the EPA has developed separate regulatory regimes for various subcategories of mobile non-road diesel engines. Specifically, large marine diesel engines (>50hp), recreational marine diesels and locomotive engines are regulated separately from all other land-based non-road diesel engines. Similarly, underground mine engines are separately regulated by the Mining Safety and Health Administration.

Even after excluding marine, locomotive and mining engines, the broad residual subcategory of non-road engines – which we have referred to as “off-road” engines – contains diesel engines with horsepower ratings between 10 - 3,000 horsepower. In contrast, on-highway diesel engines typically range between 120 and 600 horsepower. The wide range of diesel engines is required by the diversity of off-road applications. Because of the diversity of equipment applications discussed below, the same basic engine platform will often be offered in a wider range of horsepower ratings than similar engines sold for on-highway applications. These additional models are produced through variations in compression ratios, fuel injection equipment, tuning and enhanced turbo charging.

The best illustration of the greater diversity of off-road engines is seen in the number of different off-road engine families certified by the EPA under their “off-road” regulations. On average, the EPA issues over four times as many off-road engine emissions certifications as heavy-duty on-highway certifications. For example, in 2001 the EPA issued 661 different heavy-duty diesel off-road emissions certificates and only 159 certifications for heavy-duty on-highway engines. The EPA issues a separate emissions certification for each “family” or class of engines that are expected to have similar emissions characteristics. The heavy-duty highway engine category includes both diesel- and gasoline-powered engines.
Diversity of Equipment Applications, Mechanical Demands and Duty Cycles

Non-road diesel engines are employed in an extremely diverse range of equipment applications – from ocean-going container ships to lawn tractors. Even within the off-road subcategory of non-road engines, diesels power an astounding number of different types of equipment. Table 6 is a sampling of mobile off-road diesel equipment applications compiled by the EPA.

Each off-road equipment application presents different mechanical and duty cycle demands on the diesel engine. This diversity of mechanical demands in turn requires a correspondingly wide range of different engine designs and configurations to power each different type of equipment as discussed above.

Equally important, the operating requirements of off-road equipment subject these engines to a much more strenuous and varying set of demands and duty cycles than on-highway equipment. Most off-road equipment relies on their engines both to propel the vehicle and to operate attachments like buckets, blades and shovels. Off-road vehicle propulsion requires an engine capable of maintaining traction and maneuverability for heavy off-road equipment over a broad range of terrain profiles and physical conditions. Most off-road construction, mining and farming equipment also use engine-driven hydraulic pumps to power the attachments that do the lifting, pushing, drilling, pumping, loading and dumping that the equipment is designed to accomplish. These additional accessories create additional unique power demands on the engine that are not found in on-highway engines, where power is primarily used for propulsion.

Off-road engines are also subject to higher-temperature operating environments than on-highway engines. Unlike on-highway trucks, most off-road equipment runs at very low vehicle speeds. As a result, off-road engines must operate without the benefit of “ram air” for cooling. Ram air is the airflow over the engine and cooling system created by the forward motion of the vehicle itself, which for highway vehicles can be in excess of 65 miles per hour. Off-road vehicles are relatively stationary and rarely exceed 10 miles an hour during work operations. The lack of ram air, combined with the additional
accessory loads, require off-road engine makers to install more elaborate cooling systems, which typically consume between 10-20 percent of total engine power output.\textsuperscript{31}

Because the same off-road engine model is frequently used in a variety of equipment applications, off-road engines also require a great deal of versatility within the same design. For example, a portable electric power generator may use the same engine as a front-end loader. But the two pieces of equipment will require the engine to perform over very different operating ranges and cycles. The engine in the electric power generator enjoys long periods of operation at constant speeds and steady loads, whereas the same engine installed in a front-end loader would be typically subjected to a much more challenging and variable duty cycle featuring frequent alterations between high engine speeds and loads, and periods of low-speed idling between tasks.

![FIGURE 2: Differences in Operating Characteristics Between Off-Road and On-Road Diesel Engines](image)
Progress In Reducing Non-Road Emissions

Federal emission standards have been established for almost every subcategory of non-road diesel engine manufactured or imported in the United States. Moreover, increasingly stringent standards for future model years are already in place for each engine subcategory, which will lead to further emission reductions. Therefore, even though the number of non-road diesel engines in operation will likely increase with population and economic growth, the EPA estimates that fleet turnover and the resulting replacement of old non-road engines with those that meet current and upcoming emission standards will cause a significant reduction in overall emissions.

Because the universe of non-road mobile diesel engines is too broad to be regulated effectively under a single rule, the EPA regulates large marine diesels, recreational marine diesels and diesel locomotive engines under different rules. Even with such exclusions, the remaining subcategory of “off-road” diesel equipment covers a very wide variety of engines used in many different applications, as illustrated in Table 6. The EPA has long recognized the special technical and commercial challenges presented by controlling emissions from these diverse non-road sources. Because of these challenges and complexities, which are discussed in detail below, the EPA’s approach to off-road emission standards has been to first develop technology-based diesel emissions standards for simpler, higher volume on-highway engines, and then follow those rules with later, analogous standards for off-road engines that adapt these technologies to the more challenging operating environments and varied low volume applications found in the off-road sector.

Rather than establish standards for the different segments or engine applications within the off-road diesel equipment category, the EPA has divided the category into power rating subcategories—each with different emission standards phased in on different model year schedules (called “tiers”). The specific non-road diesel equipment standards for emissions of oxides of nitrogen (NO\textsubscript{x}), hydrocarbons or non-methane hydrocarbons (HC or NMHC), carbon monoxide (CO) and particulate matter (PM) are reflected below in Table 7.

