Final Report

Evaluation of the feasibility, cost-effectiveness, and necessity of equipping small off-road diesel engines with advanced PM and/or NOx aftertreatment

Contract No. 14-300

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Abstract

Off-road emissions represent one of the largest sources of NOx and PM emissions in California. The existing standards for tier 4 off-road engines were developed based on a Regulatory Impact Analysis (RIA) conducted back in 2004, and do not require aftertreatment for NO_x below 75 horsepower (hp) (i.e., 56 kilowatts (kW)) or PM below 25 hp (i.e., 19 kW). Since aftertreatment control devices for diesel vehicles and equipment are considerably more common now, the use of these strategies for small off-road diesel engines (SORDEs) may be considerably more viable than when the standards were last updated, which could warrant renewed consideration for adopting more stringent exhaust standards for these engines.

The objective of this study is to evaluate the potential effectiveness, feasibility, and cost-effectiveness of implementing more stringent emission regulations on mobile off-road diesel engines with rated powers of less than 75 hp that could be achieved using advanced emission control strategies, such as diesel particulate filters (DPFs) and selective catalytic reduction (SCR). This project included a comprehensive review of available aftertreatment and other technologies, demonstration of selected aftertreatment technologies on actual engines and verification of the emissions performance of these devices through a series of emissions and durability tests, evaluation of the cost implications of the added emissions control strategies, evaluation of the potential impacts of additional emissions controls on the emissions inventory, and evaluation of the potential impact on the small engine marketplace and consumer choice in that area. The demonstrations included two DPF applications for the under 25 hp category on a transportation refrigeration unit (TRU) and a mini-excavator, and two SCR/DPF applications for the 25 to 50 hp category on a ride mower and skid steer. Note that the demonstrations for the NOx control devices were specifically targeted for under 50 hp applications to demonstrate the feasibility of lower NOx emissions standards for off-road diesel engines less than 50 hp.

The results showed that the application of aftertreatment systems for PM for under 25 hp engines and for NOx for 25 to 75 hp was technically feasible. Given the wide variety of applications for off-road engines, however, the practicality of implementing such aftertreatment systems could vary between applications depending on the potential to transition to electric motors or gasoline engines, the cost of the aftertreatment system relative to the overall cost of the equipment it is being used in, and the complexity of the controls that would be required to manage the aftertreatment system for different applications. Preliminary estimates suggest that reductions in the off-road equipment emissions inventory of 2.1% in PM and 8.8-13.6% in NO_x emissions could be achieved through additional regulations on emissions for the under 25 hp category for PM and for the 25 to 75 hp category for NOx. Cost-effectiveness of the demonstrated controls was estimated to be \$0.36 to 0.59/lb NOx and \$19.10/lb PM, which compares very favorably to other rulemakings adopted by CARB.

Acronyms and Abbreviations

AEM..Association of Equipment Manufacturers
ASTM..American Society for Testing and Materials
APU..auxiliary power unit
CARB..California Air Resources Board
CE-CERT...College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CFR...Code of Federal Regulations
CO...carbon monoxide
COV..coefficient of variation
CO_2..carbon dioxide
CPC...condensation particle counter
CVS...constant volume sampling
DEF...diesel emissions fluid
DI..direct injection
DMM...Dekati Mass Monitor
DOC..diesel oxidation catalyst
DPF...diesel particulate filter
ECM..engine control module
EGR...exhaust gas recirculation
EMA..Truck and Engine Manufacturers Association
EPA...United States Environmental Protection Agency
FID..flame ionization detector
hp...horsepower
IDI...indirect injection
kW...kilowatt
lpm..liters per minute
LNT...lean NO_x trap
MECA...Manufacturers of Emissions Controls Association
NMHC...non-methane hydrocarbons
NO_x...nitrogen oxides
OEM..original equipment manufacturer
OPEI..Outdoor Power Equipment Institute
PDP-CVS..positive displacement pump - constant volume sampling
PEMS..portable emissions measurement systems
PM...particulate matter
PN..particle number
QC...quality control
RIA..Regulatory Impact Analysis
RPM..revolutions per minute
ROG..reactive organic gases
scfm...standard cubic feet per minute
SCR...selective catalytic reduction
SCRT...Selective Continuous Regenerating Technology
SIDI...spark-ignited direct-injection
SOF...soluble organic fraction

THC..total hydrocarbons
TWC...three way catalyst
UCR ....University of California at Riverside
ULSD ....ultralow sulfur diesel
VERL ....Vehicle Emissions Research Laboratory

Executive Summary

Off-road emissions represent one of the largest sources of oxides of nitrogen (NOx) and particulate matter (PM) emissions in California. The existing standard for tier 4 off-road engines were developed based on a Regulatory Impact Analysis (RIA) conducted back in 2004, for which compliance is achievable without using aftertreatment for NO_x below 75 horsepower (hp) (i.e., 56 kilowatts (kW)) or PM below 25 hp (i.e., 19 kW). Since aftertreatment control devices for diesel vehicles and equipment are considerably more common now, the use of these strategies for small off-road diesel engines (SORDEs) may be considerably more viable than when the standards were last updated, which could warrant renewed consideration for adopting more stringent exhaust standards for these engines.

The objective of this study is to evaluate the potential effectiveness, feasibility, and cost-effectiveness of implementing regulations on mobile off-road diesel engines with rated powers of less than 75 hp (i.e., 56 kW) that could be achieved using advanced emission control strategies, such as diesel particulate filters (DPFs) and selective catalytic reduction (SCR). This project included a comprehensive review of available aftertreatment and other technologies, demonstration of selected aftertreatment technologies on actual engines and verification of the emissions performance of these devices through a series of emissions and durability tests, evaluation of the cost implications of the added emissions control strategies, evaluation of the potential impacts of additional emissions controls on the emissions inventory, and evaluation of the potential impact on the small engine marketplace and consumer choice in that area.

Technology Overview

A comprehensive product review of existing and emerging emission control technologies to significantly reduce PM and NO_x that could be employed by off-road diesel engines with power ratings of <75 hp was carried out as part of this project. The review included after-treatment technologies such as DPFs, SCR, cooled exhaust gas recirculation (EGR), electronic fuel injection (EFI), as well as alternative fuels and other emerging technologies that might be cost-effective for these engines.

As part of the technology overview, a review of engine technologies and applications was made. The breakdown of engine manufacturers was primarily based on the 2004 EPA rulemaking, as this was the latest publically available characterization of sales data. From this data, the EPA estimated that sales of engines in the 0 to 25 hp category comprised 18 percent (approximately 135,828 units) of the nonroad market. The largest manufacturers of engines in this category were Kubota (36,601 units), Yanmar (32,126 units), and Kukje (21,216 units). The next largest category surveyed by EPA was the 25 to 75 hp engines, with no differentiation made for the 25 to 50 hp engines. Of the categories surveyed by EPA, this was the largest in terms of the number of units, with approximately 281,157 units sold in year 2000, comprising 38 percent of nonroad engines sold that year. The EPA separated the sales fractions based on direct-injection (DI) and indirect injection (IDI) engines. DI and IDI and engines have different combustion chamber designs. DI engines have a more traditional cylinder design where the fuel is injected directly into the cylinder. IDI engines have a "pre-chamber" where fuel is injected before it travels into the actual combustion chamber. DI engines accounted for 59 percent of this category with 165,427 units. Yanmar and Kubota represented an important fraction of this market, with Yanmar and Kubota comprising 19 percent and 13 percent, respectively, of the DI engines sold. Other major manufacturers of DI engines at the time included Deutz (16%), Hatz (12%), Isuzu (10%), Caterpillar/Perkins (10%), and Deere (8%). Kubota represented 51 percent of the sale of engines with IDI. Other major manufacturers of IDI engines at the time were Daewoo Heavy Industries (12%), Ihi-Shibaura (12%), Isuzu (8%), and Caterpillar/Perkins (5%).

A breakdown of equipment types by population in California was provided by ARB staff. A summary of this breakdown is provided in Table ES-1. For the under 25 hp category, these engines are separated into two categories: 0-10 and 10-25 hp. These data indicate that the largest fraction of equipment types are lawn and garden tractors, agricultural tractors, commercial turf equipment, generator sets, and transportation refrigeration units.

Emissions controls for the SORDE category include both engine controls and exhaust aftertreatment. Engine certification data from 2014, the time period when the prescreening for the field demonstrations was being conducted, indicate that both DI and IDI engines are still both prevalent in production. In the under 25 hp category, emissions control in this power size category was predominantly through engine design modifications. In the 25 to 50 hp category, more sophisticated emission control strategies were utilized. Nearly all engines specify either engine design modifications or the use of EGR or cooled EGR, with most of the engines showing EGR control. The majority of the engines also include some level of DPF including DPFs in combination with DOCs. Many of the DPF-equipped engines are also equipped with electronic controls. In terms of future emissions controls, the most prominent technologies included the application of DPFs for under 25 hp engines and the application of SCR for engines between 25 to 75 hp.

ES 1. Population Breakdown of Small Off-road Diesel Engines under 50 hp in California

Small Off-Road Equipment Category by hp range	population			
	0-10	10-25	25-50	50-75
Total	**10448**	**125057**	**79662**	**41666**
Agricultural Tractors		31511	26029	28229
Transport Refrigeration Units	255	7789	26799	
Lawn & Garden Tractors		42716		
Commercial Turf Equipment		11943		
Welders		3646	5254	
Generator Sets		9890	5102	
Pumps	4305	5572	2233	
Air Compressors		172	1051	
Other Agricultural Equipment		751		
Crushing/Proc. Equipment			213	
Hydro Power Units	55	218		
Pressure Washers		325	122	
Sprayers		290	435	150
Signal Boards	3752	3745	18	
Rollers	806	1141	3967	33
Cement and Mortar Mixers	681	740		
Plate Compactors	429	428		
Other General Industrial/Construction Equipment	165	384	2176	823
Skid Steer Loaders		2554	2747	9324
Aerial Lifts		1241	3518	3106

Technology Demonstrations

As part of the technology review, aftertreatment control devices from a variety of different suppliers were reviewed. This included Johnson Matthey, BASF, Proventia, Donaldson, Rypos, Dinex, and other representative member companies from the Manufacturers of Emission Control Association (MECA). Based on this survey, applications/technologies were selected for the technology demonstration. This included two DPF applications for the under 25 hp category, and two SCR/DPF applications for the 25 to 50 hp category. The DPF applications included a transportation refrigeration unit (TRU) with a Proventia DPF and a mini-excavator with a DCL DPF. The 25 to 50 hp demonstrations included a ride mower with a BASF/Continental/Donaldson SCR system and a skid steer with a Johnson Matthey/Tenneco selective continuous regenerating technology (SCRT). Note that the demonstrations for the NOx control devices were specifically targeted for under 50 hp applications to demonstrate the feasibility of lower NOx emissions standards for off-road diesel engines less than 50 hp. Table ES-2 provides a summary of these demonstrations.

ES 2. Summary of Demonstrations for SORDE

Small Off-Road Equipment Category	OEM Aftertreatment	Aftertreatment Retrofitting Methodology	hp range
TRU	None	Proventia DPF	< 25
Mini-excavator	None	DCL DPF	< 25
Ride mower	DPF/DOC	BASF/Donaldson/Continental SCR system	25-50
Skid Steer	DOC	Johnson Matthey/Tenneco SCRT system	25-50

Emissions Testing

Emissions testing was conducted in conjunction with each of the demonstration projects, including a baseline, and degreened baseline (where the aftertreatment equipped engine was tested after 25 hours of aging), and at the completion of the field demonstration at 1,000 hours. Additional testing was also conducted for the mini-excavator and skid steer demonstrations, as 1,000 hours of field demonstration could not be obtained for these demonstrations, and hence additional engine dynamometer aging was required to simulate a full 1,000 hours of use. A summary of the emissions results is as follows:

- For the Proventia DPF on the TRU engine, PM reductions of >98% were found for both the degreened and the 1,000 hour aging tests. Some increases in NO_x emissions were also observed with this unit, as the heating unit used to facilitate DPF regeneration was placed on the intake side of the engine. Proventia has addressed this issue in some newer designs of the unit by putting the heating unit on the exhaust side of the engine.
- The DCL DPF on the mini-excavator showed similar PM reductions in the >98% range for both the degreened and the 1,000 aging tests.
- The tests on the SCR-equipped ride mower engine showed significant NO_x reductions 70.4%, 47.4%, and 57.0%, respectively, for the C1, NRTC cold start, and NRTC hot start baseline degreened tests, and NOx reductions of 90.5%, 25.8%, and 64.95%, respectively, for the C1, NRTC cold start, and NRTC hot start 1,000 tests. The SCR also provided additional reductions of THC, NMHC, and CO emissions, despite the initially low levels for OEM engine that was equipped with a DOC and DPF.
- The tests on the SCRT-equipped engine for the skid steer showed significant NO_x reductions over the C1, for the degreened baseline, post field demonstration, and 1,000 hour aging tests, ranging from 78 to 88%, with no indication of deterioration between the degreened baseline and 1,000 hour aging test. The reductions for the hot start and cold start NRTCs were lower, ranging from 52 to 59%, which could be attributed to the SCR not reaching the dosing temperature threshold of 190 °C during the initial parts of these cycles.

Emissions Inventory Analysis

Emissions inventory analyses were also conducted to evaluate the potential emissions benefits implementing additional regulations in the under 50/75 hp SORDE category. A summary of the baseline emissions inventories for the under 25 hp (PM) and 25 to 75 hp (NO_x) engines is provided in Table ES-3. The baseline emissions inventory data was obtained from CARB's on-line emissions inventory tools (https://www.arb.ca.gov/orion/) for the calendar 2017 in conjunction with information provided by the CARB off-road diesel analysis section/emissions inventory modeling group. For the estimates of potential reductions, the main control technologies considered were DPFs and SCRs. For these calculations, DPFs were estimated to reduce PM by 95%. The SCR reductions were estimated to reduce NO_x emissions by 55 to 85%. These reductions are based on the results summarized in the Emissions Testing section above. These results show that application of a DPF would reduce PM emissions from 0.391 tons per day to 0.019 tons per day for small off-road diesel engines less than 25 hp. The results show the application of SCR could reduce NO_x from 22.654 tons per day to 10.194-3.398 tons per day for small off-road diesel engines in the 25 to 75 hp range, assuming 55% and 85% control efficiencies, respectively. These reductions, in turn, would provide a 3.8% reduction in PM and 8.8-13.7% reduction in NO_x emissions for the total 2017 off-road equipment emissions inventory. In terms of the mobile source category overall, this would represent a 0.4% reduction in PM and 1.2-1.8% reduction in NO_x emissions for 2017 for total mobile sources.

ES 3: Small Off-Road Diesel Engine Emission Benefits

Emission Rate (tons/day)	Horsepower range									
	0-10		10-25		25-50			50-75		
	PM		PM		NO_x			NO_x		
Small Off-Road Equipment Category	Current	95% Reduction	Current	95% Reduction	Current	55% Reduction	85% Reduction	Current	55% Reduction	85% Reduction
Totals	**0.019**	**0.0000**	**0.372**	**0.019**	**13.692**	**6.161**	**2.054**	**8.962**	**4.033**	**1.344**
Agricultural Tractors			0.105	0.005	3.416	1.537	0.512	7.998	3.599	1.200
Transport Refrigeration Units	0.001	0.000	0.034	0.000	7.049	3.172	1.057			
Lawn & Garden Tractors*			0.106	0.005						
Commercial Turf Equipment*			0.0708	0.004						
Welders			0.012	0.001	1.006	0.453	0.151			
Generator Sets			0.026	0.001	0.575	0.259	0.086			
Pumps	0.008	0.000		0.001	0.340	0.153	0.051			
Air Compressors			0.001	0.000	0.224	0.101	0.034			
Other Agricultural Equipment			0.002	0.000						
Crushing/Proc. Equipment*					0.104	0.047	0.016			
Hydro Power Units	0.000	0.000		0.000						
Pressure Washers			0.000	0.000	0.003	0.001	0.000			
Sprayers			0.000	0.000	0.067	0.030	0.010	0.037	0.017	0.006
Signal Boards	0.007	0.000		0.000	0.004	0.002	0.001			
Rollers	0.001	0.000		0.000	0.266	0.120	0.040	0.009	0.004	0.001
Cement and Mortar Mixers	0.001	0.000		0.000						
Plate Compactors	0.000	0.000		0.000						
Other General Industrial/Construction Equipment	0.001	0.000	0.001	0.000	0.327	0.147	0.049	0.172	0.077	0.026
Commercial Turf Equipment										
Skid Steer Loaders			0.015	0.001	0.162	0.073	0.024	0.635	0.286	0.095
Aerial Lifts			0.002	0.000	0.149	0.067	0.022	0.111	0.050	0.017

*These data obtained from Off-Road 2007 (CARB, 2019b)

Cost/Benefit Analysis

A preliminary cost/benefit analysis was conducted based on approximate engine and aftertreatment costs and rough estimates of expected emissions reductions for the DPF and SCR aftertreatment control systems. Aftertreatment costs were estimated to be \$266 + \$62 = \$328 for a DPF + DOC for under 25 hp engines based values for the 1.5-liter engines available in the literature. For the cost of adding SCR NO_x aftertreatment to 25 to 75 hp engines, an estimate of \$474 was utilized, which represents an average of the cost estimates for 2- and 2.5-liter engines available in the literature.

The cost estimates for the DPF+DOC can be combined with the engine populations for the <25 hp engines to provide a cost estimate for implementing more stringent regulations on PM emissions in this engine size range. These costs would be applied to 10,448 engines for the 0 to 10 hp category and 82,340 engines for the 10 to 25 hp category. So, the total cost of implementing DPF + DOCs for the entire fleet of under 25 hp small off-road diesel engines would be \$30,434,464.

The cost estimates for the SCR systems can be combined with the engine populations for the 25 to 75 hp engines to provide a cost estimate for implementing more stringent regulations on NO_x emissions in this engine size range. These costs would be applied to 79,451 engines for the 25 to 50 hp category and 41,666 engines for the 50 to 75 hp category. So, the total cost of implementing SCR technology for the entire fleet of under 25 to 75 hp small off-road diesel engines would be \$57,409,458.

A summary of the cost benefits for enhanced emissions controls for 25 to 75 hp (NO_x) and under 25 hp (PM) SORDEs is provided in Table ES-4. Based on these estimates, the cost benefits in \$ per lb of emission reduction were \$15.29 for PM for the under 25 hp category and range from \$0.38 to \$0.59 for NO_x in 25 to 75 hp. For PM, the cost benefits in \$ per lb of emission reduction are \$23.09 for the 0 to 10 hp category and \$14.87 for the 10 to 25 hp category. For the 25 to 50 hp category, the cost benefits in \$ per lb of emission reduction range from \$0.42 to \$0.64 for NO_x. For the 50 to 75 hp category, the cost benefits in \$ per lb of emission reduction range from \$0.33 to \$0.51 for NO_x. According to CARB staff, these NO_x costs are cheaper than approximately 70 to 80% of estimates for previous CARB rulemaking efforts.

ES 4: Cost-Benefit Analysis

	PM			NO_x					
	(Control efficiency 95%)			(Control efficiency 55%)			(Control efficiency 85%)		
	0-10 hp	10-25 hp	Total	25-50 hp	50-75 hp	Total	25-50 hp	50-75 hp	Total
Cost of DOC/DPF ($)	328	328	NA	NA	NA	NA	NA	NA	NA
Cost of SCR ($)	NA	NA	NA	474	474	NA	474	474	NA
Unit	10448	125057	135505	79622	41666	121288	79622	41666	121288
Total Incremental Cost ($)	$ 3,426,944	$ 41,018,696	$ 44,445,640	$ 37,740,828	$ 19,749,684	$ 57,490,512	$ 37,740,828	$ 19,749,684	$ 57,490,512
Total Emissions Reduction (tons)*	74.21	1378.82	1453.03	29416.09	19252.67	48668.76	45458.03	29755.91	75213.94
Cost per Ton ($)	$ 46,176.52	$ 29,749.17	$ 30,588.20	$ 1,283.00	$ 1,025.82	$ 1,181.26	$ 830.23	$ 663.72	$ 764.36
Cost per lb. ($)	$ 23.09	$ 14.87	$ 15.29	$ 0.64	$ 0.51	$ 0.59	$ 0.42	$ 0.33	$ 0.38

* Assuming that the turn over of the entire statewide off-road fleet will take 30 years, and that the annual fleet turn over rate is evenly distributed over those 30 years.

Market Survey

A market survey was conducted to evaluate the potential impacts of more stringent regulation on the marketplace for SORDE engines and equipment. The survey evaluated the feasibility of advanced emission controls for SORDE engine and equipment, the impacts on production costs and product development cycles, the impacts on engine/equipment performance and operation, operational costs, and the impacts on costs and the potential that diesel engines could be replaced by gasoline engines or electric motors. The literature was also reviewed to better understand product development cycles. The surveys were sent to engine, equipment, and aftertreatment manufacturers and related trade associations. No responses were obtained from any engine or equipment manufacturers, or engine or equipment manufacturer trade associations, so the information obtained was only from aftertreatment manufacturers.

A typical 3-stage product development cycle for the development of diesel engines is shown in Figure ES-1, based on a recent presentation by Perkins Engine Company Limited, a subsidiary of Caterpillar Inc. This includes a stage 1 concept or proof of concept phase, a phase 2 development phase that would include system optimization, durability testing, and emissions testing, and phase 3 that would include performance verification in a machine.

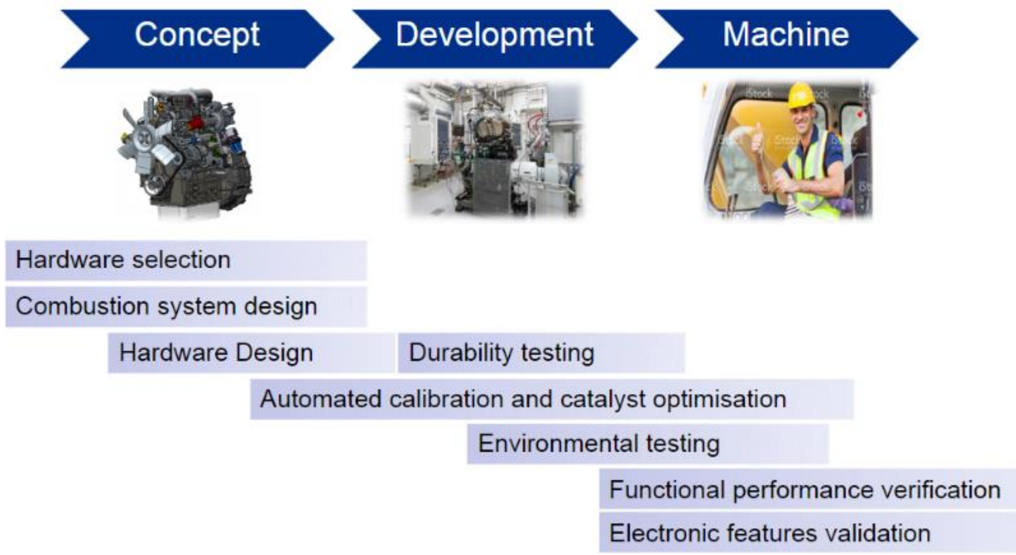


Figure ES-1. Engine Testing to Satisfy Customer Requirements

For the survey itself, the aftertreatment manufacturers that responded to the survey included both small and large businesses providing aftertreatment for mobile, off-road, and stationary applications over a size range from ≤ 7 hp to 5,000 hp. While the aftertreatment manufacturers generally thought the application of aftertreatment to SORDEs was feasible, these applications could require additional accessories, such as electrically heated devices, that the feasibility could be case-specific, and that the aftertreatment costs would represent a greater fraction of the final costs than for higher horsepower applications. The aftertreatment manufacturers suggested costs/time for design, development, and verification as 2 to 3 years, $150,000 to $250,000 per application, and 2,000 to 3,000 full-time equivalent (FTE) hours, although this may not represent the full costs to bring the products to market in a fully integrated piece of equipment. In terms of operating impacts, the aftertreatment manufacturers indicated potential fuel economy impacts, the need for DPF ash cleaning, and the addition of DEF fluid. In terms of durability, the aftertreatment manufacturers did not anticipate that the aftertreatment systems would significantly impact the lifetime of the engine itself, with some adding that 8,000 to 10,000+ hours or 7 years of operational life is typical of such systems. In terms of potential marketplace impacts, there was a range of responses to the question about whether the aftertreatment costs were reasonable compared to the full cost of the equipment. Some aftertreatment manufacturers suggested the costs would be a bit high or not reasonable, and some provided ranges that the aftertreatment costs would be 20% of the cost of the equipment to 50% of the cost of the engine. The aftertreatment manufacturers also suggested that the implementation of regulations requiring aftertreatment on SORDEs could encourage the replacement of diesel engines with gasoline engines or electric motors.

It should be noted that while the information obtained from the aftertreatment manufacturers provides a good starting point for understanding the potential impacts of implementing more stringent standards, the extent of this information is still limited due to the lack of responses from the engine and equipment manufacturers. In particular, the engine and equipment manufacturers have the most direct role in development, demonstration, durability testing, and certification of the final product engines or equipment, and the more direct interaction with the final end users of these products. It is expected that if more stringent regulations in the SORDE category are pursued, that additional feedback from engine and equipment manufacturers should be sought to more accurately access the regulatory impacts on the marketplace.

Conclusions

This study demonstrated the technical feasibility of implementing aftertreatment systems for PM for under 25 hp off-road engines and for NOx for 25 to 75 hp off-road engines. DPFs were demonstrated on two under 25 hp engines in a TRU and mini-excavator. The DPFs showed >98% PM reductions for a baseline degreened and 1,000 hour aging tests. NOx aftertreatment was demonstrated on two 25 to 50 hp engines in a ride mower and skid steer, where the demonstrations were specifically selected to evaluate the potential effectiveness of such systems for <50 engines. The NOx aftertreatment systems provided reduction ranging from 70 to 91% for a steady-state C1 cycle. Lower NOx reductions from 26 to 65% were seen for hot and cold start NRTC tests, as the exhaust temperature was below that required to begin doing during the initial parts of these cycles. Given the wide variety of applications for off-road engines, however, the practicality of implementing such aftertreatment systems could vary between applications depending on the potential to transition to electric motors or gasoline engines, the cost of the aftertreatment system relative to the overall cost of the equipment it is being used in, and the complexity of the controls that would be required to manage the aftertreatment system for different applications. Preliminary estimates suggest that reductions in the off-road equipment emissions inventory of 3.8% in PM and 8.8-13.7% in NO_x emissions could be achieved through additional regulations on emissions for the under 25 hp category for PM and for the 25 to 75 hp category for NOx. Cost-effectiveness of the demonstrated controls was estimated to be $0.38 to 0.59/lb NOx and $15.29/lb PM, which compares very favorably to other rulemakings adopted by CARB.

1 Introduction

EPA's report on *Nonroad Engine and Vehicle Emission Study*-was issued in 1991 and was the first organized accounting of the emissions from these source categories (EPA, 1991). In that report EPA considered over 80 different equipment types from off-road sources. Some of the equipment types include more than one kind of equipment. For example, 'commercial turf equipment' includes turf mowers, walk-behind multi-spindle mowers and other kinds of equipment. Organizing equipment is further complicated as some equipment has multiple engine manufacturers. Because of the numerous pieces of equipment and engine manufacturers, the EPA organized equipment types into ten categories:

1. Lawn & garden
2. Airport service
3. Recreational
4. Recreational marine
5. Light commercial
6. Industrial
7. Construction
8. Agricultural
9. Logging
10. Commercial marine vessels

EPA issued regulations to control emissions from these sources and further categorized the regulations according to engine size and the date of implementation. The next section discusses those regulations.

1.1 Early standards for nonroad equipment

Tier 1-3 Standards for new nonroad diesel engines were adopted in 1994 for engines over 50 hp (37 kW) and were phased-in from 1996 to 2000. On August 27, 1998, the EPA introduced Tier 1 standards for equipment under 50 hp and increasingly more stringent Tier 2 and Tier 3 standards for all equipment with phase-in schedules from 2000 to 2008. Tier 1-3 standards were met through advanced engine design, with no/limited use of exhaust gas aftertreatment. Tier 3 standards for oxides of nitrogen (NO_x) + hydrocarbons (HC) were similar to the 2004 standards for highway engines; however, Tier 3 standards for particulate matter (PM) were never adopted.

Tier 4 Standards. On May 11, 2004, EPA signed the final rule introducing Tier 4 emission standards, which were phased-in over the period of 2008-2015. The Tier 4 standards require that emissions of PM and NO_x be further reduced by about 90%. Such emission reductions can be achieved through the use of control technologies, including engine modifications and advanced exhaust gas aftertreatment, similar to those used by those manufacturers meeting the 2007-2010 standards for highway engines.

Table 1-1. Tier 4 Emission Standards—Engines up to 750 hp, g/kWh (g/bhp-hr)

Engine Power	Year	CO	NMHC	NMHC+NO_x	NO_x	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	–	7.5 (5.6)	–	0.4[a] (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	–	7.5 (5.6)	–	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008	5.5 (4.1)	–	7.5 (5.6)	–	0.3 (0.22)
	2013	5.5 (4.1)	–	4.7 (3.5)	–	0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	–	4.7 (3.5)	–	0.3[b] (0.22)
	2013	5.0 (3.7)	–	4.7 (3.5)	–	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014[c]	5.0 (3.7)	0.19 (0.14)	–	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014[d]	3.5 (2.6)	0.19 (0.14)	–	0.40 (0.30)	0.02 (0.015)

a - hand-startable, air-cooled, DI engines may be certified to Tier 2 standards through 2009 and to an optional PM standard of 0.6 g/kWh starting in 2010
b - 0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012
c - PM/CO: full compliance from 2012; NOx/HC: Option 1 (if banked Tier 2 credits used)—50% engines must comply in 2012-2013; Option 2 (if no Tier 2 credits claimed)—25% engines must comply in 2012-2014, with full compliance from 2014.12.31
d - PM/CO: full compliance from 2011; NOx/HC: 50% engines must comply in 2011-2013

1.2 Standards after the 2014 model year

EPA's Title 40: Protection of Environment Part 1039 specifies the *Control of Emissions from New and In-Use Nonroad Compression-Ignition Engines.* Details on the specifications are listed in the table below. See[1]the CFR

Table 1-2. Tier 4 Exhaust Emission Standards in g/kW-hr after 2014 Model Year, §1039.101

Maximum engine power	Application	PM	NO_X	NMHC	NO_X+NMHC	CO
kW <19	All	[2]0.40			7.5	[3]6.6
19 ≤kW <56	All	0.03			4.7	[4]5.0
56 ≤kW <130	All	0.02	0.40	0.19		5.0
130 ≤kW ≤560	All	0.02	0.40	0.19		3.5
	Generator sets	0.03	0.67	0.19		3.5
kW >560	All except generator sets	0.04	3.5	0.19		3.5

[2]See paragraph (c) of this section for provisions related to an optional PM standard for certain engines below 8 kW.
[3]The CO standard is 8.0 g/kW-hr for engines below 11 hp.

[4]The CO standard is 5.5 g/kW-hr for engines below 75 hp.

The EPA defined the *Optional PM standard for engines below 8 kW.* "You may certify hand-startable, air-cooled, direct injection engines below 8 kW to an optional Tier 4 PM standard of 0.60 g/kW-hr. The term hand-startable refers to engines started using a hand crank or pull cord. This PM standard applies to both steady-state and transient testing, as described in paragraphs (a) and (b) of this section. Engines certified under this paragraph (c) may not be used to generate PM or NO_x+NMHC emission credits under the provisions of subpart H of this part."

[1]https://www.ecfr.gov/cgi-bin/text-idx?SID=c0c8fdec8b4d90edbd135543fb499bbc&mc=true&node=pt40.36.1039&rgn=div5

1.3 Useful life

An important factor in the application of emission standards is the length of time those engines are expected to meet the emission standard. This time is called the Useful Life and those values are shown in Table 1-3. The values give a perspective on times that might be used in the certification process.

Table 1-3. Useful Life Values from §1039.101

If your engine is certified as . . .	And its maximum power is . . .	And its rated speed is . . .	Then its useful life is . . .
(i) Variable speed or constant speed	kW <19	Any Speed	3,000 hours or five years, whichever comes first.
(ii) Constant speed	19 ≤kW <37	3,000 rpm or higher	3,000 hours or five years, whichever comes first.
(iii) Constant speed	19 ≤kW <37	Less than 3,000 rpm	5,000 hours or seven years, whichever comes first.
(iv) Variable	19 ≤kW <37	Any Speed	5,000 hours or seven years, whichever comes first.
(v) Variable speed or constant speed	kW ≥37	Any speed	8,000 hours or ten years, whichever comes first.

1.4 Environmental Benefit and Cost

1.4.1 1998 Regulation

At the signing of the 1998 rule, the EPA estimated that by 2010 NO_x emissions would be reduced by about a million tons per year, the equivalent of taking 35 million passenger cars off the road. The costs of meeting the emission standards were expected to add <1% to the purchase price of typical new nonroad diesel equipment, although for some equipment the standards may cause price increases on the order of 2-3%. The program was expected to cost about $600 per ton of NO_x reduced.

1.4.2 Tier 4 Regulation

When the full inventory of older nonroad engines are replaced by Tier 4 engines, the national annual emission reductions are estimated at 738,000 tons of NO_x and 129,000 tons of PM. Further by 2030, 12,000 premature deaths would be prevented annually due to the implementation of the proposed standards. The estimated costs for added emission controls for the vast majority of equipment was estimated at 1-3% as a fraction of the total equipment price. For example, for a 175 hp bulldozer, that costs approximately $230,000, it would cost up to $6,900 to add the advanced emission controls and to design the bulldozer to accommodate the modified engine.

EPA estimated the average cost increased 7 cents per gallon for 15 ppm S fuel and that 3 cents would be recovered by savings in maintenance costs due to low sulfur diesel. These studies provide useful metrics as to what was viewed as cost-effective since the establishment of that number is a value judgment.

1.4.3 California regulation

In most cases, federal nonroad regulations apply in California, whose authority is limited to set emission standards for new nonroad engines. The federal Clean Air Act Amendments of 1990 (CAA) preempt California's authority to control emissions from new farm and construction equipment under 175 hp *[CAA Section 209(e)(1)(A)]* and require California to receive authorization from the federal EPA for controls over other off-road sources *[CAA Section 209 (e)(2)(A)]*.

The majority of mobile source off-road diesel engines sold as new since 2011 are subject to federal and State regulations that require compliance with stringent PM and NO_x exhaust standards based on the use of advanced aftertreatment technologies, such as Diesel Particulate Filters (DPF) for PM removal and Selective Catalytic reduction (SCR) for control of NO_x. However, off-road diesel engines less than 75 hp are allowed to certify with emissions at higher levels due to the belief that advanced aftertreatment would severely impact the cost of these smaller engines.

A Regulatory Impact Analysis (RIA) was conducted to support the 2004 federal rulemaking for the current Tier 4 standards for new off-road engines. The RIA estimated the costs of anticipated emission control technologies that were not in wide production at the time. However, some of the control technologies anticipated in the RIA are now common today in both the off and on-road diesel sectors. Thus, the “economies of scale” of today’s market, as well as the availability of additional exhaust control strategies and techniques not evaluated originally in the RIA, warrant renewed consideration for adopting more stringent exhaust standards for the < 75 hp sector.

2 Objective

The objective of this study is to evaluate the potential effectiveness, feasibility, and cost-effectiveness of implementing regulations on mobile off-road diesel engines with rated powers of less than 75 horsepower (hp) that will require the use of advanced emission control strategies, such as DPFs and SCR. This project includes a comprehensive review of available aftertreatment and other technologies, demonstration of selected aftertreatment technologies on actual engines and verification of the emissions performance of these devices through a series of emissions and durability tests, evaluation of the cost implications of the added emissions control strategies, evaluation of the potential impacts of additional emissions controls on the emissions inventory, and evaluation of the potential impact on the small engine marketplace and consumer choice in that area.

3 Preliminary Evaluation of Emission Control Strategies

A comprehensive product review of existing and emerging emission control technologies to significantly reduce PM and NO_x that could be employed by off-road diesel engines with power ratings of <75 hp was carried out as part of this project. The review included after-treatment technologies such as DPFs, SCR, cooled EGR, EFI, alternative fuels and other emerging technologies that might be cost-effective for these engines.

3.1 Characterization of Engines

3.1.1 Engine Manufacturers

One of the most complete sources of data on the characterization of engines in this category is available through the documentation prepared by EPA in developing the 2004 rulemaking for non-road engines. The EPA characterized the sales by engine manufacturer based on information from the Power Systems Research database and trade journals, based on the year 2000. From this data, the EPA estimated that sales of engines in the 0 to 25 hp category comprised 18 percent (approximately 135,828 units) of the nonroad market. The largest manufacturers of engines in this category were Kubota (36,601 units), Yanmar (32,126 units), and Kukje (21,216 units).

The EPA also provided additional, but somewhat conflicting information on the sales for the under 25 hp category for the 6 largest manufacturers. This information is provided in Table 3-1. These six leading manufacturers produced 46 percent of the equipment in this category, with equipment ranging from generator sets, skid-steer loaders, agricultural tractors, commercial mowers, and refrigeration/air conditioning units. A more detailed discussion of the types of equipment in this category is provided below.

Table 3-1. Characterization of the 6 largest Engine Manufacturers in the under 25 hp category (U.S. EPA, 2004).

Original Equipment Manufacturer	Major Equipment Manufactured	Average Annual Sales	Percentage of Market	Engine Characterization*
Ingersoll-Rand	Refrigeration/AC, Skid-steer loaders, and Excavators	13,394	12%	W,NA, I
Deere & Company	Agricultural tractors, Commercial mowers, Lawn & garden tractors	11,042	10%	W,NA, I
Korean Gen-sets	Generator Sets	9,970	9%	W,NA, I
China Gen-sets	Generator Sets	5,559	5%	W,NA,D/ I
SDMO	Generator Sets	5,191	5%	W/A,NA, D/I
Kubota Corp.	Ag tractors,Lawn & garden tractors Commercial mowers	5,117	5%	W,NA,I

The next largest category surveyed by EPA was the 25 to 75 hp engines, with no differentiation made for the 25 to 50 hp engines. Of the categories surveyed by EPA, this was the largest in terms of the number of units, with approximately 281,157 units sold in year 2000, comprising 38 percent of nonroad engines sold that year. The EPA separated the sales fractions based on direct-injection (DI) and indirect injection (IDI) engines, with DI engines accounting for 59 percent of this category with 165,427 units. Yanmar and Kubota also represented an important fraction of this market, with Yanmar and Kubota comprising 19 percent and 13 percent, respectively, of the DI engines sold, and with Kubota comprising 51 percent of the sale of engines with IDI. Isuzu and Caterpillar/Perkins were two other large manufacturers of engines in this category, with Isuzu representing 10% of the direct injection sales and 8% of the IDI sales and Caterpillar/Perkins representing 10% of the direct injection sales and 5% of the IDI sales. Other major manufacturers of DI engines at the time included Deutz (16%), Hatz (12%), and Deere (8%). Other major manufacturers of IDI engines at the time Daewoo Heavy Industries (12%) and Ihi-Shibaura (12%). The top 90 percent of the market was supplied by 60 different companies.

A breakdown of sales information for the 6 largest manufacturers in the 25 to 75 hp category is provided in Table 3-2. These six leading manufacturers produced 53 percent of the equipment in this category, with equipment ranging from agricultural tractors, generator sets, skid-steer loaders, and refrigeration/AC. Ingersoll- Rand made up approximately 17 percent of the total sales.

Table 3-2. Characterization of the 6 largest Engine Manufacturers in the 25 to 75 hp category (U.S. EPA, 2004).

Original Equipment Manufacturer	Major Equipment Manufactured	Average Annual Sales	Percentage of Market	Engine Characterization*
Ingersoll-Rand	Refrigeration A/C, Skid-steer loaders, Air compressors	40,199	17%	W/O,NA/T,D/I
Case New Holland	Agricultural tractors, Skid-steer loaders	23,194	10%	W/O,NA/T,D/I
Thermadyne Holdings	Generator sets	19,090	8%	A,NA,D
Deere & Company	Agricultural tractors, Skid-steer loaders, Commercial mowers	17,752	7%	W,NA/T,D
Kubota Corp.	Agricultural tractors, Excavators, Wheel Loaders, Bulldozers	14,391	6%	W,NA/T,D/I
United Technologies Co.	Refrigeration/AC	12,484	5%	W,NA,D/I

3.1.2 Equipment Types

A breakdown of equipment types by population in California was provided by CARB staff. This breakdown is shown below for the under 25 hp engines in Table 3-3. These engines are separated into two categories: 0-10 and 10-25 hp. These data indicate that the largest fraction of equipment types are agricultural tractors, transportation refrigeration units, lawn & garden Tractors, commercial turf equipment, generator sets, pumps, and signal boards.

Table 3-3. Estimates of the Populations of Engines based on Equipment Type for California in the under 25 hp category.

hp range	0-10	10-25	0-25
Agricultural Tractors		31511	31511
Transport Refrigeration Units	255	7789	8044
Lawn & Garden Tractors		42716	42716
Commercial Turf Equipment		11943	11943
Welders		3646	3646
Generator Sets		9890	9890
Pumps	4305	5572	9877
Air Compressors		172	172
Other Agricultural Equipment		751	751
Hydro Power Units	55	218	273
Pressure Washers		325	325
Sprayers		290	290
Signal Boards	3752	3745	7497
Rollers	806	1141	1947
Cement and Mortar Mixers	681	740	1421
Plate Compactors	429	428	857
Other General Industrial/Construction Equipment	165	384	549
Skid Steer Loaders		2554	2554
Aerial Lifts		1241	1241

These data can be compared to earlier national estimates based on the 2004 EPA nonroad rulemaking RIA (U.S. EPA, 2004). For the under 25 hp category, they identified 29 different categories of equipment types that they categorized and ranked based on 1996-2000 sales volumes. A breakdown of these equipment types along with their sale volumes is provided below in Table 3-4. These results show that generator sets, agricultural tractors, commercial mowers, and refrigeration/AC had the largest sales volumes, with generator sets representing the highest sales fractions. Overall, the results seem to be relatively comparable, at least in terms of the largest types of equipment sales, with some differences, such as a higher sales fraction of agricultural equipment in California, where agricultural is one of the more dominant industries.

Table 3-4. Estimates of the Populations of Engines based on Equipment Type in the under 25 hp category (U.S. EPA, 2004).

Application Description	Five-year sales Volume (1996-2000)	Average Annual Sales	Percentage of Total Sales
Generator sets	171,435	34,287	31.1
Agricultural tractors	59,863	11,973	9.5
Commercial mowers	59,713	11,943	9.5
Refrigeration/AC	57,668	11,534	9.2
Welders	32,284	6,457	5.1
Light plants/Signal boards	28,239	5,648	4.5
Skid-steer loaders	23,685	4,737	3.8
Lawn & garden tractors	17,879	3,576	2.8
Pumps	16,262	3,252	2.6
Rollers	12,063	2,413	1.9
Pressure washers	11,959	2,392	1.9
Plate compactors	11,535	2,307	1.8
Utility vehicles	8,502	1,700	1.4
Aerial lifts	7,058	1,412	1.1
Excavators	6,118	1,224	1.0
Mixers	4,639	928	0.7
Scrubbers/sweepers	2,829	566	0.4
Commercial turf equipment	2,627	525	0.4
Finishing equipment	2,351	470	0.4
Other general industrial equipment	2,334	467	0.4
Tampers/rammers	2,156	431	0.3
Tractor/loader/backhoes	1,794	359	0.3
Dumpers/tenders	1,689	338	0.3
Air compressors	1,516	303	0.2
Hydraulic power units	797	159	0.1
Trenchers	776	155	0.1
Concrete/industrial saws	733	147	0.1
Irrigation sets	614	123	0.1
Wheel loaders/bulldozers	502	100	0.1
Other agricultural equipment	426	85	0.1
Surfacing equipment	362	72	0.1
Bore/drill rigs	275	55	0.0
Listed Total		110,137	91.4
Grand Total		110,289	100.0

A breakdown of equipment types for 25 to 75 hp engines by population in California was also provided by CARB staff. This breakdown is shown below in Table 3-5. These data indicate that the largest fraction of equipment types are agricultural tractors, transportation refrigeration units, skid steer loaders, aerial lifts, welders, generator sets, rollers, pumps, and other general industrial/construction equipment.

Table 3-5. Estimates of the Populations of Engines based on Equipment Type for California in the 25 to 75 hp category.

hp range	25-50	50-75
Agricultural Tractors	26029	28229
Transport Refrigeration Units	26799	
Welders	5254	
Generator Sets	5102	
Pumps	2233	
Air Compressors	1051	
Crushing/Proc. Equipment	213	
Pressure Washers	122	
Sprayers	435	150
Signal Boards	18	
Rollers	3967	33
Other General Industrial/Construction Equipment	2176	823
Skid Steer Loaders	2747	9324
Aerial Lifts	3518	3106

For comparison, a breakdown of equipment types along with their sale volumes is provided below in Table 3-6 from the EPA's 2004 nonroad rulemaking RIA. For the under 25 to 75 hp category, they identified 55 different categories of equipment types. The equipment types include some broad categories of equipment that are similar to those in the under 25 hp category, with the best-selling pieces of equipment being agricultural tractors, generator sets, skid-steer loaders, and refrigeration/AC. The earlier EPA sales fractions show similarities with the more recent California data in terms of agricultural tractors, generator sets, and refrigeration/AC, but much lower fractions of lawn and garden tractors and commercial turf equipment.

Table 3-6. Estimates of the Populations of Engines based on Equipment Type in the 25 to 75 hp category (U.S. EPA, 2004).

Application Description	Five-year sales Volume (1996-2000)	Average Annual Sales	Percentage of Total Sales
Agricultural tractors	286,295	57,259	24%
Generator sets	223,960	44,792	19%
Skid-steer loaders	177,925	35,585	15%
Refrigeration/AC	142,865	28,573	12%
Welders	60,035	12,007	5.0%
Commercial mowers	47,735	9,547	3.9%
Air compressors	33,840	6,768	2.8%
Trenchers	26,465	5,293	2.2%
Aerial lifts	25,810	5,162	2.1%
Forklifts	23,480	4,696	1.9%
Rollers	18,010	3,602	1.5%
Excavators	16,485	3,297	1.4%
Rough terrain forklifts	13,530	2,706	1.1%
Scrubbers/sweepers	11,770	2,354	1.0%
Light plants/signal boards	11,720	2,344	1.00%
Pumps	9,290	1,858	0.77%
Bore/drill rigs	9,000	1,800	0.74%
Utility vehicles	8,460	1,692	0.70%
Wheel Loaders/bulldozers	6,985	1,397	0.58%
Pressure washers	6,700	1,340	0.55%
Pavers	6,395	1,279	0.53%
Commercial turf	5,760	1,152	0.48%
Tractor/loader/backhoes	5,115	1,023	0.42%
Irrigation sets	4,300	860	0.36%
Concrete/industrial saws	3,400	680	0.28%
Other general industrial	3,400	680	0.28%
Chippers/grinders	2,625	525	0.22%
Crushing/processing equipment	2,305	461	0.19%
Hydraulic power units	1,950	390	0.16%
Terminal tractors	1,765	353	0.15%
Surfacing equipment	1,490	298	0.12%
Dumpers/tenders	1,055	211	0.09%
Listed Total		239,984	99.3%
Grand Total		241,710	100.0%

3.1.3 Engine Types

In developing control strategies for the small off-road diesel engine category, it is important to understand the types of engines that are available in the marketplace and the level of engine controls and aftertreatment systems already incorporated into the engine designs. For example, engines with some level of electronic controls can more readily be modified to include aftertreatment systems that require control of regenerations or the injection of urea. Also, engines with existing aftertreatment, such as DPFs, can be more readily adapted to adding systems such as SCR-coated DPFs, as there would likely be less spatial constraints in adapting any added hardware to the existing area where the engine is located on a piece of equipment.

A listing of engines certified in the under 25 hp category for the 2014 model year is provided below in Table 3-7. This represents the time period when the prescreening for the field demonstrations was being conducted. This information is from the EPA certification database for the 2014 model year. This table shows that the engines include a variety of both DI and IDI engines. Emissions control in this power size category is predominantly through engine design modifications. In some cases, the manufacturer specifies that electronic controls and/or EGR are utilized, although the information provided in input by the engine manufacturer, and hence different levels of information can be provided for different manufacturers. The engine manufacturers represent many of the same manufacturers that are discussed under section 3.1.1, including Yanmar and Kubota, along with some Kukjie engines. Other engine manufacturers include ISM, Kohler, Motorenfabrik Hatz, Daedong, Iseki, and Mitsubishi.

