CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD

STAFF REPORT: TECHNICAL SUPPORT DOCUMENT

PROPOSED CONTROL MEASURE FOR DIESEL PARTICULATE MATTER FROM ON-ROAD HEAVY-DUTY DIESEL-FUELED RESIDENTIAL AND COMMERCIAL SOLID WASTE COLLECTION VEHICLE DIESEL ENGINES

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State of California
California Environmental Protection Agency
AIR RESOURCES BOARD

Technical Support Document for the Proposed Control Measure For Diesel Particulate Matter From On-Road Heavy-Duty Residential And Commercial Solid Waste Collection Vehicle Diesel Engines

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List of Acronyms

ARB, or the Board	Air Resources Board
BACT	Best available control technology
CAS	Clean Air Systems
CNG	Compressed natural gas
CO	Carbon monoxide
DECS	Diesel emission control strategy or system
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
FBC	Fuel borne catalyst
FTF	Flow through filter
g/bhp-hr	Grams per brakehorse power hour
HC	Hydrocarbon
JM	Johnson Matthey
LNG	Liquified natural gas
Low sulfur diesel fuel	Diesel fuel with a sulfur content less than 15 parts per million by weight
LPG	Liquid petroleum gas
MY	Model year
NO_x	Oxides of nitrogen
PM	Particulate matter
Procedure	Diesel Emission Control Strategy Verification Procedure
SAEFL	Swiss Agency for the Environment, Forests, and Landscape
SCAQMD	South Coast Air Quality Management District
SWCV	Solid waste collection vehicle
U. S. EPA	United States Environmental Protection Agency

I. Summary

Recognizing the considerable impacts of implementing a regulation to reduce the health risks from diesel particulate matter emission from solid waste collection vehicles, the staff of the Air Resources Board has undertaken this technical review in support of its proposed control measure for diesel particulate matter from on-road heavy-duty diesel-fueled residential and commercial solid waste collection vehicle engines.

In this report, Air Resources Board staff reviews the PM reduction technologies both currently available and projected to be available in the near future, not only for solid waste collection vehicles but also for other diesel mobile and stationary engines. For each type of technology, staff describes the technology, discusses potential limitations and in-use experiences, and identifies technology that has been verified by the Air Resources Board. The Report also discusses in more detail in-use experiences with diesel particulate matter reduction technologies by the City of Los Angeles and internationally. Demonstrations conducted by Air Resources Board are also reviewed. Finally, staff reports on the results of studies undertaken to investigate the applicability of potential diesel emission control technologies to California's collection vehicles and the implications of the data for retrofit feasibility.

II. Introduction

Recognizing the considerable impacts of implementing a regulation to reduce the health risks from diesel particulate matter (PM) emission from solid waste collection vehicles (SWCVs), the Air Resources Board (ARB or the Board) has undertaken this technical review in support of its proposed control measure for diesel PM from on-road heavy-duty diesel-fueled residential and commercial SWCV engines. In this report, ARB staff reviews the PM reduction technologies both currently available and projected to be available in the near future, not only for SWCVs but also for other diesel mobile and stationary engines. More specifically to support the proposed SWCV rule, staff also reports on the results of studies undertaken to investigate the applicability of potential diesel emission control technologies to California's collection vehicles.

Throughout this report, a diesel emission control strategy or system (DECS) is the term used to mean any device, system, or strategy employed with an in-use diesel vehicle or piece of equipment that is intended to reduce emissions. While this definition does not exclude systems that reduce emissions of oxides of nitrogen, in this report we focus on strategies that reduce PM engine exhaust emissions. Examples of DECSs include, but are not limited to, add-on hardware, such as a diesel particulate filter (DPF), a diesel oxidation catalyst (DOC), or flow-through filter; alternative diesel fuels or fuel additives; and integrated systems that combine hardware with an alternative diesel fuel or fuel additive. The effectiveness of a DECS to reduce PM ranges, by Board regulation, from 25 percent (Level 1) up the maximum achievable. For example, a DOC may achieve the minimum 25 percent reduction, primarily from removal of the soluble organic fraction of diesel PM, whereas the effectiveness of a DPF ranges from 85 to over 99 percent.