"Compared to highway vehicles, the rate of non-road emission reduction has been much more dramatic."
The EPA established these standards under two separate rulemakings published in 1994 and 1998.\textsuperscript{34} The 1994 rule established the Tier 1 standards for off-road diesel engines with rated power of 50 hp or greater, largely harmonizing with the California standards for engines rated at 175 hp or greater adopted the year before. The 1998 rule established the Tier 1 and 2 standards for the smaller (<50 hp) engine categories, along with the Tier 2 and 3 standards for the larger engine categories. In 2000, California harmonized its state regulations with the federal standards adopted in the 1998 rule.

The phase-in period for both the California and the federal standards began with 1996 models of off-road diesel engines. In 2000, the last Tier 1 standards took effect, thereby completing the first phase of the implementation schedule. The Tier 2 phase-in began in 2001 and will continue until 2006, when the Tier 3 standards will begin to take effect. Barring any regulatory changes, Tier 3 will be fully implemented by 2008. With EPA’s separate diesel locomotive and marine vessel rules, and with the emission standards for underground mine equipment established by the Mining Safety and Health Administration of the Department of Labor,\textsuperscript{35} federal emission standards are now in place to regulate virtually every category of mobile, non-road diesel engine on the market.

Although non-road emissions regulations are relatively recent in comparison to on-highway diesel standards, which were first established in 1974, compared to highway vehicles, the rate of non-road emission reduction has been much more dramatic. For heavy-duty diesel engines in the 175-750 horsepower range, PM emissions have been reduced 85 percent since EPA regulations went into effect in 1996. NO\textsubscript{X} emissions have been reduced by 70 percent in that same timeframe, and will be reduced by another 40 percent by 2006 under current regulations, resulting in a total NO\textsubscript{X} reduction of 82 percent.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{Rated Power (hp)} & \textbf{Representative Applications} & \textbf{Tier} & \textbf{Model Year} & \textbf{NO\textsubscript{X}} & \textbf{HC} & \textbf{NMHC + NO\textsubscript{X}} & \textbf{CO} & \textbf{PM} \\
\hline
Less 11 & pumps, generators, refrigeration than units, mowers & Tier 1 & 2000 & --- & --- & 7.8 & 6.0 & 0.75 \\
& & Tier 2 & 2005 & --- & --- & 5.6 & 6.0 & 0.60 \\
11-25 & refrigeration units, mowers, welders, generators & Tier 1 & 2000 & --- & --- & 7.1 & 4.9 & 0.60 \\
& & Tier 2 & 2005 & --- & --- & 5.6 & 4.9 & 0.60 \\
25-50 & mowers, refrigeration units, skid-steer loaders & Tier 1 & 1999 & --- & --- & 7.1 & 4.1 & 0.60 \\
& & Tier 2 & 2004 & --- & --- & 5.6 & 4.1 & 0.45 \\
50-100 & skid-steer loaders, refrigeration/AC units & Tier 1 & 1998 & 6.9 & --- & --- & --- \\
& & Tier 2 & 2004 & --- & --- & 5.6 & 3.7 & 0.30 \\
& & Tier 3 & 2008 & --- & --- & 3.5 & 3.7 & \\
100 – 175 & backhoes, rubber-tired loaders, forest equipment, air compressors, generators & Tier 1 & 1997 & 6.9 & --- & --- & --- \\
& & Tier 2 & 2003 & --- & --- & 4.9 & 3.7 & 0.22 \\
& & Tier 3 & 2007 & --- & --- & 3.0 & 3.7 & \\
175-300 & agricultural tractors, excavators, crawlers, rubber-tired loaders & Tier 1 & 1996 & 6.9 & 1.0 & --- & 8.5 & 0.40 \\
& & Tier 2 & 2003 & --- & --- & 4.9 & 2.6 & 0.15 \\
& & Tier 3 & 2006 & --- & --- & 3.0 & 2.6 & \\
300-600 & scrapers, crawlers, off-highway trucks & Tier 1 & 1996 & 6.9 & 1.0 & --- & 8.5 & 0.40 \\
& & Tier 2 & 2001 & --- & --- & 4.8 & 2.6 & 0.15 \\
& & Tier 3 & 2006 & --- & --- & 3.0 & 2.6 & \\
600-750 & generators, off-highway trucks, other construction equipment & Tier 1 & 1996 & 6.9 & 1.0 & --- & 8.5 & 0.40 \\
& & Tier 2 & 2002 & --- & --- & 4.8 & 2.6 & 0.15 \\
& & Tier 3 & 2006 & --- & --- & 3.0 & 2.6 & \\
Greater 750 & generators, off-highway trucks, than crawlers & Tier 1 & 2000 & 6.9 & 1.0 & --- & 8.5 & 0.40 \\
& & Tier 2 & 2006 & --- & --- & 4.8 & 2.6 & 0.15 \\
\hline
\end{tabular}
\caption{Off-Road Diesel Engine Emission Standards (g/bhp-hr)\textsuperscript{34}}
\end{table}
compared to typical pre-regulation era engines of that size. These non-road emissions reductions will be achieved in a period of only 10 years. In contrast, while comparable rates of emission reduction from on-highway engines will be achieved with the 2004 on-highway standards, these reductions are being achieved 30 years after the first on-highway standards went into effect.

Both federal and California standards apply to new engines. These new engines enter service as fleets grow and older engines are replaced which is a gradual process. Diesel engines are extremely durable, so fleet turnover in many cases is not rapid. Despite the long life of older engines, and despite the growth in the number of engines, the federal emission standards for non-road diesel engines have already led to cleaner air, and will produce even more significant air quality benefits in the years to come. For example, Figure 3 depicts the projected drop in NO$_x$ emissions from the off-road diesel category through the year 2020.

