Diesel Retrofit Technology

An Analysis of the Cost-Effectiveness of Reducing Particulate Matter and Nitrogen Oxides Emissions from Heavy-Duty Nonroad Diesel Engines Through Retrofits

United States
Environmental Protection
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Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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EPA United States
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Executive Summary

The Environmental Protection Agency's (EPA) National Clean Diesel Campaign (NCDC) is a comprehensive initiative to reduce pollution from diesel engines throughout the country, including vehicles on highways, city streets, construction sites, and ports. The NCDC comprises both regulatory programs to address new engines and innovative programs to address the millions of diesel engines already in use. On the regulatory side, EPA is successfully implementing emissions standards for engines in the 2007 Heavy-Duty Highway Engine Rule and the Tier 4 Nonroad Rule and developing new emission requirements for locomotives and marine diesel engines, including large commercial marine engines. On the innovative side, EPA is addressing engines that are already in use by promoting a variety of innovative emission reduction strategies such as retrofitting, repairing, replacing and repowering engines, reducing idling, and switching to cleaner fuels. The innovative programs are accomplished in partnership with state and local governments, environmental groups and industry.

The emissions standards for new engines will reduce both highway and nonroad engine emissions by roughly 90%. However, these emission reductions occur over a long period of time as new engines are phased into the fleet. Retrofitting diesel engines currently in use will allow significant and immediate emission reductions from diesel engines that would not otherwise be addressed.

The purpose of this technical analysis is to evaluate the cost effectiveness of retrofitting existing heavy-duty diesel nonroad engines to reduce particulate matter (PM) and nitrogen oxides (NOx). (The cost effectiveness of the regulatory measures EPA has implemented is addressed by the rulemakings.) Analysts in EPA's Office of Transportation and Air Quality (OTAQ) evaluated the costs and emissions benefits of retrofitting nonroad equipment such as tractors/loaders/backhoes, excavators, cranes, generator sets, agricultural tractors, crawler tractors/dozers and off-highway trucks with diesel oxidation catalysts (DOCs) and catalyzed diesel particulate filters (CDPFs), two of the most common PM emissions reduction technologies for diesel engines as well as with selective catalytic reduction (SCR) systems and engine upgrade kits for NOx reduction.

The methodology used to perform these calculations is the same as those outlined in the U.S. EPA Technical Report: Diesel Retrofit Technology: An Analysis of the Cost-Effectiveness of Reducing Particulate Matter Emissions from Heavy-Duty Diesel Engines Through Retrofits EPA420-S-06-002 March 2006.

For these nonroad engines, EPA relied primarily on data from the NONROAD2005 model to determine the cost-effectiveness of installing DOCs, CDPFs, SCR systems, and engine upgrade kits. These data covered factors such as hours of operation, vehicle/equipment useful life, emission rates and retrofit technology effectiveness. EPA also consulted with technology and engine manufacturers regarding retrofit technology cost effectiveness and applicability.

EPA calculated that the cost effectiveness for both diesel oxidation catalyst and catalyzed diesel particulate filter retrofits ranged from $18,700 to $87,600 per ton of PM reduced. In addition, EPA calculated the cost effectiveness for both selective catalytic reduction systems and engine upgrade kits ranging from $1,900 to $19,000 per ton of NOx reduced.

The results can be compared to similar estimates for other EPA programs targeted at reducing diesel particulate matter. For example, EPA estimates that the cost effectiveness of retrofitting school buses and class 6-8b trucks ranges from $11,100 to $69,900 per ton of PM reduced. In addition, EPA estimates that the cost effectiveness of the Urban Bus Retrofit and Rebuild program is $31,500 per ton of PM reduced, the 2007 Heavy-Duty Highway diesel emission standards is $14,200 per ton, and the Nonroad Tier 4 emission standards is $11,200 per ton.

The results can also be compared to similar estimates for those same programs targeted at reducing nitrogen oxides. For example, EPA estimates that the cost effectiveness of the 2007 Heavy-Duty Highway emissions standards is $2,100 per ton of NOx reduced and the Nonroad Tier 4 emission standards is $1,000 per ton.

The findings from this study indicate that retrofits can be a cost effective way to reduce air pollution and health impacts associated with diesel emissions.

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I. INTRODUCTION

I.A. NATIONAL CLEAN DIESEL CAMPAIGN

The Environmental Protection Agency's (EPA's) National Clean Diesel Campaign (NCDC) is a comprehensive initiative to reduce pollution from diesel engines. EPA's Office of Transportation and Air Quality (OTAQ) manages the NCDC, which comprises both regulatory programs to address new engines and innovative programs to address the millions of diesel engines already in use.

Particulate matter (PM), one of the primary pollutants from diesel exhaust, is associated with many different types of respiratory and cardiovascular effects, and premature mortality. EPA has determined that it is a likely human carcinogen. Fine particles (smaller than 2.5 micrometers), in particular, are a significant health risk as they can pass through the nose and throat and cause lung damage. People with existing heart or lung disease, asthma, or other respiratory problems are most sensitive to the health effects of fine particles as are children and the elderly. Children are more susceptible to air pollution than healthy adults because their respiratory systems are still developing and they have a faster breathing rate. EPA expects reductions in air pollution from diesel engines to lower the incidence of these health effects, as well as contribute to reductions in regional haze in our national parks and cities, lost work days and reduced worker productivity, and other environmental and ecological impacts.