Table 3-7. Engines Certified in the under 25 hp category for 2014 Model Year

Manufacturer	Engine Family	Power Level	Fuel metering
ISM (H3X)	EH3XL.761F1C	hp<11	IDI
KOHLER CO. (KHX)	EKHXL.442155	hp<11	DI
KOHLER CO. (KHX)	EKHXL.34935D	hp<11	DI
KUBOTA (KBX)	EKBXL.276KCB	hp<11	IDI
KUBOTA (KBX)	EKBXL.325NCB	hp<11	IDI
KUBOTA (KBX)	EKBXL.325KCB	hp<11	IDI
KUBOTA (KBX)	EKBXL.416KCB	hp<11	IDI
MOTORENFABRIK HATZ (HZX)	EHZXL.347C30	hp<11	DI
MOTORENFABRIK HATZ	EHZXL.517M51	hp<11	DI
MOTORENFABRIK HATZ	EHZXL.517M50	hp<11	DI
DAEDONG (DCL)	EDCLL01.4D80	11<=hp<25	IDI
DAEDONG (DCL)	EDCLL01.0D75	11<=hp<25	IDI
ISEKI (ICL)	EICLL1.50C3X	11<=hp<25	IDI
ISEKI (ICL)	EICLL1.12B3X	11<=hp<25	IDI
ISM (H3X)	EH3XL1.49N3C	11<=hp<25	IDI
ISM (H3X)	EH3XL2.224LC	11<=hp<25	IDI
ISM (H3X)	EH3XL1.13LCS	11<=hp<25	IDI
ISM (H3X)	EH3XL.761F2V	11<=hp<25	IDI
ISM (H3X)	EH3XL1.13F2C	11<=hp<25	IDI
ISM (H3X)	EH3XL1.13F2V	11<=hp<25	IDI
ISM (H3X)	EH3XL1.49F2C	11<=hp<25	IDI
ISM (H3X)	EH3XL1.13SLV	11<=hp<25	IDI
ISM (H3X)	EH3XL1.49N3V	11<=hp<25	IDI
ISM (H3X)	EH3XL1.49NTV	11<=hp<25	IDI
ISM (H3X)	EH3XL1.49FTV	11<=hp<25	IDI
ISM (H3X)	EH3XL1.49F2V	11<=hp<25	IDI
KOHLER CO. (KHX)	EKHXL1.37SF1	11<=hp<25	IDI
KOHLER CO. (KHX)	EKHXL1.259LD	11<=hp<25	DI
KOHLER CO. (KHX)	EKHXL1.86DIM	11<=hp<25	DI
KUBOTA (KBX)	EKBXL.778KCB	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL01.5BCC	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL01.3DCC	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL01.0BCC	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL01.7ECB	11<=hp<25	DI
KUBOTA (KBX)	EKBXL01.5BCB	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL02.2RCB	11<=hp<25	DI

KUBOTA (KBX)	EKBXL.719NCB	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL01.1DCB	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL.719KCC	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL.898KCB	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL01.3DCB	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL.719KCB	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL01.0BCB	11<=hp<25	IDI
KUBOTA (KBX)	EKBXL01.5FCC	11<=hp<25	IDI
KUKJE MACHINERY (KMC)	EKMCL1.17A33	11<=hp<25	IDI
MITSUBISHI (MVX)	EMVXL01.3EEE	11<=hp<25	IDI
MITSUBISHI (MVX)	EMVXL01.0EEE	11<=hp<25	IDI
MITSUBISHI (MVX)	EMVXL01.0EBA	11<=hp<25	IDI
MITSUBISHI (MVX)	EMVXL01.3GGG	11<=hp<25	IDI
MITSUBISHI (MVX)	EMVXL01.3FFF	11<=hp<25	IDI
MOTORENFABRIK HATZ (HZX)	EHZXL1.72C41	11<=hp<25	DI
MOTORENFABRIK HATZ	EHZXL1.72M41	11<=hp<25	DI
MOTORENFABRIK HATZ	EHZXL.997M40	11<=hp<25	DI
MOTORENFABRIK HATZ	EHZXL.997C40	11<=hp<25	DI
MOTORENFABRIK HATZ	EHZXL.667C82	11<=hp<25	DI
MOTORENFABRIK HATZ	EHZXL.722M90	11<=hp<25	DI
YANMAR (YDX)	EYDXL1.50S3T	11<=hp<25	DI
YANMAR (YDX)	EYDXL1.33S3N	11<=hp<25	DI
YANMAR (YDX)	EYDXL1.27NS1	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.27NS1	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.27NS2	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.27NS2	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.27NS3	11<=hp<25	IDI
YANMAR (YDX)	EYDXL0.99NS1	11<=hp<25	IDI
YANMAR (YDX)	EYDXL0.99NS2	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.64NKA	11<=hp<25	DI
YANMAR (YDX)	EYDXL0.99NPA	11<=hp<25	IDI
YANMAR (YDX)	EYDXL0.57NXA	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.64NMA	11<=hp<25	DI
YANMAR (YDX)	EYDXL0.99NWA	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.27NWA	11<=hp<25	IDI
YANMAR (YDX)	EYDXL2.09NFA	11<=hp<25	DI
YANMAR (YDX)	EYDXL0.99NS3	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.27NS4	11<=hp<25	IDI
YANMAR (YDX)	EYDXL0.99NS4	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.27NUA	11<=hp<25	IDI
YANMAR (YDX)	EYDXL0.99NUA	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.27NPA	11<=hp<25	IDI
YANMAR (YDX)	EYDXL1.64NGA	11<=hp<25	DI

DI = Direct Injection, IDI = Indirect Injection

A listing of engines certified in the 25 to 50 hp category for the 2014 model year is provided below in Table 3-8 from the EPA certification database. This table shows that the engines include a variety of both DI and IDI engines, similar to the under 25 hp category. Emissions control in this power size category is more sophisticated than in the under 25 hp category. It should be noted that although not explicitly included in the EPA database, it is assumed that the ISM manufacturer engines are all equipped with cooled EGR, a DOC, and DPF. Nearly all engines specify either engine design modifications or the use of EGR or cooled EGR, with most of the engines showing EGR control. The majority of the engines also include some level of DPF including DPFs in combination with DOCs. Many of the DPF-equipped engines are also equipped with electronic controls. The engine manufacturers represent many of the same manufacturers that are discussed under section 3.1.1, including Yanmar and Kubota, Isuzu, Deere, and Deutz. Other engine manufacturers include Doosan, ISM, Kohler, Kukji, M&M, and PSA Peugeot Citroen.

Table 3-8. Engines Certified in the 25 to 50 hp category for 2014 Model Year

Manufacturer	Engine Family	Power Level	Fuel metering
DEERE (JDX)	EJDXL02.4074	25<=hp<50	DI
DEERE (JDX)	EJDXL02.9216	25<=hp<50	DI
DEERE (JDX)	EJDXL02.9217	25<=hp<50	DI
DEUTZ (DZX)	EDZXL02.9021	25<=hp<50	DI
DOOSAN (DIC)	EDICL01.8LEA	25<=hp<50	DI
ISM (H3X)	EH3XL2.22TF3	25<=hp<50	IDI
ISM (H3X)	EH3XL1.49AB1	25<=hp<50	IDI
ISM (H3X)	EH3XL2.22AB2	25<=hp<50	IDI
ISM (H3X)	EH3XL2.22AB3	25<=hp<50	IDI
ISM (H3X)	EH3XL2.22AB6	25<=hp<50	IDI
ISM (H3X)	EH3XL2.22AB7	25<=hp<50	IDI
ISM (H3X)	EH3XL2.00CN1	25<=hp<50	IDI
ISM (H3X)	EH3XL2.22CN2	25<=hp<50	IDI
ISM (H3X)	EH3XL1.49AB8	25<=hp<50	IDI
ISM (H3X)	EH3XL2.22AB5	25<=hp<50	IDI
ISM (H3X)	EH3XL1.49TFV	25<=hp<50	IDI
ISM (H3X)	EH3XL2.22NFV	25<=hp<50	IDI
ISUZU (SZX)	ESZXL02.2ZTB	25<=hp<50	DI
KOHLER CO. (KHX)	EKHXL2.48ESM	25<=hp<50	DI
KUBOTA (KBX)	EKBXL01.8EKD	25<=hp<50	DI
KUBOTA (KBX)	EKBXL01.5BPD	25<=hp<50	IDI
KUBOTA (KBX)	EKBXL02.4GND	25<=hp<50	DI
KUBOTA (KBX)	EKBXL02.4EKC	25<=hp<50	DI
KUBOTA (KBX)	EKBXL02.6GND	25<=hp<50	DI
KUKJE MACHINERY (KMC)	EKMCL2.29A48	25<=hp<50	IDI
KUKJE MACHINERY (KMC)	EKMCL1.72A31	25<=hp<50	IDI
KUKJE MACHINERY (KMC)	EKMCL1.72AN3	25<=hp<50	IDI
M&M (MML)	EMMLL02.7C49	25<=hp<50	DI
M&M (MML)	EMMLL02.7C40	25<=hp<50	DI
M&M (MML)	EMMLL02.7NEF	25<=hp<50	DI
M&M (MML)	EMMLL02.7M40	25<=hp<50	DI
M&M (MML)	EMMLL02.7M30	25<=hp<50	DI
M&M (MML)	EMMLL02.7C38	25<=hp<50	DI
M&M (MML)	EMMLL02.7C33	25<=hp<50	DI
M&M (MML)	EMMLL02.7C42	25<=hp<50	DI
PSA PEUGEOT CITROEN (PEX)	EPEXL01.6DV6	25<=hp<50	DI

YANMAR (YDX)	EYDXL1.50L3T	25<=hp<50	DI
YANMAR (YDX)	EYDXL1.64L3N	25<=hp<50	DI
YANMAR (YDX)	EYDXL2.19NDA	25<=hp<50	DI
YANMAR (YDX)	EYDXL1.57TDA	25<=hp<50	DI
YANMAR (YDX)	EYDXL1.64NDA	25<=hp<50	DI
YANMAR (YDX)	EYDXL2.19NFA	25<=hp<50	DI
YANMAR (YDX)	EYDXL1.57HDA	25<=hp<50	DI

DI = Direct Injection, IDI = Indirect Injection

3.2 Potential Emissions Control Strategies

This section reviews some of the potential control strategies that could be applicable to under 50 hp small off-road diesel engines.

3.2.1 NO_x Control Strategies

Oxides of nitrogen (NO and NO_2, collectively called NO_x) are formed at high temperatures during the diesel combustion process from nitrogen and oxygen present in the intake air. The NO_x formation rate is exponentially related to peak cylinder temperatures and is also strongly related to nitrogen and oxygen content (partial pressures). NO_x control technologies for diesel engines include aftertreatment systems designed to remove NO_x via catalytic reactions downstream of the engine and engine modifications designed to reduce NO_x emissions by lowering the peak cylinder temperatures and by decreasing the oxygen content of the intake air.

3.2.1.1 Selective Catalytic Reduction (SCR) Technology

SCR is the most commonly used technology for the control of NO_x, and is almost universally being used for on-road heavy-duty engines/vehicles meeting the 2010 emissions standards. SCR has also been used to control NO_x emissions from stationary sources such as power plants for over 20 years. SCR system utilize a chemical reductant, ammonia, which is injected in front of a metallic or ceramic substrate to convert NO_x into molecular nitrogen, oxygen, and water. Urea, often termed diesel exhaust fluid (DEF), is used as the aqueous reductant typically used in SCR applications as it is safe and easier to use than other sources of ammonia, such as aqueous or anhydrous ammonia. The urea thermally decomposes into ammonia after injection, which is used in the SCR catalytic processes. Typical catalytic reactions for the SCR systems include the following. Low temperature SCR is promoted by NO_2. Of the three competing reactions over a vanadia catalyst, the third reaction is the slowest and the second reaction is the fastest.

$$4\,NH_3 + 4\,NO + O_2 \longrightarrow 4\,N_2 + 6\,H_2O$$
$$2\,NH_3 + NO + NO_2 \longrightarrow 2\,N_2 + 3\,H_2O$$
$$8\,NH_3 + 6\,NO_2 \longrightarrow 7\,N_2 + 12\,H_2O$$

SCR catalysts are made from a ceramic material with an active catalytic agent. The active catalytic components are zeolites or oxides of base metals. Zeolites are generally used because they have good thermal durability, which is important when SCR systems are utilized in conjunction DPFs, which produce temperatures up to 800°C. Copper-zeolites have good low temperature performance, while iron-zeolites provide better high temperature performance. Copper and iron can be used together for a balanced performance over a broad range of temperatures. Vanadia is cheaper and more tolerant to sulfur, and has been used in earlier applications, but it deteriorates at temperatures greater than 600°C.

New zeolites are being developed for low temperature conversion without copper and new catalyst families based on acidic zirconia are also emerging.

The injection of urea is typically controlled by an algorithm that estimates the amount of NO_x present in the exhaust stream. The algorithm relates NO_x emissions to engine parameters such as engine revolutions per minute (rpm), exhaust temperature, backpressure, and load. In closed loop systems, a sensor that directly measures the NO_x concentration in the exhaust is used to determine how much reductant to inject. The performance of SCR technologies is typically a strong function of temperature, especially below 200°C, where urea can not be effectively injected. The temperature dependence of SCR control efficiency for different types of SCR substrates is provided in Figure 3-1.

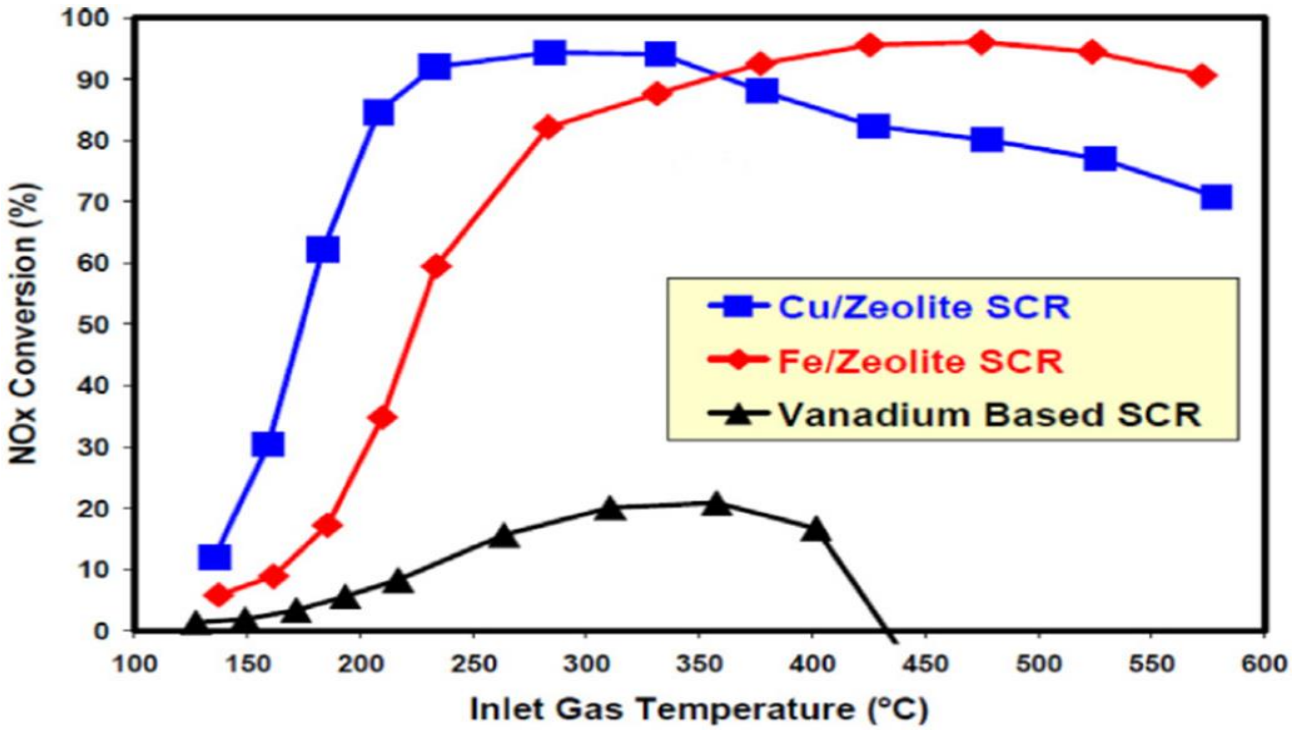


Figure 3-1. Catalytic Conversion of Carbon Monoxide and Hydrocarbons (Cavataio et al., 2007)

3.2.1.2 Lean-NO_x Trap or NO_x Adsorber Technology

Another type of aftertreatment technology that is applicable to diesel engines is known as lean NO_x traps (LNT) or NO_x adsorber catalysts. These catalysts store NO_x on the catalyst washcoat during lean exhaust conditions and release and catalytically reduce the stored NO_x during rich operation. Conceptually, NO_x adsorbers/catalysts are based on acid-base washcoat chemistry. NO and NO_2 are acidic oxides and can be trapped on basic oxides. The most common compound used to capture NO_x is Barium Hydroxide or Barium Carbonate. Under lean air to fuel operation, NO reacts to form NO_2 over a platinum catalyst followed by reaction with the Barium compound to form $BaNO_3$. Following a certain amount of lean operation, the trapping function will become saturated and must be regenerated. This is commonly done by operating the engine in a fuel-rich mode for a brief period of time to facilitate the conversion of the barium compound back to a hydrated or carbonated form and giving up NO_x in the form of N_2 or NH_3. The fuel-rich period can be achieved by running the engine rich for a brief period of time or by the direct injection of fuel. By alternating the lean storage and rich release-and-conversion phases, the applicability of the three-way catalyst has been extended to lean burn engines.

There are several key challenges to the application of LNTs. LNTs tend to be relatively sensitive to sulfur poisoning. The highest conversion efficiencies for these devices also occur within a narrow temperature range. Optimizing the storage/purging periods can also be technically challenging, as too frequent rich operation creates a fuel penalty while insufficient rich operation reduces the trapping efficiency. LNT technologies are not widely used on heavy-duty vehicles in the US, as these vehicles require high NO_x conversion efficiencies over high mileages. LNT is more widely used on smaller passenger cars in Europe, where the requirements for NO_x reduction are less stringent.

3.2.1.3 Lean-NO_x Catalyst Technology

Lean-NO_x catalysts are another technology that has been developed over the years. Lean-NO_x catalysts are based on the principle that conversion of NO_x to molecular nitrogen in the exhaust stream requires a reductant (HC, CO or H_2). These reactions are inherently difficult to achieve in diesel engines, however, because they inherently run lean, and sufficient quantities of reductant are not present to facilitate the conversion of NO_x to nitrogen. Lean-NO_x catalysts use the injection of small amounts of fuel upstream of the catalyst as the hydrocarbon reductant. These hydrocarbons react with NO_x, rather than with O_2, to form nitrogen, CO_2, and water.

Lean-NO_x catalysts are comprised of porous zeolite materials with a highly ordered channel structure), along with either a precious metal or base metal catalyst. The zeolites provide microscopic sites where the hydrocarbons adsorb, and where fuel/hydrocarbon-rich reduction reactions can take place. The washcoat will incorporate platinum or other precious metals to promote the oxidation reactions at lower temperatures, an important consideration with diesel exhaust that typically has lower temperatures, as well as eliminating any unburned hydrocarbons that can occur if too much reductant is injected.

The major disadvantage of Lean-NO_x catalysts is their low conversion efficiencies. Currently, peak NO_x conversion efficiencies typically are around 10 to 30 percent, at reasonable levels of diesel fuel reductant consumption. Earlier work has shown active lean-NO_x catalysts have been shown to provide up to 30 percent NO_x reduction under limited steady-state conditions, but with a fuel economy penalty of up to 7%, while reduction during the FTP was more on the order of 12% due to the periods where temperatures were too low to efficiently reduce NO_x. Lean-NO_x catalysts are also known to have issues with low hydrothermal stability.

3.2.1.4 Engine Design NO_x Control Technologies

In addition to aftertreatment technologies, modifications to engine design can be utilized to reduce the formation of NO_x emissions during combustion. Because NO_x forms primarily when a mixture of nitrogen and oxygen is subjected to high temperature, the main focus of engine design modification is on reducing the temperature of combustion. Some of the engine modifications that can be used include fuel injection timing retard, fuel-injection rate control, charge air cooling, exhaust gas recirculation (EGR) and cooled EGR. Although these modifications can help in controlling NO_x emissions, the reductions that can be achieved through engine design modifications alone are generally much less than the levels that can be achieved with aftertreatment control.

EGR is a control strategy that is used on off-road engines in the 25 to 75 hp category, and to a more limited extent in the under 25 hp category (Dallmann and Menon, 2016). EGR works by circulating a portion of the exhaust gases back into the intake manifold. The exhaust gases act as a diluent in reducing the oxygen content of the intake air. EGR reduces the temperature of the combustion by providing gases inert to combustion (primarily CO_2) and with a higher specific heat than air to act as an absorbent of combustion heat to reduce peak combustion temperatures. Since NO_x formation is a strong and nonlinear function of temperature, providing sufficient EGR to reduce combustion temperatures to below the optimal levels for NO_x formation can provide significant reductions in NO_x. Often a heat exchanger is used to cool the exhaust gases before they are reintroduced prior to the combustion, which is known as cooled EGR. This allows for the introduction of a greater mass of recirculated exhaust. Adding EGR by itself makes combustion less efficient, which can lead to reductions in power and fuel economy. The lower temperature/less efficient combustion can also lead to increases in PM emissions. As such, the implementation of EGR must be done as part of an overall combustion management strategy.

3.2.2 PM Control Strategies

PM from diesel engines includes several different components including agglomerated solid carbonaceous material or soot, volatile or soluble organic compounds, sulfate, and inorganic ash. The soot portion of the PM is generally formed during combustion in locally rich regions of combustion. These particles are inherent to diesel combustion, for which the fuel and air distribution is heterogeneous. Another part of the PM is the volatile or organic fraction, generally described as the soluble organic fraction or SOF. This portion of the PM can include contributions from the fuels, but also atomized and evaporated lube oil. The sulfate portion of the PM comes from a small fraction of the sulfur in the fuel and the oil that is oxidized to SO_3, as opposed to SO_2. The inorganic ash is produced from metal and other inorganic compounds that are found in the fuel and lube oil.

3.2.2.1 Diesel Particle Filters

The most prevalent control technology for PM is a DPF. These filters are commonly used on non-road engines that are greater than 25 hp. DPFs are typically wall flow filters that remove PM from the exhaust by filtering the PM using a ceramic honeycomb structure similar to an emissions catalyst substrate but with the channels blocked at alternate ends. Although the gaseous components are able to flow through the porous wall structure, the PM is trapped behind and is deposited on the filter walls. As PM accumulates on the DPF, it is eliminated or removed from DPF by burning it off in a process called regeneration.

Regeneration occurs at periods of elevated temperatures during the in-use operation of the DPF. DPFs can be regenerated by either passive or active means or some combination of these two. Passive regeneration is when temperatures high enough to burn off the soot in the DPF are produced during normal operation without any additional action to force the regeneration. Passive regeneration is facilitated by using a catalytic coating on the DPF surface that acts to reduce the ignition temperature of the accumulated PM. Passive regeneration can be used in some applications, but in other applications the exhaust temperature is too low to initiate regeneration. Active regeneration is accomplished by changing parameters in the engine/DPF to increase the exhaust temperatures in the DPF. The most commonly applied method of active regeneration is to introduce a temporary change in engine mode operation or an oxidation catalyst to facilitate an increase in exhaust temperature. This includes post-injection of diesel fuel in the exhaust upstream of an oxidation catalyst and/or catalyzed particulate filter, fuel injection during the combustion process, or throttling the air intake into one or more of the engine cylinders. Active regeneration can also be triggered by an external device such as an on-board fuel burner or electrical resistive heater to heat the DPF and oxidize the soot. Such processes can result in a penalty in fuel economy, which is usually optimized as part of the overall system design.

DPF systems combinations typically include a diesel oxidation catalyst (DOC) upstream of the actual DPF substrate. The DOC has several different functions. One of the key functions of the DOC is in the oxidation of some of the NO_x to produce nitrogen dioxide (NO_2), which oxidizes carbon at a lower temperature than oxygen. The DOC can also be used to generate heat and to facilitate regeneration. The DOC oxidizes unburned HC and CO in the exhaust through an exothermic reaction that generates heat that flows into the DPF itself. During active regeneration events, this process is enhanced by adding fuel to the exhaust ahead of the DOC.

3.2.2.2 Flow-Through Filters

Flow-through filters (FTFs) have a more open structure than wall-flow DPFs, but still provide a relatively sizeable reduction in PM emissions. In this type of device, the exhaust gases and PM are able to flow or pass through a relatively open substrate, unlike DPFs that actually physically block and trap the PM. The flow, however, includes a large number of interrupted flow channels, that give rise to turbulent flow. Thus, the exhaust gases have considerable contact and exposure to the catalytic surface, where partial removal of the PM occurs. Although the PM reductions achieved with these devices is less than for a wall-flow DPF, the simpler design allows for operation without active regeneration over a wider range of operating conditions and minimizes the maintenance requirements in terms of ash removal. Flow-through devices are typically able to achieve the ARB's level 2 verification standard for PM reduction of >50% to 84%. The filter element can be made up of a variety of materials and designs such as sintered metal, metal mesh or wire, or a reticulated metal or ceramic foam structure. Flow-through filters can be coated with catalyst materials to assist in oxidizing the soot or used in conjunction with an upstream DOC to oxidize diesel soot. These metal devices may see advantages in applications requiring special shapes or having space limitations due to their relatively smaller package size. Flow-through filters generally do not accumulate inorganic ash constituents present in diesel exhaust. The ash passes through the device, reducing the need for filter cleaning in most applications.

3.2.2.3 Diesel Oxidation Catalysts

Catalytic converters consist of a monolith honeycomb substrate coated with platinum group metal catalyst, packaged in a stainless steel container. The honeycomb structure consists of many small parallel channels that provide a large catalysed surface area for the exhaust gasses to contact. The diesel oxidation catalyst is designed to oxidize CO and gas phase HCs, and the soluble organic fraction (SOF) of the PM to CO_2 and H_2O. These reactions are catalysed by O_2, as shown below. In diesel exhaust, the concentration of O_2 varies between 3 and 17%, depending on the engine load. As such, diesel exhaust contains sufficient amounts of oxygen necessary for these reactions:

$$CO + \frac{1}{2}O_2 \rightarrow CO_2$$
$$[Hydrocarbons] + O_2 \rightarrow CO_2 + H_2O$$
$$[SOF] + O_2 \rightarrow CO_2 + H_2O$$

Exhaust temperature is an important consideration in the conversion of the different pollutants. CO and HC are some of the main pollutants for pollutants converted by a DOC. A typical conversion efficiency curves for CO and HC for a DOC are given in Figure 3-2. This figure shows that catalyst activity increases with exhaust temperature and that there is a minimum exhaust temperature needed to activate the catalyst, which is typically called the "light off" temperature. At sufficiently elevated temperatures, conversion efficiencies of higher than 90% can be achieved, depending on the catalyst size and design.

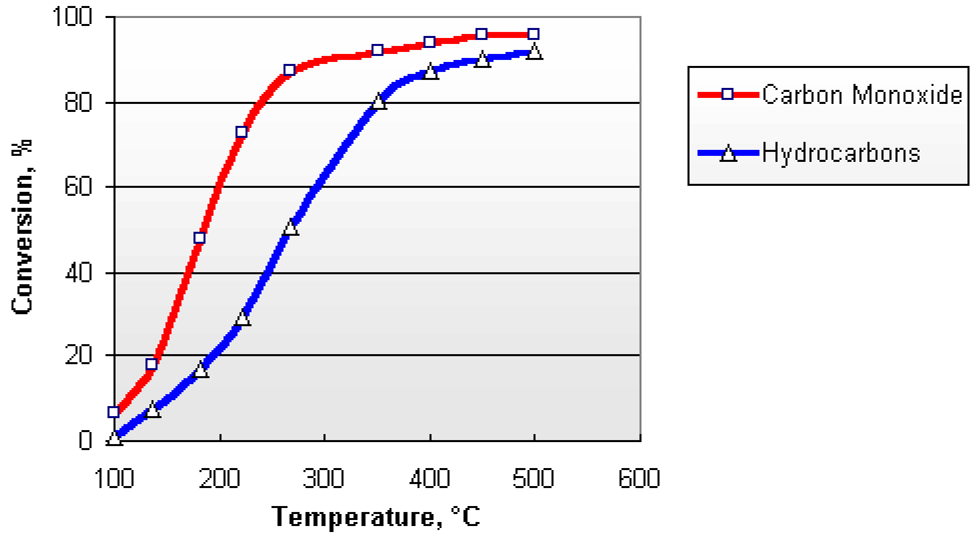


Figure 3-2. Catalytic Conversion of Carbon Monoxide and Hydrocarbons

DOCs also play some role in the conversion of diesel PM, although this is not the primary role of the DOC. The conversion efficiency depends on the specific constituent of the PM that is being converted. Figure 3-3 shows typical conversion efficiencies for different constituents of the PM. The SOF is the primary PM constituent that is eliminated by the DOC. Conversion efficiencies of SOF can reach or exceed 80% at high enough temperatures. On the opposite side, DOCs also have the potential to oxidize sulfur dioxide (SO_2) to sulfur trioxide (SO_3), which combines with water forming sulfuric acid. This reaction occurs at temperatures above 400°C, and at higher temperatures of ~450°C and depending on the sulfur level in the exhaust can offset the reductions in SOF.

$$SO_2 + \frac{1}{2}O_2 \rightarrow SO_3 \xrightarrow{H_2O} H_2SO_4$$

$$SO_2 + \frac{1}{2}O_2 \rightarrow SO_3 \xrightarrow{H_2O} H_2SO_4$$

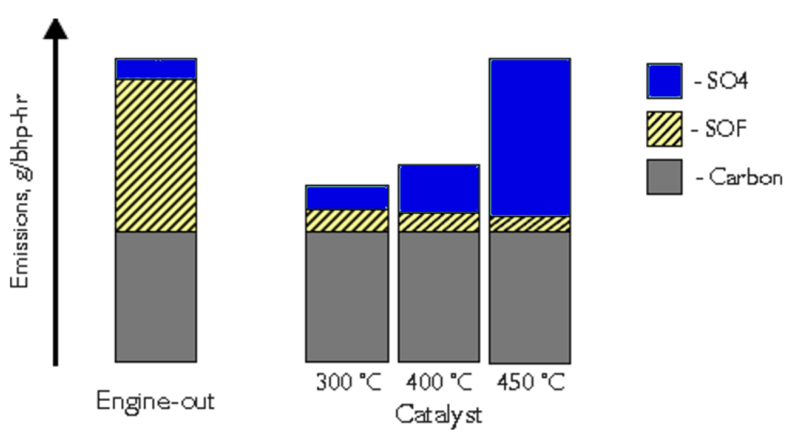


Figure 3-3. Catalytic Conversion of DOC

The diesel oxidation catalyst, depending on its formulation, may also exhibit some limited activity towards the reduction of nitrogen oxides in diesel exhaust. NO_x conversions of 10-20% are usually observed. The oxidation of NO to NO_2 is one of the more important DOC reactions, as shown below. This reaction is actually an important part of the function of DPFs, as described above, since NO_2 can help oxidize PM and facilitate the regeneration of DPFs. On the other hand, increased levels of NO_2 can have negative impacts in that NO_2 is more toxic than NO_x and can be more reactive, so preventing excessive levels of NO_2 in the tailpipe of the exhaust is a consideration in systems that combine DOCs and DPFs. The NO_x conversion exhibits a maximum at medium temperatures of about 300°C. The NO_x conversion potential for a DOC, and potential negative impacts of the NO_2 formation, are less important issues when the DOCs are used in combination with DPF/SCR systems.

$$NO + \frac{1}{2} O_2 = NO_2$$

3.2.2.4 In-Cylinder PM Control

The production of PM in diesel engines is primarily due to the inhomogeneous nature of the combustion, which gives rise to localized rich areas during combustion. The strategies for reducing PM emissions in the engine design are primarily designed to improve the mixing of the fuel and oxygen to promote improved combustion. A number of improvements in combustion systems have been implemented in diesel engines over the years including improved fuel injection systems and improvements to the design of the combustion chamber and combustion area. Improvements to the fuel injection system can include more precisely controlled fuel injection and higher injection pressures. Controlling the rate of the fuel injection (charge shaping) can improve combustion, such as injecting a small portion of the fuel early to act like a pilot injection. Higher injection pressures lead to better atomization and smaller fuel droplets that vaporize more readily than larger droplets. The cylinder head, air intake valve, and piston head can also be designed to provide optimal air motion for better fuel-air mixing. The position and angle of the injector in the cylinder head and the design of the nozzle can be optimized to minimize emissions. PM is also formed from lubricating oil on the cylinder wall that is partially burned. Newer designs minimize the amount of seepage of crankcase oil past the piston rings into the combustion to reduce oil consumption and PM formation from lubricant oil.

3.3 Applicability of These Control Strategies to Small Off-Road Diesel Engines

This section discusses some of the important aspects related to applicability of different control technologies to small off-road diesel engines, including operating temperatures, durability, and maintenance.

3.3.1 Operating Temperatures

An important aspect of the operation of exhaust aftertreatment systems is achieving sufficient temperatures for the catalytic reactions that eliminate the PM and NO_x. For DPFs with catalytic coatings, typically temperatures of 250°C or greater are required for the regeneration of a DPF, with higher rates of regeneration possible for higher exhaust temperatures. The catalytic coating on the DPF is critical in enabling regeneration at these temperatures, as DPF without a catalytic coating would require temperatures in excess of 600°C to regenerate.

3.3.2 Durability

An important aspect of validating the feasibility of the aftertreatment systems will be confirming their durability in in-use operation. This will include the ability of the aftertreatment system to operate free of problems for a prolonged period of time without significant issues such as filter plugging or extensive maintenance issues. System durability will be evaluated more extensively during the field demonstration portion of this study.

3.3.3 Maintenance

Another aspect of the application of DPFs is that the filters collect inorganic material or ash from lubricants, engines and other sources that do not combust during the typical regeneration process. Over the lifetime of the DPF, the ash will accumulate in the filter. This can lead to a gradual increase in the pressure drop over the DPF that can lead to a degradation in engine performance. Depending on the amount of ash build up, the DPFs can require periodic cleaning over time. Filter systems have been designed to minimize the need for DPF cleaning, and the frequency of cleaning can also be reduced with the use of lubricants with low ash levels.

3.4 Feasibility of Control Strategies for Small Off-Road Diesel Engine Prototype Development and Demonstration

This section describes potential prototypes demonstrations based on discussions and other communications UCR has had with a wide variety of aftertreatment manufacturers. The section is organized with a discussion of potential aftertreatment technologies that might be available by organization/company. The results and potential prototypes demonstrations are then summarized at the end of the section.

3.4.1 Proventia

Proventia is an aftertreatment system manufacturer that is based in Finland. Proventia manufacturers aftertreatment systems for both vehicles and machines/equipment. Proventia has considerable experience in developing aftertreatment systems for TRU applications. Proventia provides aftertreatment control systems for TRUs manufactured by ThermoKing/Yanmar in the 25 to 50 hp. Proventia has indicated that these systems would be adaptable to smaller TRU engines as well. Since Proventia is well acquainted with TRU applications and the associated temperature profiles, they have developed a prototype DPF installation for an under 25 hp TRU engine. They completed development testing for a DPF for a TRU engine in the 12 to 19 hp range in Finland priority to the demonstration for this project. The development process included both engine dynamometer as well as in-field testing. This is the type of TRU that can be applied to bobtail size trucks. A typical installation is shown in Figure 3-4 and Figure 3-5. UCR purchased the same engine as was used in the development process in Finland for this in-field demonstration. The engine is a 1.116 liter Yanmar TK 376N engine. Proventia also made arrangements for the DPF unit to be installed and demonstrated in a Bobtail truck with U.S. Foods.

Figure 3-4. TRU unit installed on a Bobtail truck.

Figure 3-5. Overview picture of TRU unit installed on a Bobtail truck.

We also had discussions with Proventia with respect to SCR applications in the 25 to 50 hp range. They indicated that SCR coated DPF in the 25 to 50 range would be possible. They suggested the unit costs for such installations would be similar to those for larger engines. In addition to the costs for the aftertreatment system itself, other costs would include the cost of control software, tanks, lines, 2 NO_x sensors, and temperature sensors. They suggested units could be in the range of $6,000 to $7,000 per system.

3.4.2 DCL DPF system for a mini-excavator

DCL provided a DPF with their CATFIRE control system for this demonstration. The CATFIRE system provides fuel injection for active regeneration of the DPF when temperatures were not sufficient for passive regeneration. The DPF was installed on in a mini-excavator that was equipped with a 24 hp Kubota V1505 engine. The mini-excavator and engine installation are shown in Figure 3-6. This unit was deployed in the field with a general contractor as well as a plumbing company over the course of the field demonstration.

Figure 3-6. Mini-Excavator and DPF-Equipped Engine Pictures

3.4.3 BASF/Continental/Donaldson SCR system for a ride mower

BASF provided a substrate for an SCR aftertreatment device. The substrate was designed to work with an engine already equipped with a DPF. A John Deere Z997R commercial ride mower was selected for this demonstration. This mower is powered by a 3 cylinder, 37.4 hp (27.5 kW), liquid cooled, DPF-equipped, 3TNV88C Yanmar diesel engine that meets EPA Final Tier 4 standards. This mower was put in service with the UC Riverside landscape and grounds keeping department. Note that the demonstrations for the NOx control devices were specifically targeted for under 50 hp applications to demonstrate the feasibility of lower NOx emissions standards for off-road diesel engines less than 50 hp. The mower and engine are shown in Figure 3-7.

Figure 3-7. John Deere Ride Mower and Engine Pictures

The SCR system was being designed based on engine-out emissions/concentrations, mass air flow, and exhaust temperatures obtained directly from John Deere. Additional measurements of the exhaust temperature were obtained for several days of operation with the mower in-service at UCR. These exhaust temperature measurements are shown in Figure 3-8. The canning and urea dosing equipment for this substrate was provided by Continental in conjunction with Donaldson, which are third party suppliers that were identified through discussions with MECA.

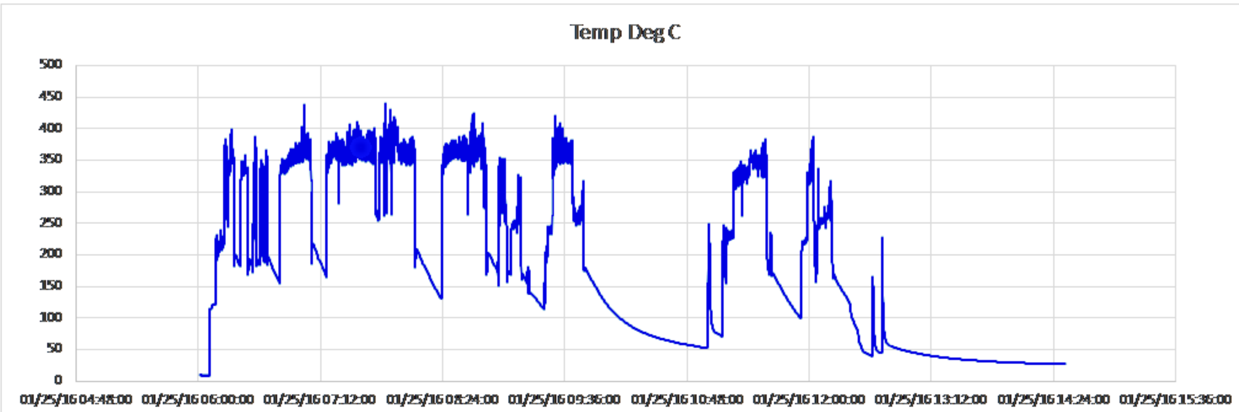


Figure 3-8. Exhaust Temperature Measurements for several days of operation with the John Deere ride mower.

The finished SCR system required a dosing map that was developed based on exhaust flow, NO_x sensors, and exhaust temperature during the engine dynamometer testing.

3.4.4 Johnson Matthey/Tenneco SCRT for a skid steer

Johnson Matthey provided a Selective Continuous Regenerating Technology (SCRT)[2] system for this program. The SCRT is a combination SCR and Continuously Regenerating Diesel Particulate Filter that provides reductions in NO_x and PM, as well as CO and THC. The DOC/DPF system passively regenerates, and as such does not require extensive interfacing with the engine controls to operate. The configuration and urea dosing equipment was provided by Tenneco. The SCRT was installed in a skid steer equipped with a 49 hp Doosan engine. Note that the demonstrations for the NOx control devices were specifically targeted for under 50 hp applications to demonstrate the feasibility of lower NOx emissions standards for off-road diesel engines less than 50 hp. A picture of the skid steer and the SCRT-equipped engine is provided in Figure 3-9. The skid was put in service with an outside construction contractor for the field demonstration. A dosing map was needed for the SCR also, as discussed above. The dosing map was developed based on the exhaust flow rate, NO_x sensors, and exhaust temperature during the engine dynamometer testing. The NO_x sensors and exhaust temperature sensor are already incorporated onto the unit. Tenneco and JM provided support for engine dynamometer installation and developing a dosing map.

[2] https://www.jmsec.com/fileadmin/user_upload/pdf/current_news_releases/johnson_matthey_stationary_emissions_control_jm_sec_scrt__nr_052013.pdf

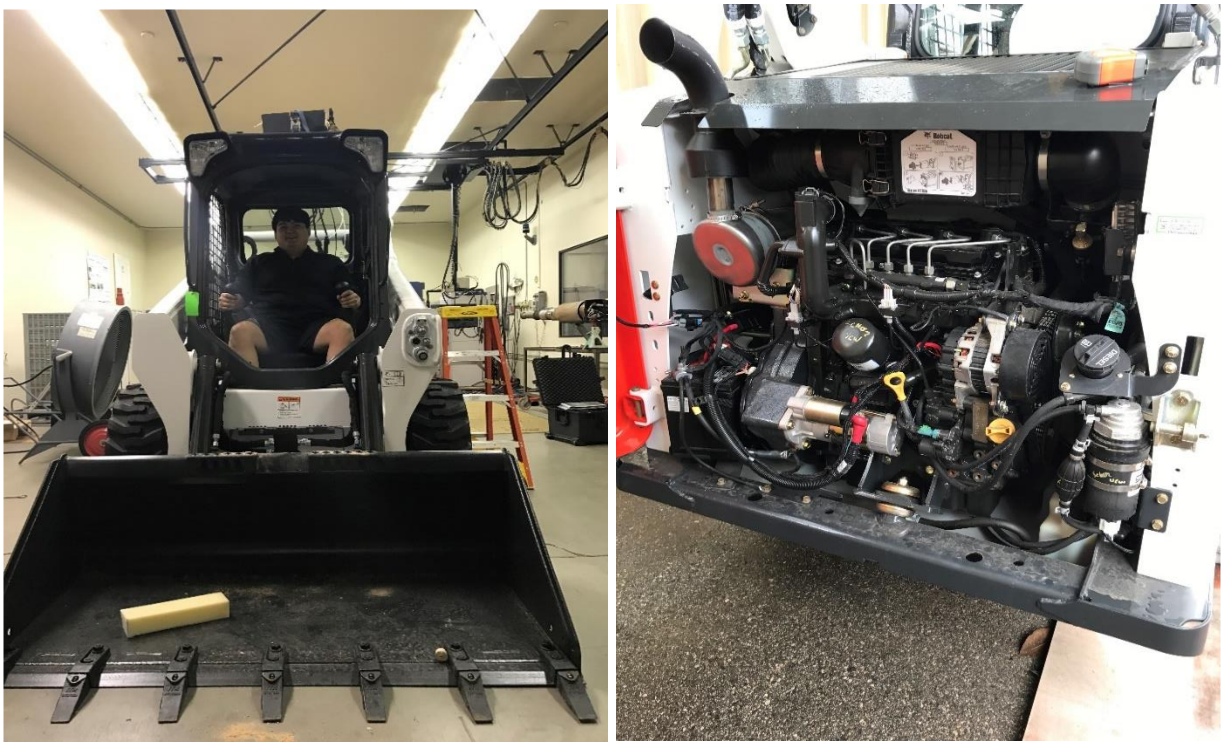


Figure 3-9. Skid Steer and SCRT-equipped Engine Pictures

3.4.5 Other Potential Demonstrations

The following are other potential aftertreatment systems or demonstrations that were evaluated for, but were not included in the demonstration program

Rypos

Rypos is a leading manufacturer of aftertreatment systems for TRUs located out of Hollistan, MA. Rypos suggested that they would have been willing to provide a ULETRU DPF for a TRU. This would have been a level 3 DPF device that could be utilized with either Thermo King or Carrier Transcold TRU systems. This would have been an active, electrically regenerated DPF. Approximately 3,000 such systems have been sold on the market. This unit is currently used in conjunction with a 36 hp, non-derated engine. The demonstration proposed by Rypos would have been for a 24.5 hp derated engine. The potential significance of this demonstration was that it would have involved additional engineering to make sure the system works with a derated 24.5 hp engine to ensure that the 2 hp needed for regeneration could be accommodated during in-use operation. Rypos would have provided on-site engineering support to help with the dyno installation and set up, and with training on the system use. The unit would have been a bolt-on system for the field. Rypos indicated that they would also have provided the additional engineering work to ensure the system would work at the lower hp. This system was not included in the demonstration as another DPF for a TRU was already incorporated into the program.

Dinex/Carrier

Dinex is an aftertreatment manufacturer that is based in Denmark. Dinex also manufacturers aftertreatment synstems for heavy-duty diesel and gas engines. Dinex has its core technology and production platforms for emission substrates, coating facilities, as well as complete system integration and production. Dinex also has considerable experience with aftertreatment systems for TRUs and is a primary supplier for Carrier TRU applications.

Dinex manufactures a DPF-based system that can be used for TRUs over a power range extending below the 25 hp. This system can be used with < 25 hp 2012 to 2015 Kubota model V2203L-DI-EF01e engines. These engines are used in Carrier X4 7300 and 7500 TRUs, Vector 8500 and 8600MT TRUs, and Carrier UG and RG TRU generator sets. This system includes a DPF with an active regeneration system along with an upfront DOC. This system has been verified as a Level 3 diesel emission control strategy by the ARB. The cost of these systems is in the $5,000 to $10,000 range, which is similar to the cost of the comparable engines in this size range.

Dinex communicated with Carrier about the potential to provide such a system to the program, but in the end, it was determined that such a system could not be provided to the program.

4 Emissions and Durability Testing

This section describes the engine testing and results for the Transportation Refrigeration Unit (TRU), ride mower, mini-excavator, and skid steer engines with the associated aftertreatment systems.

4.1 Experimental

4.1.1 Engines and Test Fuels

Testing was conducted on a total of 4 engines, including a TRU engine, a ride mower engine, an excavator engine, and a skid steer engine. The characteristics of each of the engines are provided in Table 4-1.

Table 4-1. Description of Test Engines

System	**Transportation Refrigeration Unit**	**Ride Mower**	**Excavator**	**Skid Steer**
Engine vendor	Yanmar	John Deere	Kubota	Doosan
Engine family	8YDXL1.11W3N	FYDXL1.64NDA	GKBXL01.5BCB	FDICL02.4LEA
Engine model	3TNV76	3TNV88C-DJMZ	V1505	DL02-LEL03
Engine power (hp/kW)	20.25/15.10	37.4/27.9	24.80/18.50	49/37
OEM AT	None	DPF/DOC	None	DOC
AT vendor	Proventia	BASF, Donaldson, Continental	DCL	Johnson Matthey & Tenneco
AT type	DPF	SCR	DPF	SCRT*

* functions as both a DPF and an SCR

The test fuel used was a California No. 2 diesel fuel with equal portions taken from an Arco, Shell, and Chevron station. This fuel was obtained in a single batch of six drums, which should be sufficient for the pre- and post-testing and degreening on all 4 test engines. Fifteen gallons of fuel from each fuel station was mixed into separate 55-gallon drums, and then each drum was mixed with an air-driven stirrer for 15 minutes. A fuel sample from this batch of fuel was sent to CARB staff in El Monte for analysis using CARB methods for the following properties: density (ASTM D4052), sulfur (ASTM D5453), distillation (ASTM D86), aromatics and polycyclic hydrocarbons (ASTM D5186), and cetane index derived from a density and distillation properties. The results of the fuel analyses are shown below in Table 4-2.

Table 4-2. Fuel Properties of Test Fuel

Analytical Method	Fuel Analysis & Methods Evaluation Section (FAME) Monitoring and Laboratory Division, CARB									
	ASTM D5186 - modified SFC/FID				ASTM D86 Automatic			ASTM D5453 Antek	ASTM D4052 Density Mtr	ASTM D3343 Calculation
Analysis Date	2016/10/31				2016/10/28			2016/10/31	2016/10/31	NR
Sample I.D.	Total Aromatics (vol %)	Total Aromatics (mass%)	Polycyclic Aromatics (mass%)	Biodiesel (mass%)	T10 (deg C)	T50 (deg C)	T90 (deg C)	Sulfur (ppm)	Density (g/mL)	Carbon / Hydrogen (mass%)
2R1604	20.1	20.5	2.2	4.0	216	272	335	7.8	0.8348	*

4.1.1.1 TRU Engine

The TRU engine was purchased directly from a dealer. This engine will only be used for the engine dynamometer test with and without the DPF. In the field, the DPF was equipped directly to an engine that is already in an existing TRU for the 1,000-hour demonstration.

In conjunction with the installation of the DPF, an electric heating element was utilized for the DPF regenerations. This heating element essentially heats the intake air. For the DPF dynamometer set up, a separate power supply was set up to power the heating element for the intake air. A Hioki meter was used to measure the power used during regenerations. This system was triggered by the measured back-pressure in the DPF and regenerates the DPF by increasing the exhaust temperature to a level where the catalyzed DPF substrate is activated for regeneration. Based on the results in Figure 5, the regenerations were mostly associated with engine loads above 75%. When the TRU engine operates in use, it is generally running at a 50% load. A picture of the TRU engine with the DPF and heating element installed is provided in Figure 4-1.

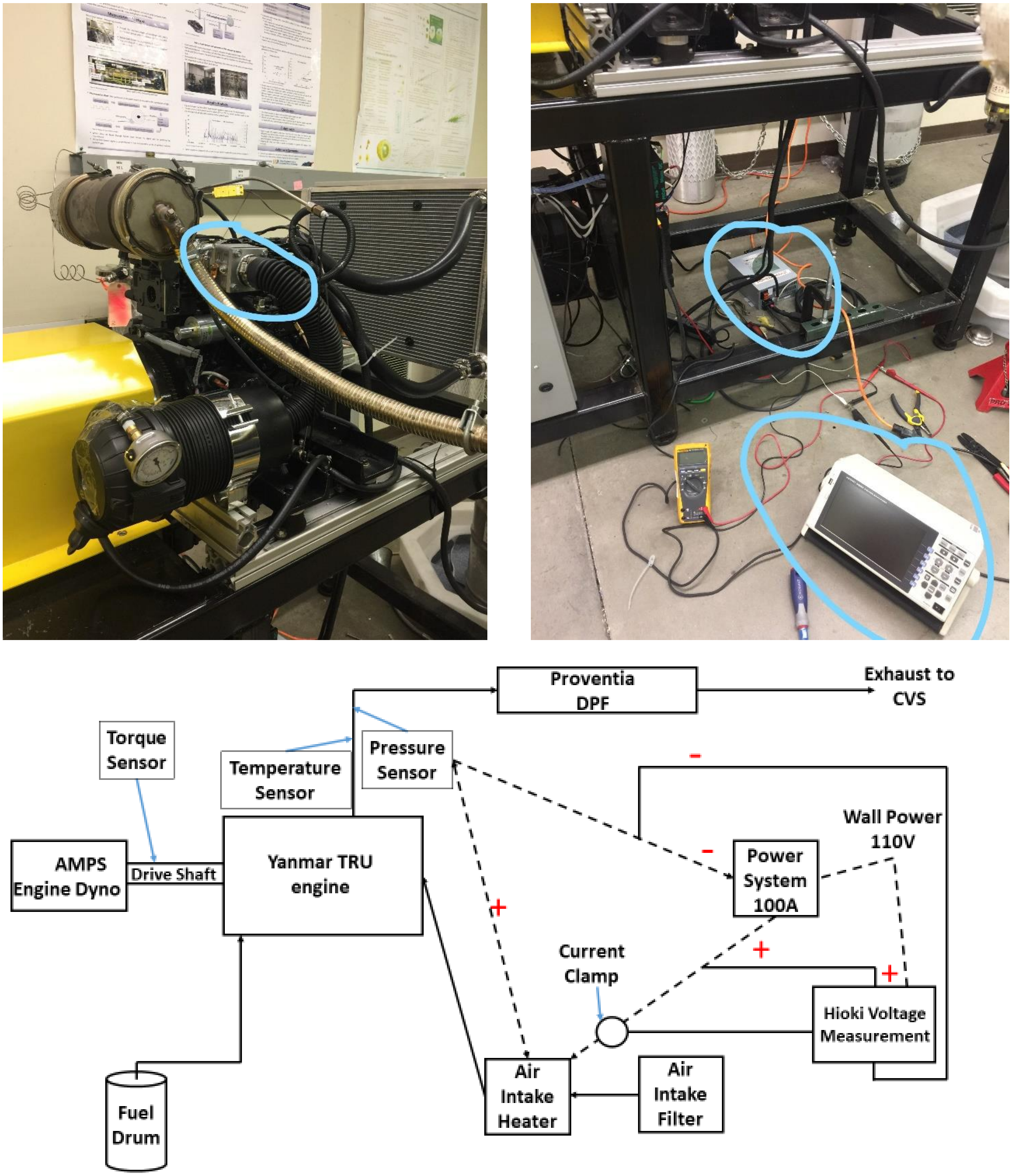


Figure 4-1. TRU Engine on the Engine Dynamometer with the DPF the Regeneration Heating Unit

4.1.1.2 Ride Mower Engine

The ride mower engine in its original equipment manufacturer (OEM) configuration was equipped with a DPF. Prior to testing, it was operated for about 173 hours in the field in its original configuration. After the break-in period in the field, the SCR system was installed on the ride mower engine while it was still housed in the ride mower. This allowed the functionality of the SCR to be verified prior to its installation on the engine dynamometer.

