FINAL DRAFT

DIESEL RETROFIT TECHNOLOGY AND PROGRAM EXPERIENCE

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EXECUTIVE SUMMARY

OVERVIEW

This report provides a detailed review and analysis of diesel retrofit technology application and program planning/implementation experience in the U.S. since 2000. Information in the report is derived from two sources: 1) publicly available articles, reports, and other documents and 2) information collected directly from retrofit projects in the U.S. The literature search focus was on retrofit experience in the U.S. during the period from January 2000 to the present, supplemented with information on diesel retrofit technology and program experience in other countries since the 1990s. Over 200 documents were reviewed in preparing this report. Over 220 projects were identified throughout the U.S. Information was requested from each of them and was received from nearly two-thirds.

This report was prepared for the U.S. Environmental Protection Agency's (EPA) Office of Transportation and Air Quality, Certification and Compliance Division* as part of an on-going, comprehensive EPA evaluation of the diesel retrofit experience in the U.S. since the EPA's Voluntary Diesel Retrofit Program (VDRP) was established in 2000. EPA created the VDRP to promote and facilitate the implementation of voluntary retrofit programs at the state and local level in order to reduce emissions from diesel engines. The VDRP serves to complement the Agency's aggressive program to reduce particulate matter (PM) and oxides of nitrogen (NOx) emissions from new on-road and nonroad diesel vehicles and equipment by up to 90% or more over the next decade. EPA has set a long-term goal of retrofitting, rebuilding, repowering, or replacing the estimated 11 million existing diesel engines in the U.S. by 2014. EPA defines the term "retrofit" broadly to include technology retrofits, fuel-based strategies, early vehicle/equipment retirement, engine rebuilds, repowers and operations-based strategies such as reduced idling. This report focuses primarily on technology- and fuel-based strategies, but information on other strategies is included in those instances where they were used in combination with retrofit technology and fuel strategies.

This report is designed to serve both as a reference tool on U.S. retrofits technologies and programs for interested parties, and to document important experience gained and valuable lessons learned. This experience and lessons learned will assist those considering retrofit initiatives to effectively assess, plan, implement, and evaluate retrofit programs. EPA will also use the information provided in the report, combined with other evaluations, including an in-use testing program for verified technologies, to insure the continued effective implementation of the VDRP.

INTRODUCTION AND SUMMARY OF FINDINGS

Section 1.0 provides background discussion on EPA's ongoing evaluation of retrofit experience and details the scope of the report. This section also provides a summary of findings, including information on available retrofit technologies, information on U.S. retrofit projects by technology and applications, and highlights of lessons learned.

* The name of the EPA Certification and Compliance Division is expected to change.

RETROFIT TECHNOLOGY EVALUATION

Section 2.0 of the report reviews the full range of experience with technology- and fuel-based retrofit strategies including: diesel oxidation catalysts (DOCs), passive and active, high- and low-efficiency diesel particulate filters (DPFs), fuel-borne catalysts (FBCs), lean NOx catalysts (LNCs), selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), low-pressure exhaust gas recirculation (EGR), closed crankcase ventilation (CCV) systems, ULSD, biodiesel, emulsions, fuel additives, and others. Information reported on each retrofit technology focuses primarily on engine applications; retrofit product performance; durability; cost; fuel requirements; installation requirements and experience; recommended technology maintenance vs. actual maintenance experience; overall operating experience; warranties; failure rates; causes and any documentation of failures; and action taken, if any, to correct problems. For fuel-based strategies, information is provided on fuel properties, specifications, manufacture/ blending, delivery, storage, costs, any problems, and actions taken, if any, to correct problems.

Retrofit technology programs can be grouped into two broad categories. The first type is designed to demonstrate the applicability, performance, and emission reduction characteristics (frequently with extensive emission testing) of a given technology. Reports found in the literature tended to focus on these technology demonstration-type programs, and this provided useful examples of "lessons learned". The second type is designed to apply the technologies with the primary goal of achieving emission reductions to improve air quality. Most of the projects in the U.S. in which data was collected fit into this second category, and typically did not include emission testing. Rather, the program relied on other means of quantifying emissions reductions (e.g. developing emission reduction estimates from EPA- or CARB-verified emission reduction levels for a given technology).

All of these technology- and fuel-based strategies generally deliver the operating and emission reduction results that are claimed for them, but the levels of emission control achieved in some cases was highly dependent on the emission test cycle used. In those instances in which problems did occur, several factors were identified. In some cases, problems occurred when technologies were extended to applications that were marginal including programs specifically designed to evaluate the limits of the technology. In other cases, technical problems resulted because the sulfur levels in the fuels were too high for successful application of the technology or the technology was applied incorrectly. This situation was well illustrated in several projects involving catalyst-based DPFs. In other cases, there were mechanical problems, such as the failure of retrofit equipment mounting brackets. In most instances where technological problems occurred, corrections were identified and implemented in subsequent projects. In still other cases, problems could be traced directly to insufficient or inadequate knowledge on the part of users or program creators/administrators. As with any other new or unfamiliar technology, successful use requires an understanding of product function, proper installation and use, attention to recommended product selection criteria, and operating and maintenance requirements. Problems identified with fuel-based retrofit strategies were mostly related to a lack of measures to prevent misfueling (using low sulfur fuel instead of ULSD for DPF-equipped vehicles), and more generally, a lack of fuel quality control measures (in both the fuel itself and local storage/dispensing equipment) that resulted in vehicle performance problems of various types.

RETROFIT PROGRAM DESIGN, PLANNING, IMPLEMENTATION AND EVALUATION

Section 3.0 discusses retrofit program design, planning, implementation, and evaluation issues. Retrofit programs fall into two major categories: mandatory programs and voluntary programs. Each type of program structure has its advantages and disadvantages. For example, mandatory programs have the benefit of generating emission reduction benefits that are more easily quantifiable, more "permanent" and enforceable than those of some voluntary programs. Conversely, voluntary programs are dependent on prospective technology users to "come forward" and offer to operate their vehicles or equipment with retrofit products, without the potential for having to face any penalties for noncompliance. Information from the available literature and retrofit projects suggests that each form of program structure seems to have been successful, even though each type has needed to address various planning and implementation issues which are discussed in the report.

The report reviews the experience with mandatory programs in the U.S. (e.g., California Diesel Risk Reduction Plan, DRRP), as well as programs in Switzerland, Hong Kong, Sweden and elsewhere. Factors to consider when adopting a mandatory program are also discussed in the report.

For voluntary programs, information is provided in the report on project descriptions and objectives, partners, sources of funding, outreach, project planning, implementation, and evaluation elements. The project objectives, scope of the projects (e.g. number of vehicles/equipment), sources of funding, degree of technical support provided, and method of evaluating the project varied considerably. Examples of different types of voluntary programs are provided in the report.

The U.S. retrofit programs examined for this study involved a wide variety of vehicles and equipment, including school buses, transit buses, utility vehicles, delivery vehicles, refuse trucks and nonroad equipment. Funding sources included Federal, state, and local governments, enforcement settlement funds, and private sector funding.

RETROFIT TECHNOLOGY AND PROGRAM EXPERIENCE LESSONS LEARNED

A number of successful retrofit programs have been completed or are underway that have used emerging or more established retrofit technologies. As experience grows with retrofit technology and program issues, valuable lessons learned are emerging that will prove extremely helpful as future retrofit initiatives move forward. Section 4.0 of the report identifies a number of lessons learned regarding both the technologies and programs. In some cases, these lessons learned are technology- or fuel-specific, while in other instances they are more universally applicable. These lessons learned cover such topics as:

- ***Retrofit Technology- and Fuel-Based Strategies***
    - Accessing and estimating emissions reduction for a given retrofit technology and vehicle/equipment application.

- Vehicle/equipment applications and experience.
- Selecting the appropriate retrofit technology strategy.
- Selecting the appropriate fuel-based strategy.
- Retrofit product delivery.
- Pre-installation actions, installation, vehicle/equipment and technology maintenance, and operation.
- Estimating fuel economy impacts.
- When retrofit technology monitoring equipment should be employed.
- Fuel quality, transport, handling and storage.
- Vehicle/equipment preparation when switching to a fuel other than conventional on-road or nonroad diesel fuels.

- ***Retrofit Programs***
  - Selecting the appropriate vehicle/equipment application for the technology/fuel used.
  - Technician and operator education and training.
  - Public outreach and education.
  - Project funding.
  - Project implementation.
  - Retrofit product procurement issues.

CONCLUSIONS

Retrofit technology optimization and applications continues to advance at a rapid rate both with established technologies such as DOCs and DPFs as well as with emerging technologies such as flow-through filters, SCR, low-pressure EGR, LNC and CCV technologies. On occasion, issues have arisen in some U.S. programs during the period covered by this report due to such factors as incorrect application of technology, misfueling or fuel contamination, mechanical failures, and problems with monitoring equipment. These issues are becoming better understood and field fixes are being developed and employed to reduce the instances of such problems. Similarly, experience with fuel-based strategies is rapidly advancing and some of the initial issues (e.g., fuel contamination, failure to meet specifications, blending, and storage) are now better understood, and appropriate precautions have been identified and are being implemented. Today, a wide range of retrofit strategies is available for nearly any vehicle or equipment application. Care must be taken, however, to match a given retrofit strategy with the specific engine, vehicle/equipment type, operating mode and duty cycle.

The number of retrofit programs in the U.S. has dramatically increased in the U.S. since 2000 when EPA created the VDRP. The growing popularity of these programs is based on several factors, including: the need to find additional methods for improving air quality (beyond the establishment of more stringent emission standards that are applied to newly-manufactured future engines and vehicles), greater knowledge and concern about the health effects of vehicle exhaust constituents, availability of a variety of retrofit products from reputable product suppliers and meaningful levels of financial incentives/support. A growing body of retrofit program and project experience is being developed. Much of this experience, however, has not been previously reported extensively or documented. The retrofit technology application and retrofit program experience documented in this report should provide valuable guidance to those pursuing retrofit strategies in the future.

The current level of interest for initiating retrofit programs is beginning to far exceed the available funding for such projects. A major future challenge in advancing retrofit initiatives is to make available the funding and other incentives needed to enable these projects to go forward. A second challenge is to insure that adequate, effective and competent technical support is available for retrofit projects, particularly at the technology selection, vehicle/equipment selection, product installation and operational phases.

1.0 INTRODUCTION AND SUMMARY OF FINDINGS

1.1 BACKGROUND ON EPA's EVALUATION OF RETROFIT EXPERIENCE

In 2000, EPA officially announced the creation of its VDRP, culminating efforts and activities in promoting the retrofit of existing diesel engines. The program is structured to promote and facilitate the implementation of voluntary retrofit programs at the state and local level in order to reduce emissions from diesel engines. EPA's retrofit program serves to complement the Agency's aggressive program to reduce PM and NOx emissions from new highway and nonroad diesel vehicles and equipment by up to 90% or more over the next decade. Even with a comprehensive program in place to reduce emissions from new diesel engines in the future, existing diesel engines, because of their well recognized durability, will continue to be a significant source of PM and NOx emissions. The VDRP was created to help address the challenge of reducing these emissions from existing diesel engines. EPA has set a long-term goal of retrofitting, rebuilding, repowering, or replacing the estimated 11 million existing diesel engines in the U.S. by 2014. As another step toward achieving this goal, EPA announced the award of 18 diesel retrofit projects in February 2005.

Under EPA's VDRP, states may employ verified retrofit technologies in qualifying retrofit programs and apply these emission reductions in their State Implementation Plans (SIPs). A critical element of EPA's program is that only retrofit technologies verified under a rigorous evaluation process may be used in retrofit programs funded by EPA and, in most cases, by states as well. Congress has provided several million dollars in funding in EPA's FY 2003, 2004, and 2005 budgets to help promote retrofit projects under the Agency's clean diesel initiatives. Additional funding for retrofit programs has come from both the public and private sectors. Retrofit projects under EPA's program have included installing emission control technology, engine rebuilds, fuel additives, improved fuels, e.g., ultra-low sulfur diesel fuel (ULSD) and biodiesel, and engine retirement/replacement. Since its inception, EPA's VDRP has energized the level of interest and activity in reducing emissions from diesel engines.

EPA has initiated a comprehensive evaluation of diesel retrofit technologies and retrofit program design, implementation and experience based on the four-year experience since the VDRP was established. This evaluation will include: 1) a review of existing publicly available written articles, reports, and other documents, 2) information collected from retrofit programs, and 3) in-use testing of EPA-verified retrofit technologies. EPA's objective is to document the experience and identify the "lessons learned" over the past four years focusing for example, on what the successes were and why they occurred, as well as on what the problems were, why they occurred, and how they were addressed. EPA plans to issue the final report in 2005.

1.2 SCOPE AND ORGANIZATION OF THE REPORT

This report covers the first and second phases of EPA's comprehensive evaluation. It provides a review of publicly available written articles, reports, and other documents related to diesel retrofit technologies, as well as retrofit program design, implementation, and experience. The literature focus was on retrofit experience in the U.S. during the period from January 2000 to the present. This information is supplemented with material collected on diesel retrofit technology and experience in other countries since the 1990s. Relative to retrofit programs and projects, over 220 were identified throughout the U.S. Information was requested from each of them and was received from nearly two-thirds.

Information from the publicly available documents and the U.S. retrofit projects provided information on retrofit technologies in current use, including, but not limited to, DOCs, passive and active, high- and low-efficiency DPFs, FBCs, LNCs, SCR, SNCR, low-pressure EGR, CCV systems, emulsions, fuel additives, and others. Information collected on each technology/project focused primarily on on-highway; nonroad; marine and locomotive engine applications; retrofit product performance; durability; cost; fuel requirements; installation requirements and experience; recommended technology maintenance vs. actual maintenance experiences; overall operating experience; warranties; failure rates; causes and any documentation of failures; and action taken, if any, to correct problems. Where available, information was included on overall retrofit project experience; project costs and benefits; funding sources and mechanisms; program design experience; implementation experience and issues; project operation; project termination; and lessons learned.

This report provides an analysis of and describes the available information on retrofit experience and organizes it into four general categories: 1) Retrofit Technology Evaluation, 2) Retrofit Program Design/Implementation Experience, 3) Lessons Learned from Retrofit Technology Application and Experience, and 4) Lessons Learned from Program Design/ Implementation Experience. In this context, Section 2.0 of this report describes the technologies that have been applied to vehicles and equipment involved in various retrofit programs and projects. Section 3.0 contains information on the structure and implementation aspects of the various retrofit projects that were reviewed. Section 4.0 provides a distillation of the "lessons learned" from the retrofit documents and project information reviewed. Section 5.0 contains the observations and conclusions drawn from review of the literature and information obtained from the retrofit projects throughout the U.S. and used as the basis for the content for this report.

Section 6.0 contains the bibliography and references used in developing the report. ***Please note that literature sources used as references in this report are identified by the document number (from Section 6.0) being placed in brackets [ ], while references related to project information are identified by the project number contained in parentheses (P),*** where it was deemed appropriate to provide a project reference.

Each project and assigned project number are listed in Appendix A, along with the project location and a brief description. Appendix B contains summaries for the projects that provided sufficient information for a summary to be created.

1.3 SUMMARY OF FINDINGS

Over 200 documents and information from nearly 140 projects (of the more than 220 projects that were identified) were reviewed to develop the content of this report. The bulk of these documents describe diesel retrofit programs and projects involving a variety of technologies and vehicle/equipment applications. A significant number of these documents are also cited as references within this report.

Table 1-1 is a summary of the technologies represented in the programs and projects for which documentation was obtained. More details and specific information on each is contained in Section 2.0. Table 1-1 shows the wide range of retrofit technology strategies available to suit

Table 1-1, Summary of Available Retrofit Technologies for Reducing Diesel Emissions

Emission Control Technology	EPA or CARB Verified	Commercially Available	Breadth of Application	Estimated Number of Retrofits
DPF	Yes	Yes	Application-Specific	>150,000 (Worldwide)
DOC	Yes	Yes	Nearly universal	>350,000 (Worldwide)
LNC/DPF	Yes	Yes	Application-specific	>3,000 (Worldwide)
EGR/DPF	Yes	Yes	Application-specific	>3,000 (Worldwide)
SCR	Yes	Yes	Application-specific	>2,000 (Worldwide)
CCV Systems	Yes	Yes	Nearly universal	>2,000 (U.S.)
ECM Reflash	Yes	Yes	Application-specific	>50,000 (U.S.)
Emulsions	Yes	Yes	Nearly universal	Use in >200 vehicles (U.S.)
Additives	Some In Process	Yes	Nearly universal	Use in 2,000 vehicles (U.S.)
Biodiesel	Yes	Yes	Nearly universal	>1.2 Million gal/yr (U.S.)
ULSD	Yes	Yes	Nearly universal	>137 Million gal/yr (U.S.)

nearly any vehicle/equipment application in operation today. All of these technologies generally deliver the operating and emission reduction results that are claimed for them, but as discussed below, the levels of emission control achieved are in some cases highly dependent on the emission test cycle used. In those instances in which problems did occur, several factors were identified. In some cases, problems occurred when technologies were extended to applications that were marginal as an experiment in a pilot project to evaluate the limits of the technology. In other cases, technical problems resulted because the sulfur levels in the fuels were too high for successful application of the technology. This situation was well illustrated in several projects involving catalyst-based DPFs. In other cases, there were mechanical problems, such as the failure of retrofit equipment mounting brackets. In most instances where technological problems occurred, corrections were identified and implemented in subsequent projects. In other cases, problems could be traced directly to insufficient or inadequate knowledge on the part of users or program creators/administrators. As with any other new or unfamiliar technology, successful use requires an understanding of product function, proper installation and use, and attention to recommended product selection criteria, and operating and maintenance requirements.

For discussion, retrofit programs were organized into two major categories: mandatory programs and voluntary programs. Each type of program structure has its advantages and disadvantages. For example, mandatory programs have the benefit of generating emission reduction benefits that are more easily quantifiable, more "permanent" and enforceable than those of some voluntary programs. Conversely, voluntary programs are dependent on prospective technology users to "come forward" and offer to operate their vehicles or equipment with retrofit products, without the potential for having to face any penalties for noncompliance. Information from the available literature and retrofit projects suggests that each form of program structure seems to have been successful, even though each type has needed to address various issues. It is not clear from the documents available for this report or the information provided from the projects that one type of program.

Table 1-2 is a summary of the retrofit projects underway in the U.S. based on the data obtained from requests by the authors of this report. Compared to the nearly 35-year history of emission control system technologies/products and national and state programs to control diesel engine emissions, diesel retrofit programs are relatively new. The growing popularity of these programs has resulted from several factors, including: the need to find additional methods for improving air quality (beyond the establishment of more stringent emission standards that are applied to newly-manufactured engines and vehicles), greater knowledge and concern about the health effects of vehicle exhaust constituents, availability of a variety of retrofit products from reputable product suppliers, and meaningful levels of financial incentives/support. A growing body of retrofit program and project experience is being developed. Much of this experience, however, has not been reported extensively or documented at this time.

Key points of observation include the following:

- The range of emission reduction associated with each retrofit technology and product can vary widely, depending on test method, duty cycle, engine/vehicle condition, types of test equipment used, etc. The verification procedures established by EPA and the California

Table 1-2, Summary of U.S. Retrofit Programs and Projects by Technology and Application

Retrofit Technology	Vehicle/Equipment Application*						
	School Buses	Transit Buses	Utility Vehicles	Freight/ Delivery Vehicles	Refuse Trucks	Nonroad Engines	TOTALS
DPF	25	8	5	3	7	1	49
DOC	48	1	9	2	8	19	87
LNC/DPF	0	4	2	0	2	2	10
EGR/DPF	0	3	2	0	1	2	8
SCR	0	0	1	1	0	1	3
DOC/CCV Systems	9	0	1	1	4	2	17
Diesel Fuel Emulsions	2	4	1	0	0	1	8
Diesel Fuel Additives (Including FBC)	1	0	1	1	1	1	5
Biodiesel	10	1	1	0	1	3	16
ULSD (Only)	3	2	0	0	0	2	7
ULSD with Other Retrofit Technology	33	13	8	2	8	11	75
TOTALS	**131**	**36**	**31**	**10**	**32**	**45**	**285**

*Note: Some programs/projects involve multiple fleets. For example, the State of Washington School Bus Program has over 200 individual school districts participating in the program, and various programs in California involve multiple school bus and transit bus fleets.

Air Resources Board (CARB) has helped to provide "benchmark" levels of emission reductions for retrofit products that retrofit program administrators and users can rely on as "representative" for the products tested.

- Use of DPFs requires knowledge and correct application in order to be most effective and operate with minimal problems. Careful application design, including matching the DPF design (passive or active) to the operating exhaust temperature profile of the engine, ensuring appropriate catalyst sizing and thermal insulation, and matching the fuel sulfur level to the DPF design are several of the continued improvements made to enhance effective operation. Successful application of DPFs can be enhanced further by comprehensive suitability testing, careful systems monitoring and field inspections.

- To minimize problems with diesel retrofit products designed to operate with ULSD, measures need to be established to prevent misfueling of vehicles with diesel fuel of higher sulfur content. Segregated fuel storage and dispensing equipment (from that used for diesel fuel of higher sulfur content) is likely to be needed until ULSD becomes widespread. Users of ULSD should ensure that they purchase fuel with lubricating properties meeting those of the latest diesel fuel specifications for ASTM International D 975, Grade S15, and if fuel economy is important, that the energy content of the fuel meets the minimum requirements of the fleet.

- For projects involving fuel technologies (e.g., ULSD, biodiesel, diesel fuel emulsions) consideration should be given to fuel supply logistic aspects. If a project involves multiple vehicle/equipment operators, like those found at a construction site, issues such as the need to respect the fuel supplier agreements for each of the participants and accommodate individual vehicle/equipment refueling requirements may be difficult to address or to obtain agreement among the participants. These issues should be addressed early in the project planning process to avoid potential problems after the project has begun.

- Retrofit technology and product selection should be accomplished with the knowledge in mind of the operating and maintenance capabilities of vehicle/equipment fleet. Fleets not having the time and attention to devote to complying with recommended practices for installation, operating and maintenance, should consider technologies and products that require minimal care and attention. In selecting technologies for a retrofit project, a balance must be struck among: 1) the need for achieving desired emission reductions, 2) complexities of program/technology implementation, 3) working within technical capabilities/limitations of the fleet, 4) available funding and 5) other program goals.

- Current technology costs are an important consideration in both the decision to undertake a retrofit project and in selecting the technology to be used. Cost does not seem to have been a significant deterrent to the establishment or growth in retrofit programs worldwide, but clearly, the level of interest in the diesel retrofit programs would increase if costs are reduced. Retrofit technology costs are likely to be reduced as the market for retrofit products and new engine original equipment (OE) applications grows, and the technologies are further optimized. One to two orders of magnitude in product demand will be needed before more substantial cost reductions can be realized.

- Retrofit programs are growing (in number of programs, projects and vehicles/equipment involved in them), and retrofit products are getting better, as results of more field experience work their way into product improvements. Product-related problems have been and continue to be addressed.

- The knowledge base required to plan and implement a sound retrofit project is growing, but is not at a level that has allowed universal project success.

- Successful programs in the U.S. have some or all of the characteristic cited below:

    - A project "champion(s)" to oversee program planning/implementation and the technological aspects of the program.

    - Adequate funding to conduct the program.

    - Careful planning, including recruiting the necessary partners, setting the goals for the program and building support on the part of participating fleets.

    - Continuous communications with all participating parties.

    - Strong, competent, and effective technical support.

    - Careful evaluation and selection of technologies.

2.0 RETROFIT TECHNOLOGY EVALUATION

This report section discusses information contained in the literature and information provided by retrofit project managers and others relating to the experience with the technical aspects of the various retrofit technologies (including fuel and fuel additive-based technologies) for reducing emissions from both highway and nonroad diesel engines. Topics discussed include:

- Emission reduction performance and testing.
- Vehicle/equipment applications.
- Technology delivery, installation, maintenance, and technical support
- Cost and warranties.
- Technology operating performance, problems and solutions.
- Impact on engine performance and fuel economy.
- The role of fuels and lubricants.

A summary of the major commercially available technology options is presented in Table 2-1.

Retrofit technology programs can be grouped into two broad categories. The first type is designed to demonstrate the performance and emission reduction characteristics (frequently with extensive emission testing) of a given technology and represents the subjects of many of the reports found in the literature. The second type is designed to apply the technologies with the primary goal of achieving emission reductions to improve air quality. Most of the projects involved in the data collection effort that was performed for this report fit into this category. Typically they do not include emission testing, but rely on other means of quantifying emissions reductions (e.g. developing emission reduction estimates from EPA- or CARB-verified emission reduction levels for a given technology).

As anticipated, some technologies received considerably more attention in the literature than others. For example, DPFs, which have been used for retrofit applications for a number of years and are the most effective technology for reducing PM, were widely addressed in the literature. Far less information was available on LNCs and low-pressure EGR systems. These are relatively new, emerging retrofit technologies, and have received far less evaluation for the period covered by this report. DOC technology, which is well established and widely used did not receive significant attention in the literature published over the past four years. While the body of literature on the technical aspects of the various diesel retrofit technologies did not address every issue for every technology or implementation strategy, the information available does provide useful insight into the capabilities, limits, issues, and experience with various retrofit technologies.

Table 2-1, Summary of Available Retrofit Technologies for Reducing Diesel Emissions

Emission Control Technology	EPA or CARB Verified	Percent Emission Reduction				Product Cost (175-300 hp)	Other Cost Items	Breadth of Application	Estimated Number of Retrofits
		PM	NO_X	HC	CO				
[1]DPF	Yes	Up to 90+	--	60-90	60-90	\$5500-\$8000	4-8 hrs. for install. DPF cleaning.	Application-specific	>150,000 (Worldwide)
[2]DOC	Yes	20-50	--	30-90	30-90	<\$1000-\$2000+	1-4 hrs. for Install.	Nearly universal	>350,000 (Worldwide)
[3]LNC/DPF	Yes	Up to 90+	25	60-90	60-90	\$15,000+	Up to 16 hrs. for install. Slight FE loss.	Application-specific	>3,000 (Worldwide)
[4]EGR/DPF	Yes	Up to 90+	Up to 50	60-90	60-90	\$15,000+	Up to 16 hrs. for install. DPF cleaning.	Application-specific	>3,000 (Worldwide)
[5]SCR	Yes	30-50	Up to 90+	50-90	50-90	\$15,000+	Up to 8 hrs for install. Urea supply equiv. to up to 4% FE penalty.	Application-specific	>2,000 (Worldwide)
[6]CCV Systems	Yes	10-25	--	30-40	30-35	\$500-\$600	Replace filter 25,000 miles or annually. Filter cost \$20-\$50.	Nearly universal	>2,000 (U.S.)
[7]ECM Reflash	Yes	--	Up to 25	--	--	No cost, unless a DOC or DPF is included as a system.		Application-specific	>50,000 (U.S.)
[8]Emulsions	Yes	16-60	10-25	[8]V	[8]V	[11]\$0.15-\$0.25/gal	--	Nearly universal	Use in >[12]200 vehicles (U.S.)
[9]Additives	Some In Process	--	Up to 5	--	--	[11]\$0.05-\$0.15/gal	--	Nearly universal	Use in >[12]2,000 vehicles (U.S.)
[10]Biodiesel	Yes	[10]V	[10]V	[10]V	[10]V	[10]V	--	Nearly universal	>1.2 Million gal/yr (U.S.)
ULSD	Yes	3-18	--	--	--	[11]\$0.05-\$0.30/gal	--	Nearly universal	>[13]137 million gal/yr (U.S.)

Notes:

1) Information based on a catalyst-based, passive DPF. Other DPF technologies are available such a DPF+FBC systems and a variety of active systems. The hardware and other costs will vary among DPF systems. See Report Section 2.1 for a detailed discussion of DPF technology.
2) Information based on performance of DOC alone. DOC technology can be combined with FBC, SCR, and LNC technology as well. See Report Section 2.2 for a detailed discussion of DOC technology.
3) Information based on performance of LNC/DPF system because this is the system that is verified. See Report Section 2.3 for a detailed discussion of LNC technology.
4) Information based on performance of an EGR/DPF system because the low pressure EGR technology used in retrofit applications requires the use of a DPF to function effectively. See Report Section 2.4 for a detailed discussion of EGR technology.
5) Information based on performance of SCR technology alone. SCR technology can be combined with SNCR, DOC, and DPF technology. See Report Section 2.5 for a detailed discussion of SCR technology.
6) Information based on crankcase emission control technology alone. However, crankcase emission control technology has only been verified as a combined system with DOC technology. See Report Section 2.7 for a detailed discussion of crankcase emission control technology.
7) Information from CARB. See Report Section 2.8 for a detailed discussion of ECM Reflash technology.
8) HC and CO results vary (V) and yield emission reductions or increases, depending on several engine and operating factors.
9) Not including FBC additives.
10) Emission reductions and cost vary (V) with concentration of biodiesel in diesel fuel blend.
11) Typical range of cost differential compared to No. 2 conventional on-road low sulfur diesel fuel. Estimated from information provided to Emissions Advantage, LLC, for retrofit projects.
12) U.S. DOE-EIA data for ULSD production in 2004.

The amount of information collected from retrofit project managers and others similarly varied among technologies. For example, a great deal of information was obtained on DOC and DPF experience because they are the predominant technologies used in U.S. retrofit projects. For other technologies such as SCR, LNC/DPF, low-pressure EGR/DPF, and flow-through DPFs, less information was available because these technologies have been used in only a few projects.

The information collected from the U.S. retrofit projects complements and, in many instances, confirms the information on retrofit technology experience reported in the literature. For example, information collected from the retrofit projects provided useful additional insights on such issues as product delivery, installation, training, technical support, operational, and project implementation issues. Together, these two sources of information provide valuable insight into all aspects of the retrofit technology experience and provide useful lessons learned.

2.1 DIESEL PARTICULATE FILTER

2.1.1 Overview

A DPF is a device that collects or traps PM from engine exhaust. Since it will eventually fill with PM, the filter must be cleaned or "regenerated", by oxidizing (burning) the PM. To minimize the possibility of a catastrophic regeneration (one that damages the filter), a continuously or semi-continuously regeneration process may be preferred to one in which regeneration occurs after significant amounts of PM are collected. The temperature of diesel exhaust gases is not always sufficient to burn off the PM collected in the DPF. As a result, a variety of strategies are being developed and used to ensure that the DPF operating temperature is high enough for regeneration to occur. These strategies include: 1) using catalyst technology to generate nitrogen dioxide (NO_2) from the oxidation of nitric oxide (NO) to assist in the combustion of soot, 2) raising the exhaust temperature by the oxidation of unburned hydrocarbons (HC) and carbon monoxide (CO) contained in the exhaust stream, and 3) using fuel-borne catalysts, and 4) heating the exhaust with a burner.

For certain special applications, the DPF can be removed periodically from the vehicle exhaust system and heated with an external heat source or physically cleaned and then re-installed. In limited applications, an external heat source has been used to regenerate the filter while the DPF remains installed on the vehicle or equipment. Several DPF systems have been verified under the EPA and CARB retrofit programs. All of these verified systems require the use of ULSD. [See www.epa.gov/cleandiesel and www.arb.ca.gov/diesel/diesel.htm] Figure 2-1 illustrates a DPF being regenerated using external heating/cleaning equipment.

Some of the newest DPF systems being introduced are designed to provide exhaust flow turbulence and increased PM residence time. These "flow-through" filters have achieved PM reductions of 40% to more than 65%. Several different designs are currently being developed and evaluated. They have been referred to as "high-efficiency DOCs", "partial flow DPFs", "DPFs", and "wire mesh DOCs". A version of the flow-through filter concept has been verified under the CARB Diesel Risk Reduction Plan (DRRP) as achieving a 50% reduction in PM.

Figure 2-1, DPF Being Regenerated Using External Heating/Cleaning Equipment

Another version is being evaluated on a transit bus in Michigan. (P141) This technology is composed of three elements: 1) a wire mesh filter media, 2) an air pulsation system, and 3) a soot reclamation/incineration system. The wire mesh media consists of layers of various compactness augmented with screens of various mesh size. This system agglomerates sub-micron and nano-size PM into dendrites (collections of tiny particles that resemble the shape of a tree or snow flake). As these dendrites grow in size, they break off and are collected on additional filter screens. The wire mesh media is then regenerated through pulsation of compressed air and subsequent collection in an external "collection bag". (P141)

The majority of the retrofit studies documented in the literature focus on DPF technology. A significant portion of these studies analyzed retrofit experience in Europe where diesel retrofit activity has been used extensively since the mid-to-late 1990s. With the expanding number of retrofit programs in the U.S., a growing number of DPF studies are now being conducted in this country. The majority of these documents cover on-highway retrofit experiences. Similarly, the majority of the information collected from retrofit project managers and others on DPF experience cover highway experience because most of the retrofit projects involve highway vehicles. Some information, however, was available on nonroad applications.

DPF technologies most commonly used in retrofit applications are often referred to as “passive” because they do not typically require additional internal or external regeneration strategies to function effectively, but rather employ catalyst technology to ensure that regeneration occurs. The vast majority of DPF projects in the U.S. involve passive filters. The European studies cover a somewhat broader range of technologies including passive DPFs, DPF plus FBC, and active DPF systems.

2.1.2 Emission Reduction Experience and Testing Practices

2.1.2.1 *Information from the Literature*

DPFs can provide greater than a 90% reduction in PM. These results were achieved on a variety of highway and nonroad vehicles and equipment including transit buses, school buses, line-haul trucks, refuse trucks, and construction equipment. [117, 128, 130, 147, 205] DPFs also can be designed to control up to 90% or more of the HC and CO emitted by a diesel engine. [117, 130, 154] DPFs are extremely effective in controlling the ultra-fine carbon fraction of PM. Reports of several studies indicate that DPFs reduce carbon-based PM by over 99%. [90, 129, 130] DPFs generally have no impact on NOx emissions. [90, 131] One study analyzing a DPF/FBC system on London taxis found a 3% NOx reduction on non-EGR equipped vehicles and a slight increase in NOx emissions on a taxi equipped with EGR. [90]

Several documents report that catalyst-based DPFs were effective in significantly reducing toxic pollutants. For example, one study examining the destruction of polyaromatic hydrocarbons (PAH), nitropolyaromatic hydrocarbons (Nitro-PAH), and carbonyls, found that DPF-equipped urban buses reduced PAH by more than 80%, nitro-PAH by more than 90%, and toxic carbonyls by more than 99%. [130] Other reports documented the ability of DPFs to significantly reduce toxic hydrocarbons such as benzene, ethylene, propylene and toluene. DPFs also reduce smoke and the pungent odor of diesel exhaust. [99]

One increasingly important issue for DPF systems that generate NO_2 to assist in the oxidation of accumulated PM is the relatively high tailpipe NO_2 emissions levels of vehicles or equipment using these types of DPFs. Several documents report that these DPF technologies can produce increased NO_2 emissions. [114, 129, 131, 205] A DPF fleet test in California reported that baseline NO_2 was only 6% of the total NOx, while NO_2 emissions from DPF-equipped grocery trucks ranged from 26% to 34%. NO_2 emissions from tankers and transit buses ranged from 29% to 34%. [205] Also noted was that the NO/NO_2 fraction did not change significantly when either conventional California diesel fuel or ULSD was used. A test program with city buses in Switzerland reported varying levels of NO_2 increase. The authors were unable to identify a reason, but note that engines, mileage accumulation, and types of DPF systems were different, and suggest that an NO_2 store-and-release phenomenon may have been a factor. [129]

Work is underway to minimize the increase NO_2 production in DPF-equipped vehicles. [3, 4] This is being accomplished through improvements in system design and catalyst formulations. For example, with one iron-based FBC composition, not only was there a 5% to 10% reduction in NOx emissions observed, but also a greater than 50% reduction in NO_2 emissions. [90, 153] The findings from this study have led to the development of a base metal coating for DPF's that is effective in reducing tailpipe NO_2 emissions. [154] Its effectiveness was evaluated on an urban bus. The base metal coated DPF proved effective in oxidizing HC and CO as well as significantly reducing NO_2 emissions. Testing with a base metal DPF on underground mining equipment has also shown reduced NO_2 emissions. [174] When a DPF is combined with a NOx control strategy such as EGR or SCR, any potential NO_2 increase can be offset by an overall reduction in NOx, including NO_2.