Nitrogen oxides (NOx), the main ingredient of forming ground-level ozone, react with Volatile Organic Compounds (VOC) in the presence of heat and sunlight through complex chemical reactions to produce air pollution. NOx are emitted largely from highway vehicles, nonroad equipment, power plants, and other sources of combustion. Based on a large number of recent studies, EPA has identified several key health effects caused when people are exposed to levels of ozone found today in many areas of the country. Short-term exposures (1-3 hours) to high ambient ozone concentrations have been linked to increased hospital admissions and emergency room visits for respiratory problems. For example, studies conducted in the northeastern U.S. and Canada show that ozone air pollution is associated with 10-20 percent of all of the summertime respiratory-related hospital admissions. Repeated exposure to ozone can make people more susceptible to respiratory infection and lung inflammation and can aggravate preexisting respiratory diseases, such as asthma. Prolonged (6 to 8 hours), repeated exposure to ozone can cause inflammation of the lung, impairment of lung defense mechanisms, and possibly irreversible changes in lung structure, which over time could lead to premature aging of the lungs and/or chronic respiratory illnesses such as emphysema and chronic bronchitis.

New regulations from EPA require stringent pollution controls on new highway and nonroad diesel engines, including engines operating in the freight, transit, construction, agriculture, and mining sectors. The new regulations will also reduce sulfur content in diesel fuel by 97 percent. By combining tough exhaust standards with cleaner fuel requirements, these rules will cut emission levels from new engines by over 90 percent. The new lower sulfur diesel fuel will immediately result in reduced PM emissions. New engines sold in the US after 2007 for highway use (and after 2008 for nonroad use) must meet the more stringent standards, but the effect of these cleaner engines will be achieved over time as the existing fleet is gradually replaced. The benefits of these new rules will not be fully realized until the 2030 time frame. As a result EPA is promoting a suite of innovative programs to address emissions from the existing fleet of diesel vehicles and equipment.

The NCDC innovative programs are designed to address existing diesel vehicles and equipment through emission reduction strategies that can provide immediate air quality and health benefits. These programs focus on vehicles and equipment in the school bus, construction, port, freight and agricultural sectors. The NCDC works with partners in state and local government, industry, and environmental organizations to promote a wide range of measures to reduce diesel emissions including retrofitting vehicles/equipment with new or improved emission control equipment, upgrading engines, replacing older engines with newer/cleaner engines, and using cleaner fuels. Additionally, idle reduction is an effective strategy provided within the NCDC. Eliminating unnecessary idling can save fuel, prolong engine life, and reduce emissions. It can also help reduce the noise levels associated with construction and freight movement. Unnecessary idling occurs when trucks wait for extended periods of time to load or unload materials or supplies, or when equipment is left on when it is not being used. Managing equipment operations and training workers to reduce unnecessary idling is a relatively easy way to lower operating costs and help reduce the environmental impact.

I.B. STUDY OBJECTIVE AND METHODS

Stakeholders - including states that are developing their plans to achieve the National Ambient Air Quality Standards for ozone and fine particles - are searching for cost effective ways to reduce emissions from existing diesel engines in order to improve air quality and protect public health. The purpose of this study is to estimate the cost effectiveness of retrofit strategies for various nonroad applications that reduce emissions.

Retrofit technologies offering PM and/or NOx reductions were evaluated for the following types of nonroad equipment:

1) off-highway trucks (250 horsepower (hp))
2) tractors/loaders/backhoes (150 hp)
3) excavators (250 hp)
4) cranes (250 hp)
5) generator sets (100 hp)
6) crawler tractors/dozers (250 hp), and
7) agricultural tractors (250 hp)

EPA chose these examples of nonroad equipment for three reasons. First, a further evaluation of the cost effectiveness of retrofit technologies for nonroad equipment was needed. Second, data generated from EPA's grant projects provide the most recent information for these types of equipment. Finally, these nonroad equipment exist in large numbers across the country, thus ensuring that this cost effectiveness analysis will be relevant to a wide audience.

Two most common diesel retrofit technologies for PM reductions, diesel oxidation catalysts (DOCs) and catalyzed diesel particulate filters (CDPFs), were evaluated. CDPFs use either passive or active regeneration systems to oxidize the PM in the filters. In this report, a passive filter is analyzed. Also, selective catalytic reduction (SCR) systems and engine upgrade kits for NOx reductions were chosen. An SCR system may be combined with a DOC or CDPF for further emissions reductions. In this report, an SCR system alone is analyzed.

For this analysis, EPA relied primarily on data from the NONROAD2005[1] model to determine the cost-effectiveness of DOCs, CDPFs, SCR systems, and engine upgrade kits. EPA also consulted additional data sources where appropriate.

Annual equipment usage, equipment useful life, engine emission rates[2], retrofit technology effectiveness, and technology costs to calculate the cost-effectiveness of these retrofit strategies were analyzed, in terms of $ per ton of PM and/or NOx reduced. It is important to note that, in many cases, heavy-duty nonroad diesel retrofit strategies provide other emission benefits such as reductions in hydrocarbons and carbon monoxide. This study only evaluates the cost-effectiveness of reducing PM from DOCs and CDPFs as well as NOx from SCR systems and engine upgrade kits. The following section will detail our methods for calculating the cost-effectiveness of PM and NOx reductions from retrofits including factors such as equipment activity, survival rates, emissions factors, costs of technologies, and emissions reductions from retrofit technologies. In Section III the results are presented and in Section IV the summary remarks about the relative cost-effectiveness of diesel retrofit technology for heavy-duty nonroad engines are provided.