The SCR for this engine was provided in-kind by a collaboration between BASF, Donaldson, and Continental. The components provided by BASF, Donaldson, and Continental included a substrate, a mixer, and the dosing hardware, respectively. The SCR system was added to the system immediately after the OEM DPF. A picture of the ride mower engine with the SCR installed on the engine dynamometer is provided in Figure 4-2.

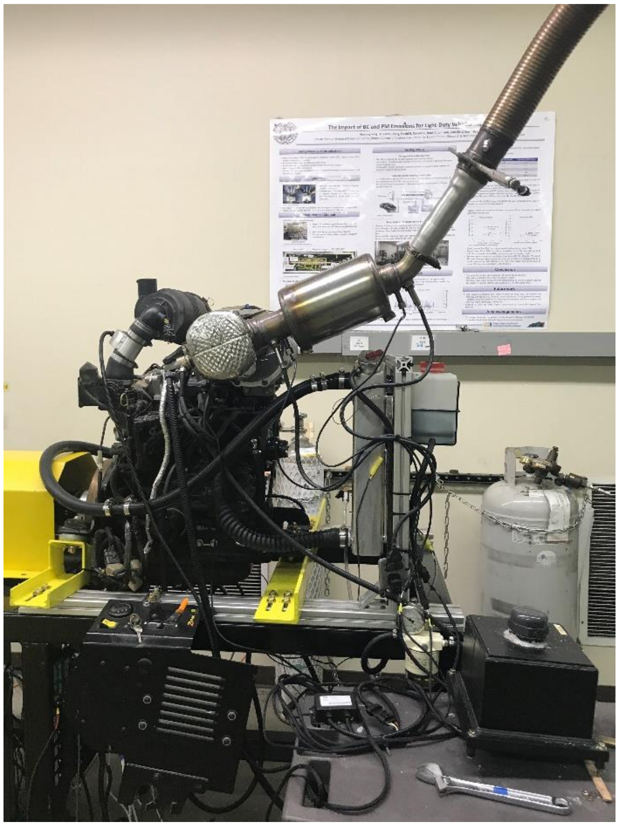


Figure 4-2. Ride Mover Engine on the Engine Dynamometer with the SCR

4.1.1.3 Excavator Engine

For the excavator, the engine in its original configuration did not have any aftertreatment. Prior to testing, it was operated for about 25 hours in the field in its original configuration. After the break-in period in the field, the DPF system was installed on the excavator engine while it was still housed in the excavator. This allowed the functionality of the DPF to be verified prior to its installation on the engine dynamometer.

The DPF for this engine was provided by DCL. This system utilizes an active regeneration system where diesel fuel is injected upstream of a DOC. The combustion or reaction of the diesel across the DOC creates heat that is used to raise the temperature of the exhaust gas to a level that is sufficient to regenerate the PM on the DPF. The DPF regeneration is triggered based on back-pressure, which was set at a default value of 60 in-H_2O. A picture of the excavator engine with the DPF installed on the engine dynamometer is provided in Figure 4-3.

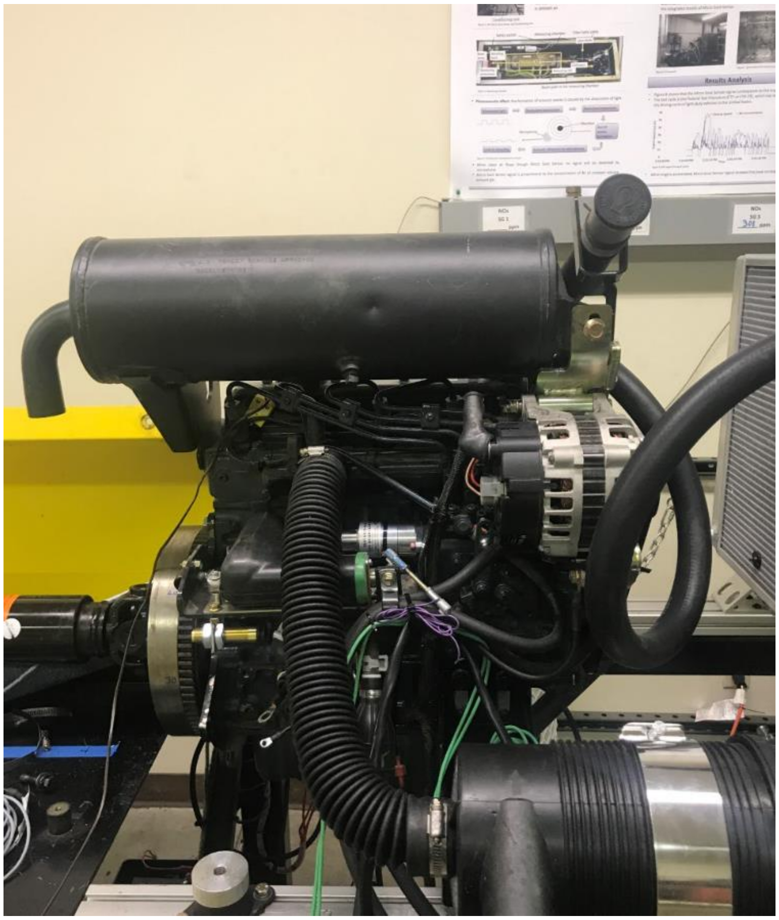


Figure 4-3. Mini-Excavator Engine on the Engine Dynamometer with the DPF

4.1.1.4 Skid Steer Engine

For the skid steer engine, the engine is equipped with a DOC in its original configuration. The SCRT system was installed on the skid steer engine while it was still housed in the skid steer. This allowed the functionality of the SCRT and urea dosing to be verified prior to its installation on the engine dynamometer.

The SCRT for this engine was provided by Johnson Matthey and Tenneco, where the substrate was provided by Johnson Matthey and the dosing system was provided by Tenneco. The SCRT system uses a DOC/DPF/SCR combined to allow the control of both PM and NO_x. CO/HC/PM emissions are controlled using the DOC/DPF combination. The regeneration principle for the DPF uses NO_2 produced by the DOC to burn soot collected by the filter at typical operating temperatures. The SCR catalyst is vanadium based on a cordierite substrate. A platinum group metal (PGM) catalyst on the cordierite substrate is used to prevent NH_3 slip.

Figure 4-4. Skid Steer Engine on the Engine Dynamometer with the SCRT

4.1.2 Engine Dynamometer Testing

4.1.2.1 Engine Dynamometer

Engine testing was conducted on a 50 hp dynamometer from Alternative Motive Power Systems (AMPS). The engine dynamometer uses a Baldor / Reliance IDBRPM25504 motor. The motor provides 50 hp at 1770 rpm at a torque of 150 ft-lbs. The motor can absorb 50 hp of power from 1770 up to 3540 rpm. At the higher speeds, the motor can provide constant hp up to 3540 rpm at 75 ft-lbs of torque (torque reduces to maintain hp). The maximum continuous torque for the motor is 150 ft-lbs at an engine speed of 1770 rpm or less. The motor provides a short term peak (60 seconds) overloading rating of 75 hp (150%) 1770 rpm with 225 ft-lbs. A picture of the full engine dynamometer set-up with a typical engine in the lab is provided in Figure 4-5.

Figure 4-5. Engine Dynamometer used for Testing

4.1.2.2 General Test Sequence

Two different general test sequences were used throughout the testing. These sequences are shown in Table 4-3 and Table 4-4. For these tables, the main elements of the test sequence numbered, with the testing shaded in green and the durability demonstration shaded in orange. The main difference in the test sequences is the order of testing between the baseline testing and the degreened testing. The engines were initially uninstalled from the associated OEM equipment where it is originally installed. After the installation of the engine and aftertreatment system on the dynamometer, the primary test sequence in Table 4-3 proceeded with testing the engine in its baseline or original condition. The aftertreatment system was then installed and the engine with aftertreatment was then degreened for a period of 25 hours. This was the sequence followed for the TRU engine and the skid steer engine. Testing was then conducted on the degreened system with the aftertreatment installed. It should also be noted that for the TRU application, only the DPF was common to both the engine testing and the durability demonstration. The engine used for the engine dynamometer testing for the TRU engine was of the same make and engine family as the TRU engine that the DPF was installed on in the field.

Since some of the aftertreatment systems were installed in the engines before were pulled out of the equipment, it was decided to test some engines with the aftertreatment installed first, and then subsequently to do the baseline testing without the aftertreatment system. This would provide as much consistency as possible between how the aftertreatment is installed in the field compared with the dynamometer set up. The sequence for these engines is provided in Table 4-4. Following the testing with the degreened aftertreatment installed, the aftertreatment was uninstalled and such that the engine was returned to its original OEM configuration. This was done for the ride mower and mini-excavator applications. It should be noted that the 25 hours of degreening was done for the aftertreatment configuration regardless of whether the baseline or the degreened aftertreatment test was conducted first. This test sequence was used for the ride mower and mini-excavator engines.

Table 4-3. Summary of the Test Sequence for the Engine Dynamometer Testing for Engines Mounted Before Aftertreatment Installation.

Description
1. Engine Mounting without Aftertreatment
Testing Preparation/pretesting/development testing
2. Baseline Testing (no aftertreatment)
Aftertreatment Installation
3. Aftertreatment Degreening (25 hours)
4. Degreened Aftertreatment Testing
Engine Removal
5. 1000 Hour In-Field Demonstration or Catalyst Aging
Engine Installation
6. Final Aftertreatment Durability Testing
Engine Removal

Table 4-4. Summary of the Test Sequence for the Engine Dynamometer Testing for Engines with Aftertreatment Installed before Engine Mounting

Description
1. Engine Installation with Aftertreatment
Testing Preparation/pretesting/development testing
2. Aftertreatment Degreening (25 hours)
3. Baseline Degreened Aftertreatment Testing
Aftertreatment Removal
4. Baseline Testing (no aftertreatment)
Engine Removal
5. 1000 Hour In-Field Demonstration or Catalyst Aging
Engine Installation
6. Final Aftertreatment Durability Testing
Engine Removal

Following the completion of the initial baseline and degreened testing, the engine was then removed from the engine dynamometer and replaced in the equipment that it was originally installed in for the 1,000-hour durability demonstration. Following completion of at least 1,000 hours of operation in the field, the engine/aftertreatment system were returned to UCR, reinstalled on the engine dynamometer, and the final emissions test was conducted. In the case of the skid steer and mini-excavator applications, these units were unable to complete the 1,000 field demonstration, so additional catalyst aging was done for these applications, as described below.

The degreening was predominantly done on the steady-state test cycles that were used for the actual emissions testing. This included the G2 cycle for the TRU engine and the C1 cycle for the ride mower, mini-excavator, and skid steer engines. These cycles were repeated back to back until 25 hours of operation was accumulated on the engine + aftertreatment combinations. Some of the hour accumulation may have also included other types of operation, such as engine maps, steady-state operations at different load conditions that might be used to investigate the operation of the engine under different conditions to verify that it was ready for the actual emissions testing, and over the NRTC cycle.

4.1.2.3 Engine Mapping

For each engine, an engine map was conducted both in its original conditions and with the aftertreatment installed. The engine maps were used to determine the load points for the steady-state C1 and G2 tests, and the engine rpm and torque values for the associated NRTC cycle.

For the TRU engine, the engine maps in the "baseline" and "degreened baseline" tests are shown in Figure 4-6, along with the backpressure for both conditions. These engine maps were used to determine the load points for the G2 cycle for the corresponding "Baseline" and "Degreened Baseline" tests. The engine maps show that the maximum achievable power with the DPF installed was less than that for the engine without the DPF, so this had to be accounted for in the setting of the load points. The maximum engine rpm was set at 2450 rpm based on the engine maps, since the dyno torque value drops off significantly after 2450 rpm, as shown in Figure 4-6.

Figure 4-6 shows that the back-pressure increases with the addition of the DPF from approximately 7 in H_2O without a DPF up to 52 in H_2O when the DPF is installed. This could affect the performance of this 20 hp small diesel engine since the engine needs to work harder at the same load than without a DPF. Therefore, the engine was not able to meet the same maximum dyno torque with the addition of DPF, especially in the higher rpm range. Based on the engine maps, the maximum torque for the baseline and degreened baseline tests were selected to be 480 in-lbs and 450 in-lbs, respectively, to set up the G2 cycle test points.

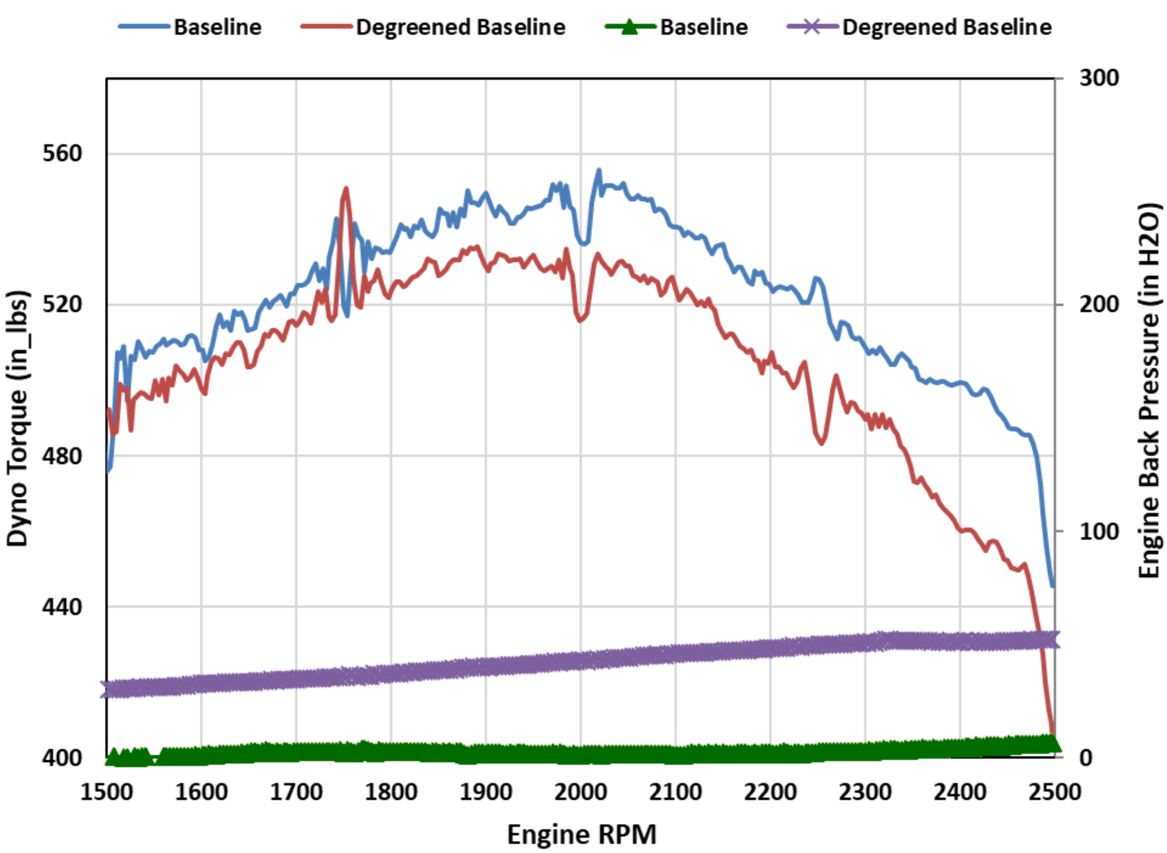


Figure 4-6. Engine Map and Corresponding Engine Back-Pressure

The engine maps for the ride mower in both the "Baseline" and "Degreened Baseline" conditions are shown in Figure 4-7. These engine maps were used to determine the load points for the C1 cycles and Non-Road Transient cycles (NRTC) for the corresponding "Baseline" and "Degreened Baseline" tests. Since SCR aftertreatment performance is being evaluated, the same load points were selected for both "Baseline" and 'Degreened Baseline" test. The idle and maximum engine rpm were set at 1525 rpm and 3030 rpm based on information on the engine label and discussions with the engine manufacturer.

The engine maps on "Baseline" and "Degreened Baseline" are relatively close to each other. The difference between the two engine maps on maximum dyno achievable torque would be primarily contributed by the additional back-pressure from the added SCR aftertreatment. However, this study was focus on the SCR removal efficiency on the NO_x emissions, so the tests were run at the same rpm and torque settings for both "Baseline" and "Degreened Baseline" tests.

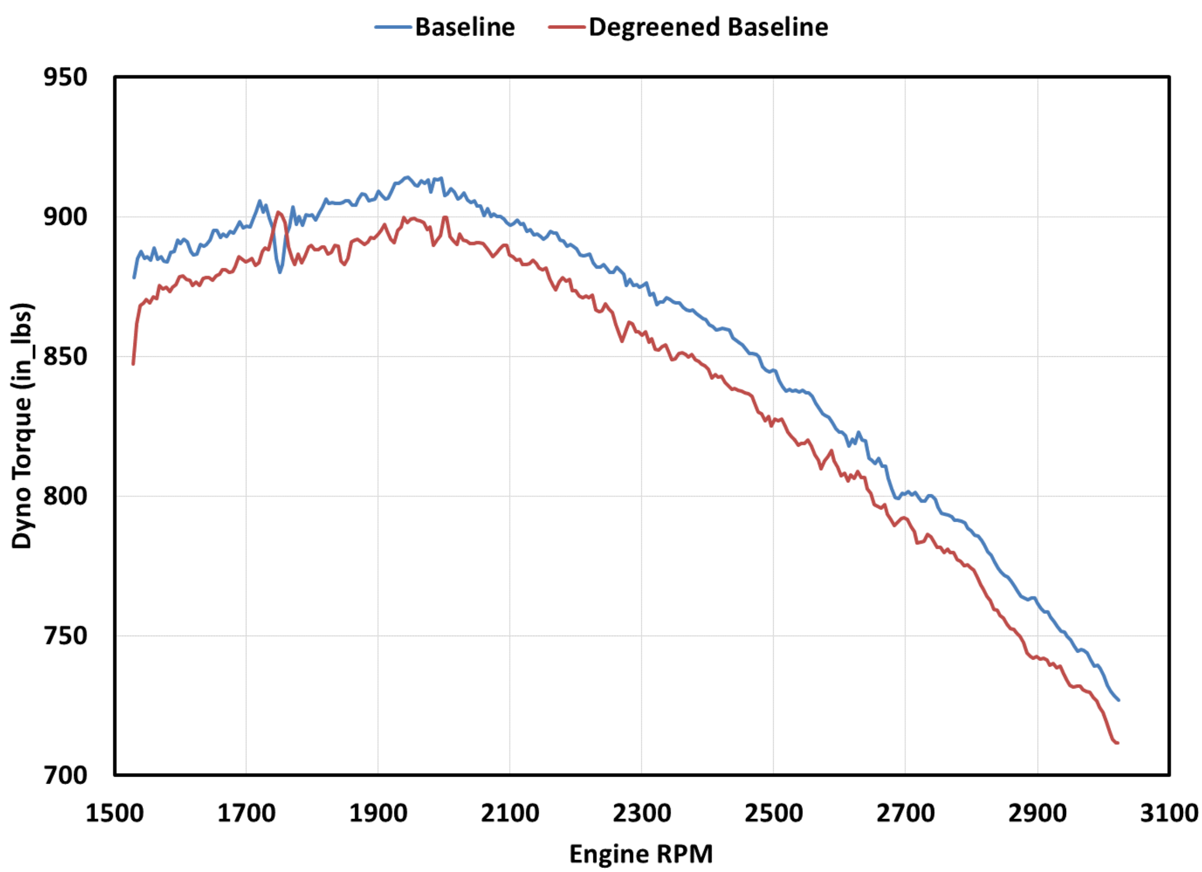


Figure 4-7. Engine Maps for Ride Mower Engine

The engine maps the mini-excavator for the "Baseline" and "Degreened Baseline" conditions are shown in Figure 4-8, along with the backpressure for both conditions. These engine maps were used to determine the load points for the C1 and NRTC cycles for the corresponding "Baseline" and "Degreened Baseline" tests. The maximum engine rpm was set at 2300 rpm on the engine maps based on information on the engine label and discussions with the engine manufacturer.

The back-pressure level for this engine was about 35 in H_2O with the addition of DPF during the Degreened Baseline testing, while the back-pressure for the Baseline testing was not measured. The testing rpm range for this engine was 1200-2300 rpm. The engine maps suggested that the torque did not change much between the DPF configuration and the original muffler at the higher rpms above

1500, but the torque output at rpm values less than 1500 was lower when the DPF was equipped. Based on the engine maps, the maximum torque for both baseline and degreened baseline tests was selected to be 725 in-lbs for intermediate speed and 600 in-lbs for maximum speed to set up the C1 and NRTC test points. The 725 in-lbs was slightly below the maximum available torque, to provide a margin of safety in running the engine, and also to utilize a torque level that could safely be utilized for both the baseline and degreeened baseline tests.

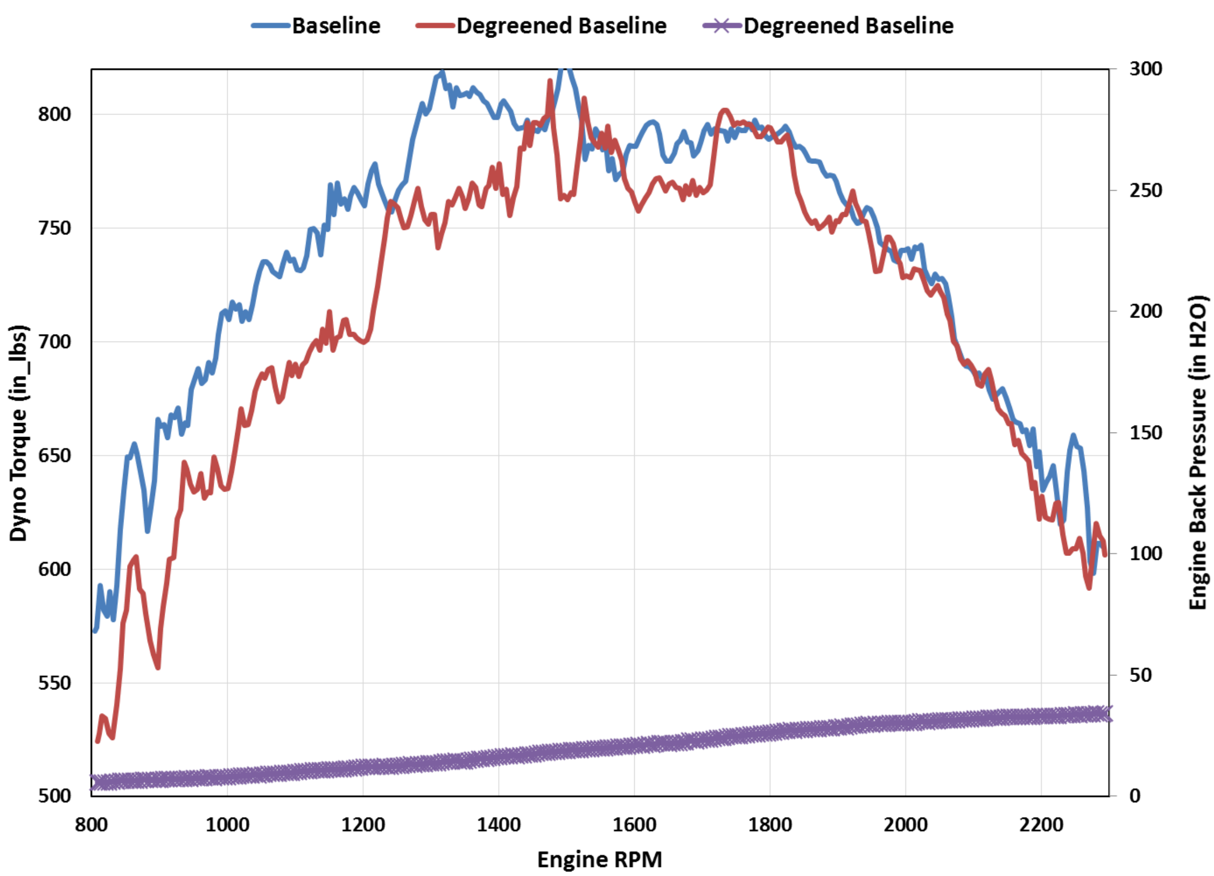


Figure 4-8. Engine Maps and Corresponding Engine Back-Pressure for Mini-Excavator

The engine maps of the skid steer for the “Baseline” and “Degreened Baseline” conditions are shown in Figure 4-9, along with the backpressure for both conditions. These engine maps were used to determine the load points for the C1 and NRTC cycles for the corresponding “Baseline” and “Degreened Baseline” tests. The maximum engine rpm was set at 2600 rpm on the engine maps based on information on the engine label and discussions with the engine manufacturer.

Figure 4-9 shows that the back-pressure increases with the addition of the SCRT from approximately 20 in H_2O without an SCRT up to 75 in H_2O when the SCRT is installed. This could affect the performance of this 49 hp small diesel engine since the engine needs to work harder at the same load than without an SCRT. Therefore, the engine was not able to meet the same maximum dyno torque with the addition of SCRT, especially in the intermediate rpm range. The testing rpm range for this engine was 1200-2600 rpm. Based on the engine maps, the maximum torque for the baseline and degreened baseline tests were selected to be 1129 in-lbs and 1100 in-lbs, respectively, to set up the C1 and NRTC test points. The 1100 in-lbs was slightly below the maximum available torque, to provide a margin of safety in running the engine, and also to utilize a torque level that could safely be utilized for both the baseline and degreeened baseline tests.

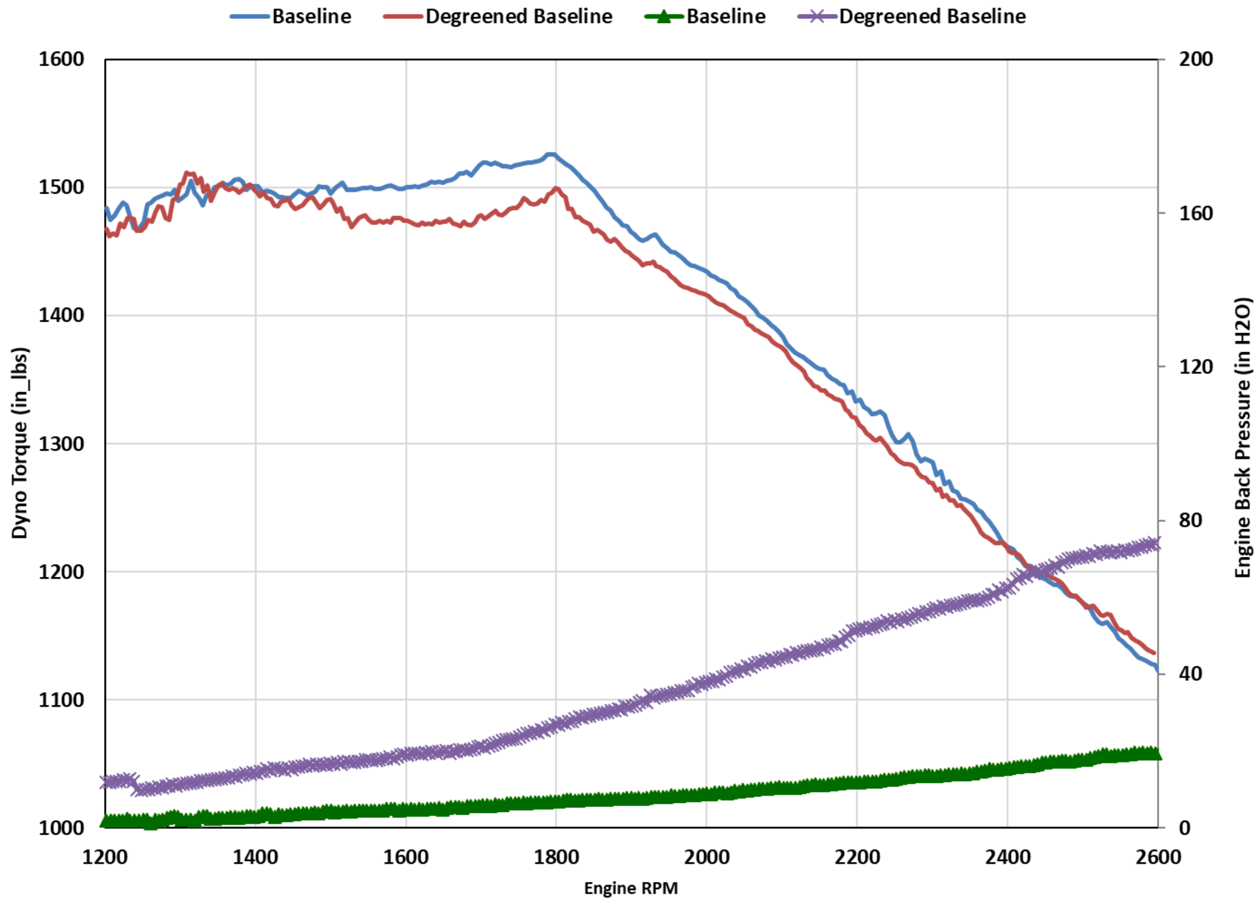


Figure 4-9. Engine Maps and Corresponding Engine Back-Pressure for Skid Steer Engine

4.1.2.4 Test Cycles

The emissions testing for the TRU engine was conducted in triplicate over the G2 test cycles. A G2 test cycle is a 6-mode ramped modal test cycle (described in 40 CFR 1039 Appendix II (b)(2)). The ramped modal tests were run as hot stabilized tests, with the engine warmed up prior to the start of each emissions test. At the beginning of each test day, the engine was at maximum speed and power at 2450 rpm for 20 minutes to warm-up, and then an engine map was run. Prior to each test, the engine was warmed up for 5 minutes at the maximum load at the maximum rpm where the max load was determined by an engine map run in the morning of each test day. This warm-up procedure provided a stabilized engine temperature, such that the engine coolant/block/or head temperature was within ±2% of its mean value for at least 2 minutes, as per 40 CFR 1065.530. A description of the G2 test cycle is provided in Figure 4-10. A summary of an idealized daily sequence for testing is given in Table 4-5 for the TRU engine. The sequence of the tests for the actual testing was determined at the time of testing depending on logistical and other considerations. Note that the preconditioning for each test cycle remained consistent regardless of the specific order in which the tests were run. During the course of the engine installation and preparation, the engine was run over variety of engine maps, where the engine was run from the base idle to maximum engine speed while measuring the maximum power and torque at each speed. The engine map was used to determine the speed and torque test points for the G2 test cycles.

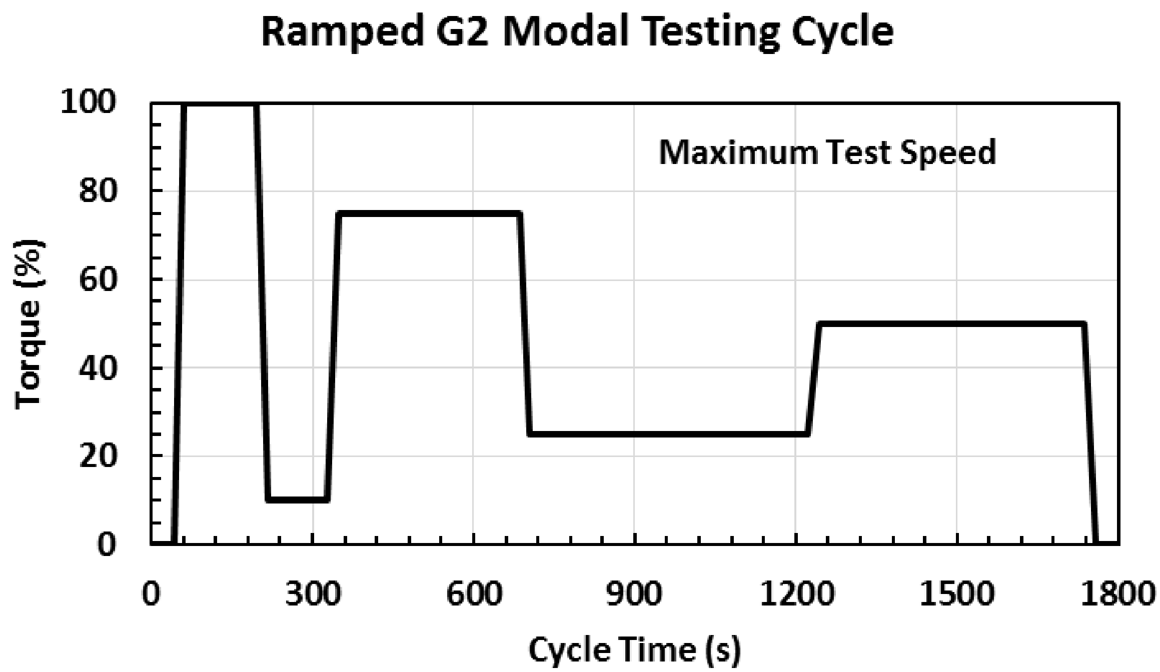


Figure 4-10. Graphical Presentation of the G2 Modal Test Cycle. Note that the entire test was run at a constant speed equal to 100% of maximum speed

Table 4-5. Summary of the Test Sequence for the Yanmar TRU

Testing Activity for TRU Engine	Test Number	Blue is full testing
VERL warm up		
20 Minutes Engine Warmup		Yellow is soak
Engine Map		
Soak		Green Is break
5 Minutes Engine Warmup		
Ramped-modal G2 testing	1	Red is prep/Conditioning
Soak		
5 Minutes Engine Warmup		Warm up/ Shutdown
Ramped-modal G2 testing	2	
Soak		
5 Minutes Engine Warmup		
Ramped-modal G2 testing	3	
VERL shut down and Data process		

Regeneration events were observed periodically over the course of the emissions testing. These regeneration events were representative of typical operation of the DPF, so they were not eliminated from the emissions results. The regeneration results are shown in Figure 4-11 below, which shows the voltage across the Hioki meter related to when the heating circuit is triggered. The DPF is considered to be regenerating when there is voltage being sent to the heating circuit. The fraction of the test when regenerations occurred seemed to increase with subsequent tests, as shown in Figure 4-11. The regenerations mostly happened during the maximum load and 75% load period during the test. For the first test with the DPF, there was only one regeneration event for 122 seconds, accounting for 6.8% of the test time of a G2 test cycle. For the second and third tests with the DPF, there were two regeneration events for a total of 437 seconds and 559 seconds, respectively, which accounted for 24.3% and 31.1% of the test time for the G2 test cycle. Note that the voltage did show some instability during portions of the regeneration. This can be attributed to hysteresis in the heating circuit. This stability should improve with a more responsive circuit. Although regenerations were not specifically recorded during the degreening process, it was observed that regenerations occurred at roughly the same frequency during the degreening as was observed during the emission testing.

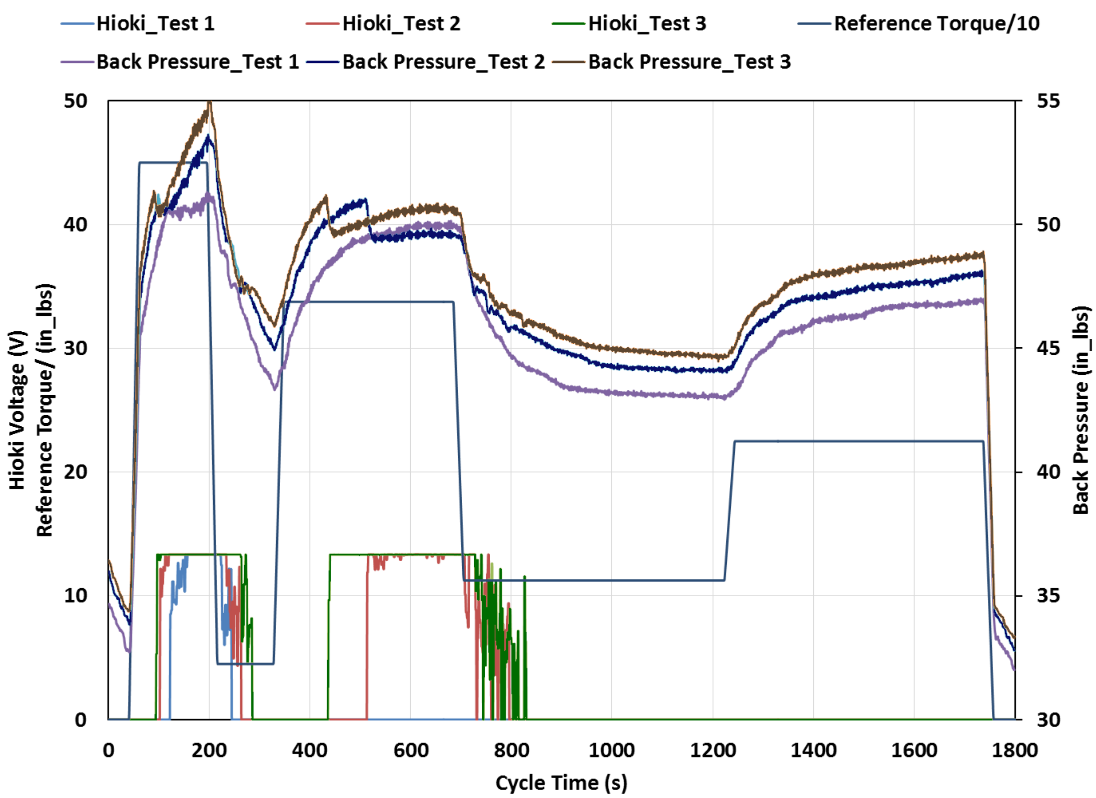


Figure 4-11. Regeneration Results for TRU DPF

The emissions testing for the ride mower, mini-excavator, and skid steer engines were conducted in triplicate over the C1 test cycle. The C1 test is an 8-mode ramped modal test cycle (described in 40 CFR 1039 Appendix II (c)(2)). The ramped modal tests were run as hot stabilized tests, with the engine warmed up prior to the start of each emissions test. Prior to each C1 test, the engine was warmed up for 5 minutes at the maximum load at the maximum rpm. This warm-up procedure provided a stabilized engine temperature, such that the engine coolant/block/or head temperature was within ±2% of its mean value for at least 2 minutes, as per 40 CFR 1065.530. A description of the C1 test cycle is provided in Figure 4-12. These engines were also tested over both a cold start and a hot start NRTC. The hot start test was conducted in such a manner that the soak time between the end of the cold start test and the start of the hot start test will be as close as possible to 20 minutes. A description of the NRTC test cycle is provided in Figure 4-13. A summary of the general test sequence is given in Table 4-6 for the ride mower, mini-excavator, and skid steer engine. It should be noted that the sequence in Table 4-6 represents the target test matrix. The sequence of the tests for the actual testing was determined at the time of testing depending on logistical and other considerations. Note that the preconditioning for each test cycle remained consistent regardless of the specific order in which the tests were run.

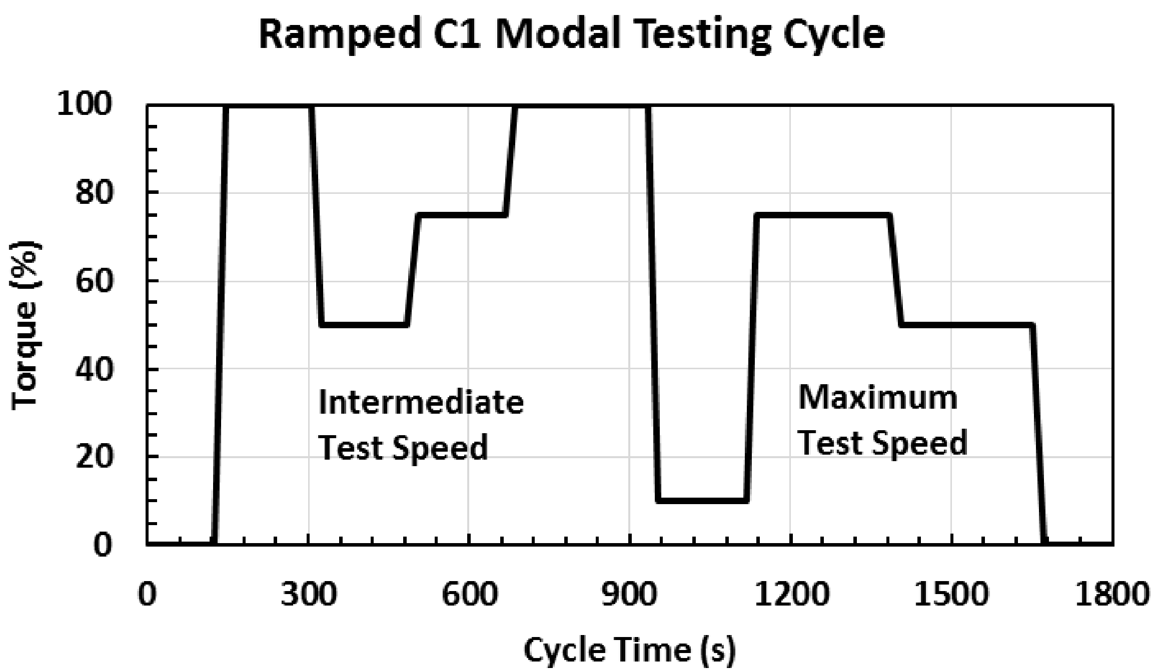


Figure 4-12. Graphical Presentation of the C1 Modal Test Cycle

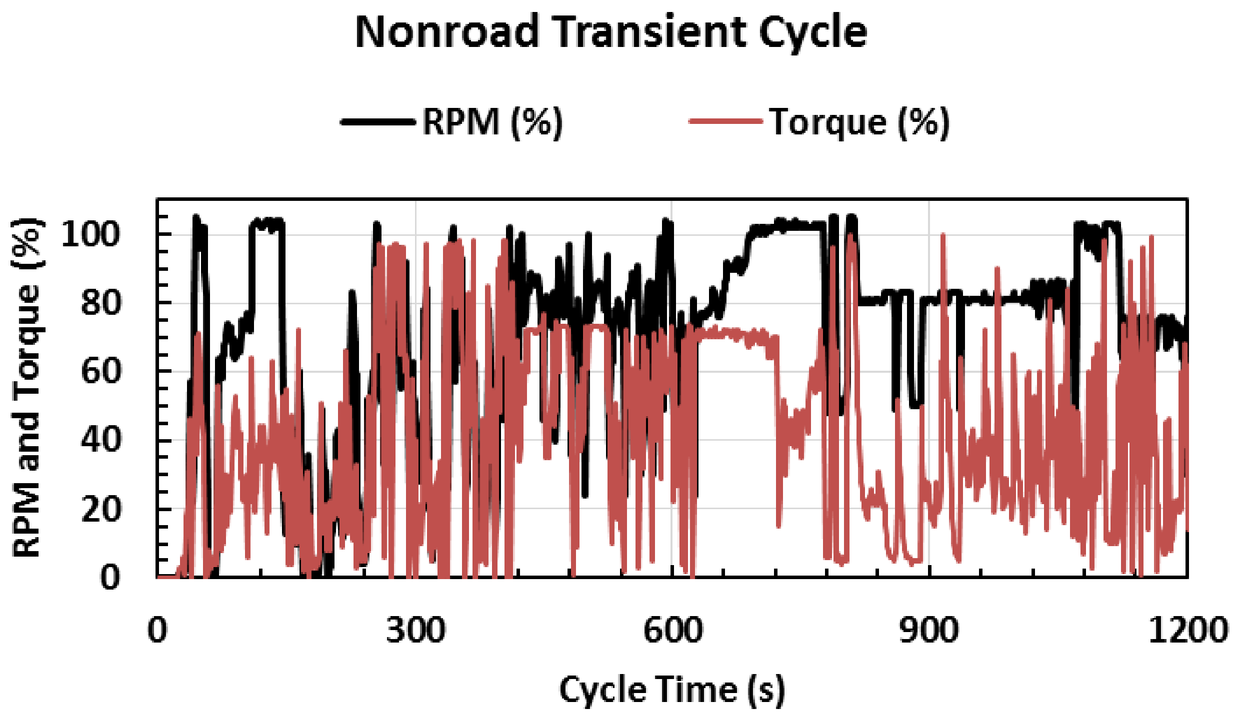


Figure 4-13. Graphical Presentation of the Nonroad Transient Cycle (Target)

Table 4-6. Summary of the Test Sequence for the Ride Mower, Mini-excavator, and Skid Steer Engines

Testing Activity for Ride Mower Engine	Test Number
Day 1	
VERL warm up	
Engine Warmup	
Ramped-Mode C1 testing	1
Soak	
Engine Warmup	
Ramped-Mode C1 testing	2
Soak	
Engine Warmup	
Ramped-Mode C1 testing	3
Soak	
NRTC Prep	
VERL shut down and Data process	
Day 2	
VERL warm up	
Cold start NRTC	4
Soak	
Hot start NRTC	5
VERL shut down and Data process	

Blue is full testing
Yellow is soak
Green Is break
Red is prep/Conditioning
Warm up/ Shutdown

It should be noted that for the SCR configuration, it needed to be verified that the SCR urea injection was functional during the test period. As such, the urea injection were both verified through the NO_x

concentration during the warm-up period before each cycle, as well as the urea level in the urea tank before and after each test.

It should be noted that for this particular DPF configuration, the DPF regenerates on a relatively infrequent basis. As such, no regenerations were observed over the course of testing, and it was determined that the amount of time that would have been needed to prepare the engine such that it would trigger a regeneration during a C1 or NRTC was beyond the scope of the project. Provisions for not making adjustments to measured emissions results for aftertreatment devices that regenerate infrequently are covered under Title 40 Code of Federal Regulations 1039.525.

4.1.3 Emissions Testing

Emissions tests were conducted to evaluate the effectiveness of the aftertreatment in terms of PM and NO_x performance. The emissions tests were conducted in CE-CERT’s Vehicle Emissions Research laboratory (VERL). This facility is CE-CERT’s primary facility for testing of light-duty vehicles, but is also the facility that CE-CERT has utilized in the past for conducting emissions tests of small engines. The VERL was initially equipped with a CVS dilution tunnel with a bag sampling system and a Pierburg AMA-4000 emissions bench. This includes a flame ionization detector (FID) for THC emissions, a chemiluminescence analyzer for NO_x emissions and a non-dispersive infrared (NDIR) analyzer for CO and CO_2. The analyzer bench is capable of providing both modal and integrated bag measurements of dilute tailpipe gas-phase emissions. The VERL was also equipped with a particulate sampling system that is 1065/1066 compliant for measuring PM mass via gravimetric analysis. Towards the later part of the program, beginning with the baseline testing for the skid steer and for all the post-field demonstration testing, the analyzers and CVS sampling system in the VERL was replaced by newer AVL equipment, including a AVL AMA SL™ (SlimLine) Exhaust Measurement System for gas-phase pollutants and a AVL 478 Smart Sampler (SPC) for PM sampling. These systems both sample raw exhaust. For each test, gas-phase and PM emissions were reported in g/kW-hr for the integrated results. In addition, modal files for the gas-phase pollutants can be provided in g/second units. Emissions measurements were evaluated to determine the reduction efficiency of the aftertreatment by comparing the baseline and the degreened aftertreatment testing.

4.1.4 Field Demonstrations and Additional Catalyst Aging

While the initial goal of the testing was to complete 1,000 hours of field demonstration on all of the demonstration units, the 1,000-hour goal was only obtained for the TRU and ride mower applications. The mini-excavator and skid steer applications did not have sufficient use to be able to complete the full 1,000 hours in the field, as the use patterns for these pieces of equipment in the field were much less on a daily basis. Specifically, field demonstrations for the mini-excavator and skid steer accumulated 186 and 233 hours of operation, respectively. Additionally, for the mini-excavator the DPF was found to be damaged during the initial post field demonstration engine dynamometer testing, so post field emission testing data was not available for this DPF.

Given that the mini-excavator and skid steer were not able to achieve the 1,000 hours of accumulation in the field, and that post-field demonstration data was not available for the mini-excavator DPF, it was decided that additional aging be conducted on CE-CERT’s engine dynamometer for those aftertreatment systems in order to achieve a level of deterioration comparable to what would be experienced from the 1,000 hours in the field. It is important to note that for simplicity the aging protocol used consisted primarily of thermal aging and soot accumulation and may not be fully representative of real-world aging, which could be subject to additional deterioration mechanisms such as ash from the engine oil.

In developing the catalyst aging protocols, CE-CERT had discussions/email exchanges with the Manufacturers of Emission Controls Association (MECA) as well as the aftertreatment suppliers for both the skid steer and the mini-excavator. Based on this, a two-temperature mode aging profile was developed, with a lower temperature that facilitated soot accumulation and a higher temperature that simulated regeneration conditions. Field data was downloaded from both the skid steer and mini-excavator to determine the in-field temperature profiles. These data are provided in Figure 4-14 and Figure 4-15, respectively, below for the mini-excavator and skid steer.