Projects evaluating DPF emission control performance used a variety of different test equipment, test methods and duty cycles. Testing equipment included engine dynamometers and mobile chassis dynamometers, high-speed idle CO instrumentation, and opacity measurement.

[54, 64, 79, 90, 108, 185] A variety of test cycles were used in an effort to replicate the actual driving cycle of the vehicles or equipment being evaluated. Standard test cycles such as the EPA heavy-duty engine (HDE) transient cycle, the European Transient Cycle (ETC), the Central Business District (CBD) cycle, the New York Bus (NYB) cycle and many others were used. [54, 90, 131] In a number of instances, special test cycles were developed for the specific vehicle/ equipment operating modes to match actual operating conditions more closely. [33, 185] For example,in a pilot program designed to evaluate the emission control performance of DPFs and DOCs on various types of nonroad construction equipment, specific test cycles were developed for five pieces of equipment. Data logging was used to record typical in-use operating conditions and a videotape of the basic operating sequences was filmed. These operating patterns were timed and filmed an average of five-to-six times. [185]

Emission data will usually vary from test cycle to test cycle because some cycles are more rigorous than others, which in turn, can impact the level of engine-out emissions. For example, testing refuse haulers over the New York City Garbage Truck (NYCGT) cycle, which has a great deal of idle time and high-load power operation, resulted in higher emissions when reported on a gram-per-mile basis than on other test cycles. [205] Interestingly, in at least one instance, while the engine-out PM emissions varied from cycle to cycle, the DPF-equipped vehicle showed less of a difference in PM level. [108] In that study, the engine out emissions without a DPF on transit buses were four-to-five times higher on the NYB cycle, which is more rigorous, compared to the CBD cycle, but the emissions of the DPF-equipped buses were about the same on both cycles.

Other factors, in addition to the test cycle used, can impact emission results, including test-to-test variability in driver performance, variation in engine and exhaust operating temperatures, as well as analyzer drift. [147]

2.1.2.2 *Information from U.S. Retrofit Projects*

In most projects, no DPF emission testing was performed. In many instances, DPF emission reductions were estimated using CARB or EPA verified levels reported on their respective websites, or the EPA emissions calculator. (e.g., P23, P59, and P43.1) Some emission testing was performed in a limited number of projects. A mobile chassis dynamometer was used for emission testing in several projects. (P116, P123, P128) One project reported up to 90-95% reductions in PM, HC and CO. Another project reported average emission reductions compared to using ULSD alone of 88% for PM, 85% for HC and 83% for CO. A laboratory-based heavy-duty chassis dynamometer was use for emission testing in several projects. (e.g., P120, P131)

Opacity testing was performed in several projects. (P56, P68, P126.1) For example, the opacity data for one project showed that opacity levels were reduced from an average of 3.3% to 0.4% after the DPF was installed. (P68) In another project, baseline levels of 19% were reduced to immeasurable levels with the DPF-equipped vehicle. (P56)

In-cabin and/or ambient emission testing was conducted in several school bus retrofit projects. (P68)

2.1.3 Vehicle Applications

2.1.3.1 *Information from the Literature*

DPFs were first installed on nonroad equipment in the mid-1980s. The number of vehicles retrofitted, the number of programs implemented, and the interest in new programs all have grown significantly over the past few years. Today, over 150,000 DPF systems have been retrofitted on diesel powered vehicles and equipment worldwide. [125, 168] These applications include trucks, buses, construction equipment, material handling equipment, mining equipment and locomotives.

Unlike a DOC, which has near universal application as a retrofit device, a DPF is an application-specific technology. Factors to be evaluated when considering DPF retrofit for a specific vehicle or piece of equipment include: engine-out PM emission levels (including those from engine lubricating oil), the engine duty cycle and the resultant exhaust temperatures, available space, and fuel sulfur levels. To ensure that the engine exhaust gas temperature is adequate to initiate regeneration for a specific vehicle or equipment application, data logging of temperature profiles is recommended. [152]

Development work continues to expand the application range of these high-efficiency DPFs. [3, 4] Also, as mentioned above, particulate filter systems are being introduced that are designed to provide exhaust flow turbulence and increased particulate residence time. These "flow-through" filters have achieved PM reductions of 40% to 70%. [60, 168] A version of this type of DPF has been verified under EPA's Voluntary Diesel Retrofit Program. In addition, flow-through DPFs are being offered as a retrofit technology for late model year diesel passenger cars and are being evaluated for original OE car and heavy truck applications in Europe. [168]

2.1.3.2 *Information from U.S. Retrofit Projects*

In the U.S. over the past four years, the number of retrofit projects utilizing DPF technology has grown considerably. [59] Also, the variety of vehicle/equipment applications is growing. Table 2-2 summarizes the number of DPF retrofit projects, by application, based on data supplied by retrofit project contacts.

Table 2-2, DPF Retrofit Application Projects in the U.S.

Application	Number of DPF Retrofit Projects
School Buses	25
Transit Buses	8
Utility Vehicles (e.g., dump trucks, street sweepers)	5
Grocery Trucks	3
Refuse Trucks	7
Nonroad Engines	1
TOTAL	49

The three major factors that have limited the selection and use of DPFs in retrofit projects are: 1) unavailability or high cost of ULSD fuel, 2) age of vehicle/equipment (and the corresponding high levels of PM emissions), and 3) exhaust temperature profiles of candidate vehicles/ equipment that were too low to initiate regeneration.

A number of retrofit projects that ultimately selected DOCs as the technology to utilize noted that the lack of an available supply of ULSD was a critical factor in not selecting DPF technology for the project. In several cases, while ULSD could be made available, the cost premium was too high to justify its use.

As was reflected in the literature, DPF retrofit projects in the U.S. involved later model year vehicles and equipment. In virtually every case, the projects involved 1993 or later model vehicles/equipment, and about a third of applications were for model year 2000 or newer.

In several projects involving school buses, transit buses, or utility vehicles in which DPFs were a candidate technology, exhaust temperature data logging revealed that the exhaust temperatures were too low to support utilization of DPFs. In those cases DOCs were selected for use.

Flow-through filters are now being employed in the U.S. in projects involving school and transit buses as well as nonroad equipment. For example, an EPA-verified wire-mesh flow-through filter is being employed on school buses owned by the Bellingham School District in Washington (P173), and with an FBC product on school buses in Oregon. Recently, this flow-through DPF system design was installed on two large diesel-powered construction cranes in New York City. [78], (P133)

An unverified wire mesh, air pulsation, PM soot reclamation/incineration system is being evaluated on a transit bus in Traverse City, Michigan.(P141) While the application of this technology may be broader than conventional DPFs, inadequate exhaust temperature profiles can be a limiting factor for flow-through filters as well.

2.1.4 Technology Delivery

As a result of a significant surge in the global demand for retrofit products (most notably in Japan) a shortage in the supply of DPF ceramic filters and DOC ceramic cores occurred in the beginning of the second half of 2003. This resulted in the delay, in many cases, of delivery of DPFs in the U.S. that continued into 2004. In some cases, these delays were up to four months and sometimes longer. In response to the increased product demand, the major suppliers of DPF ceramic filters and DOC ceramic substrates have dramatically increased their manufacturing capacity to produce these components. With increased manufacturing capacity in place, the ability to meet demand has been greatly improved. Any delays in delivery of products are expected to decrease over time. [132] However, with continued worldwide growth in the demand for both retrofit and OE DPFs, future delays remain a possibility. Retrofit projects providing information on DPF delivery time noted delivery times of 6 to 16 weeks from the date the order was placed. (see e.g. P149, P106, P84) Projects that reported on deliveries in terms of the delay beyond the scheduled delivery cited delays of one to four weeks. (see, e.g. P70, P56, P39) A number of projects reported that DPFs were received on time. (see e.g. P43.1, P72, P83)

2.1.5 Technology Installation and Maintenance

2.1.5.1 *Pre-Installation Maintenance*

2.1.5.1.1 *Information from the Literature*

Manufacturers of diesel retrofit technologies recommend that prior to installing any retrofit device, engine maintenance be performed to ensure proper engine operation condition, and that the engine be well maintained during the period the device is on the vehicle or equipment. [99] The documents on retrofit experience reviewed for this report do not detail the type of engine maintenance that was performed.

One report describes an evaluation of solid waste collection vehicle fleet maintenance practices in California. [161] The evaluation found that publicly-owned fleets were better maintained than privately-owned fleets. The study also concluded that privately-owned fleets with ten or more vehicles had better maintenance practices than fleets with less than ten vehicles. The study evaluated a number of factors including, number of service technicians as a function of fleet size, service technician training, organization of the maintenance shop, and cleanliness of the shop and fleet. The report recommends that retrofit DPF manufacturers and product suppliers invest in training for vehicle service technicians to provide instruction on proper retrofit product maintenance procedures, and for vehicle/equipment operators to provide instruction on responding to DPF backpressure warning alarms.

2.1.5.1.2 *Information from U.S. Retrofit Projects*

Pre-installation maintenance practices reported by U.S. retrofit projects since 2000 were very modest, ranging from performing of normal maintenance only to ensuring that vehicles were operating properly. (P126.1, P120, P128) In several instances, no pre-installation maintenance was reported as being performed. It is possible that the lack of reported pre-installation maintenance may be related to pre-screening of fleet vehicle/equipment retrofit candidates to eliminate those with a history of high engine lubricant consumption or other engine problems.

2.1.5.2 *DPF Installation*

2.1.5.2.1 *Information from the Literature*

In some applications, DPFs were described as a “simple retrofit” while in others, the space available for DPF installation on the vehicle or equipment was very restricted. Consequently, a variety of geometric layouts of DPF inlet and outlet sections and engine exhaust system pipes were sometimes needed to complete various installations. [89] In many applications, the DPF was installed as a muffler replacement. [138, 205] In some cases the DPF was designed to match the dimensions of the conventional muffler in both highway and nonroad applications. [128, 138] In other cases the DPFs were custom designed for each vehicle application. [205] DPFs have been designed to be comparable to or better than the noise attenuation level of the original muffler. [138, 148]

To facilitate removal of the DPF for cleaning, quick-release clamps are often used. [89] One installation issue discussed in the literature was the need to ensure that the DPF's installation employ sufficiently strong clamps and brackets. [142] On heavy-duty trucks, DPF's often replace the muffler located in the exhaust stack. Since a DPF typically weighs more and may be larger than the muffler, stronger clamps and brackets must be used in place of those used with the original muffler. Failure to utilize appropriate hardware can result in a mechanical failure of support brackets and in turn, cause damage to the DPF. [205] Insulation of the exhaust pipe, from the engine to the DPF inlet, has been employed to reduce exhaust gas heat rejection and retain an adequate temperature profile at the DPF location. [205]

2.1.5.2.2 *Information from U.S. Retrofit Projects*

The DPF installation experience reported from retrofit projects in the U.S. is consistent with that reported in the literature, and provided additional insight regarding the organizations that performed the installations, installation time, and related problems.

In virtually every project, the initial DPF installation was performed by the technology provider. (P39, P106, P164) Subsequent removal of the DPF for filter cleaning and reinstallation was typically performed by fleet service technicians.

The time required for DPF installation was a function of modifications needed (pre-fabricated vs. custom fit), and the available space to work with (e.g., need for engine removal before DPF installation could proceed) to fit the DPF to the vehicle/equipment properly. Installation times ranged from 2 hours to 12 hours. The DPF installation time for school buses was frequently less than that required for other applications such as refuse trucks or commuter buses. (P39, P56, P43.1, P126.1) This may be related to the greater availability under chassis space and pre-engineered DPF installation kits for school buses.

Examples of issues that occurred during DPF installation included:

- The need to modify the DPF to fit on the vehicle/equipment.
- Problems with mounting brackets that had to be replaced with those of a stronger design.
- Shorts in the DPF backpressure alarm system wiring harnesses that required the wiring harness to be redesigned. (P150).
- The need to fit the DPF into in a tight, hard-to-reach space. (P43.1).

In a number of school bus projects, the installation included a safety inspection from the state department of motor vehicles.

2.1.5.3 *Technology Maintenance*

2.1.5.3.1 *Information from the Literature*

Periodic cleaning of DPFs is typically necessary to remove the build-up of incombustible residues of fuel-based PM, ash from the engine lubrication oil, and/or FBC ash. [70, 151] Build-up of these materials on the filter can increase engine exhaust backpressure and potentially cause DPF failure. [152] One study showed that ash accumulation in DPFs can be accelerated under conditions of cold engine duty cycles that do not provide the exhaust temperature/time profile conditions needed for effective regeneration. [89] DPF design improvements to reduce the amount of ash accumulation on a filter are being developed. [3, 4]

The composition of the ash from engine lubricating oil depends, in part, on the lubricating oil formulation. Studies examining this subject found that the lubricating oil ash typically consists of phosphorous, sulfur, calcium, and zinc. [129] A number of studies found that the principal need for DPF cleaning resulted from high accumulation of ash from the engine lubricating oil. [70, 89] Accumulation of high levels of ash from engine lubricating oil is more likely to be a factor with older engines. [35]

Where an FBC is used as part of the DPF system, DPF cleaning must be performed more frequently than in applications where the particulate filter itself is catalyzed. The interval required between cleanings can be lengthened by reducing the FBC content in the fuel. [151] This has been done in Europe for OE light-duty vehicle application.

Recommended intervals for DPF cleaning varied depending on such factors as engine age, vehicle/equipment application, engine operating cycles, sulfur level in the fuel, engine-out PM emissions, engine lubricating oil consumption, and FBCs (if used). [90, 129, 151] Recommended cleaning intervals ranged from 15,000 km to over 100,000 km. Reports of several programs recommend filter cleaning on an annual basis. For construction equipment in Switzerland, DPF cleaning is recommended every 2000 hours of operation but a number of pieces of equipment have operated for well over 2000 hours without requiring DPF cleaning. [128] In some instances rather than establishing a preset cleaning interval, monitoring of engine exhaust backpressure was used to determine if and when DPF cleaning was necessary. [70]

In those instances where very low sulfur content diesel fuels (e.g., ULSD) were used, engine lubricating oil consumption was low, and exhaust temperatures were sufficient to ensure proper regeneration, vehicles accumulated significant mileage without the need for DPF cleaning. For example, grocery delivery trucks equipped with DPFs operated over 300,000 miles over three and one-half years with one or no filter cleanings. [117]

The reviewed literature describes several different types of DPF cleaning methods, including: washing, pressurized air and vacuum cleaning, heating ovens, and heating ovens combined with a machine to shake loose material from the filter. [89, 151] Generally, studies showed that after DPF cleaning, backpressure levels returned to acceptable levels. [70] One study showed that manual cleaning of the DPF resulted in removal of 18% to 71% of PM and ash, and that using an industrial oven process removed substantially more ash and PM. [89] Several reports stress the importance of providing training courses for vehicle/equipment service technicians on filter cleaning procedures. [151]

2.1.5.3.2 *Information from U.S. Retrofit Projects*

The experience with retrofit projects in the U.S. provides useful insights on the actual intervals between filter cleaning, the type of cleaning methods being employed, organizations that perform the cleaning, and issues that have arisen.

Scheduled cleaning intervals for filter cleaning vary somewhat depending on the miles driven, hours of operation, or type of duty cycle. For many projects the technology provider recommended that filter cleaning be performed annually. In some cases, the technology provider examined the condition at least one DPF-equipped vehicle after it had operated for several months to assess DPF ash accumulation, exhaust temperature profile and backpressure history. A recommended cleaning interval was then established based on this information. (P146, P147) For applications in which the exhaust temperature profile is adequate to initiate regeneration, DPFs typically have not needed cleaning before the scheduled maintenance point. Most vehicles/equipment retrofitted with DPFs have been equipped with backpressure monitors. These devices signal that the filter should be cleaned in advance of the scheduled cleaning. In cases where the exhaust temperature profile has been too low to initiate proper filter regeneration when needed, DPFs have plugged after very short intervals and required frequent filter cleanings. For example, a number of King County Metro Transit buses have required cleaning every 30 days. (P150) DPFs can be designed for quick removal to facilitate the cleaning process. For example, the Wisahickon School District reported that about 15 minutes was required to remove a filter for cleaning. (P39)

DPF cleaning methods reported to have been used include:

- Using compressed air to blow the ash from the filter (and capturing the ash and other materials exiting the filter into a sealed container).
- Using compressed air to blow the ash from the filter, combined with a vacuum system and a sealed container.
- Connecting the filter to an oven/hot air blower.
- Removal, reversal, and reinstallation of the filter into the vehicle exhaust system. This method is not recommended because it results in the accumulated ash and other material on the filter being emitted directly into the ambient air. Also, this method is not as effective as the other methods listed above.

Simply using compressed air was not always sufficient to clean the filters properly. (P68) In most cases, filter cleaning and proper disposal of the ash was performed by the DPF supplier, often at a different location. (P56, P170, P172) However, some fleets are showing a growing interest in purchasing their own cleaning equipment to reduce the downtime for a given vehicle and to save on the costs of filter cleaning. (P23, P150)

Retrofit projects using flow-through filters reported that no maintenance was required. (P173, P141) Some flow-through filters designs normally do not require maintenance. (P173) One flow-through filter design requires application of pulsed air every 3,000 miles. This typically takes 1-2 minutes and is generally performed during scheduled vehicle maintenance intervals, and reportedly does not negatively impact vehicle operation. (P141)

2.1.6 Monitoring and Alarm Systems

2.1.6.1 *Information from the Literature*

The literature emphasized that use of a device to monitor the exhaust backpressure is important to ensure continued effective DPF operation. A variety of exhaust backpressure monitors are available to provide both visual and audible alarms to signal when backpressure has exceeded recommended levels. Alarm systems can be customized for each application and can provide information on whether the DPF is regenerating effectively, alert the operator that a problem may exist with the DPF, and provide an alert for determining when DPF cleaning is required. Virtually every DPF retrofit project documented in the literature used a backpressure monitor alarm system. [70, 89, 117, 128, 156]

2.1.6.2 *Information from U.S. Retrofit Projects*

The DPF retrofit experience in the U.S. since 2000 confirms the importance of having an effective backpressure monitoring and alarm system to provide early warning that a problem with filter plugging is occurring and needs to be addressed before catastrophic filter failure occurs and/or the performance of the vehicle is degraded. Retrofit project managers and others stated that alarms systems were helpful in determining when to schedule maintenance and to avoid problems with the DPF or vehicle operation before they arose. (P23, P83, P172)

All DPF systems were equipped with at a minimum, a backpressure alarm system. In a number of cases monitoring systems employed a diagnostic and programming module that recorded such information as the history of control parameter settings, operating hours, exhaust temperature and backpressure. The typical backpressure monitor consisted of a two-light alarm. An illuminated yellow light signaled a problem that required inspection and indicated the need for possible maintenance. An illuminated red light signaled the need to cease normal vehicle operation because of excessive backpressure. Some of these alarm systems included the means to reduce engine power settings to a level that would allow the vehicle “limp home” when the second stage alarm was triggered.

Alarm lights were located either in the view of the vehicle operator (typically on the dashboard) or in the engine compartment. The advantage cited for locating the alarm in view of the driver was to allow the driver to take immediate action, if needed. The disadvantage cited was that if a false alarm occurred (by being illuminated even though there was not a backpressure problem), the vehicle operator would be unnecessarily distracted by the alarm and might take unnecessary corrective action. If the alarm lights are located in the engine compartment, they can be observed at the end of a daily operating cycle as part of a routine maintenance check.

2.1.7 Technical Support and Training

Retrofit project managers and others viewed technical support and training as critical elements of a successful DPF retrofit project. The major source of technical support came from the technology manufacturer or product supplier, but other groups also played a critical role in many projects. Those sources included the U.S. EPA (both headquarters and regional offices), state environmental agencies, regional and local air quality agencies, multi-state regional organizations such as the Northeast States for Coordinated Air Use Management (NESCAUM), independent technical contractors, and others. For most projects, retrofit project managers and fleet managers alike appeared satisfied that the level of technical support was adequate in terms timeliness and quality. In several projects, the strong commitment of the technology supplier to be available for trouble shooting and problem solution was viewed as critical to the ultimate success of the project. Projects that had a high level of technical support and the strong commitment of the technology supplier helped to sustain the support and willingness of fleet personnel to address problems as they arose. In several projects, the level of technical support from the technology manufacturer and/or product supplier was viewed by fleet personnel or project partners as inadequate.

Training for vehicle service technicians and vehicle operators was cited as being provided in a number of projects. In some cases there was no or minimal training and in other cases vehicle operators were not included in the training. Training for vehicle service technicians covered such topics as DPF installation, servicing, monitoring, and maintenance, including filter cleaning. (P23, P126.1, P158) This training frequently included instruction on downloading information from the DPF alarm/monitoring system. (P147) Training for operators focused on recognizing and taking appropriate action when problems arose during vehicle/equipment operation. (P39, P164) For example, operators were instructed on action to be taken if the backpressure indicator light was illuminated and how the vehicle would behave in a derated power mode situation. (P68)

2.1.8 Technology Performance, Problems and Solutions

2.1.8.1 *Information from the Literature*

The literature reflects the fact that most highway DPF retrofit projects to date have used passive DPF systems as well as DPFs plus FBC. In nonroad applications, such as construction and mining, a mix of passive and active systems has been applied successfully. Active systems, which employ either an internal regeneration strategy such as a fuel burner or an external regeneration strategy such as removal/cleaning, are required for applications where the engine exhaust temperature is lower than would otherwise be needed for passive systems. [28] The various studies related to highway vehicles have shown that passive DPF systems work effectively for extended periods of time providing high PM control efficiency. [35, 89, 114, 117, 129, 131, 151] These studies illustrate that successful application of a passive DPF often hinges on several factors, including the need to:

- Maintain engine exhaust temperature at a sufficient level over a sufficient percentage of engine operation to permit the filter to regenerate.
- Use diesel fuel with a maximum of 50ppm sulfur content.
- Involve only engines that are well maintained and that do not consume excess engine lubricant.

Under these conditions, DPFs have demonstrated excellent durability with heavy-duty diesel engines, and have operated effectively for up to 300,000 miles or more. [99, 205]

Virtually every project involving the successful application of passive DPF systems has demonstrated that the exhaust temperature profiles were excellent for passive DPF application. Class 8 trucks operating on long haul routes appeared to be particularly good candidates for DPF application. For example, a report on the successful ARCO multi-vehicle demonstration project notes that fuel delivery trucks in the project operated with the exhaust temperature at 375C about 44% of the time and at 300C greater than 50% of the time. School buses operated in the range of 250C to 350C, with 42% of the operating time above 300C. These are considered good operating conditions for a passive DPF product. [70] Another study found that a minimum exhaust temperature of about 300°C or greater for a significant part of the operating time (greater than 15% to 20%) of the retrofitted systems duty cycle was needed to keep the DPF operating effectively. [117] Another study concluded that temperatures in the 250C to 450C range were best for DPF operation. [121] When the exhaust time/temperature profile requirement for a particular DPF system is not met, PM accumulates in the DPF, resulting in unacceptably high backpressure with a negative impact on fuel economy and engine performance, and presenting a risk of a catastrophic regeneration event that can damage the filter. Another study involving retrofit of DPFs on construction equipment showed that the overall emission control performance of a backhoe (equipped with a catalyzed DPF) was relatively poor when it was operated at a significantly lower exhaust temperature range of approximately 250C. [185]

A recent project was performed to characterize the operational aspects (particularly related to regeneration effectiveness) of catalyst-based DPFs. The project related DPF performance to engine speed and load, and provided a tool (in the form of a statistical model of filter response) to further describe the response of a DPF over a wide range of operating conditions (in the form of a DPF "map"). [58] Further development of these techniques will allow a better understanding of DPF operating limitations under real-world duty cycle conditions.

In those instances where exhaust temperature profiles are not suitable for passive DPF systems, DPF/FBC systems and active DPF systems have been successfully applied with extended durability and effective emission control performance. [90, 148, 154, 198] For example, a DPF/FBC system on London (England, U.K.) taxis regenerated effectively even though the vehicles operated at exhaust temperatures above 200C less than 50% of the time. Another study examined construction equipment, including a backhoe with an uncatalyzed DPF with an active regeneration system. [185] This DPF was designed to be regenerated at the end of the shift operation, with the use of electrical heaters. The system achieved an 81% reduction in PM, but only 12% to 16% reduction for HC and CO due to the absence of a catalyst. Another DPF/FBC technology demonstration project involving a delivery truck in California operating at low load/exhaust temperature with an EGR-equipped diesel engine resulted in over 90% DPF operating efficiency with a flow-through type DPF. [198]

Reports on several different retrofit evaluation/demonstration programs provide some useful information on various aspects of the DPF retrofit technology performance experiences, including durability, failure rates, causes of failures and corrective actions. Examples include the following:

- ***ARCO Fleet:*** A variety of late model trucks and buses were equipped with passive DPFs and operated on ULSD fuel. After one year, during which several vehicles accumulated over 100,000 miles, there was no significant DPF deterioration. Twenty grocery delivery trucks accumulated over 100,000 miles with no filter cleaning and achieved a 95% PM reduction. DPF control efficiency on tanker trucks did not deteriorate over the first 15 months, achieving a 96% PM reduction. School buses accumulated an average of 44,000 miles and achieved about a 96% PM reduction. Refuse trucks after 20,000 miles of operation, achieved 95% PM reduction. [205] After three and one-half years, grocery delivery trucks accumulated an average of 340,000 miles and achieved greater than a 99% PM reduction with little or no impact on fuel economy. One truck operated three years without having its DPF cleaned and still exhibited low back pressure. The DPFs on the other grocery delivery trucks required cleaning only once during the three and one-half- year period. [117]

- ***City Buses in Europe**:* A recent report documented the experience with DOC plus DPF systems on 16,000 transit buses in several European cities over an eight-year period. [89] The report focuses on those instances where DPF failures occurred and the successful solutions that were applied. Buses that experienced DPF failures used 50ppm sulfur content fuel. This fuel was found to degrade the NO to NO_2 conversion over the DOC and resulted in a sharp increase in failures to regenerate the DPF. Typically, the buses would operate trouble free for 20,000 km before a rapid increase in backpressure, which was often followed by an exothermic failure of the DPF. The solution to this problem included increasing the catalyst length by three to six inches. Also, in some cases an improved sulfation-resistant DOC formulation was introduced; and subsequent service with the upgraded DOCs provided superior longevity with 50ppm sulfur content fuel. The upgraded DOC/DPF systems tested after 80,000 km showed excellent conversion efficiency of NO to NO_2 while operating on 50ppm sulfur content fuel. No further problems with the buses were reported. Several other buses had DFP failures attributable to high backpressure or damaged filters due to the exothermic heat developed upon regeneration with excessive accumulated PM. It was discovered that the exhaust temperature on these buses was unusually low. This problem was solved by increasing the DOC length, using an improved catalyst material, and making improvements in thermal insulation of the exhaust system upstream of the DOC/DPF systems, as well as servicing the filters every 30,000 km.

  The report also notes that passive filters are reliable for the most part, but passive regeneration makes them vulnerable to regeneration failures. Problems can be minimized by:

  - Careful application design, including appropriate catalyst sizing and thermal installation.

  - Improved predictive capability by using exhaust temperature, and NOx and PM emissions measured under realistic conditions.

  - Improvements in passive regeneration performance (especially catalyst sulfation resistance).

- In-service monitoring of backpressure.

- Improved (appropriate) DPF cleaning.

- ***Construction Equipment in Switzerland:*** A recent report highlights experience with Switzerland's mandatory diesel construction equipment DPF retrofit program, which went into effect in 1998. [148] A number of passive and active DPFs systems have been approved for use in this program. Over 7000 engines were equipped with DPFs as of the end of 2004. Many of these DPFs are achieving a minimum of 99% reduction in carbon-based PM and are performing well after extended hours of operation. One DPF achieved a 98.6% carbon-based PM reduction after 22,000 hours of operation. The study did not identify any typical aging phenomenon and no durability-constraining factors were observed.

  DPF failure due to mechanical and thermal damage was initially about 10%. By 2000, the failure rate was reduced to 6%. With technology and operational improvements, the yearly failure rate during 2003 was only about 2%. The Swiss target for its construction equipment retrofit program is to retrofit 15,000 pieces of equipment with DPFs that meet the 5,000 operating hours durability requirement with failure rates below 1%. [92]

  The reported causes for DPF failures included:

  - Defective canning of the ceramic monoliths.

  - Material defects in ceramic material.

  - Customer handling accidents.

  - Failure to install the DPF properly on the vehicle.

  - Operating errors (e.g., using high sulfur content fuel).

  - Inappropriate application (e.g., engine exhaust gas operating temperature insufficient for regeneration).

  - Installation on equipment with engines that have excessive engine lubricating oil consumption (greater than 2% of engine fuel consumption).

  Study results also showed that after prolonged operation, DPF failures were much less frequent, and that the three main causes of such failures included:

  - Neglecting the alarm that warns of excessive engine exhaust backpressure.

  - Careless or incomplete DPF cleaning.

  - Lack of proper engine maintenance.

Study results also indicate that DPF cleaning was needed no more frequently than once every 2000 hours of engine operation, which suggests that after three to four cleanings the DPF may need to be replaced. Finally, the study also noted that use of low-ash engine lubricating oil extends the life of the DPF.

2.1.8.2 *Information from U.S. Retrofit Projects*

Consistent with information contained in the literature, the U.S. DPF retrofit experience since 2000 confirms the critical importance of maintaining the exhaust temperature levels that are adequate to initiate regeneration of passive DPFs. Where problems with filter plugging occurred, the most commonly identified cause was that the vehicle/equipment exhaust temperatures were too low to support proper filter regeneration. Problems were also caused by:

- Engine component wear or failure.
- Improper filter sizing for the specific application.
- Misfueling with diesel fuel of the incorrect sulfur level.
- Incomplete filter cleaning.
- DPFs that were installed on OE engines with high-pressure EGR systems.
- Monitoring alarm system malfunctions.

2.1.8.2.1 *Adequate Temperatures to Support Regeneration*

Exhaust temperature data logging was performed to some degree in virtually every project considering or applying DPF technology. In a number of projects, the decision was made (correctly) not to use DPFs based on data indicating that the exhaust temperature was too low to support filter regeneration. In many cases, the data logging process provided information indicating that the vehicles/equipment were good candidates for DPF retrofit. After subsequent installation, the DPFs functioned without any problems.

In other cases, however, even though data logging of the exhaust temperature profile suggested that DPFs could be applied, problems with premature filter plugging occurred because the operating temperatures were too low to support proper regeneration. Typically where premature plugging occurred, the problem could be traced to the fact that the temperature profile of the vehicle(s)/equipment used for data logging did not reflect the actual "worst case" operating cycles in terms of engine speed, load and idle time. These factors include more stop-and-go driving, lower speeds, fewer hills, lighter passenger/cargo loads and more idling than was reflected in the driving cycle that was use during the data logging process. In several cases, extended idling was specifically cited as a contributing factor in premature filter plugging. In a number of cases the issue of idling was minimized by having reduced idling requirements/ practices in place. In a few instances, retrofit project contacts indicated that the technology supplier was perhaps too optimistic with regard to the minimum time/temperature profile needed to support DPF application.

Where problems occurred with premature DPF plugging, as was the case with some transit and school buses, the operating routes typically involved urban-type, low-speed, frequent stop-and-go driving as opposed to rural or highway routes that involved high speeds and few stops where DPFs did not typically experience any problems.

In some cases where operating temperatures where marginal for supporting filter regeneration, insulating blankets were applied to the exhaust system upstream of the DPF. (e.g., P169)

Projects that did not experience problems with premature plugging typically had data logging information based on a representative, worst case scenario in terms of vehicle application and operating cycle. These projects typically included an additional margin to the minimum time/temperature data profile to account for unforeseen differences between actual vehicle/equipment operation and that used for defining DPF selection acceptability.

2.1.8.2.2 *Engine Component Wear or Failure*

Proper engine maintenance is necessary to ensure that excess fuel or engine lubricating oil is not introduced into the engine combustion process and cause a negative impact on DPF performance. For example, information from several projects noted that worn fuel injectors would leak fuel into the combustion chamber causing excess PM to collect on the filter contributing to increased backpressure. In one instance, a filter failed because the engine turbocharger malfunctioned.

2.1.8.2.3 *Filter Sizing*

In at least one instance, the problem of premature plugging could be traced to the size of the DPF. A nine inch diameter filter equipped on several transit buses required cleaning every three month or less. The original filter was replaced with 10.5-inch diameter filter that resulted in the cleaning interval being extended to one year or longer. (P68).

2.1.8.2.4 *Misfueling*

Problems with misfueling DPF-equipped vehicles do not appear to be significant in ongoing U.S. retrofit projects. In one case, however, a refuse truck was fueled with regular low sulfur highway diesel fuel and the filter plugged quickly. After the filter was cleaned and the vehicle switched to diesel fuel with less than 30ppm sulfur content, no further problems occurred. (P43.1) Reportedly, the vehicle operator had been advised by the product supplier that ULSD was recommended for use with the DPF, but that regular low-sulfur diesel fuel could also be used.

2.1.8.2.5 *DPF Cleaning*

In several cases, the DPF cleaning method employed in the project did not adequately clean the filter, resulting in the need for cleaning more frequently than expected. For example, compressed air cleaning or reversing the filter may not be sufficient to clean the filter if a considerable portion of the accumulated material consists of more viscous, oily liquid and tends to stick to the filter, as opposed to dry ash that can be removed via air cleaning.

2.1.8.2.6 ***OE High-Pressure EGR-Equipped Vehicles***

Several projects involving DPF retrofits on transit buses have reported problems with DPFs that were installed on vehicles with engines originally equipped with high-pressure EGR systems.

2.1.8.2.7 ***Monitoring, Data Collection and Alarm System Malfunctions***

Several projects reported interruptions in vehicle operation because of malfunctions with the exhaust backpressure sensor, exhaust temperature thermocouple, and/or control software module. (P68, P159, P164) For example, there have been instances were the backpressure alarm singled a backpressure problem when none exists. This problem has been attributed to several causes including issues with the control system software or the sensitivity of the backpressure measurement probes when used in the harsh, high-vibration environment of a heavy-duty vehicle/equipment exhaust system. The technology providers are working to address these problems and progress is being made.

Projects utilizing flow-through filter technology have not reported any operational problems even though the vehicles in these projects have not been equipped with backpressure alarm systems. (P173, P141)

2.1.9 Technology Costs

2.1.9.1 ***Information from the Literature***

Costs associated with DPF applications include those for hardware, installation, maintenance costs, and operation. The impact of fuel economy (an operating cost issue) is discussed in Section 2.1.11. Cost estimates tend to vary based on such assumptions as the number of units being produced or sold. Also, cost estimates for technology tend to decrease over time because as technologies are optimized, their costs tend to decrease. Various estimates for hardware, installation, maintenance and operating costs are discussed below.

With regard to hardware costs, MECA, in 2002, reported that the average price of a DPF being sold for retrofit applications was in the range of $7500. [152]

In 2000, CARB provided an estimate of DPF hardware costs based on horsepower rating, as shown in Table 2-2.