II. RETROFIT EFFECTIVENESS FACTORS

In order to estimate the relative cost effectiveness of various PM and NOx retrofit strategies, it is necessary to estimate a number of factors, including:

- equipment activity
- equipment survival rates
- emissions rates of equipment
- effectiveness of DOCs, CDPFs, SCR systems and engine upgrade kits
- costs of retrofits

The following sections II.A - II.F outline our methodologies for estimating each of these factors.

II.A. EQUIPMENT ACTIVITY ANALYSIS

One of the first steps in estimating emission reductions from retrofit strategies is to develop an estimate of annual equipment activity. This requires identifying operating hours and engine load for these nonroad equipment. This information can then be used to estimate annual equipment emissions and emission reductions from retrofits.

The methodology for estimating emission reductions from nonroad equipment is to estimate annual and lifetime activity (use patterns). This activity was estimated based on data from the technical documentation for the NONROAD inventory emissions model (see www.epa.gov/otaq/nonrdmdl.htm for a description of the NONROAD model). Nonroad engine activity is expressed in terms of hours of operation (annual and lifetime) and load factors (average engine operating power as a percentage of rated engine power). The estimated annual hours of operation and typical load factors (LF) are listed in Table 1.

Table 1: Annual Hours of Operation and Load Factors

Equipment	Hours	LF
Off-highway Trucks	1,641	0.59
Tractors/Loaders/ Backhoes	1,135	0.21
Excavators	1,092	0.59
Cranes	990	0.43
Generator Sets	338	0.43
Crawler Tractors/ Dozers	936	0.59
Agricultural Tractors	475	0.59

Crane carrying timber

II.B. EQUIPMENT SURVIVAL RATE/SCRAPPAGE ANALYSIS

The scrappage rate describes the fraction of vehicles/equipment (relative to the total number originally sold) that are no longer in the fleet from one year to the next. This factor reflects vehicle/equipment loss through accidents, deterioration, and export. From a retrofit perspective, scrappage is a necessary component of cost effectiveness analysis because it dictates how long older equipment will stay in service, and hence the potential benefit which will accrue from a retrofit at a certain point in time.

The NONROAD model has intrinsic scrappage rates built into the model. These rates are used to project the distribution of nonroad equipment in a population by age. The median life from the NONROAD model is used to estimate the lifetime of the nonroad equipment. This number is the number of hours of rated engine operation that the median example of a nonroad diesel engine is expected to operate. Dividing that number by the load factors in Table 1 converts the median life from hours of operation at rated power to hours of operation at typical operating power levels (i.e., it converts it to actual hours of operation). The median life for a 150 hp diesel engine from the NONROAD model is 4,667 hours at rated power. Dividing this number by the load factor of tractors/loaders/backhoes in Table 1 (4,667 hours rated / 0.21) returns a median life at typical operating conditions of 22,224 hours. Given annual operating hours of 1,135 hours, the expected lifetime for the median 150 hp tractors/loaders/backhoes can be found as 19.6 years.

II.C. EMISSION RATES ANALYSIS

The NONROAD engine model uses emission rates for nonroad diesel engines based on the emission standards, historic engine certification data, and projections of in-use deterioration of emissions over the lifetime of the engine. Additionally, the nonroad model includes a factor to correct for observed differences in emissions production between in-use operating cycles and the steady-state emissions test results. The projected in-use emissions rates are therefore the product of the expected new certification emissions level, the ratio of transient emission rates to steady-state emission rates, and projected deterioration rates over time (i.e., as the equipment ages EPA projects emissions will increase). The result of this methodology is that new (beginning of life) nonroad equipment is estimated to have a lower emission rate than the same equipment would after a period of operation.

In order to simplify the analysis for PM, the adjustment for transient emissions and deterioration were combined into a single static number of 1.5 (i.e., a 50% increase in emissions over the certification levels) which roughly approximates the combined factors for an off-highway truck in the nonroad model for PM reductions. This approach may undercount the emissions from a typical piece of nonroad equipment making it less cost effective when compared to the NONROAD model where the transient adjustment factor (TAF) ranges from 1.23 to 1.97 and the deterioration factor varies from 1.0 at 0 hours to 1.473 at full useful life. Hence, the NONROAD model adjustment would range from 1.2 to 2.9 (1.0 X 1.23 to 1.473 X 1.97) over the range of engines and through the equipment life. However, the use of a simplified single value of 1.5 is appropriate for this analysis since the goal is to estimate a nominal ratio of emission reductions and cost.

However, NOx TAF ranges from 0.95 to 1.10 and the deterioration factor varies from 1.0 at 0 hours to 1.024 at full useful life. With the limited range in value for each factor, a NOx deterioration factor of one and the individual TAF were applied for this analysis.

EPA has developed a retrofit modeling function within the National Mobile Inventory Model (NMIM) that fully incorporates the features of the NONROAD model and will allow states and local authorities to more accurately estimate the potential for emission reductions through retrofits.

II.D. EFFECTIVENESS OF RETROFIT TECHNOLOGIES

II.D.1. Background on Retrofit Technology Verification

The NCDC innovative programs encourage air quality agencies and owners of fleets of diesel powered vehicles and equipment to implement clean diesel strategies such as installing new or enhanced emission control technology and using cleaner fuels. To help these organizations make informed decisions regarding which retrofit technologies are appropriate for their fleets and what emission reductions can be expected, EPA created the Retrofit Technology Verification Program. This process evaluates the emission reduction performance of retrofit technologies, including their durability, and identifies engine operating criteria and conditions that must exist for these technologies to achieve those reductions.