Integrated systems, such as a DOC coupled with a fuel-water emulsion or a lightly-catalyzed DPF used with a fuel additive, may also be an effective DECS. Such systems are capable of functioning in a range of engines/vehicles and applications, which will help to ensure that an emission control strategy option should be available to most, if not all, SWCVs by the proposed implementation dates.

III. Verification of Diesel Emission Control Strategies

As a way to thoroughly evaluate the emissions reduction capabilities and durability of a variety of DECSs, ARB has developed the Diesel Emission Control Strategy Verification Procedure (Procedure).[1] The purpose of the Procedure is to verify strategies that provide reductions in diesel PM emissions, which include, but are not limited to, DPFs, DOCs, exhaust gas recirculation, selective catalytic

[1] Approved by the Board in May 2002. Sections 2700 through 2710, Title 13, California Code of Regulations.

reduction systems, fuel additives, and alternative diesel fuel systems. The development of the verification procedure is based on experience gained with passive DPFs, but has been crafted to apply to all DECSs.

Those DECS currently verified for use in SWCV applications are listed in the "BACT Status" section at the end of each technology discussion below. A complete and up-to-date list of verified DECSs and the engine families for which they have been verified, along with letters of verification, may be found on our web site:

http://www.arb.ca.gov/diesel/verifieddevices/verdev.htm.

IV. Best Available Control Technology for Particulate Matter Reduction in Solid Waste Collection Vehicles

A variety of strategies can be used for controlling emissions from diesel engines, including aftertreatment hardware, such as filters, fuel strategies, and engine modifications. The two main types of technologies discussed here are hardware, add-on technologies such as DPF and DOC, and fuel or fuel additives. These technologies can be combined to form additional DECSs. In addition, this report will discuss alternative fuels, such as compressed natural gas (CNG) and repowering to a cleaner engine.

A. Hardware Diesel Emission Control Strategies

Currently, hardware DECSs consist of the DPF, both passive and active, and the DOC, each of which have been used in both on- and off-road vehicles and equipment for many years. Recently, a new hardware DECS has been developed, which is termed the flow through-filter (FTF).

1. Diesel Particulate Filter

In general, a DPF consists of a porous substrate that permits gases in the exhaust to pass through but traps the PM. DPFs are very efficient in reducing PM emissions, achieving typical PM reductions in excess of 90 percent. Most DPFs employ some means to periodically regenerate the filter (i.e., burn off the accumulated PM). These can be divided into two types of systems, passive and active.

a. Passive Diesel Particulate Filter

A passive catalyzed DPF reduces PM, carbon monoxide (CO) and hydrocarbon (HC) emissions through catalytic oxidation and filtration. Most of the DPFs sold in the United States use substrates consisting of ceramic wall-flow monoliths to capture the diesel particulates. Some manufacturers offer silicon carbide or other metallic substrates, but these are less commonly used in the United States.

These wall-flow monoliths are either coated with a catalyst material, typically a platinum group metal, or a separate catalyst is installed upstream of the particulate filter. The filter is positioned in the exhaust stream to trap or collect a significant fraction of the particulate emissions while allowing the exhaust gases to pass through the system.

Effective operation of a DPF requires a balance between PM collection and PM oxidation, or regeneration. Regeneration is accomplished by either raising the exhaust gas temperature or by lowering the PM ignition temperature through the use of a catalyst. The type of filter technology that uses a catalyst to lower the PM ignition temperature is termed a passive DPF, because no outside source of energy is required for regeneration.

Passive DPFs have demonstrated reductions in excess of 90 percent for PM, along with similar reductions in CO and HC. A passive DPF is a very attractive means of reducing diesel PM emissions because of the combination of high reductions in PM emissions and minimal operation and maintenance requirements.

i. In-Use Experience with Passive Diesel Particulate Filters

Passive DPFs have been successfully used in numerous applications, including collection vehicles. As of 2000, over 10,000 trucks and buses had been retrofitted worldwide (MECA 2000). Internationally, retrofit programs exist in Sweden, Germany, Switzerland, Hong Kong, Taiwan, London, Paris, Mexico City, and Tokyo (MECA 2002). In the United States, the use of DPFs is growing more common, with DPF retrofit programs underway in California, New York, and Texas. In California, diesel-fueled school buses, SWCVs, urban transit buses, medium-duty delivery vehicles, people movers, and fuel tanker trucks have been retrofitted with DPFs through various demonstration programs (See Section V).