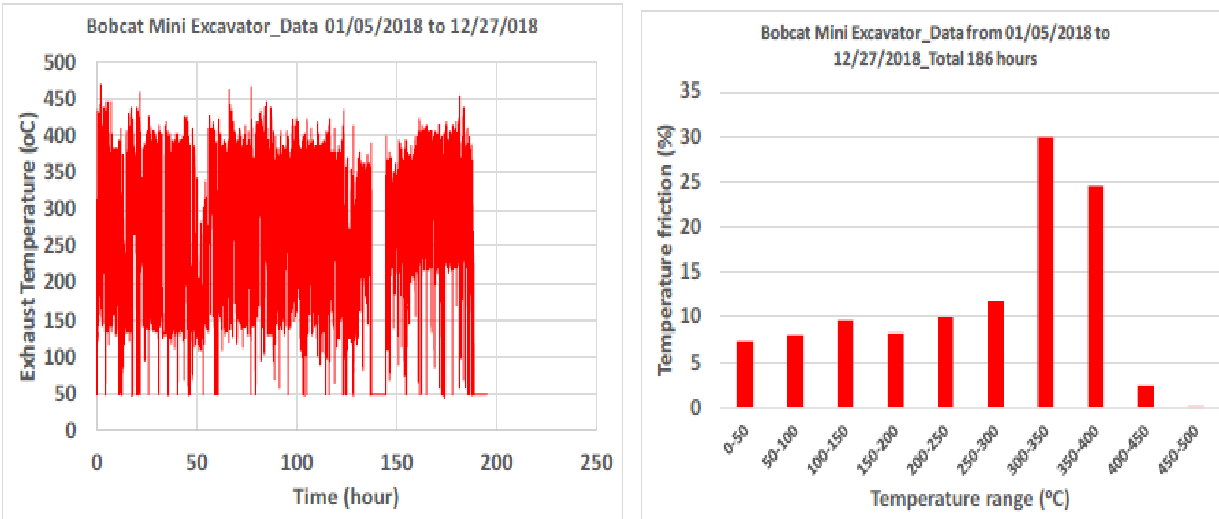


Figure 4-14. Temperature Profiles from mini-excavator field demonstration

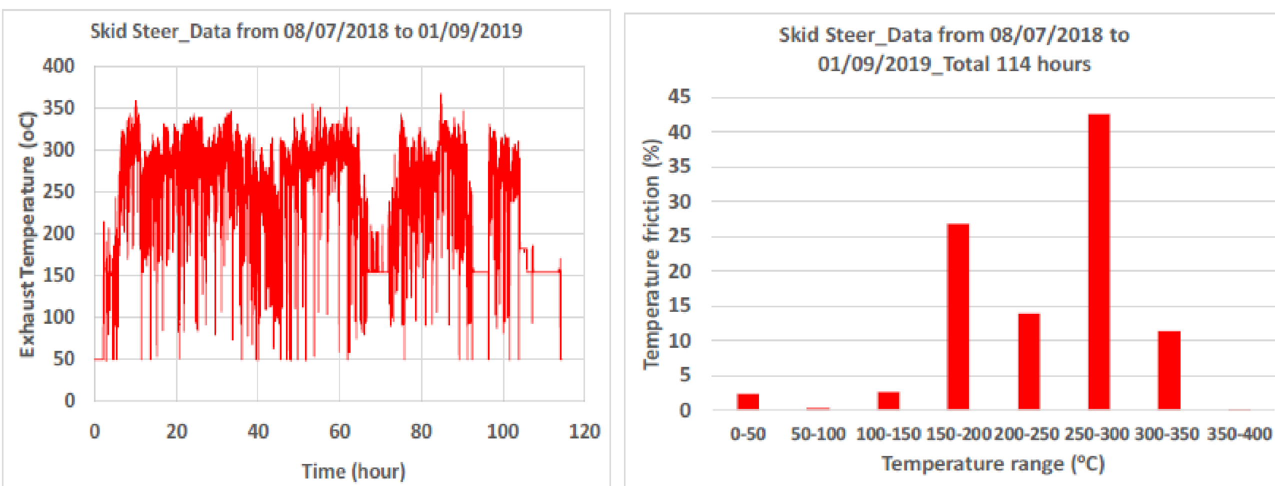
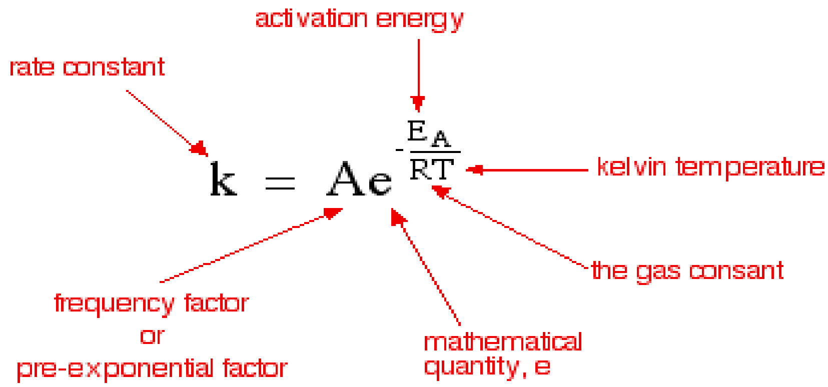


Figure 4-15. Temperature Profiles from skid steer field demonstration

The catalyst aging approach was based on the Diesel Aftertreatment Accelerated Aging Catalyst (DAAAC) methodology developed by Southwest Research Institute (SwRI) (Bartley, 2012). This methodology was developed as part of a consortium to develop aging cycles for heavy-duty diesel emissions control systems. The basis of this method is that the thermal aging of a catalyst is an exponential function of temperature based on the Arrhenius equation, as given below. The full DAAAC protocol also includes provisions to represent chemical aging with enhanced oil consumption procedures that were not included in this program. Arrhenius equation calculations were based on the field demonstration data for both the mini-excavator and skid steer. Based on these equations, it was estimated that 30 hours of operation at 355.5°C would be needed for the skid steer to provide the necessary aging to represent 767 additional hours to provide a full 1,000 hours of aging. For the mini-excavator DPF, a second new DPF system was obtained to evaluate deterioration. The new mini-excavator DPF was aged for 30 hours at 446.7°C to represent the full aging needed to simulate 1,000 hours in the field. The DAAAC temperature calculations results are provided below for the mini-excavator and skid steer in Table 4-7 and Table 4-8, respectively. These tables include the number of hours that need to be represented in each temperature bin for the aging hours to be simulated, and the equivalent number of hours that would be needed at high aging temperature to simulate this number of hours.



$$k = Ae^{-\frac{E_A}{RT}}$$

Table 4-7. DAAAC Temperature Profile Information for the Mini-excavator

Temperature Bins °C	Average Temperature Kelvin	Hours Represented at Temperature	Equivalent Hours at Max. Temperature
<150	348	167.1	1.99E-10
150-199	447.5	82.5	1.34E-05
200-249	497.5	93.0	0.00096
250-299	547.5	117.5	0.036
300-349	597.5	269.7	1.41
350-399	647.5	246.1	14.01
400-449	697.5	23.6	10.42
450-500	748	0.5	1.36
Etc.	**Total time**	1000	
Equivalent time at		719.7	30
Desired aging temperature =		719.7	Kelvin
		446.7	°C

Table 4-8. DAAAC Temperature Profile Information for the Skid Steer

Temperature Bins °C	Average Temperature Kelvin	Hours Represented at Temperature	Equivalent Hours at Max. Temperature
<150	348	33.1	1.65E-09
150-199	447.5	207.6	0.0014
200-249	497.5	85.3	0.04
250-299	547.5	318.6	4.09
300-349	597.5	103.8	22.55
350-400	647.5	0.3	0.63
Etc.	**Total time**	756	
Equivalent time at		628.5	30
Desired aging temperature =		628.5	Kelvin

Temperature Bins °C	**Average Temperature Kelvin**	**Hours Represented at Temperature**	**Equivalent Hours at Max. Temperature**
		355.5	°C

The high-temperature operation was interdispersed with operation at a lower temperature where some soot build-up can occur. The operating conditions for the lower temperature mode were based on real-time PM measurements that were collected during the course of a C1 cycle. Specifically, the lower temperature operation mode was a mode where relatively high PM emissions were observed, while the operating temperature was approximately 300°C. The cycling of the sooting and high-temperature modes was done in intervals of 30 minutes each. This was based on recommendations from Johnson Matthey. This would provide equal operating time at each mode, and will provide sufficient time for some soot build up in between high-temperature operation periods.

It should be noted that while the engine dynamometer aging should adequately represent the thermal aging that would be experienced, other sources of deterioration in the field would include poisoning from elements coming from the fuel, oil, or other sources that would not be experienced under the shorter operating times for the engine dynamometer aging. This could include urea oxidation, or ash, sulfur, phosphorous, zinc, or calcium poisoning. In any case, it is expected that the contribution of the poisoning would be much smaller than that of the thermal aging on deterioration, so it is expected that the engine dynamometer aging would provide reasonable estimates of the magnitude of the deterioration that might be seen in the field.

4.2 Emissions Testing Results

4.2.1 TRU Emissions Testing Results

The regulated gaseous and PM emissions results are shown below in Table 4-9 and Figure 4-16 in g/kw-hr units. The error bars for this and other figures in this section represent the standard deviation of the average. The results in g per test are also provided in Appendix A.

PM emissions are the primary pollutant of interest in terms of emissions reductions for this DPF. For the baseline testing, the PM emissions level was at 0.149 g/kw-hr, which is comparable to the certification value of 0.17 g/kw-hr for this engine. After installing the DPF and degreening it for 25 hours, the PM emissions were reduced to 0.003 g/kw-hr and remained low at 0.002 g/kw-hr after the 1,000-hour testing. Thus, the PM emission reductions with the DPF were >98% for both the degreened and the 1,000-hour test.

The average NO_x emissions were 5.33 g/kw-hr for the baseline testing, 6.05 g/kw-hr for the degreened DPF testing, and 6.62 g/kw-hr for the 1,000-hour testing. This represents a 9.4% to 19.6% increase of NO_x emissions with the addition of the DPF. The increase in NO_x emissions can be attributed to slightly higher NO_x concentrations coupled with lower work for the DPF tests. NO_x emissions on a g/test basis were higher for the tests conducted with the DPF, as opposed to the tests conducted without the DPF. The g/test results are provided in Appendix A. The NO_x g/test results show a general trend of higher average emission rates, but also higher emissions rates specifically for tests #2 and #3, where regeneration was more frequent. As discussed above, regenerations are performed by heating the intake air. The higher temperature for the intake air leads to higher combustion temperatures, which would lead to higher NO_x emissions, and also higher levels of NO_2. Additionally, the engine equipped with the DPF was also not able to achieve the same power levels as the engine without the DPF, as discussed above. As such, the average engine work for the baseline tests was 3.19 kw-hr compared to 3.00 kw-hr for the DPF equipped test, a reduction of 5.8 to 6.2%. So both of these factors contributed to the overall higher NO_x emissions for the DPF tests. The total NO_x increases for the baseline testing of about 9% are consistent with the increases seen by Proventia during their preliminary testing in Finland. The slightly higher NO_x increases for the 1,000-hour testing could be due to other reasons, such as some slight changes in the engine operation between the degreened and 1,000 hour engine tests.

The DPF also provided reductions in THC, NMHC, and CO emissions. The DPF substrate is catalyzed and also includes a DOC component, both of which contribute to the observed THC, NMHC, and CO reductions. The emissions for these pollutants were reduced 85.29 to 90.30% for THC, 87.93 to 90.49% for NMHC, and 99.27 to 99.95% for CO. The CH_4 emissions for these tests were at/below the background levels for the initial testing with the dilute CVS system.

CO_2 emissions showed an increase from 947.1 g/kw-hr for the baseline testing to 1047.5 to 1037.1 g/kw-hr for the degreened DPF baseline and the 1,000-testing, respectively. This represents a 9.5 to 10.6% increase in CO_2 emissions per unit work with the addition of the DPF. This result could be associated with the impact of the back-pressure and the reduction in the work over the cycle, although the highest CO_2 emissions were found for the tests where higher levels of regeneration were found.

Table 4-9. Gaseous and PM results for TRU engine

Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.172	0.174	0.000	0.937	5.526	931.532	0.1486	3.1940
Test 2	0.164	0.168	0.000	0.980	5.559	958.411	0.1416	3.1931
Test 3	0.174	0.178	0.000	0.954	5.520	951.236	0.1574	3.1934
Degreened Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.024	0.024	0.000	0.002	5.799	1030.181	0.0025	2.9951
Test 2	0.017	0.017	0.000	0.000	6.121	1052.406	0.0030	2.9958
Test 3	0.009	0.009	0.000	0.000	6.240	1059.935	0.0028	2.9959
After 1,000 hrs. Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.023	0.023	0.001	-0.014	6.597	1037.676	0.002	3.0063
Test 2	0.026	0.020	0.005	0.021	6.645	1034.092	0.003	3.0127
Test 3	0.027	0.020	0.007	0.015	6.607	1039.442	0.002	3.0063
Ave	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Power (kW-hr)**
Baseline	0.170	0.174	0.000	0.957	5.53	947.1	0.1492	3.1935
Degreened Baseline	0.017	0.017	0.000	0.001	6.05	1047.5	0.0028	2.9956
After 1,000 hrs.	0.025	0.021	0.004	0.007	6.616	1037.1	0.002	3.008
	THC (g/kW-hr)	**NMHC (g/kW-hr)**	**CH4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
% Change Degreened Baseline to Baseline	-90.30%	-90.49%	0.00%	-99.95%	9.37%	10.61%	-98.14%	-6.20%
% Change 1,000 hour to Baseline	-85.29%	-87.93%	-	-99.27%	19.64%	9.50%	-98.66%	-5.81%

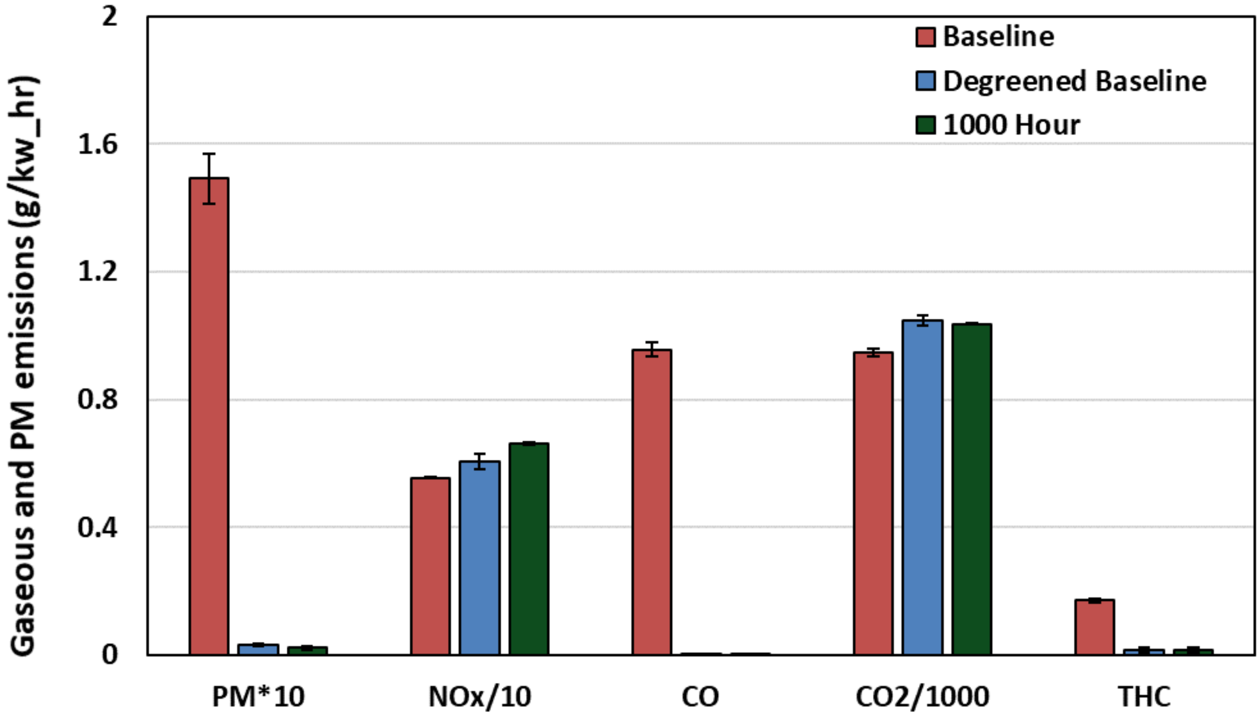


Figure 4-16. Gaseous and PM results for TRU engine

4.2.2 Ride Mower Emissions Testing Results

The regulated gaseous and PM emissions results are shown below in g/kw-hr units in Table 4-10 and Fig 4-17

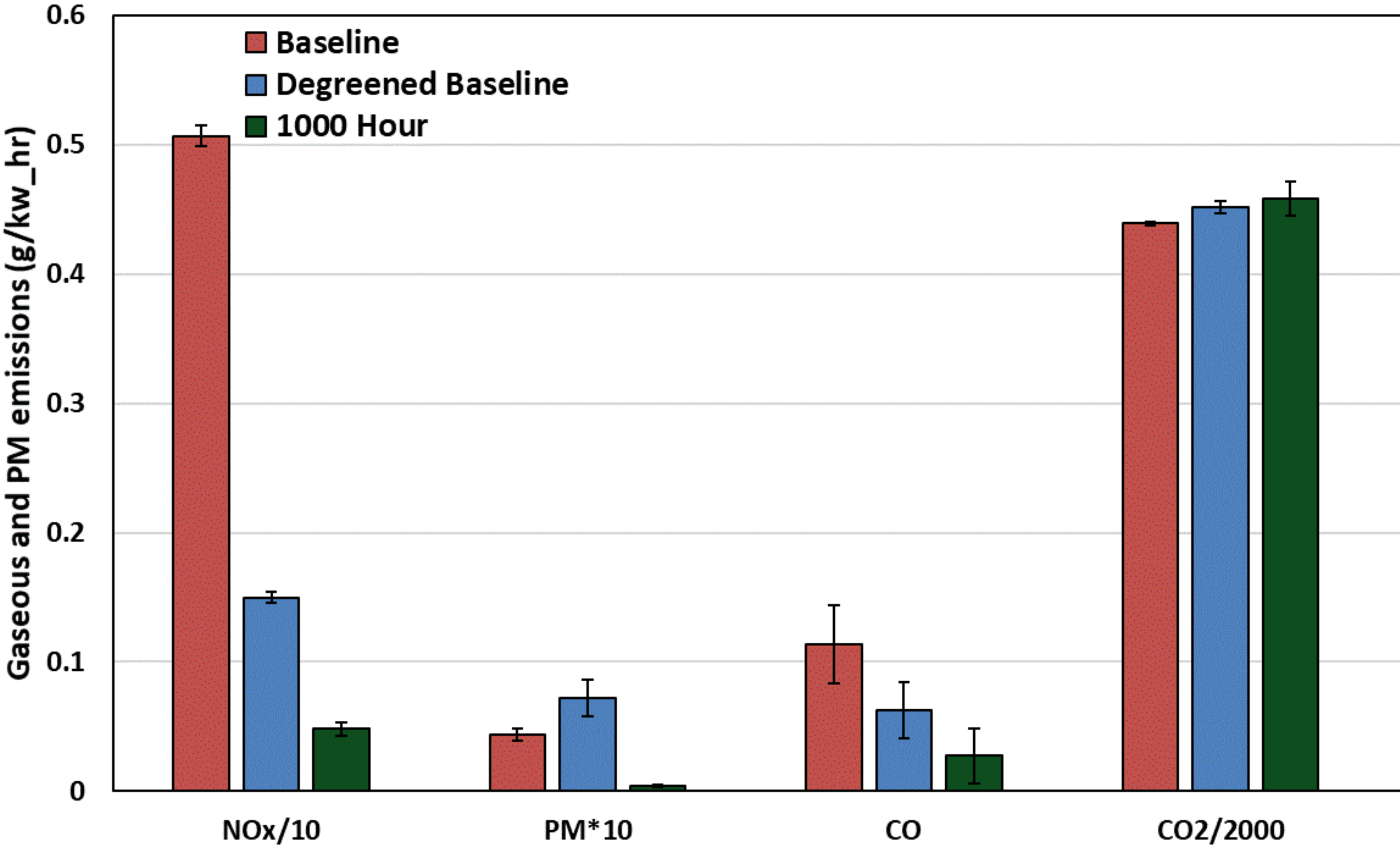


Figure 4-17 for the C1 cycle, and in

Table **4-11** and Figure 4-18 for the NRTC. Note that in the Figure the NO_x and CO_2 emissions were divided by 10 and 2000, while the PM results were multiplied by 10, respectively, to allow all the pollutants to be shown in the same graph. The results in g per test are also provided in Appendix B.

NO_x emissions are the primary pollutant of interest in terms of emissions reductions for this SCR. For the baseline testing, the average NO_x emissions levels were 5.07, 4.445, and 3.928 g/kw-hr, respectively, for the C1, NRTC cold start, and NRTC hot start tests. For the tests with the degreened SCR, the average NO_x emissions were 1.50, 2.337, and 1.689 g/kw-hr, respectively, for the C1, NRTC cold start, and NRTC hot start tests. Thus, the NO_x emission reductions with the SCR were 70.4%, 47.4%, and 57.0%, respectively, for the C1, NRTC cold start, and NRTC hot start tests. For the 1,000 hour tests after the field testing, the average NO_x emissions were 0.48, 3.296, and 1.377 g/kw-hr, respectively, for the C1, NRTC cold start, and NRTC hot start tests. Thus, the NO_x emission reductions with the SCR for the 1,000 tests were 90.5%, 25.8%, and 64.95%, respectively, for the C1, NRTC cold start, and NRTC hot start tests. The relatively high efficiencies of the SCR after the 1,000 field demonstration for the C1 and hot start NRTC suggest that there was not significant deterioration of the SCR catalyst. The lower reductions for the cold start NRTC after the 1,000 hours is likely due to lower SCR temperatures during the initial part cycle for the 1,000 hour test. Real-time NO_x emissions plots for the baseline and SCR-equipped tests are shown in Figure 4-19, Figure 4-20, and Figure 4-21, respectively, for the C1, NRTC cold start, and NRTC hot start tests. These plots show that the lower efficiencies for some of the cold start and hot start NRTC tests are due to lower SCR efficiencies during early portions of the cycles when the SCR temperatures are below the optimal operating temperatures.

The average PM emissions were low for both the C1 and NRTC cycles, since this engine was originally equipped with an OEM DOC and DPF. The PM emissions were consistent with the levels expected for a DPF-equipped engine and were within the certification limits for all test sequences. For the regulated gaseous emissions, THC, NMHC, and CO emissions were also relatively low for the baseline testing, due to the OEM DOC and DPF, but showed some additional reductions for the SCR tests. THC emissions were reduced by 96.5%, 8.1%, and 11.6%, respectively, for the C1, NRTC cold start, and NRTC hot start SCR-equipped tests degreened SCR-equipped tests, and THC emissions were reduced by 21.7%, 11.2%, and increased by 2.7%, respectively, for the C1, NRTC cold start, and NRTC hot start 1,000 hour SCR-equipped tests. NMHC emissions were reduced by 100.0%, 5.5%, and 17.2%, respectively, for the C1, NRTC cold start, and NRTC hot start degreened SCR-equipped tests, and NMHC emissions were reduced by 34.5%, 15.8%, and 8.95%, respectively, for the C1, NRTC cold start, and NRTC hot start 1,000 hour SCR-equipped tests. CO emissions were reduced by 45.0%, 0.6%, and increased by 23.7%, respectively, for the C1, NRTC cold start, and NRTC hot start tests degreened SCR-equipped tests, and CO emissions were reduced by 75.9%, increased by 5.9%, and reduced by 62.0%, respectively, for the C1, NRTC cold start, and NRTC hot start 1,000 hour SCR-equipped tests. The CH_4 emissions for these tests were at/below the background levels for the initial testing with the dilute CVS system.

CO_2 emissions were comparable with and without SCR tests. CO_2 emissions rates for the C1 tests were within 5% for with and without SCR tests. CO_2 emissions rates for the hot start and cold start NRTC tests with and without the SCR were within 10%, and showed lower values for the 1,000 hour test. It should be noted that CO_2 emissions might be expected to increase slightly due to the additional back-pressure from the SCR unit. Given the results, it is expected that the use of this SCR configuration will not have a significant impact on fuel consumption over extended periods of use.

Fig 4-17

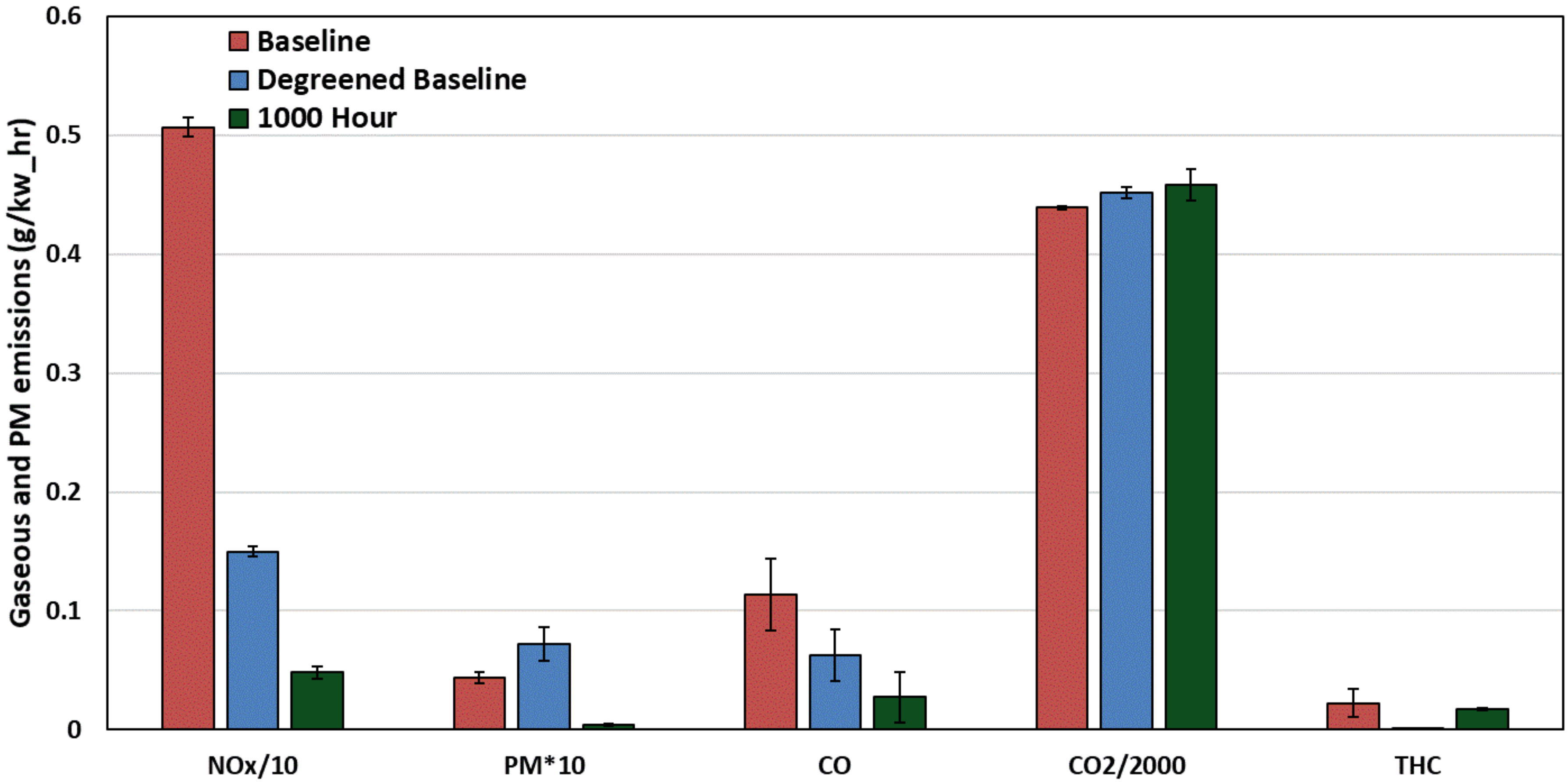


Figure 4-17. Gaseous and PM results for Ride Mower engine C1 cycle

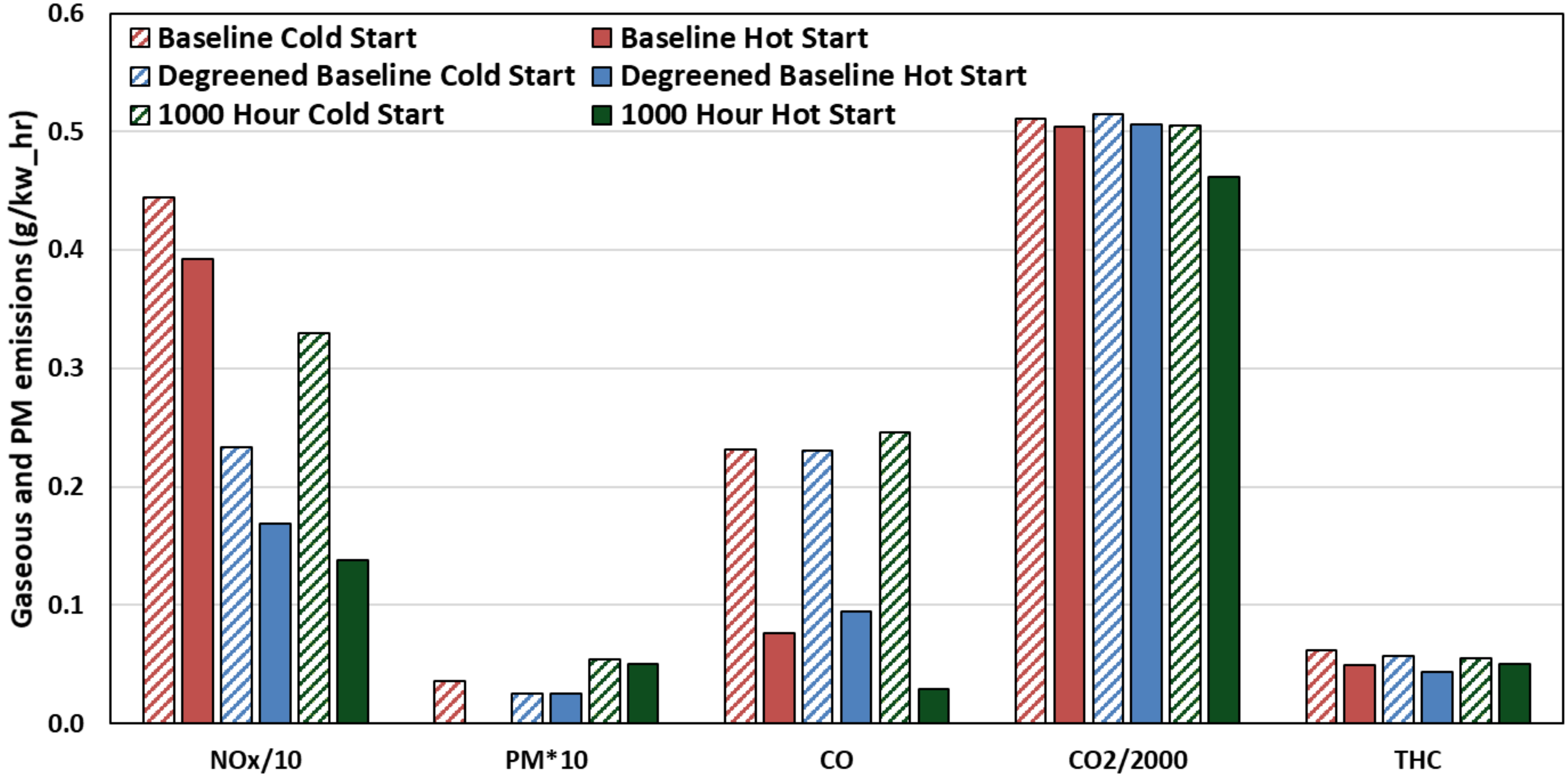


Figure 4-18. Gaseous and PM results for Ride Mower engine NRTC cycle

Table 4-10. Gaseous and PM results for Ride Mower engine C1 cycle. Note that 1,000 hour testing was not completed for this engine.

Baseline	THC (g/kw-hr)	NMHC (g/kw-hr)	CH_4 (g/kw-hr)	CO (g/kw-hr)	NO_x (g/kw-hr)	CO_2 (g/kw-hr)	PM (g/kw-hr)	Work (kw-hr)
Test 1	0.009	0.004	0.000	0.079	5.151	875.281	0.0047	7.0154
Test 2	0.030	0.025	0.000	0.128	4.987	881.142	0.0039	7.0164
Test 3	0.028	0.025	0.000	0.134	5.067	879.744	0.0046	7.0177
Degreened Baseline	**THC (g/kw-hr)**	**NMHC (g/kw-hr)**	**CH_4 (g/kw-hr)**	**CO (g/kw-hr)**	**NO_x (g/kw-hr)**	**CO_2 (g/kw-hr)**	**PM (g/kw-hr)**	**Work (kw-hr)**
Test 1	0.001	0.000	0.000	0.073	1.501	892.744	0.0081	7.0163
Test 2	0.001	0.000	0.000	0.077	1.542	905.756	0.0081	7.0186
Test 3	0.001	0.000	0.000	0.037	1.455	911.091	0.0056	7.0175
1,000 Hour	**THC (g/kw-hr)**	**NMHC (g/kw-hr)**	**CH_4 (g/kw-hr)**	**CO (g/kw-hr)**	**NO_x (g/kw-hr)**	**CO_2 (g/kw-hr)**	**PM (g/kw-hr)**	**Work (kw-hr)**
Test 1	0.0165	0.0109	0.0056	0.0498	0.5316	932.5421	0.0005	6.9827
Test 2	0.0168	0.0121	0.0047	0.0254	0.4241	932.4544	0.0003	7.0094
Test 3	0.0183	0.0124	0.0060	0.0073	0.4899	886.3936	N/A	7.0244
Ave	**THC (g/kw-hr)**	**NMHC (g/kw-hr)**	**CH_4 (g/kw-hr)**	**CO (g/kw-hr)**	**NO_x (g/kw-hr)**	**CO_2 (g/kw-hr)**	**PM (g/kw-hr)**	**Work (kw-hr)**
Baseline	0.022	0.018	0.000	0.114	5.07	878.7	0.0044	7.0165
Degreened Baseline	0.001	0.000	0.000	0.063	1.50	903.2	0.0072	7.0175
1,000 Hour	0.0172	0.012	0.0054	0.027	0.48	917.1	0.0004	7.0055
	THC (g/kw-hr)	**NMHC (g/kw-hr)**	**CH_4 (g/kw-hr)**	**CO (g/kw-hr)**	**NO_x (g/kw-hr)**	**CO_2 (g/kw-hr)**	**PM (g/kw-hr)**	**Work (kw-hr)**
% Change Degreened Baseline to Baseline	-96.45%	-100.00%	0.00%	-45.04%	-70.42%	2.79%	64.44%	0.01%
% Change 1,000 Hour to Baseline	-21.74%	-34.46%	N.A.	-75.88%	-90.50%	4.37%	-90.85%	-0.16%

Table 4-11. Gaseous and PM results for Ride Mower engine NRTC cycle. Note that 1,000 hour testing was not completed for this engine.

Baseline	THC (g/kW_hr)	NMHC (g/kW_hr)	CH_4 (g/kW_hr)	CO (g/kW_hr)	NO_x (g/kW_hr)	CO_2 (g/kW_hr)	PM (g/kW_hr)	Work (kW_hr)
Cold	0.062	0.051	0.000	0.232	4.445	1020.879	0.0036	3.2197
Hot	0.049	0.040	0.000	0.076	3.928	1009.147	-0.0001	3.2187
Degreened Baseline	**THC (g/kW_hr)**	**NMHC (g/kW_hr)**	**CH_4 (g/kW_hr)**	**CO (g/kW_hr)**	**NO_x (g/kW_hr)**	**CO_2 (g/kW_hr)**	**PM (g/kW_hr)**	**Work (kW_hr)**
Cold	0.057	0.049	0.000	0.230	2.337	1030.097	0.0025	3.2180
Hot	0.043	0.033	0.000	0.094	1.689	1011.484	0.0025	3.2209
1,000 Hour	**THC (g/kW_hr)**	**NMHC (g/kW_hr)**	**CH_4 (g/kW_hr)**	**CO (g/kW_hr)**	**NO_x (g/kW_hr)**	**CO_2 (g/kW_hr)**	**PM (g/kW_hr)**	**Work (kW_hr)**
Cold	0.055	0.043	0.012	0.246	3.296	1009.366	0.0054	3.2449
Hot	0.050	0.036	0.014	0.029	1.377	923.408	0.0050	3.2479
Cold	**THC (g/kW_hr)**	**NMHC (g/kW_hr)**	**CH_4 (g/kW_hr)**	**CO (g/kW_hr)**	**NO_x (g/kW_hr)**	**CO_2 (g/kW_hr)**	**PM (g/kW_hr)**	**Work (kW_hr)**
% Change Degreened Baseline to Baseline	-8.09%	-5.48%	0.00%	-0.60%	-47.43%	0.90%	-30.79%	-0.05%
% Change 1,000 Hour to Baseline	-11.16%	-15.77%	N.A.	5.89%	-25.84%	-1.13%	51.42%	0.78%
Hot	**THC (g/kW_hr)**	**NMHC (g/kW_hr)**	**CH_4 (g/kW_hr)**	**CO (g/kW_hr)**	**NO_x (g/kW_hr)**	**CO_2 (g/kW_hr)**	**PM (g/kW_hr)**	**Work (kW_hr)**
% Change Degreened Baseline to Baseline	-11.56%	-17.18%	0.00%	23.73%	-57.01%	0.23%	N.A.	0.07%
% Change 1,000 Hour to Baseline	2.73%	-8.95%	N.A.	-62.01%	-64.95%	-8.50%	N.A.	0.91%

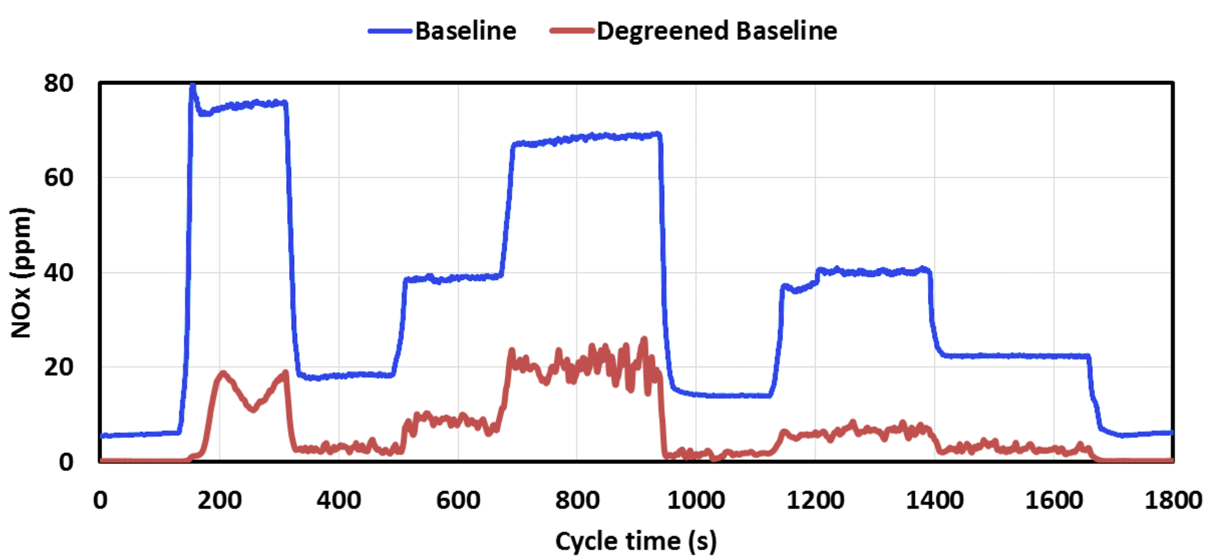


Figure 4-19. Real time NO_x result for Ride Mower engine C1 cycle

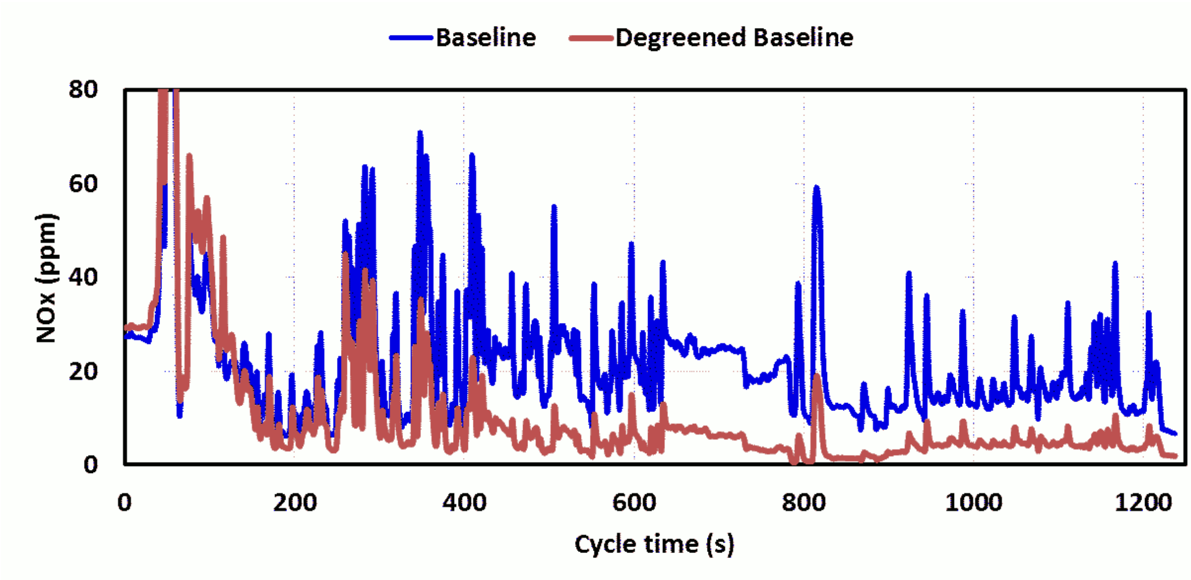


Figure 4-20. Real-time NO_x result for Ride Mower engine NRTC cycle cold start

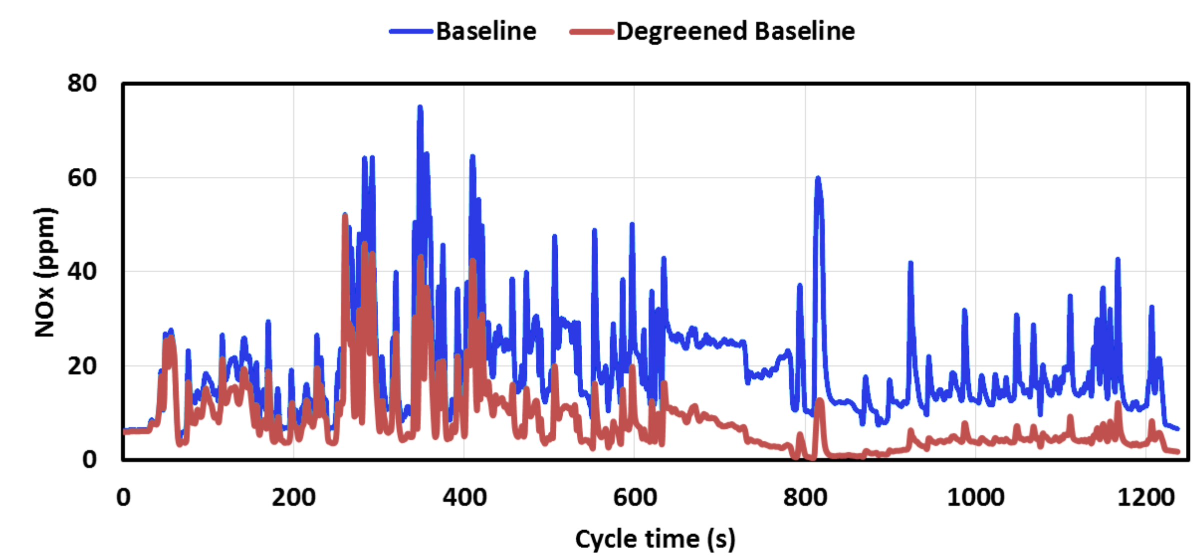


Figure 4-21. Real-time NO_x result for Ride Mower engine NRTC cycle hot start

4.2.3 Mini-Excavator Emissions Testing Results

The regulated gaseous and PM emissions results are shown below in g/kw-hr units in Table 4-12 and and

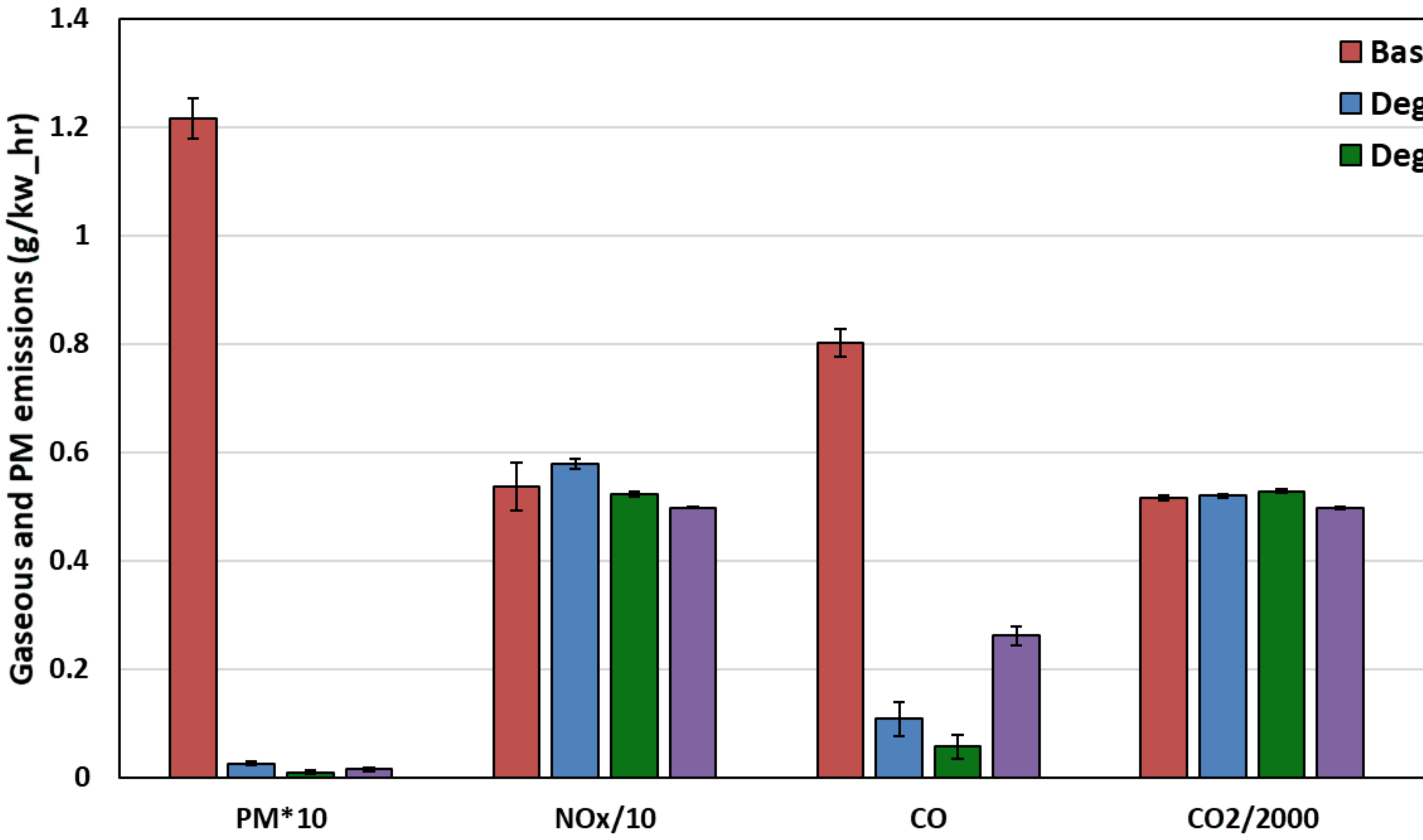


Figure **4-22** for the C1 cycle, and in Table 4-13 and

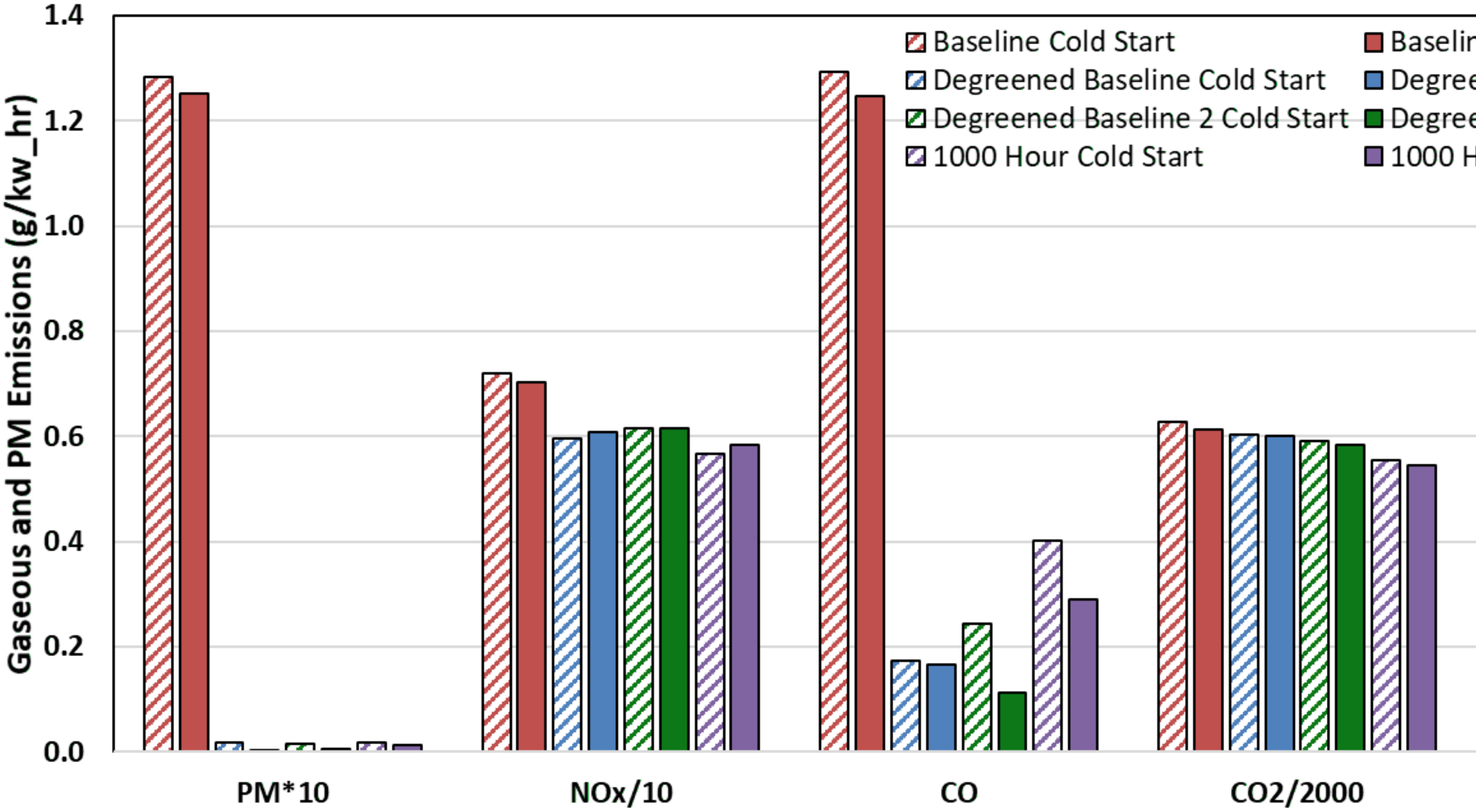


Figure 4-23 for the NRTC. Since the DPF was found to be damaged during the engine testing on the DPF that was returned from the field demonstration, a second DPF was degreened and then aged on the engine dynamometer for the equivalent of 1,000 hours using a temperature profile designed to provide aging that would be equivalent to 1,000 hours of used in the field. As such, data are presented to two different degreened DPFs. In the Figure, the PM results were multiplied by 10, while the NO_x and CO_2 emissions were divided by 10 and 2000, respectively, to allow all the pollutants to be shown in the same graph. The results in g per test are also provided in Appendix C.

PM emissions are the primary pollutant of interest in terms of emissions reductions for this DPF. For the baseline testing, the average PM emissions levels were 0.122, 0.128, and 0.125 g/kw-hr, respectively, for the C1, NRTC cold start, and NRTC hot start tests. The PM emissions for all of the tests conducted with the DPFs, including the degreened #1 and #2 baselines and the 1,000-hour tests, were all very low, and ranged from 0.000 to 0.003 g/kw-hr. Compared to the baseline uncontrolled emissions, this represented PM emissions reductions ranging from 97.9 to 99.7% under all testing conditions.