This figure shows that the current federal emission standards more than offset predicted growth in the use of off-road diesel engine equipment, resulting in cleaner air at least through the year 2020.

### Improvement of Off-Road Diesel Emissions Performance

Diesel engines have achieved these emissions reductions through the use of a number of advanced emissions reduction technologies. In the past, off-road diesel emissions have been controlled through the same types of techniques that have been applied to highway diesel engines. As discussed above, off-road and on-highway standards have been developed in a staggered tandem sequence that has allowed more complex low volume off-road engines to take advantage of technology that is first developed, tested, and proven in less complex and higher volume production on-highway engines which are used in less demanding operating environments.

Accordingly, engine makers met the challenge of Tier 1 and 2 off-road standards by adapting technology that was already being employed in on-highway engines under existing 1990s highway emissions standards, such as electronic engine controls and in-cylinder combustion optimization. Similarly, the Tier 3 off-road standards, which begin phase-in in 2006, were developed with the hope and expectation that off-road engines could use the types of technology that would be developed for the 2004 on-highway standards. The emissions reductions for Tiers 1-3 are depicted in Figure 4.
In each of these prior rulemakings, the EPA has acknowledged the unique challenges presented by efforts to transfer technology from highway to off-road engines. From a technical perspective, these challenges include greater heat generation, higher sulfur fuel, harsher operating environments and more transient duty-cycles. Technology transfer also raises significant commercial challenges arising from the fact that off-road engines are produced in significantly lower volumes and installed in a much greater number of diverse equipment applications.

Because of these significant challenges, on-highway emissions technology is not readily transferable to off-road equipment. Certain types of on-highway technologies will not be adaptable to off-road engine applications at all, and in many cases where on-highway technology can be transferred, it will not be capable of producing the same level of emissions reductions in off-road engines. Each of these technical and commercial challenges is discussed in more detail in a section below.

Tier 1 & 2 Off-Road Emissions Reduction Technologies
Like the on-highway standards implemented in the 1990s, Tier 1 & 2 off-road emissions reductions were achieved through modifications within the engine itself. The modifications helped control combustion temperature, including offsetting the temperature increases caused by systems adopted to reduce PM emissions. NO\textsubscript{X} reductions have been achieved principally through improved fuel delivery, including electronic fuel injection and variable injection timing, and through air-to-air charge cooling, which reduces the higher temperatures created by turbo charging. Tier 2 PM reductions were accomplished by improvements designed to ensure a more complete burn of fuel within the engine. The primary PM reduction enhancements included improved fuel delivery systems, improved configuration of combustion chambers and turbo charging. The various techniques used to achieve these emission reductions are discussed in detail in Appendix A.

Tier 3 Off-Road Emissions Reduction Technologies
The Tier 3 off-road standards generally tracked the 2004 on-highway standards and were intended to rely on the same types of technologies anticipated to meet the 2004 on-highway standards. The Tier 3 off-road technology is expected to rely on further advances to the Tier 2 technologies described above, as well as two new engine technologies: cooled exhaust gas recirculation and advanced electronic fuel injection. These engine technologies are discussed in more detail in Appendix B.
The Challenge of “Tier 4” Off-Road Emissions Standards

The next generation of diesel emissions control technologies, which is the basis of the most recent set of on-highway diesel emissions standards and regulations (the 2007 Highway Standards) are also expected to be applied to varying degrees to off-road engines and equipment to meet future “Tier 4” off-road standards. The 2007 Highway Standards’ emissions reductions will rely on advanced exhaust aftertreatment technology, which will be enabled by reductions in fuel sulfur content. The 2007 Highway Standards represent a significant departure from previous approaches to diesel emissions reductions. The previous on-highway and off-road emissions standards focused on reductions that could be achieved from engineering improvements to the engine alone. The EPA’s 2007 Highway Standards require a systems-based approach to emission reductions that can only be achieved through refinements to diesel power systems as a whole, which include engines, diesel fuel and exhaust aftertreatment devices. These standards are known as “technology-forcing” regulations, meaning that they will require the development of new technology or new applications and combinations of existing technology in order to meet the required emissions levels.

Exhaust treatment will involve particulate traps, which can reduce more than 90 percent of engine emissions before they leave the tailpipe, and catalytic converters that convert emissions to harmless substances. Lower sulfur diesel fuel is required to enable use of advanced diesel aftertreatment technology. The most promising technologies under development for meeting the proposed 2007 Highway Standards for new engines are discussed in Appendix C.

The extent to which this new “systems approach” can be transferred to the off-road sector is far from clear at this time. The EPA and off-road engine manufacturers are currently focusing on a number of significant challenges as they work to determine what the appropriate scope of future “Tier 4” off-road regulations should be.

Unique Challenges for Off-Road Engines and Equipment: Technical, Product and Market Diversity

The diversity of off-road engine sizes, power ratings and equipment applications presents perhaps the single largest challenge for achieving further emission reductions with 2007 Highway Standards-type systems. This diversity creates challenges from both a technical and a commercial perspective.

The large number of different engines and applications means that, from a technical perspective, manufacturers must design, test and implement an equally large and diverse set of emissions reduction strategies to meet new emission standards. Each off-road engine and power rating will present a unique set of engineering issues, and each engine-specific strategy will need further development and refinement for use in each equipment application.
The diversity of off-road engines and equipment also creates significant challenges from a commercial perspective. The engineering and production costs of developing new off-road emission reduction technologies are generally higher than those for on-highway equipment due to the technical complexities discussed below, yet these costs must be distributed among a much lower production volume. The annual production volume of individual off-road engine models is quite small relative to the annual production volume of a comparable on-highway engine model. Further, even a small-volume engine may need to be configured and adapted to a number of different equipment applications. There are over 1,700 different manufacturers in the mobile non-road equipment industry, producing hundreds of different types of off-road machines. In contrast, there are only a few dozen different truck manufacturers using diesel engines in heavy-duty on-highway trucks; and less than a half-dozen produce the vast majority of these vehicles. Finally, there are a number of non-road engine and equipment makers who do not make on-highway engines, and therefore do not have technology on the shelf to even consider transferring. The commercial challenges for these manufacturers will be even greater.