DOC on construction equipment

Under this program, companies can apply for EPA verification of the effectiveness of their emission control technology. The verification protocol requires the same tests as defined by the Code of Federal Regulations (CFR) for new engine family certification before sale in the U.S. The protocol tests the stand-alone engine, and then the engine with the emission control technology. Both new and aged technologies must be tested. The emission reduction percentage that EPA verifies will reflect the performance of the new and used technologies. Once a technology is verified, the company receives an official EPA verification letter, and the technology is listed on EPA's web site as a verified technology. There is no restriction on who may apply for verification. To date, EPA has verified nearly 30 technologies from different emission control technology companies.

The measures that EPA verifies can be very general - for example, an emission control technology company may receive verification for a diesel oxidation catalyst (DOC) technology that can reduce particulate matter from any uncontrolled or Tier 1 nonroad diesel engine by 20 percent - or the verification can be specific to an engine model made over specific model years. While retrofit technologies are the most common clean diesel strategy verified by EPA, there is a wide range of measures that can reduce diesel emissions. For example, the replacement of older engines or equipment may be more beneficial or a necessary condition for using retrofit technologies.

II.D.2. Technology Effectiveness Analysis

EPA's List of Verified Technologies provided the retrofit technology applications and emission reduction information for this study. The verified PM emission reduction figures for DOCs and CDPFs were applied for nonroad engines. The NOx emission reductions associated with upgrading a Tier 0 (unregulated) engine to Tier 1 and a Tier 1 engine to Tier 2 emission levels were estimated. Finally, NOx emission reductions from SCR systems were also estimated based on existing technical reports. However, exhaust temperature requirements of SCR systems may limit the applicability of this technology in the legacy fleet.

The estimated reduction in PM:
1) from adding a DOC to a nonroad engine and changing to ≤ 500 ppm sulfur fuel is 20%
2) from adding a CDPF to a nonroad engine and changing to ultra low sulfur diesel (ULSD) fuel is 90%

The estimated reduction in NOx:
1) from adding an SCR system to a nonroad engine is 70%
2) from adding an engine upgrade kit to a Tier 0 (unregulated) engine or to a Tier 1 nonroad engine is 40%

One requirement of the verification process is that applicants must test their systems after they have been installed for a period of time. The manufacturer must begin in-use testing after they have sold a certain number of units of the verified technology. EPA must approve the manufacturer's sampling plan to gather units to be tested. The manufacturer must test units aged in the field to a minimum fraction of the designated durability testing period in two different phases. Manufacturers are given wide latitude in the type of emissions testing equipment they use, although test cycles are well defined. The manufacturer must test at least four units in each phase. Individual failures lead to additional testing or possible removal from the Verified Technology List. This part of the verification process is still in its early stage and, as such, EPA is just now receiving preliminary results from in-use testing from retrofit technology manufacturers. As EPA receives these additional in-use test results, they will be examined to ensure these verified technologies are performing properly in the field.

The reduction of other criteria air pollutants by retrofit technology should also be recognized. A DOC, CDPF, SCR system or engine upgrade kit may reduce hydrocarbon and carbon monoxide emissions on the order of 20 to 90 percent.

II.E. COSTS

II.E.1. Background

Several sources of information are available on the current price of retrofit technologies. These include a December 2000 survey[3] and an April 2006 report[4] by the Manufacturers of Emission Controls Association (MECA), and current price information for grant recipients under the NCDC's funding assistance programs. These sources give ranges for CDPF prices of \$3,000 to \$10,000 depending on size, expected product sales volumes, and configuration (i.e., in-line or muffler replacement). Similarly, these sources suggest DOCs will range in price from \$425 to \$2,000 depending on size, sales volume and configuration. These sources also suggest SCR systems range from \$12,000 to \$20,000. While the high end of the ranges is reflective of current prices for PM and NOx retrofit technologies applied to nonroad equipment, future retrofit costs are likely to drop substantially as a result of the Heavy-Duty Highway 2007 and the Nonroad Tier 4 emission regulations.

II.E.2. Cost Analysis

EPA has estimated the production cost for DOCs and CDPFs for nonroad engines in the Nonroad Tier 4 rule-making.[5] The analysis in that rule-making was based on preliminary data available to EPA regarding the actual manufacturing costs for CDPF and DOC technologies.

Based on the Nonroad Tier 4 Regulatory Impact Analysis (RIA), the CDPF costs ranged from \$178 to \$6,405 and DOC from \$105 to \$734 depending on the horsepower and average engine displacement.

However, the Tier 4 RIA did not include the costs for additional exhaust tubing, datalogging and installation which could add another $593 for a CDPF and $280 for a DOC as described in the Diesel Retrofit Technology report[6]. Based on the estimates from this report, the Nonroad Tier 4 RIA, and our current experience with nonroad retrofit technology, a nominal average cost is estimated. That typical cost is $1,000 per DOC and $5,000 per CDPF retrofit depending on the horsepower and average engine displacement.

EPA has consulted several sources of information regarding cost estimates for SCR systems and engine upgrade kits. These sources of information provide an average cost of selective catalytic reduction systems ranging from $10,000 to $20,000 per system depending on the size of the engine, the sales volume, and other factors. Given this range and the current cost of SCR systems in existing programs, the cost is estimated to be approximately $13,000 per unit. The cost of the nonroad engine upgrade kit is estimated to be between $2,000 and $4,000 per equipment. For this analysis, the average estimated cost is $3,000 per equipment.