The DPF also provided reductions in THC, NMHC, and CO emissions. The DPF substrate is catalyzed and also include a DOC component, both of which contribute to the observed THC, NMHC, and CO reductions. For THC, the emissions were reduced by 97.0%, 86.8%, and 80.1%, respectively, for the C1, NRTC cold start, and NRTC hot start tests for the first degreened DPF. Compared to the initial baseline, the second DPF showed lower THC reductions ranging from 70 to 72% for the degreened testing and from 48 to 52% for the 1,000-hour testing. For CO, the emissions were reduced from 86.5% to 86.8% for the first degreened DPF and from 90 to 94% for the second degreened DPF. The CO emissions were still significantly reduced for the second DPF after the 1,000 hours of aging, with reductions ranging from 67 to 77%. The less significant reductions seen for the second DPF for THC and the 1,000-hour aging test for CO could be indicative of some deterioration or inconsistency in the control of these pollutants, but it could also be due to some minor differences in engine operation that may have occurred between the different test periods. The CH_4 emissions for these tests were at/below the background levels for the initial testing with the dilute CVS system.

The average NO_x emissions generally showed reductions relative to the baseline tests, with the exception of the C1 cycle for the first degreened DPF. These reductions ranged from 3 to 21%. Again, some of the changes in emissions in comparing the different tests could be due to subtle differences in the engine operation that may have occurred between the different test periods.

CO_2 emissions were comparable with and without DPF tests. CO_2 emissions rates for all the test DPF-related sequences were within 5% of those for the baseline test, with the exception of the cold start and hot start NRTC for the 1,000-hour aging test on the second DPF, which were 11-12% lower than the baseline. Overall, the results do not seem to show a significant change in fuel use between the DPF and non-DPF configurations, although additional testing would be needed to confirm this.

Table 4-12. Gaseous and PM results for mini-excavator engine C1 cycle

Baseline	THC (g/kW-hr)	NMHC (g/kW-hr)	CH_4 (g/kW-hr)	CO (g/kW-hr)	NO_x (g/kW-hr)	CO_2 (g/kW-hr)	PM (g/kW-hr)	Work (kW-hr)
Test 1	0.212	0.212	0.000	0.785	4.917	1020.588	0.1180	4.4762
Test 2	0.220	0.216	0.000	0.786	5.386	1031.011	0.1254	4.4747
Test 3	0.222	0.213	0.000	0.831	5.808	1041.187	0.1210	4.4746
Degreened Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.009	0.009	0.000	0.071	5.684	1032.482	0.0023	4.4744
Test 2	0.006	0.004	0.000	0.126	5.865	1042.770	0.0023	4.4746
Test 3	0.005	0.003	0.000	0.126	5.823	1040.763	0.0030	4.4775
Degreened Baseline #2	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.060	0.044	0.017	0.033	5.213	1061.191	0.0013	4.423
Test 2	0.059	0.046	0.013	0.062	5.168	1048.263	0.0008	4.428
Test 3	0.063	0.052	0.011	0.076	5.264	1055.316	0.0007	4.423
1,000 Hour	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.144	0.115	0.030	0.243	4.957	991.127	0.0019	4.4506
Test 2	0.101	0.086	0.015	0.264	4.996	994.590	0.0015	4.4380
Test 3	0.092	0.079	0.013	0.277	4.987	996.269	0.0012	4.4341
Ave	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Baseline	0.218	0.214	0.000	0.801	5.37	1030.9	0.1215	4.4752
Degreened Baseline	0.007	0.005	0.000	0.108	5.79	1038.7	0.0026	4.4755
Degreened Baseline #2	0.061	0.047	0.013	0.057	5.215	1054.923	0.001	4.425
1,000 Hour	0.113	0.093	0.019	0.261	4.980	993.996	0.002	4.441
	THC (g/kW-hr)	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
% Change Degreened Baseline to Baseline	-97.00%	-97.61%	0.00%	-86.56%	7.83%	0.75%	-97.89%	0.01%
% Change Degreened Baseline #2 to Baseline	-72.13%	-77.84%	-	-92.93%	-2.89%	2.33%	-99.22%	-1.13%
% Change 1,000 Hour to Baseline	-48.31%	-56.36%	-	-67.38%	-7.27%	-3.58%	-98.74%	-0.77%

Table 4-13. Gaseous and PM results for mini-excavator engine NRTC cycle

Baseline	THC (g/kW-hr)	NMHC (g/kW-hr)	CH_4 (g/kW-hr)	CO (g/kW-hr)	NO_x (g/kW-hr)	CO_2 (g/kW-hr)	PM (g/kW-hr)	Work (kW-hr)
Cold	0.309	0.306	0.000	1.294	7.204	1254.274	0.1283	2.1164
Hot	0.321	0.319	0.000	1.247	7.016	1223.393	0.1251	2.1143
Degreened Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Cold	0.041	0.045	0.000	0.174	5.956	1206.684	0.0017	2.2321
Hot	0.064	0.066	0.000	0.165	6.081	1202.031	0.0004	2.2306
Degreened Baseline 2	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Cold	0.093	0.090	0.003	0.244	6.156	1180.987	0.001	2.226
Hot	0.090	0.084	0.007	0.113	6.162	1168.202	0.001	2.208
1,000 Hour	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Cold	0.158	0.152	0.006	0.400	5.665	1107.230	0.002	2.2181
Hot	0.154	0.149	0.005	0.290	5.837	1088.440	0.001	2.2056
Cold	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
% Change Degreened Baseline to Baseline	-86.78%	-85.40%	0.00%	-86.53%	-17.31%	-3.79%	-98.67%	-6.23%
% Change Degreened Baseline #2 to Baseline	-69.84%	-70.60%	0.00%	-81.15%	-14.54%	-5.84%	-98.85%	5.18%
% Change 1,000 Hour to Baseline	-49.00%	-50.31%	0.00%	-69.06%	-21.36%	-11.72%	-98.59%	4.80%
Hot	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
% Change Degreened Baseline to Baseline	-80.09%	-79.26%	0.00%	-86.77%	-13.33%	-1.75%	-99.69%	-6.18%
% Change Degreened Baseline #2 to Baseline	-71.91%	-73.80%	0.00%	-90.92%	-12.17%	-4.51%	-99.48%	4.45%
% Change 1,000 Hour to Baseline	-52.06%	-53.14%	0.00%	-76.77%	-16.80%	-11.03%	-99.06%	4.32%

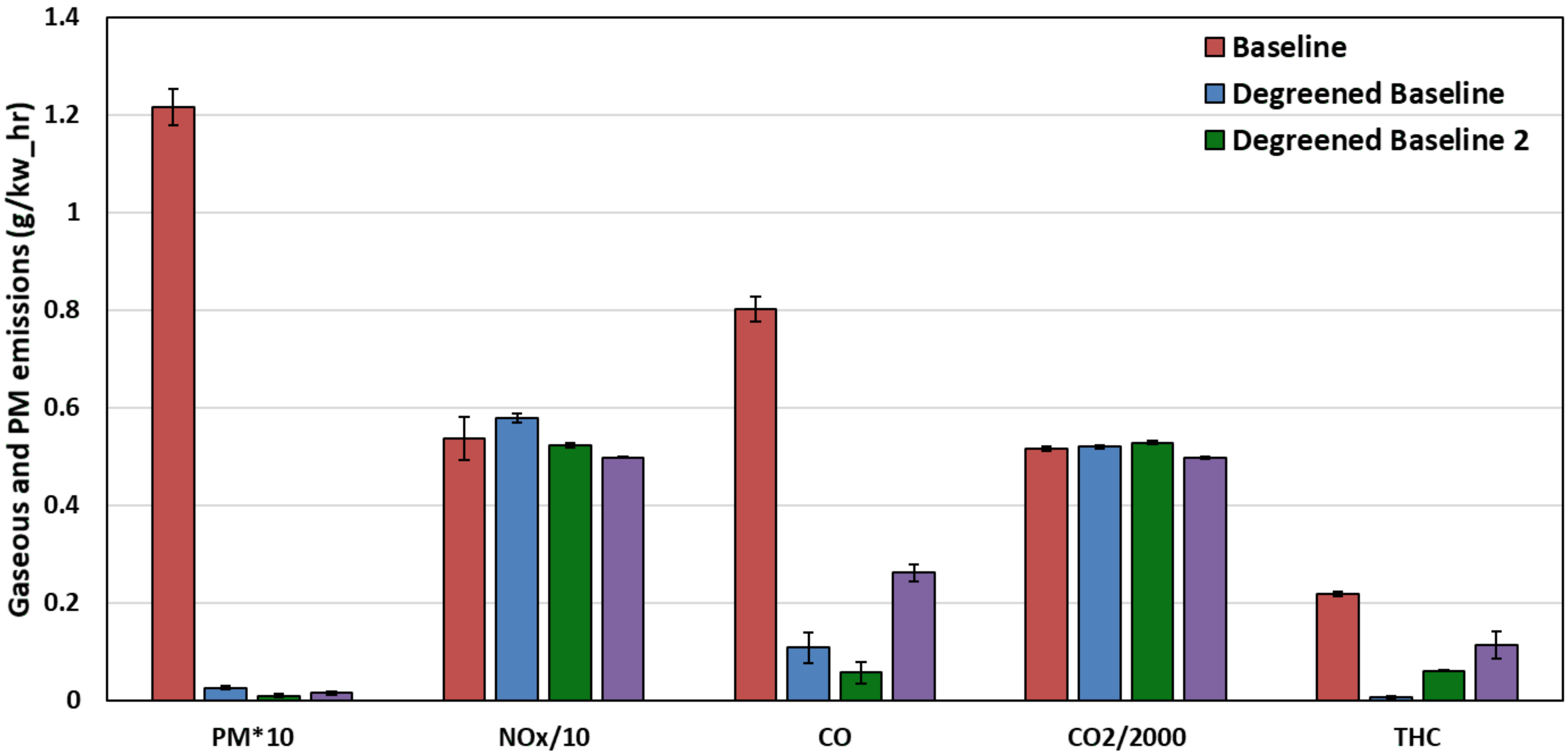


Figure 4-22. Gaseous and PM results for mini-excavator engine C1 cycle

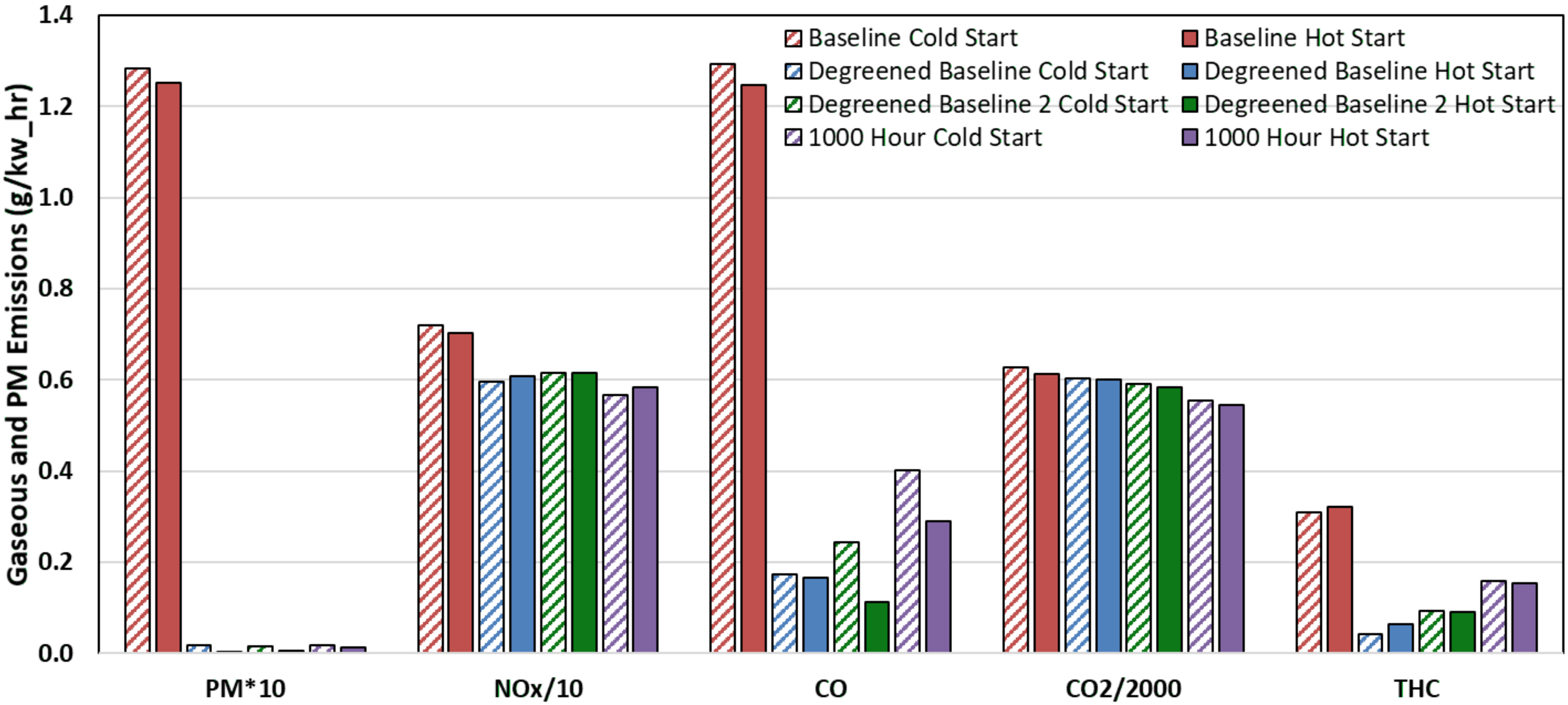


Figure 4-23. Gaseous and PM results for mini-excavator engine NRTC cycle

4.2.4 Skid Steer Emissions Testing Results

The regulated gaseous and PM emissions results are shown below in g/kw-hr units in Table 4-14 and

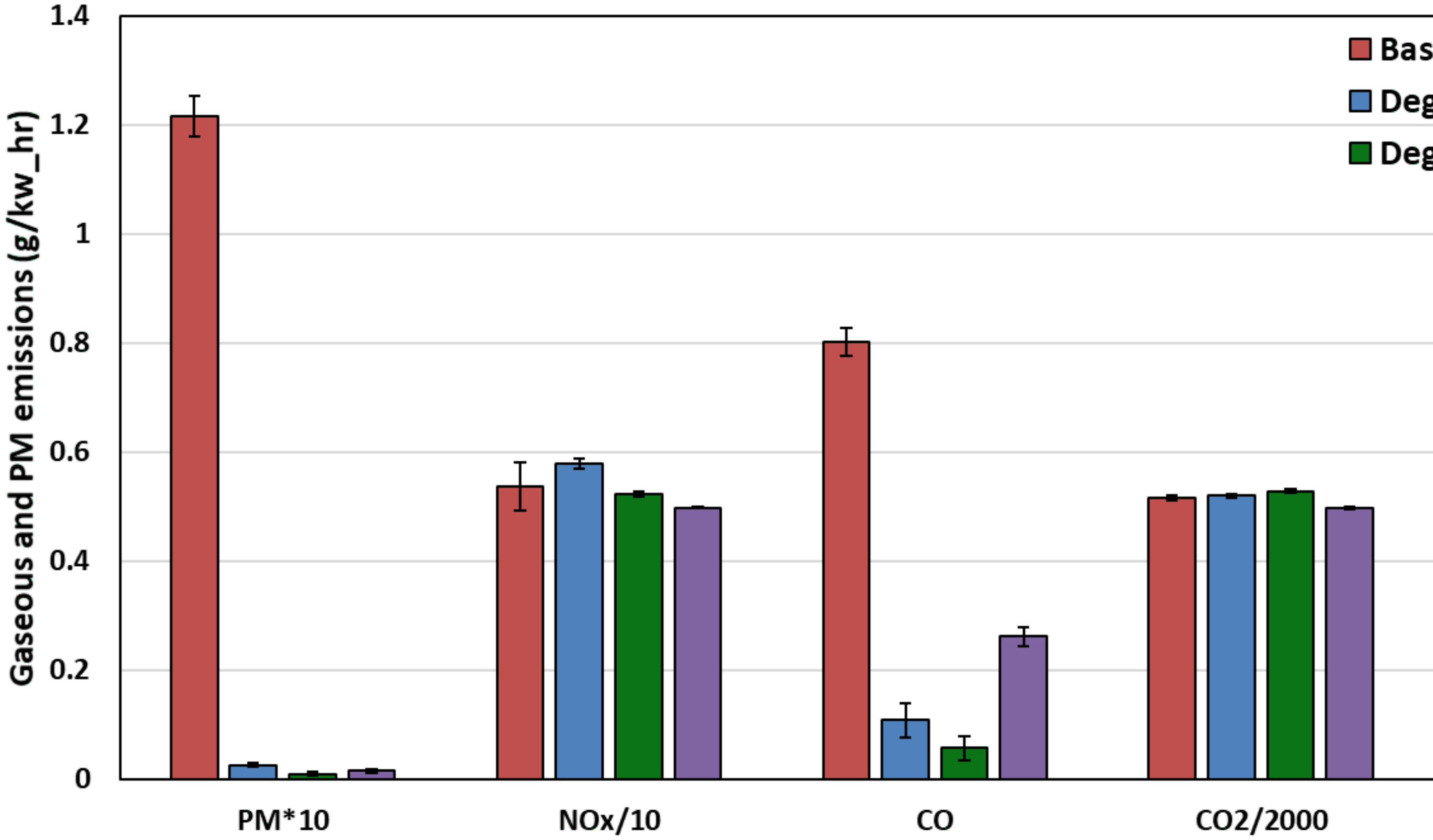


Figure **4-22** for the C1 cycle, and in Table 4-15 and

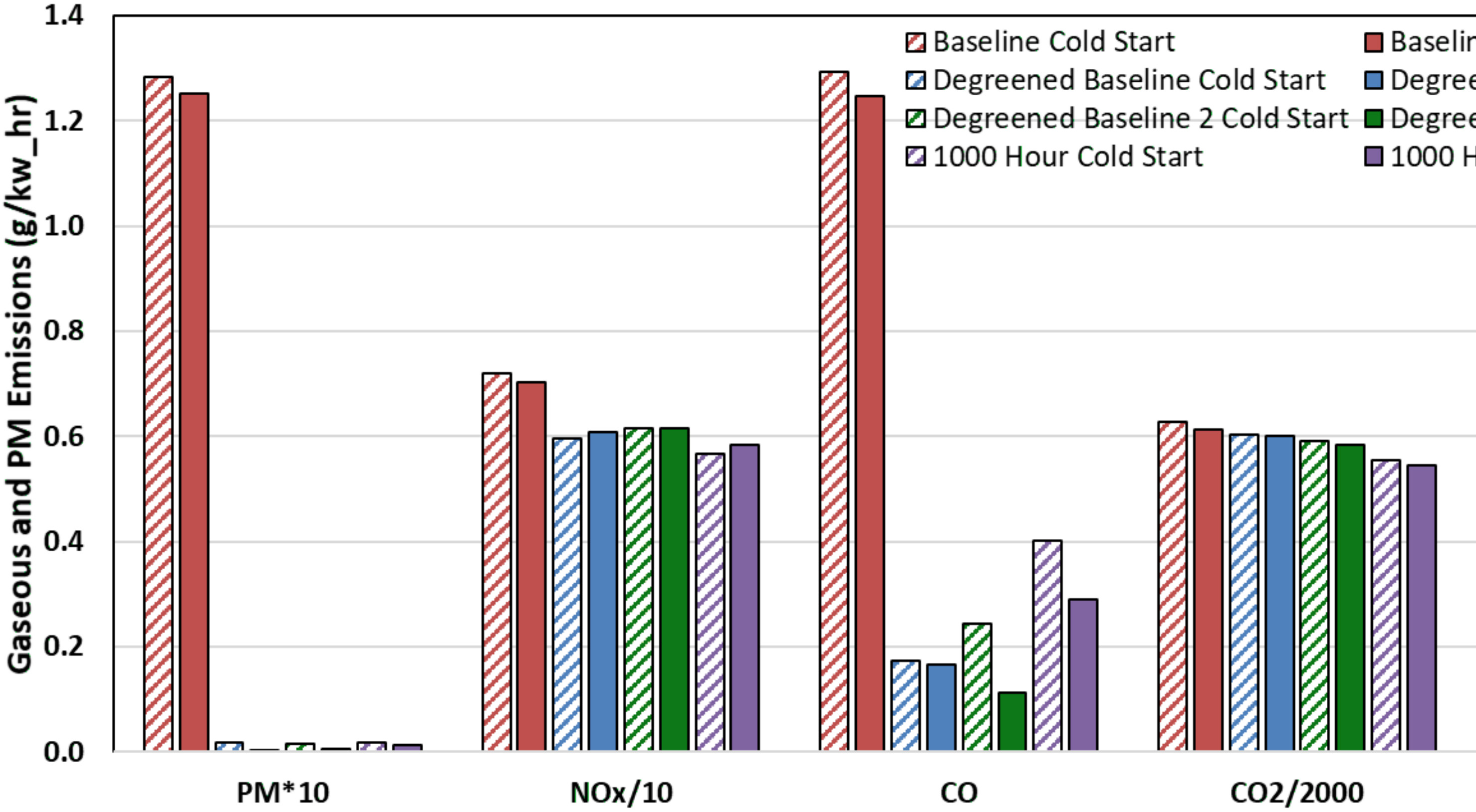


Figure 4-23 for the NRTC. Note that in the Figures the PM results were multiplied by 10, while the NO_x and CO_2 emissions were divided by 10 and 2000, respectively, to allow all the pollutants to be shown in the same graph. The results in g per test are also provided in Appendix D.

NO_x is the primary pollutant of interest in terms of emissions reductions for this SCRT system. For the baseline testing, the average NO_x emissions levels ranged from 3.923 to 4.058 g/kw-hr for the different tests. The tests on the SCRT-equipped engine showed significant NO_x reductions over the C1, for the degreened baseline, post field demonstration, and 1,000-hour aging tests, ranging from 78 to 88%, with no indication of deterioration between the degreened baseline and 1,000-hour aging test.

The reductions for the hot start and cold start NRTCs were lower, ranging from 52 to 59%. To better understand this trend, real-time NO_x emissions plots for the baseline and SCRT-equipped tests are shown in Figure 4-23, Figure 4-24, and Figure 4-25, respectively, for the C1, NRTC cold start, and NRTC hot start tests. The real-time plots show that the initial portions of the test do not show strong NO_x reductions for the SCRT. This is due to the SCRT not reaching the dosing temperature threshold of 190 °C. The period where the SCRT does not reach its dosing temperature is the shortest for the C1 cycle, since this cycle begins as a hot running cycle, where the engine is warmed up prior to starting the cycle. The C1 cycle is also longer in duration compared to the NRTC, so a smaller fraction of the total cycle is spent in a mode where the dosing temperature is not reached. The NRTC test shows a low NO_x conversion efficiency for almost the full first half of the test because the SCR temperatures did not reach the dosing temperature threshold. As shown in Figure 4-24 and Figure 4-25, the urea dosing starts ~10 minutes into the test run, and hence the overall NO_x conversion efficiency comes out to be lower. If the engine is calibrated such that the engine-out exhaust temperatures are higher during transients, the SCRT can have a much better conversion efficiency. Also, the dosing control strategy for the SCRT system was developed using only feed-forward control for urea dosing, since there was not sufficient time to do a full calibration that included the use of a storage control strategy. Using a storage control strategy helps the catalyst to reduce the NO_x before the SCR reaches the dosing temperature threshold, as it stores the ammonia on the catalyst based on absorption and adsorption phenomenon. Having the storage controls would help considerably during transients where the temperatures rise slowly, in that they would still provide for a good NO_x conversion efficiency.

The average PM emissions for the SCRT equipped engine were all very low, ranging from 0.000 to 0.005 g/kw-hr. These levels are comparable to the levels found for the other DPF devices for the TRU and mini-excavator engines. Compared to the baseline PM emissions, this represented reductions ranging from 81 to 98%. It should be noted that the skid steer engine in the baseline configuration was certified to a PM emissions level approximately an order of magnitude lower than those for the TRU and mini-excavator engines, and the skid steer was equipped with a DOC as well as having more advanced engine controls. As such, the reductions are not fully representative of the DPF PM reduction efficiency for an uncontrolled engine, which would be higher.

Similarly, the THC, NMHC, and CO emissions for the baseline testing were considerably lower than those for the other less controlled engines that were not equipped with a DOC in their original configurations. CO emissions still showed relatively consistent reductions ranging from 29 to 70% for the cold start and hot start NRTCs. For the C1 cycle, CO emissions were near the lower detection limits for all of the tests conducted both in the baseline and DPF-equipped configurations, so there were no significant reductions found under these operating conditions. THC and NMHC emissions did show reductions in emissions for the degreened tests, and emissions comparable to the baseline for the 1,000-hour aging test. THC and NMHC emissions actually showed higher emissions for the post field demonstration tests. This could be due to an operational issue with the engine during that test, as these results were not found for the later 1,000-hour aging test. Overall, the results suggest that an SCRT shows the potential to provide additional reductions beyond those obtained with a DOC only, which could be optimized as part of the development process.

Table 4-14. Gaseous and PM results for skid steer C1 cycle

Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.023	0.017	0.006	0.003	4.043	912.396	0.019	9.5536
Test 2	0.023	0.020	0.003	-0.014	3.807	913.572	0.021	9.5578
Test 3	0.022	0.021	0.002	-0.011	3.920	912.462	0.020	9.5564
Degreened Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.000	-0.003	0.003	-0.014	0.777	848.968	0.0004	9.3615
Test 2	-0.002	-0.003	0.002	0.019	0.891	848.342	0.0003	9.3632
Test 3	-0.002	-0.003	0.001	0.025	0.896	848.432	0.0004	9.3630
Post Field Demo	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.495	0.495	0.000	-0.029	0.605	843.507	0.0012	9.3609
Test 2	0.133	0.134	-0.001	-0.040	0.387	849.653	0.0014	9.3595
Test 3	0.097	0.097	-0.001	-0.036	0.450	850.557	0.0014	9.3584
1,000 Hour	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Test 1	0.031	0.033	-0.003	-0.038	0.553	857.396	0.0022	9.3616
Test 2	0.025	0.029	-0.003	-0.035	0.578	832.690	0.0013	9.3613
Test 3	0.022	0.026	-0.003	-0.031	0.595	860.492	0.0012	9.3618
Ave	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Baseline	0.023	0.019	0.004	-0.007	3.92	912.8	0.0199	9.5559
Degreened Baseline	-0.001	-0.003	0.002	0.010	0.85	848.6	0.0004	9.3626

Post Field Demo	0.241	0.242	-0.001	-0.035	0.481	847.906	0.001	9.360
1,000 Hour	0.026	0.029	-0.003	-0.035	0.575	850.193	0.002	9.362
	THC (g/kW-hr)	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
% Change Degreened Baseline to Baseline	-105.17%	-117.05%	0.00%	-230.34%	-78.21%	-7.04%	-97.99%	-2.02%
% Change Post Field Demo to Baseline	952.94%	1162.53%	-115.70%	369.78%	-87.75%	-7.11%	-93.35%	-2.05%
% Change 1,000 Hour to Baseline	13.62%	52.47%	-184.47%	368.76%	-85.33%	-6.86%	-92.11%	-2.03%

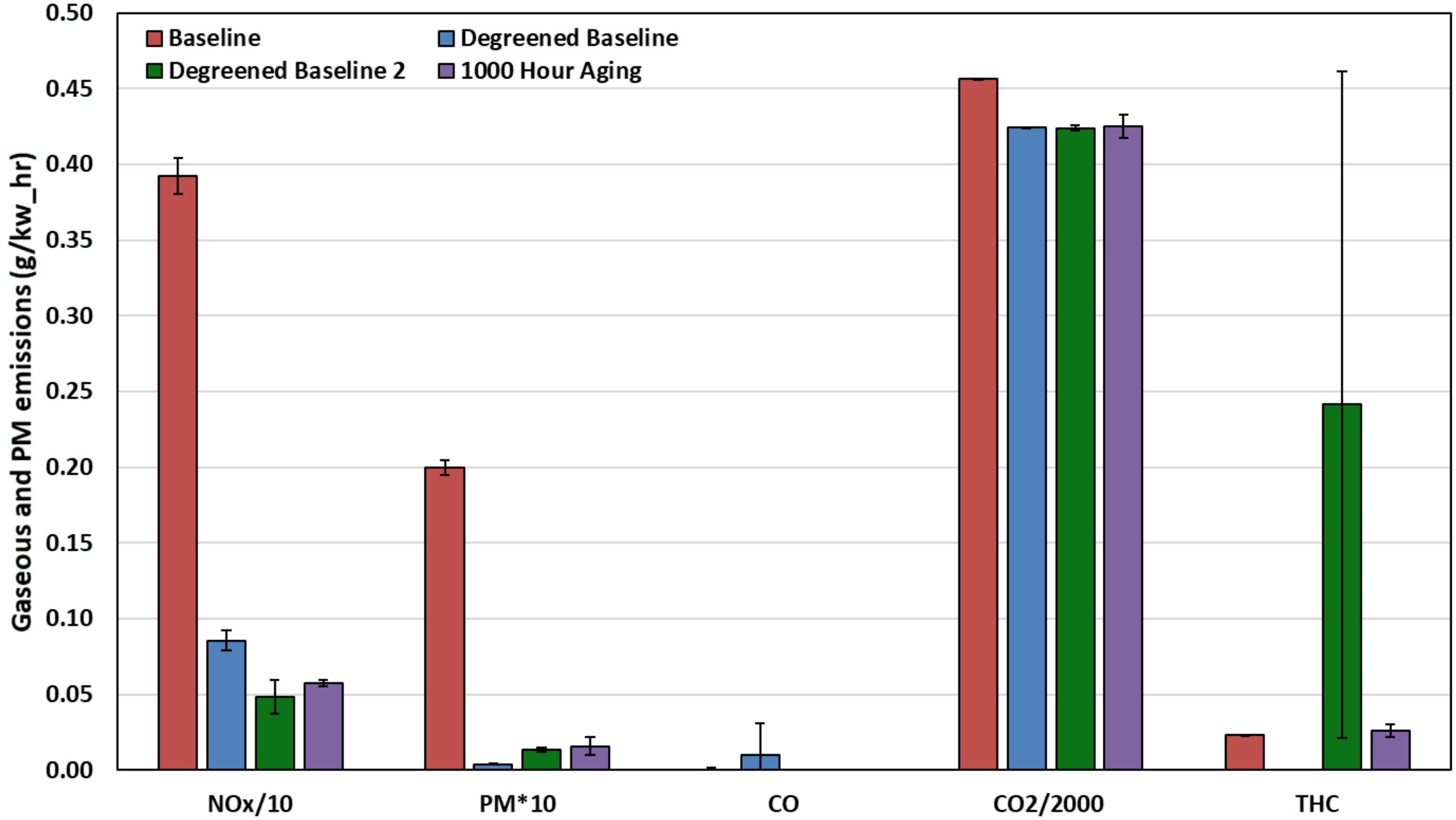


Figure 4-24. Gaseous and PM results for skid steer engine C1 cycle

CO_2 emissions on a g/kW-hr basis were slightly lower for the tests with the SCRT compared to those without the SCRT, ranging from about 7 to 11% lower. This could be attributed in part to the slightly lower work for the DPF equipped tests compared with the baseline tests. It should be noted that CO_2 emissions might be expected to increase slightly due to the additional back-pressure from the SCRT unit. Given the results, it is expected that the use of this SCRT configuration will not have a significant impact on fuel consumption over extended periods of use.

Table 4-15. Gaseous and PM results for skid steer engine NRTC cycle

Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Cold	0.141	0.124	0.018	2.694	4.034	1063.449	0.0291	4.3602
Hot	0.085	0.072	0.013	0.844	4.058	1042.203	0.0264	4.3618
Degreened Baseline	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Cold	0.145	0.132	0.013	1.359	1.865	941.966	0.0014	4.2949
Hot	0.043	0.033	0.010	0.323	1.682	921.818	0.0006	4.2953
Post Field Demo	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Cold	0.503	0.490	0.013	1.811	1.944	957.213	0.0053	4.3027
Hot	0.680	0.672	0.008	0.256	1.647	930.524	0.0029	4.3080
1,000 Hour	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
Cold	0.102	0.095	0.007	2.131	1.883	969.509	0.0016	4.3040
Hot	0.097	0.092	0.004	0.599	1.921	956.527	0.0033	4.3030
Cold	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
% Change Degreened Baseline to Baseline	2.53%	7.00%	0.00%	-49.56%	-53.77%	-11.42%	-95.33%	-1.50%
% Change Post Field Demo to Baseline	255.58%	296.32%	-25.20%	-32.76%	-51.81%	-9.99%	-81.82%	-1.32%
% Change 1,000 Hour to Baseline	701.12%	831.91%	-36.04%	-69.72%	-59.42%	-10.72%	-89.12%	-1.23%
Hot	**THC (g/kW-hr)**	**NMHC (g/kW-hr)**	**CH_4 (g/kW-hr)**	**CO (g/kW-hr)**	**NO_x (g/kW-hr)**	**CO_2 (g/kW-hr)**	**PM (g/kW-hr)**	**Work (kW-hr)**
% Change Degreened Baseline to Baseline	-49.31%	-54.82%	0.00%	-61.73%	-58.54%	-11.55%	-97.69%	-1.52%
% Change Post Field Demo to Baseline	701.12%	831.91%	-36.04%	-69.72%	-59.42%	-10.72%	-89.12%	-1.23%
% Change 1,000 Hour to Baseline	13.99%	28.22%	-66.22%	-28.98%	-52.66%	-8.22%	-87.50%	-1.35%

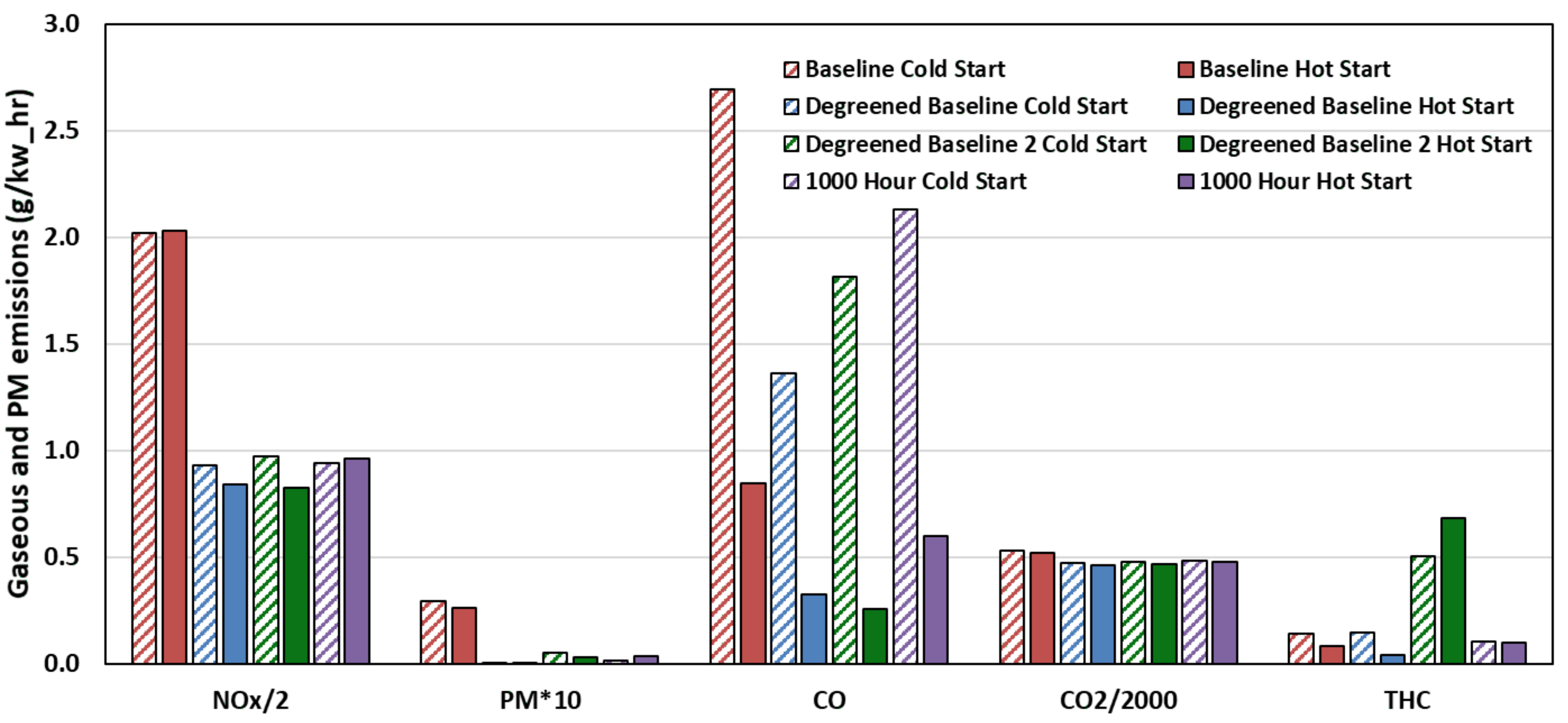


Figure 4-25. Gaseous and PM results for skid steer engine NRTC cycle

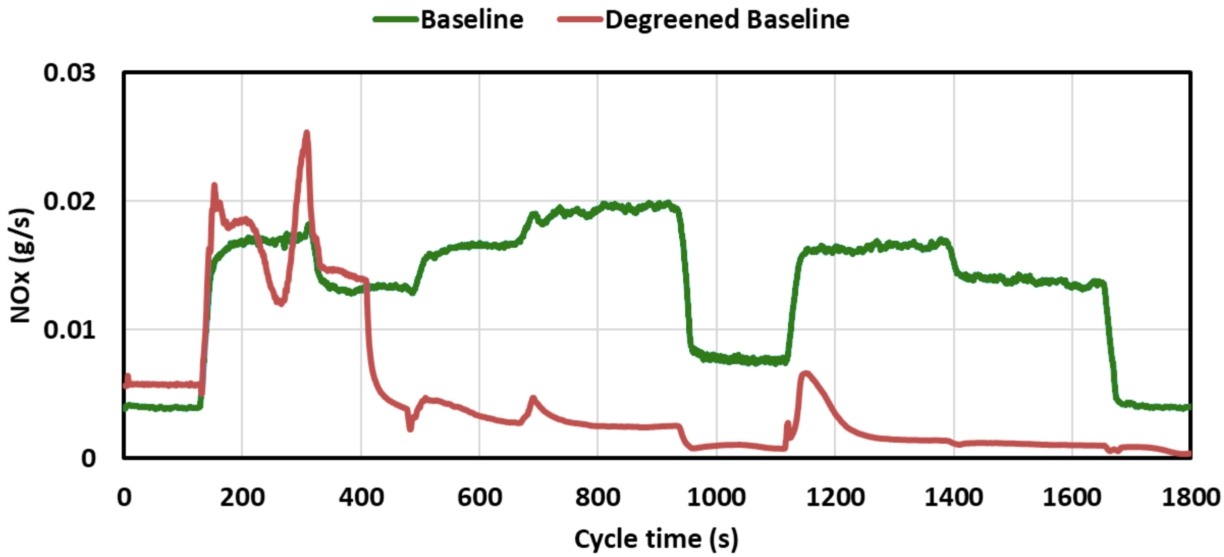


Figure 4-26. Real time NO_x result for Skid Steer engine C1 cycle

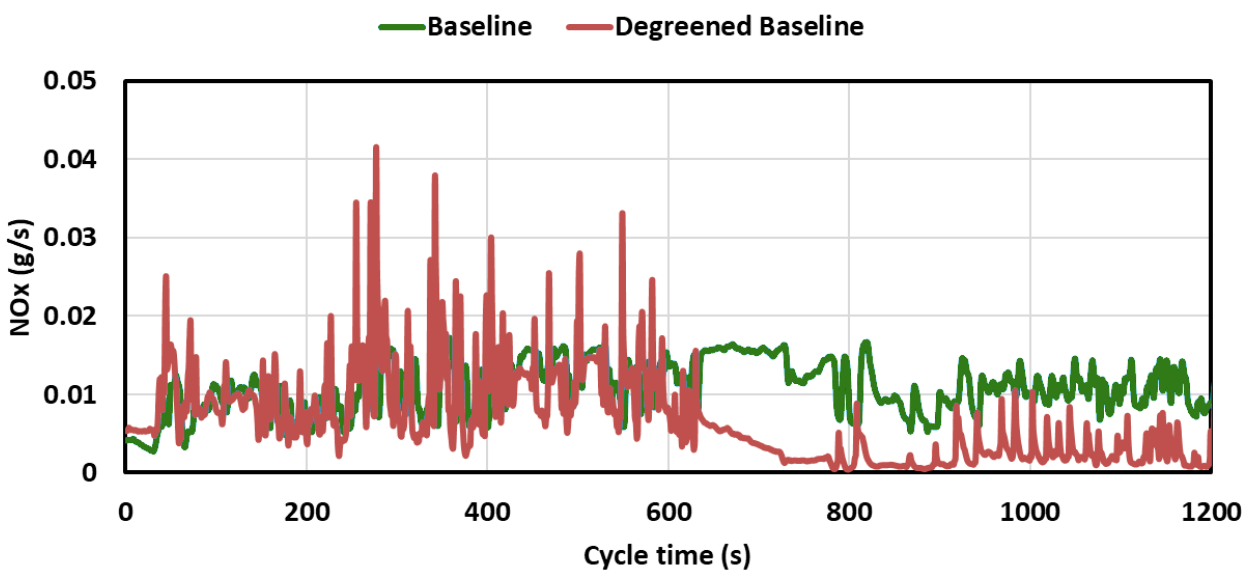


Figure 4-27. Real time NO_x result for Skid Steer engine NRTC cycle cold start

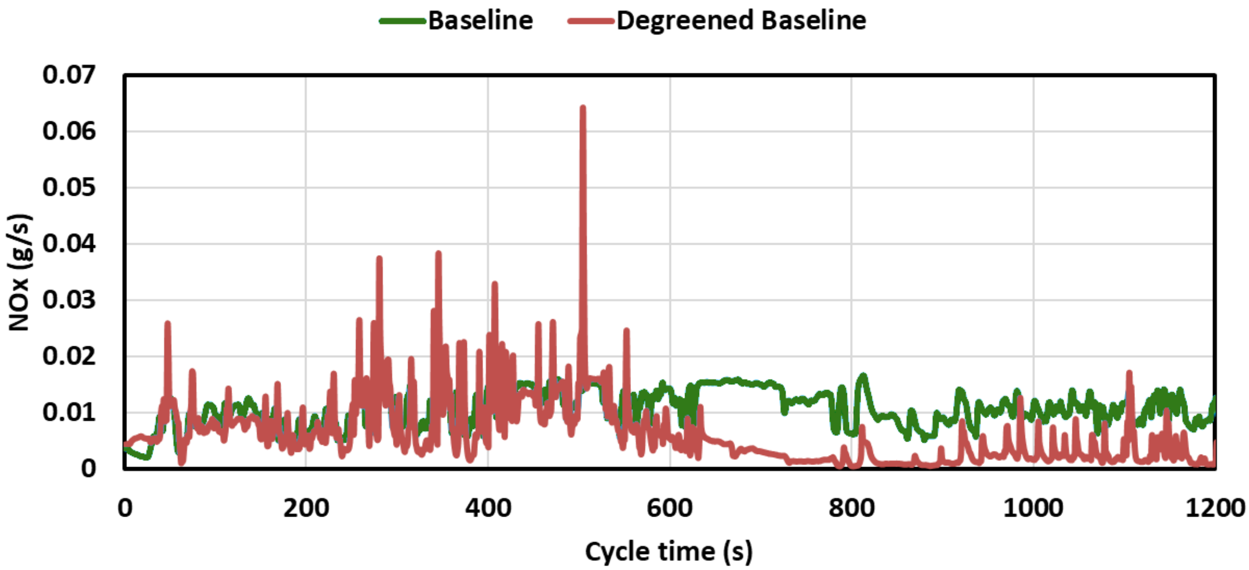


Figure 4-28. Real time NO_x result for Skid Steer engine NRTC cycle hot start

5 Cost/Benefit analysis of advanced emission control strategies for small off-road diesel engines

Another element of this study was to do an evaluation of the cost/benefits of applying aftertreatment control strategies to SORDEs. For this task, information from cost/benefit analyses that were done by the EPA as part of its 2004 rulemaking effort were evaluated. Then a preliminary cost/benefit analysis was performed based on estimates of the incremental cost of aftertreatment technologies utilized for emissions improvements, and estimates of their overall emissions benefits.

5.1 EPA 2004 Cost/Benefit Analysis

In evaluating the potential costs and associated benefits of more stringent standards for SORDEs, it is useful to examine the EPA analyses that were conducted in 2004 as part of their regulatory impact analysis for the Nonroad Diesel Engines Tier 4 Standards (U.S. EPA, 2004). Although somewhat dated, this analysis represents one of the most comprehensive such analyses related to this topic.

5.1.1 Cost Estimates

The EPA considered a number of different cost elements in evaluating the overall regulatory costs. These included engine fixed costs, engine variable costs, and engine operating costs. The engine fixed costs included costs for engine R&D, tooling, and certification. The engine variable costs were costs for new hardware required to meet the new emission standards. These costs are variable because hardware costs tend to be directly related to engine characteristics—for example, emission control devices are sized according to engine displacement so costs vary by displacement; fuel-injection systems vary in cost according to how many fuel injectors are required so costs vary by number of cylinders.

Total operating costs include the following elements: the change in maintenance costs associated with applying new emission controls to the engines; the change in maintenance costs associated with low-sulfur fuel such as extended oil-change intervals (extended oil change intervals results in maintenance savings); the change in fuel costs associated with the incrementally higher costs for low-sulfur fuel (which would not be an issue in California which already has low-sulfur off-road diesel fuel), and the change in fuel costs due to any fuel consumption impacts associated with applying new emission controls to the engines. The increased fuel consumption would be related to additional fuel needed for periodic regeneration for the DPF, which is estimated to be a small increase. Maintenance costs associated with the new emission controls on the engines are expected to increase, since these devices represent new hardware and therefore new maintenance demands. Offsetting this cost increase will be a cost savings due to an expected increase in oil-change intervals, because low-sulfur fuel is far less corrosive than current nonroad diesel fuel. Less corrosion corresponds with a slower acidification rate (i.e., less degradation) of the engine lubricating oil and therefore more operating hours between oil changes.

The fixed engine costs and variable engine costs from the 2004 EPA RIA report are provided in Table 5-1 and Table 5-2. The fixed equipment costs and variable equipment costs from the 2004 EPA RIA report are provided in Table 5-3 and Table 5-4.

Table 5-1. EPAs estimated fixed engine costs per unit (2002 USD) (U.S. EPA, 2004)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
0<hp<25	$ 38	$ 37	$ 36	$ 35	$ 34	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
25<=hp<50	$ 49	$ 48	$ 47	$ 46	$ 45	$ 74	$ 73	$ 71	$ 70	$ 69	$ -	$ -	$ -	$ -	$ -	$ -	$ -
50<=hp<75	$ 50	$ 49	$ 49	$ 48	$ 47	$ 76	$ 75	$ 73	$ 72	$ 71	$ -	$ -	$ -	$ -	$ -	$ -	$ -
75<=hp<100	$ -	$ -	$ -	$ -	$ 80	$ 78	$ 108	$ 106	$ 104	$ 29	$ 28	$ -	$ -	$ -	$ -	$ -	$ -
100<=hp<175	$ -	$ -	$ -	$ -	$ 78	$ 77	$ 108	$ 105	$ 103	$ 29	$ 29	$ -	$ -	$ -	$ -	$ -	$ -
175<=hp<300	$ -	$ -	$ -	$ 225	$ 220	$ 217	$ 290	$ 285	$ 74	$ 73	$ 72	$ -	$ -	$ -	$ -	$ -	$ -
300<=hp<600	$ -	$ -	$ -	$ 527	$ 521	$ 515	$ 735	$ 727	$ 220	$ 218	$ 216	$ -	$ -	$ -	$ -	$ -	$ -
600<=hp<=750	$ -	$ -	$ -	$ 1,156	$ 1,138	$ 1,122	$ 1,630	$ 1,606	$ 509	$ 502	$ 495	$ -	$ -	$ -	$ -	$ -	$ -
>750hp	$ -	$ -	$ -	$ 570	$ 561	$ 553	$ 545	$ 1,447	$ 897	$ 884	$ 872	$ 860	$ -	$ -	$ -	$ -	$ -

Table 5-2. EPAs estimated variable engine costs per unit (2002 USD) (U.S. EPA, 2004)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
0<hp<25	$ 129	$ 129	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123
25<=hp<50	$ 147	$ 147	$ 139	$ 139	$ 139	$ 887	$ 887	$ 675	$ 675	$ 675	$ 675	$ 675	$ 675	$ 675	$ 675	$ 675	$ 675
50<=hp<75	$ 167	$ 167	$ 158	$ 158	$ 158	$ 837	$ 837	$ 636	$ 636	$ 636	$ 636	$ 636	$ 636	$ 636	$ 636	$ 636	$ 636
75<=hp<100	$ -	$ -	$ -	$ -	$ 1,133	$ 1,133	$ 1,122	$ 1,122	$ 1,122	$ 1,122	$ 1,122	$ 1,122	$ 1,122	$ 1,122	$ 1,122	$ 1,122	$ 1,122
100<=hp<175	$ -	$ -	$ -	$ -	$ 1,375	$ 1,375	$ 1,351	$ 1,351	$ 1,351	$ 1,351	$ 1,351	$ 1,351	$ 1,351	$ 1,351	$ 1,351	$ 1,351	$ 1,351
175<=hp<300	$ -	$ -	$ -	$ 1,981	$ 1,981	$ 1,536	$ 1,937	$ 1,937	$ 1,937	$ 1,937	$ 1,937	$ 1,937	$ 1,937	$ 1,937	$ 1,937	$ 1,937	$ 1,937
300<=hp<600	$ -	$ -	$ -	$ 2,609	$ 2,609	$ 2,021	$ 2,545	$ 2,545	$ 2,545	$ 2,545	$ 2,545	$ 2,545	$ 2,545	$ 2,545	$ 2,545	$ 2,545	$ 2,545
600<=hp<=750	$ -	$ -	$ -	$ 4,944	$ 4,944	$ 3,825	$ 4,807	$ 4,807	$ 4,807	$ 4,807	$ 4,807	$ 4,807	$ 4,807	$ 4,807	$ 4,807	$ 4,807	$ 4,807
>750hp	$ -	$ -	$ -	$ 1,973	$ 1,973	$ 1,543	$ 1,543	$ 8,335	$ 8,335	$ 6,734	$ 6,734	$ 6,734	$ 6,734	$ 6,734	$ 6,734	$ 6,734	$ 6,734

Table 5-3. EPAs estimated fixed equipment costs per unit (2002 USD) (U.S. EPA, 2004)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
0<hp<25	$ 15	$ 15	$ 14	$ 14	$ 14	$ 13	$ 13	$ 13	$ 12	$ 12	$ -	$ -	$ -	$ -	$ -	$ -	$ -
25<=hp<50	$ 8	$ 8	$ 8	$ 7	$ 7	$ 42	$ 41	$ 40	$ 40	$ 39	$ 32	$ 31	$ 31	$ 30	$ 30	$ -	$ -
50<=hp<75	$ 8	$ 8	$ 8	$ 8	$ 8	$ 44	$ 43	$ 42	$ 42	$ 41	$ 33	$ 33	$ 32	$ 32	$ 31	$ -	$ -
75<=hp<100	$ -	$ -	$ -	$ -	$ 109	$ 107	$ 132	$ 130	$ 128	$ 126	$ 124	$ 122	$ 120	$ 118	$ 24	$ 24	$ -
100<=hp<175	$ -	$ -	$ -	$ -	$ 170	$ 168	$ 207	$ 204	$ 201	$ 197	$ 194	$ 192	$ 189	$ 186	$ 37	$ 37	$ -
175<=hp<300	$ -	$ -	$ -	$ 302	$ 297	$ 291	$ 360	$ 353	$ 348	$ 342	$ 336	$ 331	$ 326	$ 65	$ 64	$ 63	$ -
300<=hp<600	$ -	$ -	$ -	$ 529	$ 523	$ 518	$ 642	$ 635	$ 628	$ 622	$ 615	$ 609	$ 603	$ 121	$ 120	$ 118	$ -
600<=hp<=750	$ -	$ -	$ -	$ 1,210	$ 1,192	$ 1,175	$ 1,451	$ 1,430	$ 1,410	$ 1,390	$ 1,371	$ 1,353	$ 1,335	$ 266	$ 263	$ 259	$ -
>750hp	$ -	$ -	$ -	$ 177	$ 175	$ 172	$ 170	$ 1,377	$ 1,358	$ 1,339	$ 1,320	$ 1,302	$ 1,285	$ 1,114	$ 1,100	$ 1,085	$ 1,072

Table 5-4. EPAs estimated variable equipment costs per unit (2002 USD) (U.S. EPA, 2004)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
0<hp<25	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
25<=hp<50	$ -	$ -	$ -	$ -	$ -	$ 20	$ 20	$ 16	$ 16	$ 16	$ 16	$ 16	$ 16	$ 16	$ 16	$ 16	$ 16
50<=hp<75	$ -	$ -	$ -	$ -	$ -	$ 21	$ 21	$ 17	$ 17	$ 17	$ 17	$ 17	$ 17	$ 17	$ 17	$ 17	$ 17
75<=hp<100	$ -	$ -	$ -	$ -	$ 45	$ 45	$ 48	$ 48	$ 48	$ 48	$ 48	$ 48	$ 48	$ 48	$ 48	$ 48	$ 48
100<=hp<175	$ -	$ -	$ -	$ -	$ 46	$ 46	$ 49	$ 49	$ 49	$ 49	$ 49	$ 49	$ 49	$ 49	$ 49	$ 49	$ 49
175<=hp<300	$ -	$ -	$ -	$ 58	$ 58	$ 46	$ 62	$ 62	$ 62	$ 62	$ 62	$ 62	$ 62	$ 62	$ 62	$ 62	$ 62
300<=hp<600	$ -	$ -	$ -	$ 110	$ 110	$ 88	$ 117	$ 117	$ 117	$ 117	$ 117	$ 117	$ 117	$ 117	$ 117	$ 117	$ 117
600<=hp<=750	$ -	$ -	$ -	$ 116	$ 116	$ 92	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123	$ 123
>750hp	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 123	$ 123	$ 98	$ 98	$ 98	$ 98	$ 98	$ 98	$ 98	$ 98

A more detailed summary of the engine fixed, engine variable costs, and operating costs is provided on a sales-weighted basis for each horsepower category is provided in Table 5-5.