The commercial challenges are further magnified by the fact that, in sharp contrast to on-highway engine production, non-road engines and equipment are produced for a global market. Because non-road engines and equipment are produced in relatively small quantities for use around the world, producing multiple variations of engines with varying emissions performance is neither technically nor economically practical. Ideally, future non-road emissions standards should work toward global harmonization of standards to facilitate the most efficient adoption of the next generation of engines and non-road equipment.
For all of these reasons, the marginal cost to manufacturers – and ultimately to consumers – of emission improvements is much higher than with on-highway equipment. These costs are relevant to overall air quality improvement: higher consumer costs can slow equipment turnover and investment in newer, lower emission equipment.

In addition to the general challenge of the diversity of the off-road sector, there are a number of more specific technical issues associated with each aspect of the systems approach to emissions reduction: engines, aftertreatment and fuel.

**Engine Enhancement Challenges**

Applying highway engine technologies (like EGR, advanced electronic fuel injection and turbo charging) to off-road equipment presents special challenges. Off-road equipment must function in a comparatively harsh operating environment. These machines are exposed to high levels of dust and debris, which present special challenges for air filtration and cooling systems. Off-road engines also must endure high vibration and shock levels.

As discussed above, off-road engines confront a wide variety of mechanical demands and operate across a spectrum of duty cycles. This variability makes it difficult to optimize engine tuning for emissions reduction, since optimal tuning can vary as a function of engine load and duty cycle. A system or approach that works at high loads or speeds may be relatively ineffective at idle or with lower loads.

The high operating temperatures of off-road engines create particular difficulties for the implementation of engine-based approaches, like cooled EGR. As discussed earlier, off-road engines are subject to a number of additional power demands associated with auxiliary hydraulic systems and accessories, which increase engine loads and temperatures. Similarly, the dirt and dust found in the off-road environment prevents the use of the more efficient dense radiator cores found in on-highway cooling systems. The lack of ram air for cooling puts a large burden on off-road cooling systems, to the point that the addition of another heat-generating system like EGR may be difficult or impossible. EGR systems also consume a great deal of space in the engine compartment – space that may not be available in certain types of equipment.

**Aftertreatment Integration Challenges**

The integration of aftertreatment systems in the design of off-road equipment is especially challenging. The development of Tier 4 off-road equipment with aftertreatment will, for the first time, require design coordination between as many as four separate entities: the engine makers, aftertreatment makers, off-road equipment makers and fuel refiners. The level of integration and coordination between manufacturers required by this approach is unprecedented.

The major challenge for the use of exhaust aftertreatment systems is that current systems must operate in a narrow temperature window in order to be effective. Diesel particulate filters need to be operated above a certain temperature to ensure regeneration, and NO\(_X\) aftertreatment has both a low and high temperature requirement. The effectiveness of all NO\(_X\) control systems declines dramatically at exhaust temperatures below approximately 250° C. This presents a problem for off-road equipment that experiences frequent periods of low-load operation or idling, when exhaust temperatures can drop to 150° C or lower.
The exhaust temperature profiles for off-road engines will vary widely depending on the equipment, which makes maintenance of optimum exhaust temperatures particularly challenging. Solutions to this issue, when they are developed, must then be adapted to a very wide range of engine sizes.

Engineering the placement of aftertreatment in off-road equipment also creates special challenges. Off-road equipment has safety, visibility and functionality requirements that place special constraints on engine compartment size and packaging. Off-road equipment must allow the operators to have a wide and unobstructed field of view to maintain the safety and utility of the equipment. For example, off-road equipment operators must have an unobstructed view of the operating area for vehicle attachments like shovels, blades and buckets. Similarly, these attachments need to be able to move freely through their entire range of motion without being obstructed by the engine compartment. Off-road equipment also has unique operator safety issues not found in on-highway vehicles. Equipment designs must comply with OSHA and other worksite safety standards for visibility, rollover protection, stability, engine/PTO lockouts and other requirements that must be met along with the introduction of any additional emissions control systems.

The feasibility of adding an aftertreatment device will depend on the amount of additional space that is available on a particular piece of equipment. Engine compartment space is frequently quite limited in off-road equipment. While some equipment using a given engine may have sufficient room to accommodate additional aftertreatment devices, the same engine employed on another piece of equipment may not have enough room. The problem of developing integrated engine and aftertreatment systems is particularly complicated for non-vertically integrated engine makers who will need to devote significant resources to determining the particular design constraints associated with large numbers of non-standardized low-volume pieces of equipment.
Fuel Sulfur Challenges
Much of the non-road diesel fuel currently used in all non-road engines, including off-road equipment, is not regulated by the EPA and has a relatively high sulfur content. Typical non-road diesel fuel meets ASTM specification D975, which sets a maximum sulfur level of 5,000 ppm. Fuel meeting the ASTM standard typically has a sulfur level of around 3,000 ppm. On-highway diesel sulfur content is currently limited to 500 ppm by regulation, and typically has an average of 300 ppm. In many areas of the country, significant amounts of on-highway diesel fuel are used in non-road applications.

The emissions reductions established by the 2007 Highway Standards will require the use of aftertreatment devices that are sulfur-sensitive. Higher fuel sulfur levels tend to degrade the effectiveness and longevity of some aftertreatment devices by inhibiting the function of catalysts and filters. The EPA concluded that sulfur with a maximum of 15 ppm would be required to enable the use of these aftertreatment devices. The Tier 4 off-road standards may also require the use of sulfur-sensitive aftertreatment devices.