ARCO, a BP company, completed a one-year demonstration program in 2001 to evaluate its low sulfur (<15 parts per million by weight sulfur content) diesel fuel and passive DPFs in five truck and bus fleets (LeTavec *et al.* 2002). The five fleets, all of which operated in southern California, included grocery trucks, tanker trucks, refuse haulers, school buses, and transit buses. Data on the SWCV demonstration fleet will be discussed in greater detail in Section V.A.

Over the one-year demonstration, DPF-equipped vehicles accumulated over 3,525,000 miles without any major incidents attributed to the DPFs or the low sulfur diesel fuel. Most of the grocery trucks and all of the tanker trucks accumulated over 100,000 miles of operation between test rounds. Diesel PM emission reductions were maintained after one year, with no signs of deterioration. The test vehicles retrofitted with the passive DPFs and fueled with low sulfur diesel had over 90 percent lower PM emissions when operated on the low sulfur than the control vehicles with factory mufflers and operated on CARB diesel fuel. In addition, the passive DPF and low sulfur diesel fuel combination either did not or only had a minor affect on fuel economy (LeTavec *et al.* 2002).

As of March 2003, many of the trucks still have their DPFs operating. Data are currently available for the grocery trucks. Six out of ten of the grocery trucks with DPFs have accumulated over 300,000 miles each without needing cleaning of the traps; the other four trucks accumulated over 250,000 miles with one DPF cleaning. After three years of operation, the emission reductions have been maintained and there has been no fuel economy penalty (Smith 2003).

ii. BACT Status of Passive Diesel Particulate Filters

The Engelhard DPX and the Johnson Matthey CRT DPF plus low sulfur diesel fuel have been verified for use with most 1994 to 2002 model year (MY) diesel engines in on-road applications (**Table 1**). All of the applicable engines are four-stroke, turbocharged, and were certified in California to the 0.1 g/bhp-hr PM emission standard. Also, the Clean Air Partners passive DPF, manufactured by Engelhard, is verified for use with certain Power Systems Associates and Caterpillar engines converted to bi-fuel operation using the Power Systems Associates and Clean Air Partners bi-fuel retrofit system. All three passive DPF achieve a Level 3 verified 85 percent or greater PM reduction.

Table 1. 1994 to 2002 Model Year Verified Engines for Use with Engelhard's DPX Catalyzed DPF (ARB 2003b) and Johnson-Matthey's CRT Catalyzed DPF (ARB 2003a).

Make	Engine Series (All Horsepower)
Caterpillar	3116, 3126, 3176, 3306, 3406, C10, C12, C15, C16
Cummins	L10, M11, N14, ISB, ISC, ISM, ISX, Signature, B-Series, C-Series
Detroit Diesel	Series 50, Series 60
International	T444, DT466, 530, 7.3 DIT
Mack	E7, EM7
Volvo	VE D7, VE D12

iii. Successful Use of a Passive DPF

The successful application of a passive DPF is primarily determined by the average exhaust temperature at the filter's inlet and the rate of PM generated by the engine. These two quantities are determined by a host of factors pertaining to both the details of the application and the state and type of engine being employed. As a result, the technical information provided to ARB for verification by the manufacturer serves as a guide, but additional information may be required to determine whether a passive DPF will be successful in a given application.

The rate of PM generation is influenced by a variety of factors and the engine certification level cannot be used, in all cases, to predict PM emission levels in-use. Testing done by West Virginia University, for example, shows that a given diesel truck can generate a wide range of PM emission levels depending on the test cycle (Nine *et al.* 2000). Engine maintenance is another factor in determining the actual PM emission rate. The ARB's informational package for the heavy-duty vehicle inspection programs lists sixteen different common causes of high smoke levels related to engine maintenance (ARB 1999).

The average exhaust temperature in actual use is also difficult to predict based on commonly documented engine characteristics, such as the exhaust temperature at peak power and peak torque. The exhaust temperature at the DPF inlet is highly application dependent, in that the particular duty cycle of the truck plays a prominent role, as do heat losses in the exhaust system. Very vehicle-specific characteristics enter the heat loss equation, such as the length of piping exhaust must travel through before it reaches the DPF. Lower average exhaust temperatures can also be the result of operating vehicles with engines oversized for the application.