Table 2-2, CARB Estimated Costs of DPF Technology

Engine Horsepower	Hardware Cost
40 hp	$3,300 - $5000
100 hp	$5,000 - $7,000
275 hp	$6,900 - $9,000
400 hp	$10,500
1,400 hp	$32,000 - $44,000

CARB also estimated an installation cost of $50 to cover miscellaneous parts, plus 1.5-to-6 man-hours of labor per installation. [170] Other cost estimates for DPFs ranged from $6000 to $9000. [104, 167] DPF manufacturers predict that as technology is optimized and the sales volume for DPF increases (both retrofit and OE applications), DPF product costs will be reduced. [99]

The principal maintenance costs associated with DPFs is a periodic cleaning of the filter. In 2000, CARB estimated the annual maintenance costs ranged from $156 to $312 with a labor requirement of about two to four man-hours per year. [170] One recent report contains fairly comprehensive information on maintenance and operating costs, other than those for DPF cleaning. [142] In this report, the total maintenance cost for all forms of maintenance (e.g., exhaust, fuel, electrical, brake, cooling systems, etc.) was identified as $0.064 per mile for trucks operating on baseline fuel without a DPF. The corresponding cost for DPF-equipped trucks operating on ARCO's low-emission diesel fuel was $0.067 per mile. The exhaust system maintenance costs for baseline and DPF-equipped trucks was $0.0007 per mile and $0.0023 per mile, respectively. During this particular retrofit project, no servicing of the DPFs was required. Had servicing been required, two to four hours of labor would have been needed to disassemble, clean and reassemble the DPFs. Some maintenance work was required for the DPF systems, but for the most part, this was directed towards checking DPF integrity and clamps. The use of ARCO's low-emission test fuel with its low aromatic content gave rise to leaks in fuel lines. Those lines were replaced at an unspecified cost.

2.1.9.2 *Information from U.S. Retrofit Projects*

DPF retrofit costs reported in the U.S. appear to be generally in line with the costs reported in the literature. The DPF costs reported ranged from $4000 to slightly more than $10,000. In most instances the product cost included installation and the monitoring equipment. In cases where installation costs were identified, they ranged from $300 to as much as $1500. One project listed the price for the DPF monitoring system at $670. (P146)

The costs of flow-through filters currently being used in U.S. retrofit projects range from approximately $3,000 for the wire mesh designs to $8,000 for the technology that utilizes a pulsation platform. (P173, P141)

The cost of filter cleaning ranged considerably, from about $22 to $600 annually. (P39, P68, P172)

2.1.10 Warranties

2.1.10.1 *Information from the Literature*

Retrofit product warranties are typically negotiated as part of the purchasing contract between product vendors and their customers. Such warranties typically cover defects in materials or workmanship for a specified period expressed in terms of year(s), mileage and/or operating hours.

As part of the CARB DRRP, CARB has established detailed warranty requirements for DPFs and other retrofit technologies. These requirements include specified periods for the warranty covering emission performance and defects in materials and workmanship, as shown in Table 2-3 below.

Table 2-3, CARB DPF Warranty Requirements

VEHICLE CATEGORY	WARRANTY REQUIREMENT
Heavy, heavy-duty vehicles which exceed 33,000 lbs. GVWR with engine ratings above 250 hp and where (i) the truck typically is driven over 100,000 miles per year, and (ii) has less than 300,000 miles on the odometer at the time of installation.	Two years; unlimited mileage.
Vehicles with GVWR of at least 33,000 lbs. And engines rated above 250 hp	Five years or 150,000 miles, whichever occurs first.
Vehicles with GVWR of 19,500 lbs. to 33,000 lbs.	Five years or 100,000 miles, whichever occurs first.
Vehicles with GVWR less than 19,000 lbs.	Five years or 60,000 miles, whichever occurs first.

2.1.10.2 *Information from U.S. Retrofit Projects*

Where information on warranty coverage was reported, it generally follows the duration of warranty coverage provided by the CARB DRRP. In some cases, the warranty coverage was less. Several school bus projects reported warranties of one year or 20,000 miles, whichever occurred first. (see, e.g. P61, P146) In several cases no warranty was provided in exchange for a reduced price for the DPF. (P128, P123)

2.1.11 Impact on Vehicle Performance and Fuel Economy

2.1.11.1 *Information from the Literature*

The only DPF impact on engine/vehicle performance discussed in the literature focuses on the potential for increased engine exhaust system backpressure. As noted above, in those instances where backpressure exceeded the engine manufacturer's specification, the problem was addressed by cleaning the DPF. Relative to DPF impact on fuel economy, several studies report a small (1% to 3%), but not necessarily statistically significant, fuel economy penalty. [36, 147] Other studies report no detectable fuel economy penalty. [35, 70, 142] For example, the results of a study involving a demonstration project of 20 Class 8 trucks (operating for over 50,000 miles) in California showed that trucks equipped with DPFs and ULSD exhibited fuel consumption levels that were "essentially the same as" the control trucks operating on California diesel fuel. [35] Several reports note that there was no significant fuel economy impact even in instances where high exhaust backpressure was encountered. [35, 138] A fuel economy penalty of less than 2% was reported for a burner-assisted regeneration DPF system. [29]

In one project involving DPF-equipped grocery delivery trucks, a 2% to 3% fuel economy penalty was observed. The fuel economy penalty was not attributed to the DPF, but rather to the lower energy content of the test fuel being used (a California low emission diesel fuel). [205] A project involving a DPF/FBC system installed on taxis without EGR systems reported a fuel economy improvement of up to 4.5%. [53] The one taxi that was equipped with EGR experienced a fuel economy penalty.

2.1.11.2 *Information from U.S. Retrofit Projects*

In a large number of U.S. DPF retrofit projects involving diverse vehicle applications including school buses, transit buses, and trucks, no adverse impact on vehicle performance was reported. (see e.g. P23, P106, P116, P120) In several projects, operators specifically commented that they did not notice any change in vehicle performance. (P123, P124)

The principal problem cited by the project contacts, was premature plugging of the filter resulting from inadequate exhaust temperature to initiate regeneration. When it occurred, this problem resulted in more frequent filter cleaning, vehicle downtime for making a road call to tow the vehicle and for DPF removal and reinstallation. No other DPF-related vehicle performance issues were reported.

A number of projects indicated there were no reported or measurable impacts on fuel consumption. (see e.g. P43.1, P124, P131) One project observed a 1% to 3% penalty on some vehicles but indicated the difference was not statistically significant. (P123) A school bus fleet reported a slight decrease in fleet fuel economy from approximately 14 miles per gallon to 13 miles per gallon. (72) One project involving line-haul trucks reported a fuel economy penalty of about 5%. (P220)

Projects employing flow-through filters reported no adverse impact on vehicle performance or fuel economy. (P173, P141)

2.1.12 Impacts of Fuels and Lubricants

2.1.12.1 *Information from the Literature*

The literature offers a thorough discussion of the impact of fuel properties on DPF performance. Sulfur in diesel fuel is, without question, the most important fuel property affecting DPFs. For catalyst-based DPFs, the level of sulfur in the fuel directly influences the amount of sulfate that a catalyst-based DPF generates. Sulfur also adversely impacts the temperature at which regeneration occurs. [57] Virtually all of the retrofit projects reported in the literature used either a low sulfur content (less than 50ppm) diesel fuel or ULSD.

Several successful applications of DPFs are reported where diesel fuel with sulfur content of less than 50ppm was used. [73, 138, 185] For example, six Class 8 trucks were operated in Europe and after accumulating 85,000 km, the DPFs continued to operate effectively. The DPF system used an FBC and a specially designed filter to be more tolerant of ash buildup. Results of a study of buses in Europe equipped with a catalyst-based DPF designed to operate on less than 10ppm sulfur content fuel showed a sharp increase in failures when 50ppm sulfur was used, because the higher level sulfur in the fuel degraded the NO to NO_2 conversion that is needed to bring about regeneration successfully. The technology supplier was able to improve the sulfur tolerance of the NO oxidation catalyst used in the DPF system and as a result, the overall performance of the DPF system improved when used on vehicles operated on 50ppm sulfur content diesel fuel. [89]

Results of a project involving New York City transit buses with Detroit Diesel Corporation (DDC) Series 50 engines fueled with diesel fuel of 30ppm sulfur content show that after eight months, the DPFs on the buses had successfully regenerated and there were no reported adverse operational or maintenance issues. [130] The results of another study showed that using diesel fuel with less than 25ppm sulfur content was critical for the successful operation of transit buses in Europe. [129] A number of reports provide information on DPFs and the use of ULSD, and describe that with ULSD, the DPFs performed effectively for extended periods of time, in some cases, well in excess of several hundred-thousand miles. [35, 117, 205]

It is inevitable that a small portion of an engine's lubricating oil will find its way into the engine combustion chamber, with the resulting products of lubricating oil combustion found in the engine exhaust. The base stocks of engine lubricants and their additives contain sulfur, zinc, phosphorus and sulfated ash that are not well-tolerated by exhaust emission control technologies such as DPF, DOCs and other retrofit devices used with diesel engines. As such, lubricant manufacturers are developing lubricants and additive packages that can be better tolerated by diesel aftertreatment devices with fewer negative impacts related to catalyst poisoning and DPF plugging. [103, 183] Successful DPF retrofit programs worldwide are using engine lubricants specifically formulated with low levels of ash, sulfur and phosphorus. [85, 156]

Combustion of engine lubricating oil also results in higher levels of PM. For this reason, greater than "normal" lubricant consumption in vehicle operation can lead to premature failure of emission control devices, or more frequent regeneration intervals for vehicles equipped with DPFs. As noted previously, laboratory testing has shown that engine/vehicle operating conditions have a significant impact on the composition of the PM. [184]

2.1.12.2 *Information from U.S. Retrofit Projects*

All but a few of the DPF retrofit projects currently in place in the U.S. are using ULSD. Several programs are using diesel fuel with sulfur limited to 30ppm and have reported no problems. (P43.1, P126.1, P172) A few projects are using a biodiesel/ULSD blend and reported no adverse impacts on the DPF. (P65, P87, P150, P161) The one reported instance when a vehicle was misfueled with regular highway low sulfur diesel fuel resulted in premature filter plugging. Once the vehicle switched to diesel fuel with less than 30ppm sulfur content, there were no further problems with premature plugging.

Both projects employing flow-through filter technology are using regular highway low sulfur diesel fuel (less than 500ppm sulfur content). (P173, P141)

One project involving the use of a vehicle-installed engine lubricant management system noted a premature DPF plugging that was likely attributed to the system. (P220) Engine lubricant management systems function by removing a small amount of used engine lubricant (while the vehicle is operating) and replacing it with new lubricant from an onboard reservoir. These systems are used as a means of replenishing engine lubricant without the time and expense of performing manual oil changes, and are available as retrofit products from several diesel engine equipment suppliers. They are also offered as OEM-installed systems on certain new engines. The problem these systems create for DPFs stems from the direct combustion of engine lubricant at rates that are much higher than the DPF would be exposed to under conditions of normal engine lubricant consumption.

At the advice of the DPF technology developer, the fleet manager for this project deactivated the engine lubricant management system, however, DPF filter plugging continued. Apparently, even though the electronically controlled lubricant management system was deactivated, the system continued to inject used engine lubricant into the engine fuel system for combustion. The solution to the problem was complete removal of the lubricant management system. The technology developer now requires that any engine lubricant management systems be removed from the vehicle before installing its DPFs.

2.2 DIESEL OXIDATION CATALYST

2.2.1 Overview

A DOC reduces emissions by catalytically converting harmful pollutants to water and CO_2. A DOC reduces engine-out HC and CO by up to 90% or more, and PM by 20% to 50% depending on exhaust temperature, sulfur level in the fuel, composition of engine-out PM and other factors. [11, 32, 57] DOCs control the soluble organic fraction (SOF) of the PM by up to 90%. However, on older engines with higher lubricating oil consumption that typically emit a high fraction of SOF, the PM reduction levels will be greater than on engines with a lower concentration of SOF in the total PM. The PM SOF from a diesel engine is related, in part, to the engine lubricating oil consumption characteristics and in-cylinder combustion characteristics. DOCs also reduce smoke emissions from older vehicles by over 50% and virtually eliminate the pungent odor associated with diesel engines. DOC performance is not reduced significantly when used with conventional low sulfur content (up to 300ppm to 500ppm) diesel fuel. The emission control performance of a DOC is enhanced, however, if it is operated with ULSD. [99, 204] Figure 2-2 is a picture of a commercially available muffler-replacement-style DOC for retrofit applications.

Figure 2-2, Commercially Available Muffler Replacement DOC

Several DOC products have been verified under EPA's Voluntary Diesel Retrofit program and the CARB DRRP. Systems verified include DOCs as a stand-alone technology, a DOC/FBC system, and a DOC plus CCV system. Also, a DOC/engine modification retrofit system was approved for use in the EPA urban bus retrofit rebuild program. Products based on DOC technology (verified and non-verified) are available commercially in both OE and retrofit applications in the U.S and around the world.

The DOC is the most commonly used technology for diesel retrofit applications. However, within the boundaries of the literature review documented in this report, only a small number of reports discuss DOC technology. This is probably explained by the fact that most of the product development and application engineering work necessary to demonstrate the utility of DOCs for retrofit application was performed in the 1980s and 1990s when the technology was being evaluated and optimized for commercial application. Much useful background information is available regarding the operational characteristics of DOCs from this older body of literature.

By contrast, substantial information on DOCs is available from U.S. retrofits projects since 2000. Indeed, the overwhelming majority of retrofit projects in the U.S. involve DOC technology.

2.2.2 Emission Reduction Experience and Testing Practices

2.2.2.1 *Information from the Literature*

Numerous reports cite PM emission reductions of DOCs in the 20% to 50% range. [108, 185, 194] In situations where exhaust operating temperatures are very low, the PM reduction may be lower. In one case, a dump truck with an average exhaust gas operating temperature of only 205C had a PM reduction level of only 17%. [185] Reported reductions for CO range from less than 20% to over 90%, and reductions for HC range from approximately 30% to 90%. [108, 185, 194] Again, where the exhaust temperatures are very low, the reduction levels of HC and CO can suffer. [185] As mentioned previously, other factors that can impact the emission reductions of DOCs include the catalyst formulation, the SOF percentage of total PM, and the sulfur level in the diesel fuel. [99]

In general, DOC technology was found to have no impact on NOx emissions. The results of one study involving school buses, transit buses, and heavy-duty trucks in New York City showed on average, that NOx emissions were not affected by the DOC, but there was variation between different vehicles and tests. [194] As DOC technology continues to develop and mature, further improvements in performance and emission reduction benefit can be expected. For example, the ability to suppress the oxidation of NO to NO_2 within a DOC is being addressed by DOC product development scientists, with the ultimate goal of limiting tailpipe NO_2 emissions.

DOC technology is generally effective in reducing diesel exhaust smoke and odor. [99] Data from a variety of heavy-duty vehicle types in Hong Kong revealed that after operation of older engines at extended periods of light load or no load, a short-term heavy white smoke problem occurred. The formation of white smoke was caused by unburned fuels and lubricants condensing and depositing on the DOCs when operated at conditions of low exhaust gas temperature during low-load or no-load operation, with subsequent evaporation when load was applied and the exhaust temperature increased. The smoke emissions ceased once the DOC became hot enough to catalyze the unburned fuel and lubricants. The problem with smoke emissions was far less of an issue on well-maintained vehicles. [108] A retrofit project conducted by the Ada County Highway District reported that exhaust smoke opacity testing of 17 DOC-equipped trucks showed nine vehicles with higher opacity readings than the other eight vehicles. No reasons were identified for the differences in opacity readings. [39]

A DOC/engine modification retrofit kit, approved for use in the EPA Urban Bus Retrofit/Rebuild program in the 1990s, and still available today, was able to reduce PM emissions from a DDC 6V92TA engine from certified levels of 0.6 grams per bhp-hr to 0.1 grams per bhp-hr while still meeting the applicable NOx limits for that engine. The system included a specially designed camshaft and combination of cylinder kit components, a highly efficient turbocharger that delivered more air for combustion, adjustment of fuel injection timing, and a DOC. [54]

As discussed previously in this report section, a variety of testing equipment and test cycles have been used to evaluate the emission control performance of retrofit technologies, including DOCs. A study of transit buses, heavy trucks and school buses operating with DOCs in New York City illustrated the relative impact various test cycles can have in assessing DOC emission reductions. [194] Vehicles were tested on both the CBD and the NYC cycles. For a DDC 6V92TA engine equipped with DDEC-II electronic engine controls, PM reductions averaged 19% over the NYC and 26% over the CBD. For a vehicle with a DDC 6V71N non-electronically controlled engine, PM averaged 34% over the NYC and 44% over the CBD cycles. For HC, the DOC achieved greater percent reductions over the NYC compared to CBD cycle because the engine exhaust gas temperatures are higher on NYC cycle.

2.2.2.2 *Information from U.S. Retrofit Projects*

Most retrofit projects involving DOC technology did not include an emission testing component. Rather, emission reductions were estimated using the EPA retrofit calculator, the EPA and/or CARB technology verification levels, or information provided directly by the technology vendor. (P42, P95, P10, P41, P99) A few projects have indicated plans for performing limited emission testing.

Opacity testing was performed in several projects. In one project the testing was performed in conjunction with license renewal and in another as part of an engine diagnostic check. (P56, P104, P117)

2.2.3 Vehicle Applications

2.2.3.1 *Information from the Literature*

Unlike technologies such as DPFs, LNCs, EGR and SCR that are application specific, DOC technology has near universal application as a retrofit strategy. Also, DOCs can be installed on very old engines. [108] The only factors potentially limiting the application are whether there is space available on the vehicle or equipment to properly install the DOC, whether the vehicles or equipment in question have extremely low engine exhaust operating temperature (less than 200C), and whether the vehicles or equipment are operated on diesel fuel with sulfur levels substantially higher than 500ppm). Plugging is very rare, but it can occur, particularly if the soot is wet, as is often found in older or poorly maintained vehicles. DOC design modifications are available for use in the rare instances where plugging is a potential problem (see report Section 2.2.7).

Over the past three decades, over 250,000 nonroad engines and well over 100,000 highway vehicles have been retrofitted with DOCs. DOC retrofit applications cited in the literature include transit buses, school buses, a wide variety of commercial trucks, mining equipment, construction equipment, material handling equipment, and marine vessels. [54, 99, 108, 194] A number of retrofit programs in the U.S. have employed DOCs including numerous school bus fleets that have received grants under the EPA's Clean School Bus USA program. DOCs combined with crankcase emission controls have been install on vehicles in several retrofit programs (e.g., several school bus fleets in the EPA Clean School Bus program); DOCs combined with FBC are also being used in retrofit applications such as the Coca Cola fleet retrofit program. [38, 105]

2.2.3.2 *Information from U.S. Retrofit Projects*

In the U.S. over the past four years, the overwhelming majority of retrofit projects have utilized DOC technology. From the retrofit project data provided for this report, 66 projects in the U.S. were identified as using DOC technology, as shown in Table 2-3. The number of different vehicle/equipment applications has grown significantly over the past four years. DOC/FBC systems have been installed on school buses, delivery trucks and refuse trucks.

Table 2-3, DOC Retrofit Application Projects in the U.S.*

Application	Number of DOC Retrofit Projects
School Buses	48*
Transit Buses	1
Utility Vehicles (e.g., dump trucks, street sweepers)	9
Freight/Delivery Trucks	2
Refuse Trucks	8
Nonroad Engines	19
TOTAL	87

*Note: The State of Washington is counted as one project. As of September 30, 2004, 214 individual school districts were participating in the Washington Program.

The popularity of DOCs for retrofit applications can be attributed to several factors:

- The technology's near universal application.
- Relatively straightforward installation of the DOC products.
- Lack of any technology maintenance requirement.
- Lack of operational issues or impacts on vehicle/equipment performance.
- Lower cost compared to other retrofit technology strategies.
- Ability to fuel vehicle/equipment with conventional diesel fuel.

2.2.4 Technology Delivery

As noted above, a significant surge in the global demand for catalyst-based retrofit products resulted in a shortage in the supply of DOC ceramic cores beginning in the second half of 2003. This resulted, in many cases, in DOC delivery delays that continued well into 2004. While a number of projects reported on-time deliveries, other projects reported delays of anywhere from one to more than four months. (see, e.g. P43.1, P83, P158) Delivery of some of the DOCs ordered at several schools participating in one school bus project were delayed anywhere from two to eight months. (see e.g. P147) Part of the cause of these delays were attributable to the industry-wide shortage of DOC substrates, but part of the problem apparently was the inability of the state contractor to keep up with the greater than expected demand for

DOC products, and the fact the state was committed to ensure that all participating school districts received at least a partial delivery of DOCs on roughly the same schedule. The delay in DOC deliveries was particularly troublesome for school districts because many of them planned to install the DOCs during the summer months. When the DOCs deliveries were delayed into the start of the school year, a number of school districts were faced with the task of retrofitting DOCs while keeping enough buses in service to meet the daily student transportation needs.

The major suppliers of ceramic substrates for DOCs have dramatically increased their manufacturing capacity to produce these components. With increased manufacturing capacity in place, the ability to keep up with demand has been greatly improved. Delays in delivery of products are expected to decrease. [132] However, future disruptions in delivery will be influenced by the extent to which rapidly growing demand for products out-paces the planned increase in manufacturing capacity.

2.2.5 Technology Installation and Maintenance

2.2.5.1 *Information form the Literature*

The literature reported that retrofitting DOCs to diesel-powered vehicles and equipment typically requires one to three hours, and the installation process is relatively straightforward. For maximum emission reduction effectiveness, DOCs should be located as close to the engine exhaust manifold as possible. For many applications, DOCs can be retrofitted as a muffler replacement. [99, 108, 194] The technical literature recommends that as is the case with all retrofit technologies, routine engine maintenance should be performed prior to retrofitting DOCs. This maintenance should include a check of the vehicle exhaust system integrity. [99]

Attractive features of DOCs as a diesel retrofit technology selection strategy include a lack of maintenance requirements, ease of installation, and the fact that there is virtually no impact on engine performance or fuel economy. While rare, instances of DOC plugging have been known to occur in situations where an engine idles for a long period of time in cold climates (e.g., winter in Alaska) and with very old engines that have not been properly maintained. As a result, the DOC can be overwhelmed with unburned fuel and lubricants. No DOC failures or repairs are reported in the literature reviewed for this report. If the potential for plugging is a concern, one strategy is to use a DOC employing a catalyst substrate with lower cell density (the lower the cell density, the larger the cell channels, and the less likely cell channels will become completely plugged). For example, original equipment DOCs installed on heavy-duty trucks typically use substrates with a cell density of 300 to 400 cells per inch (cpi). If very high levels of PM are expected to be found in diesel exhaust (particularly if the PM is wet) 200 cell per inch substrates can be used to reduce the chances of plugging. Currently in the U.S., the bulk of the retrofit products are 300cpi and 400cpi, with some 200cpi products being used.

2.2.5.2 *Information from U.S. Retrofit Projects*

The information collected on DOC installation and maintenance from the U.S. retrofit projects is very consistent that reported in the literature. In general, retrofit installation of DOCs was typically quick and straightforward, and the need for maintenance was almost never required.

As was the case with DPF installation, a few retrofit projects reported performing pre-installation maintenance. Several projects noted that vehicles not operating properly were rejected for consideration of DOC retrofit installation. (P8, P81) Some projects reported that the engine and exhaust system were inspected for problems such as oil leaks, exhaust system leaks and/or damaged supporting clamps. (P42) Vehicles were also inspected to determine whether they were already equipped with DOCs, as further described in report Section 4.2.4.3. (P8, P101) In one project involving high-emitting older delivery trucks, engines were rebuilt or replaced. (P117) In one project involving the installation on a commuter train locomotive, the engine received a top deck overhaul prior to installation of the DOC. (P34)

DOC installations typically took one to three hours, and a number of projects reported installation sometimes was completed in less than an hour. (P8, P42, P76, P96) In some instances the installation process took more than three hours, but those cases typically involved special circumstances, such as the need to reconfigure and cut the exhaust pipes for the DOC to properly fit on the vehicle. (e.g., P33) Another installation issue that arose was related to difficulty in obtaining the appropriate DOC installation hardware. (P117) On rare occasions, vehicles or equipment were rejected for DOC retrofit consideration because the DOC could not be configured to fit within the available space. This situation occurred, for example, with some construction equipment used in the Massachusetts Central Artery/Tunnel Project. (P28) Other installation issues with school buses involved the need to modify pre-engineered installation kits to account for differences in the chassis configuration, even among school buses of the same make, model year and configuration.(P8)

In a large number of projects, the retrofit installations were performed by fleet personnel. In most of those cases, the technology provider or technical support contractor conducted training and/or supervised the installation on the first few vehicles, then the fleet personnel assumed the responsibility for remaining installations. (P8, P41, P33, P59, P204) In other cases, installations were handled by the product supplier.

With regard to maintenance, almost every project reported that no maintenance was required once the DOC was installed on the vehicle/equipment. The only reported instances in which a DOC required cleaning were in a two-stoke locomotive engine demonstration project (subsequently terminated because the extremely high levels of PM clogged the DOC) and a project involving very old and high-emitting delivery trucks before the engines were refurbished or replaced. (P117) The Seattle-Tacoma International Airport is planning a DOC retrofit project involving runway construction equipment, including a large scraper. Since some of this equipment emits high levels of PM, the project plans to install backpressure monitors on the equipment. If soot builds up on the DOCs, it will be detected and the devices be removed for cleaning. (P177).

2.2.6 Monitoring and Alarm Systems

In almost every retrofit project involving DOCs, no backpressure monitoring or alarm systems were installed as part of the DOC system. As noted above, there were a few exceptions. In New York, a number of older, high-emitting delivery trucks were equipped with monitors to warn of premature DOC plugging, and the Seattle-Tacoma International Airport plans to equip at least some of the runway construction equipment involved in its retrofit project with backpressure monitoring systems. (P117, P177) Also, City of Seattle fleet vehicles retrofitted with DOCs are equipped with backpressure alarm/limp mode systems as an added safety measure to allow continued vehicle mobility if a malfunction should occur while a vehicle is near a railroad crossing or intersection. (P161) One school bus fleet had backpressure monitors installed on DOC-equipped school buses, but provided no indication whether these devices proved useful. (P171)

2.2.7 Technical Support and Training

The level of training and technical support provided in DOC retrofit projects varied considerably. A few projects had no training, while others provided training for fleet technicians but not operators. Still others provided training for both fleet technicians and operators. Technical support was most often provided by the technology supplier, but other organizations provided technical support as well, including the U.S. EPA, state air quality agencies, regional and local air quality agencies, regional multi-state air quality organizations, independent technical consultants, industry associations, and fleet personnel from other fleets.

While DOC selection, installation, and operation is far less complex than other technologies such as DPFs or SCR technology, training and technical support proved extremely beneficial in a number of ways. The benefits of strong technical support were cited by retrofit project contacts for support with:

- Selecting the best vehicles/equipment for retrofit.
- Preparation of DOC procurement requests for proposal (RFPs).
- Selecting the best product/vendor.
- Dealing with technical and logistical issues, including obtaining the correct installation hardware.
- Educating and building ongoing support for the project among fleet management, vehicle service technicians, vehicle operators, public awareness groups, and others.

2.2.8 Technology Performance, Problems, and Solutions

2.2.8.1 *Information from the Literature*

DOC technology is generally regarded as a straightforward retrofit strategy that almost always performs without problems for up to several hundred-thousand miles or more. [99] The excellent performance record of DOC technology is reflected in the literature reviewed. No performance problems were identified other than the two instances where elevated smoke levels were reported and the situation in which extremely low exhaust temperatures (around 200C) can cause PM, CO, and HC emission reductions from a DOC to diminish. [39, 108, 185]

2.2.8.2 *Information from Retrofit Projects*

As reported in the literature, the experience with DOC retrofits over the past four years in the U.S. has demonstrated that this technology is straightforward and typically operates without problems for long durations in both highway and nonroad applications. (P10, P28, P133)

Problems with DOCs were rare. Two projects reported that a DOC substrate broke apart and in those instances, a replacement DOC was quickly provided. (P84, P161) As noted above, a DOC installed on a two-stroke locomotive engine in a commuter train application plugged after about three weeks and was eventually removed. DOCs installed on older, high-emitting delivery trucks plugged before the engines were rebuilt or replaced. (P34) Several DOCs equipped on construction equipment were damaged because the contractor planned to remove the DOCs when the construction project was complete and, as a result, failed to properly secure the DOC to the equipment. (P4)

2.2.9 Technology Costs

2.2.9.1 *Information in the Literature*

Some cost information is available in the literature for DOC systems. In 2002, MECA estimated the cost of a DOC to be in the range of $425 to $1,750 depending on engine size, sales volume, and whether the installation is a muffler replacement or an in-line installation. [99] In 2000, CARB estimated the hardware costs and other expenses associated with retrofitting a DOC as shown in Table 2.4. [170]

Table 2-4, CARB-Estimated Costs of DOC Technology

Engine Horsepower	Hardware Cost
40 hp	$400 - $600
100 hp	$680 - $1,356
275 hp	$2,100 - $3,700
400 hp	$2,800 - $3,700
1,400 hp	$10,000 - $20,000

Given that the need for DOC cleaning has been quite rare, the cost for DOC cleaning should in most instances be zero or substantially less than that estimated by CARB.

In the Port of Long Beach retrofit program, 25 diesel engine yard hustlers were equipped with DOCs and closed crankcase filtration systems. [95] The total cost of this installed system was $2,940 ($2,640 for the devices and $300 for installation). No breakdown of this cost or information about operating costs was made available. For the Buncombe County and Asheville City Schools pilot project, school buses were retrofitted with EPA-verified muffler replacement DOCs. [133] The total cost, including installation, averaged $850 per vehicle. No cost breakdown was made available. Other programs have reported DOC costs in the range of $1,500 to $2,500. [158, 167] As noted previously, the cost of retrofit technologies, including DOCs, are expected to decline over time as sales volume increases and the technology is further optimized to bring about cost savings.

2.2.9.2 *Information from U.S. Retrofit Projects*

Generally, the cost of DOCs used in U.S. retrofit programs over the past four years was in line with, and perhaps somewhat lower than the costs reported in the literature. DOC technology costs varied considerably among the U.S. retrofit projects. Factors such as the number of vehicles retrofitted under a given purchase order and/or the type of vehicle/equipment being retrofitted had an impact on DOC costs. But even when the vehicle type was the same and the number of units order similar, the cost range still varied somewhat.

The per-unit cost of DOCs for school buses ranged from approximately $750 uninstalled to over $2,500 installed. In one project, the state established a contract with a single product supplier to provide DOCs and installation services to the school districts throughout the state. Under the state contract, the most common DOC kit costs $1,182 installed. [200] Less common DOC kits cost $1,353 to $1,706, but the price of these devices is reduced to $1,182 when the quantity purchased is over 100 units. (P10) The state estimates that the successfully negotiated bulk equipment purchase of DOCs has resulted in a savings of over $500,000.

DOC installation cost for school buses ranged for ranged from $80 to $300. Installation hardware when not included was reported to be in the range of $30 to $150. The backpressure monitor installed on the delivery trucks referenced above cost $230.

2.2.10 Warranties

As noted earlier in this section, warranty coverage is typically part of the commercial contract negotiation process between product suppliers and their customers, and can vary considerably. A summary of the warranty requirements for products verified under CARB's Diesel Risk Reduction Program can be found in Section 2.1.11.

Warranty information from U.S. DOC retrofit projects was somewhat limited. Warranties for school buses ranged from one year or 20,000 miles (whichever occurs first) to 5 years or 150,000 miles. (P8, P61, P45, P204). One project reported that the DOC warranty for construction equipment was 4,000 hours.

2.2.11 Impact on Vehicle Performance and Fuel Economy

2.2.11.1 *Information in the Literature*

In the literature reviewed for this report, no adverse impacts on engine performance resulting from retrofitting DOCs on vehicles and equipment were cited. Generally, the literature reviewed reported no significant impact on fuel economy from retrofitted DOCs. For example, a fuel economy penalty of zero to 1.7% resulted from testing of DOCs installed on transit buses, school buses, and heavy trucks, but the results were considered to be within the margin of measurement error. [194] This study report noted that fuel economy of the transit buses actually improved and that this improvement may have been due to the lower backpressure of the DOC compared to the OE muffler the DOC replaced.

2.2.11.2 *Information from U.S. Retrofit Projects*

Over the full range of vehicle/equipment applications in U.S. DOC retrofit projects since 2000, virtually no instances of adverse impacts on vehicle performance or fuel economy were reported. A number of favorable comments were received from projects including comments from bus drivers who commented positively regarding the lack of smoke and odor from DOC-equipped vehicles. The only issues reported related to DOC plugging were from older high-emitting vehicles and equipment (e.g., two-stroke locomotive engine, old delivery trucks).

2.2.12 Impacts of Fuels and Lubricants

All liquid hydrocarbon fuels contain some sulfur compounds. During the combustion process, these compounds are converted to sulfur dioxide (SO_2). Over a platinum (or other precious metal) catalyst surface in the presence of oxygen, some of the SO_2 is oxidized to sulfur trioxide (SO_3), which interacts with water vapor to form sulfuric acid (H_2SO_4). Sulfate is measured as a particulate on most testing regimes such as the EPA heavy-duty engine certification testing procedures. A comprehensive industry/government study examined the impact of fuel sulfur level (ranging from 3ppm to 350ppm sulfur content) on the fresh and aged performance of DOCs. [57] The investigators found a strong correlation between fuel sulfur level and the quantity of sulfuric acid formed across DOC catalysts. While catalyst formulations can be optimized to minimize H_2SO_4 formation over a catalyst, the results of the study suggest that the most effective way to reduce H_2SO_4 formation by the DOC is to reduce the fuel sulfur level in the diesel fuel. Also, little evidence was found to suggest that sulfur contained in diesel exhaust deteriorated DOC performance. However, in the limited durability phase of the study (250 hours of DOC aging) there was a measurable loss of activity of the DOC catalysts that, in part, may be due to sulfur poisoning.

DOC retrofit programs reviewed in the literature involved diesel fuel with sulfur content ranging from 50ppm to 2000ppm. None of the reports provide detailed information on the relative impacts of diesel fuels with varying levels of sulfur, or the impact of sulfur on catalyst performance over time. The report on one study of DOC retrofits in Hong Kong noted that DOC performance was affected when high sulfur content diesel fuel was used (up to 2000ppm) and as a consequence, the Hong Kong EPA established two different PM reduction requirements. For commercial vehicles operating exclusively in Hong Kong where 50ppm fuel is available, DOCs must demonstrate a 35% PM reduction capability. Commercial vehicles that may operate outside of Hong Kong part of the time where diesel fuel has sulfur levels up to 2000ppm, DOCs must meet a 25% PM reduction requirement. [108]

In the U.S. since 2000, the vast majority of DOC retrofit projects have used regular highway low sulfur (less than 500ppm sulfur content) diesel fuel. A growing number of projects are starting to use ULSD, biodiesel fuel, or a combination of both. DOCs are also being used in combination with fuel emulsions and FBC additives. There have been no reports of adverse impacts on DOCs being attributable to fuels, emulsions, or FBCs.

2.3 LEAN NOx CATALYST

2.3.1 Overview

The exhaust of diesel engines is oxygen-rich because they operate at relatively lean air/fuel ratios (compared to gasoline spark ignition engines). Consequently, the conventional three-way catalyst used on gasoline-fueled engines cannot be used on diesel engines to control NOx. As a result, LNCs are designed to function effectively at the lean operating conditions found with diesel engines. In an LNC system, a small amount of diesel fuel or other on-board liquid hydrocarbon-based reductant is injected into the exhaust to serve as the reducing agent. Without the added fuel or other reducing agent, reduction reactions that convert NOx to nitrogen would not take place due to the excess oxygen present in the exhaust. [33] An exhaust HC/NOx ratio of six-to-one is needed to achieve good NOx reduction. For retrofit applications, LNCs have been used in combination with DPFs or DOCs. An LNC/DPF system has been verified by CARB for retrofit use. Figure 2-3 illustrates an example of a commercially available LNC/DPF system for retrofit applications.