Using today's nominal cost as a future cost estimate is very conservative because of the greater diversity and smaller retrofit fleet sizes typical of nonroad equipment. Nonroad retrofits are expected to occur one piece of equipment at a time, even in relatively high volumes. These projections represent the best estimate of the nominal cost for retrofitting equipment with diesel engines with various displacements. In practice, significant variability above and below these price estimates is expected due to a wide range of other factors which were not accounted for in this analysis (e.g., retrofit fleet size, profit margin differences, etc.). Nevertheless, these estimates adequately reflect the nominal cost for future PM and NOx retrofit technologies.

II.E.3. Operating Costs

Operating costs related to the application of the retrofit technologies are not accounted for in this analysis. Operating costs could include the differential cost for using 15 ppm sulfur fuel, fuel economy impacts related to increased exhaust backpressure, or changes to maintenance practices related to the use of retrofit technologies. Any premium for 15 ppm sulfur fuel in this analysis has not been accounted for because 15 ppm sulfur highway diesel fuel is now the predominant diesel fuel used in highway applications. At the same time nonroad engines are changing to fuel with less than 500 ppm sulfur and then in 2010 will change to 15 ppm sulfur diesel fuel. A change in fuel consumption related to the use of retrofit technology was not accounted for in this analysis because current data from existing retrofits show no significant difference in fuel economy for equipment with and without these retrofit technologies. In practice, the impact of retrofit technologies on fuel consumption is strongly related to engine load and therefore varies significantly depending upon the vehicle/equipment application.

II.F. ESTIMATING LIFETIME EMISSION REDUCTIONS

II.F.1. Background

In order to compare the relative cost effectiveness (i.e., tons of emissions reduced per dollar spent) of retrofit programs to other emission control programs, it is necessary to estimate the lifetime emissions reduction EPA projects will occur with retrofit technology. In concept, estimating the emission reductions is simple and can be viewed as the product of the lifetime hours usage, the baseline emission rate for the equipment (grams/horsepower-hour) and the emission reduction potential of the retrofit technology (e.g., 90% for CDPFs). In practice, the estimate is more complicated since vehicle/equipment scrappage, variations in hour usage as the equipment ages, and the relative value of emission reductions realized in the current year versus a future time must be accounted for. Furthermore, estimates of the lifetime emission reductions for retrofit technologies must address the age of the vehicle/equipment when the retrofit is installed (i.e., retrofitting a one year old piece of equipment would be expected to result in a larger emission reduction compared to a ten-year-old equipment). These factors in our analysis for the nominal case were accounted for, but it should be recognized that factors such as annual hour usage can vary significantly between different types of equipment.

II.F.2. Emission Reduction Analysis

To obtain emission reductions, the annual and lifetime emissions for every piece of nonroad equipment were first calculated. To calculate annual emissions for nonroad equipment, the TAF adjusted emission rates on Tables 2 - 11 in Appendices A and B were used to multiply horsepower and annual usage. These annual figures can then be brought back to a net present value at a defined discount rate (3 percent) to give a discounted lifetime emissions. This result is shown in the fourth column of Tables 2 - 11. The lifetime emissions are the baseline emissions which are then used to multiply the reduction rate of each retrofit technology to obtain lifetime emission reductions. Because equipment retrofitted at different ages will have different lifetime emission reductions, estimates were made for retrofits for various model years as if the equipment were retrofitted in calendar year 2007. Hence, a 2006 model year equipment retrofitted in model year 2007 would be one year old, and a 2001 model year equipment retrofitted in model year 2007 would be six years old. Tables 2 - 11 organize the equipment of different ages by column designating both the model year of the retrofitted equipment (e.g., 2001) and the age of the equipment when retrofitted in 2007 (e.g., 6 years old). Engine upgrade kits are used to upgrade Tier 0 (unregulated) engines to Tier 1 emission levels and Tier 1 to Tier 2. The implementation of Tier 3 standards generally starts on model year 2006 for a 250 horsepower (hp) nonroad engine and 2007 for 100 and 150 hp nonroad engines with phase-in schedules. Therefore, the analysis begins with model year 2006 as described in Tables 2 - 11. Those lifetime emission reductions calculated in this paper in the previous section along with the cost of each retrofit technology are used to obtain the cost per ton as shown in the fifth and sixth columns of Tables 2 - 11.

III. RESULTS

Tables 12 and 13 summarize the range of cost effectiveness figures estimated for the selected retrofit cases in this paper. As noted previously, these estimates represent a nominal projection of the future cost per ton of emission reduction. These cost effectiveness estimates have not factored in the co-benefits from reducing other pollutants such as hydrocarbons. The cost effectiveness of retrofit programs can vary significantly depending on a number of factors, including actual annual average activity (i.e., annual operating hours for nonroad).

The results summarized in Table 12 can be compared to similar estimates for other EPA programs targeted at reducing diesel particulate matter. For example, the cost-effectiveness of DOC and CDPF retrofits for school bus and Class 6-8b trucks range from approximately $11,000 to $69,900 published in the Diesel Retrofit Technology report in March 2006.[6] In addition, retrofits of diesel engines can be as cost-effective as recent EPA rule-makings to address diesel particulate matter, such as the 2007 Heavy-Duty Highway emissions standards and the Nonroad Tier 4 emissions standards which EPA estimates will cost $14,200 per ton of PM reduced and $11,200 per ton of PM reduced, respectively.