Table 5-5. Sales Weighted Average Near-Term and Long-Term Costs by Power Category

(2002 USD, for the final emission standards to which the equipment must comply) (U.S. EPA, 2004)

	0<hp<25	25<=hp<50	50<=hp<75	75<=hp<100	100<=hp<175	175<=hp<300	300<=hp<600	600<=hp<=750	>750 hp
Near-term costs calculated in the year:	2008	2013	2013	2012	2012	2011	2011	2011	2015
Engine variable costs									
Fuel System	$0	$182	$184	$0	$0	$0	$0	$0	$0
EGR	$0	$136	$0	$0	$0	$0	$0	$0	$1,451
CCV[b]	$0	$1	$3	$10	$39	$49	$56	$79	$91
CDPF	$0	$316	$454	$642	$795	$1,213	$1,649	$3,274	$6,218
CDPF regen system	$0	$259	$198	$190	$197	$226	$256	$370	$575
NOx adsorber	$0	$0	$0	$583	$691	$986	$1,294	$2,442	$0
DOC	$129	$0	$0	$0	$0	$0	$0	$0	$0
Engine Fixed Costs									
R&D	$15	$51	$54	$50	$51	$126	$414	$1,023	$861
Tooling	$8	$7	$6	$16	$16	$69	$76	$72	$107
Cert	$15	$16	$16	$14	$12	$29	$37	$61	$478
Equipment Variable Costs	$0	$20	$21	$45	$46	$58	$110	$116	$123
Equipment Fixed Costs	$15	$42	$44	$109	$170	$302	$529	$1,210	$1,377
Near-term Total Engine & Equipment Costs	$180	$1,030	$980	$1,660	$2,020	$3,060	$4,420	$8,650	$11,280
Long-term Total Engine & Equipment Costs in the year 2030	**$120**	**$700**	**$650**	**$1,170**	**$1,400**	**$2,000**	**$2,660**	**$4,930**	**$6,830**
Operating Costs (discounted lifetime $)									
Fuel Costs	$110	$260	$650	$910	$1,390	$2,290	$4,890	$11,780	$23,110
Oil Change Costs (Savings)	-$310	-$310	-$550	-$430	-$660	-$640	-$980	-$1,900	-$3,790
System regenerations	$0	$50	$120	$90	$130	$220	$470	$1,130	$4,430
CCV maintenance	$0	$0	$10	$30	$50	$70	$100	$300	$620
CDPF maintenance	$0	$90	$140	$100	$150	$70	$80	$240	$500
Total Incremental Operating Costs (Savings)	**-$200**	**$90**	**$370**	**$710**	**$1,070**	**$2,000**	**$4,560**	**$11,550**	**$24,870**
Baseline Operating Costs (fuel and oil only)	$2,170	$3,410	$7,630	$9,490	$13,400	$21,360	$44,980	$108,430	$212,720

a. Near-term costs include both variable costs and fixed costs; long-term costs include only variable costs and represent those costs that remain following recovery of all fixed costs.
b. For 25 to 75 hp engines, CCV costs in 2013 will be long term because CCV systems are first required in 2008.

In addition to the unit costs, the EPA calculated aggregated for the full implementation of the Tier 4 Nonroad emissions standards. This included costs associated with engine development and implementation, as well as the costs that were needed to transition the market to ultralow sulfur fuel, which was not universally available at the time. Aggregate costs were obtained using the volume market share for different engine categories. The estimated aggregate costs for the 2004 nonroad Tier 4 rule are presented in Table 5-7 for the years from 2007 to 2036 and for the full 30 year time period. Of course, these values represent the costs for a full implementation of the regulation throughout the U.S. The California costs would have to be scaled to the populations of different engines being used within the state.

Table 5-6. Summary of Aggregate Costs for the NRT4 Final Engine and Fuel Program ($Millions of 2002 dollars) (U.S. EPA, 2004)

Year	Engine Costs	Equipment Costs	Fuel Costs	Other Operating Costs	Net Operating Costs	Total Annual Costs
2007	$ -	$ -	$ 142	$ (161)	$ (18)	$ (18)
2008	$ 81	$ 5	$ 249	$ (282)	$ (33)	$ 53
2009	$ 82	$ 5	$ 254	$ (288)	$ (34)	$ 53
2010	$ 80	$ 5	$ 561	$ (349)	$ 212	$ 297
2011	$ 403	$ 62	$ 591	$ (302)	$ 289	$ 754
2012	$ 718	$ 106	$ 704	$ (299)	$ 406	$ 1,229
2013	$ 882	$ 121	$ 797	$ (286)	$ 512	$ 1,515
2014	$ 973	$ 146	$ 874	$ (294)	$ 581	$ 1,699
2015	$ 950	$ 149	$ 938	$ (288)	$ 650	$ 1,749
2016	$ 920	$ 150	$ 954	$ (274)	$ 680	$ 1,750
2017	$ 910	$ 150	$ 971	$ (261)	$ 710	$ 1,770
2018	$ 901	$ 146	$ 988	$ (250)	$ 738	$ 1,785
2019	$ 890	$ 147	$ 1,006	$ (240)	$ 766	$ 1,802
2020	$ 900	$ 147	$ 1,022	$ (231)	$ 791	$ 1,838
2021	$ 913	$ 99	$ 1,039	$ (224)	$ 815	$ 1,827
2022	$ 927	$ 66	$ 1,056	$ (219)	$ 838	$ 1,830
2023	$ 940	$ 56	$ 1,073	$ (214)	$ 859	$ 1,855
2024	$ 954	$ 36	$ 1,090	$ (210)	$ 880	$ 1,869
2025	$ 967	$ 32	$ 1,107	$ (207)	$ 900	$ 1,899
2026	$ 980	$ 32	$ 1,124	$ (204)	$ 920	$ 1,932
2027	$ 994	$ 33	$ 1,141	$ (202)	$ 938	$ 1,965
2028	$ 1,007	$ 33	$ 1,158	$ (201)	$ 956	$ 1,997
2029	$ 1,021	$ 33	$ 1,174	$ (201)	$ 974	$ 2,028
2030	$ 1,034	$ 34	$ 1,191	$ (201)	$ 991	$ 2,059
2031	$ 1,048	$ 34	$ 1,208	$ (201)	$ 1,007	$ 2,089
2032	$ 1,061	$ 35	$ 1,225	$ (201)	$ 1,024	$ 2,119
2033	$ 1,074	$ 35	$ 1,242	$ (202)	$ 1,040	$ 2,149
2034	$ 1,088	$ 35	$ 1,259	$ (203)	$ 1,056	$ 2,179
2035	$ 1,101	$ 36	$ 1,276	$ (204)	$ 1,072	$ 2,209
2036	$ 1,115	$ 36	$ 1,293	$ (205)	$ 1,088	$ 2,239
30 Yr NPV at 3%	$ 14,054	$ 1,281	$ 16,326	$ (4,517)	$ 11,809	$ 27,144
30 Yr NPV at 7%	$ 7,215	$ 754	$ 8,538	$ (2,745)	$ 5,793	$ 13,762

5.1.2 Emission Inventory Estimates

Emissions inventory estimates for the 2004 nonroad Tier 4 rule were developed by the EPA for $PM_{2.5}$, NO_x, SO_2, VOC, and CO. These estimates were developed with the NONROAD2004 model, which was in a draft stage at the time. The estimates for exhaust emissions in the draft NONROAD2004 model were developed using the following equation, where each term is defined as follows:

$$I_{exh} = E_{exh} \cdot A \cdot L \cdot P \cdot N$$

I_{exh} = the exhaust emission inventory (gram/year, gram/day),
E_{exh} = exhaust emission factor (gram/hp-hr),
A = equipment activity (operating hours/year),
L = Load factor (average proportion of rated power used during operation (percent)),
P = average rated power (hp)
N = Equipment population (units).

Emissions are then converted and reported as tons/year or tons/day. For diesel engines, each of the inputs was applied to sub-populations of equipment, as classified by type (dozer, tractor, backhoe, etc.), rated power class (50-100 hp, 100-300 hp, etc.) and regulatory tier (tier 1, tier 2, etc.). The exhaust emissions factors were determined using a zero-hour emission factor that was adjusted for deterioration based on the age distribution of the equipment for a particular year and also for the differences between emissions under transient conditions and emissions under steady-state conditions, which is where the majority of the certification emissions testing is done. Activity estimates were determined separately for each different type of equipment, and remain constant for each simulation year. Rated power represents the average rated power for equipment, as assigned to each combination of equipment type and rated-power class represented by the model. For equipment populations, the model generates separate sub-populations for individual combinations of equipment type and rated-power class. Model estimates were also conducted for commercial marine vessels and locomotives, because these were impacted by the changes in the fuel sulfur rules at the time, and for recreational marine vessels, since a percentage of the outboard motors are diesel. The emissions benefits for the Tier 4 rules were estimated by taking the difference between baseline estimates without the implementation of the Tier 4 regulations and estimates with Tier 4 controls put in place. A summary of the estimated reductions in PM2.5 and NO_x emissions is provided in

Table **5-7**. Comparisons of emissions inventory estimates for the base case compared to the controlled case are provided in Figure 5-1.

Table 5-7. Emission Reductions Associated with the NRT4 Final Fuel and Engine Program and the Fuel-only Scenario (tons) (U.S. EPA, 2004)

Year	NRT4 Fuel and Engine Program			NRLM Fuel-only Program	
	PM	NOx+NMHC	SOx	PM	SOx
2007	10,700	0	133,000	10,700	133,000
2008	19,500	200	235,400	19,000	235,400
2009	20,400	400	240,100	19,400	240,100
2010	22,300	700	255,500	20,600	255,500
2011	25,900	19,100	268,600	21,600	268,600
2012	32,100	49,600	277,800	22,400	277,700
2013	39,200	84,400	285,700	23,000	285,500
2014	46,900	143,600	291,600	23,500	291,500
2015	54,900	203,000	297,400	24,000	297,300
2016	62,400	261,100	302,600	24,400	302,400
2017	69,600	316,900	307,700	24,800	307,500
2018	76,400	368,500	312,900	25,200	312,700
2019	82,800	417,300	318,300	25,600	318,000
2020	88,800	463,000	323,300	26,000	323,100
2021	94,400	504,400	328,300	26,400	328,000
2022	99,700	542,400	333,600	26,900	333,400
2023	104,600	578,100	338,800	27,300	338,500
2024	109,400	611,100	344,000	27,700	343,700
2025	113,900	642,300	349,200	28,100	348,900
2026	118,200	671,400	354,400	28,500	354,100
2027	122,300	698,200	359,600	28,900	359,300
2028	125,900	723,200	364,800	29,400	364,500
2029	129,500	746,900	370,000	29,800	369,700
2030	132,900	768,500	375,300	30,200	374,900
2031	136,000	788,800	380,500	30,600	380,100
2032	139,100	808,400	385,800	31,000	385,400
2033	142,100	827,300	391,000	31,500	390,600
2034	145,000	845,600	396,300	31,900	395,900
2035	147,800	863,100	401,600	32,300	401,200
2036	150,500	880,100	406,900	32,700	406,400
30 Yr NPV at 3%	1,430,500	7,077,900	5,725,900	461,000	5,722,100
30 Yr NPV at 7%	690,800	3,142,700	3,164,100	254,800	3,162,300

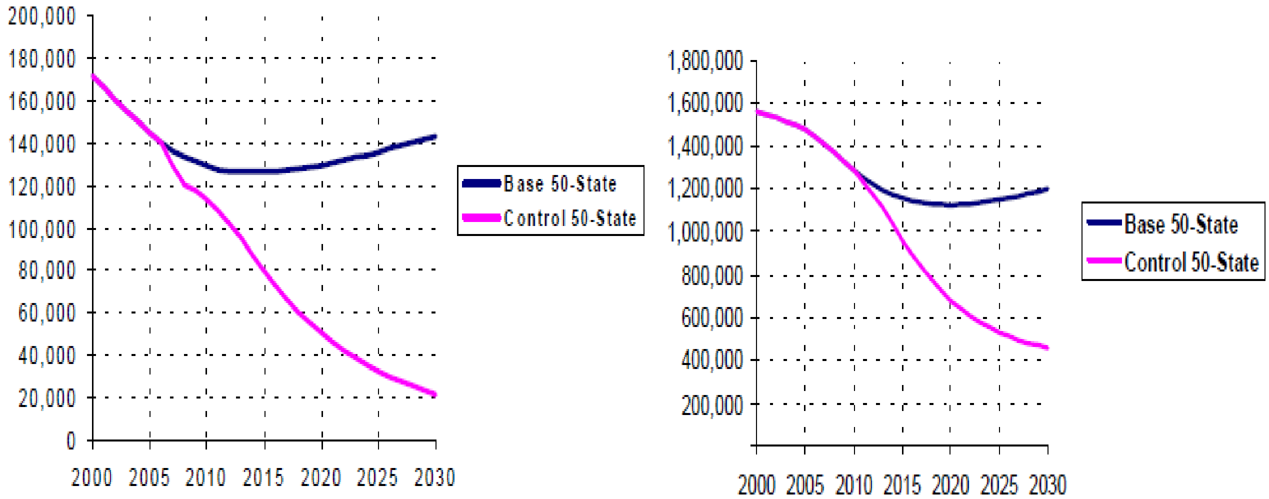


Figure 5-1. Estimated Reductions in PM2.5 and NO_x Emissions From Land-Based Nonroad Engines (tons/year)

These values can be compared to total emissions inventory estimates for different sources, as summarized in Table 5-8. PM2.5 emissions from land-based nonroad diesel engines were found to be 46 percent of the total diesel PM2.5 emissions in 1996, with this percentage increasing to 72 percent by 2030. PM2.5 emissions from land-based nonroad diesel engines are 8 percent of the total manmade PM2.5 emissions in 1996, and this percentage drops slightly to 6 percent in 2020 and 2030. The contribution of land-based diesel engines to total mobile source PM2.5 emissions is 33 percent in 1996, rising slightly to 35 percent by 2030. NO_x emissions from land-based nonroad diesel engines are 6 percent of the total emissions in 1996, and this percentage increases to 8 percent by 2030. The contribution of land-based diesel engines to total mobile source NO_x emissions is 12 percent in 1996, rising to 24 percent by 2030. Some estimates were also made for specific local cities, which included the California cities of Sacramento and San Diego, CA, as summarized in Table 5-9.

Table 5-8. Annual Land-Based Nonroad Diesel Engine Emissions Contributions to the Mobile and Total Source Categories (U.S. EPA, 2004)

Category	1996			2020			2030		
	short tons	% of mobile source	% of total	short tons	% of mobile source	% of total	short tons	% of mobile source	% of total
PM2.5	186,507	32.60%	8.40%	129,058	34.70%	6.20%	142,484	34.60%	6.40%
NOx	1,564,904	12.10%	6.40%	1,119,481	22.20%	7.40%	1,192,833	24.30%	7.80%

*These are 48-state inventories. They do not include Alaska and Hawaii.

Table 5-9. Annual Land-Based Nonroad Diesel Engine Contribution to Emission Inventories in Different California Cities (U.S. EPA, 2004)

Location	Category	Year	Land-Based Diesel (short tons)	Mobile Sources (short tons)	Total Man-Made Sources (short tons)	Land-Based Nonroad Diesel as % of Total	Land-Based Nonroad Diesel as % of Mobile Sources
Sacramento	PM2.5	1996	529	2,140	7,103	7%	25%
San Diego	PM2.5	1996	879	3,715	9,631	9%	24%
Sacramento	PM2.5	2020	391	1,301	5,505	7%	30%
San Diego	PM2.5	2020	678	2,478	9,135	7%	27%
Sacramento	PM2.5	2030	447	1,445	5,890	8%	31%
San Diego	PM2.5	2030	777	2,770	10,096	8%	28%
Sacramento	NOx	1996	5,666	55,144	58,757	10%	10%
San Diego	NOx	1996	9,460	99,325	107,024	9%	10%
Sacramento	NOx	2020	4,297	18,870	23,111	19%	23%
San Diego	NOx	2020	7,464	46,005	51,909	14%	16%
Sacramento	NOx	2030	4,806	17,498	21,952	22%	27%
San Diego	NOx	2030	8,401	43,930	50,296	17%	19%

*Includes only direct exhaust emissions.
*Based on inventories developed for the proposed rule.

5.1.3 Cost per Ton Estimates

The EPA calculated the cost per ton of the final rule based on the net present value of all costs incurred and all emission reductions generated over a 30-year time window following implementation of the program. This approach captured all the costs and emission reductions from the final rule, including costs incurred and emission reductions generated by both the new and the existing fleet. The baseline (i.e., the point of comparison) for this evaluation was the existing set of engine standards (i.e., the Tier 2/Tier 3 program) and fuel standards (i.e., unregulated sulfur level). The 30-year time window was meant to capture both the early period of the program when there are a small number of compliant engines in the fleet, and the later period when there is nearly complete turnover to compliant engines. The final rule also required reducing sulfur content in nonroad diesel fuel with a 500 ppm cap beginning in 2007, a 15 ppm NR cap beginning in 2010, and a 15 ppm L&M cap beginning in 2012.

The calculations of cost per ton of each emission reduced under the EPA final program divides the net present value of the annual costs assigned to each pollutant by the net present value of the total annual reductions of each pollutant – NO_x+NMHC, PM and SO_x. The net present values of the costs associated with each pollutant, calculated with a three percent discount rate, were $7.2 billion for NO_x+NMHC, $16.0 billion for PM and $3.9 billion for SO_x. The 30-year net present values, with a three percent discount rate, of emission reductions were 7.1 million tons for NO_x+NMHC, 1.4 million tons for PM and 5.7 million tons for SO_x. The cost per ton of emissions reduced for the NRT4 final rule is calculated by dividing the net present value of the annualized costs of the program through 2036 by the net present value of the annual emission reductions through 2036. These results are summarized in Table 5-10.

Table 5-10. Aggregate Costs and Costs per Ton for the NRT4 Final Rule 30-year Net Present Values at a 3% and 7% Discount Rate (2002 USD)

Item	Units	3% discount rate	7% discount rate
500ppm at $0.021/gal, 2007-2010	(10^6 gallons)	29,690	25,207
500ppm at $0.033/gal, 2010-2012	(10^6 gallons)	7,068	5,500
500ppm at $0.035/gal, 2012-2014	(10^6 gallons)	1,660	1,196
15ppm at $0.058/gal, 2010-2012	(10^6 gallons)	15,223	11,715
15ppm at $0.064/gal, 2012-2014	(10^6 gallons)	17,998	12,800
15ppm at $0.070/gal, 2014+	(10^6 gallons)	191,091	89,805
500ppm Fuel Cost	($million)	$915	$753
15ppm Fuel Cost	($million)	$15,411	$7,785
Other Operating Costs*	($million)	-$4,517	-$2,745
Engine Costs	($million)	$14,054	$7,215
Equipment Costs	($million)	$1,281	$754
Total Program Costs	($million)	$27,144	$13,762
NOx+NMHC Costs	($million)	$7,169	$3,652
PM Costs	($million)	$16,041	$8,134
SOx Costs	($million)	$3,934	$1,976
NOx+NMHC Reduction	(10^6 tons)	7.1	3.1
PM Reduction	(10^6 tons)	1.4	0.7
SOx Reduction	(10^6 tons)	5.7	3.2
Cost per Ton NOx+NMHC	($/ton)	$1,010	$1,160
Cost per Ton PM	($/ton)	$11,200	$11,800
Cost per Ton	($/ton)	$690	$620

5.2 Cost/Benefit Analysis for the implementation of more stringent emissions standards in California for SORDEs

This section provides a cost-benefit analysis for the implementation of more stringent emissions standards in California for SORDEs. This cost/benefit analysis includes two elements: estimates of the incremental cost of any aftertreatment of other technologies utilized for emissions improvements, and estimates of the emissions benefits. These two elements are addressed separately in subsections 5.2.1 and 5.2.2, and are then combined in section 5.2.3 to give an overall cost/benefit analysis for the potential regulatory implementation.

5.2.1 Incremental costs of enhanced emissions standards for SORDEs

Determining the incremental costs of enhanced emissions standards involves understanding the costs of the baseline engines and then the costs of the aftertreatment or other technologies needed to meet these standards. The baseline aftertreatment costs and engine costs are described in subsections 5.2.1.1 and 5.2.1.2, respectively.

5.2.1.1 Baseline Aftertreatment Costs

Baseline emission control strategy costs were obtained from a variety of sources. This includes costs of systems that are already on the market for other categories of engines, available data in the literature, discussions with engine and aftertreatment manufacturer industrial contacts and trade associations and experts in the field.

The costs of several different sized DPFs were discussed with Proventia. Their DPF for the APU is already verified and available for purchase. The APU DPF costs about $2,000 (price to dealer, so probably $2,400 with dealer markup). The APU by itself without a DPF costs $4000, while the price of a full APU unit is $9000 to $10000. For the slightly larger TRU bobtail DPF that is being used for this demonstration, Proventia estimated that it would cost about $2800 to the dealer (or $3360 with markup). The TRU engine of this size without a DPF is approximately $7000, while a full TRU unit of this size is $16,000. For a large 2-liter TRU engine application (typical of the larger TRU market), DPF costs are estimated to be around $3500 to the dealer (or $4200 with markup). This type of TRU engine costs about $9000 to $10000 retail, a full TRU unit costs $24000.

These values can be compared with those estimated by ICCT for DOCs and DPFs being used on light-duty vehicles, as some of the smaller engines in light-duty vehicles are comparable in size to those used in SORDEs in the 0 to 75 hp range. Summary DOC cost estimates are provided in Table 5-11 for engines ranging in size from 1.5 to 3 liters. Elements included in this costs analysis include the cost of precious metals, washcoat, and substrate, manufacturing including canning, accessories, and labor, and other costs such as warranties. For these costs estimates, a sweep volume ratio of 0.75 of the engine volume. Precious metal costs were based on an average Pt and Pd loading of Pt=0.66 g/L and Pd=0.33 g/L for a DOC multiplied by the market price of PGM (Pt=$43/g and Pd=$11/g). The substrate cost was based on 6.0*CV + 1.92, where CV is the catalyst volume in liters based on an inflation corrected estimate used in the EPA’s 2000 RIA for on-road heavy-duty engines. Then a cost of $5.10 per liter of catalyst was applied, assuming that the costs of R&D, overhead, marketing, and profits are included in this number. The canning cost was based on assuming a catalyst brick face area of 100 cm2, with the can length was calculated based on the catalyst volume, and a canning cost of $5 per liter of catalyst. The cost of accessories was estimated as $5.0 for Vd≤2.0L and $10 for larger engines. Labor and overhead costs are assumed similar to those used previously for TWCs, i.e. $6 per catalyst. Warranty costs were based on a 3% rate claim and parts and labor cost per incident. Finally, a 10% cost reduction discount was applied for long-term costs. Based on these estimates to long term cost for a DOC for a 1.5-liter diesel engine, approximately the size of a 25 to 50 hp SORDE, would be $62 per unit.

Table 5-11. DOC Cost Estimates by Engine Size (2011 USD) (Sanchez et al., 2012)

NO	COST ITEM				
1	Engine displacement, Vd (L)	1.50	2.00	2.50	3.00
2	Catalyst volume, CV (SVR=0.75), liters	1.13	1.50	1.88	2.25
3	Pd cost, 0.66 g/L x CV x $35/g	$32	$43	$53	$64
4	Pd cost, 0.33 g/L x CV x $7/g	$3	$3	$4	$5
5	**Total PGM ([3]+[4])**	**$35**	**$46**	**$57**	**$69**
6	Substrate ($6.0*CV+1.92)	$10	$12	$15	$17
7	Washcoat ($5.10*CV)	$6	$8	$10	$11
8	**Total PGMs+ washcoat + substrate ([5]+[6]+[7])**	**$51**	**$66**	**$82**	**$97**
9	Canning ($5*CV)	$6	$8	$9	$11
10	Accessories	$5	$5	$10	$10
11	**Total manufacturing ([8]+[9]+[10])**	**$62**	**$79**	**$101**	**$118**
12	Labor with overhead @ 40%	$6	$6	$6	$6
13	**Total direct costs to manufacturing ([11]+[12])**	**$68**	**$85**	**$107**	**$124**
14	Warranty costs (3% claim rate)	$2	$3	$3	$4
15	**Baseline costs ([13]+[14])**	**$70**	**$88**	**$110**	**$128**
16	**Long Term Costs (0.9*baseline cost)**	**$62**	**$78**	**$99**	**$116**

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A summary of DPF cost estimates is provided in Table 5-12 for engines ranging in size from 1.5 to 3 liters. For these costs estimates, the catalyst volume was estimated to be 2.0 times the engine volume. Precious metal costs were based on a PGM loading of 1.0 g/L with a 3:1 ratio for Pt and Pd. The substrate cost was based on $30*CV, where CV is the catalyst volume in liters. The washcoast cost was based on $10*CV, where CV is the catalyst volume in liters. The cost of manufacturing included canning costs based on some of the assumptions used for the DOCs, the cost of accessories estimated as $10.0 for Vd≤2.0L and $15 for larger engines, and the cost of the regeneration system. Labor and overhead costs were estimated to be slightly higher than those used for the DOC. Warranty costs were based on a 3% rate claim and parts and labor cost per incident. Finally, a 20% cost reduction discount was applied for long-term costs. Based on these estimates to long term cost for a DPF for a 1.5-liter diesel engine would be approximately $266 per unit.

Table 5-12. DPF Cost Estimates by Engine Size (2011 USD) (Sanchez et al., 2012)

NO	COST ITEM				
1	**Engine displacement, Vd (L)**	**1.50**	**2.00**	**2.50**	**3.00**
2	Catalyst volume, CV (SVR=2.0), liters	3.00	4.00	5.00	6.00
3	Pt cost, 0.75 g/L x CV x $35/g	$97	$129	$161	$194
4	Pd cost, 0.25 g/L x CV x $11/g	$8	$11	$14	$17
5	**Total PGM**	**$105**	**$140**	**$175**	**$211**
6	Substrate ($30*CV)	$90	$120	$150	$180
7	Washcoat ($10*CV)	$30	$40	$50	$60
8	**Total PGMs + substrate+ washcoat ([5]+[6]+[7])**	**$225**	**$300**	**$375**	**$451**
9	Canning ($5*CV)	$15	$20	$25	$30
10	Accessories	$10	$10	$15	$15
11	Regeneration system	$61	$61	$61	$61
12	**Total Manufacturing ([8]+[9]+[10]+[11])**	**$311**	**$391**	**$476**	**$557**
13	Labor costs and overhead	$12	$12	$12	$12
14	**Total Direct costs to Mfr. ([12]+[13])**	**$323**	**$403**	**$488**	**$569**
15	Warranty costs (3%claim rate)	$10	$12	$15	$17
16	**Baseline costs ([14]+[15])**	**$333**	**$415**	**$503**	**$586**
17	**Long-term costs (0.8*baseline)**	**$266**	**$332**	**$402**	**$468**

A summary of SCR cost estimates is provided in Table 5-13 for engines ranging in size from 1.5 to 3 liters. For these costs estimates, the catalyst volume was estimated to be 2.0 times the engine volume. The SCR system itself does not require extensive precious metals, but a downstream NH_3 slip catalyst would require approximately 1/5 catalyst loading for the catalyst size at a loading of 1.0 g/L. The substrate and washcoat cost was estimated to be $20 per liter of catalyst substrate, while the canning cost is estimated to be $15 per liter of catalyst substrate. The urea system includes a number of components, including a urea tank, level sensor, tank accessories, pump, injector, tubing, mounting accessories, heating system, temperature sensors, and a mixer. Labor and overhead costs were estimated to be four times higher than those used for the DOC, as the system is more complex and requires more assembly. Warranty costs were based on a 3% rate claim and parts and labor cost per incident. Finally, a 20% cost reduction discount was applied for long-term costs. Based on these estimates to long term cost for a DPF for a 1.5-liter diesel engine would be approximately $418 per unit.

Table 5-13. SCR Cost Estimates by Engine Size (2011 USD) (Sanchez et al., 2012)

NO	COST ITEM				
1	**Average engine displacement, Vd (L)**	**1.50**	**2.00**	**2.50**	**3.00**
2	Catalyst volume, CV (SVR=1.0), liters	1.50	2.00	2.50	3.00
3	Pt, Pd, and Rh are not required for NOx control	$0	$0	$0	$0
4	NH_3 slip catalyst, CV (SVR=0.2), 1 g/L PGM @ $43/g	$13	$17	$22	$26
5	**Total PGM ([3]+[4])**	**$13**	**$17**	**$22**	**$26**
6	Substrate and washcoat ($20/L*CV)	$30	$40	$50	$60
7	Canning ($15*CV)	$23	$30	$38	$45
8	**Total SCR catalysts: PGMs + substrate+ washcoat ([5]+[6]+[7])**	**$66**	**$87**	**$110**	**$131**
9	Urea tank volume (8*Vd), liters	12	16	20	24
10	Urea tank cost	$94	$114	$132	$149
11	Urea level sensor ($60 commercial price/2.5)	$24	$24	$24	$24
12	Urea tank accessories (brackets, bolts, spacers)	$15	$15	$20	$20
13	Urea pump ($130 commercial price/2.5)	$52	$52	$52	$52
14	Urea injector ($86 commercial price/2.5)	$34	$34	$34	$34
15	Tubing Stainless Steel ($35 commercial price/2.5)	$14	$14	$14	$14
16	Urea Injection pipe section D2.5"x38cm ($35 commercial price/2.5)	$14	$14	$14	$14
17	Urea Injection mounting parts (brackets, bolts, gaskets, spacers, tubing connectors)	$15	$15	$20	$20
18	Urea heating system- 200 W, 12 V DC.	$40	$40	$40	$40
19	Temperature sensors (x2) ($2.5 thermocouple/2.5 +$50 transmitter, commercial price/2.5)	$42	$42	$42	$42
20	Urea mixer ($125/2.5)	$50	$50	$50	$50
21	**Total Urea System ([9]+[10]+...+[20])**	**$394**	**$414**	**$442**	**$459**
22	**Total Manufacturing: SCR Catalyst and Urea system ([8]+[21])**	**$460**	**$501**	**$552**	**$590**
22	Labor costs with overhead	$48	$48	$48	$48
23	**Total Direct Costs to Manufacturing ([22]+[23])**	**$508**	**$549**	**$600**	**$638**
24	Warranty costs (3%claim rate)	$15	$16	$18	$19
25	**Baseline costs — near term**	**$523**	**$565**	**$618**	**$657**
28	**Long term cost (0.8*baseline)**	**$418**	**$453**	**$494**	**$526**

Additional estimates were obtained from discussions with different sources in the field. One estimate was based on a 5-liter engine size for a light-duty vehicle that can be scaled downward for a DOC, DPF, SCR, and ammonia slip catalyst (ASC). This cost estimate for the material costs for a DOC was $380, based on a sweep volume ratio (SVR)=0.5, platinum group metals (PGM)=3 g/liter @ $35/gram, and wash coat (WC) = 4.25 g/liter @ $0.055/g. This estimate for the material costs for a DPF was $470, based on a SVR=1.5, PGM= 1g/liter @ $40/gr, and WC= 20 g/l @ 0.055/gr This estimate for the material costs for an SCR was $470, based on an SVR of 2.4 and a catalyst=140 g/liter@ 0.045/gr 5 liter. This estimate for the material costs for a ASC was $36.60, based on a SVR=0.25, catalyst: 0.4 g/liter @$30, and WC: 100 g/liter @$0.05/ g. The summed material costs based on these estimates are $1100 for a 5-liter engine. In further discussions about scaling these estimates to a ~1.5-liter engine, the following rough costs were suggested, material costs $250 (scaling the costs discussed above), urea dosing, including the tank, lines, and injectors = $150 to $250, canning $50 to $75, and a NO_x sensor for $150. Based on this, system for a ~1.5-liter engine can be estimated based on $250 (materials) + $225 (urea dosing) + $75 (canning) + $150 ($NO_x$ sensor) = $700.

The baseline costs for adding enhanced emissions controls can be estimated based on the cost estimates above and the total market share of engines in each of the different categories. For this, the cost of adding a DPF + DOC for under 25 hp engines is estimated to be $266 + $62 = $328, using the values for the 1.5-liter engines given in Table 5-11 and Table 5-12, respectively. For the cost of adding SCR NO_x aftertreatment to 25 to 75 hp engines, an estimate of $474 was utilized, which represents an average of the cost estimates for the 2- and 2.5-liter engines given in Table 5-13.

The engine populations are developed under sections 3 & 6, and include 256,833 engines in the 0 to 75 hp category, 10,448 engines for the 0 to 10 hp category, 125,057 engines for the 10 to 25 hp category, 79,622 engines for the 25 to 50 hp category, and 41,666 engines for the 50 to 75 hp category.

The cost estimates for the DPF+DOC can be combined with the engine populations for the < 25 hp engines to provide a cost estimate for implementing more stringent regulations on PM emissions in this engine size range. These costs would be applied to 10,448 engines for the 0 to 10 hp category and 125,057 engines for the 10 to 25 hp category. So, the total cost of implementing DPF + DOCs for the entire fleet of under 25 hp small off-road diesel engines would be $44,445,640.

The cost estimates for the SCR systems can be combined with the engine populations for the 25 to 75 hp engines to provide a cost estimate for implementing more stringent regulations on NO_x emissions in this engine size range. The total number of engines in the 25 to 50 hp category is 79,622 engines, and the total number of engines in the 50 to 75 hp category is 41,666 engines. This gives a total of 121,288 engines in the 25 to 75 hp engine size range that would be outfitted with SCR technology. So, the total cost of implementing SCR technology for the entire fleet of under 25 to 75 hp small off-road diesel engines would be $57,490,512.

5.2.1.2 Baseline Engine Costs

Baseline engine costs were also developed from searches of the internet and other sources where these engines can be purchased. These estimates were cross-correlated with discussions with engine manufacturers and industry associations that service the SORDE engine category.

A summary of engine costs is provided in Table 5-14. This includes engines for various hp categories from various engine manufacturers. The estimates include both new and used engine prices to provide a broader context for understanding the typical costs for engines in this category. Note that the costs for newer engines are the most critical for the cost/benefit analysis, as the newest emissions standards would be implemented on the newest engines that are on the market. Based on this data, the cost of the typical new engine in this category ranges from approximately $3,000 to $11,000 for the 0 to 50 hp category. The cost of the typical used engine in this category ranges from approximately $750 to $6,000 depending on the engine condition.

Table 5-14. Summary of Engine Costs (2016 USD)

Engine Manufacturer	Engine Model	HP/HP Group	Engine Counts	New ($)	Used ($)
KUBOTA CORPORATION	V1505	50	1853	5843	
KUBOTA CORPORATION	D1105	50	1032	5012	
DETROIT DIESEL CORPORATION	R1238K33	50	756	3655	
LIEBHERR COMPANY	LOM444LA	50	413		4800
KOMATSU, LTD.	SA6D114E-2	50	406	9995	
ISUZU MOTORS LIMITED	AL6UZ1X	50	386	3800	
KUBOTA CORPORATION	D1803	50	356	10403	
CATERPILLAR, INC.	C-32 ACCERT	50	285	8500	6700
CATERPILLAR, INC.	3412E DITA	50	282	2999	1700
KOMATSU, LTD.	SAA12V140ZE-2	50	227	4995	
INGERSOLL RAND	KUBOTA VT203-E	50	225		1999
CUMMINS ENGINE CO., INC.	3412	50	197	8500	
CUMMINS ENGINE CO., INC.	N-14	50	150	4150	
CNH ENGINE CORP., INC.	667T/m2	50	137	2999	2655
CATERPILLAR, INC.	3508BTA	50	128	5800	
KUBOTA CORPORATION	V360-T-ET02	50	125	4800	
DEUTZ AG	120HX	50	110	4350	
CUMMINS ENGINE CO., INC.	SDA16V160	50	109	6600	2750
KUBOTA CORPORATION	T-650	50	107	4150	
YANMAR CO., LTD.	3TNV70-XBV	50	105	999	750
CUMMINS ENGINE CO., INC.	LTA10-C	50	99	3950	
JOHN DEERE POWER SYSTEMS	40045TF37BC	50	97		1895
FORD	F700	50	95	4000	
CUMMINS ENGINE CO., INC.	SAA12V140E3	50	74	3950	
CUMMINS ENGINE CO., INC.	544D10	50	73		1499
KOMATSU DRESSER CORPORATION	SAA12V140E-3	50	71	4539	
CUMMINS ENGINE CO., INC.	KT38C	50	71		1999
CUMMINS ENGINE CO., INC.	6BTA 5.9 C	50	67		1895
CATERPILLAR, INC.	C-27	50	62		1699
CUMMINS ENGINE CO., INC.	B 5.9	50	57		2100
CATERPILLAR, INC.	C6.6	50	55	3800	
KUBOTA CORPORATION	U17	50	46	5899	
YAMAHA MOTOR CORPORATION	3TNE82A-TB	50	40	4350	
KUBOTA CORPORATION	V3307-DI-T-ET03	50	38		1450
MAN	LD2842LE103	50	34	3950	
KUBOTA CORPORATION	KX121R3TA	50	34	3950	

CUMMINS ENGINE CO., INC.	KTA38	50	34	3800	
JOHN DEERE POWER SYSTEMS	4045HT054	50	32		1699
DEUTZ AG	TD2.9L4	50	31		1750
CATERPILLAR, INC.	C-32	50	28	3950	
CUMMINS ENGINE CO., INC.	B3.3	50	27	3800	2400
JOHN DEERE POWER SYSTEMS	4045HF275CDEFJ	50	27		2100
KUBOTA CORPORATION	V6108-CR-TI-EF0	50	26	3800	2400
KOMATSU, LTD.	Saa12V140E	50	25		1999
CATERPILLAR, INC.	305.5ERC	50	24		1699
CATERPILLAR, INC.	C27-ACERT	50	24	4350	
CATERPILLAR, INC.	C32ACERT	50	23	4150	
CUMMINS ENGINE CO., INC.	B3.9-C	50	23	3800	2400
ISUZU MOTORS LIMITED	AA-GHK1X	50	23	3800	
JOHN DEERE POWER SYSTEMS	G9-43A	50	23	4350	
KOMATSU, LTD.	SAA6D107E 2	50	22	3950	
KUBOTA CORPORATION	KX121-3	50	22		1699
PERKINS ENGINES COMPANY LTD.	1006e6	50	22	3800	1599
KUBOTA CORPORATION	V2203-M-DI	50	21	6995	5250
PERKINS ENGINES COMPANY LTD.	C4.4ACERT T	50	21	3800	2400
KOMATSU, LTD.	SA12V170	50	21	4150	
KOMATSU, LTD.	SAA12V140E	50	21	3800	2400
Hatz	1B20X-9901	4.6		1699.99	
Hatz	1B20X-9901	4.6		1599	
Hatz	1B20X-9902	4.6		2199.99	
Hatz	1B20X-9902	4.6		1999	
Kohler	KD3502001A	6.1		2129.97	
Kohler	KD350-1001	6.7		1888.22	
Kohler	KD350-2001	6.7		2254.23	
Hatz	1B30X-9903	6.8		1949.99	
Hatz	1B30X-9904	6.8		2399.99	
Hatz	1B30X-9903	6.8		1799	
Hatz	1B30X-9904	6.8		2299	
Lombardini	15LD350-ED6B56E0-SD	7.5		1050	
Kohler	PAKD4402001	9.1		2679.97	
Kohler	PAKD4402101	9.1		2769.97	
Kohler	PAKD4202001	9.75		3199.99	
Kohler	KD400-1001	9.8		2153.7	
Kohler	KD420-2101	9.8		2707.39	
Kohler	KD400-2001	9.8		2612.1	
Hatz	1B40-9928	9.9		2499.99	
Hatz	1B40-9929	9.9		3049.99	
Hatz	1B40-9928	9.9		2399	

Hatz	1B40-9929	9.9		2799	
Lombardini	15LD400-ED3A84E3	10		1200	
Hatz	1B50U29358	10.2		2999	
Kohler	KDW7021001A	15.4		4199.97	
Kohler	KDW702-1001	16.8		4458.08	
Kubota	KD1305-1J417-00000	17.6		3250	
Yanmar	3TNM68-ASA3	18.9		2850	
Hatz	2G409909	19.9		5995	
Yanmar	3TNM72-ASAT	22.9		3495	
Kohler	PAKDW10031001A	23.4		4199.99	
Kohler	PAKDW10031001-SD	23.4		3350	
Briggs	522447-0105	23.5		4250	
Briggs	522447-0106	23.5		4250	
Kubota	D902-E4B-ARS-1	24.8		4489.97	
Kubota	D902-E4B-SCG-1	24.8		4489.97	
Kubota	D902-E4B-STN-1	24.8		4489.97	
Kohler	KD6252-2001	25		5086.48	
Kohler	KD625-2-1001	25		4828.32	
Kohler	PAKD62525002	25.2		4599.99	
Kohler	KDW1003-1001	26.1		4767.11	
Briggs	582447-0405	31		3850	
Kohler	KDW1404-1001	34.9		5359.24	
Yanmar	3TNV84T-KSA	39		4225	
Kohler	KDW1601-1001	40.2		6766.27	
Deutz	D2001LO3	46		8995	
Kubota	Z600	15.5			5995
Kubota	722	20			5995
Perkins	1.1 L Power Unit	20			6995
Kubota	D905	25			6995
Ford	FSD 425	40			7995
Kubota	V3300	50			8995
Deutz	D2009-L04	48			9995
Deutz	D2011-L03	49			8995
Perkins	GN65629N	50			7700

Additional estimates were obtained from a local Kubota dealership. For these estimates, engines representing different ranges and types with the different engine size categories were selected. A summary of the engine cost information provided by the Kubota dealership is summarized in Table 5-15. Based on these estimates, the range of engine costs was estimated to be $3,000 to $4,000 for the 0-10 hp category, to be $4,000 to $6,000 for the 10-25 hp category, and to be $6,000 to $11,000 for the 25-50 hp category. The estimate of $11,000 per engine will also be used for the 50 to 75 hp category. These estimates are used for the market share cost estimates provided in Table 5-15.

Table 5-15: New Engine Costs for Engines in Different Size Categories (2016 USD)

	Engine Type	HP	List $	Prox Frt	REF>	Total	Series Population
0-10 hp	EA330-E4-NB1	6.9	$ 3,074.47	$ 130.00	1J194-00000	3,204.47	NA
	OC95-E4	9.4	$ 3,782.00	$ 130.00	1J198-21000	3,912.00	NA
10-25 hp	V1505-E4BG	20.2	$ 5,843.58	$ 250.00	1J938-00000	6,093.58	1821
	D1105-E4B	24.8	$ 5,012.04	$ 250.00	1J096-00000	5,262.04	1027
25-50 hp	D1803-CR-E4B	37.5	$ 10,022.26	$ 300.00	1J453-20000	10,322.26	353
	D1803-CR-T-E4B	49.6	$ 10,784.74	$ 300.00	1J454-20000	11,084.74	

The baseline engine costs can be multiplied by the total number of engines in each of the categories to provide an estimate of the total market share of engines in each of the different categories. The engine populations are developed under sections 3 and 6, and include 256,833 engines in the 0 to 50 hp category, 10,448 engines for the 0 to 10 hp category, 125,057 engines for the 10 to 25 hp category, 79,622 engines for the 25 to 50 hp category, and 41,666 engines in the 50 to 75 hp category. Based on these population and engine cost estimates, the total market for SORDEs in California is approximately $1,467,630,000 to $2,126,302,000 for the 0 to 50 hp category. The total market for SORDEs in California is approximately $31,344,000 to $41,792,000 for the 0 to 10 hp category, $500,228,000 to $750,342,000 for the 10 to 25 hp category, $477,732,000 to $875,842,000 for the 25 to 50 hp category, and $458,326,000 for the 50 to 75 hp category.

5.2.2 Emission Benefit Estimates

Estimates of the emissions benefits of more stringent emissions standards are based on the calculations conducted in section 6. For these calculations, DPFs were estimated to reduce PM by 95% and SCRs were estimated to reduce NO_x emissions by 55 to 85%. Based on the results in section 6, the estimated emissions reductions would be 12.46 (55% SCR efficiency) to 19.256 (85% SCR efficiency) tons per day of NO_x for the 25 to 75 hp category. The estimated PM reductions would be 0.372 (95% DPF efficiency) tons per day for the under 25 hp category. Note that no additional PM benefits are anticipated in 25-75 hp category and no NO_x benefits are assumed for the under 25 hp category.

Based on the amount of anticipated NO_x and PM emissions reduction per day that could be achieved from enhanced emissions control technologies, the total emissions reductions that would be achieved over a full year can be estimated by multiplying by 252 days, which is the number of working days in a year. Note that only working days were included for this estimate, as much of the equipment in the engine category would be used for industrial work-related tasks. Using this calculation, the emissions reductions that would be provided comparing the baseline when no controls are in place to the time when the fleet is fully outfitted with advanced emissions controls would be 3139.9 (55% SCR efficiency) or 4852.5 (85% SCR efficiency) tons per year of NO_x for 25 to 75 hp engines and 93.74 (95% DPF efficiency) tons per year of PM for under 25 hp (PM) categories.

For the purposes of this estimates, a 30-year time horizon were utilized for the complete turnover of the fleet to advanced emissions controls, consistent with the time frame utilized in the EPA estimates for Tier 4 construction equipment, as discussed above. It was assumed that fleet turnover is equally distributed over the full 30 year period, so for each year $1/30^{th}$ of the fleet would turn over. Thus, for the first year, the NO_x and PM reductions would be:

$$R_{NOx1}\ (55\%) = 3139.9 \text{ x } (1/30) = 104.66 \text{ tons,}$$

$$\text{or } R_{NOx1}\ (85\%) = 4852.5 \text{ x } (1/30) = 161.75 \text{ tons,}$$

$$\text{and } R_{PM1}\ (95\%) = 93.74 \text{ x } (1/30) = 3.12 \text{ tons,}$$

where R_{NOx1} and R_{PM1} represent the NO_x and PM emissions reductions for year 1, respectively.

For any given year *n* within the 30 year window, the NO_x and PM reductions in year *n* would be:

$$R_{NOxn}\ (55\%) = 3139.9 \text{ x } (n/30) = 104.66 \text{ x } n \text{ tons,}$$

$$\text{or } R_{NOxn}\ (85\%) = 4852.5 \text{ x } (n/30) = 161.75 \text{ x } n \text{ tons,}$$

$$\text{and } R_{PMn}\ (95\%) = 93.74 \text{ x } (n/30) = 3.12 \text{ x } n \text{ tons,}$$

where R_{NOxn} and R_{PMn} represent the NO_x and PM emissions reductions for year *n*, respectively.

The amount of PM and NO_x reductions for each year are shown in Table 5-16.