Figure 2-3, Commercially Available LNC/DPF System

Very limited discussion of retrofit experience with LNCs was found in the documents available for this report. For example, the literature reviewed does not contain information relating to LNC durability experience, impact on engine performance, or installation/ maintenance/repair issues. The limited coverage in the literature is likely related to the fact that LNC retrofit technology is relatively new compared, for example, to DPFs and DOCs that have been applied in retrofit applications for a few decades. Experience with LNC/DPF systems in U.S. retrofit projects, however, is starting to grow. This experience provides insight into the technology's vehicle/equipment applications, installation, maintenance, and operations.

2.3.2 Emission Reduction Experience

According to a report by the Manufacturers of Emission Controls Association, retrofit LNCs have demonstrated NOx reductions of 10% to over 25%, depending on vehicle operation. [88] Field experience illustrating LNC emission reductions is very limited and results have been mixed. One of the few examples involves an early design of an integrated LNC/DOC system that was evaluated on a transit bus in Denmark. The report from this study indicated that no reduction in NOx was achieved by the system. No explanation was given for the lack of NOx control. [114] In a pilot program conducted in Houston, the same type integrated LNC/DOC system design was evaluated on three trucks. On one truck NOx emissions were reduced by up to 10%, but on the other two trucks NOx emissions actually increased. [33] The report provided no explanation for the increased NOx emissions. This integrated system did, however, reduce PM emissions by up to 54% and CO emissions by up to 71%. In the U.S, a LNC/DPF system has been verified by CARB to achieve an 85% reduction in PM and a 25% reduction in NOx.

2.3.3 Vehicle Applications and Experience

Although introduced fairly recently in the retrofit products market, the literature reports that over one thousand LNC/DPF systems have been retrofitted in the U.S. [See www.dieselforum.org] These systems have been installed on both highway vehicles such as refuse haulers and transit buses, as well as nonroad engines such as backhoe loaders. The LNC/DPFs, verified by CARB, require the use of ULSD and an exhaust gas temperature of 260C for at least 25% of the daily duty cycle. [See www.cleaire.com/site/products] These are being retrofitted on diesel engines throughout California and Texas for a variety of highway vehicle and nonroad equipment applications.

From the retrofit project data provided for this report, ten projects in the U.S. are using LNC/DPF technology as shown in Table 2-5.

Table 2-5, LNC/DPF Retrofit Application Projects in the U.S.

Application	Number of LNC/DPF Retrofit Projects
School Buses	0
Transit Buses	4
Utility Vehicles (e.g., dump trucks, street sweepers)	2
Freight/Delivery Trucks	0
Refuse Trucks	2
Nonroad Engines	2
TOTAL	10

2.3.4 Technology Delivery, Installation, Maintenance, and Technical Support

Limited information is available regarding the delivery times for LNC/DFPs system. The one project providing information on this topic reported that the retrofit products were delivered on time. (P187)

Again, there is limited information regarding product installation. Typically, installation is performed by the retrofit technology supplier. The one project providing information noted that the installation on utility vehicles required two to three days at the vendor's site, and five days was required to accomplish a custom fit installation on vehicle with a vertical exhaust system. (P187)

Since the system includes a DPF, filter cleaning is required. The types of cleaning methods, the time to complete cleaning, and duration between cleaning is discussed in Section

2.1.5.2. LNC/DPF systems are equipped with backpressure monitors and alarm systems. The technology vendor provides training to the fleet personnel. (P119, P187)

2.3.5 Technology Costs and Warranties

Projects involving LNC/DPF systems reported installed costs that ranged from approximately $13,000 to $22,000. (P119, P187)

As noted earlier in this section, warranty coverage is typically part of the commercial contract negotiation process between product suppliers and their customers, and can vary considerably. A summary of the warranty requirements for products verified under CARB's DRRP can be found in Section 2.1.11.

2.3.6 Technology Performance, Problems and Solutions

Generally, LNC/DPF systems have performed very well in service. One project reported that 120 highway maintenance vehicles equipped with the LNC/DPFs have been operating for several years and the overall experience has been without problems. (P119) A small percentage of LNC/DPF units in this and other projects did experience some instances of PM plugging on the front face of the LNC. (P13, P119, P187) The technology manufacturer and product supplier made software changes to correct the problem, but the problem still occurs in a few instances, particularly on International T444E engines. (P187) Other reported issues included a few instances of premature DPF plugging requiring unscheduled cleaning and backpressure sensors being overly sensitive and illuminating the warning light even though no backpressure problem existed. (P13, P187) With regard to the latter problem, the technology manufacturer is working to adjust the sensitivity of the sensor. (P13)

2.3.7 Impact on Vehicle Performance and Fuel Economy

The U.S. retrofit projects for which information was provided reported no adverse impacts on engine performance from the LNC element of the system. As with other projects using DPF technologies, one project reported a problem of premature DPF plugging on a limited number of vehicles resulting in vehicle downtime to clean the filter.

The diesel fuel used as the reducing agent to convert NOx to nitrogen in an LNC does not contribute to the propulsion needs of the vehicle. As such, use of LNCs typically consume enough extra fuel to create a fuel economy penalty of about 3%. [88] Several projects in the U.S. using the LNC/DPF system reported a slight decrease in fuel economy, but did not quantify the reduction. (P119, P187)

2.3.8 Impacts of Fuels and Lubricants

The emission control performance of LNCs is adversely affected by sulfur contained in the diesel fuel. [88] The LNC/DPF system verified by CARB is designed to operate with ULSD. LNC/DPF retrofit projects in the U.S. are using ULSD. (P119, P187)

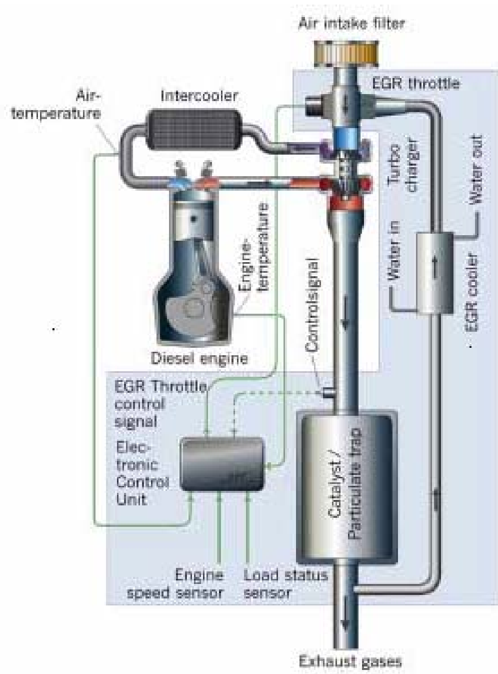
2.4 LOW-PRESSURE EXHAUST GAS RECIRCULATION

2.4.1 Overview

EGR reduces engine-out NOx emissions by lowering the temperature at which the fuel burns in the combustion chamber, and by diluting the oxygen content of the fuel-air mixture in the engine combustion chamber. Engines employing EGR recirculate a portion of the engine exhaust back to the engine inlet system. The oxygen-depleted exhaust gas is mixed with the fresh air that enters the combustion chamber, diluting the oxygen content of the air in the chamber. EGR can reduce NOx emissions by up to 40% or more. Beginning as early as 2002, a number of heavy-duty diesel engine manufacturers incorporated EGR as original equipment on their new diesel engines in order to meet a 2.0 g/bhp-hr NOx emission limit, and most manufacturers have announced that EGR will be an integral part of their approach to meeting the 2007 and later model year emission standards for heavy-duty diesel engines. To date, one technology supplier has received CARB verification of a low-pressure EGR/DPF system.

Unlike the high-pressure EGR systems used on new diesel engine vehicles, EGR systems designed for retrofit applications employ low pressures because such systems do not require the engine to be modified. Low-pressure EGR systems are typically combined with a DPF to minimize the accumulation of PM in and ensure the proper functioning of the EGR system. These systems, which typically require the use of ULSD, are commercially available in Europe and are being evaluated and introduced in the U.S. [99] Figure 2-4 is a representative example of an EGR/DPF system schematic illustration.

Figure 2-4, Example of an EGR/DPF System Schematic Illustration



A few reports provide reviews of the emission control performance of retrofit low-pressure EGR systems, but very little additional information is available from the literature. This is probably a direct consequence of the fact that a variety of technologies were being evaluated in the reports that discuss EGR. Also, since low-pressure EGR systems are relatively new for retrofit applications, it is to be expected that the initial focus of studies would be to demonstrate the degree of NOx reduction capability of the technology.

2.4.2 Emission Reduction Experience

A report of one study that evaluated two DPF/EGR systems fitted onto urban buses showed NOx reductions of 25% to 50% NOx, together with high levels of PM reductions. [114] A second report on the Houston Diesel Field Demonstration project also discussed the evaluation of a variety of emission control technologies including an EGR/DPF system. [33] Results showed that DPF/EGR systems achieved up to 80% NOx and 80% PM reductions for an automated side load waste truck and a heavy vacuum cleaner vehicle. No description of the EGR technology was provided.

A two-part European DPF/FBC study included a single taxi equipped with "a simple vacuum operated EGR system". [138, 53] A total of four taxis were retrofitted with DPF/FBC systems; one was also equipped with EGR. The EGR-equipped taxi exhibited a small increase in NOx emissions. [138] During much of the test cycle, NOx conversion was greater than 50%, but was high during the start and idle phases. No explanation was advanced for this phenomenon. In another series of measurements from this study a small reduction in NOx was noted. [53]

Initial testing of an EGR-equipped transit bus in Denmark showed a 25% NOx reduction, which was below the expected 40% level of NOx reduction. It was determined that the engine calibration was incorrect and a new calibration was developed that increased the NOx reduction potential of the EGR system to 50%. [114] This study also reported that the EGR system reduced the NO_2 formed by the DPF. Projects in Houston involving EGR/DPF systems on transit buses and refuse trucks reported a NOx reduction of approximately 40%.

The EGR/DPF system recently verified by CARB provides a PM reduction of 85% and NOx reduction of 40%.

2.4.3 Vehicle Applications and Experience

Low-pressure EGR systems include a DPF, and are therefore a vehicle/equipment-specific technology. The considerations in applying an EGR/DPF system to a particular engine are the same as those that must be considered when applying a stand-alone DPF system (see Sections 2.1.3 and 2.1.4 above). These factors include making sure that:

- ULSD is used to protect the catalyst-based DPF.
- An adequate range of exhaust temperature exists to ensure passive regeneration of the DPF, or an active regeneration system is employed.
- The engine is well maintained and does not burn high levels of lubricating oil.

Information from various sources suggests that over 3000 EGR/DPF systems are operating worldwide. Current experience with these systems is in the engine power range of 240kW to 600 kW, but larger EGR systems are being developed to cover diesel engine applications up to an engine power level of 1350 kW. [204] EGR systems are now being utilized in Europe and demonstration projects are taking place in the U.S. in locations such as Texas and California. [152]

In the U.S., several retrofit projects utilizing low-pressure EGR/DPF systems are underway on transit buses (3 projects), utility vehicles (2 projects), refuse trucks (1 project), and nonroad engine applications (2 projects). These projects provide useful information on the application of this technology.

2.4.4 Technology Delivery, Installation, Maintenance, and Technical Support

Issues relating to product delivery, installation, maintenance, and technical support for an EGR/DPF system are very similar to those related to a stand-alone DPF system (see report Sections 2.1.4, 2.1.5, 2.1.6, and 2.1.7).

For the limited number of projects in the U.S. involving EGR/DPF systems, there were no reported problems with product delivery. (e.g. P189) The installation is performed by the technology provider and typically takes a two-man team approximately eight hours to complete. (P189) In one project involving refuse trucks, the fleet provided the wrong data on the vehicles being retrofitted, so that when the retrofit products were delivered, they did not fit. (P188) The systems needed to be reconfigured to fit the vehicles, delaying the installation schedule. (P188)

Generally, the maintenance recommended and performed for EGR/DPF systems corresponds to the maintenance experience with DPF-only systems (see Section 2.1.5). For example, one project reported some problems with premature PM build-up in the filters requiring more cleaning more frequently than the annual cleaning interval that was anticipated, and more intense cleaning methods than expected. The project also reported problems with backpressure alarms malfunctioning. (P189) The fleet officials indicated that the PM build-up may be attributable to the fact that the buses in question are not always achieving the exhaust temperatures needed for DPF regeneration and, possibly, that worn fuel injectors may start to leak fuel into the cylinder combustion chamber contributing to PM build-up on the DPF.

From an engine maintenance viewpoint, the main drawback associated with EGR-equipped engines is the level of soot introduced to the engine lubricating oil via the engine intake system, which can lead to higher soot-related wear, as well as an increase in lubricating viscosity. Introduction of EGR can also impact the lubricating oil's oxidation rate and ability to resist soot-related thickening (and thus, cold-start pumpability). Lubricating oil manufacturers have worked with engine manufacturers to develop specifications for advanced lubricants that combat the harsher engine operating conditions created by EGR systems.

The EGR/DPF technology supplier provides training for fleet personnel. Several projects reported that where issues had arisen, the technology manufacturer and product supplier were actively engaged in trying to find solutions. (P188, P189)

2.4.5 Technology Costs and Warranties

The literature reports the estimated cost of an EGR/DPF system to be approximately $15,000. [99] Installed costs for EGR/DPF systems reported by projects in the U.S. were approximately $18,000 for such applications as refuse trucks, transit buses, and commuter buses. (P188, P189)

As noted earlier, warranty coverage is typically part of the commercial contract negotiation process between product suppliers and their customers, and can vary considerably. A summary of the warranty requirements for products verified under CARB's DRRP can be found in Section 2.1.11.

2.4.6 Technology Performance, Problems and Solutions

Several projects currently underway in the U.S. reported few, if any problems, with the low-pressure EGR/DPF systems. (P13, P188) As with the DPF-only systems, EGR/DPF systems experienced problems with occasional premature PM build-up on the filter and/or malfunctioning of backpressure monitor/alarms. (P189)

Several issues were reported with regard to the EGR component of the system. The Houston METRO Transit bus project reported that after about 220 systems had been installed, METRO began to detect elevated levels of aluminum and chromium in the engine oil. Fleet officials expressed the view that elevated levels of condensation, likely caused by the EGR system, mixed with the sulfur in the exhaust to form sulfuric acid. This in turn resulted in etching of the exhaust pipes. METRO noted that the increased condensation issue has not been a problem in Dallas where these retrofit systems are also being used. METRO officials hypothesized that perhaps Houston's extremely high ambient humidity might have been a contributing factor to the elevated condensation. It was thought that the condensation problems occurred primarily during fast idle. A software change was introduced that disables the EGR function during fast idle. However, METRO reports that the problem of elevated condensation remains an issue. The technology provider has been working with METRO to resolve this issue.

Another issue identified was physical damage to the EGR from heavy vibration in the exhaust system. A transit authority noted that since the platforms differ from bus to bus, different vibration characteristic result. In a few cases, the EGR systems were damaged. The damage to the EGR system did not impact emission control performance, but in some cases the installation needed to be reengineered. (P18)

2.4.7 Impact on Vehicle Performance and Fuel Economy

Test results from one study in the literature showed an increase in operating costs, due to increased fuel consumption, in the range of less than 1% to 4%, depending on the particular engine and the test cycle used [205].

Other than the problems discussed in Section 2.4.6 above that required some vehicle downtime to address them, information form the retrofit projects indicate that no other adverse impacts on vehicle performance have been attributable to the EGR/DPF systems.

2.4.8 Impacts of Fuels and Lubricants

As noted earlier, the EGR/DPF systems currently operating in Europe and the U.S. require the use of ULSD. Section 2.1.12 provides information on the impact of various diesel fuel sulfur levels on the DPF portion of the system.

The diesel engine industry recommends the use of engine lubricants with an API CI-4 designation as the recommended products for model year 2002-2006 engines and any others that have been equipped with an EGR system, and is likely to recommend lubricants with an API designation of PC-10 for model year 2007 engines. [17, 18, 67, 143] Diesel engine lubricants with the CI-4 designation provide optimum protection against corrosion and soot-related accumulation tendencies that may accompany EGR-equipped engines. Test data and limited operational experience have shown that engines with EGR systems should have their lubricating oil drain intervals reduced, compared to non-EGR engines. [143] Fleets that have instituted routine used engine lubricant analysis programs will have a significant benefit in being able to tailor oil change intervals based on lubricant condition rather than a fixed mileage interval.

2.5 SELECTIVE CATALYTIC REDUCTION

2.5.1 Overview

SCR technology is designed to permit the NOx reduction reaction in the oxygen-rich environment of diesel exhaust. To make the system work, a reductant is introduced into the exhaust. The technology is called "selective" because the catalytic reduction of the NOx with the reductant occurs preferentially to the oxidation of reductant with the oxygen. In mobile source applications, urea typically is used as the reductant, but ammonia can also be used. [99, 113, 176] SCR technology must be designed to inject the proper amount of reductant for the particular engine operating mode. This can be achieved by utilizing a carefully designed reductant delivery system combined with sensors, and/or with prior engine mapping of engine operating modes. [99, 150, 204]

SCR has been used on stationary sources since the 1980s, but only recently has been applied to mobile sources. To date, retrofitting SCR systems has been limited, but this technology has been installed on both highway and nonroad engines in demonstration projects in the U.S. Application experience is growing. As of the date of this report, an SCR system has been verified under CARB's DRRP for application on 1991-1994 model year nonroad Cummins 5.9liter engines rated from 150 to 200 horsepower. These engine power various types of construction equipment. The system has been verified as achieving 80% NOx reductions and 25% PM reductions. SCR technology can be combined with DPF technology to provide even greater PM reduction than can be achieved with SCR systems alone. [111] Figure 2-5 illustrates an SCR/DPF system installed on a heavy-duty diesel truck.

Figure 2-5, Example of an SCR/DPF System Installed on a Heavy-Duty Diesel Truck

While several reports in the literature provide reviews of the emission control performance of SCR technology, the discussion related to other aspects of experience with this technology is limited. In this regard, the experience with SCR applications in U.S. retrofit projects since 2000 provides useful insight.

2.5.2 Emission Reduction Experience

SCR technology can reduce NOx emissions by up to 90%, while simultaneously reducing HC and CO emissions by 50% to 90% for each, and PM emissions by 30% to 50%. [33, 42, 204]

In the City of Houston's Diesel Field Demonstration Project, one application employing an SCR/SNCR System (ammonia was the reductant) was evaluated. [33] ULSD fuel was used in this experiment. The piece of test equipment was a Gradall model G3WD with a Cummins 5.9liter, 190 horsepower engine. Reductions of 78% NOx, 27% PM, 65% HC and 76% CO were obtained. In a related experiment as part of the same project, the Gradall was also equipped with a catalyzed DPF. The emission reductions were very impressive: 84% NOx, 78% PM, 86% HC and 84% CO.

SCR systems used in marine applications have achieved up to a 99% NOx reduction, up to about 90% reduction in HC and CO emissions, and PM reductions up to 40%. These systems also provided a noise reduction benefit of 30dB to 35dB on large marine engines. [204]

Excess ammonia or "ammonia slip" can be emitted downstream of the SCR system if the injected reductant is not consumed during the catalytic NOx reduction process. Ammonia slip can be avoided or minimized by having a well-designed reductant injection system and/or utilizing a DOC downstream of the SCR catalyst system to destroy the excess ammonia by oxidation. For example, tests conducted in Europe on a 10liter, 190kW Volvo heavy-duty excavator engine equipped with an SCR system achieved a 77% to 88% NOx reduction on the

ETC and European ISO 8178-C1 off-road cycles with essentially no ammonia slip. [42] When the calibrations were changed to increase the NOx reduction to 99.7%, the level of ammonia in the exhaust was quite high. The introduction of an oxidation catalyst behind the SCR catalyst would eliminate the high levels of ammonia slip.

Emission testing in conjunction with an on-going SCR retrofit project on rubber-tire excavators and a dump truck sponsored by the City of Houston was carried out at the University of Houston's Diesel Vehicle Emissions facility. (188.1) Emission testing was conducted on a chassis dynamometer using a modified EPA Urban Dynamometer Driving Schedule (UDDS) for heavy-duty vehicles. Additional testing was performed on several pieces of construction equipment at the testing facilities of Environment Canada. Results from the SCR/DOC/DPF system tests showed PM reductions of up to 56% and NOx reductions of up to 67%. [34]

2.5.3 Vehicle Applications and Experience

2.5.3.1 *Information from the Literature*

Interest in SCR technology for mobile source applications is growing and SCR systems have been retrofitted on a variety of engines including those used to power trucks, buses, construction equipment, locomotives, and marine vessels. For example, over 100 marine vessels worldwide have been equipped with SCR technology including cargo vessels, ferries and tugboats with engines ranging from approximately 800kW to 19,000 kW. A smaller number of SCR systems also have been installed on diesel locomotives principally in Europe. [204]

As noted earlier, SCR technology has been combined with DPF technology to achieve simultaneous high emission reduction efficiencies for both NOx and PM. For example, in 2001 in California, an SCR/DPF system was installed on a 300-ton gantry crane powered by a turbocharged, after-cooled diesel engine rated at 1500 kW. The expected reductions were an 85% reduction in PM and a 90% reduction in NOx. The actual emission reductions have not been reported. [204]

SCR technology is an engine-specific application. Critical factors in applying SCR technology include whether the engine exhaust temperature window is suitable to the SCR application and whether there is available space on the vehicle or equipment to properly locate the SCR system components without disrupting the operation of the vehicle or equipment. Also, designing an SCR system to function in the transient engine operating modes of most mobile source applications offers special challenges. Care must be taken to design the SCR system to fit the particular application involved. [99]

Both precious metal and base metal catalysts have been used in SCR systems. Various base metal catalysts are used where engine operating exhaust temperatures are in the range of 220C to 580C. Precious metal catalysts can be employed where lower operating exhaust temperatures are present (in the range of 160C to 275C). In order to apply SCR technology over the full range of operating temperatures, catalytic formulations using both base and precious metals can be utilized. [88] Recent work optimizing the NO/NO_2 ratio entering the SCR catalyst from the upstream DOC has demonstrated the ability to achieve NOx reduction efficiencies of greater than 50% at temperature ranges as low as 200C to 250C. [177]

Engine mapping is a critical requirement for proper sizing and optimization of SCR systems for maximum NOx reductions and to minimize any ammonia slip from the system. Typically, engine mapping is performed by the technology supplier. The process of developing an engine "map" requires that an engine (of the same model as that for which the SCR system is to be installed) be installed on an engine dynamometer and operated over the full range of speed-load conditions to obtain data on NOx emissions at different engine speed-load points. This information is essential for proper design of the urea (or other reductant) injection system. The amount of reductant to be injected is established during the engine mapping process. (P132)

2.5.3.1 *Information from U.S. Retrofit Projects*

Currently, there are five projects utilizing SCR technology on such applications as refuse trucks (one project), rubber tire excavators and gantry cranes (two projects), dump trucks (one project), and a freight transport vehicle (one project). Also, a demonstration project for a locomotive application is planned for mid-2005.

2.5.4 Technology Delivery, Installation, Maintenance, and Technical Support

2.5.4.1 *Information from the Literature*

The literature suggests that, as is the case with other retrofit technologies, performing the necessary maintenance on the engine prior to retrofitting the SCR system is recommended. Also, as noted above, to ensure that the SCR reductant delivery system is properly calibrated to match the engine operating profile, engine mapping in many instances will be needed, which may add to the overall costs to the user.

Equipment for on-site storage of the needed supply of the reducing agent available for use by vehicles or equipment will also be necessary. This issue is more easily addressed in situations where vehicles or equipment are fueled from a central location and a supply of reductant can be kept on hand to refill the on-vehicle reductant storage containers when needed.

Finding adequate space on highway vehicles and smaller nonroad engine applications can be challenging. For example, initial designs of SCR systems were quite large, and in one case, a prototype did not meet the space requirements because the SCR unit was 250 mm longer than the muffler it replaced. [42] The reference notes that improvements have been made in optimizing SCR systems to fit in the available space and, as a result, SCR systems have been successfully installed on a variety of mobile source applications. Also, the weight of the SCR system can in some instances add 30% to 60% to the weight of the muffler being replaced. [204] In such cases care must be taken to ensure that the appropriate installation hardware is used to mount and hold the heavier device properly.

Other than the need to ensure a continuous supply of reductant and the need for periodic cleaning if a DPF is part of the system, the literature reviewed was largely silent on other maintenance issues associated with SCR systems or their impact on engine performance.

2.5.4.2 *Information from U.S. Retrofit Projects*

The recent U.S. experience with SCR retrofit installation and maintenance is generally consistent with information reported in the literature. SCR installations are performed by the technology provider. Installation times will vary depending on the type of vehicle/equipment and any issues in fitting the device on the vehicle/equipment. For example, normal installation of an SCR/DOC system on rubber tire excavators typically required one day. However, when some installation issues arose on some makes and models, additional time was needed for the installation team to resolve those problems. (P188.1) Retrofit project sources reported that the only maintenance required for an SCR system is to ensure that the on-board supply of the reductant is replenished when needed. SCR systems typically have warning devices to alert the operator or mechanic that the supply of reductant is getting low. One example of such a warning system is a device installed in the engine compartment that consists of a series of lights that indicate which of the two ammonia containers is being used and which container, if any, is empty. Another system used two warning lights (yellow and green) installed on the dashboard. The yellow light indicated a urea dosing problem (e.g., sensor failure, dosing control unit communication problem and/or component failure) and the green light indicated a low level of urea in the on-board tank.

Since the technology is somewhat complex and requires maintenance personnel to check and refill the reductant at fairly regular intervals, training is routinely provided for vehicle/equipment service technicians and operators. For example, in the City of Houston fleet SCR program, the technology supplier provided safety training during the course of the installations. (P188.1) Once the day-to-day ammonia refills are turned over to fleet personnel, additional and more comprehensive training is planned.

Fleet personnel and others involved in this SCR retrofit project reported that the technical support provided by the technology provider was instrumental in addressing issues when they arose and keeping the project moving forward.

2.5.5 Technology Performance, Problems, and Solutions

SCR systems retrofitted on line-haul trucks in Europe operated successfully for up to 350,000 miles or more. [99] Typical SCR catalyst life in marine applications was reported to be in the range of 10,000 to 40,000 hours. [204]

The City of Houston project reported no problems other than one instance in which an operator complained about an ammonia smell. The cause was traced to ammonia slip due to an incorrect input to the software in the control module. Once the adjustment was made, the ammonia smell disappeared.

2.5.6 Technology Costs and Warranties

In the literature, cost estimates for SCR systems vary greatly depending on the source providing the estimate, whether engine mapping is required, and the engine size and vehicle/ equipment application being considered. In 2000, MECA reported estimated costs in terms of cost to the user that varied widely even for applications in the same range of horsepower ratings. [120] For example, for engines in the 301 to 500 horsepower range, MECA estimated that the costs to user could range from $18,500 to $50,000, assuming 500 SCR retrofit systems were sold annually and from $11,000 to $20,000, assuming 10,000 SCR retrofit systems were sold annually. CARB estimated that installation costs for SCR could be as high as $5000, which no doubt includes the cost of product installation and engine mapping. [170]

In 2000, CARB estimated the cost of an SCR system to be in the $50 to $60 per horsepower range (e.g., a 300 horsepower engine would be $15,000 to $18,000). [170] CARB estimated the installation costs at $500 to $5000 depending on the application. The high end of this installation cost estimate likely includes the cost of engine mapping. Finally, CARB estimated annual maintenance costs to range from $715 for a 275 horsepower engine, to $1,500 for a 1,400 horsepower engine.

The estimated hardware costs for SCR technology, like other retrofit technologies, is likely to be reduced as the technology is further optimized and sales volumes of retrofit and OE applications increase. Also, overall costs of SCR systems to the user are expected to decline as NOx sensors are developed and commercialized. The availability of advanced sensors will help reduce or eliminate the costly need to perform engine mapping. [99]

SCR cost information from U.S. retrofit projects is quite limited. The City of Houston SCR program involving rubber tire excavators reported the system cost at approximately $15,000 for each SCR system. (P188.1)

As noted earlier in this section, warranty coverage is typically part of the commercial contract negotiation process between product suppliers and their customers, and can vary considerably. A summary of the warranty requirements for products verified under CARB's Diesel Risk Reduction Program can be found in Section 2.1.11. The SCR systems used in the City of Houston project carried a five year warranty for parts and service.

2.5.7 Impact on Vehicle Performance and Fuel Economy

The literature reviewed on SCR technology did not report any adverse impact of the technology on the fuel economy of the vehicles/equipment tested. However, the need for a continuing supply of the reductant adds to the overall operating costs of the SCR system. CARB estimated the operating costs for using aqueous urea to be equivalent to $300 per ton of NOx removed. [170] The cost of using a reductant is sometimes expressed in terms of an equivalent fuel consumption penalty. That equivalent cost will vary depending on the relative costs per gallon of diesel fuel and the reductant, but historically the amount of the equivalent fuel economy penalty for using the reductant has been in the 2% to 4% range.

No reported adverse impacts on vehicle/equipment performance from SCR were reported from the U.S. retrofit projects. In the City of Houston project, fuel economy was not measured, but during dynamometer emission testing, there appeared to be a slight increase in fuel consumption. (P188.1)

2.5.8 Impacts of Fuels and Lubricants

Like all catalyst technologies, SCR technology performance can be adversely impacted by the level of sulfur in the fuel. However, unlike catalyst-based DPFs and certain LNC systems, low sulfur fuel is not a requirement. Nevertheless, SCR performance can be enhanced when low sulfur content diesel fuel (including ULSD) is used. [99] The SCR system verified by CARB is approved for use with both conventional and ULSD fuel.

One test program involving DPF, DOC and SCR technologies simulated heavy-duty vehicle driving distances up to 155,000 km and found no impact on the catalytic activities from the engine lubricating oil ash. [111] However, in subsequent tests where high-ash engine lubricating oil doping was introduced, the DPF system backpressure increased rapidly, but no impact on the SCR system was reported.

The level of sulfur in the diesel fuel used in U.S. SCR retrofit programs varied from that of ULSD to that of highway low sulfur diesel fuel. In the City of Houston SCR project, regular highway low sulfur (less than 500ppm) diesel fuel is being used. However, when the existing SCR/DOC systems are upgraded to SCR/"hybrid" DPF system, the equipment will use ULSD fuel.

2.6 SELECTIVE NONCATALYTIC REDUCTION

2.6.1 Overview

As noted previously, conventional three-way catalyst technology will not function effectively in the oxygen-rich environment of diesel exhaust. SCR and LNC technologies employ a reducing agent in combination with catalyst technology to achieve a reduction in NOx emissions. Another approach for achieving NOx reductions in diesel exhaust is selective non-catalytic reduction or "thermal DeNOx" as it is sometimes called. With SNCR, a reducing agent such as ammonia, is added to the high temperature (greater than 925C) area of the exhaust stream of a diesel engine. It is reported that for NOx reduction to occur, the engine exhaust temperature must be strictly controlled to within a narrow temperature window of 925C to 1125C in order to maintain the NOx reduction selectivity of the SNCR process. [176] Kinetics of the chemical system drives the selectivity. The ammonia radical reacts with hydoxyl (OH) to form the chemical radical NH_2 and water. In the primary path, the formed NH_2 radical reacts with NO to form nitrogen and water, and in the secondary pathway, the formed N_2H also reacts to nitrogen. Some NOx reduction can also occur in the 725C to 925C temperature range. SNCR has been widely used in stationary source applications, but as a stand-alone approach it is not well suited for mobile source applications where exhaust temperatures as low as 125C are often found (e.g., at idle). [176]

SNCR combined with SCR technology has been evaluated on mobile sources with NOx emission reductions in the range of 80% or more. [33, 176] In an SCR/SNCR system, a control system meters the ammonia into the high temperature exhaust stream, allowing the non-catalytic chemical reduction of the NOx to occur. The exhaust then enters the SCR catalyst where NOx is further reduced.

The available literature on SCR/SNCR applications as a retrofit application for mobile sources is quite limited. The limited literature availability on this technical approach for mobile source applications is understandable given that SCR/SNCR systems are a relatively recent development in the field of mobile source diesel engine retrofit strategies.

No information on SNCR programs in the U.S. was available.

2.6.2 Technology Performance

A laboratory evaluation compared the relative emission reduction capabilities of dual catalysts alone, a single catalyst with ammonia addition, and dual catalysts with ammonia addition. [176] Test results showed that NOx reductions were 11% for catalysts alone, 52% for the single catalyst plus ammonia, and 70% for the dual catalysts plus ammonia. CO emissions were reduced by 78% by the dual catalysts alone, 69% for the single catalyst plus ammonia, and 70% for the dual catalysts plus ammonia. Finally, test results showed HC emissions were reduced by 67% for the catalyst alone and by 70% by both the single catalyst plus ammonia and the dual catalyst plus ammonia. In another study an SCR/SNCR system installed on a Cummins 5.9liter engine, achieved reductions of 78% for NOx, 27% for PM, 65% for HC and 76% for CO. [33]

2.7 CLOSED CRANKCASE VENTILATION SYSTEMS

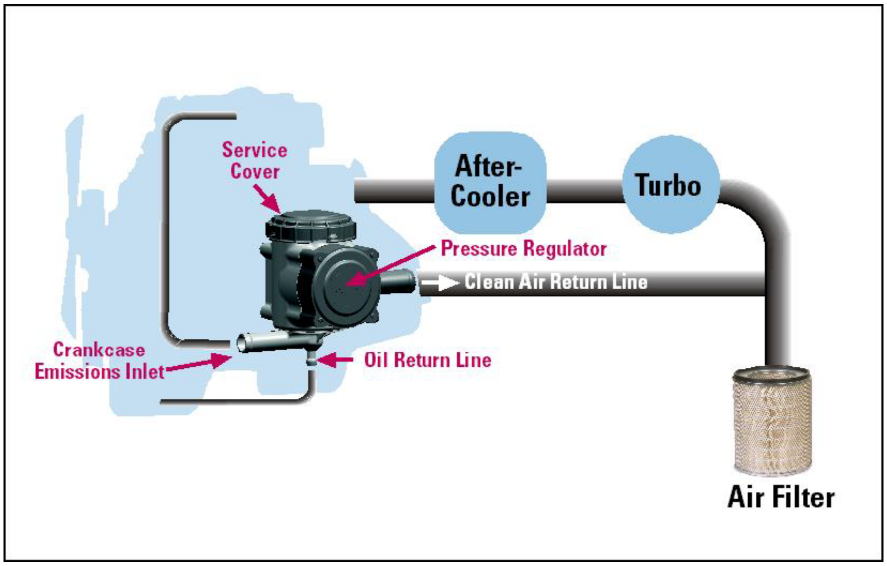
2.7.1 Overview

All piston engines leak some combustion gases past the piston rings. These gases are referred to as "blow-by" and pressurize the engine crankcase (which serves as the reservoir for engine lubricating oil), picking up engine oil mist as they leave via the crankcase vent. The volume of this blow-by increases as the pistons rings and cylinder liners wear, and at a typical engine overhaul interval, the blow-by flow rate is double that of a new engine. Blow-by gases that leave the crankcase contain products of fuel combustion (and, therefore, all of the pollutants related to fuel combustion), partially combusted engine lubricating oil (containing a wide variety of hydrocarbon aerosols and heavy hydrocarbon materials), and various sizes of oil droplets (frequently in the form of a mist). Crankcase ventilation to the atmosphere was eliminated on light-duty gasoline engine vehicles beginning in 1963. The closed crankcase ventilation systems designed for this purpose returned crankcase blow-by gases to the engine intake for subsequent combustion during the engine combustion process. These systems included a positive crankcase ventilation (PCV) valve that was specially designed for each engine to regulate the flow rate of blow-by gases (as a function of engine operating condition) returned to the engine intake. Checking the function of the PCV valve for proper operation, and replacement as needed, has became a routine and minimal cost maintenance practice for most automotive gasoline engines.