Table 12. Summary of Cost Effectiveness for Various Diesel PM Retrofit Scenarios

Equipment	Retrofit Technology	Range of $/ton PM Emission Reduced	
Off-highway Trucks	DOC	$21,700	$78,800
	CDPF	$24,200	$87,600
Tractors/ Loaders/ Backhoes	DOC	$25,900	$49,900
	CDPF	$28,800	$55,400
Excavators	DOC	$22,300	$61,900
	CDPF	$24,800	$68,800
Cranes	DOC	$20,900	$60,000
	CDPF	$23,300	$66,700
Generator Sets	DOC	$18,700	$46,100
	CDPF	$20,800	$51,300

Table 13. Summary of Cost Effectiveness for Various Diesel NOx Retrofit Scenarios

Equipment	Retrofit Technology	Range of $/ton NOx Emission Reduced	
Tractors/ Loaders/ Backhoes	Upgrade Kit	$2,600	$4,900
	SCR	$6,500	$12,100
Excavators	Upgrade Kit	$2,300	$6,600
	SCR	$5,800	$16,400
Crawler Tractors/ Dozers	Upgrade Kit	$2,200	$6,600
	SCR	$5,600	$16,500
Cranes	Upgrade Kit	$2,100	$6,100
	SCR	$5,100	$15,100
Agricultural Tractors	Upgrade Kit	$1,900	$7,700
	SCR	$4,700	$19,000

The results summarized in Table 13 can also be compared to similar estimates for other EPA programs targeted at reducing diesel nitrogen oxides. For instance, the cost effectiveness of the 2007 Heavy-Duty Highway emissions standards is $2,100 per ton of NOx reduced and the Nonroad Tier 4 emission standards is $1,000 per ton.

The results summarized in Tables 12 and 13 above and given in more detail in Tables 2 - 6 and 7-11, respectively, are characterized by increasing cost per ton of emission reduction for the retrofit of older equipment in comparison to newer equipment. This characteristic is to be expected as older equipment will have a shorter remaining lifetime and hence lower remaining emissions to be reduced prior to equipment scrappage. In some cases, the cost per ton of emission reductions decreases with older equipment because of older equipment's relatively high emissions level. That is, retrofitting an emission control technology on an older engine that, due to historically more lenient emissions standards has higher emissions, may lead to a larger emission reduction for the same retrofit cost. This benefit from retrofitting older dirtier equipment is offset by the shorter remaining life of the older equipment.

IV. CONCLUSION

This analysis demonstrates that diesel retrofit strategies can be a cost effective way to reduce air pollution. The cost-effectiveness of DOC and CDPF retrofits for nonroad equipment were calculated ranging from approximately $18,700 to $87,600 per ton of PM reduced. The cost-effectiveness of SCR systems and engine upgrade kits for nonroad equipment were calculated ranging from approximately $1,900 to $19,000 per ton of NOx reduced. These estimates depend on a number of factors such as equipment activity, survival rates, emissions rates, effectiveness of DOCs, CDPFs, SCR systems and engine upgrade kits, and their costs.

It is important to note that, while the cost effectiveness estimates were based on robust and recent data sources, there is a significant amount of variability in both the costs and the emission reductions from retrofit technologies in the field. Also, the analysis adequately represents the cost effectiveness of DOC, CDPF, SCR system, and engine upgrade kit retrofits for nonroad equipment, but the cost-effectiveness of retrofits for specific engines and equipment fleets may differ in certain situations.

EPA has developed a module as part of the National Mobile Inventory Model (NMIM) that will allow users to predict the impact of retrofitting their particular fleets. This new module is able to generate national, county-level, or fleet-specific mobile source emissions inventories and then use these inventories to estimate emission reductions from retrofit technologies.

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Appendix A
PM Cost Per Ton Estimates with DOC and CDPF

Table 2. Tractors/Loaders/Backhoes PM Cost per Ton Estimates with DOC and CDPF

Age	Model Year	Emission Rate (TAF adjusted)	Discounted Life Time Emissions	DOC C/E	CDPF C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	0.270	0.150	$33,400	$37,100
2	2005	0.270	0.144	$34,800	$38,700
3	2004	0.270	0.137	$36,400	$40,500
4	2003	0.270	0.131	$38,200	$42,500
5	2002	0.420	0.193	$25,900	$28,800
6	2001	0.420	0.182	$27,400	$30,500
7	2000	0.420	0.171	$29,200	$32,500
8	1999	0.420	0.160	$31,300	$34,800
9	1998	0.420	0.148	$33,800	$37,500
10	1997	0.420	0.136	$36,800	$40,900
11	1996	0.603	0.177	$28,200	$31,300
12	1995	0.603	0.159	$31,500	$35,000
13	1994	0.603	0.140	$35,700	$39,700
14	1993	0.603	0.120	$41,500	$46,200
15	1992	0.603	0.100	$49,900	$55,400

Table 3. Generator Sets PM Cost per Ton Estimates with DOC and CDPF

Age	Model Year	Emission Rate (TAF adjusted)	Discounted Life Time Emissions	DOC C/E	CDPF C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	0.360	0.116	$43,300	$48,100
2	2005	0.360	0.113	$44,200	$49,100
3	2004	0.360	0.111	$45,100	$50,100
4	2003	0.360	0.108	$46,100	$51,300
5	2002	0.705	0.207	$24,100	$26,800
6	2001	0.705	0.202	$24,700	$27,500
7	2000	0.705	0.197	$25,400	$28,200
8	1999	0.705	0.192	$26,100	$29,000
9	1998	0.705	0.186	$26,900	$29,800
10	1997	0.705	0.180	$27,700	$30,800
11	1996	1.080	0.267	$18,700	$20,800
12	1995	1.080	0.258	$19,400	$21,500
13	1994	1.080	0.249	$20,100	$22,300
14	1993	1.080	0.239	$20,900	$23,300
15	1992	1.080	0.229	$21,900	$24,300