Table 5-16. Summary of Emissions Reduction

Year	PM Reductions			NO_x Reductions					
	Tons/year			Tons/year					
	(Control efficiency 95%)			(Control efficiency 55%)			(Control efficiency 85%)		
	0-10 hp	10-25 hp	Total	25-50 hp	50-75 hp	Total	25-50 hp	50-75 hp	Total
1	0.16	2.97	3.12	63.26	41.40	104.66	97.76	63.99	161.75
2	0.32	5.93	6.25	126.52	82.81	209.33	195.52	127.98	323.50
3	0.48	8.90	9.37	189.78	124.21	313.99	293.28	191.97	485.25
4	0.64	11.86	12.50	253.04	165.61	418.66	391.04	255.96	647.00
5	0.80	14.83	15.62	316.30	207.02	523.32	488.80	319.96	808.75
6	0.96	17.79	18.75	379.56	248.42	627.98	586.56	383.95	970.50
7	1.12	20.76	21.87	442.82	289.83	732.65	684.31	447.94	1132.25
8	1.28	23.72	25.00	506.08	331.23	837.31	782.07	511.93	1294.00
9	1.44	26.69	28.12	569.34	372.63	941.98	879.83	575.92	1455.75
10	1.60	29.65	31.25	632.60	414.04	1046.64	977.59	639.91	1617.50
11	1.76	32.62	34.37	695.86	455.44	1151.30	1075.35	703.90	1779.25
12	1.92	35.58	37.50	759.12	496.84	1255.97	1173.11	767.89	1941.00
13	2.07	38.55	40.62	822.39	538.25	1360.63	1270.87	831.89	2102.76
14	2.23	41.51	43.75	885.65	579.65	1465.30	1368.63	895.88	2264.51
15	2.39	44.48	46.87	948.91	621.05	1569.96	1466.39	959.87	2426.26
16	2.55	47.44	50.00	1012.17	662.46	1674.62	1564.15	1023.86	2588.01
17	2.71	50.41	53.12	1075.43	703.86	1779.29	1661.91	1087.85	2749.76
18	2.87	53.37	56.25	1138.69	745.26	1883.95	1759.67	1151.84	2911.51
19	3.03	56.34	59.37	1201.95	786.67	1988.62	1857.42	1215.83	3073.26
20	3.19	59.30	62.50	1265.21	828.07	2093.28	1955.18	1279.82	3235.01
21	3.35	62.27	65.62	1328.47	869.48	2197.94	2052.94	1343.82	3396.76
22	3.51	65.23	68.75	1391.73	910.88	2302.61	2150.70	1407.81	3558.51
23	3.67	68.20	71.87	1454.99	952.28	2407.27	2248.46	1471.80	3720.26
24	3.83	71.16	75.00	1518.25	993.69	2511.94	2346.22	1535.79	3882.01
25	3.99	74.13	78.12	1581.51	1035.09	2616.60	2443.98	1599.78	4043.76
26	4.15	77.10	81.24	1644.77	1076.49	2721.26	2541.74	1663.77	4205.51
27	4.31	80.06	84.37	1708.03	1117.90	2825.93	2639.50	1727.76	4367.26
28	4.47	83.03	87.49	1771.29	1159.30	2930.59	2737.26	1791.75	4529.01
29	4.63	85.99	90.62	1834.55	1200.70	3035.26	2835.02	1855.74	4690.76
30	4.79	88.96	93.74	1897.81	1242.11	3139.92	2932.78	1919.74	4852.51
Total Reduction	74.21	1378.82	1453.03	29416.09	19252.67	48668.76	45458.03	29755.91	75213.94

5.2.3 Cost/Benefit Analysis for California SORDEs

Based on the cost estimates developed in subsection 5.2.1 and the emissions benefits in subsection 5.2.2, cost-benefit estimates can be made. A summary of the cost benefits for enhanced emissions controls for 25 to 75 hp (NO_x) and under 25 hp (PM) SORDEs is provided in Table 5-17. Based on these estimates, the cost benefits in $ per lb of emission reduction were $15.29 for PM for the under 25 hp category and range from $0.38 to $0.59 for NO_x in 25 to 75 hp. For PM, the cost benefits in $ per lb of emission reduction are $23.09 for the 0 to 10 hp category and $14.87 for the 10 to 25 hp category. For the 25 to 50 hp category, the cost benefits in $ per lb of emission reduction range from $0.42 to $0.64 for NO_x. For the 50 to 75 hp category, the cost benefits in $ per lb of emission reduction range from $0.33 to $0.51 for NO_x. According to CARB staff, these NO_x costs are cheaper than approximately 70 to 80% of estimates for previous CARB rulemaking efforts (CARB, 2001, 2004, 2005, 2007).

Table 5-17. Cost-Benefit Analysis

	PM			NO_x					
	(Control efficiency 95%)			(Control efficiency 55%)			(Control efficiency 85%)		
	0-10 hp	10-25 hp	Total	25-50 hp	50-75 hp	Total	25-50 hp	50-75 hp	Total
Cost of DOC/DPF ($)	328	328	NA	NA	NA	NA	NA	NA	NA
Cost of SCR ($)	NA	NA	NA	474	474	NA	474	474	NA
Unit	10448	125057	135505	79622	41666	121288	79622	41666	121288
Total Incremental Cost ($)	$ 3,426,944	$ 41,018,696	$ 44,445,640	$ 37,740,828	$ 19,749,684	$ 57,490,512	$ 37,740,828	$ 19,749,684	$ 57,490,512
Total Emissions Reduction (tons)*	74.21	1378.82	1453.03	29416.09	19252.67	48668.76	45458.03	29755.91	75213.94
Cost per Ton ($)	$ 46,176.52	$ 29,749.17	$ 30,588.20	$ 1,283.00	$ 1,025.82	$ 1,181.26	$ 830.23	$ 663.72	$ 764.36
Cost per lb. ($)	$ 23.09	$ 14.87	$ 15.29	$ 0.64	$ 0.51	$ 0.59	$ 0.42	$ 0.33	$ 0.38

* Assuming that the turn over of the entire statewide off-road fleet will take 30 years, and that the annual fleet turn over rate is evenly distributed over those 30 years.

6 Emissions inventory and air quality impacts of emission control measures

An emission inventory is an estimation of the amount of pollutants actually or potentially discharged into the atmosphere that can be broken down by specified source categories. Emissions inventories play an important role in evaluating the potential impacts of emissions from a variety of different sources to the overall air quality. Consolidated emissions inventories along with weather forecast information are fed into models like the EPA's Community Multi-scale Air Quality (CMAQ) model to predict air quality for both temporal and spatial dimensions. In this way, emissions inventories provide the basis for the development of State Implementation Plans (SIPs) and the establishment of regulations and emissions standards needed to meet air quality goals. In this section, the potential impact of adopting more stringent future emissions standards for under 75 hp SORDEs will be evaluated. This evaluation includes an assessment of the potential benefits within the SORDE category itself, as well as benefits within the larger off-road equipment category and to the overall inventory. The information developed under this task could then be subsequently utilized in CMAQ runs to evaluate the potential benefits of more stringent SORDE emission standards to the overall air quality.

6.1 Overall Emissions Inventories in California

California has one of the largest emissions inventories of any state within the U.S. The overall emission inventory includes particulate matter (PM, PM2.5, PM10), NO_x, and reactive organic gases (ROG), as well as oxides of sulfur (SOx) and CO. The overall emission inventory incorporates a variety of different sources including on-road sources, off-road sources, stationary sources, areawide sources, and natural sources. The emissions inventory information was obtained from the CARB on-line emissions inventory data for 2017 (CARB, 2019a) with some information from Off-Road 2007 (CARB, 2019b). The overall emission inventory for California includes 3904.4 tons per day of PM emissions and 1481.6 tons per day of NO_x emissions, the two most critical pollutants in terms of the emissions controls evaluated in this study. Stationary sources and mobile sources, the latter of which includes the off-road sources category, are two of the main contributors to the overall emissions inventory, particularly for NO_x. A brief description of these major categories is provided in this section to provide a context for understanding the contribution of off-road emissions sources. For NO_x, these two categories combined account for 89.0% of the total statewide emissions. The contribution for these two sources for PM emissions is less, however, representing only 10.6% of the total statewide emissions, with areawide sources, such as road dust, fugitive dust, and construction and demolition, and natural sources, such as wildfires making up the majority of the PM contribution.

6.1.1 Stationary Sources

Stationary sources include emission categories like fuel combustion, waste disposal, cleaning and surface coating, petroleum production and marketing, and industrial processes. The fuel combustion subcategory includes manufacturing and industrial, service and commercial, electric utilities, food and agricultural processing, and petroleum refining. The waste disposal subcategory includes incinerators, landfills, sewage treatment, and soil remediation. The cleaning and surface coatings subcategory includes laundering, degreasing, coatings and related process solvents, printing and adhesives and sealants. The petroleum production and marketing subcategory includes oil and gas production, petroleum refining, and petroleum marketing. The industrial processes subcategory includes mineral processes, chemical, food and agriculture, glass and related products, and metal processes. The stationary source emission inventory includes 262.2 tons per day of NO_x emissions and 316.3 tons per day of PM emissions. Stationary sources also represent 17.7% of NO_x emissions and 8.1% of PM emissions in the overall statewide emissions inventory.

6.1.2 Mobile Sources

California has the largest transportation fleet of any state within the U.S. Mobile sources include emission categories like on-road motor vehicles and other mobile sources. On-road motor vehicles include light-duty passenger cars, light-duty trucks, heavy-duty gasoline trucks, heavy-duty diesel trucks, school buses, motor homes, and etc. Other mobile sources including aircraft, trains, ships, off-road equipment, recreational boats, etc. The mobile sources emission inventory includes 1,056.8 tons per day of NO_x emissions and 96 tons per day of PM emissions. Mobiles sources contribute 71.3% of NO_x emissions and 2.5% of PM emissions to the overall statewide emissions. On-road mobile sources contribute 43.0% of NO_x emissions, while other mobile sources contribute 28.3%. On-road mobile sources contribute 1.6% of PM emissions, while other mobile sources contribute 0.8%.

6.1.3 Off-Road Sources

Off-road sources include emission categories like transport refrigeration units, forklifts, tractors, loaders, scrapers, air compressors, off-highway trucks, light commercial equipment, contraction and mining equipment, industrial equipment, generator sets, excavators, lawn & garden tractors, yard tractors and etc. Emissions from off-road equipment are about 140.7 tons per day in NO_x emissions and 9.9 tons per day on PM emissions. Off-road equipment contributes 13.3% of NO_x emissions and 10.3% of PM emissions to the total mobile sources.

6.2 Emissions Inventory for Small Off-Road Diesel Engines

The emissions inventory for less the 75 hp SORDEs incorporates a variety of different sources including agricultural tractors, transport refrigeration units, lawn & garden tractors, welders, generator sets, pumps, etc.

In the off-road category, source emissions in general terms are calculated using an equation of the form shown below. Key metrics are the number of units (population), age of unit, hours of use, horsepower typical load factor, and efficiency of the emissions controls.

$$\mathbf{M_i = N * HRS * HP * LF * Ef_i *(1 - (ER/100))}$$

where

M_i = mass of emissions of ith pollutant

N =source population (units)

HRS = annual hours (gallons) of use

HP = average rated horsepower

LF = typical load factor

Ef_i = average emissions of ith pollutant per unit of use (e.g. grams/hp-hr)

ER = overall emission reduction efficiency, %

For the estimates in this section, the information was obtained from CARB's on-line emissions inventory tools (https://www.arb.ca.gov/orion/) for the calendar year 2017 in conjunction with information provided by the ARB off-road diesel analysis section/emissions inventory modeling group from Off-Road 2007 (CARB, 2019b). This information is provided in Table 6-1. Note that these emissions inventories include only PM and NO_x, as these are considered to be the most important contributions of SORDEs to the emissions inventory. These emissions inventories show that the major categories selected for this modeling represent 0.422, 9.398, 13.692, 8.962, and 32.474 tons per day of NO_x emissions, respectively, for 0 to 10 hp engines, 10 to 25 hp engines, 25 to 50 hp engines, 50 to

75 hp engines, and for all engines under 75 hp. These categories also represent 0.019, 0.372, 0.826, 0.671, and 1.889 tons per day of PM emissions, respectively, for 0 to 10 hp engines, 10 to 25 hp engines, 25 to 50 hp engines, 50 to 75 hp engines, and for all engines under 75 hp.

Table 6-1. Small Off-Road diesel engine population (pop.) and emission properties

Emission Rate (tons per day)	Horsepower range														
Small Off-Road Equipment Category	0-10			10-25			25-50			50-75			Totals 0-75		
	pop.	NO_x	PM	pop.	NO_x	PM	pop.	NO_x	PM	pop.	NO_x	PM	pop.	NO_x	PM
Total	**10448**	**0.4224**	**0.019**	**125057**	**9.398**	**0.372**	**79662**	**13.692**	**0.826**	**41666**	**8.962**	**0.671**	**256833**	**32.474**	**1.889**
Agricultural Tractors				31511	2.743	0.100	26029	3.416	0.343	28229	7.998	0.627	85769	14.157	1.070
Transport Refrigeration Units	255	0.021	0.001	7789	0.229	0.009	26799	7.049	0.255				34843	7.299	0.265
Lawn & Garden Tractors*				42716	2.731	0.106							42716	2.731	0.106
Commercial Turf Equipment*				11943	1.8917	0.0708							11943	1.892	0.071
Welders				3646	0.232	0.012	5254	1.006	0.074				8900	1.238	0.086
Generator Sets				9890	0.513	0.026	5102	0.575	0.036				14992	1.088	0.062
Pumps	4305	0.151	0.008	5572	0.265	0.014	2233	0.340	0.022				12110	0.757	0.045
Air Compressors				172	0.020	0.001	1051	0.224	0.017				1223	0.243	0.018
Other Agricultural Equipment				751	0.044	0.002							751	0.044	0.002
Crushing/Proc. Equipment*							213	0.104	0.008				213	0.104	0.008
Hydro Power Units	55	0.003	0.000	218	0.019	0.001							273	0.021	0.001
Pressure Washers				325	0.003	0.000	122	0.003	0.000				447	0.006	0.000
Sprayers				290	0.004	0.000	435	0.067	0.006	150	0.037	0.003	875	0.109	0.009
Signal Boards	3752	0.173	0.007	3745	0.173	0.007	18	0.004	0.000				7515	0.350	0.014
Rollers	806	0.035	0.001	1141	0.068	0.003	3967	0.266	0.023	33	0.009	0.001	5948	0.378	0.027
Cement and Mortar Mixers	681	0.013	0.001	740	0.016	0.001							1421	0.029	0.001
Plate Compactors	429	0.011	0.000	428	0.011	0.000							857	0.022	0.001
Other General Industrial/Construction Equipment	165	0.015	0.001	384	0.065	0.002	2176	0.327	0.030	823	0.172	0.011	3547	0.579	0.044
Skid Steer Loaders				2554	0.318	0.015	2747	0.162	0.009	9324	0.635	0.027	14625	1.115	0.050
Aerial Lifts				1241	0.053	0.002	3518	0.149	0.003	3106	0.111	0.003	7865	0.313	0.009

*These data obtained from Off-Road 2007 (CARB, 2019b)

6.3 Impact of Advanced Emission Controls for Small Off-Road Diesel Engines

Utilizing the emissions inventories provided in Table 6-1, estimates of the potential emissions inventory benefits of adding advanced emissions controls to SORDEs can be made. For these estimates, the main control technologies considered were DPFs and SCRs. For these calculations, DPFs were estimated to reduce PM by 95%. This was based on the emissions testing results, which showed greater than 95% PM reductions for both DPF applications. The SCR reductions were estimated to reduce NO_x emissions by 55 to 85%, where the 55% represents roughly the lower end of the emissions reductions seen during the hot start NRTC test, which both segments where the exhaust temperature is both too low to achieve good NO_x control and other segments where the good NO_x control is achieved. The 85% is a rough estimate of what a more optimized SCR system could achieve when it is integrated into an OEM application. To estimate the potential impact of control technologies, it was assumed that PM control technologies could be applied to engines under 25 hp and NO_x control technologies could be applied to engines range from 25 to 75 hp in the SORDE category. Hence, PM reductions are applied only to the under 25 hp engine category and NO_x reductions are applied only to the 25 to 75 hp engine category.

The results of these estimates are provided in Table 6-2, based on CARB's on-line emissions inventory estimates for calendar year 2017 and information supplied by ARB off-road diesel analysis n/emissions inventory modeling group. These results show that application of a DPF would reduce PM emissions from 0.391 tons per day to 0.019 tons per day for small off-road diesel engines less than 25 hp. The results show the application of SCR could reduce NO_x from 22.654 tons per day to 10.194-3.398 tons per day for small off-road diesel engines in the 25 to 75 hp range, assuming 55% and 85% control efficiencies, respectively. These reductions, in turn, would provide a 3.8% reduction in PM and 8.8-13.7% reduction in NO_x emissions for the total 2017 off-road equipment emissions inventory. In terms of the mobile source category overall, this would represent a 0.4% reduction in PM and 1.2-1.8% reduction in NO_x emissions for 2017 for total mobile sources.

Table 6-2. Small Off-Road diesel engine emission properties with aftertreatment system

Emission Rate (tons/day)	Horsepower range									
	0-10		10-25		25-50			50-75		
	PM		PM		NO_x			NO_x		
Small Off-Road Equipment Category	Current	95% Reduction	Current	95% Reduction	Current	55% Reduction	85% Reduction	Current	55% Reduction	85% Reduction
Totals	**0.019**	**0.0000**	**0.372**	**0.019**	**13.692**	**6.161**	**2.054**	**8.962**	**4.033**	**1.344**
Agricultural Tractors			0.105	0.005	3.416	1.537	0.512	7.998	3.599	1.200
Transport Refrigeration Units	0.001	0.000	0.034	0.000	7.049	3.172	1.057			
Lawn & Garden Tractors*			0.106	0.005						
Commercial Turf Equipment*			0.0708	0.004						
Welders			0.012	0.001	1.006	0.453	0.151			
Generator Sets			0.026	0.001	0.575	0.259	0.086			
Pumps	0.008	0.000		0.001	0.340	0.153	0.051			
Air Compressors			0.001	0.000	0.224	0.101	0.034			
Other Agricultural Equipment			0.002	0.000						
Crushing/Proc. Equipment*					0.104	0.047	0.016			
Hydro Power Units	0.000	0.000		0.000						
Pressure Washers			0.000	0.000	0.003	0.001	0.000			
Sprayers			0.000	0.000	0.067	0.030	0.010	0.037	0.017	0.006
Signal Boards	0.007	0.000		0.000	0.004	0.002	0.001			
Rollers	0.001	0.000		0.000	0.266	0.120	0.040	0.009	0.004	0.001
Cement and Mortar Mixers	0.001	0.000		0.000						
Plate Compactors	0.000	0.000		0.000						
Other General Industrial/Construction Equipment	0.001	0.000	0.001	0.000	0.327	0.147	0.049	0.172	0.077	0.026
Skid Steer Loaders			0.015	0.001	0.162	0.073	0.024	0.635	0.286	0.095
Aerial Lifts			0.002	0.000	0.149	0.067	0.022	0.111	0.050	0.017

*These data obtained from Off-Road 2007 (CARB, 2019b)

7 Evaluation of how new regulatory control measures could affect consumer choices and manufacturer market share

7.1 Background

Having a control technology that is technically feasible, cost-effective and has significant environmental benefits is likely to go forward, especially as diesel PM is toxic. However, an important question while implementing such technology is how it will affect the economic interest of the small off-road diesel engine manufacturers. From the ten thousand feet view, it is clear that products introduced by manufacturers in response to regulations will drive consumer choice and market share. It can be difficult to gauge how increasing the cost of controlling NO_x and PM emissions with each of the tested technologies might affect the economic interests of small off-road diesel engine manufacturers. As the cost of diesel-fueled engines increase, this could increase the likelihood of consumers switching from diesel-fueled to either gasoline-fueled engines or electric motors. A potential mass transition from diesel-fueled to gasoline-fueled engines in this sector of the off-road industry assuming ARB was to adopt more stringent NO_x and PM emission standards could also put some manufacturers at a competitive disadvantage based on the technologies identified and evaluated by the contractor.

The objective of this task of the study was to evaluate the potential impacts of more emissions regulations on small off-road diesel engines on the associated market for such engines or equipment. The approach for this task was to develop a survey to distribute to various engine, equipment, and aftertreatment manufacturers. In understanding the potential impacts on the marketplace, it is important to understand how such regulatory changes might impact production costs and product development cycles, and engine/equipment performance and operation, operational costs.

7.2 Factors that could impact the marketplace introduction of new technology for SORDE's

To address questions associated with imposing stricter limits on diesel exhaust, efforts were made to better understand the impacts on each of the different stakeholders, including the engine and equipment manufacturers, the aftertreatment providers, and the consumers who use this equipment. One common process used by the engine and equipment manufacturers is the product development cycle, so that was the starting point for this analysis.

7.2.1 Manufacturer Product Development Cycle

Introduction of a different product into a market requires a number of key decisions by a manufacturer starting with whether they have a solution for the stricter emissions limits to deciding whether the solution will be profitable. Towards that end, most companies follow a set approach and process for evaluating new product introduction. Discussions with a small engine manufacturer indicated they use a new product development process; however, their business model is proprietary and they will not share it.

Notwithstanding their response, leading companies have overhauled their product innovation processes after discovering through best practice research a form of a Stage-Gate new product development process. According to independent research studies between 70-85% of leading U.S.

companies now use Stage-Gate Process to drive new products to market. A simplified version is shown in Figure 7-1 and activities in each stage in Table 7-1.

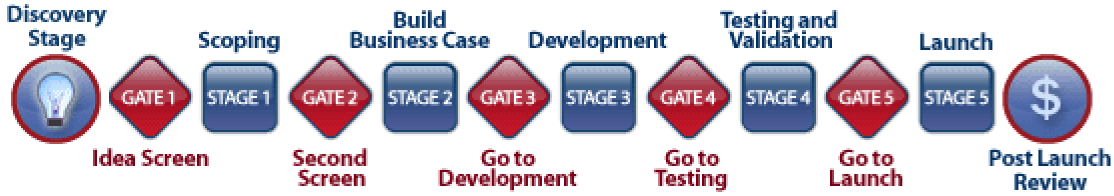

Figure 7-1 Stages Broken into Individual Elements

Table 7-1 Activities during the Individual Stages of a Stage Gate Process

Stage 0	**Discovery**: Activities designed to discover opportunities and to generate new product ideas.
Stage 1	**Scoping:** A quick and inexpensive assessment of the technical merits of the project and its market prospects
Stage 2	**Build Business Case:** This is the critical homework stage - the one that makes or breaks the project. Technical, marketing and business feasibility are accessed resulting in a business case which has three main components: product and project definition; project justification; and project plan
Stage 3	**Development:** Plans are translated into concrete deliverables. The actual design and development of the new product occurs, the manufacturing or operations plan is mapped out, the marketing launch and operating plans are developed, and the test plans for the next stage are defined.
Stage 4	**Testing and Validation:** The purpose of this stage is to provide validation of the entire project: the product itself, the production/manufacturing process, customer acceptance, and the economics of the project.
Stage 5	**Launch:** Full commercialization of the product - the beginning of full production and commercial launch.

Other published configurations are different and recognize the depth of projects may differ and the stage-gate is tailored to the complexity of the product changes. Copper (2014) is generally credited with identification of the Stage-Gate process and is most often referenced in the literature. Recent examples of scalable Stage-Gate Processes are shown in Figure 7-2.

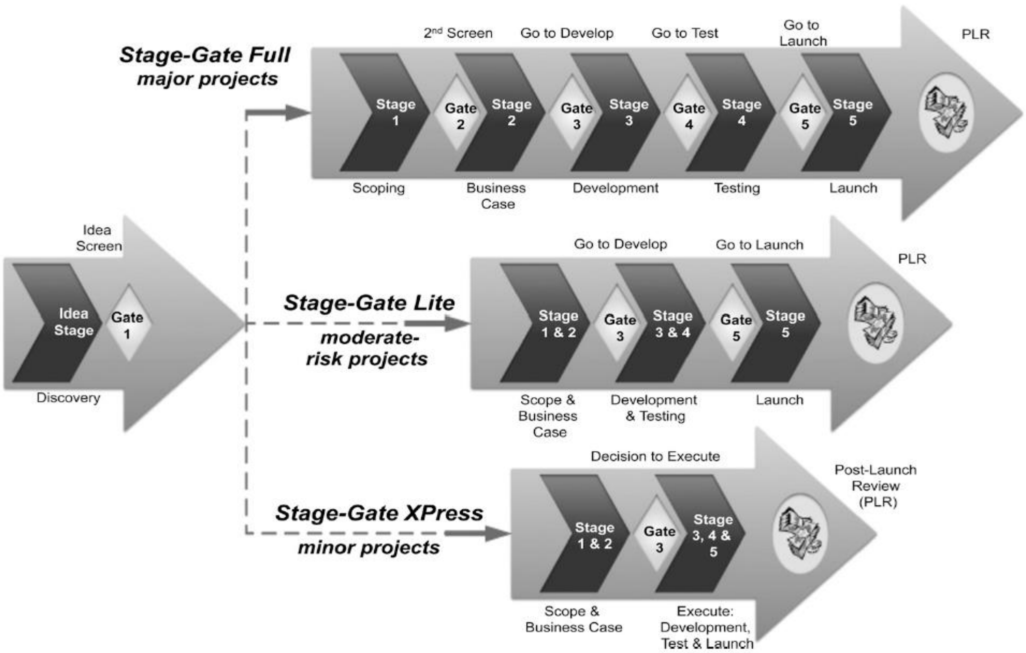

Figure 7-2 Scalable Stage-Gate Systems

As is evident in Figure 7-2, the depth of the Stage-Gate Process/System depends on the complexity of changes to the product platform and ranges from a Major platform change to a Minor project, or in their words as from Stage-Gate Full to Stage-Gate Xpress. For the case of a project reformulated to meet more stringent emissions standards, this involves adding emissions control units to an existing product manufacturing platform. Thus, the product development process for the CARB project would likely fall into Category 3 or Stage-Gate Xpress where individual stages are lumped together. Currently, the ARB and UCR project is carrying out the scoping and development of the technology with proven suppliers of emission control systems and leaving it to the product manufacturer to determine a business case at each stage in the process.

7.2.2 Applying the Cooper Stage-Gate Process to Stricter Emissions Standards

The stage-gate flow diagram for the current ARB and UCR project would likely be the Cooper Stage–Gate Xpress as shown in Figure 7-3. The current phase of the work is an active Proof of Concept to include building and testing a unit for 1,000 hours in the field. Measurements during this phase can be used to figure the benefits and cost-effectiveness of an enhanced regulation for small engine emissions.

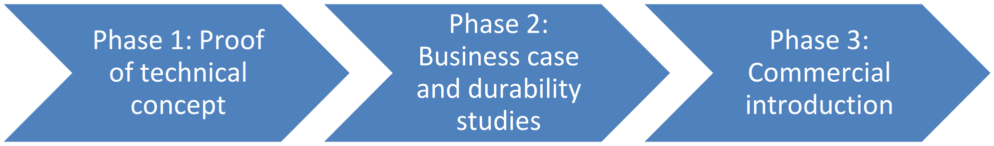

Figure 7-3 Stage-Gate Process for the Current ARB Project

Phase 1…This project was all about Phase 1 and showing that technology was available to reduce emissions from existing equipment with small diesel engines. Specifically, the project targeted adding NO_x control to engines near 50 hp, and PM control for engines near 25 hp. Issues related to the cost of control and whether the cost-effectiveness of removing pollutants was reasonable based on Carl Moyer standards or some other metrics were not considered during Phase 1. Notwithstanding, in order to improve the likelihood that such technology could be commercialized, the project worked with recognized and long-standing suppliers of emission control technology, both those in the United States and off-shore.

On reflection, Phase 1 took longer than expected to identify manufacturers of emissions control equipment who were willing to participate in the ARB demonstration project. Some were flatly not interested as they did not have the resources based on existing business demands. Given the need to cover existing business, there was no urgency even with those that moved the project forward and who looked to the opportunity to be ready ahead of competition if/when the small engine rules are toughened.

Phase 2…The Proof of Concept Phase would be followed by a manufacturer reviewing whether a business case can be developed based on the proposed regulation and data from the demonstration. These data include the added cost for the control technology and the actual performance in the field, both durability and acceptance by the user. When regulatory requirements are forced upon manufacturers in the areas of safety, emissions or fuel economy, the new regulations force trade-offs because the design changes or new features cannot pay for themselves but must be incorporated regardless of customer expectations and other considerations. Trade-offs decisions are complex due to the multiple operating systems on a product. For example, adding a DPF can create undesirable back-pressure on the engine if the soot is not burned off. Thus, the many operating systems on the unit must be handled holistically for safety and proper operation, otherwise the product may not meet customer expectations.

Phase 2 also brings into focus the work to demonstrate that the product can pass all emissions tests required for certification. Subsequent to certification is the requirement that the product be durable and for the useful life, as defined by ARB, can stay within the emissions requirements. This phase will require more field testing and emissions monitoring.

Phase 3…The final phase of the lower emission new product is the introduction and use in California. Some manufacturers questioned whether the California market is big enough to cover the cost of introducing a new product and how the new product will be received by their traditional customers. For the case studies underway, the engine manufacturers were contacted to learn what technical options fit within their company strategic plan. For example, while the current project focuses on adding emissions control technology, it is possible for a company to look to a technical solution based on an all-electric/battery solution. It is also possible for a company to review their market sales and decide to pull out of the California market, leaving California as a niche marketplace. One hypotheses is that control technology has advanced significantly since 1998 so only small changes are needed for the diesel engine to meet stricter emission limits. This hypothesis remains to be tested in surveys of the engine and equipment manufacturers.

7.2.3 Example of Perkins Engine Ltd. Stage-Gate Process

A more defined view of an overall Stage-Gate process on the development of diesel engines was included in a recent presentation[3] by Perkins Engine Company Limited, a subsidiary of Caterpillar Inc. The Perkins three Stage-Gate process is in Figure 7-4 and is similar to the three steps outlined by Cooper's Stage-Gate Xpress. Fortunately, Perkins provides more information and insight into

[3] SAE International Webinar on *Heavy-Duty Engine Design*, 7 June 2018.

the activities and tasks within each Phase. Based on the Perkins format, this project will have completed the concept phase or the proof of concept phase. Their Phase 2 focuses on meeting environmental compliance and durability testing to establish the warranty period. In Phase 2 multiple units will be field-tested for durability and for ensuring the product meets the environmental certification lifetime.

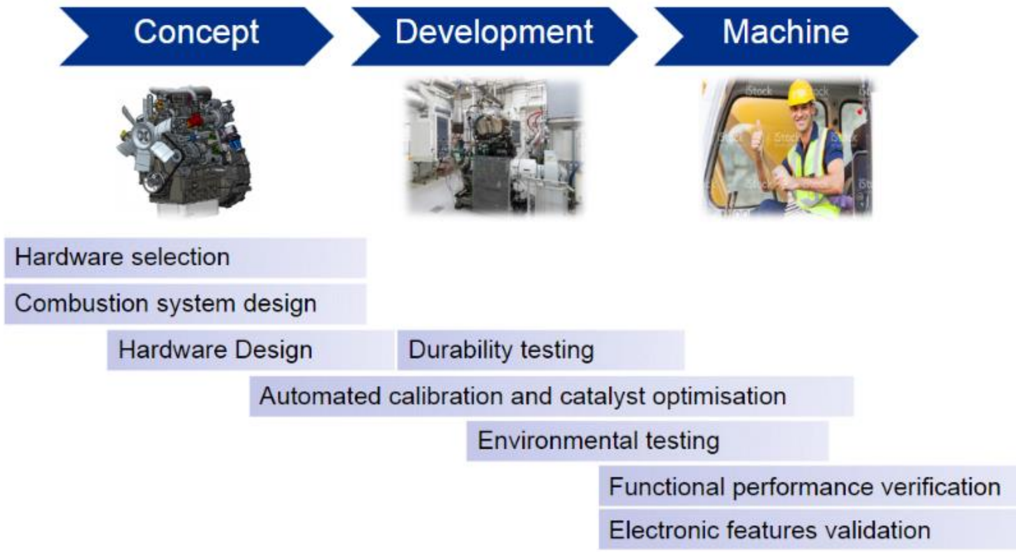

Figure 7-4 Engine Testing to Satisfy Customer Requirements

7.2.4 Input to Product Design: Satisfying Customer Requirements.

The specific Perkins Stage-Gate illustration for new product development says the important factor is satisfying customer needs/wants. But what are their expectations for performance improvements and how do you identify them?

As part of the normal business process, data from customers are collected continuously with modern data logging tools. An example from the Perkins presentations shows how the real-world operating cycles are obtained continuously from off-road equipment at all hours and locations. This is shown in Figure 7-5. Such user data enters into the decisions made by the product development team.

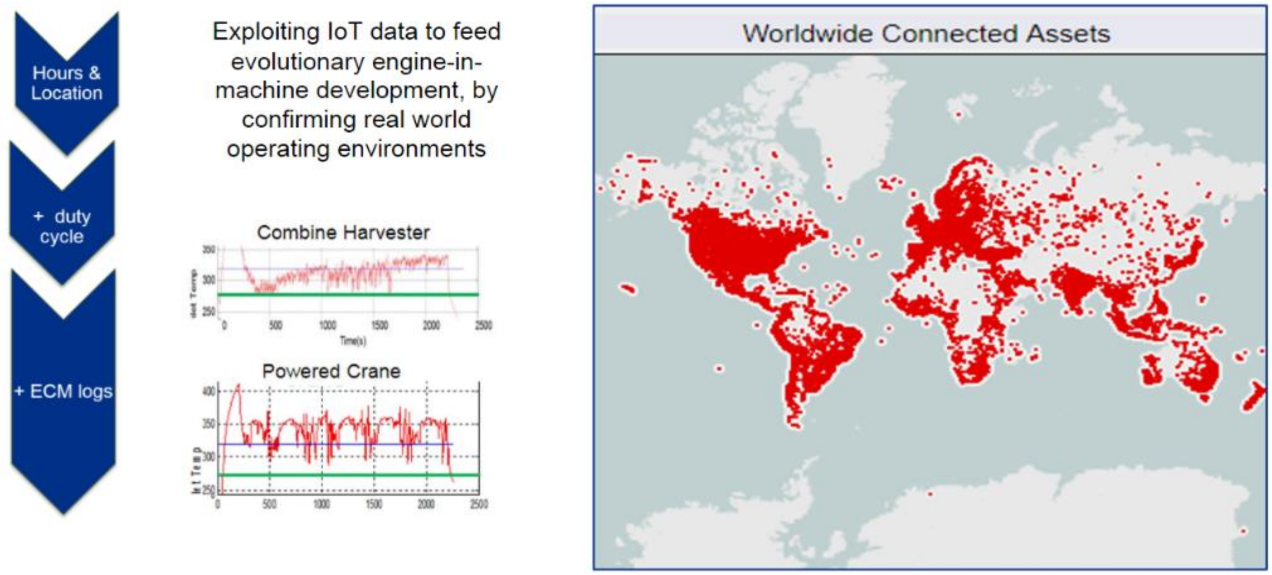

Figure 7-5 Data on Real-World Operations

Other approaches for gathering customer's interests include: 1) Voice of the Customer (VOC) and 2) External factors, see Table 7-2. VOC is a tool to survey customers' expectations, requirements and desires in a product. While VOC is important for defining both product performance and accessory features, it is usually a "look back" to what is already in the market rather than a 'look ahead' to the future. However, many factors other than VOC influence the final product definition, including a company decision to: target a known market niche, meet competition, or pursue perceived new opportunities. While the VOC data are an important driver in decisions for new product introduction, other demand-side inputs are at least as important, and in the end, the manufacturer weighs consumer choices, competition and especially the financial bottom line as the product specification and manufacturing plans are defined. Assuming the economic model developed for the new product meets company goals, the product moves through the first stage-gate and is integrated into the Annual Production Strategy. In the end, sales are the ultimate metric of success of a newly introduced product.

Table 7-2 Continuous Data Included in Early Stage Analysis

Voice of Customer (VOC) Data	External Factors
• Market research • Quality surveys • Dealer input • Focus groups • Market pulse studies	• Social/demographic projections • Political/regulatory trends • Economic outlook • Energy outlook • Strategic supplier assessment • Strategic competitor assessment

While no diesel engine manufacturer offered their approach to identifying customer requirements, Appendix A presents a detailed and step by step description of what the automotive industry goes through with each new major platform introduction. Clearly, in each step along the process, decisions are made as to whether the project is moving forward or getting pulled either for economic or product development reasons. Decisions on what product improvement to add are made in an organized and structured process.

7.2.5 Other Considerations when introducing new products

Besides the factors covered in the earlier sections, other factors enter into the company decision as to whether to go forward with a new product or to abandon that market. As companies do not want product proliferation, limiting the number of products is an important goal. However, limiting product designs is problematic due to the complexity associated with each country having: 1) its own fuel specifications; 2) a requirement that a specified percentage of the parts must be from that country and 3) each country having its emission standards and 4)… A global map presented by John Deere gives a glimpse of just the "Tier regulations" that companies are concerned about, as shown in Figure 7-6. Overlayed on this figure is the number of fuel specifications in those countries and other requirements, and you can imagine how difficult it is for the engine manufacturers to produce a limited number of engines or products.

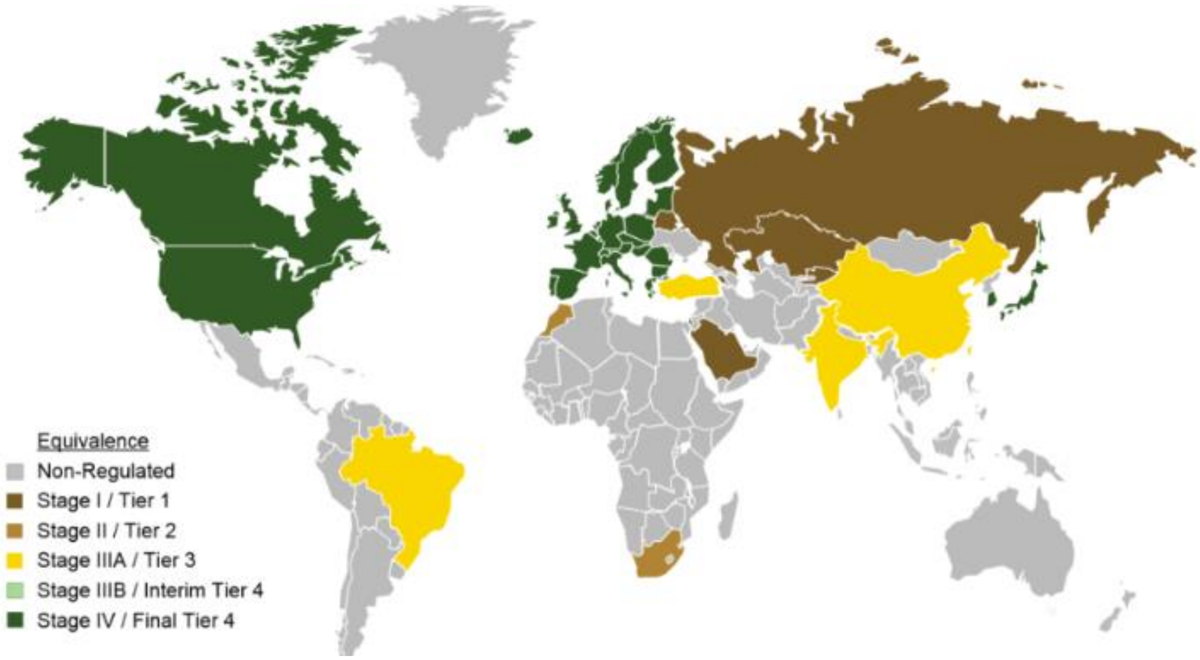

Figure 7-6 Global Nonroad Emissions Regulations are Diverse

7.3 Development of surveys for small engine and equipment manufacturers

As part of the project, it was hoped that some of the engine or equipment manufacturers or their trade associations, such as the engine Manufacturers Association, would share their perspective on several issues related to the introduction of a new regulation. The trade association covering emission controls was also contacted. Of interest was determining what specific changes might result for the SORDE marketplace as a consequence of stricter emission limits. For example, some equipment has key features that prohibit stricter controls. In another example, torque is important for a Bobcat and simply changing to the power of the engine may not be sufficient. Other metrics include affordability, on-site fueling, do the controls change the configuration and center of gravity of the product so that it is awkward/unstable/unsafe to handle, weight, etc. Towards that end, CARB and CE-CERT developed a broad survey of key information needed to better anticipate issues that might arise from the introduction of stricter standards. See the survey in Appendix F.

The survey was divided into four main sections:

1. Company Background…this section was to identify the engines/equipment the company already manufacturers and specifically the size ranges and what emissions control systems were in use.
2. Impact of stricter emission limits…this section provided manufacturer perspective on the feasibility of advanced emissions controls and impacts on production and associated costs. It was especially of interest to learn more about the time for the enhanced product to move from Stage 2 to Stage 3 in the stage-gate process.
3. Impacts of enhanced emissions controls on engine/equipment performance, operation, and operational costs. This included information on the initial capital expense (CAPEX) and operating expense (OPEX) of the new, lower-emission equipment.
4. Marketplace impacts…This section addressed how stricter emissions controls might lead to the replacement/substitution of diesel engines with gasoline engines or electric motors.

The surveys were modified slightly depending on whether the survey was directed towards and engine, equipment, or after-treatment manufacturer.

7.4 Survey Results

Surveys were distributed to engine and equipment manufacturers with high-market share and to engine and equipment manufacturer trade associations, and to the emission control trade association. A number of calls and correspondences were held with the engine and equipment manufacturers over an extended period of time, but in the end we were unable to get any survey responses from engine/equipment manufacturers. The only complete responses that were received were from members of the aftertreatment association.

The aftertreatment manufacturers provide controls for mobile, off-road, and stationary sources using both gasoline and diesel fuels. For the diesel off-road applications, all but one aftertreatment manufacturer provided both DPF and SCR systems. The horsepower range for their controls was from ≤ 7 hp to 5000 hp. The responsive aftertreatment manufacturers included both big and small businesses.

On the question of whether SORDE were candidates for additional controls, most thought adding aftertreatment or engine controls was feasible and could be done for a reasonable cost. One manufacturer noted the aftertreatment for < 25 hp diesel applications was feasible using a passively regenerating DPF in combination with an electrical heating device.

Another manufacturer with an electrically heated device observed that due to the additional power requirements that a case-by-case study would be needed to know what applications would be successful.

Another manufacturer indicated that the wall-flow DPFs and SCRs used for on-road applications would not be transferable to <50 hp category due to high design costs coupled with low price targets for finished products diesel particulate filters. They did believe that DOCs and partial flow DPFs might be feasible.

Aftertreatment manufacturers believed that 2 to 3 years would be needed to add DPF systems. Aftertreatment systems add additional complexity in terms of new sensors and ECM calibration, and upgraded alternators or stators for electrically heated systems One manufacturer suggested these costs would be about a few hundred dollars while another said the sensors were commercially available at a low cost. This is clearly a topic with associated uncertainty. In terms of additional development time for a new DPF system, two manufacturers suggested the technology was developed, with one noting that additional validation would be needed, and the other manufacturer suggested 2,000 full-time equivalent (FTE) hours. In any case, as shown in Figure 7-4, a major portion of getting through the second stage-gate is verifying the added aftertreatment will meet regulatory specifications for activity and longevity. This requires a significant number of units to be field-tested. As to the costs/time required for design, field testing and warranty of new certification units, one manufacturer suggested one to two months per engine family, although this probably does not represent the time needed for the associated engine development and to accumulate the needed field hours to prove the new design. It seems rather short. Another manufacturer suggested $250,000 per application, and another suggested $150,000 to certify and verify a new design.

For SCR systems, manufacturers similarly suggested a 2-3-year lead times to market, the need for a new ECM and production sensors. One manufacturer suggested 3,000 hours of field testing for new SCR applications. Another manufacturer pointed to the added urea tank as a placement problem on some off-road equipment. In terms of the costs for the design, field testing, and warranty of new certification, one manufacturer suggested production costs would be about twice the cost of a DPF system due to the complexity of the mixer/controller and space requirements; a second suggested costs similar to those of a DPF, and a third suggested the substrate and SCR wash-coat development costs should not exceed $25,000 for engines less than 2 liters. Like DPFs, the SCR technology is transferrable; however, data on specific applications are lacking so uncertainty in cost and time to implement is high. Likely over 3 years will be needed.

For questions raised about performance and operational impacts and costs, the aftertreatment manufacturers described a number of concerns, many of which were solved in developing on-road applications. These concerns included the higher back-pressure with DPFs and the potential for plugging and engine damage if not accounted for in the design. Other concerns included: the higher tailpipe gas temperature during regeneration and up to 10% increased fuel consumption for a DPF. One manufacturer said increases in fuel consumption of 1-2% are equivalent to about 3% of the power output. Some concerns were noted on the added weight and placement of the DEF tank and the essential need for durability testing in the field.

Based on DPF and SCR applications in on-road applications, the aftertreatment manufacturers believed that proper overall system design for the combustion and aftertreatment processes would provide equipment meeting all user and regulatory requirements. Manufacturers recognized that a new soot management module would be needed in the ECM. Another noted that new designs of the combustion process with SCR and reduced/no EGR could allow increased engine power and fuel efficiency.

It was clear that a new operator training would be required and OPEX could increase. With added aftertreatment, there would be a burden on operations to clean the DPF and to refill the urea tank used for the SCR. DPFs require ash cleaning approximately every 2,000 to 8,000 hours, which can take up to 6 hours, or using a DPF-exchange taking up to 2 hours. Frequency of refilling the urea tank depends on use but likely can be designed to occur with an oil change. The OPEX with added aftertreatment was estimated to be about $300 to $400 per cleaning. Aftertreatment manufacturers did not expect changes to the current useful life of the engine and equipment, now ranging from 8,000 to 10,000 hours or 7 years of operational life.

There was a range of responses to the question about whether the aftertreatment costs were reasonable compared to the full cost of the equipment. It is suggested that up to 10% of the new equipment cost might be reasonable. Some aftertreatment manufacturers suggested the costs could range to 20% of the cost of new equipment to 50% of the cost of the engine. Other manufacturers were not sure so an answer to this question will need further investigation.

Aftertreatment manufacturers suggested that the implementation of significantly stricter emission regulations will motivate SORDEs equipment manufacturers to work with their suppliers to identify solutions, including adding aftertreatment to the diesel engine or replacing diesel engines with gasoline engines or even replacing diesel engines with electric motors. One manufacturer noted that depending on the application, most off-road equipment users prefer diesel engines because their lifetime is twice that of gasoline engines and diesel fuel is used with the larger off-road equipment so it allows a common fuel in the field and less chance for mistakes. With seemingly daily advances in electrical applications and lower costs, one manufacturer thought there might be a path to replace diesel engines with powerful electric motors if batteries with sufficient lifespans become available.

Perhaps the most interesting question was about their views on which off-road applications would be easier to install aftertreatment. Here the manufacturer's suggested that DOCs, TWCs with gasoline engines, and partial flow DPFs and other passive systems would be the easiest to implement. One manufacturer suggested steady speed applications like water pumps, TRUs, generators, skid-steer loaders, and welders would be most adaptable, while multi-speed/transient applications would be more difficult. Designing a fixed precious metal content on the DOC/DPF to assure a high level of catalyst efficiency over a wide/variable speed range is quite challenging and might lead to a high and costly metals loading.

A total DOC+DPF add-on system is considerably more complex, would be more difficult and expensive to add based on what was learned in the on-road applications. One manufacturer said that active DPFs and SCR would be possibly cost-prohibitive and that the use of emissions controls would likely need to be incentivized through legislation.

It should be noted that while the information obtained from the aftertreatment manufacturers provides a good starting point for understanding the potential impacts of implementing more stringent standards, the extent of this information is still limited due to the lack of responses from the engine and equipment manufacturers. In particular, the engine and equipment manufacturers have the most direct role in development, demonstration, durability testing, and certification of the final product engines or equipment, and the more direct interaction with the final end users of these products. It is expected that if more stringent regulations in the SORDE category are pursued, that additional feedback from engine and equipment manufacturers should be sought to more accurately access the regulatory impacts on the marketplace.

7.5 Electrification of SORDE Equipment

7.5.1 Background

In the earliest development of this project, a core question was about identifying aftertreatment technology that could be transferred from the large diesel engine applications to the small off-road diesel engine applications. A second question was raised about the numbers of diesel engines that would be replaced with gasoline engines.

What was not anticipated at the launch of this project was the rapid development of hybrid and electrical applications for all-sizes of on- and off-road equipment and the plummeting price of batteries. Much of this revolution was brought about by the investment strategies of CARB and by the increasing sales of all electric cars that lead to economies of scale for battery production. Thus, today the SORDE equipment marketplace has the potential for a revolution, like being experienced in the automotive marketplace. When this project was launched there were a few electric car options, and today, electric and plug-in hybrid electric cars are now 7.8 percent of all new car sales.[4]

We believe that SORDE and other off-road equipment are in a transition/revolutionary period and like the automotive market, will change considerably in the next few years. Clearly, the number of hybrid and all-electric units will grow rapidly. Some changes have already taken place and are discussed in the following section. This section includes a brief discussion of the TRU, ride mower, and broader construction categories, representing some of the applications that were evaluated for aftertreatment technologies in the current study.

7.5.2 Hybrid and Electric Transportation Refrigeration Units

As truck manufacturers move toward electric-powered vehicles and components, not surprisingly, the same trend is emerging for trailer refrigeration[5]. This is particularly important, as the global refrigerated vehicle market is expected to reach $16.5 billion by 2022. Suppliers of transport refrigeration units are quickly moving down the path of the all-electric TRU as they design and test prototypes of future products. These developments were driven by customer demand for increased efficiency and lower maintenance costs, and by emerging regulations which would ban diesel exhaust emissions from reefer units. Electric-powered reefers also are a potential solution to compliance with new reefer emissions reduction mandates being promoted by the California Air Resources Board.

One of the market share leaders is Carrier Transicold, and today they offer a hybrid refrigeration system with all-electric standby capability when parked for loading or unloading. This enables the unit to cool the transport without a diesel engine. Carrier suggests the use of electric standby also reduces operating costs by 40-70%, depending on the cost of fuel. The use of electric standby can also reduce engine run-time and help to extend maintenance intervals. Another advantage of electric standby is that when a reefer trailer is parked for loading, unloading or staging, it can be operated via an electric power source, providing full refrigeration capacity while eliminating noise and emissions from the refrigeration unit.

The other major market share leader is Thermo King and they recently announced a partnership with electric-vehicle manufacturer Chanje to collaborate on an all-electric step van for refrigerated deliveries. The prototype, a version of Chanje's V8100 all-electric medium-duty panel van, is equipped with a Thermo King V-520 RT refrigeration unit and ThermoLite solar panels. Thermo King was also the first company to offer European customers hybrid and non-diesel trucks and trailer refrigeration units. Currently, more than 20,000 trucks and trailers are on the road with these all-electric technologies. This technology can also work in medium-duty, refrigerated applications,

[4] https://ww2.arb.ca.gov/news/sales-electric-cars-breaking-records-california
[5] https://www.ttnews.com/articles/electric-powered-reefer-units-gaining-momentum

which are increasing in the U.S. due to a steady increase in consumers doing their shopping online and expecting fast home deliveries.

Others are trying to enter the market with all-electric TRUs for Class 6-8 trucks. These products are undergoing demonstration.

7.5.3 Electric Ride Mowers

There have also been considerable advances in the electrification of mowers[6]. In terms of cordless electric walk-behind mowers, the number of available mower models has increased from around 5 to over 50 different models. These models typically use interchangeable lithium batteries in the 36, 54 and 72-volt size range, and reportedly have sufficient capacity to mow up to a 1/2 acre. This sector continues to grow as homeowners and corporations look for ways to be more environmentally friendly.

MTD has developed lawn tractors/ride mowers that are available in the U.S. The Cub Cadet CC 30 e ride mower is equipped with a 1,500 watt-hours, 56V lithium-ion with a 30-inch single blade and up to a 1-hour or 1-acre cut time. Their larger Cub Cadet XT1-LT42e is an all-electric lawn tractor/ride mower with a 42-inch tractor that uses a 3,000 watt-hours, 56-volt lithium-ion (60-amp-hour) battery, and three brushless direct-drive motors. It provides up to 1.5 hours of cut time or 2 acres. There is also a Cub Cadet RZT S Zero–Residential Electric Zero-Turn that uses a deep discharge battery instead of lithium-ion battery. It has a 42-inch deck and also incorporates a regenerative circuit for downhill braking and charging the battery.

Ryobi currently has two electric zero-turns and two electric riders on the market. The Ryobi RY48ztr100 is a 48V Zero Turn Electric Riding Mower powered by 75 amp-hour or 100 amp-hour batteries and 4 high-powered brushless motors. This mower has a 42 in. steel deck and can cut up to 2.25/3.0 acres on a single charge. Another Ryobi ride mower is the RM480E – RM480ex electric riding mower with a deep discharge battery.