Some engine and off-road equipment manufacturers intend to use EGR engine technology to meet future NO\textsubscript{x} reduction requirements. These manufacturers are concerned that when EGR is applied, high sulfur fuel can lead to acidic condensates in the engine’s intake tract and exhaust system when combined with the dust and particulates associated with off-road uses. This intake air chemistry can cause corrosion and wear and generally reduce engine durability. End users of EGR-equipped off-road equipment may wish to use the lower sulfur on-highway diesel if durability is a concern, at least until Tier 4 off-road standards and lower sulfur non-road fuels are required by the EPA.

To enable the same types of emissions control technology to be applied to off-road diesel engines as will be used in on-highway diesel engines, very low sulfur off-road diesel fuel (i.e., 15 ppm) will also be needed. Creating similar emissions standards for off-road vehicles could compound the supply and distribution issues that have been raised with respect to on-highway diesel if careful attention is not paid to the non-road diesel fuel sulfur reduction phasing and timing when the EPA establishes the Tier 4 off-road engine/fuel requirements.

In addition to fuel sulfur challenges, Tier 4 standards will likely demand further optimization and increased fuel injection pressures, as well as increased hydraulic and mechanical demands on key components, such as the fuel injection systems. As a result, engine component manufacturers and fuel refiners will need to jointly agree on a new ULSD lubricity specification to ensure system reliability and emission compliance over the full useful life of the engine.

![Figure 7: Total U.S. Petroleum Consumption: 2001](image-url)
While recently issued emissions standards for new non-road engines continue to be phased in, and while future emissions standards are debated, substantial efforts to reduce emissions from existing engines are also taking place. Across the country and around the world, an increasing number of air quality planners and diesel fleet operators are conducting emissions performance upgrades on existing non-road diesel engines in order to achieve near-term emissions reductions that contribute to meeting air quality goals. Non-road emissions upgrades raise many of the same technical challenges associated with development of more stringent emissions standards for new non-road engines. Accordingly, non-road emissions upgrades are generally more difficult than on-highway upgrade and retrofit projects.

In spite of these significant challenges, successful non-road emissions upgrade projects have significantly reduced emissions from hundreds of thousands of non-road diesel engines in many non-road applications. Many project proponents have found that non-road diesel emissions upgrades can be cost-effective emission control measures under the right circumstances. Whether the underlying project rationale is to help the region attain compliance with an EPA air quality standard, or to mitigate the localized effects of concentrated heavy-duty equipment activity, diesel equipment retrofits and upgrades are becoming a significant strategy to achieve cleaner air.

Experience with non-road diesel retrofits began in the underground mining and materials handling sectors, with the introduction of oxidation catalysts that reduce PM, CO and HC emissions. In more recent years, oxidation catalysts have also been retrofitted to construction and other types of diesel equipment—not only to improve the immediate working environment, but also to improve ambient air quality and to reduce noise, smoke and odor. To date, over 250,000 oxidation catalysts have been installed on pieces of non-road diesel equipment, making oxidation catalyst technology a leading non-road retrofit control strategy for certain applications.
Other emission upgrade technologies are also being used on off-road diesel equipment. For instance, particulate filters have been installed on such equipment since the mid-1980s, totaling more than 20,000 units installed worldwide on a wide range of applications including mining equipment, forklifts, street sweepers and utility vehicles. When combined with low-sulfur diesel fuel, today’s diesel particulate filters can reduce PM emissions by more than 90 percent across all particulate size ranges. In addition to using oxidation catalysts and particulate filters, recent experience has also been gained with selective catalytic reduction technology. This emissions control technology is already a common strategy to reduce NO\textsubscript{x} and HC emissions from stationary sources, and has proven capable of being applied to non-road mobile sources with relatively stable load conditions, such as marine vessels. Selective catalytic reduction technologies have been installed on these types of mobile sources since about 1995, including more than 20 marine vessels with engines ranging from 1250 hp to almost 10,000 hp.

One of today’s largest off-road diesel equipment retrofit programs was developed by a partnership of state agencies and private parties in order to mitigate air quality impacts from construction activities at Boston’s massive Central Artery/Tunnel Project (otherwise known as the “Big Dig”). The $14 billion Big Dig highway construction project required 24-hour use of several hundred pieces of heavy-duty off-road diesel equipment. Its location through the heart of central Boston not only presented enormous engineering challenges, but also raised significant concern regarding localized air quality impact. In order to mitigate these air quality concerns, the Massachusetts Turnpike Authority (MTA) entered 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 eight excavators and front-end loaders with oxidation catalysts. After contractors found that the retrofitted equipment did not experience a significant loss of power or other operational problems, did not consume more fuel, and did not require increased maintenance, project sponsors began to retrofit many more pieces of heavy-duty construction equipment. To date, over 100 pieces of construction equipment at the Big Dig have been retrofitted with oxidation catalysts—including front-end loaders, large bulldozers, excavators, backhoes, cranes, air compressors and small power-generators. Given the program’s success, project officials have now decided to retrofit all major construction equipment at the Big Dig—about 200 pieces—with aftertreatment emission control devices. In implementing these plans, state officials plan to take advantage of recent advances in retrofit technology that will enable significant reduction not only in CO, HC and PM emissions, but will also significantly reduce NO\textsubscript{x} emissions as well.