The applicability of passive DPFs in SWCVs will be discussed in detail in the second half of this report.

b. Active Diesel Particulate Filter

An active DPF system uses an external source of heat to oxidize the PM. The most common methods of generating additional heat for oxidation involve electrical regeneration by passing a current through the filter medium, injecting fuel to provide additional heat for particle oxidation, or adding a fuel-borne catalyst or other reagent to initiate regeneration. Some active DPFs induce regeneration automatically on-board the vehicle or equipment when a specified backpressure is reached. Others use an indicator, such as a warning light, to alert the operator that regeneration is needed, and require the operator to initiate the regeneration process. Some active systems collect and store diesel PM over the course of a full shift and are regenerated at the end of the shift with the vehicle or equipment shut off. A number of the filters are removed and regenerated externally at a regeneration station.

For applications in which the engine-out PM is relatively high, and the exhaust temperature is relatively cool, actively regenerating systems may be more effective than a passive DPF. Because active DPFs are not dependent on the heat carried in the exhaust for regeneration, they potentially have a broader range of application than passive DPFs.

i. In-Use Experience with Active Diesel Particulate Filters

Active DPFs have been used successfully in Europe (Zelenka *et al.* 2002). Their use in Europe has been more successful, however, with applications with a regular driving pattern, such as forklifts (MTC AB 2003). Off-road applications of these active systems have been implemented in Europe since the early 1990's.

Additionally, a system manufactured by Cleaire, which combines an active DPF with a lean NO_x catalyst, has been demonstrated in the U.S. on a transit bus with a 2000 Cummins ISM engine. Testing conducted after 1000 hours of operation indicated PM emission reductions in excess of 85 percent could be achieved on stop and go duty cycles when operated using low sulfur (sulfur content less than 15 parts per million by weight) diesel fuel.

ii. BACT Status of Active Diesel Particulate Filters

No active DPF system is currently verified for use in SWCVs or any other application. If one were to become verified, it would likely achieve a Level 3 DECS status.

2. Flow Through Filter

Flow-through filter technology is a relatively new method for reducing diesel PM emissions. Unlike a DPF, in which only gases can pass through the substrate, the FTF does not physically "trap" and accumulate PM. Instead, exhaust flows through a medium (such as a wire mesh) that has a high density of torturous flow channels, thus giving rise to turbulent flow conditions. The medium is typically treated with an oxidizing catalyst that is able to reduce emissions of PM, HC, and CO, or used in conjunction with a fuel-borne catalyst. Any particles that are not oxidized within the FTF flow out with the rest of the exhaust and do not accumulate.

Consequently, the filtration efficiency of an FTF is lower than that of a DPF, but the FTF is much less likely to plug under unfavorable conditions, such as high PM emissions and low exhaust temperatures. The FTF, therefore, is a candidate for use in applications unsuitable for DPFs. Staff expects that an FTF will achieve between 30 and 60 percent PM reduction, lower than a DPF, for a Level 1 or 2 verification.

Relative to a DOC, which typically has straight flow passages and laminar flow conditions, the FTF achieves a greater PM reduction owing to enhanced contact of PM with catalytic surfaces and longer residence times. The better performance of an FTF when compared to a DOC may come at the cost of increased backpressure. No data are available on how the capital cost of the two technologies will compare in the marketplace.

a. In-Use Experience with Flow Through Filters

In September 2002, ARB began demonstrating a FTF plus fuel additive system on collection vehicles in the South Coast Air Basin. Beginning Spring 2003, ARB will demonstrate six FTFs without the use of a fuel additive on SWCVs also in the South Coast Air Basin. Additional details of these demonstrations are found in Section V.

b. BACT Status of Flow Through Filters

No FTF system is currently verified by ARB.

3. Diesel Oxidation Catalyst

A DOC reduces emissions of CO, HC, and the soluble organic fraction of diesel PM through catalytic oxidation alone. Exhaust gases are not filtered, as in the DPF. In the presence of a catalyst material and oxygen, CO, HC, and the soluble organic fraction undergo a chemical reaction and are converted into carbon dioxide and water. Some manufacturers integrate HC traps (zeolites) and sulfate suppressants into their oxidation catalysts. HC traps enhance HC reduction efficiency at lower exhaust temperatures and sulfate suppressants minimize the generation of sulfates at higher exhaust temperatures. A DOC can reduce total PM emissions up to 30 percent.

a. In-Use Experience with Diesel Oxidation Catalysts

This technology is commercially available and devices have been installed on tens of thousands of mobile diesel-fueled engines. As a result of the United States Environmental Protection Agency's (U.S. EPA's) Urban Bus Retrofit/Rebuild program, several models have been certified by the U.S. EPA and through ARB's aftermarket parts certification program. Nationwide, thousands of DOCs are installed on urban transit buses with engines older than 1994 MYs.