Weibang makes a rear-engine electric rider. It has a 30-inch deck with a 72-volt lithium-Ion Battery with the capacity of 1/3 to 3/4-acre yards and will mow up to 2 hours on a charge**.** Mean Green Mowers has a complete line of lithium-powered commercial riding, stand-on, walk-behind and trimming mowers. They feature interchangeable high-capacity battery packs that can quickly be exchanged to power their mowers all day long.

Outside of the U.S., Husqvarna sells a Rider Battery, which is its first battery-powered ride mower. It uses a 36-volt, 125 amp-hour battery, 1500-Watt drive motor, and two 800-Watt decks motors. It has a 33-inch deck and has a maximum runtime of 90 minutes.

7.5.4 New Hybrid and Electric Construction Equipment

Construction equipment applications are another important opportunity for replacement of diesel engines with all-electric engines. The following subsection covers selected examples of electrification efforts. As noted, the SORDE world is changing rapidly so this section only represents a current snapshot of the equipment but the possibilities are endless as creativity and application boundaries expand.

[6] https://todaysmower.com/2019-electric-riding-mowers/

Bobcat has produced a 1-ton fully electric mini excavator, the E10e zero tail swing (ZTS).[7] Bobcat unveiled the prototype for their E10e electric mini excavator back in 2016.[8] The excavator was developed at Bobcat's innovation center in Dobris, Czech Republic. The E10e can run for a full for an eight-hour day on its lithium-ion batteries when coupled with an external supercharger with normal work breaks factored in. The excavator takes just two and a half hours to charge.

JCB has developed an electric excavator, 19C-1 E-Tec mini excavator.[9] This mini-excavator has a 2-ton (1.9-tonne) capacity, and can work all day on a single, six-hour charge, with a fast charger capable of cutting the charge time in half also available.

NASTA, Norway's largest distributor of construction equipment, in cooperation with Siemans and Sintef, is developing a 30-inch excavator with battery and fuel cell technology.[10] NASTA and Siemens provide expertise in construction applications, while the hydrogen and battery expertise are provided by SINTEF. NASTA specializes in Hitachi products, and the first prototype will be built on the chassis of an existing Hitachi excavator. The excavator is being developed as part of the Zero Emissions Digger (ZED) program in cooperation with the Research Council of Norway, Enova, and Innovation Norway. The prototype was planned to be demonstration ready for use at construction sites near Oslo in 2019.

Tobroco-Giant introduced the G2200E and G2200E X-TRA, which are electric compact wheel loaders.[11] They are equipped with a 48-volt lithium-ion battery that has a minimum capacity of 12.3 kilowatts. The loaders have two separate electric motors of 6.5 kilowatts to drive the machine and 11.5 kilowatts for hydraulics. The standard G2200E has a capacity of 3,657 pounds and the X-TRA version has a lift capacity of 4,850 pounds. The loaders are designed for indoor operations or urban construction sites.

Volvo Construction Equipment introduced the EX2 mini-excavator with two lithium-ion batteries that deliver 38kWh and can operate for eight hours. Volvo CE has announced their intention to develop 10 new electric excavators and loaders in 2020.[12] The new machines will include electrified versions of the company's smallest compact excavators (EC15 to EC27) and its smallest compact wheel loaders (L20 to L28). The company is planning to stop new diesel engine-based development on the models that are going electric. Volvo also is testing hybrid concepts, which includes an LX1 compact loader and a dual-power EX1 excavator that can operate with its diesel engine or an onboard electric motor.[13] Volvo has also partnered with Skanska on an electric quarry demonstration.[14] In addition to substantial reduction in emissions of criteria pollutants, the results

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[7] https://www.equipmentworld.com/bobcat-rolls-out-the-z10e-its-first-electric-mini-excavator/
[8] https://www.constructconnect.com/blog/electric-dreams-will-heavy-construction-equipment-go-electric
[9] https://www.equipmentworld.com/equipment-roundup-jcb-case-ardco/
[10] https://cleantechnica.com/2018/01/30/scandinavia-home-heavy-duty-electric-construction-equipment-truck-development/
[11] https://www.equipmentworld.com/tobroco-giant-unveils-g2200e-its-first-electric-compact-wheel-loader-alongside-three-new-articulated-loaders/
[12] https://www.equipmentworld.com/volvo-ce-to-launch-up-to-10-electric-excavators-and-loaders-by-2020-replacing-diesel-models-entirely/
https://electrek.co/2019/01/17/construction-equipment-electric-volvo-ce/
[13] https://www.constructionequipment.com/charge-ahead-electric-machines
[14] https://www.equipmentworld.com/volvo-electric-site-quarry-test-reduced-emissions-by-95/

of the demonstration showed a 98 percent reduction in carbon emissions, a 70 percent reduction in energy costs, and a 40 percent reduction in operator costs.

Hyundai Construction Equipment and Cummins announced they are working together to develop electrified heavy equipment.[15] The two companies have demonstrated a battery-powered mini excavator. This mini excavator is powered by eight battery modules created by Cummins that provide a 35 kWh of total energy. The mini-excavator is designed to work an eight-hour shift with a three-hour charge.

Caterpillar has significant market share in off-road equipment and announced that it will divide its Energy & Transportation segment into two divisions, one of which will focus entirely on powering equipment with electrification.[16] Caterpillar UK has also partnered with AVID Technology, a British company that specializes in the electrification and hybridization of construction equipment, to develop a battery system for heavy machinery.[17] Caterpillar has developed a D7E bulldozer that uses a generator to produce 480 volts of AC power which is changed with 640 volts of DC power.[18] Caterpillar more recently announced its Next Generation Electric Drive crawler dozer, the D6 XE. The D6 XE's propulsion module uses a single motor and a single electronic control module, versus two on their existing D7E. In Norway, Pon Equipment, in association with Caterpillar, has developed a 25-inch electric excavator called the 323F that will be sold as part of the company's Z Line of zero-emissions earth-moving and construction equipment.[19] The machine can operate for up to 7 hours on a single battery charge. With a 1000-volt charger, a full battery charge can be obtained in about 90 minutes. The electric digger is intended for use in urban areas where noise and emissions standards are becoming increasingly restrictive.

Komatsu's HB365LC-3 hybrid excavator, building on the HB215LC-1's design, uses a generator-motor behind the engine and an electric swing motor that captures swing-deceleration energy via regenerative braking.[20] The captured energy is stored in an ultra-capacitor, which subsequently releases that energy to assist swing motor acceleration during the next cycle.

John Deere has developed several hybrid wheel loaders.[21] The 644K Hybrid uses an engine-driven AC generator that sends power, via a power-control module, to an AC electric motor, which drives a simplified three-speed power-shift transmission having no torque converter and no reverse clutch. The more recent 944K Hybrid wheel loader uses a different approach, where the engine drives two electrical generators, which send power to the electric motor positioned at each wheel hub.

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[15] https://www.equipmentworld.com/hyundai-cummins-unveil-jointly-developed-delectric-mini-excavator/

[16] https://www.equipmentworld.com/cat-separates-energy-segment-into-divisions-for-electric-power-and-oil-gas-marine-amid-executive-shuffle/

[17] https://www.equipmentworld.com/cat-strikes-uk-alliance-with-avid-technology-to-develop-batteries-for-heavy-equipment/

[18] https://www.constructionequipment.com/charge-ahead-electric-machines

[19] https://cleantechnica.com/2018/01/30/scandinavia-home-heavy-duty-electric-construction-equipment-truck-development/

[20] https://www.constructionequipment.com/charge-ahead-electric-machines

[21] https://www.constructionequipment.com/charge-ahead-electric-machines

Wacker Neuson has an existing lineup of zero-emissions machines including two electric wheel loaders, two battery-powered rammers, and a dual-power excavator.[22] In 2018, they debuted their first battery-powered mini excavator, the EZ17e, which will be available in Europe in 2019. The EZ17e runs on lithium-ion batteries but can also be plugged into a regular power outlet or high voltage outlet to run the machine and charge it while it operates. The EZ17e can provide seven hours of power and charges overnight on a household outlet and in four hours if plugged into a high voltage current.

These selected examples are but a glimpse of what is expected to be announced and demonstrated in the next few years. The world of hybrid and electrical innovation is exploding and opportunities not anticipated at the time of this project are endless.

[22] https://www.constructconnect.com/blog/electric-dreams-will-heavy-construction-equipment-go-electric

8 Summary and Conclusions

Off-road emissions represent one of the most important categories for emissions inventories. The existing standard for tier 4 off-road engines were developed based on a Regulatory Impact Analysis (RIA) conducted back in 2004, and do not require aftertreatment for NO_x below 75 hp or PM below 25 hp. Since aftertreatment control devices for diesel vehicles and equipment are considerably more common now, the use of these strategies for < 75 hp engines may be considerably more viable that at the time of the previous RIA, which could warrant renewed consideration for adopting more stringent exhaust standards for the < 75 hp sector.

The objective of this study is to evaluate the potential effectiveness, feasibility, and cost-effectiveness of implementing regulations on mobile off-road diesel engines with rated powers of < 75 hp that will require the use of advanced emission control strategies, such as DPFs and SCR. This project includes a comprehensive review of available aftertreatment and other technologies, demonstration of selected aftertreatment technologies on actual engines and verification of the emissions performance of these devices through a series of emissions and durability tests, evaluation of the cost implications of the added emissions control strategies, evaluation of the potential impacts of additional emissions controls on the emissions inventory, and evaluation of the potential impact on the small engine marketplace and consumer choice in that area.

A summary of the results and conclusions of this study are provided as follows.

Technology Overview

A comprehensive product review of existing and emerging emission control technologies to significantly reduce PM and NO_x that could be employed by off-road diesel engines with power ratings of < 75 hp was carried out as part of this project. The review included after-treatment technologies such as DPFs, SCR, cooled EGR, EFI, alternative fuels and other emerging technologies that might be cost-effective for these engines.

- As part of the technology overview, a review of engine technologies and applications was made. The breakdown of engine manufacturers was primarily based on the 2004 EPA rulemaking, as this was the latest publically available characterization of sales data. From this data, the EPA estimated that sales of engines in the 0 to 25 hp category comprised 18 percent (approximately 135,828 units) of the nonroad market.
- The largest manufacturers of engines in this category were Kubota (36,601 units), Yanmar (32,126 units), and Kukje (21,216 units). The next largest category surveyed by EPA was the 25 to 75 hp engines, with no differentiation made for the 25 to 50 hp engines. Of the categories surveyed by EPA, this was the largest in terms of the number of units, with approximately 281,157 units sold in year 2000, comprising 38 percent of nonroad engines sold that year.
- The EPA separated the sales fractions based on direct-injection and indirect injection engines, with DI engines accounting for 59 percent of this category with 165,427 units. Yanmar and Kubota also represented an important fraction of this market, with Yanmar and Kubota comprising 19 percent and 13 percent, respectively, of the DI engines sold, and with Kubota comprising 51 percent of the sale of engines with IDI.
- Other major manufacturers of DI engines at the time included Deutz (16%), Hatz (12%), Isuzu (10%), Caterpillar/Perkins (10%), and Deere (8%). Other major manufacturers of

IDI engines at the time Daewoo Heavy Industries (12%), Ihi-Shibaura (12%), Isuzu (8%), and Caterpillar/Perkins (5%).

A breakdown of equipment types by population in California was provided by ARB staff. For the under 25 hp category, these engines are separated into two categories: 0-10 and 10-25 hp. These data indicate that the largest fraction of equipment types are lawn and garden tractors, agricultural tractors, commercial turf equipment, generator sets, and transportation refrigeration units.

Emissions controls for the SORDE category include both engine controls and exhaust aftertreatment. Engine certification data from 2014 indicate that both DI and IDI engines are still both prevalent in production. In the under 25 hp category, emissions control in this power size category was predominantly through engine design modifications. In the 25 to 50 hp category, more sophisticated emission control strategies were utilized. Nearly all engines specify either engine design modifications or the use of EGR or cooled EGR, with most of the engines showing EGR control. The majority of the engines also include some level of DPF including DPFs in combination with DOCs. Many of the DPF-equipped engines are also equipped with electronic controls. In terms of future emissions controls, the most prominent technologies included the application of DPFs for under 25 hp engines and the application of SCR for engines between 25 to 75 hp.

Table 8-1. Population Breakdown of Small Off-road Diesel Engines under 50 hp

Small Off-Road Equipment Category by hp range	population			
	0-10	10-25	25-50	50-75
Total	**10448**	**125057**	**79662**	**41666**
Agricultural Tractors		31511	26029	28229
Transport Refrigeration Units	255	7789	26799	
Lawn & Garden Tractors		42716		
Commercial Turf Equipment		11943		
Welders		3646	5254	
Generator Sets		9890	5102	
Pumps	4305	5572	2233	
Air Compressors		172	1051	
Other Agricultural Equipment		751		
Crushing/Proc. Equipment			213	
Hydro Power Units	55	218		
Pressure Washers		325	122	
Sprayers		290	435	150
Signal Boards	3752	3745	18	
Rollers	806	1141	3967	33
Cement and Mortar Mixers	681	740		
Plate Compactors	429	428		
Other General Industrial/Construction Equipment	165	384	2176	823
Commercial Turf Equipment		11943		
Skid Steer Loaders		2554	2747	9324
Aerial Lifts		1241	3518	3106

Technology Demonstrations

As part of the technology review, aftertreatment control devices from a variety of different suppliers were reviewed. This included Johnson Matthey, Tenneco, BASF, Continental, Donaldson, Proventia, DCL, Rypos, Dinex, and other representative member companies from the Manufacturers of Emission Control Association (MECA). Based on this survey, four applications/technologies were selected for the technology demonstration. This included two DPF applications for the under 25 hp category, and two SCR/DPF applications for the 25 to 50 hp category. The DPF applications included a TRU with a Proventia DPF and a mini-excavator with a DCL DPF. The 25 to 50 hp demonstrations include a ride mower with a BASF/Continental/Donaldson SCR system and a skid steer with a Johnson Matthey/Tenneco SCRT. Note that the demonstrations for the NOx control devices were specifically targeted for under 50 hp applications to demonstrate the feasibility of lower NOx emissions standards for off-road diesel engines less than 50 hp. Table 8-2 provides a summary of these demonstrations.

Table 8-2. Summary of Demonstrations

Small Off-Road Equipment Category	OEM Aftertreatment	Aftertreatment Retrofitting Methodology	hp range
TRU	None	Proventia DPF	< 25
Mini-excavator	None	DCL DPF	< 25
Ride mower	DPF/DOC	BASF/Donaldson/Continental SCR system	25-50
Skid Steer	DOC	Johnson Matthey/Tenneco SCRT system	25-50

Emissions Testing

Emissions testing was conducted in conjunction with each of the demonstration projects, including a baseline, and degreened baseline (where the aftertreatment equipped engine was tested after 25 hours of aging), and at the completion of the field demonstration at 1,000 hours. Additional testing was also conducted for the mini-excavator and skid steer demonstrations, as 1,000 hours of field demonstration could not be obtained for these demonstrations, and hence additional engine dynamometer aging was required to simulate a full 1,000 hours of use. A summary of the emissions results is as follows:

- For the Proventia DPF on the TRU engine, PM reductions of >98% were found for both the degreened and the 1,000 aging tests. Some increases in NO_x emissions were also observed with this unit, as the heating unit used to facilitate DPF regeneration was placed on the intake side of the engine. Proventia has addressed this issue in some newer designs of the unit by putting the heating unit on the exhaust side of the engine.
- The DCL DPF on the mini-excavator showed similar PM reductions in the >98% range during both the degreened and the 1,000 aging tests.
- The tests on the SCR-equipped ride mower engine showed significant NO_x reductions 70.4%, 47.4%, and 57.0%, respectively, for the C1, NRTC cold start, and NRTC hot start baseline degreened tests, and NOx reductions of 90.5%, 25.8%, and 64.95%, respectively, for the C1, NRTC cold start, and NRTC hot start 1,000 tests. The SCR also provided additional reductions of THC, NMHC, and CO emissions, despite the initially low levels for OEM engine that was equipped with a DOC and DPF.
- The tests on the SCRT-equipped engine for the skid steer showed significant NO_x reductions over the C1, for the degreened baseline, post field demonstration, and 1,000 hour aging tests, ranging from 78 to 88%, with no indication of deterioration between the degreened baseline and 1,000 hour aging test. The reductions for the hot start and cold start NRTCs were lower, ranging from 52 to 59%, which could be attributed to the SCR not reaching the dosing temperature threshold of 190 °C during the initial parts of these cycles.

Emissions Inventory Analysis

Emissions inventory analyses were also conducted to evaluate the potential emissions benefits implementing additional regulations in the under 75 hp SORDE category. For these calculations, DPFs were estimated to reduce PM by 95%. The SCR reductions were estimated to reduce NO_x

emissions by 55 to 85%. These results show that application of a DPF would reduce PM emissions from 0.391 tons per day to 0.019 tons per day for small off-road diesel engines less than 25 hp. The results show the application of SCR could reduce NO_x from 22.654 tons per day to 10.194-3.398 tons per day for small off-road diesel engines in the 25 to 75 hp range, assuming 55% and 85% control efficiencies, respectively. These reductions, in turn, would provide a 3.8% reduction in PM and 8.8-13.7% reduction in NO_x emissions for the total 2017 off-road equipment emissions inventory. In terms of the mobile source category overall, this would represent a 0.4% reduction in PM and 1.2-1.8% reduction in NO_x emissions for 2017 for total mobile sources.

Cost/Benefit Analysis

A preliminary cost/benefit analysis was conducted based on approximate engine and aftertreatment costs and rough estimates of expected emissions reductions for the DPF and SCR aftertreatment control systems. Aftertreatment costs were estimated to be $266 + $62 = $328 for a DPF + DOC for under 25 hp engines based values for the 1.5-liter engines available in the literature. For the cost of adding SCR NO_x aftertreatment to 25 to 75 hp engines, an estimate $474 was utilized, which represents an average of the cost estimates for 2- and 2.5-liter engines available in the literature.

The cost estimates for the DPF+DOC can be combined with the engine populations for the <25 hp engines to provide a cost estimate for implementing more stringent regulations on PM emissions in this engine size range. These costs would be applied to 10,448 engines for the 0 to 10 hp category and 125,057 engines for the 10 to 25 hp category. So, the total cost of implementing DPF + DOCs for the entire fleet of under 25 hp small off-road diesel engines would be $44,445,640.

The cost estimates for the SCR systems can be combined with the engine populations for the 25 to 75 hp engines to provide a cost estimate for implementing more stringent regulations on NO_x emissions in this engine size range. These costs would be applied to 79,622 engines for the 25 to 50 hp category and 41,666 engines for the 50 to 75 hp category. So, the total cost of implementing SCR technology for the entire fleet of under 25 to 75 hp small off-road diesel engines would be $57,490,512.

A summary of the cost benefits for enhanced emissions controls for 25 to 75 hp (NO_x) and under 25 hp (PM) SORDEs is provided in Table 8-3. Based on these estimates, the cost benefits in $ per lb of emission reduction were $15.29 for PM for the under 25 hp category and range from $0.38 to $0.59 for NO_x in 25 to 75 hp. For PM, the cost benefits in $ per lb of emission reduction are $23.09 for the 0 to 10 hp category and $14.87 for the 10 to 25 hp category. For the 25 to 50 hp category, the cost benefits in $ per lb of emission reduction range from $0.42 to $0.64 for NO_x. For the 50 to 75 hp category, the cost benefits in $ per lb of emission reduction range from $0.33 to $0.51 for NO_x. According to CARB staff, these NO_x costs are cheaper than approximately 70 to 80% of estimates for previous CARB rulemaking efforts.

Table 8-3: Cost-Benefit Analysis

	PM			NO_x					
	(Control efficiency 95%)			(Control efficiency 55%)			(Control efficiency 85%)		
	0-10 hp	10-25 hp	Total	25-50 hp	50-75 hp	Total	25-50 hp	50-75 hp	Total
Cost of DOC/DPF ($)	328	328	NA	NA	NA	NA	NA	NA	NA
Cost of SCR ($)	NA	NA	NA	474	474	NA	474	474	NA
Unit	10448	125057	135505	79622	41666	121288	79622	41666	121288
Total Incremental Cost ($)	$ 3,426,944	$ 41,018,696	$ 44,445,640	$ 37,740,828	$ 19,749,684	$ 57,490,512	$ 37,740,828	$ 19,749,684	$ 57,490,512
Total Emissions Reduction (tons)*	74.21	1378.82	1453.03	29416.09	19252.67	48668.76	45458.03	29755.91	75213.94
Cost per Ton ($)	$ 46,176.52	$ 29,749.17	$ 30,588.20	$ 1,283.00	$ 1,025.82	$ 1,181.26	$ 830.23	$ 663.72	$ 764.36
Cost per lb. ($)	$ 23.09	$ 14.87	$ 15.29	$ 0.64	$ 0.51	$ 0.59	$ 0.42	$ 0.33	$ 0.38

* Assuming that the turn over of the entire statewide off-road fleet will take 30 years, and that the annual fleet turn over rate is evenly distributed over those 30 years.

Market Survey

A market survey was conducted to evaluate the potential impacts of more stringent regulation on the marketplace for SORDE engines and equipment. The survey evaluated the feasibility of advanced emission controls for SORDE engine and equipment, the impacts on production costs and product development cycles, the impacts on engine/equipment performance and operation, operational costs, and the impacts on costs and the potential that diesel engines could be replaced by gasoline engines or electric motors. The literature was also reviewed to better understand product development cycles. The surveys were sent to engine, equipment, and aftertreatment manufacturers and related trade associations. No responses were obtained from any engine or equipment manufacturers, or engine or equipment manufacturer trade associations, so the information obtained was only from aftertreatment manufacturers.

A typical 3-stage product development cycle for the development of diesel engines is shown in Figure 8-1, based on a recent presentation by Perkins Engine Company Limited, a subsidiary of Caterpillar Inc. This includes a stage 1 concept or proof of concept phase, a phase 2 development phase that would include system optimization, durability testing, and emissions testing, and phase 3 that would include performance verification in a machine.

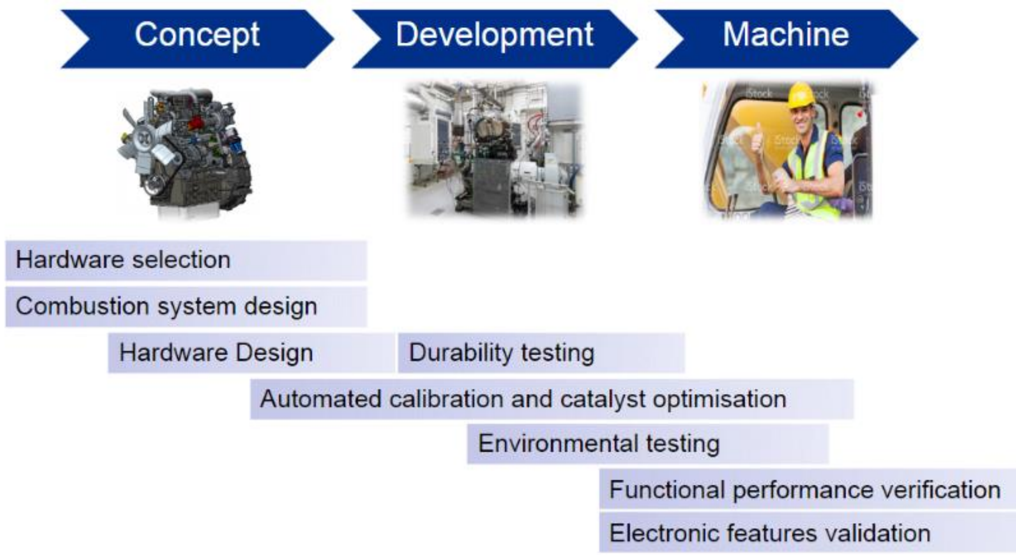

Figure 8-1 Engine Testing to Satisfy Customer Requirements

For the survey itself, the aftertreatment manufacturers that responded to the survey included both small and large businesses providing aftertreatment for mobile, off-road, and stationary applications over a size range from ≤ 7 hp to 5000 hp. While the aftertreatment manufacturers generally thought the application of aftertreatment to SORDEs was feasible, these applications could require additional accessories, such as electrically heated devices, that the feasibility could be case-specific, and that the aftertreatment costs would represent a greater fraction of the final costs than for higher horsepower applications. The aftertreatment manufacturers suggested costs/time for design, development, and verification as 2 to 3 years, \$150,000 to \$250,000 per application, and 2,000 to 3,000 FTE hours, although this may not represent the full costs to bring the products to market in a fully integrated piece of equipment. In terms of operating impacts, the aftertreatment manufacturers indicated potential fuel economy impacts, the need for DPF ash cleaning, and the addition of DEF fluid. In terms of durability, the aftertreatment manufacturers did not anticipate that the aftertreatment systems would significantly impact the lifetime of the engine itself, with some adding that 8,000 to 10,000+ hours or 7 years of operational life is typical of such systems. In terms of potential marketplace impacts, there was a range of responses to the question about whether the aftertreatment costs were reasonable compared to the full cost of the equipment. Some aftertreatment manufacturers suggested the costs would be a bit high or not reasonable, and some provided ranges that the aftertreatment costs would be 20% of the cost of the equipment to 50% of the cost of the engine. The aftertreatment manufacturers also suggested that the implementation of regulations requiring aftertreatment on SORDEs could encourage the replacement of diesel engines with gasoline engines or electric motors.

It should be noted that while the information obtained from the aftertreatment manufacturers provides a good starting point for understanding the potential impacts of implementing more stringent standards, the extent of this information is still limited due to the lack of responses from the engine and equipment manufacturers. In particular, the engine and equipment manufacturers have the most direct role in development, demonstration, durability testing, and certification of the final product engines or equipment, and the more direct interaction with the final end users of these products. It is expected that if more stringent regulations in the SORDE category are pursued, that additional feedback from engine and equipment manufacturers should be sought to more accurately access the regulatory impacts on the marketplace.

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Appendix

Appendix A - TRU Emission Results Appendix

Table A-1. TRU Emission Results

Baseline	**THC (g/exp)**	**NMHC (g/exp)**	**CH4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Test 1	0.551	0.557	0.000	2.992	17.649	2975.326	0.4746	3.1940
Test 2	0.523	0.537	0.000	3.129	17.751	3060.290	0.4521	3.1931
Test 3	0.556	0.569	0.000	3.048	17.628	3037.750	0.5026	3.1935
Degreened Baseline	**THC (g/exp)**	**NMHC (g/exp)**	**CH4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Test 1	0.072	0.072	0.000	0.005	17.368	3085.554	0.0075	2.9952
Test 2	0.051	0.051	0.000	0.000	18.337	3152.752	0.0089	2.9958
Test 3	0.026	0.026	0.000	0.000	18.695	3175.438	0.0084	2.9959
1,000 Hour	**THC (g/exp)**	**NMHC (g/exp)**	**CH4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work r (kW-hr)**
Test 1	0.070	0.069	0.002	-0.041	19.83	3119.5	0.0064	3.0063
Test 2	0.078	0.061	0.016	0.063	20.02	3115.4	0.0084	3.0127
Test 3	0.080	0.060	0.020	0.044	19.86	3124.9	0.0051	3.0063
Ave	**THC (g/exp)**	**NMHC (g/exp)**	**CH4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Baseline	0.543	0.554	0.000	3.056	17.68	3024.5	0.4764	3.1935
Degreened Baseline	0.049	0.049	0.000	0.002	18.13	3137.9	0.0083	2.9956
1,000 Hour	0.076	0.063	0.013	0.022	19.90	3119.9	0.0066	3.0084

Appendix B - Ride Mower Emission Results.

Table B-1. Ride Mower C1 Cycle Emission Results

Baseline	THC (g/exp)	NMHC (g/exp)	CH_4 (g/exp)	CO (g/exp)	NO_x (g/exp)	CO_2 (g/exp)	PM Mass (g)	Work (kW_hr)
Test 1	0.063	0.031	0.000	0.555	36.14	6140.5	0.0333	7.0154
Test 2	0.210	0.174	0.000	0.901	34.99	6182.5	0.0273	7.0164
Test 3	0.198	0.173	0.000	0.941	35.56	6173.8	0.0320	7.0177
Degreened Baseline	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW_hr)**
Test 1	0.004	0.000	0.000	0.512	10.53	6263.7	0.0566	7.0163
Test 2	0.009	0.000	0.000	0.542	10.82	6357.2	0.0566	7.0186
Test 3	0.004	0.000	0.000	0.263	10.21	6393.5	0.0392	7.0175
1,000 Hour	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW_hr)**
Test 1	0.115	0.076	0.039	0.348	3.71	6511.7	0.003	6.9827
Test 2	0.118	0.085	0.033	0.178	2.97	6535.9	0.002	7.0094
Test 3	0.129	0.087	0.042	0.051	3.44	6226.4	N.A.	7.0244
Ave	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW_hr)**
Baseline	0.157	0.126	0.000	0.799	35.56	6165.6	0.0309	7.0165
Degreened Baseline	0.006	0.000	0.000	0.439	10.52	6338.1	0.0508	7.0175
1,000 Hour	0.121	0.083	0.038	0.192	3.38	6424.7	0.003	7.0055

Table B-2. Ride Mower NRTC Cycle Emission Results

Baseline	THC (g/exp)	NMHC (g/exp)	CH_4 (g/exp)	CO (g/exp)	NO_x (g/exp)	CO_2 (g/exp)	PM Mass (g)	Work (kw_hr)
Cold	0.200	0.165	0.000	0.746	14.31	3287.0	0.0116	3.2197
Hot	0.157	0.128	0.000	0.245	12.64	3248.2	-0.0002	3.2187
Degreened Baseline	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kw_hr)**
Cold	0.184	0.156	0.000	0.741	7.52	3314.8	0.0080	3.2180
Hot	0.139	0.106	0.000	0.303	5.44	3257.8	0.0080	3.2209
1,000 Hour	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kw_hr)**
Cold	0.179	0.139	0.039	0.797	10.70	3275.3	0.018	3.2449
Hot	0.163	0.118	0.045	0.094	4.47	2999.1	0.016	3.2479

Appendix C – Excavator Emission Results

Table C-1. Excavator C1 Cycle Emission Results

Baseline	THC (g/exp)	NMHC (g/exp)	CH_4 (g/exp)	CO (g/exp)	NO_x (g/exp)	CO_2 (g/exp)	PM Mass (g)	Work (kW-hr)
Test 1	0.948	0.947	0.000	3.516	22.01	4568.4	0.5281	4.4762
Test 2	0.984	0.966	0.000	3.519	24.10	4613.5	0.5613	4.4747
Test 3	0.993	0.954	0.000	3.719	25.99	4658.9	0.5415	4.4746
Degreened Baseline	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Test 1	0.039	0.039	0.000	0.316	25.43	4619.7	0.0105	4.4744
Test 2	0.026	0.016	0.000	0.565	26.25	4666.0	0.0103	4.4746
Test 3	0.023	0.013	0.000	0.565	26.07	4660.0	0.0136	4.4775
Degreened Baseline #2	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Test 1	0.266	0.193	0.073	0.144	23.06	4693.6	0.0059	4.4229
Test 2	0.263	0.206	0.057	0.273	22.89	4642.0	0.0035	4.4283
Test 3	0.277	0.229	0.048	0.335	23.28	4667.2	0.0032	4.4226
1,000 Hour	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Test 1	0.643	0.511	0.131	1.079	22.06	4411.1	0.0084	4.4506
Test 2	0.449	0.381	0.068	1.172	22.17	4413.9	0.0067	4.4380
Test 3	0.409	0.350	0.059	1.229	22.11	4417.6	0.0053	4.4341
Ave	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Baseline	0.975	0.956	0.000	3.585	24.03	4613.6	0.5436	4.4752
Degreened Baseline	0.029	0.023	0.000	0.482	25.92	4648.6	0.0115	4.4755
Degreened Baseline #2	0.269	0.209	0.059	0.251	23.075	4667.587	0.004	4.425
1,000 Hour	0.500	0.414	0.086	1.160	22.115	4414.211	0.007	4.441

Table C-2. Excavator NRTC Cycle Emission Results

Baseline	THC (g/exp)	NMHC (g/exp)	CH_4 (g/exp)	CO (g/exp)	NO_x (g/exp)	CO_2 (g/exp)	PM Mass (g)	Work (kw-hr)
Cold	0.655	0.647	0.000	2.739	15.25	2654.6	0.2716	2.1164
Hot	0.679	0.674	0.000	2.638	14.83	2586.6	0.2645	2.1143
Degreened Baseline	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kw-hr)**
Cold	0.091	0.100	0.000	0.389	13.30	2693.4	0.0038	2.2321
Hot	0.143	0.148	0.000	0.368	13.56	2681.3	0.0009	2.2306
Degreened Baseline #2	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kw-hr)**
Cold	0.208	0.200	0.008	0.543	13.70	2628.8	0.0033	2.2260
Hot	0.199	0.185	0.015	0.250	13.61	2579.7	0.0014	2.2083
1,000 Hour	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kw-hr)**
Cold	0.350	0.337	0.013	0.888	12.57	2455.9	0.0040	2.2181
Hot	0.340	0.330	0.010	0.639	12.87	2400.6	0.0026	2.2056

Appendix D – Skid Steer Emission Results

Table D-1. Skid steer C1 Cycle Emission Results

Baseline	THC (g/exp)	NMHC (g/exp)	CH_4 (g/exp)	CO (g/exp)	NO_x (g/exp)	CO_2 (g/exp)	PM Mass (g)	Work (kW-hr)
Test 1	0.948	0.947	0.000	3.516	22.01	4568.4	0.5281	4.4762
Test 2	0.984	0.966	0.000	3.519	24.10	4613.5	0.5613	4.4747
Test 3	0.993	0.954	0.000	3.719	25.99	4658.9	0.5415	4.4746
Degreened Baseline	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Test 1	0.039	0.039	0.000	0.316	25.43	4619.7	0.0105	4.4744
Test 2	0.026	0.016	0.000	0.565	26.25	4666.0	0.0103	4.4746
Test 3	0.023	0.013	0.000	0.565	26.07	4660.0	0.0136	4.4775
Post Field Demo	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Test 1	4.6307	4.6318	-0.001	-0.2710	5.6647	7895.9953	0.0109	9.3609
Test 2	1.2448	1.2544	-0.010	-0.3743	3.6242	7952.2875	0.0136	9.3595
Test 3	0.9046	0.9105	-0.006	-0.3384	4.2087	7959.8506	0.0127	9.3584
1,000 Hour	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Test 1	0.2859	0.3124	-0.026	-0.3566	5.1764	8026.5730	0.0209	9.3616
Test 2	0.2387	0.2689	-0.030	-0.3311	5.4155	7795.0387	0.0121	9.3613
Test 3	0.2072	0.2397	-0.032	-0.2940	5.5669	8055.7145	0.0112	9.3618
Ave	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kW-hr)**
Baseline	0.975	0.956	0.000	3.585	24.03	4613.6	0.5436	4.4752
Degreened Baseline	0.029	0.023	0.000	0.482	25.92	4648.6	0.0115	4.4755
Post Field Demo	2.2600	2.2656	-0.006	-0.3279	4.4992	7936.0445	0.0124	9.3596
1,000 Hour	0.2439	0.2736	-0.030	-0.3272	5.3863	7959.1087	0.0147	9.3615

Table D-2. Skid steer NRTC Cycle Emission Results

Baseline	THC (g/exp)	NMHC (g/exp)	CH_4 (g/exp)	CO (g/exp)	NO_x (g/exp)	CO_2 (g/exp)	PM Mass (g)	Work (kw-hr)
Cold	0.655	0.647	0.000	2.739	15.25	2654.6	0.2716	2.1164
Hot	0.679	0.674	0.000	2.638	14.83	2586.6	0.2645	2.1143
Degreened Baseline	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kw-hr)**
Cold	0.091	0.100	0.000	0.389	13.30	2693.4	0.0038	2.2321
Hot	0.143	0.148	0.000	0.368	13.56	2681.3	0.0009	2.2306
Post Field Demo	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kw-hr)**
Cold	2.164	2.107	0.057	7.792	8.36	4118.5	0.0227	4.3027
Hot	2.930	2.895	0.035	1.101	7.09	4008.7	0.0124	4.3080
1,000 Hour	**THC (g/exp)**	**NMHC (g/exp)**	**CH_4 (g/exp)**	**CO (g/exp)**	**NO_x (g/exp)**	**CO_2 (g/exp)**	**PM Mass (g)**	**Work (kw-hr)**
Cold	0.440	0.408	0.031	9.172	8.106	4172.8	0.0071	4.3040
Hot	0.416	0.398	0.019	2.579	8.266	4115.9	0.0142	4.3030

Appendix E – Detailed Example of an Automotive Product Development Cycle

Introduction of a substantially different product into a market often requires a new technology platform and an in-depth review of the new product will be profitable. The product development approach used by the automotive industry is represented in reports from the Center for Automotive Research[23] (CAR) as shown in Figure E-1.

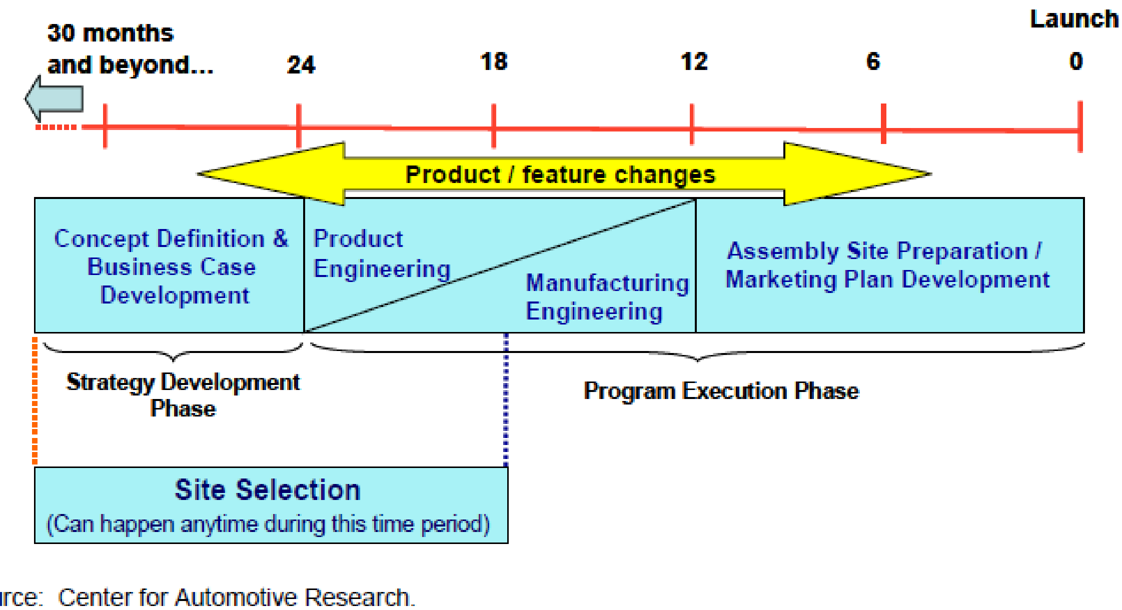

Figure E-1 Overview of the Stages of Automotive Product Development

As is evident, changing product designs or adjusting manufacturing plants to meet new specifications takes time and generally follows a set process with tough decisions made along each step. At each stage in the process, a business case analysis needs to be carried out in order to evaluate how likely the business is to recover an acceptable investment rate for investment in the new product. In any case, it takes considerable expertise and time to introduce a new product with significant/platform changes. Accordingly, time needs to be allocated for design, development and production planning for tooling and supplier contracting.

CAR also provided an in-depth perspective on the development of the detailed and real automotive business case study shown in Figure E-2. In each layer, as the onion is peeled back, more information is collected and interconnected. Apparent in the detailed analysis is the overlay of external inputs and the interconnection with the strategic plan of the company. The figure provides detail on the numerous parameters that drive the final decision. As part of the business some data are collected continuously; for example, the 1) Voice of the Customer (VOC) and 2) External factors.

[23] Hill, K., Edwards, M., Szakaly, S., Center for Automotive Research, *How Automakers Plan Their Products*, July 2007

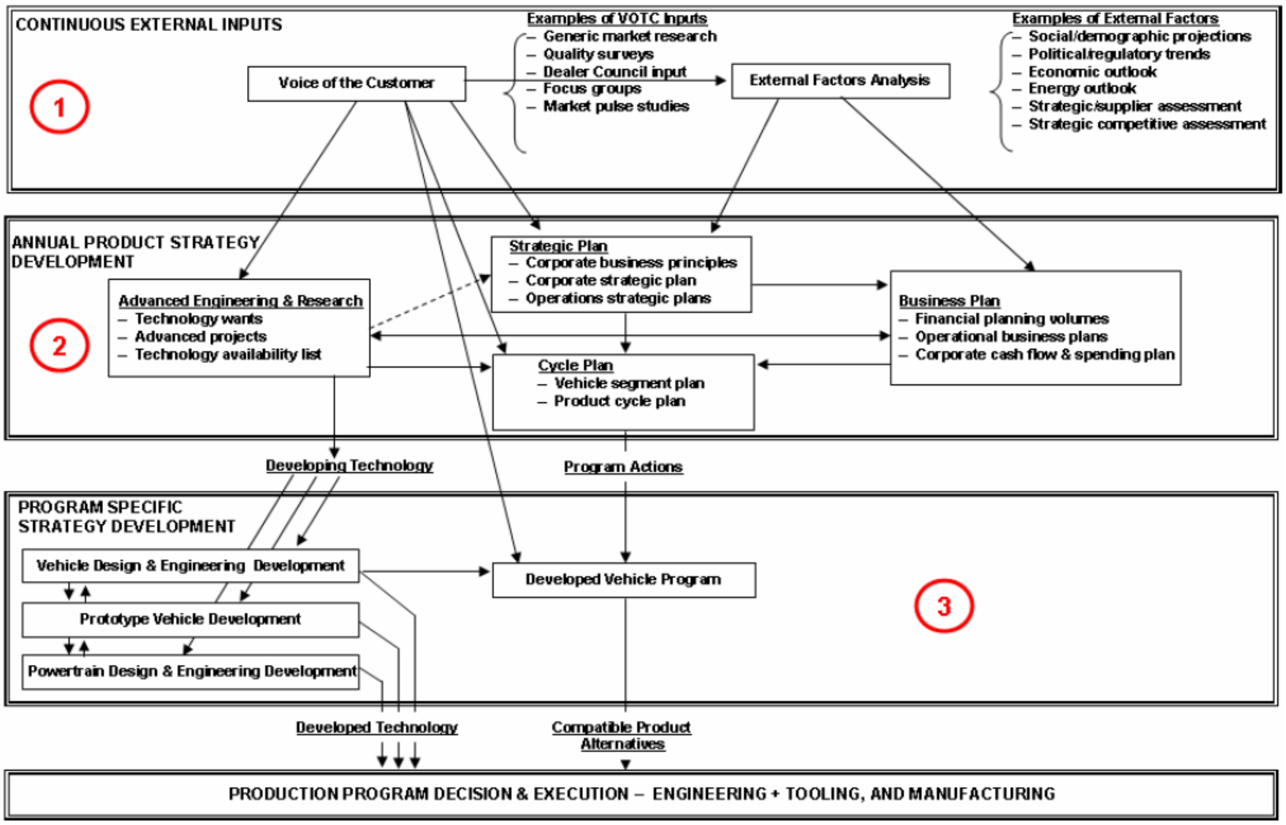

Figure E-2. Detailed Pathways for Developing an Automotive Business Case

Table E-1. Continuous Data Included in Early Stage Analysis

Voice of Customer Data	External Factors
• Market research • Quality surveys • Dealer input • Focus groups • Market pulse studies	• Social/demographic projections • Political/regulatory trends • Economic outlook • Energy outlook • Strategic supplier assessment • Strategic competitor assessment

The automotive industry uses the VOC as a tool to survey customers' expectations, requirements and desires in a product. While VOC is important for defining both product performance and accessory features such as styling, comfort and convenience items, utility attributes and electronics, it is usually a "look back" to what is already in the market rather than a 'look ahead' to the future. However, many factors other than VOC influence the final product definition, including a company decision to: target a known market niche, meet competition, or pursue perceived new opportunities. While the VOC data are an important driver in decisions for new product introduction, other demand-side inputs are at least as important, and in the end, the manufacturer weighs consumer choices, competition and especially the financial bottom line as the product specification and manufacturing plans are defined. Assuming the economic model built for the new product meets company metric, the product moves through the first stage-gate and is integrated into the Annual Production Strategy. In the end, sales are the ultimate metric of success when a new LDV is introduced.

At each stage of the planning process, decisions are made on whether to introduce a new benefit, as budget and other resource constraints enter the equation and as a consequence, no vehicle program will get all of the desired features and attributes. One can imagine the product planners must make many tough choices throughout the planning process as they compete to stay within their budget and with other organizations in the same company for different corporate resources (engineering, facilities, etc.). Within a vehicle program, the financial constraints may mean that if a new feature is added then something else must be dropped. At the end of the planning process, the products with the most robust business case will advance given the confidence of the company that the product will stay within the imposed budget and meet the values for vehicle pricing, sales volume, and profitability.

Often regulatory requirements are forced upon manufacturers in the areas of safety, emissions or fuel economy. The new regulations force trade-offs because the design changes or new features cannot pay for themselves but must be incorporated regardless of customer expectations and other considerations. In CAR’s review, fuel economy standards were viewed as incurring costs and forcing trade-offs so product planners at companies aimed for only minimum compliance. Trade-offs decisions are complex due to the multiple operating systems on a vehicle. For example, fuel economy is an outcome dependent on multiple vehicle attributes and features so its trade-offs are ideally addressed at the whole-vehicle level. CAR reports that when handled holistically, it is possible for fuel economy requirements to be met with a low level of additional costs. Moreover, when a customer benefit or brand value can be tied to the regulatory requirement, the interest and priority will increase within a company for the proposed new product.

The challenge of adopting and introducing new technology

A key challenge for automakers is the adoption of new technology and its associated up-front costs. According to Reuters, the upfront manufacturers cost includes: new assembly line equipment as well as testing to meet safety, performance and emissions standards. Changeover to introduce a new car can cost $1 billion or more to bring a new product to market and one of the reasons that a car platform remains basically unchanged for 5 to 7 years.

One problem with introducing new technology is identifying the product line(s) that will pay for it. In some cases, a new technology is developed for its initial application, as in the case of a platform-wide change, so the first program bears the full development costs. Such a situation will encumber and hinder new technology introduction because the first program to use the technology is essentially "taxed" for the full development costs. In other approaches, the costs are spread across several programs. In special cases, a new technology that is deemed important to the company may be given a discrete development budget. Automakers may also collaborate externally on technology to reduce the cost of developing and introducing new technology.

The bottom line is that business decisions are made continuously with many inherent uncertainties, not the least of which is the fact that market conditions can change dramatically. Given such complexity and that the outlook is fuzzy, it is indeed remarkable that a company takes the risk and launches a new vehicle which consumers want at the exact time they introduce it. Of course, beyond the initial product offering consumer demand must hold up throughout the vehicle’s multi-year production life prior to replacement or redesign for a vehicle program to be fully profitable.

Appendix F – Questionnaire for manufacturers of off-road equipment using diesel engines

The following survey was prepared by the University of California at Riverside's (UCR's) College of Engineering – Center for Environmental Research and Technology (CE-CERT) under a contract entitled "Evaluation of the feasibility, cost-effectiveness, and necessity of equipping small off-road diesel engines with advanced PM and/or NO_x aftertreatment" for the California Air Resources Board (CARB).

The objectives of the survey were to identify the following information if CARB were to explore more stringent NO_x and PM emissions standards:

- The feasibility, costs, development pitfalls and implementation time for additional NO_x and PM emissions controls for small off-road diesel engine/equipment (<75 horsepower).
- The potential performance impacts advanced aftertreatment might have on engines and equipment in various applications.
- The likelihood that increased costs for advanced diesel aftertreatment would cause consumers to switch from diesel-fueled to gasoline-fueled engines or electric motors.
- Industries or products that would be at a competitive disadvantage as a result of more stringent diesel-based emissions standards, or as a result of a mass transition from diesel-fueled to gasoline-fueled engines.

It should be noted that information provided by individual survey participants was to be treated as confidential, and information obtained through the survey will be aggregated so that the information cannot be traced back to a specific company. The guidelines allowed the respondent to provide a range of values as information might differ over different engine platforms.

<u>Background</u>

1. What types of engines do you produce aftertreatment systems for?
   ☐ Mobile applications ☐ off-road applications ☐ Stationary applications
2. Are there aftertreatment systems for off-road gasoline or diesel engines?
3. If the aftertreatment systems are for off-road diesel engines does it include DPFs, SCRs, or both?
4. What horsepower range are the off-road engines you produce aftertreatment for?
5. Is your company considered a "small business"[24]?_.

<u>Aftertreatment Feasibility and Impacts on Production and Associated Costs</u>

6. For off-road engines that do not have aftertreatment:
   a. Is the addition of aftertreatment technologically feasible? ☐ yes ☐ no
      i. If no, which engine types in terms of application or horsepower range would not be feasible to control and why?
      ii. If yes, please answer the following questions about <u>development of DPF aftertreatment</u> for SORDE engine types. If answers vary by engine type, please provide a horsepower range.

[24] According to AB 1033, a small business meets the following criteria: 1. Is independently owned and operated, 2. Not dominant in its field of operation, 3. Has fewer than 100 employees

1. How long to bring to market?
2. What complexities would this add to the engine development in terms of sensors and electronics and customer acceptance?
3. How many full time equivalent (FTE) hours of additional labor would be needed for development?
4. What costs would be involved for design, field testing, and warranty of new certification units?

iii. If yes, please answer the following questions about development of SCR aftertreatment for SORDE engine types. If answers vary by engine type, please provide a horsepower range.

1. How long to bring to market?
2. What complexities would this add to the engine development in terms of sensors and electronics?
3. How many hours of additional labor would be needed for development?
4. What costs would be involved?

Aftertreatment Performance and Operation and Operational Cost Impacts

7. How might the implementation of the emissions control devices impact the performance and operation costs of the of equipment?
   a. What performance issues would need to be addressed?
   b. Would the engines' performance in terms of accomplishing work be impacted?
   c. What is the ongoing emission control operating and maintenance (O&M) costs? How much downtime will be required to maintain the aftertreatment device?
   d. Are there other ongoing costs, e.g., do end users need to purchase DEF or any other additional items?
   e. Assuming proper maintenance is done, what is the lifetime of the added emission controls – is it accurate to assume the same lifetime as the small off-road diesel engine itself or do they wear out sooner and need to be replaced?
   f. Do the emission control devices affect performance or fuel efficiency? Would the businesses using the engines need to change anything about how they operate?
   g. Will training be required to operate the emission control devices?

Marketplace Impacts

8. How might the implementation of such emission control devices impact the marketplace for your business?
   a. Is the emission control cost reasonable as compared to the full cost of the equipment?
   b. Might the implementation of aftertreatment encourage the replacement of diesel engines with gasoline engines? Or perhaps electric motors?
   c. Presumably there would be a wide range for the emission control cost, and ability of businesses to pay since this covers a lot of different types of equipment. Some analysis of that variation would be useful, e.g., would certain categories be "easy" to mitigate while others would be cost-prohibitive?