Preliminary emissions reduction estimates indicate that the first 70 retrofits at the Big Dig have decreased emissions by about 36 tons/year of CO, 12 tons/year of HC, and 3 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 at the Big Dig have ranged from about $1,000 – $3,000/vehicle, with an average cost of about $2,500/vehicle. This cost was incurred with respect to vehicles that might be valued at $200,000 to $300,000. 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 emissions removed, which represents a relatively low cost for emission control.
Conclusion

Progress in improving diesel engines has been continuous, both in the performance of the engines and their roles in improving air quality. This is extremely important due to the role of diesel in world’s economy.

The Non-Road Diesel Engine is Vital to the Global Economy

The diesel engine provides a unique value of performance, reliability and efficiency unmatched by other non-road engine technologies. As demonstrated by their predominant and increasing use in both on-road and off-road applications, diesel engines are major drivers in the growth and productivity of the economy. Diesel is the dominant source of power in a significant amount of construction equipment, over two-thirds of all farm equipment, nearly all mining equipment, all freight railroad and nearly all commercial marine engines, electric power generation, logging, petroleum exploration and production, and numerous military applications.

Non-road diesel engines are designed to perform very different kinds of work compared to engines for use in on-road trucks and buses. Non-road engines have highly variable operating conditions compared to the relatively steady-state highway truck engines. The differences include the need to power hydraulic systems and engine-driven attachments, and unique operator safety considerations.

Non-Road Diesel Emissions Have Already Reduced Dramatically Under Existing Regulations

Non-road diesel engines have achieved significant emissions reductions more rapidly than comparable reductions in the on-highway sector. For heavy-duty mobile off-road diesel engines, the reductions have been especially dramatic.

For engines used in backhoes, excavators and larger farm tractors (175-700 horsepower), PM emissions have been reduced 85 percent since EPA regulations went into effect in 1996. NO\textsubscript{X} emissions have been reduced by 70 percent in that same timeframe, and will be reduced by another 40 percent by 2006 under current regulations, resulting in a total NO\textsubscript{X} reduction of 82 percent. Non-road equipment applications and operating environments make engineering non-road emissions reduction solutions particularly challenging.

The diversity of non-road diesel engine sizes and equipment applications also adds to the complexity of developing and implementing these solutions. With nearly four times the number of engine certifications compared to on-road engines, there are more off-highway engine models produced by more manufacturers, going into more kinds of equipment, but in far smaller production volumes as compared to on-road engines. Non-road diesel engines have unique manufacturing, production and distribution characteristics and are sold in a more highly globalized marketplace where harmonization of environmental standards is of extreme importance.
These non-road engines are potential candidates for emissions upgrades, but have unique challenges in technical feasibility, space limitation and operating characteristics. Not all non-road engines and equipment will be cost effective or technically feasible to upgrade; some will be better candidates for replacement or repowering.

**To Achieve Additional Non-Road Diesel Emissions Reductions, Significant Technical and Commercial Challenges Must be Overcome**

While many emissions control technologies developed for the 2007 Highway Standards potentially can be applied to future non-road engines, much of this technology will not be readily transferable. The full extent to which this “systems approach” can be applied to non-road engines is far from clear at this time. Major challenges to the transfer of these promising on-highway technologies to non-road engines are presented by the diversity of non-road engines and equipment, the extreme duty cycles, the wide range of engine and exhaust temperatures, the significant space constraints and the high sulfur content of non-road diesel fuel. In spite of these obstacles, off-road engine and equipment manufacturers, fuel refiners and aftertreatment manufacturers are working together to meet these challenges and develop systems-based emissions reduction strategies for the next generation of non-road engines.
Appendix A

Tier 1 & 2 Off-Road Emissions Reduction Technologies

> **Electronic Fuel Injection.** The development of electronic fuel injection systems for diesel engines has played a central role in reducing both PM and NO\textsubscript{X}. Electronic systems calibrate fuel injection based on information from electronic sensors that monitor engine performance and vehicle activity. They are used both to ensure a more complete fuel burn to reduce PM, and to control temperature to reduce NO\textsubscript{X}. In contrast, older diesel fuel injection systems used mechanical means to control the quantity and timing of fuel injection. With those systems, rapid ramp-up of engine speed – such as acceleration with a heavy load – led to excess fuel being injected. Much of this fuel was not burned and was emitted as soot, which created the black exhaust that many associate with old diesel engines.

> **High-Pressure Fuel Injection.** PM emissions are reduced through more complete combustion of fuel injected into the combustion chamber. More complete combustion can be achieved by improving the mix of air and fuel in the chamber. Modern high-pressure fuel injection systems force fuel into the combustion chamber through smaller diameter holes at higher pressure – in excess of 25,000 pounds per square inch. This causes the fuel to break down into tiny droplets, thereby improving the air-fuel mix to achieve a more complete burn.

> **Variable Injection Timing.** NO\textsubscript{X} emissions can be reduced by a delay in the start of fuel injection, which reduces the temperature at which combustion takes place. This technique, known as injection timing retard, requires precise control of the beginning of injection into a cylinder in relation to the position of the piston in that cylinder. Most electronic fuel injection systems allow independent control of the timing of injection to optimize emissions performance. Reduction in NO\textsubscript{X} through this technique is combined with other measures, such as high injection pressure and improved combustion chamber design, to minimize the loss of fuel economy and potential increase in PM emissions that otherwise would result from a delay in fuel injection.

> **Improved Combustion Chamber Configuration.** More complete fuel combustion and reduced PM emissions occur when fuel and air are mixed more evenly in the combustion chamber. Engine manufacturers have invested great effort in optimizing the features of combustion chambers to ensure the best possible mix. Modern combustion chamber design reflects extensive modeling of several design elements, including: (1) the shape and depth of the combustion chamber and the piston bowl (the small area at the top of the piston into which fuel is injected); (2) spiral-shaped intake ports that cause air to swirl as it enters the chamber; (3) the number of cylinder valves; and (4) the placement of fuel injectors in the combustion chamber.
> **Turbo Charging.** Turbo charging can both reduce PM emissions and improve fuel economy. A turbocharger compresses the air that enters the cylinder, forcing more air into the combustion chamber. The compressor is driven by a turbine, which in turn is powered by the engine's own exhaust. The increase in air in the combustion chamber offers two key advantages. First, it enables fuel to burn more completely, reducing PM. Second, it permits more fuel to be added to the chamber, generating more power than a similarly-sized engine without turbo charging. By generating more power from a smaller displacement engine, turbo charging reduces engine weight and improves fuel economy.