Table 4. Cranes PM Cost per Ton Estimates with DOC and CDPF

Age	Model Year	Emission Rate (TAF adjusted)	Discounted Life Time Emissions	DOC C/E	CDPF C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	0.225	0.224	$22,300	$24,800
2	2005	0.197	0.180	$27,900	$30,900
3	2004	0.197	0.162	$30,900	$34,300
4	2003	0.197	0.143	$34,900	$38,700
5	2002	0.378	0.239	$20,900	$23,300
6	2001	0.378	0.202	$24,800	$27,600
7	2000	0.378	0.163	$30,600	$34,000
8	1999	0.378	0.124	$40,400	$44,800
9	1998	0.378	0.083	$60,000	$66,700

Note: The median life for a 250 hp crane from the NONROAD model is 4,667 hours at rated power. Dividing this number by the 0.43 load factor of crane (4,667 hours rated / 0.43) returns a median life at typical operating conditions of 10,853 hours. Given annual operating hours of 990 hours, the expected lifetime for the median 250 hp crane can be found as 10.9 years. While this represents the expected median operating life, it should be recognized that significant variation about this median can be expected in practice with many pieces of nonroad equipment being used for periods well in excess of 10.9 years.

Table 5. Excavators PM Cost per Ton Estimates with DOC and CDPF

Age	Model Year	Emission Rate (TAF adjusted)	Discounted Life Time Emissions	DOC C/E	CDPF C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	0.225	0.224	$22,300	$24,800
2	2005	0.197	0.168	$29,800	$33,100
3	2004	0.197	0.138	$36,300	$40,400
4	2003	0.197	0.107	$46,900	$52,100
5	2002	0.378	0.143	$34,800	$38,700
6	2001	0.378	0.081	$61,900	$68,800

Note: The median life for a 250 hp excavator from the NONROAD model is 4,667 hours at rated power. Dividing this number by the 0.59 load factor of excavator (4,667 hours rated / 0.59) returns a median life at typical operating conditions of 7,910 hours. Given annual operating hours of 1,092 hours, the expected lifetime for the median 250 hp excavator can be found as 7.2 years. While this represents the expected median operating life, it should be recognized that significant variation about this median can be expected in practice with many pieces of nonroad equipment being used for periods well in excess of 7.2 years.

Table 6. Off-highway Trucks PM Cost per Ton Estimates with DOC and CDPF					
Age	Model Year	Emission Rate (TAF adjusted)	Discounted Life Time Emissions	DOC C/E	CDPF C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	0.225	0.225	$22,200	$24,700
2	2005	0.197	0.179	$28,000	$31,100
3	2004	0.197	0.160	$31,300	$34,800
4	2003	0.197	0.140	$35,700	$39,600
5	2002	0.378	0.230	$21,700	$24,200
6	2001	0.378	0.190	$26,300	$29,200
7	2000	0.378	0.149	$33,500	$37,300
8	1999	0.378	0.107	$46,800	$52,000
9	1998	0.378	0.063	$78,800	$87,600

Note: The median life for a 250 hp off-highway truck from the NONROAD model is 4,667 hours at rated power. Dividing this number by the 0.59 load factor of off-highway trucks (4,667 hours rated / 0.59) returns a median life at typical operating conditions of 7,910 hours. The NONROAD model estimates operating hours of 1,641 hours for off-highway trucks. However, based on program experience with the in-use fleet today, a conservative estimate of 760 hours was used. Therefore, the expected lifetime for the truck can be found as 10.4 years. While this represents the expected median operating life, it should be recognized that significant variation about this median can be expected in practice with many pieces of nonroad equipment being used for periods well in excess of 10.4 years.

Appendix B
NOx Cost Per Ton Estimates with Upgrade Kit and SCR

Table 7. Tractors/Loaders/Backhoes NOx Cost per Ton Estimates with Upgrade Kit and SCR

Age	Model Year	Emission Rates (TAF adjusted)	Discounted Life Time Emissions	Upgrade Kit C/E	SCR C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	4.510	2.502	$3,000	$7,400
2	2005	4.510	2.399	$3,100	$7,700
3	2004	4.510	2.293	$3,300	$8,100
4	2003	4.510	2.185	$3,400	$8,500
5	2002	6.215	2.856	$2,600	$6,500
6	2001	6.215	2.697	$2,800	$6,900
7	2000	6.215	2.533	$3,000	$7,300
8	1999	6.215	2.365	$3,200	$7,900
9	1998	6.215	2.191	$3,400	$8,500
10	1997	6.215	2.012	$3,700	$9,200
11	1996	9.218	2.710	$2,800	$6,900
12	1995	9.218	2.429	$3,100	$7,600
13	1994	9.218	2.139	$3,500	$8,700
14	1993	9.218	1.840	$4,100	$10,100
15	1992	9.218	1.532	$4,900	$12,100

Table 8. Agricultural Tractors NOx Cost per Ton Estimates with Upgrade Kit and SCR