Diesel engines also create blow-by gases. For many years, diesel engines used in marine applications have been equipped with OE and aftermarket closed crankcase ventilation (CCV) systems to prevent oily mist and other blow-by residue from collecting on the engines and other surfaces of marine vessel engine compartments. Some diesel engine manufacturers have also made CCV systems available as OE products for highway and other nonroad applications. Aftermarket open crankcase ventilation (OCV) systems are also available and sold as replacement products to provide an incremental improvement to the OE crankcase ventilation hardware designed for minimal capture of oil mist and some lubricant-related combustion products. [77] While aftermarket OVC systems provide an improvement to OE systems, they still allow crankcase gases to be released to the atmosphere.

Only CCV systems prevent the release of crankcase pollutants from entering the atmosphere. OVC and CCV systems are designed to allow coalesced oil to return to the crankcase. CCV systems capture, coalesce and return emitted engine lubricating oil to the crankcase sump, filter the remaining crankcase contaminants, and return the filtered gases to the engine intake for subsequent combustion. Figure 2-6 is a schematic illustration of a commercially available diesel engine CCV system.

Figure 2-6, Schematic Illustration of a Commercially Available Crankcase Emission Control System



Depending on the specific CCV design, the filter is either replaced or removed and cleaned at periodic intervals (typically every 750 hours to over 1000 hours of engine operation, or about 25,000 miles of vehicle operation). Some CCV manufacturers recommend that the filter be replaced at the time of engine lubricating oil and filter changes. OVC system designs involve a woven metallic filter element that generally requires no scheduled maintenance to be performed.

Several OCV and CCV systems are available from aftermarket manufacturers, and are readily obtained from heavy duty engine equipment and marine engine equipment suppliers. [41, 49, 50, 106, 140] A CCV or OVC system can be used on virtually any diesel engine (including those equipped with other exhaust aftertreatment retrofit products) for which a system has been designed. One CCV system manufacturer has sought and received EPA and CARB verification for retrofit of its system in combination with a DOC. The advantage of this DOC/CCV system combination is that specific emission reduction levels have been quantified as a system, and validated under the rigor required by the EPA and CARB verification programs. Additional CCV systems can be expected to receive EPA and/or CARB verification in the future.

Even though CCV systems are in common use and widely available, the available literature contains very few references to CCV system retrofit experience. This is not surprising given that the inclusion of CCV systems for funding consideration under retrofit emission reduction programs is a relative recent development.

2.7.2 Emission Reduction Experience

As noted above, crankcase emissions are composed of a combination of products of fuel and lubricating oil combustion, and a variety of engine lubricating oil contaminants. These emissions can range from 10% to 25% of the total engine emissions. [41] CCV systems can eliminate up to 100% of the crankcase HC aerosol emissions and the oil drip that typically results form an open vent crankcase system.

The impact of CCV systems used in conjunction with a DOC and a DPF has been evaluated with respect to in-cabin air quality of a school bus. The test methodology for this project utilized a “leader-follower” tandem of school buses as well as a stationary school bus. The CCV system coupled with a DOC reduced particulate count by 54% to 62%, depending on the DOC technology employed. [10]

2.7.3 Vehicle Applications and Experience

Care must be taken to ensure that the proper model CCV system is applied to the specific engine application; application of the wrong model will affect filter efficiency/life and can potentially lead to reduced engine performance. [62] CCV systems are currently installed on a number of European and U.S. diesel heavy-duty vehicles as OE products. As mentioned previously, CCV systems have been used for years in marine applications and a wide range of highway and other nonroad applications. As a result of the availability of an EPA- and CARB-verified DOC/CCV system, acquisition of DOC/CCV systems is also being funded under retrofit emission reduction programs for both highway and nonroad applications in the U.S. For example, in the Port of Long Beach retrofit project, 25 yard hustlers (with Cummins 8.3liter engines) were equipped with a DOC/CCV system. [95] DOC/CCV systems are being used in several school bus retrofit fleets, including those serving the Ann Arbor, Michigan, Public Schools; Okemos, Michigan, Public Schools; and the Manchester, New Hampshire, School District.

Currently nine DOC/CCV system projects were funded by emission reduction retrofit programs in the U.S. since 2000. The State of Washington has identified DOC/CCV systems and DPF/CCV systems as products will be eligible for state funding. (P10) Approximately 500 systems are being installed on nonroad equipment at marine ports.

2.7.4 Technology Delivery, Installation, Maintenance, and Operation

CCV systems are readily available as “catalogue items” from most heavy-duty or marine engine equipment suppliers. Delivery of DOC/CCV systems were roughly on the same schedule as for DOC systems.

According to the literature reviewed, mounting the CCV filter housing on a part of the vehicle other than the engine, (e.g., the firewall, fender or frame rail) is recommend to avoid the vibration and movement that is typical during engine operation. In choosing a mounting location, ease of servicing the filter should be considered. [62] In one school bus project, the manufacturer originally planned to mount the CCV filter housing support brackets from the radiator, but the state's department of motor vehicles would not approve this approach. The manufacturer and the school bus contractor engineered a bracket to fit on the front left of the cylinder head of the engine (P33).

Typical CCV filter replacement or cleaning (for those systems so designed) intervals range from 500 to 1500 hours of engine operation. The manufacturer of the verified DOC/CCV system recommends that the CCV filter be replaced at every oil change. The maximum recommended duration between filter replacements is 25,000 miles or 500 hours of operation, whichever occurs first. [62] This translates to a filter replacement (or cleaning) every two to three years for school buses or other vehicles that operate less than 10,000 miles per year. In two school bus retrofit projects recently implemented, the manufacturer recommended maximum mileage between filter replacement at 6,600 to 8,000 miles (P33, P72).

No reported instances of operational problems with crankcase control were found in either the literature reviewed or from being funded from U.S. retrofit projects since 2000 where DOC/CCV systems were used.

2.7.5 Technology Costs and Warranties

The literature reviewed on retrofit programs does not contain cost estimates for crankcase emission controls alone, but two reports provide cost information on a combined DOC/CCV emission control system. In the Port of Long Beach retrofit program, as noted above, 25 yard hustlers (with Cummins 8.3liter engines) were equipped with a DOC/CCV system. The total cost of this installed system was reported to be $2,940 ($2,640 for the devices and $300 for installation). No breakdown of this cost or information about operating costs was made available. A report on one school bus retrofit project reported costs of approximately $2,100 for DOC/CCV systems and installation. (P88) Cost of DOC/CCV systems reported from U.S. school bus retrofit programs ranged from about $1,100 to $2,035, with the lower cost for a lot size of a minimum of 1250 systems. (P8, P33, P81, P88, P204)

One school bus project reported that installation of the CCV/DOC systems required approximately five hours of time, at a cost of $65 per hour. Additional costs for maintenance of CCV systems are very minimal. For systems that require the filter to be replaced, the cost of these filters range from $20 to less than $50. The labor necessary to replace the filter is no more complicated or time consuming than that for changing an engine fuel or oil filter.

As noted earlier in this section, warranty coverage is typically part of the commercial contract negotiation process between product suppliers and their customers, and can vary considerably. A summary of the warranty requirements for products verified under CARB's DRRP can be found in Section 2.1.11.

2.7.6 Impact on Vehicle Performance and Fuel Economy

The literature discussing experience with CCV systems does not identify any adverse impacts on engine performance or any concerns raised by engine manufacturers. Similarly, retrofit projects using CCV systems did not report an adverse impact on vehicle performance or fuel economy (see e.g. P33). The manufacturer of the verified DOC/CCV system has noted that failure to replace a filter at the appropriate intervals can result in filter plugging, which in turn can cause a pressure buildup in the crankcase, resulting in leaking crankcase seals and possibly degraded engine performance. [62]

2.8 ENGINE CONTROL MODULE REFLASH

2.8.1 Overview

In October, 1998, a court settlement was reached between the EPA, Department of Justice, CARB and engine manufacturers (Caterpillar, Inc., Cummins Engine Company, Detroit Diesel Corporation, Volvo, Mack Trucks/Renault and Navistar/International) over the issue of high NOx emissions from heavy-duty diesel engines during certain driving modes. Since the early 1990s, the manufacturers used software in the electronic engine control module (ECM) that caused engines to switch to a more fuel-efficient (but higher NOx) driving mode during "off-cycle" steady highway cruising. These engines were built between 1993 and 1998 in a way that allowed the engines to pass EPA emission certification tests but increased emissions while the vehicle was being operated under conditions not included in the Federal Test Procedure (FTP) emission testing cycle used to establish compliance with EPA heavy duty engine emission standards. It is estimated that 1.3 million engines contain the "off-cycle" ECM software.

Compliance required the companies to introduce cleaner engines (including development of engines meeting the 2004 emission standards by October 2002, 15 months ahead of time), rebuild or reprogram older engines to cleaner levels, recall pickup trucks that have defeat devices and conduct new emissions testing. As part of the manufacturers' requirements to rebuild or reprogram older engines (1993-1998) to cleaner levels, companies developed a heavy-duty diesel engine software upgrade (known as a "reflash" or "low NOx" software) that modifies the fuel control strategy in the engine's ECM to reduce the excess NOx emissions

In California, CARB set implementation targets for a voluntary software reflash program for California-registered vehicles. CARB expected a reflash installation rate of 35% by October 2004, 60% by May 2005, 80% by January 2006 and 100% by 2010. [www.arb.ca.gov/diesel/diesel.htm] As of March 2004, only 13% of eligible heavy-duty diesel engines had the reflash installed (CARB estimated that approximately 100,000 California-registered vehicles and approximately 300,000 to 400,000 out-of-state vehicles that visit California would be subject to the reflash). At the time of the settlement, CARB expected diesel engine rebuilds to occur at around 300,000 to 400,000 miles, which was based on information gathered on engine rebuilding practices. Under that assumption, engines from the 1993-1998 model year should have all been rebuilt by 2003. However, modern diesel engines, with their increased durability, have been able to operate between 750,000 and 1,000,000 miles prior to requiring a rebuild. Therefore, a majority of the reflashes to date have not been installed. Additionally, some of the engines eligible for reflashes are school buses and motor homes, which travel significantly fewer miles than tractor-trailers and pickup trucks. Analysis of the voluntary program showed that only the Detroit Diesel Corporation was able to come close to the 35% target. The other manufacturers were only able to achieve an overall voluntary rate of 18%. CARB conducted additional analysis for the second target of 60% by May 2005 and found that it would not be sustainable.

2.8.2 Vehicle Applications

In December 2004, CARB recommended and passed the mandatory reflash program. Since DDC was able to approach CARB's initial target of 35%, it was allowed to continue on the original voluntary compliance program. For the remaining engine manufacturers, the compliance schedule shown in Table 2-6 was used, where Medium Heavy-Duty Diesel Engines (MHDDE) are used in vehicles with Gross Vehicle Weight Restrictions (GVWRs) of 14,001 to 33,000 pounds and Heavy Heavy-Duty Diesel Engines (HHDDE) are used in vehicles with GVWRs greater than 33,000 pounds:

Table 2-6, CARB Mandatory Compliance Schedule

Model Year/Application	Compliance Date
1993-1994 model year engines (all)	By April 30, 2005
1995-1996 model year engines (all)	By August 31, 2005
1997-1998 model year engines (all)	By December 31, 2005 (except MHDDE)
1997-1998 model year MHDDE	By December 31, 2006

Engines with the reflash are required to meet NOx emission standards based on the two options shown in Table 2-7.

Table 2-7, Reflash Engine Certification Options

Option A			Option B		
Model Year/ Test Cycle	Application/ Emission Standard		Model Year/ Test Cycle	Application/ Emission Standard	
1994-98	MHDDE	HHDDE	1993-98	MHDDE	HHDDE
SET	6.0 g/bhp-hr	7.0 g/bhp-hr	SET	6.5 g/bhp-hr	7.5 g/bhp-hr
NTE	7.5 g/bhp-hr	8.75 g/bhp-hr	NTE	8.1 g/bhp-hr	9.38 g/bhp-hr

Current Federal regulations do not require that complete heavy-duty diesel vehicles be emission-certified using a chassis dynamometer (as is used for light-duty vehicle emission testing), instead requiring that a manufacturer's engines be certified using an engine dynamometer. Consequently, the basic emission standards are expressed in g/bhp-hr (grams per brake horsepower-hour) and require heavy-duty diesel engine emission testing over the Transient FTP engine dynamometer cycle. For comparison, the EPA FTP NOx emission standard for 1993-97 heavy duty diesel truck engines was 5.0 g/bhp-hr and was 4.0 g/bhp-hr for 1998 heavy duty diesel truck engines. From the table above, Option B is less stringent but includes an additional model year engine.

Installation of the reflashes would be verified by CARB through its existing Heavy Duty Vehicle Inspection Program (HDVIP) and the Periodic Smoke Inspection Program. CARB already inspects vehicles as part of the HDVIP at California Highway Patrol weigh inspection stations, which are randomly located along roadsides and at fleet facilities. Penalties for failing to install the reflash would be $300 if the software was not installed within 45 days of any citation issuance. There is an additional $500 penalty if the software is not installed after 45 days of the citation issuance. The $300 penalty is waived for California-registered school buses if the reflash is installed within 45 days of the citation issuance. However, if the software is installed after 45 days of the issuance, both the $300 and $500 penalty will be applied. The fines apply to both California-registered and out-of-state registered vehicles and are in addition to any fines incurred as part of the HDVIP.

2.8.3 Emission Reduction Retrofit Applications and Experience

Reflash installations are available in California and throughout the U.S. at engine dealers and distributors. ECM reflashes were developed by the engine manufacturers to achieve compliance with existing emission standards (for the specific year of manufacture). Thus, a reflash, in and of itself, as developed for satisfaction of the 1998 Consent Decree requirement, does not constitute a means to reduce emissions below the emission standards that were in place for the specific year of manufacture, in the classic sense of diesel emission reduction retrofit products. Catalytic exhaust aftertreatment retrofit products (typically a DOC or DPF) have been combined with (legally required) ECM reflashes for at least two engine manufacturers (International and Cummins) to create retrofit systems that reduce NOx, PM, HC and CO emissions below the emission standards that were in place for the year of engine manufacture. The system for Cummins 1994 through 1998 M11 engines has been verified by CARB as providing emissions reductions of 85% for PM and 25% for NOx. The International systems is claimed to meet the U.S. EPA 2007 heavy duty diesel engine emissions standards for PM and HC, and to be allowed by CARB as being qualified to share in California funding of new school bus purchases under the DRRP.

Information from U.S. retrofit projects since 2000 indicated three projects incorporating the use of ECM reflashes an emission reduction strategy. No indication of any problems or issues was provided from these projects.

2.8.4 Technology Costs

The engine manufactures agreed, as part of their consent decrees, to voluntarily provide low NOx software upgrades free of charge to vehicle owners and operators at the time of engine rebuild or upon request. However, some engine manufacturers are not installing the reflash free of charge unless it is installed in conjunction with an engine rebuild. Consequently, dealer/distributors are passing on 30 minutes to one hour of labor charges to vehicle owners that choose to have the reflash installed without an engine rebuild. CARB has been in contact with the engine manufactures to rectify the problem so that the only cost to the owner/operator is the out-of-service time for the vehicle.

The ECM reflash retrofit systems that include an exhaust aftertreatment retrofit product typically involve an additional cost beyond that of the exhaust aftertreatment product.

2.8.5 Installation Issues and Problems

Reflashes can be arranged to be installed at the local engine dealer/distributor or in instances where a large fleet operator is involved, the software can be installed on-site. The average ECM reflash requires approximately 15 to 30 minutes for installation. One potential concern is for the engine's ECM to fail after a low-NOx software install. Based on limited information provided to CARB, failure rate of the engine's ECM is less than 1% as a result of the reflash installation.

2.8.6 Impact on Vehicle Performance and Fuel Economy

Manufactures have reported negligible impacts on fuel economy. Several fleets had the software installed prior to engine rebuilds and have reported no noticeable differences in their fuel use. However, CARB recognized that there may be an average fuel economy penalty and expects it to be less than 1%. In addition, there have been no complaints regarding vehicle performance as a result of reflash installations.

2.9 ULTRA-LOW SULFUR DIESEL FUEL

2.9.1 Regulatory Framework

The EPA's diesel fuel regulation limits the sulfur content in highway diesel fuel to 15ppm (by weight), down from the previous 500ppm. Refiners will be required to start producing the 15ppm sulfur fuel beginning June 1, 2006. At the terminal level, highway diesel fuel sold as low sulfur diesel fuel must meet the 15ppm sulfur standard as of July 15, 2006. For retail stations and wholesale purchasers, highway diesel fuel sold as low sulfur fuel must meet the 15ppm sulfur standard by September 1, 2006. [48]

Refiners can also take advantage of a temporary compliance option that will allow them to continue producing diesel fuel with up to 500ppm sulfur content in 20% of the volume of diesel fuel they produce until December 31, 2009. In addition, refiners can participate in an averaging, banking and trading program with other refiners in their geographic area.

2.9.2 Usage, Impact on Emissions and Operational Considerations

The U.S. Department of Energy, Energy Information Administration (DOE-EIA) has estimated that in 2004, 137 million gallons of ULSD were produced (prior to EPA's mandate) and made available in several areas of the country (primarily the West Coast, Mid-Atlantic, upper Mid-West, and the metro Houston areas) as a "technology enabler" to pave the way for advanced, sulfur-intolerant exhaust emission control technologies, such as DPFs and LNCs which will be needed to meet the 2007 emission standards. [195]

As discussed previously in this report section, ULSD enables catalyst-based retrofit technologies such as DPFs and DOCs to operate at maximum emission control efficiencies and effectiveness. Without the use of any other emission-reducing technology, the lower sulfur content of ULSD allows engine-out PM reductions of several percent (about 0.8% per 100ppm reduction in sulfur content) compared to conventional highway low sulfur diesel fuel. [168]

The lower sulfur content of ULSD has the benefit of reducing the acidic compounds that can promote fuel system corrosion, however, fuel-bound sulfur can help to promote fuel lubricity. The significant reduction of sulfur in ULSD, compared to conventional low sulfur diesel fuel can lead to increased wear in fuel injectors, particularly in older vehicles. Elastomer materials used in O-rings, seals and gaskets contained in fuel system components can also be degraded and fail. The diesel fuel industry is aware of this and is incorporating lubricity additives in ULSD to maintain lubricity. ASTM International has developed a fuel specification specific to ULSD [164]. The Engine Manufacturers Association (EMA) recommends that anyone using ULSD do so with ULSD fuels meeting ASTM fuel specification D 975, and further, that the fuel have a minimum cetane number of 40, a minimum lubricity level of 3100 grams, and a minimum thermal stability value of 70% reflectance after aging for 180 minutes at a temperature of 150C. [197] Overall, the use of ULSD is expected to be transparent to vehicle users. [191]

As shown in the middle column of Table 2-8, in the U.S. since 2000, seven projects (three school bus projects, two transit bus projects and two nonroad projects) were identified as using ULSD alone, as an emission reduction strategy, while 75 projects are using ULSD in conjunction with additional retrofit technologies (primarily related to DPF technology products), 45% of which are school bus projects. Table 2-8 illustrates the breakdown of ULSD usage for all of these projects.

Table 2-8, ULSD Retrofit Application Projects in the U.S.

Application	TOTAL Number of Retrofit Projects Using ULSD	Projects Using Only ULSD as the Retrofit Technology	Projects Using ULSD In Conjunction with Other Retrofit Technologies
School Buses	36	3	33
Transit Buses	15	2	13
Utility Vehicles (e.g., dump trucks, street sweepers)	8	0	8
Freight/Delivery Trucks	2	0	2
Refuse Trucks	8	0	8
Nonroad Engines	13	2	11
TOTAL	82	7	75

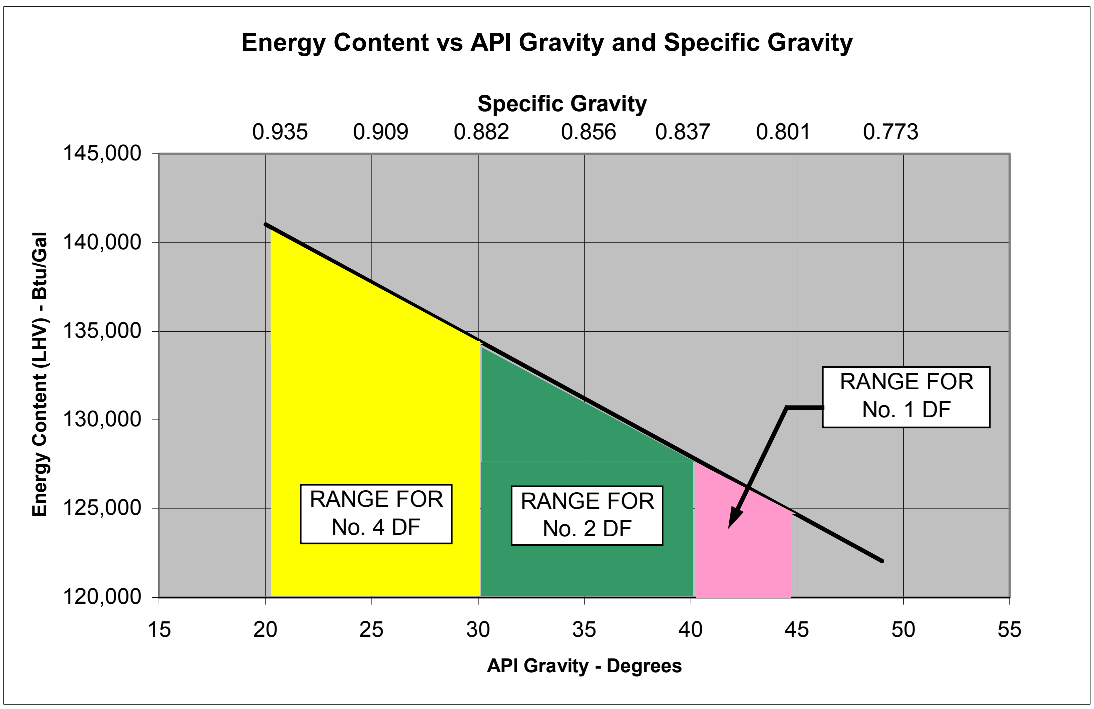
The significant majority of projects reported no problems with ULSD usage or delivery. Only one project reported a delay in obtaining fuel. (P188.2) One project reported failure of fuel pump seals on older model vehicles. (P83) Another reported that the fuel filters plugged and fuel system O-rings leaked. (P220) Once the filters and O-rings were replaced, no further problems were experienced. Yet another identified the need for periodic replacement of fuel dispensing equipment filters to achieve proper sediment and water control. (P172) This is a typical equipment maintenance practice and not considered unusual.

Misfueling of vehicles or equipment that require ULSD were discussed in Section 2.1 of this report.

Most projects did not report any impact on fuel economy when switching from regular low sulfur diesel fuel to ULSD. One project reported that the test data taken at various intervals throughout the project indicated that the ULSD it used contained about 4% less energy content than regular low sulfur diesel fuel, but that the impact on fuel economy was minimal (approximately 0.15%). However, one project involving line-haul delivery trucks reported a 3.54% fuel economy penalty attributable to the ULSD fuel it used. (P220) In both cases, the grade of fuel was not specified. Furthermore, rigorous and extensive data collection procedures and involved statistical analysis would need to be performed to be able to segregate the fuel economy effect of ULSD from that caused by other factors, including any other retrofit technology products.

It is important to note that the energy content of ULSD is not inherently lower than that of diesel fuel of higher sulfur content. As shown in Figure 2-6, the energy content of the most widely used diesel fuel grades (No. 1, No. 2, and No. 4) vary by nearly 15% across all of the grades. The energy content can vary by up to 5% for No.2 diesel fuel, and by up to 2.5% for No. 1 diesel fuel. Note from Figure 2-6 that the energy content of No. 1 diesel fuel (which is often used as a blending component to winterize the No. 2 grade in areas with abnormally cold temperatures) is lower than that of No.2 diesel fuel, which is lower than that of No.4 diesel fuel (which is typically used in large diesel engines, particularly for marine applications). Also note that for these fuels, the relationship of energy density to specific gravity and API gravity is essentially linear. More dense (or "heavier") fuels have a higher energy content than fuels of lower density. [19, 202] Since fuel economy is directly related to the energy content of a fuel, if all other things are equal, use of a fuel with a higher energy content would improve fuel economy, and vice versa.

Figure 2-6, Energy Content of Diesel Fuels



The ASTM International specification for diesel fuels (currently D 975-04c) contains no specification for diesel fuel energy content or API gravity. [164] However, the National Conference on Weights and Measures (NCWM) and the EMA proposed definitions for so called "Premium Diesel" to ensure that consumers receive a functional benefit. To be sold as Premium Diesel fuel, the fuel must meet the minimum values for at least two of five criteria: 1) heating value (energy content), 2) cetane number, 3) low temperature operability, 4) thermal stability, 5) fuel injector cleanliness. [68, 139] Thus, those that purchase Premium Diesel (of any grade) may also not be assured of getting fuel with a minimum energy content.

Diesel fuel users that are concerned about fuel quality can use a fuels hydrometer to determine the API gravity (and thus the energy content, as shown from the relationship in Figure 2-6). Fuels hydrometers are available for less than $50 to allow the API gravity of fuels to be checked at the point of delivery to the fleet, thus providing an inexpensive means of checking the energy content (and first ordered quality check) of the fuel being delivered to the fleet. Checking the API gravity of fuel deliveries is a routine practice carried out in the aviation industry and is used as a one means for identifying fuel quality problems.

In general, while the sulfur content of a fuel is not directly related to its energy content, some refinery processing methods used to remove sulfur from petroleum to the lower levels now required can alter the properties of the finished fuel in a way that results in a less dense fuel, for the same grade. [44, 188, 190] Overall, as production of ULSD becomes widespread, the DOE-EIA estimates that an overall slight decline of 0.5% to 1.8% in energy content of ULSD might be possible [188]

2.10 DIESEL FUEL EMULSIONS

2.10.1 Overview

Diesel fuel emulsions are blended mixtures of diesel fuel, water, emulsifying agents and other additives, that reduce PM and NOx emissions, as a result of the added water. Addition of water to the emulsified fuel also reduces the energy content of the fuel, with corresponding reductions in fuel economy and engine power. Depending on the specific engine application and duty cycle, use of emulsions can result in NOx reductions of 5% to 30%, and PM reductions of 20% to 50%. These ranges of results have been demonstrated in several of the reports reviewed. [see, e.g. 187] Since this technology has been introduced into commercial practice relatively recently, there is a lack of currently documented information on longer term user issues such as storage stability of mixed fuel, and the affects of ambient temperature on emulsion performance.

2.10.2 Emission and Engine Performance Considerations

Typically, reduced power and fuel economy are related to the water content in the emulsified fuel, but engine operating mode (full power vs. low power) also affects the degree of reduction. These impacts in terms of costs, tradeoffs and the related benefits of achieving emission reductions with emulsified diesel fuels are thoroughly discussed in a number of the reports that were reviewed for this report. [13, 34, 47, 101, 131, 154, 173] One study, for example, identified a small HC increase relative to the NOx benefit. [46] Several reports mention fuel consumption variability when using diesel fuel emulsions. Another report discusses a range of performance variations depending on fuel, engine and DPF combinations, including both improved and increased fuel consumption. [142] Information on diesel fuel emulsion performance was often the departure point for a demonstration or pilot project to test engine or fleet performance on various fuels under selected operating conditions, as well as being further discussed in the research findings and conclusions. [13, 20, 33]

2.10.3 Evaluations of Emulsion Performance and End-User Input

For diesel fuel emulsions, the typical evaluation context in many of the reports that have been reviewed for this report was to compare ULSD to more commonly used fleet fuels. These comparisons were subject to each particular study's test focus on engine, fleet, other emission control retrofit product or fuel performance, general emissions reductions, and related performance aspects and issues, such as operator impressions and perceptions of equipment performance using diesel fuel with lower sulfur content or diesel fuel emulsions. For example, the University of Texas emulsified diesel fuel operational assessment identified a number of "user issues", including: higher cost, engine manufacturer's reluctance to extend engine warranties when alternative fuel formulations such as diesel fuel emulsions are used, the perception of detrimental effects on certain type engines, fuel-water separation concerns, and perceived health and safety issues. [74] These observations were based on interviews with various users at different test and project locations in the northeast, southwest, and west coast. Other reports, including the Brunswick Mine Study provide an evaluation of similar worker and potential customer concerns. [28] Few if any equivalent concerns regarding conventional fuels are described in the literature reviewed.

Use of an EPA-verified emulsified diesel fuel has been the subject of several studies, and for comparative purposes in several others. This emulsified diesel fuel is a combination of diesel fuel with 20% water by weight, and an "additive package" for stabilizing the fuel-water emulsion. A 2001 report prepared by Air Improvement Resource, Inc. under contract to the diesel fuel emulsion manufacturer undertook a comparative analysis of vehicle emissions using the emulsified diesel fuel and other diesel fuels. [46] An eleven-engine database was developed to evaluate emissions from a baseline diesel fuel and the emulsified diesel fuel. The report's conclusions show that generally, the emulsified diesel fuel provided consistent reductions for NOx and PM. HC emissions were typically found to increase slightly. NOx reductions ranged from 3% to 30%, and for most of the test cases, PM reductions ranged between 24% and 83%. This study also evaluated the emulsified fuel's performance in Sacramento and Los Angeles, where the selected fleet engines represented 25% of the centrally fueled highway vehicle fleets in both locations.

Variations in emissions, performance and fuel consumption for particular engines, equipment, experimental fuel blends and operating conditions are described in other reports. The report documenting the Texas DOT emulsified diesel fuel operational assessment contains much useful information on the impacts of diesel fuel emulsions on the performance, operations and fuel consumption related to use in highway vehicles and nonroad equipment. [74]

Diesel fuel emulsions were identified as being used in seven retrofit projects in the U.S. since 2000, including two school bus projects, four transit bus projects, and one construction-related utility vehicle project. Diesel fuel emulsions were considered for use in The Big Dig construction project in Boston, but difficulties in fuel supply logistics and preexisting contractual obligations with fuel suppliers made its use impractical. (P28)

2.10.4 Technology Costs

One report includes an excellent discussion of overall operating costs using emulsions and retrofits. In this context, both the costs and benefits of specific emulsified fuel formulations are typically described (based on manufacturer information as well as recent field or laboratory tests) as reasons for their being selected as part of a particular study. [142]

2.10.5 Impact on Vehicle Performance and Fuel Economy

The power loss attributable to the lower energy content of the fuel was a concern raised in one construction-related project. A school bus fleet reported a 12% reduction in fuel economy, and that the vehicles were more difficult to start in cold weather.

2.11 DIESEL FUEL ADDITIVES

2.11.1 Overview

Fuel additives are chemicals added to fuel in very small amounts to improve one or more properties of the base fuel. Detergents, corrosion inhibitors and storage stability improvers are examples of commonly used fuel additives. More recently, additive manufacturers have developed products that improve the engine combustion process and reduce emissions, without compromising or negatively impacting the properties of the base fuel. Some emission-reducing fuel additives employ FBC materials that use catalytic processes to reduce emissions during engine combustion.

2.11.2 Fuel-Borne Catalyst Additives

A variety of different materials have been employed as FBCs including copper, cerium, cerium/platinum, iron/strontium, manganese and sodium. [101] In the U.S. and Europe, the use of FBCs has been as part of a system with DPFs or DOCs. As noted in Section 2.1, FBCs can also be used to facilitate regeneration of DPFs. As a general rule, the higher the level of FBC in the fuel, the more effective (i.e., the lower the exhaust temperature required to combust the soot) the catalyst's performance. [160] However, the higher the FBC level, the shorter the time interval before the DPF must be cleaned. One application required an FBC level of 30ppm to 60ppm for effective operation. [73] Other applications require levels in the range of 8ppm to 10ppm. [73, 101] The use of FBCs in combination with DPF or DOC technologies is discussed in more detail in Sections 2.1 and 2.2 of this report.

FBCs have also been sold as stand-alone products to be added to the fuel, even where exhaust aftertreatment emission control technology is not utilized. In one study, more than 94% of the additive was found to be retained in the engine and exhaust system. This retention level increased to 99% when a DPF was used. [72] This study results also showed that at an ultra-low additive rate of 4ppm to 8ppm, ultra-fine PM did not increase.

Four retrofit projects in the U.S. since 2000 indicated that FBC additives were being used, at least one of which was in conjunction with a DPF. Approximately 1600 delivery trucks operated by Coca-Cola have used an FBC additive. (P16)

2.11.3 Other Emission Reducing Additives

There are numerous manufacturers offering diesel fuel additives that are claimed to improve exhaust emissions, fuel economy, or both. In general, these improvements are claimed to be accomplished by improving combustion efficiency (by one means or another), resulting in reduced emissions. [137] Additive manufacturers have developed proprietary formulations or fuel treatment processes, and license the process techniques/equipment and operating technology to small independent refiners that process the fuel into the finished product and sell it to users. In general, no engine modifications or changes to any other piece of fuel storage/dispensing or operating equipment are required to use these types of additives.

Cetane number improvers are a major class of diesel fuel additives that promote emission reductions (primarily NOx). In a recent report, EPA presented the results of an analysis of the impact of cetane improvers on NOx emissions. [180] A statistical regression analysis found that if cetane improvers are added to a national average base fuel which would increase the cetane number by 5, NOx emissions would be lowered by a couple of percentage points.