> **Air-to-Air Charge Cooling.** This is a further advance in turbo charging that reduces NO\textsubscript{X} emissions. Turbochargers deliver (or “charge”) air at higher pressure, and therefore also increase the temperature of the air delivered for combustion. Air-to-air charge cooling reduces the temperature of the charged air, thereby lowering NO\textsubscript{X} emissions. Ambient air, which averages about 75° F, is used to cool the air to be charged in the combustion chamber. This is an improvement on water-based cooling systems that had been used in the past. Those systems were limited in their effectiveness by their use of water at temperatures that could run as high as 210° F.
Appendix B

Tier 3 Off-Road Emissions Reduction Technology

Cooled Exhaust Gas Recirculation. Exhaust gas recirculation ("EGR") is expected to play a central role in achieving NO\textsubscript{X} reductions for the next generation of off-road engines. 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 50 percent. The recycled exhaust gas can also be cooled; this so-called “cooled EGR” can generate further NO\textsubscript{X} emissions reductions by further lowering combustion temperatures.

Advanced Fuel Injection. Advanced fuel injection systems provide much greater control of fuel injection to improve emissions and overall engine performance. In these systems, injection pressure and injection events can be controlled independently of engine speed and load, which is a departure from traditional injection systems. Two of the most promising advanced fuel injection technologies are Common Rail Systems and Hydraulic Electronic Unit Injection systems.

> In a Common Rail System (CRS), fuel is held in a reservoir, or “rail,” that serves all of the engine’s cylinders: this is known as a “common” rail. Fuel in the common rail is maintained under pressure, and that pressure can be varied or optimized independent of the engine’s speed and load. Consequently, both the injection pressure and timing can be controlled independently to achieve emissions objectives.

> Hydraulic Electronic Unit Injection (HEUI) systems also provide for lower emissions while improving fuel economy and performance. In these systems, individual unit injectors are actuated hydraulically by a high-pressure oil pump, rather than mechanically. This high-pressure oil controls the rate of injection, while electronics control the amount of fuel injected. All of this is done independently of engine speed.

Traditional systems triggered fuel injection by mechanical means, using camshafts and plungers that were driven by the engine. This caused injection rates to rise and fall along with engine speed, and prevented independent regulation of injection timing events and pressure.

These advanced systems enable a number of emissions-reducing fuel injection techniques that previously were infeasible. For example, to reduce NO\textsubscript{X} emissions, fuel injection can be geared independently to control burn temperature. In order to reduce particulate emissions, the main fuel injection can be split into two, causing a more complete burn of fuel. Other goals that can also be achieved through this technology include the reduction of engine combustion noise.

ACERT™ Technology. The ACERT™ technology is an efficient combustion process with a flexibility that allows more freedom to design the fuel injection process. Sophisticated computer algorithms identify the optimum settings for the lowest possible NO\textsubscript{X} emissions and outstanding fuel economy. Conventional, electronically wastegated turbochargers, in series on heavy-duty engines, coupled with hydraulic-assist valve control yield a robust, flexible air management system. The system recovers exhaust energy, which improves fuel economy, and lowers in-cylinder combustion temperatures to improve emissions. The exhaust system features a tailored aftertreatment system, which changes particulate matter into carbon dioxide and water.
Appendix C

2007 Highway Standards Emission Reduction Technology

> Oxidation Catalysts. Manufacturers report that flow-through oxidation catalysts can reduce carbon monoxide and hydrocarbons in the range of 60-90 percent. (Reductions of PM in the range of 25-50 percent can also be achieved.) Oxidation catalysts are a proven technology. 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 on off-road diesels around the world for over 20 years, with over 250,000 units installed in the mining and materials handling industries. They also have been used extensively in retrofit applications, where they have been installed on U.S. urban buses and on European highway trucks, with over 10,000 units installed over the last two years.

Oxidation catalysts initiate a chemical reaction in the exhaust stream, oxidizing pollutants into water vapor and other gases, such as carbon dioxide. A typical oxidation catalyst consists of a stainless steel canister containing a honeycomb-like structure called a substrate. The interior surfaces of the substrate are coated with catalytic precious metals, such as platinum or palladium. Oxidation catalysts are sensitive to the sulfur in diesel fuel, which tends to reduce the effectiveness of the catalyst. Lowering fuel sulfur content allows catalysts to achieve greater emissions reductions and allows manufacturers to use less noble metal to lower costs.

> Selective Catalytic Reduction Devices. Selective catalytic reduction ("SCR") is another technology actively being developed. It has been found to produce significant simultaneous reductions of NO\textsubscript{X}, hydrocarbons and PM. SCR has been used to control NO\textsubscript{X} emissions from stationary sources for over 15 years. More recently, the technology has been demonstrated in retrofit applications on mobile sources. 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. An SCR system adds a reducing agent to the exhaust stream in order to convert NO\textsubscript{X} to nitrogen and oxygen. As the exhaust gases, along with the reducing agent (usually urea), pass over a catalyst coated substrate, NO\textsubscript{X}, HC and PM are converted to harmless emissions.