In general, DOCs function well on all vehicle and equipment types. ARB has begun a demonstration to explore the applicability of DOCs on older, higher emitting SWCVs.

b. BACT Status of Diesel Oxidation Catalysts

ARB has verified one stand-alone DOC, which is manufactured by Donaldson Company, at Level 1, or a minimum of 25 percent PM reduction. This stand-alone DOC is verified for some 1991 to 2002 MY engines using low sulfur diesel fuel.

B. Fuels and Fuel Additives Diesel Emission Control Strategies

1. Fuel Additives

A fuel additive is a DECS when it is designed to be added to fuel or fuel systems so that it is present in-cylinder during combustion and its addition causes a reduction in exhaust emissions. Additives can reduce the total mass of PM, with variable effects on CO, oxides of nitrogen (NO_x) and gaseous HC production. The range of PM reductions that have been published in studies of fuel additives is from 15 to 50 percent reduction in mass. Most additives are fairly insensitive to fuel sulfur content and will work with a range of sulfur concentrations as well as different fuels and other fuel additives (DieselNet 2002).

An additive added to diesel fuel in order to aid in soot removal in DPFs by decreasing the ignition temperature of the carbonaceous exhaust is often called a fuel borne catalyst (FBC). These can be used in conjunction with both passive and active filter systems to improve fuel economy, aid system performance, and decrease mass PM emissions. FBC/DPF systems are in wide spread use in Europe in both on-road and off-road, mobile and stationary applications and typically achieve a minimum of 85 percent reduction in PM emissions. Additives based on cerium, platinum, iron, and strontium are currently available, or may become available for use in the future in California.

a. In-Use Experience with Fuel Additives

ARB is currently demonstrating an additive plus a FTF on SWCVs.

Cerium based additives are in wide spread use in Europe and VERT-approved when used with DPFs. A cerium-based additive is part of Peugeot's new passenger car filter-based system and, in addition to on-road applications, cerium additives are used off-road in construction and forklift applications (Lemaire 2002).

Platinum based additives are in use in Europe with DPF systems for both on and off road applications and stationary sources (Clean Diesel Technologies 2002).

Iron based fuel additives are in-use in construction vehicles and building machinery in Germany, Austria and Switzerland for greater than five years. Additionally, several hundred city buses, garbage trucks, forklifts and cleaning machinery have used these additives for the last several years (Werner 2002).

b. BACT Status of Fuel Additives

No fuel additives are verified by ARB currently. One manufacturer has a fuel additive currently being demonstrated in conjunction with a DOC, a FTF, and a lightly catalyzed DPF on collection vehicles as of March 2002. All fuel additives must undergo an assessment of multimedia effects prior to ARB verification.

2. Alternative Diesel Fuels

An alternative diesel fuel is a fuel that can be used in a diesel engine without modification to the engine and that is not just a reformulated diesel fuel. This definition of alternative diesel fuels includes emulsified fuels, biodiesel fuels, Fischer Tropsch fuels, and any combination of these fuels with regular diesel fuel. The emissions effects of these fuels can vary widely.

No alternative diesel fuels are currently verified by ARB.

a. Fuel-Water Emulsion

A demonstrated alternative diesel fuel that reduces both PM and NO_x emissions is an emulsion of diesel fuel and water. The process mixes water with diesel and adds an agent to keep the fuel and water from separating. The water is suspended in droplets within the fuel, creating a cooling effect on the fuel that decreases NO_x emissions. A fuel-water emulsion creates a leaner fuel environment in the engine, thus lowering PM emissions. The major manufacturer of this fuel-water emulsion is Lubrizol Corporation, which produces PuriNOx™ (U.S. EPA 2002b).