2.12 BIODIESEL

2.12.1 Overview

Biodiesel is a renewable diesel fuel substitute derived from a number of vegetable oils, animal fats, or used frying oils. These oils are converted into methyl esters before they are used as diesel fuel. ASTM International defines biodiesel as the "mono alkyl esters of long chain fatty acids derived from renewable lipid feedstocks, such as vegetable oils and animal fats, for use in compression ignition engines." In the 1980s and 1990s significant R&D was conducted to evaluate a variety of biodiesel blending stocks, develop emissions data, assess engine/vehicle performance, and develop cost-effective manufacturing processes. Pure biodiesel is referred to as B100, while biodiesel blends with petroleum-based diesel fuel are referred to as BXX, where "XX" is the volume percent of biodiesel fuel blended with the petroleum-based diesel fuel. Biodiesel fuel can reduce PM, HC, and CO emissions, but typically increases NOx emissions (largely because of the chemically bound oxygen found in biodiesel). The percentage of emission reductions and increase in NOx is a function of the percentage of the fuel blend that is comprised of biodiesel. [7] According to the National Biodiesel Board, current and proposed biodiesel production plants are located in 20 states in the U.S. More than 1000 distributors are making biodiesel available in all 50 states. [See www.biodiesel.org]

2.12.2 Biodiesel Specifications and Properties

In December 1998, the ASTM International Subcommittee D02.E0 approved the first provisional standard for the manufacture of biodiesel. Prior to that time, no common standard, or specification of characteristics important for reliable engine operation was available. The most recent specification for biodiesel was established in 2003 as "ASTM D6751-03a Standard Specification for Biodiesel Fuel (B100) Blend Stock for Distillate Fuels" and is to be used for blending with ASTM Specification D975 Grades 1-D, 2-D and low sulfur 1-D or 2-D diesel fuels. [163] This current ASTM International specification includes test methods for establishing and measuring 35 individual biodiesel fuel characteristics or properties that are important to diesel engine/vehicle operation, including energy content, cetane number, cloud point, absorbed water, lubricity, viscosity, density, storage stability and flash point. [14] In comparison with petroleum-based diesel fuel, biodiesel is characterized by:

- Lower heating value (by about 10-12%)
- Higher cetane value (typically 45-60)
- About 11% oxygen content (petroleum-based diesel contains no oxygen)
- No aromatics contents (and no PAHs)
- No sulfur or extremely low sulfur content
- Better lubricity
- Higher viscosity
- Higher freezing temperature (higher cloud point and pour point)
- Higher flash point
- No toxicity or low toxicity
- Biodegradability
- Different corrosive properties

Some of the above properties, such as the high cetane value or good lubricity, are obvious advantages of biodiesel while others, including the lower heating value, high freezing point (and inferior flow properties at low temperature), or corrosion properties are its drawbacks. Biodiesel changes the character and can increase the intensity of the odor of diesel exhaust. [See www.dieselnet.com]

The diesel Fuel Injection Equipment (FIE) manufacturers and EMA have developed positions on the use of biodiesel fuels in the products of their respective member manufacturers. [94, 171] In 2000, the U.S. Army developed a Department of Defense Purchase Description (DOD PD) for the use of B20 in diesel-powered non-tactical ground vehicles. [14]

A specification for B20 is currently under development by ASTM International's Subcommittee D02.E0 as Work Item (WK) 6286. [203] Specifications are under development for three grades of B20, with the biodiesel component of the blend conforming to the requirements of ASTM D6751, and the remainder of the fuel being a middle distillate grade diesel fuel conforming to ASTM D975:

- B20 (S15) with a diesel fuel component maximum sulfur level of 15ppm.
- B20 (S500) with a diesel fuel component maximum sulfur level of 500ppm.
- B20 (S5000) with a diesel fuel component maximum sulfur level of 5000ppm.

2.12.3 Emission Reduction Experience

Since the biodiesel base stock can come from a variety of sources (several different vegetable oils, animal fats, waste cooking oils, etc.), the specific fuel properties vary somewhat, depending on the biodiesel source and degree of processing refinement. Thus, the specific emissions effects vary according to biodiesel fuel composition. Several studies and assessments of emissions from biodiesel have been completed, including extensive work by the U.S. EPA. [7, 22, 23, 107, 109, 178] Documents reviewed for this report discuss the general emission trends for a "generic" B20 blend with today's conventional highway low sulfur diesel fuel, in comparison with 100% conventional highway diesel fuel. Typical results are as follows: For total PM emissions, B20 provides about a 10-15 % reduction; for CO and HC (including the air toxics components of HC emissions), 0 to 10% reduction; for sulfate emissions (formed from SO2 emissions), up to 20% reduction; and for NOx, up to a 10% increase. $PM_{2.5}$ reductions comprise about 3% or less, of the 10% reduction for total PM.

The NOx increase is a function of engine fuel/emission control systems design, and several biodiesel properties, including cetane value, oxygen content, density, and physical properties, all of which vary with the specific biodiesel base stock. Some newer diesel engines (produced in 2002 and later) have shown less of a propensity for a NOx increase with B20. For older engines, injection timing changes can reduce or eliminate the NOx increase, but doing so can potentially violate EPA anti-tampering provisions of the Clean Air Act. Certain types of additives mixed with B20 were found to reduce or eliminate the NOx increase. [100]

Compared to petroleum-based diesel fuel, biodiesel has been shown to reduce vapor-phase hydrocarbons in the C1 to C12 range, aldehydes and ketones, PAH and NPAH emissions, and has generated no new emission species compared to those currently present in diesel or biodiesel exhaust. [179]

A Japanese researcher evaluated a 30% water-emulsified biodiesel blend with EGR to assess the effect on emissions, and found an over 80% reduction in NOx compared to the baseline diesel fuel configuration. [146]

2.12.4 Use of Biodiesel

Researchers from South Dakota State University and the University of Missouri-Columbia undertook a survey of U.S. state transportation agencies to collect performance, storage and economic information related to the use of biodiesel fuels, and found that B20 was the most common biodiesel blend used across the country. [27] This survey found five states that have mandated the use of biodiesel in state government vehicles, and that nearly 65% of the states in the U.S. reported either considering or enacting biodiesel blended fuel mandates, or using biodiesel blended fuel. Table 2-9 illustrates the states that currently require the use of biodiesel in some form, and those that offer incentives for biodiesel production or use, or both. Nearly 40% of the states indicated some level of experience using biodiesel blend, either in tests or as policy. In addition, there are a multitude of non-state DOT government agencies and private sector fleets that have either tested or are currently using biodiesel blends. B20 is an allowable fuel for satisfying the state government and fuel provider requirements for alternative fuel vehicle acquisition/usage under the Energy Policy Act of 1992 (EPACT).

Table 2-9, States Requiring Use of Biodiesel or Providing Incentives

State	Legislation Requiring Biodiesel Use	Legislation Providing Incentives for Biodiesel Production or Use
Arkansas		X
Iowa		X
Idaho		X
Illinois	X	X
Indiana		X
Kansas	X	
Kentucky	X	X
Maryland		X
Michigan	X[1]	X
Minnesota	X	
Missouri	X	X
Mississippi		X
Montana		X
North Carolina		X
North Dakota		X
Nebraska		X
New Jersey		X
Rhode Island		X
South Dakota		X
Texas		X
Washington	X	X

[1] Approved by the Michigan House Agriculture Committee. Pending approval in the Michigan House

There are several projects that have documented the use of biodiesel in diesel engine fleet applications as a retrofit strategy. The reasons most often cited are the effectiveness of emission reductions, ease of transition to use, and minimal impacts on current operating equipment and vehicles. [6, 31, 186] According to the National Biodiesel Board, nearly 1.2 million gallons of biodiesel fuel were used in 2004, and as of January, 2005, there were more than 400 major fleets using biodiesel, including all branches of the U.S. military, Yellowstone National Park, NASA, several state departments of transportation, major public utility fleets, various city agencies, and over 50 school districts. [See www.biodiesel.org]

2.12.5 Operational Issues

The FIE manufacturers have documented a number of operating problems with biodiesel fuels (particularly those used before the ASTM specifications were created). The key concern of these manufacturers is related to resistance to oxidation. Aged or poor quality biodiesel fuel may contain organic acids, free water, peroxides and products of fuel processing that may attack engine and fuel system components leading to reduced service life. [94] The DOE National Renewable Energy Laboratory (NREL) has conducted a nationwide survey of biodiesel quality, and found several B100 specification failures (4 samples out of 27) for acid number, total glycerin or phosphorous. [149] Further, of 50 samples of B20 taken nationwide, only 32 samples were actually found to contain about 20% biodiesel. [149] Additives of the types used commercially in diesel fuel have been shown to provide improvements to the quality of biodiesel blends in areas such as detergency, water separation, cold flow characteristics, fuel system corrosion and foaming. [26] Such additives should not be applied by fleet fuel users unfamiliar with fuels manufacturing and distribution.

Eighteen retrofit projects in the U.S. since 2000 reported as using biodiesel fuels in school bus, transit bus, utility vehicle and nonroad applications. Five of these projects reported using a mixture of biodiesel with ULSD. Several projects reported the typical start-up problems when the change was made to biodiesel, including fuel tank sediment pick-up, filter plugging, difficulties in cold weather, and inconsistent fuel quality. Once the causes of these "start-up" problems were identified and solved, problem-free use was achieved for the most part.

Currently, there are no DOC or DPF technologies that have been verified specifically for use with biodiesel fuels, although in general, limited field data suggest that biodiesel blends appear to be compatible for use with diesel oxidation catalysts and diesel particulate filters. The specific catalyst supplier should be consulted before using any catalytic retrofit product with a specific biodiesel formulation (and regarding any limitations on fuel properties). Limited engine and vehicle testing suggest that compared to diesel fuel, the use of biodiesel with DPFs, can extend the time to regeneration by up to 4 times. [31] There is at least one DPF technology provider that is in the process of seeking verification with biodiesel fuels.

2.12.6 Costs

The cost of biodiesel can vary as a function of several factors, including the cost and type of the biodiesel feedstock, specifics of the manufacturing process, production plant size, distance from production plant to blending and distribution points, the value of Federal and state production incentives and/or tax credits, and price supports to users. As such, a range of costs has been reported and can be found across the U.S. Data collected and developed by EPA show that in 2002, B100 could be purchased for $1.95 to $3.00 per gallon (or about twice the price of conventional diesel fuel), and that B20 was priced at $0.30 to $0.40 more per gallon than conventional diesel fuel, exclusive of any production or use incentives or price supports. [37] A recent report prepared by the DOE-EIA analyzed the factors that comprise the cost of biodiesel production, and concluded that over the next few years, the cost of producing biodiesel was not likely to be competitive with that of petroleum diesel. [25] Various production incentives, tax credits and price supports are likely to continue to create a pricing structure that can be favorable to biodiesel fuel users.

3.0 PROGRAM DESIGN/IMPLEMENTATION EXPERIENCE

3.1 OVERVIEW

Retrofitting diesel engines with supplemental exhaust emission controls dates to the 1960s and 1970s when DOCs were first installed on nonroad diesel engines for occupational health reasons. In the 1980s, retrofit activity continued to focus on nonroad engines, but several highway retrofit programs involving both DOCs and DPFs were initiated.

In the 1990s, a growing number of retrofit demonstration programs were initiated in the U.S., Latin America, Europe and Asia. Also in the early 1990s, the U.S. EPA, in response to a 1990 Clean Air Act Amendments mandate, established the urban bus retrofit/rebuild requirement. This program required certain transit buses in large metropolitan areas to install technology at the time of engine rebuild to reduce PM emissions by 25% or to meet a 0.1 g/bhp-hr PM level. Tens of thousands of buses were involved in the program and the principal technology utilized was the DOC. [152] In 1994, occupational health authorities in Germany and Switzerland required that DPFs be installed on underground mining and tunnel equipment, and in 1998, the Swiss EPA extended this requirement to all construction equipment. [128] Finally, Sweden established its Clean Cities program requiring trucks and buses to meet certain emissions requirements that has resulted in a number of heavy-duty vehicles being retrofitted with DPFs. [89]

In the current decade, EPA implemented its Voluntary Diesel Retrofit Program (along with several sub-programs) and CARB initiated its Diesel Risk Reduction Program under which mandatory reductions in PM emissions from selected fleets of trucks, buses and nonroad engines have been or will be established. Today, worldwide over 500,000 highway and nonroad diesel engines have been retrofitted. [see e.g. 99, 204]

Retrofit programs have covered a wide range of vehicles and equipment, emission reduction strategies, fleet sizes, pollutants, sponsoring/implementing agencies, and program objectives. Retrofit products have been applied to trucks, buses, taxis, construction equipment, materials handling equipment, mining equipment, marine vessels, locomotives and other forms of diesel engine vehicles/equipment. Technology strategies have included DOCs, DPFs, LNCs, SCR, SNCR, EGR, CCV systems, ULSD, biodiesel, emulsions and additives (including FBCs). The target pollutant for the vast majority of retrofit programs has been PM, but programs have also sought to reduce CO, HCs (including toxic HCs), NOx and smoke, in general.

A growing number of states are becoming more proactive in promoting retrofit initiatives in order to demonstrate improvements in local and regional air quality management. Sufficient awareness of advances and improvements in equipment and fuels exists that government agencies (particularly those at the state level dealing with mandated air quality compliance goals that must be met in the years to come) are now willing to promote retrofit programs. These efforts guide, promote and advocate engine retrofitting to reduce diesel emissions as one key component of broader air, energy, and environmental management programs. An important strategy that has been used to build confidence in the private sector for using retrofit technologies is to promote the funding of retrofit projects in government-owned/operated vehicle and equipment fleets. As such, the focus of many of these retrofit programs is on diesel engines used in large, public-sector vehicle and equipment fleets. The objective of focusing on these fleets is to allow governments, businesses, school districts, municipal transportation authorities and other organizations to assess opportunities for incremental emission reduction improvements; and to consider options related to engine retrofitting, fuels, partial fleet replacement, and operator practices as components of program planning.

The largest collection of literature reviewed for this report focused on emission control technology demonstration and/or emission control capability evaluations. Consequently, documentation of retrofit program planning, design and implementation is quite limited. A number of the documents reviewed and referenced in this report concern specific program projects, tests and assessments undertaken by, or in coordination with the states that are leading these efforts. By way of contrast, information collected regarding U.S. retrofit project experience since 2000 provides useful insights into the programmatic aspects of retrofit projects.

3.2 RETROFIT PROJECTS IN THE U.S.

Over 220 retrofit projects were identified in the U.S. Requests for information were made for each of them. Information was obtained from about two-thirds of those projects and was used, along with information from publicly available literature sources, as the basis for the content in this report. Table 3-1 provides a summary of the number of retrofit projects, by retrofit technology and vehicle/equipment application, for which information was received. Table 3-2 illustrates the number of retrofit projects by state. Appendix A provides a brief description of all of the retrofit projects that were identified in the U.S. Summaries of each project that provided sufficient information for their development are contained in Appendix B.

Table 3-1, Summary of U.S. Retrofit Programs and Projects by Technology and Application

Retrofit Technology	Vehicle/Equipment Application*						
	School Buses*	Transit Buses	Utility Vehicles	Freight/ Delivery Vehicles	Refuse Trucks	Nonroad Engines	TOTALS
DPF	25	8	5	3	7	1	49
DOC	48	1	9	2	8	19	87
LNC/DPF	0	4	2	0	2	2	10
EGR/DPF	0	3	2	0	1	2	8
SCR	0	0	1	1	0	1	3
DOC/CCV Systems	9	0	1	1	4	2	17
Diesel Fuel Emulsions	2	4	1	0	0	1	8
Diesel Fuel Additives (Including FBC)	1	0	1	1	1	1	5
Biodiesel	10	1	1	0	1	3	16
ULSD (Only)	3	2	0	0	0	2	7
ULSD with Other Retrofit Technology	33	13	8	2	8	11	75
TOTALS	**131**	**36**	**31**	**10**	**32**	**45**	**285**

*Note: Some programs/projects involve multiple fleets. For example, the State of Washington School Bus Program has over 200 individual school districts participating in the program, and various programs in California involve multiple school bus and transit bus fleets.

Table 3-2, Number of Retrofit Programs and Projects By State*

AK	AL	AZ	CA	CO	CT	DC	DE	FL	GA	IA
2	1	2	30	4	6	2	1	2	4	1
ID	IL	IN	KY	MA	MD	ME	MI	MN	MO	MS
2	6	3	1	11	3	1	5	1	2	2
MT	NC	NE	NH	NJ	NM	NV	NY	OH	OR	PA
1	2	1	2	5	1	3	14	5	3	7
RI	SC	TN	TX	UT	VA	WA	Multi-state			
1	1	2	12	1	2	47	8			

*Note: Some programs/projects involve multiple fleets. For example, the State of Washington School Bus Program has over 200 individual school districts participating in the program, and various programs in California involve multiple school bus and transit bus fleets.

3.3 PROGRAM TYPES

Relative to implementation, retrofit programs can be grouped into two general categories, mandatory and voluntary. Mandatory programs are established by legislation or some regulatory agency that generally creates specific emission reduction compliance requirements for designated category or categories of vehicles or equipment. These programs typically focus on publicly owned or publicly funded fleets (e.g., transit buses, refuse vehicles, construction equipment used on a particular construction project). Voluntary programs are generally undertaken to achieve a particular goal, such as reducing exposure of harmful pollutants to sensitive populations or reducing criteria and/or precursor pollutants such as HC, PM or NOx, often as part of an overall strategy to help achieve attainment with applicable air quality standards. The number of voluntary programs in the U.S. far exceeds the number of mandatory programs. In California, Europe and Asia, there is more of a mix of mandatory- and voluntary-based programs.

3.3.1 Mandatory Programs

Examples of mandatory programs include Switzerland's DPF retrofit requirement for construction equipment, CARB's DRRP, Hong Kong's DOC retrofit requirement for selected commercial vehicles, and Tokyo's heavy-duty engine PM reduction program. While each of these programs requires a specified level of emission reduction, the manner in which that requirement is expressed differs.

The Swiss EPA, beginning in 1998, required that all construction equipment be retrofitted with DPFs capable of achieving at least a 95% reduction in carbon-based PM. To be certified for use under the program, a technology must demonstrate compliance with the 95% reduction requirement with a loaded DPF, a new DPF and regenerated DPF, as well as during regeneration. After 2000 hours of operation, a deterioration of only 5% is accepted. Many certified products show 99.9% reduction in carbon-based PM with hardly any deterioration. [128] A number of DPF systems have been certified and over 7000 pieces of equipment were equipped with DPFs by the end of 2004. The annual failure rate fell from 6% in 2000, to about 2% in 2003. The Swiss EPA has a goal of completing DPF retrofits on 15,000 pieces of construction equipment and having a failure rate of less than 1%. [148] The written reports discussing the Swiss program did not provide a date by which the Swiss EPA expects to achieve the 15,000 retrofit goal**.**

In 2000, CARB adopted its DRRP that contained a number of program elements including a call for a series of regulatory initiatives to establish emission reduction requirements for a variety of highway and nonroad fleets. To date, CARB has established fleet emission reduction requirements for several categories of diesel engine vehicles and equipment. [See www.arb.ca.gov/diesel.dieselrrp.htm] Other program initiatives are scheduled in the coming months. Unlike the Swiss program, the California program does not specify the type of retrofit technology that must be used. Rather it has established three levels to which technologies can be approved for use, under a rigorous verification process: Level 1: PM reductions of 25% or more; Level 2: PM reductions of 50% or more; and Level 3: PM reductions of at least 85%, or PM level of 0.01g/bhp-hr.

As described in Section 2.9, CARB had also set implementation targets for a voluntary software reflash program for California-registered diesel vehicles, expecting an installation rate of 35% by October 2004, 60% by May 2005, 80% by January 2006 and 100% by 2010. Since the voluntary rate of implementation expectation has not been achieved, CARB recommended and received approval for its mandatory reflash program in December 2004.

All retrofit technologies used for compliance with the California program must be verified by CARB. Technologies verified under the EPA program under certain circumstances are also eligible for use in California. As a means toward harmonization of retrofit product verification requirements between CARB and EPA, in June, 2004, these two agencies executed a Memorandum of Agreement committing each of them to work toward accepting PM and NOx verification levels assigned by the other's verification programs, and to coordinate in-use testing conducted by retrofit product manufacturers so that data generated may satisfy the requirements of each agency's program.

The Hong Kong Environmental Protection Department established a set of PM reduction requirements that selected categories of commercial vehicles must meet. For cross-boundary vehicles that may operate on diesel fuel with sulfur levels reaching 2000ppm, a 25% PM reduction is required, and for local vehicles that operate exclusively on 50ppm sulfur diesel fuel, a 35% reduction is required. Approximately, 40,000 vehicles are covered by the program. The principal technology used in this program is the DOC. The DOC products used in the program must be evaluated, approved and warranted for 250,000 km. Approximately $180 million has been made available to cover the cost of retrofitting these and other vehicles operating in Hong Kong. Other engines targeted for retrofit include those on sanitation trucks and those used in construction equipment. [75, 108, 152]

Another type of mandatory or "quasi-mandatory" program exists in which a specified emission reduction is required as a condition for vehicle or equipment operation in a particular geographic area (e.g. inner city corridors) or application (e.g., as a requirement for being awarded a publicly-funded construction contract). These programs have taken several forms.

One example is Sweden's Clean Cities program where commercial vehicles above 3.5 metric tons are prohibited from entering Environmental Zones, which typically are the central business areas, unless they meet specific emission limits. This requirement has led to older vehicles being retrofitted with emission control technologies capable of achieving up to an 80% reduction in PM. Both DOCs and DPFs have been used to meet this requirement. [89, 99] Recently, the program established a requirement for older vehicles to meet a 35% reduction in NOx emissions as well.

In the U.S., Local Law 77, which was signed into law in December 2003, requires the phase-in of ULSD and "Best Available Technology" (BAT) for emission control use in all diesel-powered off-road equipment used construction projects in New York City. [115] The requirements apply to all diesel nonroad engines rated at 50 horsepower or greater that are owned by, operated by or on behalf of, or leased by a city agency. Some exemptions are provided in the law. The requirements are being phased in with all city-owned, operated, or leased nonroad heavy-duty vehicles in Lower Manhattan covered in the first phase that took effect on June 19, 2004. The provisions of the law will be fully effective as of December 19, 2005. An approved list of products will be used for selecting BAT with preference being given to technologies that reduce PM (NOx is considered of secondary importance). The program will be enforced with penalties of up to $20,000 plus twice the amount of money saved by failing to comply with the requirements or making false claims. New York City is currently developing a definition of what constitutes BAT. The State of New Jersey is also considering legislation that would establish a mandatory retrofit program for selected fleets.

The Coordinated Construction Act for Lower Manhattan (New York City) requires contractors involved in New York State construction projects in Lower Manhattan to use only ULSD fuel to power diesel-powered construction equipment with engines of 60 horsepower or more, and where practicable, to incorporate DPFs, DOCs, or other technologies with comparable or better effectiveness. [40]

Several retrofit programs have required, as a condition of being awarded a publicly funded construction contract, that equipment be retrofitted with emission control technology. One example is the program in Connecticut to reduce emissions from Federally funded construction along I-95. The Connecticut Department of Transportation has added a contract specification that requires all contractors and sub-contractors to reduce emissions from construction equipment 60 horsepower and greater by installing emission control technology or using cleaning fuels. Under this program a number of pieces of construction equipment have been retrofitted with DOCs. [167] Another example is a program in Massachusetts that required that construction contractors working on the Massachusetts Central Artery/Tunnel project in Boston retrofit construction equipment with DOCs. The requirement was based on a contractual obligation to reduce aldehyde odors.

3.3.2 Voluntary Programs

Several voluntary programs are addressed in the literature and are referenced in Section 6.0 of this report. These programs involve Federal, state, local government or other regionally based agency (e.g., school districts) initiatives. As noted previously, these initiatives are not specifically mandated, but rather have been undertaken to achieve a particular objective. Objectives of voluntary programs have included pilot projects designed to demonstrate the effectiveness of a particular technology. Such projects help to demonstrate the commercial viability of a retrofit product in a particular application; and to assess the emission reduction capabilities of the technology, and the impact of the technology on engine performance and fuel economy. Voluntary demonstration projects also provide valuable information for those with an interest in implementing more extensive retrofit programs.

At the national level, the EPA's VDRP established a broad range of technical support functions and grant assistance to organizations desiring to create effective retrofit projects. This program spawned the creation of EPA's Clean School Bus USA Program and several other grant competitions to assist a wide range of retrofit interests. In May 2004, for example, a special retrofit grant program was established to benefit sensitive populations. Total funding of $1.6 million was made available to support 18 diesel retrofit projects across the U.S., as the EPA launched its new Clean Diesel Campaign.

Through the EPA's Clean School Bus USA program established in 2003, EPA is advocating that buses manufactured prior to 1990 be replaced with new, cleaner buses equipped with pollution control devices, purchase retrofit products, or to acquire school buses that operate on cleaner fuels. The program was funded at $5 million per year for FY 2003 and 2004. Current funding for FY 2005 is $7.5 million. Grants have funded 40 projects to date in Arizona, California, Colorado, Florida, Georgia, Illinois, Indiana, Iowa, Maine, Massachusetts, Michigan, Mississippi, Montana, Nebraska, New Hampshire, New Jersey, New Mexico, New York, North Carolina, Ohio, Oregon, Pennsylvania, Rhode Island, Tennessee, Texas, Utah, and Washington. Additionally, a grant was provided to the National School Transportation Association that, in partnership with its members (contract school bus providers), established and administers a subgrant program for retrofit products and ULSD. These grant projects have included a wide range of technologies, including DPFs, DOCs, FBC systems, CCV systems, ULSD, and alternative fuels such as biodiesel and natural gas. [See www.epa.gov/otaq/schoolbus]

Several states, including Washington and Maine have established statewide school bus programs. The Washington program is discussed in more detail below.

In California and Texas, nonattainment status of several metropolitan areas has been a driver for development of their respective voluntary retrofit programs as a strategy to reduce emissions. [33, 46, 74, 142, 161, 175] Key points from CARB's voluntary school bus retrofit program include the following:

- It is important for local government agencies to have and maintain flexibility in selecting projects for implementation, while maintaining focus on improving health benefits to children.
- Based on program progress to date (Spring, 2005), DPFs appear to be the most cost-effective means of achieving the program goals of children's health protection.
- Feedback from school officials recommends that a greater share of retrofit program funding be used for school bus replacement.
- Acceleration of PM retrofit technology development and application is an important additional benefit provided by the school bus retrofit program.

The Texas Emissions Reduction Plan (TERP) was created by legislation in 2001 and is a program using voluntary incentive for project to reduce NOx emissions in the nonattainment and near-nonattainment areas of Texas. Funding for the program through 2008 is expected to total $550 million. Funding sources for the program include: 1) a portion of the vehicle title fee ($15 to $20), 2) a 2% surcharge on the sale, lease, rental, storage, use and consumption of HDDE nonroad equipment, 3) a 2.5% surcharge on the sale, lease or use of pre-1977 HDDV and 1% for 1997 and LMY vehicles, 4) a 10% surcharge on registration feels for truck tractors and commercial motor vehicles and 5) a $10 fee on commercial vehicles that are required to be inspected. Eligible projects include new purchases, vehicle replacement, repowering, retrofit, and infrastructure for reduced idling, electrification, and qualifying infrastructure.

For several years, the New York State Energy Research and Development Authority (NYSERDA) has funded and provided technical support to the development and deployment of transportation technologies designed to reduce vehicle emissions and fuel/energy consumption. Examples of NYSERDA-funded projects include those that have supported diesel engine idle reduction, alternative fuels, and retrofit applications. In its August, 2004, three-year strategic outlook document, NYSERDA identifies a transportation environmental mission to develop and establish cost-effective approaches to reduce emissions from New York State's inventory of diesel engines that have been or will be manufactured before more stringent emission certification standards become effective for the 2007 model year. For this purpose, a Clean Diesel Technology Program has been established. The program is currently funded at $2 million to support development, demonstration and commercialization of innovative clean diesel technologies, and for demonstration and evaluation of emission control technology for nonroad applications. [135]

3.4 PROGRAM PARTNERS

Many of the partners in U.S. retrofit projects consisted of Federal, state and local agencies, as well as multi-state consortiums. Examples of such are EPA, U.S. Department of Transportation (DOT) and U.S. Department of Energy (DOE) on the Federal level. Partnering by these agencies often involved being the major source of funding and has sometimes included program and technical support. State agencies participants included those representing air quality, transportation, and public works functions, as well as state-funded universities. Although not a source of funding, state universities provided use of equipment, such as dynamometers and emissions measurement instrumentation, and conducted emissions testing and data logging on participating vehicles. In projects that involved school bus retrofits, the local school district, board of education, or city was always involved in some fashion, either in funding, conducting public outreach or providing the school bus fleet for retrofit. Regional consortiums, which often provided technical assistance, guidance for program requirements, and sometimes funding, were involved in retrofit projects. Examples include NESCAUM, the West Coast Diesel Emissions Reduction Collaborative (EPA Regions 9 and 10), Diesel Solutions (the Puget Sound Clean Air Agency and other public and private sector partners), various Clean Cities Coalitions and the Northwest Pollution Authority. Also partnering in retrofit projects were technology providers, product suppliers, and fuel suppliers. Independent technical consultants or professional technical services firms were sources that provided technical assistance of various forms.

3.5 PROGRAM/PROJECT FUNDING

Sources of funding can take several forms including grants from Federal, state, and local government agencies, as well as private sector funding. Program and technical reports in the literature do not focus in detail on funding issues or mechanisms of funding transfer (which can be a significant hurdle in getting government-based grant funding to private sector fleets or equipment operators). In documents reviewed for this report, funding is typically mentioned in one of two ways: either in the introductory section of a report discussing project set-up, parameters, schedule and sponsors; or as dollar amounts and/or an element of budget cycles.

While several of the reports in the literature cite the ability to have cost covered as a consideration in the decision to implement or participate in a retrofit project, there were few indications that efforts were thwarted or suspended due to lack or shortage of funds. Reports on projects involving school bus retrofits generally acknowledged funding as a factor impacting engine repower or vehicle replacement schedules. [12, 118, 133, 155]

Incentives are a critical element in initiating voluntary retrofit programs and recruiting the participation of willing fleet vehicle or equipment operators. The greatest incentive is the availability of funding that can be used for the acquisition of retrofit products or to offset increased operating costs (e.g., fuel cost differential), but incentives can take other forms as well. Incentives can include reductions in vehicle registration fees, taxes or user fees; preferential parking; or access to high-occupancy-vehicle (HOV) lanes; giving "bonus points" to contractors who commit to use low emission equipment on publicly funded projects; and giving recognition awards and/or favorable publicity to participating fleet operators.

The EPA is a major source of retrofit project funds. Grant money for individual projects provided by EPA ranged from approximately $50,000 to approximately $450,000. EPA funding was used to purchase a variety of retrofit products for vehicles and equipment, including school buses, dump trucks, refuse haulers, nonroad vehicles and ferries. The predominant retrofit technologies and fuel acquired as a part of EPA-funded projects included DOCs, DPFs, B20, and ULSD.

Several retrofit projects were funded by revenues generated from settlement of U.S. EPA, state or local enforcement actions in the form of Supplemental Environmental Projects (SEPs). In some cases, the companies funding the SEP was an active participant in the planning and implementation of the program, while in others they were not

Several projects were funded through the U.S. DOE by way of the State Energy Program grants. (P116, P118, P172) Funding for these projects ranged from approximately $250,000 to approximately $550,000. State Energy Program grants are Federally-sponsored, state-based funds that are distributed to states based on a formula. Each state can then carry out its own programs to promote energy efficiency and the use of renewable energy sources (e.g., biodiesel). The program is funded at $45 million and cost-shared by all states, territories and the District of Columbia. Several retrofit projects in the U.S. used SEP funding for DOC and DPF school bus retrofits, as well as fueling school bus fleets with ULSD. (see e.g. P8, P20, P21, P22, P30, P46, P50, P59, P116, P118, P127)

Several states have made good use of Congestion Mitigation and Air Quality (CMAQ) funds that are provided to states by the U.S. DOT, including Texas, California and others. In the San Francisco Bay Area, for example, a two-year project began in early 2004 and will continue throughout 2005 to help transit operators in the San Francisco Bay Area purchase nearly 1,700 DPF/LNC emission control systems to reduce NOx and PM from transit buses. In June, 2003, The Metropolitan Transportation Commission (MTC) allocated $13.8 million from available CMAQ funds and $1.8 million in local matching funds to support the program. The program calls for retrofits to be accomplished on diesel buses from model year 1994 onward. Retrofit products are to be verified by CARB as capable of reducing PM emissions by up to 85% and NOx by up to 25%. The program estimates that up to 2500 pounds per day of NOx and 300 pounds per day of PM may be eliminated as a result of the MTC transit bus retrofit program. [See www.dieselforum. org]

Several projects were funded in part out of U.S. DOT funds, for example to pay a portion of the retrofit technology used on transit buses and for retrofitting construction equipment.

In California state-funded retrofit projects, CARB was a major source of funds, in some instances contributing upwards of $800,000 for an individual project. (P106) The Carl Moyer Memorial Air Quality Standards Program (Carl Moyer Program) is a voluntary program that provides incentive funding to reduce emissions from diesel-powered vehicles and equipment. The Carl Moyer Program is administered by CARB with support from local and regional air pollution control districts, such as the South Coast Air Quality Management District. The program funds emission reductions that are not already required by a CARB mandate. As of February 2004, the program has funded approximately 4950 cleaner engines, reduced NOx emissions by approximately 14 tons per day, and received approximately $114 million in appropriations. The CARB DRRP has provided over $50 million in state funding for school districts to have the option to purchase new, low emitting new diesel powered buses, purchase alternative fueled buses, or to retrofit existing school buses with emission control technology. This program also has provided funding for the re-powering of highway, nonroad, and stationary diesel engines.

In coordination with CARB, The Sacramento Air Quality Management District's (AQMD's) Heavy Duty Vehicle Incentive Program offers a variety of financial incentives to entities that lower NOx emissions from heavy-duty vehicles (both highway and nonroad vehicles and equipment). This includes purchasing new alternative fuel vehicles (AFVs) as well as retrofitting older diesel vehicles to provide for emission reductions. Private businesses and public agencies in the six-county Sacramento ozone nonattainment area are eligible to apply for funding from the program

One component of the State of Washington's initiative is the state-funded voluntary school bus retrofit program made possible through funding that was approved by the 2003 Washington State Legislature. The Legislature has committed to a funding level of $5 million annually for five years to reduce emissions from about 5000 of the approximate 9000 school buses in the state. The focus of the program is on reducing fine PM and air toxic emissions. The program will reach all areas of the state, leveraging additional Federal funding in the hope of reaching nearly all school buses and school children in the state. Turnkey grants are also being offered to cover retrofit hardware costs and part of the price differential for ULSD. The program is being managed through a partnership that includes the Washington State Department of

Ecology, the Office of the Superintendent of Public Instruction, the Puget Sound Clean Air Agency and other local agencies across the state: the Northwest Air Pollution Authority, Olympic Region Clean Air Agency, Southwest Region Clean Air Agency, Yakima Regional Clean Air Authority, Benton Clean Air Authority and Spokane County Air Pollution Control Agency. [See www.ecy.wa.gov/programs/air]

Texas-based retrofit projects were heavily funded by the Texas Commission on Environmental Quality (TCEQ) through the TERP grants and other TERP financial incentives at approximately $4 million. (P188.1, P188.2) The TERP program was established to reduce the amount of NOx emissions through a voluntary incentive program. As of January, 2005, TERP has funded 282 projects and has awarded in excess of $120 million. The program also includes a comprehensive evaluation of a variety of retrofit technology options and fuel strategies. [33] State-based funding, along with CMAQ funds, are being made available to support retrofit products and clean fuels for a variety of highway vehicle and nonroad equipment applications.

In addition to Federal and state funding, local government funds have been used to support a number of U.S. retrofit projects. Local municipalities, cities and school districts contributed to or provided in-kind contributions to augment state and Federal grant funds. Funding levels typically ranged between approximately $10,000 and $40,000 for various retrofit projects.

The private sector has made substantial in-kind contributions to advancing retrofit programs ranging from technology suppliers providing on-going technical training and support, to fleet operators providing vehicles for retrofit, personnel to install and maintain retrofit equipment and to pay the incremental costs of using ULSD. Funding contributions from the private sector (not counting SEP payments) have been relative rare. One example was a contribution of several hundred thousand dollars made by 3M to help fund school bus retrofits in Pennsylvania.

Other forms of funding initiatives and/or incentives have included SIP credits, which rely on the voluntary actions of individuals or businesses to achieve emission reductions, Mobile Source Emission Reduction Credits (MERCS), which are generated when a company reduces transportation emissions beyond what is required and sells the credits to other companies covered by a tradable permit system, and consideration of building permit fee rebates for construction companies (as an incentive to reduce the emissions associated with construction projects). [69]

3.6 PROGRAM/PROJECT PLANNING AND IMPLEMENTATION

Available documentation in the literature provides little information regarding the general tasks associated with retrofit program planning and implementation. To some extent, this is due to the fact that many of the documents reviewed describe projects that emphasized a scientific approach to analyzing and reporting results. As such, discussion of more subjective aspects of retrofit program planning and implementation, including outreach to and education of stakeholders and users, was not their focus. A few reports did address specific elements of program planning and implementation, including fits with the need for addressing air quality/

emissions exposure issues; and efforts applied to technology, product and product supplier selection. These topics are addressed in the paragraphs that follow.