> Particulate Filters. Advanced diesel particulate filter systems are currently in development to produce 90+ percent PM emissions reductions. Reductions of hydrocarbons and carbon monoxide greater than 90 percent are also achieved. (Some versions of this new generation of filters currently are being marketed in Europe, where low sulfur fuel is readily available, and others have been used for years as retrofits to existing engines.) These systems consist of a filter positioned in the exhaust stream to collect particulate emissions as the exhaust gases pass through the system. The key challenge is posed by the volume of particulate trapped by the filter: over time the filter must be changed or regenerated. Development work is currently focused on disposal of the trapped particulate by automatically burning or oxidizing the particulate in the filter so that filter replacement is not required as a regular maintenance item. (This is known as filter regeneration.) Work is continuing to improve both filter efficiency and filter regeneration.

> NO\textsubscript{X} Catalysts. Two catalyst technologies are being developed specifically to reduce NO\textsubscript{X} emissions by up to 90 percent.
The first, so-called “lean NO\textsubscript{x} catalyst,” works like SCR in that it adds a reducing agent to the exhaust stream to facilitate catalytic conversion. Systems using lean NO\textsubscript{x} catalysts inject diesel fuel into the exhaust gas to add hydrocarbons. The hydrocarbons act as a reducing agent to facilitate the conversion of NO\textsubscript{x} to nitrogen and water vapor in the catalyst.

The second technology, “NO\textsubscript{x} adsorbers,” operates in two stages. First, the NO\textsubscript{x} is converted and adsorbed into a chemical storage site within the system. Then when the NO\textsubscript{x} adsorber becomes saturated, it is regenerated by adding extra diesel fuel to the exhaust stream. The addition of the fuel causes the NO\textsubscript{x} adsorber to work like a lean NO\textsubscript{x} catalyst — it converts the collected NO\textsubscript{x} into simple nitrogen and oxygen which is emitted from the system.

**Advanced Turbochargers.** In addition to aftertreatment technologies, continued improvements in engine technologies, like advanced turbocharger systems, may be used to meet the 2007-2010 standards. The next generation of turbo charging systems will feature increased use of variable geometry turbochargers and electrically assisted turbochargers.

**Variable Geometry Turbochargers** work by adjusting the size of the air passage at the turbine wheel inlet in order to optimize turbine power. At low engine speeds, when the exhaust gas flow at the turbine wheel inlet is low, the air passage at the inlet is focused by a nozzle. This causes the turbine wheel to spin faster and increases the turbocharger’s boost pressure. In contrast, at high engine speeds and loads, which create greatly increased exhaust flow, the inlet nozzle opens to moderate turbine speed and turbocharger boost pressure. Variable geometry turbochargers thus have a quicker response time during vehicle acceleration, and at the same time prevent over-boosting at high speeds. This allows the vehicle to burn fuel more efficiently over the full range of operation, producing fewer emissions and achieving better fuel economy.

**Electrically Assisted Turbochargers** use a high-speed electric motor to provide additional turbo boost during short periods of acceleration, such as initial acceleration, passing and hill climbing. These systems use sophisticated electronics to monitor the demand for power and instantly supply additional boost air to the engine during these transient increases in engine load. This provides more air for combustion during these fuel-rich operating periods. The increased air permits more complete combustion, resulting in reduced emissions and better fuel economy.

**Diesel Fuel Sulfur Content.** The primary purpose of lower sulfur fuel is to enable or improve the performance of aftertreatment technologies. However, reduced sulfur will also provide an emissions benefit by reducing sulfate PM and sulfur oxide emissions from existing engines directly. Sulfur in diesel fuel contributes to a small portion of particulate formation, so reducing the sulfur content of diesel fuel has the potential to reduce total PM emissions from the existing non-road fleet by approximately 17 percent without the addition of any aftertreatment device.
Footnotes

1. Willard W. Pullcrabek, Engineering Fundamentals of the Internal Combustion Engine, Prentice Hall, 1997. The temperature in the exhaust system of a typical compression ignition engine will average between 200° and 500°C, whereas the temperature in the exhaust system of a typical spark ignition engine will average 400° to 600° C, and will rise to about 900°C at maximum power. A full list of references can be found at the end of this report.


5. USDA, Economic Research Service, Natural Resources and Environment Division, Agricultural Resources and Environmental Indicators, “Production Inputs,” 1995, pp. 135–136. The data in this report include electricity in addition to liquid fuels. However, data on electricity use in agriculture ceased to be available after 1991. The data reported above are for liquid fuels—gasoline, diesel, and LP gas.


21. 2002 Diesel and Gas Turbine Catalog


23. U.S. DOT, Maritime Trade and Transportation ‘99, Table 1-16.


See, 40 C.F.R. Part 89 (Off-road); 40 C.F.R. Part 92 (Locomotives); 40 C.F.R. Part 94 (Commercial and Recreational Marine)


The only diesels not subject to federal emissions standards would be certain vehicles and engines manufactured pursuant to military vehicle regulatory exemptions.


40 C.F.R. § 89.112, Table 1 (2001) (values in g/kW-hr have been converted to g/bhp-hr); U.S. EPA, “Final Regulatory Impact Analysis: Control of Emissions from Nonroad Diesel Engines,” EPA420-R-98-016, pp. 5-7, August 1998.


30 C.F.R. pts. 7, 36, 56, 57, 70, and 75.


The Diesel Technology Forum maintains a searchable database containing project-specific details of various diesel retrofit programs across the country. See www.dieselforum.org/retrofit/activitymatrix.asp.


www.bigdig.com/thtml/envair01.htm

Edward Kunce and Steven Lipman, Massachusetts Department of Environmental Protection, “Massachusetts Diesel Retrofit Program (MDRP),” Presented at the Innovative Technology/Aftermarket Retrofit Program Workshop, Houston, Texas (September 2000).


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