Age	Model Year	Emission Rates (TAF adjusted)	Discounted Life Time Emissions	Upgrade Kit C/E	SCR C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	2.600	2.477	$3,000	$7,500
2	2005	3.800	3.436	$2,200	$5,400
3	2004	3.800	3.246	$2,300	$5,700
4	2003	3.800	3.050	$2,500	$6,100
5	2002	5.301	3.973	$1,900	$4,700
6	2001	5.301	3.683	$2,000	$5,000
7	2000	5.301	3.385	$2,200	$5,500
8	1999	5.301	3.077	$2,400	$6,000
9	1998	5.301	2.760	$2,700	$6,700
10	1997	5.301	2.434	$3,100	$7,600
11	1996	5.301	2.098	$3,600	$8,900
12	1995	7.961	2.631	$2,900	$7,100
13	1994	7.961	2.096	$3,600	$8,900
14	1993	7.961	1.544	$4,900	$12,000
15	1992	7.961	0.976	$7,700	$19,000

Table 9. Excavators NOx Cost per Ton Estimates with Upgrade Kit and SCR

Age	Model Year	Emission Rates (TAF adjusted)	Discounted Life Time Emissions	Upgrade Kit C/E	SCR C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	2.600	2.605	$2,900	$7,200
2	2005	3.800	3.226	$2,300	$5,800
3	2004	3.800	2.649	$2,800	$7,000
4	2003	3.800	2.054	$3,700	$9,000
5	2002	5.301	2.011	$3,700	$9,200
6	2001	5.301	1.131	$6,600	$16,400

Note: The median life for a 250 hp excavator from the NONROAD model is 4,667 hours at rated power. Dividing this number by the 0.59 load factor of excavator (4,667 hours rated / 0.59) returns a median life at typical operating conditions of 7,910 hours. Given annual operating hours of 1,092 hours, the expected lifetime for the median 250 hp excavator can be found as 7.2 years. While this represents the expected median operating life, it should be recognized that significant variation about this median can be expected in practice with many pieces of nonroad equipment being used for periods well in excess of 7.2 years.

Table 10. Crawler Tractors/Dozers NOx Cost per Ton Estimates with Upgrade Kit and SCR

Age	Model Year	Emission Rates (TAF adjusted)	Discounted Life Time Emissions	Upgrade Kit C/E	SCR C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	2.600	2.605	$2,900	$7,100
2	2005	3.800	3.344	$2,200	$5,600
3	2004	3.800	2.866	$2,600	$6,500
4	2003	3.800	2.374	$3,200	$7,800
5	2002	5.301	2.606	$2,900	$7,100
6	2001	5.301	1.878	$4,000	$9,900
7	2000	5.301	1.128	$6,600	$16,500

Note: The median life for a 250 hp crawler tractor from the NONROAD model is 4,667 hours at rated power. Dividing this number by the 0.59 load factor of crawler tractor (4,667 hours rated / 0.59) returns a median life at typical operating conditions of 7,910 hours. Given annual operating hours of 936 hours, the expected lifetime for the median 250 hp crawler can be found as 8.5 years. While this represents the expected median operating life, it should be recognized that significant variation about this median can be expected in practice with many pieces of nonroad equipment being used for periods well in excess of 8.5 years.

Table 11. Cranes NOx Cost per Ton Estimates with Upgrade Kit and SCR					
Age	Model Year	Emission Rates (TAF adjusted)	Discounted Life Time Emissions	Upgrade Kit C/E	SCR C/E
[years]		[g/bhp-hr]	[tons]	[$/ton]	[$/ton]
1	2006	2.500	2.492	$3,000	$7,500
2	2005	4.000	3.637	$2,100	$5,100
3	2004	4.000	3.278	$2,300	$5,700
4	2003	4.000	2.907	$2,600	$6,400
5	2002	5.580	3.523	$2,100	$5,300
6	2001	5.580	2.975	$2,500	$6,200
7	2000	5.580	2.410	$3,100	$7,700
8	1999	5.580	1.828	$4,100	$10,200
9	1998	5.580	1.229	$6,100	$15,100

Note: The median life for a 250 hp crane from the NONROAD model is 4,667 hours at rated power. Dividing this number by the 0.43 load factor of crane (4,667 hours rated / 0.43) returns a median life at typical operating conditions of 10,853 hours. Given annual operating hours of 990 hours, the expected lifetime for the median 250 hp crane can be found as 10.9 years. While this represents the expected median operating life, it should be recognized that significant variation about this median can be expected in practice with many pieces of nonroad equipment being used for periods well in excess of 10.9 years.

REFERENCES

1 Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling, NR-005c (EPA420-P-04-005, April 2004), available at www.epa.gov/otaq/nonrdmdl.htm#techrept

2 Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling -- Compression-Ignition, NR-009c (EPA420-P-04-009, April 2004), available at www.epa.gov/otaq/nonrdmdl.htm#techrept

3 MECA Independent Cost Survey for Emission Control Retrofit Technologies, Manufacturers of Emission Control Association, December 5, 2000 available on EPA's Retrofit Website, www.epa.gov/oms/retrofit/documents/meca1.pdf

4 Retrofitting Emission Controls on Diesel-Powered Vehicles, Manufacturers of Emission Control Association, April, 2006 available on MECA's Retrofit Website, www.meca.org/page.ww?name=Publications&section=Resources

5 Nonroad Tier 4 Regulatory Impact Analysis (RIA), (EPA420-R-04-007, May 2004) www.epa.gov/nonroad-diesel/2004fr.htm

6 Diesel Retrofit Technology: An Analysis of the Cost-Effectiveness of Reducing Particulate Matter Emissions from Heavy-Duty Diesel Engines Through Retrofits, (EPA420-S-06-002, March 2006), available at www.epa.gov/cleandiesel/documents/420s06002.pdf