The available literature generally does not focus on programmatic issues, problems and solutions, and discussion on them is very limited. Some of the issues raised concern identifying the appropriate retrofit technology candidates for specific applications. Other issues and problems discussed in specific study reports involved unanticipated developments, slowdowns and interruptions in proceeding with research or anticipated test procedures due to equipment delays, malfunctions, failures, or incompatibility with other equipment. [28, 35, 70, 107, 155] These types of problems are cited in many of the test and evaluation projects that were conducted, and generally involved multiple equipment and technology options. Documented information on the subjects of issues, problems, and solutions relating to the technical aspects of specific retrofit technologies and their application to vehicles and equipment are discussed in Section 2.0 of this report.

On the other hand, a review of the U.S. retrofit experience since 2000 provides a number of useful insights on program planning and implementation which are highlighted below in this section and in covered in more detail in Section 4.0.

3.6.1 Role of Emission Inventory and Exposure Information on the Design of Retrofit Programs

Emission inventory and exposure information addressed in the available literature focuses on general discussions of emission impacts on worker and public health and the environment, by way of referencing a project's rationale. Metropolitan regions that are dealing with nonattainment status also cited several of reports related to health effects and environmental impacts.

Reports on the Riverside, California, Bumcombe County, North Carolina, and Fairfax, Virginia school bus emissions test studies cite exposure to diesel emissions of children riding on school buses, but the information is general, and not based on geographically-specific data. [12, 133, 155] Reports from West Virginia University and Environment Canada provide introductory references to regulatory requirements, such as those found in the Clean Air Act Amendments, as reasons for nationwide interest in the need to improve air quality for metropolitan and high population centers, as well as rural areas where regular fleet routes may impose risk factors that retrofit programs might help mitigate.

The City of Houston Diesel Field Demonstration Project report references the Houston-Galveston nonattainment status as a basis for its pilot projects. [33] Exceptions (reports where a specific population was part of the study "regimen") include the CARB Lower Emission School Bus Program that extrapolated information on individual and total fleet emissions across its population centers. [118] Using this approach, the study developed estimates of emission reductions tied to engine retrofit and older bus replacements in terms of quantitative reductions in NOx, PM and CO to actual populations.

Several other study reports, including Houston's diesel field demonstration project, make initial reference to their region's nonattainment status (Houston-Galveston) as a study "driver". In the case of several of the California and Texas studies, nonattainment status of several metropolitan areas has provided private- and public-sector fleets with an understanding of the need to pursue improvements in emissions, or risk additional mandated restrictions or loss of state and Federal highway and other grant funds, if emission reductions cannot be realized. [142]

3.6.2 Selection of Retrofit Technologies and Vehicle/Equipment Applications

Selection of emission control technologies and vehicle/equipment applications is in part, a function of the goals of a retrofit program, particularly those of a voluntary nature. The selection process is also a function of what is technologically feasible, most compatible for use with a given fleet, and/or affordable.

Several studies focused in part, on the factors that were considered when selecting the candidate vehicles or equipment for retrofit. Among other issues, reports about these studies discuss such factors as vehicle/equipment make and model, and engine age, engine condition, and operating cycles. Many documents reviewed, including those describing the CARB Lower Emission School Bus Study, the Ralph's Grocery fleet study, the City of Houston field demonstration, and the Hong Kong retrofit of in-use diesel vehicles, illustrate the factors that were considered to justify the percentage of vehicles or fleets to be involved, in order to establish a representative baseline, and therefore not compromise the study by virtue of poor baseline decision-making. [33, 108, 117, 142] Several of the documents reviewed describe this process as part of the project.

The literature reviewed for this report contains some valuable examples regarding the current awareness and perceptions of benefits and costs of various retrofit technologies, and their relationship to the success of a retrofit project. Also discussed in the literature is the need to improve understanding of retrofit program planners and funding sponsors of issues that still need to be addressed to increase the willingness of fleet managers to select certain equipment, fuels or technologies. For example, several of the studies involving ULSD recognized user perception as an important factor to address to gain support for participating in a retrofit project. This was especially obvious in the emulsified fuel user study conducted by the University of Texas, in which users of the emulsified fuel in California, the City and Port of Houston, as well as workers at Cummins Inc., and Ramos Oil Company cited impacts on planning for equipment use, fuel management, anticipating maintenance and corrosion concerns, and overall cost effectiveness, as considerations for project participation. [74] The City and Port of Houston project also included a "double blind" study within the larger study to determine the extent to which negative reactions to a different fuel product might be based on perception of performance deficiencies. Results of the "double blind" study showed less evidence of dissatisfaction, but still demonstrated the influence of user awareness and perception (often accurate) of higher costs, effects of use with certain engine types, and reduction in fuel efficiency on user conclusions about adopting retrofit and emission reduction strategies. Overall, this study highlighted, very well, the need for retrofit program planners to develop a thorough understanding of the perceptions of retrofit product users and their concerns for operational trade-offs to determine acceptable level of technology performance.

In the U.S., a large number of projects selected DOC technology because it was proven, relatively easy to install, did not require maintenance, operated virtually problem free, and did not adversely impact vehicle performance or fuel economy. While other technologies offered greater emission reductions, projects using DOCs typically viewed the PM, CO, and HC (including toxic HCs) reductions as both meaningful and cost effective. Projects looking to maximize PM reductions considered, and in many instances, elected to use DPF technology. In several cases, DPFs were a candidate technology, but DOC technology was ultimately selected because the exhaust temperatures of the candidate vehicles/equipment were not sufficient to support the use of DPF technology. In other cases, ULSD was not available or only available a high incremental cost increase.

Projects undertaken because of an interest in NOx reductions were constrained by the fact that verified NOx technology applications were no where near the applications for DOCs and DPFs. The availability of verified LNC/DPF systems, and more recently, SCR technology (limited to one engine) has spurred increase interest in moving forward with NOx-based retrofit program.

Several fleets, such as the City of Houston and Houston METRO, that are interested in evaluating emerging, but unverified, technologies, have instituted programs using these technologies. These types of programs have been and will be very helpful in evaluating the challenges and capability of these technologies and are facilitating efforts to get more technologies verified.

3.6.3 Major Steps in the Program/Project Planning Process

Frequently, the first element involved in project planning for U.S. retrofit projects was to put together the initial partners and to define the goals and objectives of the project. The next step typically was to secure adequate funding for the project to proceed. Typically, if the project was of a voluntary nature, this consisted of writing a grant proposal and submission to the funding agency. In some cases, environmental impact studies preceded the grant-writing step to determine the affects of the retrofit project on local surroundings. Preliminary planning meetings were often conducted with all involved project participants to determine individual roles and compile a timeline for achieving each of the project's goals.

After applying for and receiving funding approval, candidate vehicles or equipment are identified for potential retrofit. Typically, the selection process has been based on vehicle/equipment age, engine type (front or rear mounted engines for school buses), duty cycle and suitability with the specific retrofit technology or technologies being considered. If DPF technology was being considered, data logging of exhaust temperature profiles has been employed to characterize worst-case and best-case operating scenarios.

Once the vehicle/equipment selection has been completed and the retrofit technology has been determined, either based on physical space constraints, emission reduction goals or the results of data-logging, retrofit products are ordered and the application assessment process would begin. After selecting the fleet, vehicle or equipment and matching it with the appropriate technology, an RFP is prepared and responses are requested from product suppliers. Once the vender or supplier is selected, a product delivery timeline is established so that a retrofit product installation schedule can be set. School bus fleets have frequently tried to schedule retrofit installations for the summer months, when school is out of session. In cases where fleet service technicians performed the retrofit installations, a program was implemented to train fleet personnel.

For vehicles or equipment requiring custom installations, design templates are generated, as needed, for the mounting brackets, clamps, etc. that will be needed to install the retrofit hardware. In cases where pre-established designs have been accomplished for commonly found vehicle/engine configurations such as school buses, "retrofit kits" have been designed to simplify product installation. Such kits typically include all necessary hardware, including brackets, nuts, bolts, and installation instructions for installing the retrofit product. On occasion, changes to the retrofit kit design may need to be made to allow for a better product fit under the vehicle chassis, or servicing of the engine and accessory components without removing the retrofit device.

Other preparations must be accomplished for projects involving a different fuel. If the project calls for storing the new fuel in an existing highway diesel fuel tank, some projects took the precaution of cleaning fuel tanks or installing new fuel storage tanks prior to implementing the program. Special handling to prevent sulfur contamination is also necessary for delivery of ULSD to the fleet location. Pre-maintenance on the vehicle/equipment is also most likely necessary when utilizing biodiesel; the fuel tanks have to be cleaned and the fuel filters have to be replaced.

Post-installation of the technology can include several additional tasks. Pilot programs are established and conducted to evaluate the benefit of the technology and emission reduction strategy. A number of fleets participating in retrofits, most notably school districts, developed an anti-idling campaign and implemented anti-idling programs. Programs utilizing DPF technology sometimes established a filter cleaning program. Most Federally and state funded grant programs require that periodic updates be provided to the funding entity. This usually takes the form of progress reports. In addition, the implementing entity will frequently coordinate education and outreach events, which are discussed in the next report section.

3.6.4 Outreach and Education Activities

Several documents reviewed for this project provide an excellent blueprint for addressing public education and outreach needs. [144, 192] Among the issues addressed from a "user's perspective" are the awareness of the regulatory timeframe for the availability of ULSD, concerns about adverse impacts on engines from use of ULSD, impression of higher cost associated with fuels containing lower sulfur content, related concerns about the higher cost of new engines being developed to meet more stringent emission standards, and discussion of some recommendations that users and fleet managers would like to see. [192]

It is useful to distinguish the topic of public outreach and participation, which is often a required component of Federal and state environmental programs, from reported program tasks involving ascertaining user/worker awareness, perception and preferences in equipment, fuel and vehicle types. EPA's February, 2003, report on the effect of cetane number increase on NOx emissions, indicates that public outreach actions were taken as part of the study, essentially involving a call for comments and comment period as part of the study. [180] Conversely, most of the projects reviewed for this report have been conducted by organizations that do not have similar public participation requirements, and have provided the documentation of their work to contribute more broadly to the public benefit.

Independent of any requirement for public participation, promoting public and user awareness and understanding of, for example, benefits and tradeoffs involved in designing and implementing a retrofit program is important. This need to educate was comprehensively described in the survey of state agency decision-makers regarding biodiesel use, and by those in the private sector regarding issues such as cost, efficiency, compliance, training, and user perception and preference. [27]

Many retrofit programs involve outreach and education activities to educate the public of the benefits and advantages of emission reduction in the community. The magnitude of outreach and education activities is often in direct relationship to the amount of project funding available to support them. A typical outreach activity involves a project kick-off press event where members of the community, participating fleets, and government officials, and local press are invited. Facility tours have also occurred when universities are involved in the testing process of retrofitted vehicles.

Many fleet operators have decided to allocate some portion of project funding for education and training of fleet service technicians and managers. This is done, in part, so that the fleet managers and technicians have sense of purpose of the project. They are encouraged to be in constant contact with the technology experts to obtain added educational value. Fleet service technicians are trained on retrofit technology installations, monitoring and servicing of the technology. In some cases, EPA presented awards to the fleet managers for their hard work and dedication to the retrofit project. During the implementation of school bus fleet retrofits, some school districts decided to add a clean air curriculum to their student class program. In addition, career center automotive classes have also been developed.

Once the retrofits are completed, additional press events are typically held involving the local media. Press packages, including fact sheets detailing the program, are released to the press and for general circulation. These are used to generate both local TV and newspaper coverage. One project decided to develop a video summarizing the overall accomplishments and have it air on local TV. Seminars and presentations given by the implementing entity are held at local conferences and workshops discussing the results of the retrofit project.

Besides presenting the trials and successes of the program, the vehicle/equipment involved in the retrofit can also be displayed at the conference or workshop, typically invoking a question and answer session. In addition to the vehicle/equipment being on display, signs, banners and posters displayed on the vehicles themselves are used to inform the public that they are low emission vehicles. Lastly, no-idling zone signs are on display in and around school districts as a constant reminder to school bus drivers of the benefits of an idle reduction program. Newsletters to school bus providers and school superintendents are sometimes sent as a supplement, informing them on the idle reduction process and to provide information on the effort to reduce diesel exhaust emissions from school buses. Information sharing has also proven to be instrumental in public outreach and education. Some implementing entities have provided information to several environmental groups, which in turn included that information on the project in their newsletter, thus in effect expanding the regional audience. Information on current projects is documented, often times on websites, and shared with other entities planning to perform retrofits. Finally, in several instances, fleet personnel (fleet managers and/or service technicians) who participated in a retrofit program, met with their counterparts in other fleets to share experiences and to help promote new retrofit projects.

A number of reports in the news media described funding for specific retrofit programs either as a result of an EPA grant or from funds made available from an EPA/U.S. Department of Justice enforcement settlement containing a requirement to implement one or more SEPs. Examples of EPA funding cited in the press include numerous articles on EPA grant awards for school bus retrofit programs. [1, 141, 157] News accounts of SEP awards included a report on $5 million to retrofit school buses and commuter trains in Boston and $250,000 to retrofit transit buses in Seattle. [136, 159] Also, it was reported that CMAQ funding from the U.S. Department of Transportation was used to help fund retrofit projects in Texas and California. [See www.dieselforum.org]

3.6.5 Program/Project Evaluation

For both mandatory and voluntary programs, there is a need to track and report or demonstrate progress with regard to:

- Generating interest in the program.
- Identifying stakeholders and interested participants.
- Securing funding, consistent with a workable timetable for participants.
- Perhaps most importantly, maintaining funding and the confidence of participants, while demonstrating progress towards meeting technical and/or regulatory goals and objectives.

Several of the reports reviewed discuss or refer to these points, both from the perspective of the program source, such as the CARB or Puget Sound Clean Air Agency's goals, or more directly by parties involved such as the Washington State Ferries, or a representative of Denver's Regional Air Quality Council. [144, 173]

Many of the projects involved setting and demonstrating progress towards meeting specific goals or threshold levels. Tracking progress was most typically discussed in terms of whether these goals were being achieved, and the vast majority of the documents reviewed provide tabular findings on results of emission reductions, equipment performance, related fuel cost and consumption, and user opinions after testing, etc. Many of the documents do an excellent job of further evaluating related issues, including delivery and installation time for equipment, fleet accessibility, driver/operator training, cost and ease of access to equipment and fuels, and willingness to alter operating procedures as "tracking items" that contributed to the efficiency or difficulties in a project that was proceeding as it was intended. [28, 46, 70, 192] For example, in NESCAUM's evaluation of in-use DOCs, the equipment calibration review conducted by the project's QA/QC tracking and review process identified a need for additional engine mapping that needed to be performed. [87]

In its presentation on field experience with diesel retrofits at the EPA-NESCAUM Workshop of October, 2003, tracking implementation and progress is described as an overriding need for the NYC Transit Authority, certainly due in part to the size of the fleet being tested for retrofit equipment. [96] The starting point for benchmarking was 1996, when equipping all diesel buses in the fleet with a DOC began. In February, 2000, the testing of ULSD and DPFs began. By September, 2000, the entire fleet of over 4,500 buses had been converted to a low sulfur diesel fuel. By 2001, additional retrofitting with DPFs had begun, with a target to complete the entire fleet by the end of the 2004. Also, since 2001, over 700 new engines equipped with EGR have been added to the fleet. These vehicles have experienced a higher degree of difficulty, including additional equipment that does not fit easily into transit bus engine compartments, additional heat loading to the cooling system, and an estimated 20% DPF plugging rate. [96]

Among the issues being tracked during these large scale retrofit and fleet conversion programs were the compatibility of the ULSD, potential for mixing with diesel fuel of higher sulfur content and related depot storage issues, and the anticipated need to address the impact of reduced fuel lubricity on engine fuel system components such as fuel pumps and injectors. Generally, no problems were reported regarding these issues during the several years needed to complete the conversion. Tracking anticipated issues and problems ultimately contributed to the project's longer-term success in meeting the schedule and completing the fleet conversion, as well as meeting the compliance-related program goals. [96]

A presentation on the Regional Air Quality Council’s efforts in EPA Region 8 addresses incentives, a description of good maintenance practices, support for voluntary achievements in emission reductions, outreach publications on low emission diesel technologies, the Clean Air Fleets program, Colorado’s diesel engine inspection and maintenance (I/M) program, emission standards, funding, and school bus programs. [144] Summary information from this document focuses on goals and objectives that are being achieved (e.g., awareness, improved air quality, and introduction of new technologies).

U.S. retrofit projects have typically involved either a qualitative or quantitative evaluation process. A majority of the program evaluations are based on the number of vehicles/equipment retrofitted, either as a number of total retrofits planned or based on an annual percentage of retrofits completed. These programs also measure success by the sustainability of the project and if they can garner on-going community support. One way of determining community support is by way of pre- and post-retrofit surveys. Not only can these surveys be distributed amongst the community, but drivers, maintenance supervisors, fleet service technicians/managers, administrators, teachers and parents can also be considered when conducting a survey.

Other programs have evaluated their projects qualitatively through observations of reductions in visible smoke output and odors at the tailpipe, as reported by the vehicle/equipment owner/operator during walk-around and pre-trip inspections. Still, other projects base success on much simpler terms. One project involving DOC retrofits on construction equipment declared success because the construction workers have embraced the project as essentially “hassle free” and the Environmental Defense League included that project on its list of examples of successful projects. One school district based success on whether all of the funding was used, while another school district evaluated its project success rate on how many other school districts in its area adopted retrofit technologies and anti-idling polices.

Quantitative evaluations, in most cases, require additional funding and additional resources to facilitate testing of retrofitted vehicles and equipment. Consequently, the overwhelming majority of U.S. retrofit projects since 2000 did not include emission testing. If sufficient funds are available or required as part of a grant, emission testing, opacity testing and durability testing usually top the list. Several entities have conducted or are in the process of conducting emission testing, usually for over a period of one year. Emission testing has been performed using a variety of techniques including mobile chassis dynamometers and laboratory chassis and engine dynamometers. In those cases where testing data was reported, it was very consistent with data reported in the literature. In the absence of emission testing, emission reduction calculations are often times made using publicly available information such as the levels of emission control for which a given technology has been verified by either EPA or CARB. In some cases, programs have relied on information provided by the technology supplier. Opacity testing was conducted in a few instances.

A number of projects quantified the success of the program in terms of the number of installation, maintenance, or operational problems that occurred. For example, one project evaluated the number of road calls resulting from high backpressure incidents on DPF-equipped vehicles were recorded to help assess the durability of the technology. In another project, an engine manufacturer will perform injector testing after ULSD and biodiesel pilot programs are complete to evaluate long-term engine wear.

4.0 RETROFIT TECHNOLOGY AND PROGRAM EXPERIENCE LESSONS LEARNED

4.1 OVERVIEW

The combined information from the literature and from retrofit projects in the U.S. since 2000 provide many insights into all facets of retrofit technology and program experience. In addition, these retrofit technology and program experiences provide useful "lessons learned" about issues that can be of benefit to organizations planning, implementing and evaluating diesel retrofit programs.

4.2 TECHNOLOGY LESSONS LEARNED

4.2.1 Emission Control Performance and Measurement

The range of emission control efficiencies reported in the literature for virtually all types of retrofit technologies varies considerably. This phenomenon results from a number of factors that can influence the measured emission control performance of any retrofit technology. These include test-to-test variability and test cycle-to-test cycle differences that impact engine performance and exhaust temperatures, as well as, different types of testing equipment (e.g., engine dynamometer vs. chassis dynamometer). Although analyzers are subject to regular calibration, analyzer drift can also play a role in this variability. [147] Finally, variations in the condition of the engines prior to initial testing and the level of maintenance on those engines during the evaluation program also can influence emission testing results. [194] Consequently, in considering reported or claimed emission reductions, consideration should be given to the circumstances under which the emission test results were generated. The best assessment of the actual emission reduction potential for a given retrofit technology/engine application will be provided from product testing on an emission test cycle that, to the extent possible, reflects the actual operating cycle of the vehicle or equipment being evaluated.

The overwhelming majority of retrofit programs implemented since 2000 in the U.S. did not include an emission testing component. In many cases, emission testing was not performed for one or both of the following reasons:

- Lack of availability of special emission test equipment and/or facilities suitable for performing accurate measurements of heavy duty diesel vehicle emissions.

- High cost of acquiring the special emission testing equipment needed for performing accurate measurements of heavy duty diesel vehicle emissions. In many cases, EPA has indicated that its grant funds are not to be used to support emission testing or acquisition of emission test equipment. The most frequent reason given by EPA for funding retrofit project emission testing was that retrofit project applicants should rely on the emission reduction estimates for products listed on EPA's list of verified products. A second reason often cited was that EPA has a program of in-use emission reduction verification as part of its program with retrofit product manufacturers for continued verification of retrofit products.

If emission testing is to be performed, where possible, emissions should be obtained over multiple (two-to-three) test cycles and the range of differences assessed to account for test-to-test variability.

Emission reduction estimates developed for various retrofit projects frequently were based on the emission control levels identified in the EPA or CARB verification documents. EPA's and CARB's planned in-use testing programs of verified technologies will demonstrate whether the emission reduction percentages listed in the verification documents are accurate.

4.2.2 Fuel Economy

Care must be taken in drawing general conclusions regarding the precise impact of various retrofit technologies on fuel consumption, given the high degree of vehicle-to-vehicle and operator-to-operator variability, as well as other factors. For example, reports from a number of studies noted a slight measured fuel economy penalty with DPF-equipped vehicles, however there was no information to ascertain whether the fuel economy lost was attributable to the DPF technology or other factors (e.g., lower energy content of the fuel). (e.g., P123) However, it was appropriately determined that the differences were not statistically significant to conclude that the devices actually adversely impacted fuel consumption. Similar observations regarding fuel economy were reported from other U.S. retrofit projects as well, but also without any description of the means to determine if any difference in fuel economy could be attributed to the retrofit product(s), fuel energy content, or other factors.

4.2.3 Vehicle/Equipment Applications and Experience

4.2.3.1 *General*

Retrofit technology providers are still gaining knowledge and experience in identifying and recommending the most appropriate technology for a given vehicle/equipment and duty cycle. In the past, an inappropriate technology was occasionally recommended for a given application. As knowledge grows in applying retrofit technologies, the instances of recommending the inappropriate technology choice should diminish.

Though certain technology vendors may promote their products as "direct muffler replacements", special adaptations may be needed in order to fit the device on the vehicle/ equipment. The most effective way to ensure that the most appropriate retrofit technology is matched to candidate vehicles/equipment is for the technology supplier to visually inspect the vehicles prior to shipping products.

Diesel vehicles and equipment that have a history of high engine lubricant consumption and/or downtime for maintenance are not good candidates for retrofit. Maintenance records for individual vehicles/equipment and conversations with fleet management and technicians are useful tools in screening candidate vehicles/equipment for retrofit.

Vehicle/equipment application prerequisites and limitations will vary among the retrofit technology options. Consequently, any candidate technology must be evaluated in terms of:

- The vehicle/equipment and engine make model, and the condition of the engine.
- Vehicle/equipment operating conditions (e.g., exhaust temperature profile where necessary).
- Ambient operating temperatures (e.g. where maintaining exhaust temperature is important; very cold ambient temperatures can be an issue.
- Space available for retrofit product installation.
- Type of fuel that will be needed or is desired to be used.
- Potential impacts of technology on vehicle/equipment performance.

With regard to potential impacts on performance, a technology that has a high risk of problems may not be a good selection for an application that cannot afford unscheduled downtime, such as a small fleet of passenger ferries. (see, e.g., P 134)

4.2.3.2 *Diesel Particulate Filters*

The literature reported that for retrofit programs in place for several years, the failure rate for retrofit technologies, most notably DPFs, tends to decrease over time. For example, the annual DPF failure rate of the mandatory construction equipment retrofit program in Switzerland fell from 6% in 2000, to 2% in 2003, and is on track to meet the program goal of less than 1%. [148] The decline in failure rates reflects improvements in system design (improved catalytic formula, better sizing of devices, improvements in filter material), as well as a better understanding of the operational limits of a given technology.

The most successful passive DPF applications in terms of emission control performance, system durability, and minimum maintenance requirements were on vehicles and equipment that:

- Had operating exhaust temperature windows that were more than adequate to ensure that proper regeneration occurred.
- Involved newer, well-maintained engines with low engine lubricating oil consumption.
- Were operated on ULSD.
- Included exhaust backpressure monitoring/alarm systems to warn of excessive PM build-up on the DPF and reduce the potential for more serious engine problems to occur.

Backpressure monitoring has also been identified as a helpful tool in spotting engine operating trends that can lead to the identification of other engine-related problems. For example, one project reported an occasion where a backpressure alarm was triggered and further check of the engine diagnostic codes revealed a malfunctioning fan clutch solenoid.

Typically, problems occurred with passive DPFs as a result of: 1) inadequate exhaust temperatures necessary to ensure proper regeneration, 2) older, poorly maintained, high engine lubricant consumption engines and/or 3) operating on diesel fuels with sulfur levels above 50 ppm. The PM/NOx ratio is also important for DPF systems that rely on the NO to NO_2 conversion to facilitate filter regeneration. Problems can occur when PM levels are high relative to the NOx available to provide NO_2 for regeneration.

In making a determination whether to apply DPF technology to a particular engine, it is essential to develop and record data for the engine operating exhaust temperature profile over the expected duty cycle of that engine. Data logging of exhaust temperature profiles should include an assessment of the "worst-case operating scenario" in terms of low load and no load operation, stop-and-go driving, and idling time for a given application. Fleets with multiple depots/ operating routes should assure that vehicles used for data logging represent the range of depot operations and routes. The successful application of DPFs can be enhanced by comprehensive suitability testing, careful systems monitoring, and field inspections. Consideration of ambient operating temperatures is also an important factor in assessing the applicability of DPFs, since operation in cold weather can be a factor in locations subject to very cold ambient temperatures.

Passive regeneration DPFs are more vulnerable to regeneration failures compared to active regeneration DPFs systems. However, improvements have been made in reducing the likelihood of failures by:

- Careful application design, including appropriate sizing (i.e., with a margin of safety to allow for engine wear, fuel injector wear, overfilling with engine lubricant, and other mishaps) and thermal insulation (if needed).

- Improving predictive capability, including modeling to complement empirical temperature data.

- Improvements in catalyst formulations, including those more resistant to sulfation.

- Improvements in filter designs to be more resistant to ash build-up.

- Improving the filter monitoring systems.

- Improving the filter cleaning technique.

DPF plugging can also be caused by the failure of other engine components such as turbochargers that may be in a marginal condition, thus the value in performing an inspection of engine/vehicle condition can result in savings of maintenance time and expense after the DPF is installed. In one project, new turbochargers were installed on transit buses retrofitted with LNC/DPF systems, in order to avoid potential future problems with them.

A lesson learned in practice was to remove, rather than simply deactivate, any engine lubricant management system in order to prevent excess engine lubricant from being combusted and deposited onto the active surfaces of the DPF causing a DPF plugging failure.

A number of school districts in the U.S. are taking a "go slow" approach to utilizing DPFs so that they can gain the experience needed to use these retrofit products with success. These districts are starting out with a limited number of DPF retrofits in order to demonstrate that DPFs will operate effectively over time on their buses over the worst-case bus routes.

4.2.3.3 *Diesel Oxidation Catalysts*

While DOCs do not achieve the same level of PM control as DPFs, they provide a relatively straightforward, less costly option to improve local and regional air quality. Programs utilizing DOCs have garnered widespread support and can be applied to virtually all types of diesel highway and nonroad engines. Constraints consist of available space on the vehicle being retrofitted, extremely low temperatures of a given region and excessively high PM levels emitted from the potentially retrofitted engine. Experience in the U.S. also demonstrates that DOCs retrofits: 1) are relatively straight forward to implement, 2) almost never have any adverse impact on vehicle performance or fuel economy, and 3) have a very low rate of failures (less than 0.1%) in retrofit program in the U.S. since 2000.

Types of problems that occurred in facilitating DOCs included improper design configuration for a particular vehicle/equipment and the lack of availability of the correct installation hardware. DOC suppliers can avoid these types of problems through careful attention on their part. DOC plugging with PM occurred in extremely rare instances, typically involving older (pre-1990), high-emitting engines that may also spend considerable time at idle. In those situations in which a potential exists for DOC plugging, a possible solution includes rebuilding the engine or repowering the vehicle/equipment. In several retrofit programs where there was a concern regarding potential PM plugging causing backpressure problems, the vehicles/equipment were equipped with backpressure monitors. Also, DOCs can be designed for quick release in the unlikely event that DOC cleaning becomes necessary.

4.2.4 Technology Delivery, Installation, Maintenance, and Operation

4.2.4.1 *All Technologies*

4.2.4.1.1 *Delivery*

Delays in product delivery for some technologies, most notably DOCs and DPFs, were experienced beginning in late 2003 and continuing into 2004. These delays are expected to diminish over time in light of the substantial increase in manufacturing capacity for retrofit technology components. However, the possibility of future delays exists if the rapidly growing demand for products worldwide exceeds the continued expansion of manufacturing capabilities.

Some delays in delivery of DPFs in California were attributable to CARB's revocation of verification status over warranty issues for two DPF suppliers. The verification for one of these products has since been reinstated. The second technology has since been verified by a different technology provider.

On occasion, technology providers have been overly optimistic in estimating the time needed to deliver retrofit products and, as a result, program deadlines were missed. Retrofit program managers should build extra time into the project schedule to account for unexpected delays. For example, school districts that desire to install retrofits during the summer months when buses are in minimal use, should issue their RFPs sufficiently in advance so that an award can be made well in advance of the date(s) targeted retrofit installation.

The delivery of products should be scheduled to match the needs and capabilities of the fleets involved. In some cases, a phased delivery is appropriate while in other cases a one-time delivery of all retrofit products may be preferred. In making the determination regarding the type of product delivery, such factors as: 1) available storage space for devices prior to retrofit, 2) the availability and capability of the persons performing the installation, and 3) operational and schedule maintenance factors.

4.2.4.1.2 *Pre-Installation Maintenance*

To minimize the potential negative effects on retrofit exhaust emission control devices, vehicles should be evaluated carefully for engine lubricant consumption. Those vehicles with excessive engine lubricant consumption should not be included in a retrofit program. Vehicles equipped with retrofit products should be using engine lubricants with the lowest ash level possible, consistent with the engine manufacturer's recommendations. Lubricant experts have been suggesting that engine lubricants conforming to grade API CI-4 are preferred, until engine lubricants conforming to grade API PC-10 become available. These lubricants will generally be more expensive than those produced to meet earlier diesel engine designations.

4.2.4.1.3 *Installation*

During the installation phase, close and constant communication between the technology supplier, installer, fleet personnel and the operators can minimize delays, service interruptions and misunderstandings.

Installation proceeds more quickly and smoothly when parts are prefabricated. While many retrofit products and installation "kits" have been designed for specific engine/vehicle/ model year applications (particularly for school buses), there is frequently enough variation (even among vehicles of the same make, configuration and model year) to require some level of modification to the product installation hardware in order to effect a satisfactory installation. The fleet manager should, in consultation with the technology provider, determine in advance the estimated time and installation instruction needed to install both prefabricated and custom design systems so that installation schedules can be planned.

Installation hardware should include all the necessary parts, including connector pipes (if needed), and even new and possibly specially designed clamps, nuts and bolts to minimize the possibility that the installation will be compromised by using inappropriate, worn or defective parts that could cause problems at a later time. For retrofit products that need periodic maintenance, installation should be designed so that the retrofit device can be easily and quickly removed in the event of a problem or routine cleaning. A number of studies reported that quick release clamps (a design that also provides effective exhaust system sealing) were used to facilitate easy installation and removal of the retrofit product. Before retrofit products are installed for a given set of fleet vehicles, a "trial fit" procedure should be undertaken to ensure that the device can be properly installed and that it performs as intended.

4.2.4.1.4 *Maintenance*

One report in the literature noted that the quality of general vehicle/equipment maintenance practices can vary considerably among different types of fleets. The report found that government-owned fleets tended to have better maintenance practices then privately-owned fleets. In addition, larger privately-owned fleets tended to have better maintenance practices than smaller privately-owned fleets. [161] In implementing a retrofit program, it is important to understand the technical capabilities and needs of the fleet mechanics. An appropriate training program should be fashioned to meet those needs, as they relate to retrofit technology installation, maintenance, and operation, as well as what steps should be taken if a problem arises.

Maintenance personnel in many projects had a "can do" spirit and worked to fix the problems that arose in order to keep the vehicles/equipment in operation. In some cases, they were successful. It is important that any such adjustments be reported to fleet management and the technology supplier to: 1) insure that the fix will not cause other problems and 2) provide notice that a problem occurred, even if it was fixed, so that the technology provider can take corrective action in other programs.

4.1.4.1.5 *Training*

A number of reports in the literature stress the importance of providing training to fleet supervisors and mechanics on retrofit technology installation, operation, maintenance and troubleshooting. These reports also emphasize the importance of driver education. For example, a report on the NYC Bus Retrofit program pointed out that achievement of program goals can be enhanced significantly by incorporating driver education and training aspects. Driver training can show how extended idling contributes to excess fuel consumption, emissions and maintenance issues, thus illustrating how vehicle operators can make improvements to their driving practices by contributing to the City and Department's immediate and long term emission reduction goals. The NYC program also identified another lesson learned; do not overlook the "easy things" that should be considered in program planning, strategies and training to achieve programmatic goals and objectives. An important concept identified by the NYC program is that technician and driver education should include not only the technical and operational aspects of the program, but the economic and health benefits that are advanced by the program and the key role mechanics and drivers can play. Building a "team spirit" among fleet supervisors, mechanics and drivers can greatly enhance the likelihood of a successful program.

4.2.4.2 *Diesel Particulate Filter*

4.2.4.2.1 *Installation*

Prior to installation, any issues of engine lubricant consumption such as leaky valve seals, or leaks at the turbocharger should be addressed promptly. Also, fuel injectors should be inspected and replaced if necessary.

DPFs typically weigh more than the OE mufflers they replace and, in some cases, the DPFs have a larger diameter as well. Consequently, the installation hardware for the OE muffler should be replaced with hardware that will support the heavier DPF and will provide the larger DPF adequate clearance on the vehicle or equipment. [205]

In DPF applications, unless the operating temperature profile of the engine exhaust is clearly sufficient to assure that proper DPF regeneration will occur, the exhaust pipe between the engine and the DPF should be insulated. [127]

4.2.4.2.2 *Operation and Maintenance*

A reliable aftermarket service for the prompt and effective cleaning ("regeneration") of DPFs would help minimize the time that DPFs are out of service and could save the fleet from maintaining a large supply of spare filters or purchasing expensive cleaning equipment. [96] In some areas, DPF waste ash is considered to be a hazardous material and required to be disposed of accordingly. State or local government environmental authorities are the best source of information for determining the classification of and disposal methods for proper handling of DPF waste ash.

Both exhaust temperature and exhaust backpressure monitors are effective strategies for helping to determine, on a real-time basis, whether the DPF system is functioning effectively. A continuous monitoring system to evaluate DPF performance and an alarm system to warn of potential problems are essential to the successful application and operation of a DPF system. Alarm systems are typically triggered when elevated backpressure occurs at a certain level over a certain percentage of the time. The alarm setting should be customized for each application. [117] Increasingly, alarm systems are being utilized that include a two-stage visual alarm and an audible alarm. For example, a yellow light will be displayed when the exhaust backpressure reaches a level at which the DPF should be checked and cleaned at the first available opportunity. A red light signals that the backpressure has reached a level that vehicle or equipment should cease operation. These multi-function alarm systems help to ensure appropriate responses by the vehicle/equipment operators.

There have been several instances of problems with the sensors and instrumentation used for monitoring backpressure in the exhaust of vehicles equipped with DPFs. Typical problems were failure of the sensors or false indication of a high exhaust backpressure condition. While no reasons were given for the cause of the problems, replacement with new hardware and/or modifications to the electronics seemed to have corrected the problems.

4.2.4.3 *Diesel Oxidation Catalyst*

Since installation of DOCs is relatively straight-forward, it is cost effective to train fleet personnel and then have them install the devices.

U.S. retrofit program managers discovered that in some cases school buses targeted for DOC retrofit already had a factory (OE) DOC installed. Apparently, no readily available and accurate list of buses equipped with OE DOCs is available. This fact resulted in delays as inspections were undertaken. This issue is further complicated by the fact that it is often difficult to determine the actual model year of the bus (chassis year vs. engine year). Developing an up-to-date, accurate list of OE DOC equipped school buses would be an invaluable tool to school districts and others.

4.2.4.4. *Low-Pressure Exhaust Gas Recirculation*

To minimize any negative effects on EGR systems from excess engine lubricant consumption, lubricant experts have suggested that vehicles equipped with retrofit EGR systems have their engine lubricant intervals reduced by up to half of the original recommendations provided by the engine manufacturer.

4.2.5 Technology Costs

Statewide, regional, or even county purchase contracts can offer several advantages by: 1) providing good prices through volume purchasing and 2) minimizing the burden on individual school districts. In some cases, states have considered piggy-backing on another state's statewide purchasing agreement with a contractor.

A factor to consider in such multi-fleet programs is whether a single contractor can adequately provide technology and service to meet the market demand for a multi-fleet program. If questions exist regarding the ability of any single contractor being able to handle the entire multi-fleet program, two or more technology providers could be identified as certified suppliers under an "umbrella" contract at the same contract price. The advantage of such an approach is that it reduces the risk that products will be delayed and it creates competition in the market for better service. The disadvantage is that it may jeopardize getting as low a product cost as would be achieved under a contract with a single-source supplier.

4.3 FUELS AND FUEL ADDITIVES LESSONS LEARNED

4.3.1 ULSD

To maintain the sulfur content integrity of ULSD, pipelines and the equipment used for fuel transport and storage must be well maintained and kept free from contaminants. This includes excess sulfur residue that may have accumulated from prior handling of diesel fuels with higher sulfur content. Measures should also be taken to prevent vehicle misfueling with higher level sulfur content fuels and the resultant problems that can occur with sulfur-sensitive retrofit products such as DPFs. [86, 102] To minimize the chances of misfueling a vehicle with regular diesel fuel, signage warning of the need to refuel with ULSD can be developed and displayed in prominent places on vehicles and equipment refueling. Vehicle filler caps can also equipped with locks, the keys to which are available to only authorized personnel.

Lubricating additives have been incorporated into ULSD since compared to conventional low sulfur diesel fuel, the significant reduction of sulfur in ULSD can lead to increased wear in fuel injectors, particularly in older vehicles. The U.S. pipeline companies have indicated that they will not transport ULSD containing lubricity additives that have been blended at the refinery, since these additives have been found to contaminate other fuels (e.g., jet fuel) transported in pipelines. [134] This suggests that the additives for assuring ULSD conformance with lubricity specifications will need to be blended at the fuel distributor level, and that ULSD containing lubricity additives need to be transported in dedicated delivery vehicles. [134] Additive blending equipment is available for installation at fuel distribution facilities, at an estimated cost of about $30,000**.** [134] As such, the cost of ULSD has the potential to be higher than anticipated, until the problem of cross-fuel contamination in pipelines can be solved. Additional concerns have been raised about the contamination of ULSD products during the transport process with higher sulfur content fuels, however the EPA, fuel producers and fuel transport industries (including pipeline companies) continue to work together to make sure that high quality ULSD products get to consumers. [9, 189, 190]

While the petroleum products and pipeline industries are working to solve the problem, it is important that users of ULSD be mindful of the need to acquire the fuel in accordance with the latest ASTM International specifications, to ensure that fuel lubricity properties are adequate for the vehicles/equipment in which the fuel will be used, and that delivered fuel meets key ASTM International specifications for ULSD. The best place to have fuel quality verified (via testing) is as close to its final destination as possible, which is usually at the point of delivery to the user. Contracts for ULSD fuel supplies can be drafted to include provisions for ULSD to be stored and delivered in dedicated equipment, testing for conformance to key specifications at the point of delivery both provide a minimal level of assurance that a quality product is being off-loaded into the user's fuel storage equipment.

In general, the experience with U.S. retrofit programs switching to ULSD did not result in any adverse impacts on the vehicle/equipment operation, even when switching from off-road diesel to ULSD. This is no doubt due to the fact that steps were taken by the fuel provider to ensure that the fuel lubricity properties were adequate, and a high degree of fuel delivery system cleanliness was maintained. Nevertheless, there have been isolated cases in which engine part failures were attributed to switching to ULSD. Such was the case when ULSD was introduced for use on older diesel engine pick-up trucks where the seals in the older fuel pumps failed.

ULSD should be delivered well before the vehicles/equipment start operating with sulfur-sensitive technologies such as DPFs. This will provide time to insure that residual sulfur in fuel tanks that once contained regular diesel has been flushed out sufficiently. [57] It is highly desirable to maintain separate fuel storage facilities for any fleet that may be operating with both ULSD and regular diesel fuel (e.g., ULSD fuel storage tank and fuel dispensing facility segregated from regular diesel fueling area, if possible). Segregation of transportation and storage equipment for ULSD and diesel fuels with higher sulfur content is expected to be required, until ULSD becomes more widespread and universally used.

The lack of available ULSD fuel prevented a number of programs that otherwise were interested in retrofitting DPFs. A readily available supply, no doubt, would greatly increase the interest in implementing DPF programs.

The high differential cost between regular diesel and ULSD in some areas is due to special handling and delivery requirements. This high cost is another impediment to initiating programs with DPF, LNC/DPF and low-pressure EGR/DPF technologies. Public fleets that have installed DPFs on fleet vehicles and initially had the cost differential funded by a government grant, face a dilemma once that funding stops. A ULSD cost differential as high a $0.20 per gallon or more adds significantly to a fleet's operating expenses and creates additional problems for continuing the program. Programs that have been successful in promoting the widespread use of ULSD to multiple public fleets (school bus, transit and city fleets) in a close geographic area have been successful in obtaining a supply of ULSD with a lower price differential ($0.03 to $0.05 per gallon).

4.3.2 Diesel Fuel Emulsions

Much of the same precautions and lessons learned from use of ULSD and biodiesel can be applied to diesel fuel emulsions. Since emulsions contain water, there are potential use and storage problems related to their water content. Establishment of good fuel handing and storage practices and use of segregated equipment will help to minimize such problems.

Diesel fuel emulsions generally do not appear to be a good application for vehicles or equipment that operate primarily at high speed and/or high load. [74] Care should be given to assessing the operating characteristics of the candidate vehicles/equipment. Where the operating modes tend to be at lower loads and/or speeds fuel emulsions have been used successfully.

4.3.3 Fuel-Borne Catalysts

Progress is being made in developing precise on-board dosing FBC systems. However, in retrofit applications, particularly where a DPF system is involved, the more prudent course to avoid potential problems with imprecise on-board FBC delivery may be to use premixed fuel (e.g., the FBC is added to the fuel storage tank or a dispensing pump is used that adds the appropriate amount of the FBC when vehicle fueling occurs).

4.3.4 Biodiesel

Given the variability in properties of biodiesel feedstocks, biodiesel should be purchased in accordance with the latest ASTM International specifications. Biodiesel fuels should be purchased from known, established suppliers that can attest to the quality of the biodiesel fuel product as being manufactured according to the latest ASTM International specification. The best place to have fuel quality verified (via testing) is as close to its final destination as possible, which is usually at the point of delivery to the user. Testing for conformance to key specifications at the point of delivery provides a minimal level of assurance that a quality product is being off-loaded into the user's fuel storage equipment. Another means of assuring fuel quality is for buyers of biodiesel fuels to require that the supplier be BQ-9000 accredited by the National Biodiesel Accreditation Program. [www.bq-9000.org] This program is a unique combination of the ASTM International specification for biodiesel (ASTM D 6751) and a quality systems program that includes storage, sampling, testing, blending, shipping, distribution, and fuel management practices. The accreditation process is comprehensive and includes a detailed review of the supplier's quality system documentation, followed by a formal audit of its system. As of the writing of this report, there were two BQ-9000 accredited suppliers in the U.S., with additional suppliers involved in the accreditation process.

Clean, well-maintained and monitored equipment (preferably dedicated to exclusive use of biodiesel fuels) should be used to store and dispense biodiesel fuels, to minimize the effects of water contamination, sediment pick-up, extended storage, temperature extremes and their subsequent problems. To minimize cold weather-related problems and gelling, biodiesel blends with diesel fuel should be stored in tanks that can ensure the fuel temperature will remain at least 5F to 10F above the cloud point of the blend. [5]

The solvency action of biodiesel can loosen and carry fuel tank sediment that will collect in fuel filters and clog them. Accordingly, fuel filters used on dispensers and engines should be inspected and replaced periodically. Such filters should be identified as being compatible for use with biodiesel fuels. Some fuel filter-related field problems with biodiesel blends were reported by a number of state DOT agencies. These filter problems declined or were completely resolved once the filters were replaced. Several state agencies avoided potential weather-related problems by discontinuing the use of biodiesel during cold weather periods.

Biodiesel, particularly at blend levels with diesel fuel of greater than B20, can be contaminated by growth of biological microorganisms. These microorganisms typically grow at the fuel-water interface and may not always be captured in fuel system filters. Should this occur, biocides are available to control growth. An excellent reference on this subject, Manual 47, Fuel and Fuel System Microbiology, is available from ASTM International, and provides a good understanding of fuel and fuel system biodeterioration, sampling requirements, test methods, and remediation practices. [119]

While there are no retrofit products that have been verified for use with biodiesel fuels, available information from U.S. retrofit programs suggests that biodiesel blends do not appear to be incompatible with the use of DPFs and DOCs. Retrofit product manufacturers should be consulted before using any retrofit product with any biodiesel fuel.

In general, no engine modifications need to be performed or special fuel additives be incorporated when using biodiesel up to a blend level of B20 that has been produced to the latest ASTM International specifications. Aside for the lack of need for engine modifications, modifying an engine may potentially create a violation of EPA's engine/vehicle anti-tampering provisions of the Clean Air Act. The EMA, Stanadyne Automotive (a major supplier of diesel engine fuel system components), and most diesel engine manufacturers (including General Motors, Ford Motor Company, Detroit Diesel Corporation, Deere and Company, Caterpillar, Inc., Cummins Engine Company, and International Engine Company) limit engine warranty coverage to use of biodiesel blends of 5% or less. [24, 30, 51, 76, 98, 110, 162, 164, 171] Choice of a biodiesel blend level (particularly if the biodiesel component is greater than 20%) should be made with care, particularly if the engines using it are likely to be operating in sub-freezing conditions that may contribute to fuel gelling of the biodiesel blending component.

4.4 RETROFIT PROGRAM/PROJECT EXPERIENCE

A number of studies in the literature identify issues and problems that arose with technology selection decisions and the resultant impact on equipment, installation, and maintenance. These decisions sometimes led to complications or compromises with findings and conclusions. Experience with retrofit programs in the U.S. since 2000 suggest that while problems and issues arose, generally the problems were overcome or minimized to the point that the project was able to move forward. This suggests that while particular pilot programs or field tests are still striving to achieve desired results with a particular engine, filter, fuel or process at the program level, sufficient alternatives and options exist to produce tangible level of progress toward meeting programmatic and regulatory goals.

In this section, lessons learned from the experience reported in the literature and U.S. retrofit programs covered such topics as program planning/design, fleet/vehicle or equipment/technology selection, funding, program implementation and outreach.

4.4.1 Project Planning/Design

There is considerable value in talking to individuals and organizations that have participated in other retrofit projects. These contacts can provide insights into problems they have encountered, solutions they discovered, and successful program strategies that have been employed.

For projects involving fuel technologies (e.g., ULSD, biodiesel, diesel fuel emulsions) consideration should be given to fuel supply logistic aspects, particularly if the project is to involve multiple vehicle/equipment operators such as might be found at a construction site. Some issues, such as the need to respect the fuel supplier agreements for each of the participants, and accommodate individual vehicle/equipment refueling requirements may be difficult to address or obtain agreement among the participants. These issues should be addressed early in the project planning process to avoid potential problems after the project has begun.

If DPFs are being contemplated for a project, exhaust temperature data logging should be performed on candidate fleet vehicles early in the planning process to determine if the vehicles are a good operating match with DPFs. If DPFs are not appropriate, the use of other, more appropriate retrofit technologies should be explored.

4.4.2 Fleet, Vehicle/Equipment, and Retrofit Technology Selection

4.4.2.1 *Fleet, Vehicle or Equipment Selection*

A key to a successful program is taking the necessary steps to properly match the technologies to the fleet vehicles. This includes:

- Gathering fleet information (e.g., engine and vehicle makes and model years, annual operating mileage/hours, engine condition, exhaust system configuration, ambient temperature, access to install the retrofit device, maintenance records, and expected retirement date).

- Conducting exhaust temperature data logging when appropriate (e.g., when DPF use is contemplated).

- Consulting with technology providers and other technical experts.

Care should be used in selecting vehicle/equipment for retrofitting so that vehicles/equipment are not retired before the full benefit of the retrofit products can be realized. Typically, vehicles/ equipment to be retired within three to five years of retrofit installation will not realize the full value of the retrofit products.

Care should also be used to identify whether late model vehicles (built after October 2002) are equipped with OE exhaust catalyst or other advanced technology emission control products, so as not to spend money for retrofit products that are not needed. Recall from the discussion of ECM Reflashes in Section 3.0 of this report that the 1998 Consent Decree between the diesel engine manufacturers and DOJ/EPA required the manufacturers to design and build engines meeting the 2004 emission standards by October, 2002, 15 months ahead of time. The requirement applies to engines manufactured after October, 2002, not vehicles. Since some heavy-duty vehicle manufacturers often purchase engines well in advance of their vehicle manufacturing needs, it is very possible (and has been frequently the case) that vehicles manufactured after October 2002 contain engines that were manufactured before October, 2002. At times, this situation has led to some confusion among vehicle purchasers who may believe that vehicles purchased after October, 2002 are manufactured with engines that were designed to meet the more stringent 2004 emission standards, when in fact, they were built with pre-Consent Decree engines designed and manufactured to the less stringent 2002 emission standards. The difference is significant, since engines designed to meet the 2004 emission standards produce NOx and HC levels that are half or less than their earlier counterparts.

It is also important to note that when replacing vehicles as a means of reducing emissions under a retrofit program, the vehicles must be retired prior to the time that they would normally be retired. Thus, fleet operators should consider the relative benefits and disadvantages of spending money to accelerate vehicle/equipment retirement versus spending money for retrofit products.

4.4.2.2 *Technology Selection*

In selecting technologies for a retrofit program, a balance must be struck between:

- Achieving the emission reduction and other goals of the retrofit program.
- The complexity of individual technology options.
- The technical capability of the fleet operators and others.

As discussed previously, the application, installation, maintenance, operation and cost of technologies varies considerably. With the exception of DOCs, most of the other retrofit technologies tend to be more application specific. Often the most complex and costly technical options provide the greatest emission reductions. For example, DPFs provide up to 90% or more PM reduction and SCR technology provides up to 90% NOx reduction. These technologies, however, are application specific, relatively more expensive than other PM and NOx control technologies and technically more complex. Program planners need to be aware of the benefits and challenges of various emission control strategies, and not simply specify that vehicles to be retrofitted use the "best available technology". Doing so would generally require the use of a technically more complex technology that would likely result in at least some vehicle applications that are not suited for use with the technology. Also, in instances where more technically complex strategies are being considered, beginning with a small-scale pilot project often can be an important first step to gain experience before a large number of fleet vehicles or pieces of equipment are retrofitted. By contrast, organizations implementing retrofit programs using DOCs concluded that the application, installation and operating issues for full-scale programs were very straightforward.

Several other important issues have arisen during the technology selection process and have raised concerns for retrofit program planners to consider. These include:

- Claims made by some fleet operators of statements from some engine manufacturer representatives indicating that their engine warranty would not be honored if retrofit products were purchased from a source other than an authorized dealer of the manufacturer, even if the retrofit products from the other source were verified by EPA or CARB.

- The wide range of warranty coverage offered by retrofit product suppliers.

- The wide variation in assumptions and methods use to calculate emission reduction cost effectiveness.

All of the above have the potential to lead to misleading conclusions, can impact product/ supplier selection decisions, and need to be addressed during the retrofit project planning process.

4.4.3 Funding

Given the limited number of verified products, the restrictions on Federal and state grants to fund projects that use unverified technologies is limiting the ability of cities to conduct pilot programs to evaluate and demonstrate promising technologies and strategies.

The availability of funding to pay for retrofits was essential in moving projects forward. The overwhelming majority of projects studied involved school buses; that sector has received, by far, the greatest funding from Federal, state, regional and local governmental agencies. Federal grant programs, as well as state programs like the Carl Moyer Program in California and the TERP program in Texas, have played a critical role in advancing retrofit and other initiatives to reduce emissions from diesel engines. Key points from the TERP program include the following:

- Financial incentives for NOx reductions can and have positively impacted the retrofit and alternative fuel markets.

- The threat of lost highway funding is an effective incentive that has spurred increased participation in retrofit initiatives.

- Emission reductions continue to prove more costly than expected when the program was developed. This can create a problem for state-funded programs because there may be a need to continually increase budget estimates for program out-years.

- The grant process is slow, which results in some prospective applicants losing enthusiasm for participating in the program.

- The program has been able to involve fewer highway fleets than expected.

There are several issues that arise with grant programs. First, the application process often is time consuming and somewhat daunting, particularly for smaller companies. A cottage industry has actually emerged in Texas to help small companies interested in TERP funding.

Second, grant programs often place limitations on project or recipient eligibility. For example, some government agency programs may be limited to (or preferentially support) funding of projects in nonattainment areas and as such, preclude from participating those attainment areas that are working to reduce emissions and may have sensitive populations. Many government-funded grant programs restrict funding to preclude receipt by non-government organizations, thus making it more difficult for private sector organizations to participate in grant-funded retrofit projects. The Carl Moyer Program has funding caps and restrictions on the percentage of time vehicles/equipment must be operated that eliminate a portion of vehicles and equipment that would otherwise be considered eligible for funding.

For those projects using ULSD and a sulfur sensitive technology (e.g., DPF), an issue can arise when funding for the project ends before the vehicle is ready to be retired. In cases where outside funding ceases, the fleet operator is faced with decision whether to remove the technology that requires the use of ULSD and switch back to regular diesel or to continue to pay the incremental cost for ULSD. The latter option can result in substantial additional operating costs, particularly in areas where ULSD is not readily available and the cost differential is relatively high.

4.4.4 Project Implementation

Project partners in U.S. retrofit programs identified a number of necessary aspects of a successful project, including: (e.g., P117)

- Project team commitment and cooperation.
- Careful evaluation of technology/technology application.
- On-going communication.

The programs that were the most successful and were best equipped to deal with problems had solid and sustained technical support throughout the project. That support came from a variety of sources including most often the technology manufacturer and/or the technology supplier, but also from the U.S. EPA (both headquarters and the regional offices), multi-state regional organizations such as NESCAUM, local air quality districts such as the Puget Sound Clean Air Agency (PSCAA), independent technical consultants, and personnel from other fleets that had experience with retrofits. As the number of retrofit programs grows, finding well-qualified sources of technical support will become more challenging.

A successful program, particularly where more complex technologies are involved (DPF vs. DOC), needs to have a person or persons "on the ground" to serve as a "champion" for the technical aspects of the program. That person or persons can be the chief technician, the fleet manager, and/or someone else who deals directly with the vehicle operators and takes the lead to oversee that the installation, maintenance, and vehicle operation in order to spot problems and ensure that corrective action is taken. Programs that were successful even though they encountered some problems with technology delivery, installation, maintenance and/or operations often had dedicated technicians that worked through a number of issues and were active participants at every stage of the project.

A key to a successful project is to have a competent retrofit product supplier or other source of competent technical support that is committed to providing on-going technical support, particularly when problems arise. A project may encounter problems, but in those programs where the product supplier has been actively engaged in trying to solve the problems, the willingness of the fleet operators to support continuing efforts is much greater than in projects where the product supplier provider is not technically competent or is viewed as being less than cooperative.

If more products and/or expanded application cannot be verified in the near future, other methods need to be employed to make more products available (e.g., conditional verifications) to help state and local governments meet their air quality obligations and objectives.

It is important for the project manager to stay personally involved in the retrofit product supplier selection process. In one case, product supplier selection was handled by the finance department that sent the RFP for DOCs to aftermarket gasoline catalytic converters suppliers and not to DOC suppliers. (P40) The RPF had to be reissued, delaying the start of the program.

4.4.4.1 *Product Procurement Issues*

State, regional, or even county purchase contracts covering multiple government agency fleets offer several advantages including: 1) an attractive price through volume purchasing, and 2) less administrative burden on individual procuring agencies by eliminating the need for going through the RFP process for selecting a retrofit product supplier and negotiating a contract. In some cases, states are piggy-backing on another state's statewide purchasing agreement with a product supplier in order to provide obtain a good price on retrofit products.

The common practice (by most government agencies) of developing a product procurement specification requirement and issuing an RFP or Invitation For Bid (IFB) usually results in the award of a purchase to the product supplier with the lowest product price per **vehicle**. This practice generally works well for commodity products, but for the acquisition of retrofit products (which are not really commodity products as yet) may lead to the selection of a product or supplier that does not provide the best overall value for the vehicle **fleet**. Table 4-1 illustrates an actual example comparing two retrofit project procurement approaches for two school bus fleets for which approximately 400 buses were to be retrofitted with EPA-verified DOC products. One approach used the traditional specification/low bid selection process, while the other used a fleet-based "best performance/value" solicitation, with selection based on supplier responses to nearly 30 technical requirements.

Note several important points from Table 4-1: for the two fleets for which the comparison was made, compared to the Specification/Low Bid approach, the Best Performance/Value Solicitation approach yielded supplier responses with:

- Product warranties that were significantly longer from all product suppliers.
- Delivery and installation schedules that were significantly shorter.
- Retrofit product price per-vehicle that was at least equivalent for one supplier.

Table 4-1, Comparison of Retrofit Product Procurement Approaches

REQUIREMENT ELEMENT	SPECIFICATION/ LOW BID PROCESS	BEST PERFORMANCE/ VALUE SOLICITATION		
Retrofit product warranty	1 Year	3 yrs/100K mi. to 5 yrs/150K mi.		
Delivery and installation schedule	10 per week; 40-50 weeks to install	5 weeks for delivery of all; 12 weeks to install		
PM reduction	20%	20% to 41%		
Retrofit product price per vehicle	$840	$740 to $1900		
EMISSION REDUCTION AND COST EFFECTIVENESS COMPARISON				
	PRODUCT SUPPLIER	PRODUCT SUPPLIER		
	A	B	C	D
Retrofit product price per vehicle	$840	$1555	$878	$840
Net program cost for 400 bus fleet	$336K	$302K	$351K	$336K

- EPA-verified PM reduction levels that were equal to or greater.
- Net program costs that were lower and higher.

Note also from Table 4-1 that while the retrofit product from Supplier B was the highest price per vehicle, its overall cost to the fleet was the lowest.

In those cases where the vehicles/equipment are leased or provided under contract, there is a need to specify what happens to the retrofit products if the contract is not renewed or the contractor wishes to move the vehicle/equipment equipped with retrofit technology to a different location before the project is complete (e.g., a bus contractor moves a school bus equipped with a DOC to service another school district not participating in the program). In a number of U.S. retrofit programs, methods for addressing this issue have included adding a special contract provision that contains such remedies as the contractor paying restitution, or requiring the contractor to operate in a nonattainment area or somewhere else in the state in the case of state funding. In general, retrofit projects that involve or desire to involve private sector contractors require implementation approaches that are sensitive to the needs of the contractors and are accomplished in a way that minimizes negative impact on the competitive aspects of the market in which the contractor does business. There is significant room for some creative approaches to involving private sector vehicle/equipment operators in retrofit programs in ways that require minimal administrative burden and are sensitive to their needs, yet achieve a goal of reducing emissions from their fleets.

4.4.5 Outreach and Education

Several reports in the literature stress the importance of actively promoting participation by potentially interested stakeholders and the general public. [47, 192] The benefits of outreach and public participation are multi-faceted and include: 1) building broad-based support for the retrofit program and subsequent retrofit initiatives, 2) promoting interest with other fleets to become involved, 3) identifying new sources for funding and 4) helping to educate the public on the needs and opportunities to reduce pollution to protect public health. In doing so, state and local government agencies charged with meeting immediate and longer term emission reduction goals can now better describe to their stakeholders and the public exactly which program options are demonstrating continued progress and promise. They can also determine which programs are being slowed by technological or engineering delays that are expected to be overcome soon, and how budgetary factors are being managed to achieve results or provide evidence of the need for additional funding (or both). Private sector program sponsors and agencies soliciting private sector participants can also utilize increasing public awareness and understanding to promote voluntary efforts. Fleet operators and technicians should be involved early in the process to understand the benefits of the program, know that the retrofit product should not impact vehicle performance, know what maintenance will be required, and how to spot and deal with problems if they arise (e.g., DPF backpressure alarm is triggered)

When engaging school bus fleets to participate in retrofit initiatives, any direct suggestion that riding in their buses poses a direct health risk to the students becomes a contentious issue that may diminish fleet operator support for the program. Projects that stressed improving air quality for the region in general had better success in gaining the support of fleet operators.

4.4.6 Mandatory Programs

CARB has provided a testing ground for mandatory-type programs and a growing number of technologies are being verified. CARB discovered that the application of DPF technology to existing on- and off-road diesel engines is not as broad-based as originally envisioned. Consequently, in designing regulatory initiatives, CARB has opted to provide considerable flexibility in meeting the applicable PM emission reduction requirements. (P1.2) CARB has also conducted extensive outreach with the regulated fleet to provide information and address concerns expressed by the affected fleets, and has endeavored to provide adequate lead-time in meeting the applicable requirements.

The Connecticut DOT implemented a retrofit program establishing a contract provision requiring that retrofit technology (DOCs) or clean fuels be used by contractors performing construction on portions of I-95. DOT conducted a pre-planning meeting to address the significant issues raised by prospective construction contractors, demonstrating the benefits of early communication and education.

In establishing a mandatory retrofit program, a number of factors must be considered. The primary consideration is whether the entity seeking to impose a mandatory retrofit program possesses the legal authority to do so. Issues that must be considered include the:

- Category of vehicles or equipment covered.
- Level and type of controls required and alternative.
- Compliance strategies allowed.
- Technology approval process.
- Enforcement methods/process to be used.

The development and implementation of the critical elements of a mandatory program can all be enhanced with effective planning that includes education, outreach, and feedback from customers or the public, as appropriate, and analytical work to assess realistic expectations for emission reductions and costs to implement.

5.0 OBSERVATIONS AND CONCLUSIONS

This report covers the first two phases of EPA's comprehensive evaluation of retrofit programs. It provides a review of publicly available written articles, reports, and other documents related to diesel retrofit technologies, as well as retrofit program design, implementation, and experience. The literature focus of this report is on retrofit experience in the U.S. during the period from January 2000 to the present. This information is supplemented with material collected on diesel retrofit technology and experience in other countries since the 1990s. Over 160 documents were reviewed to develop the content of this report. The bulk of these documents describe diesel retrofit programs and projects involving a variety of technologies and vehicle/equipment applications. A significant number of these documents are also cited as references within this report. In addition to the literature sources, over 200 retrofit projects were identified as being undertaken in the U.S. Information was requested from each one and was received from nearly two-thirds of them.

A wide range of retrofit technology strategies is available to suit nearly any vehicle/ equipment application in operation today, although the current availability of verified retrofit products for nonroad applications is limited. All of these technologies generally deliver the operating and emission reduction results that are claimed for them, but the levels of emission control achieved are in some cases highly dependent on the emission test cycle used. In those instances in which problems did occur, several factors were identified. In some cases, problems occurred when technologies were extended to applications that were marginal, as an experiment in a pilot project to evaluate the limits of the technology. In other cases, technical problems resulted because the sulfur levels in the fuels were too high for successful application of the technology. This situation was well illustrated in several projects involving catalyst-based DPFs. In other cases, there were mechanical problems, such as the failure of retrofit equipment brackets. In most instances where technological problems occurred, corrections were identified and implemented in subsequent programs. In other cases, problems could be traced directly to insufficient or inadequate knowledge on the part of users or program creators/administrators. As with any other new or unfamiliar technology products, successful use requires an understanding of product function, proper installation and use, and attention to recommended product selection criteria, and operating and maintenance requirements.

A variety of retrofit programs and projects were reviewed. In this report, the various retrofit programs were organized into two major categories: mandatory programs and voluntary programs. Each type of program structure has its advantages and disadvantages. For example, mandatory programs (like those that are part of the CARB DRRP) have the benefit of generating emission reduction benefits that are more easily quantifiable, more "permanent" and enforceable than those of some voluntary programs. Conversely, voluntary programs are dependent on prospective technology users to "come forward" and offer to operate their vehicles or equipment with retrofit products, without the potential for having to face any penalties for noncompliance. Information from the available literature and retrofit projects in the U.S. suggests that each form of program structure seems to have been successful, even though each type has needed to address various issues. It is not clear from the documents available for this report that one type of program structure is any better than another.

Compared to the nearly 35-year history of emission control system technologies/products and our national and state programs to control diesel engine emissions, diesel retrofit programs are relatively new. The growing popularity of these programs has resulted from several factors, including: the need to find additional methods for improving air quality (beyond the establishment of more stringent emission standards that are applied to newly-manufactured engines and vehicles), greater knowledge and concern about the health effects of vehicle exhaust constituents, availability of a variety of retrofit products from reputable product suppliers, and meaningful levels of financial incentives/support. A growing body of retrofit program and project experience is being developed. Much of this experience, however, has not been previously reported extensively or documented at this time.

The retrofit technology and project experience captured in Sections 2.0, 3.0, and 4.0 of this report provide a overall synthesis of a broad range of "lessons learned" that are helpful to those planning and implementing retrofit programs and projects. Key points include the following:

- The range of emission reduction associated with each retrofit technology and product can vary widely, depending on test method, duty cycle, engine/vehicle condition, types of test equipment used, etc. The verification procedures established by EPA and CARB have helped to provide "benchmark" levels of emission reductions for retrofit products that retrofit program administrators and retrofit product users can rely on as "representative" for the products tested.

- Use of DPFs requires knowledge and correct application in order to be most effective and operate with minimal problems. Careful application design, including matching the DPF design (passive or active) to the operating exhaust temperature profile of the engine, ensuring appropriate catalyst sizing and thermal insulation, and matching the fuel sulfur level to the DPF design are several of continued improvements made to enhance effective operation. Successful application of DPFs can be enhanced further by comprehensive suitability testing, careful systems monitoring, and field inspections.

- To minimize problems with diesel retrofit products designed to operate with ULSD, measures need to be established to prevent misfueling of vehicles with diesel fuel of higher sulfur content. Segregated fuel storage and dispensing equipment (from that used for diesel fuel of higher sulfur content) is likely to be needed until ULSD becomes widespread. Users of ULSD should ensure that they purchase fuel with lubricating properties meeting those of the latest diesel fuel specifications for ASTM International D 975, Grade S15, and if fuel economy is important, that the energy content of the fuel meets the minimum requirements of the fleet.

- For projects involving fuel technologies (e.g., ULSD, biodiesel, diesel fuel emulsions) consideration had not always been given to fuel supply logistic aspects. If a project is to involve multiple vehicle/equipment operators such as might be found at a construction site, issues such as the need to respect the fuel supplier agreements for each of the participants, and accommodate individual vehicle/equipment refueling requirements may be difficult to address or obtain agreement among the participants. These issues should be addressed early in the project planning process to avoid potential problems after the project has begun.

- Retrofit technology and product selection should be accomplished with the knowledge in mind of the operating and maintenance capabilities of the vehicle or equipment fleet. Fleets that will not have the time and attention to devote to complying with recommended practices for installation, operating and maintenance, should consider technologies and products that require minimal care and attention. In selecting technologies for a retrofit program, a balance must be struck among: 1) the need for achieving desired emission reductions, 2) complexities of program/technology implementation, 3) working within technical capabilities/limitations of the fleet, 4) available funding, and 5) other program goals.

- While there are several incentive mechanisms available to support the acquisition of retrofit products, the most successful had been direct funding via a grant process. Mechanisms of funding transfer, however, can be a significant hurdle in getting government-based grant funding to assist private sector fleets and equipment operators. Achieving the involvement of private sector vehicle/equipment operators requires implementation approaches that are sensitive to their needs and are accomplished in a way that minimizes negative impact on the competitive aspects of the market in which the private operator does business. There is significant room for some creative approaches to involving private sector vehicle/equipment operators in retrofit programs in ways that are sensitive to their needs yet achieve a goal to reduce emissions from their fleets.

- Some retrofit project planning decisions have been made with good intentions, but with poor consequences. This suggests a need for retrofit program and project planners to either obtain expert assistance or otherwise develop a thorough understanding of the perceptions of retrofit product users and their concerns for operational trade-offs to determine an acceptable level of technology performance. Program/project planners need to be aware of not only the benefits, but the challenges as well, of various emission reduction strategies, and not simply specify that emission reductions be accomplished with the "best available technology", that could result in the application of a highly effective technology (e.g., DPFs) on vehicles with incompatible operational characteristics that would lead to overall project failure. Care, knowledge and insight also needs to be applied to vehicle/equipment selection so that any desire to "improve the entire fleet" does not result in wasting money on retrofit products being installed on vehicles that are to be retired from service in a short time, or being installed on late model vehicles that are already equipped with a high level of emission control technology.

- Common procurement practices used for acquiring commodity products based on the development of a product specification and lowest **unit** product price may not yield the best product supplier or overall best value for the vehicle/equipment **fleet**.

- Current technology costs are an important consideration in both the decision to undertake a retrofit program and in selecting the technology to be used. Cost does not seem to have been a significant deterrent to the establishment or growth in retrofit programs worldwide, but clearly, the level of interest in the diesel retrofit programs would increase if costs are reduced. Retrofit technology costs are likely to be reduced as the market for retrofit products and new engine OE applications grow, and the technologies are further optimized. One to two orders of magnitude in product demand will be needed before more substantial cost reductions can be realized.

- Retrofit programs are growing (in number of programs, projects, and vehicles/equipment in them), and retrofit products are getting better, as results of more field experience work their way into product improvements. Product-related problems have been and continue to be addressed.

- The knowledge base required to plan and implement retrofit project is growing, but is not at a level that has allowed universal project success. The programs and projects that were the most successful and were best equipped to deal with problems had solid and sustained technical support throughout the project. That support came from a variety of sources including the technology manufacturer and/or product supplier, EPA (both headquarters and the regional offices), multi-state regional organizations such as NESCAUM, local air quality districts such as the PSCAA, independent technical consultants and professional services firms, and personnel from other fleets that had experience with retrofits. As the number of retrofit programs grows, finding well-qualified sources of technical support will become more challenging.

- Successful programs in the U.S. have some or all of the characteristic cited below:

    - One or more project "champions" to oversee program planning/implementation and the technological aspects of the program.

    - Adequate funding to conduct the program.

    - Careful planning, including recruiting the necessary partners, setting the goals for the program, building support on the part of participating fleets.

    - Continuous communications with all participating parties.

    - Strong, competent, and effective technical support.

    - Careful evaluation and selection of technologies.

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