According to data submitted for the ARB's fuels certification procedure, PuriNOx™, achieved a 14 percent reduction in NO_x emissions and a 63 percent reduction in PM emissions, based on tests on one engine (ARB 2001). Similar results were found in a U.S. EPA analysis. According to U.S. EPA's analysis of available literature, a medium to heavy heavy-duty vehicle may achieve between a 51 and 58 percent reduction in PM in conjunction with a 10 to 13 percent reduction in NO_x emissions (U.S. EPA 2002b).

i. In-Use Experience with Fuel-Water Emulsion

PuriNOx™ has been used in a variety of vehicles, including construction equipment operated by the California Department of Transportation and transit buses, but not on collection vehicles to date. The California Department of Transportation experience with the fuel was generally positive, except that the emulsion tended to break down when held for over 30 days. Several companies operating at the Port of Los Angeles are also using PuriNOx™.

ii. BACT Status of Fuel-Water Emulsion

No fuel-water emulsion fuel is currently verified as a DECS for SWCVs or any other applications. ARB has granted Lubrizol's PuriNOx™ an alternative diesel fuel emissions certification through its fuels certification procedure, but not a DECS verification, which would be required in order to comply with the proposed regulation. The ARB is waiting for the completion of a multi-media analysis for toxics before a verification can be issued. Staff expects this technology will achieve a Level 2 verification, or a minimum of a 50 percent PM reduction.

b. Biodiesel

Biodiesel is a mono-alkyl ester-based oxygenated fuel, a fuel made from vegetable oils, such as oilseed plants or used vegetable oil, or animal fats. It has similar properties to petroleum-based diesel fuel, and can be blended into petroleum-based diesel fuel at any ratio. Biodiesel is most commonly blended into petroleum-based diesel fuel at 20 percent (ARB 2000), and called B20. Pure biodiesel is called B100.

Using publicly available data, the U.S. EPA recently analyzed the impacts of biodiesel on exhaust emissions from heavy-duty on-road engines (U.S. EPA 2002a). While biodiesel and biodiesel blends reduce PM, HC, and CO emissions, NO_x emissions increase, depending on the biodiesel to diesel fuel blend ratio. As the proportion of biodiesel increases, the PM, HC and CO emissions decrease while the NO_x emissions increase. For B20, the NO_x increase is reported to be two percent, with reductions of ten percent PM, 21 percent HC, and 11 percent CO. In addition, the U.S. EPA states a B20 blend is predicted to reduce fuel economy by one to two percent. The data were qualified with conclusions that the impact of biodiesel on emissions varied depending on the type of biodiesel (soybean, rapeseed, or animal fats) and the quality of the diesel fuel used in biodiesel blends.

i. In-Use Experience with Biodiesel

Biodiesel has been used successfully in heavy-duty diesel-fueled vehicles. There are no technical limitations to the use of biodiesel; rather the limitations concern cost and the increased NO_x emissions associated with biodiesel use.

ii. BACT Status of Biodiesel

B100 is not currently verified as an alternative fuel, or verified as a DECS. A biodiesel blend must meet the ASTM and ARB diesel specification when used in a motor vehicle.

C. Technology Combinations

A trend in technologies presented to ARB for verification is for applicants to combine more than one technology to maximize the amount of diesel PM reduction. This section discusses some of these combinations, including technology not yet verified.

1. Diesel Oxidation Catalyst plus Engine Modifications

The Cleaire Flash and Match™ system combines a DOC with engine modifications to achieve 25 percent PM reductions, and under certain conditions, a reduction in NO_x of 25 percent. The system is verified to Level 1 for use with specific 1994 through 1998 MY diesel engines, specifically Cummins M11 engines used in steady state application, such as a long haul truck.

2. Diesel Oxidation Catalyst plus Spiracle™

The Donaldson Company has verified two combination systems at Level 1. Each system uses a different DOC, but both systems install a closed loop crankcase with the Donaldson Spiracle ™ closed crankcase filtration system. The systems are verified for use in certain 1991 and later MY collection vehicles. One system is verified for use with California diesel fuel and the other is verified for use with low sulfur diesel fuel.

3. Fuel-Borne Catalyst with Hardware Technology

A fuel-borne catalyst can be combined with any of the three hardware technologies discussed above, the DPF, DOC, or FTF, although no system using a FBC has been verified yet. The combination of a FBC with a DPF functions similarly to a catalyzed DPF, but a FBC allows the DPF to be lightly catalyzed. The FBC enhances DPF regeneration by encouraging better contact between the PM and the catalyst material. The FBC plus DPF combination reduces both the carbonaceous and soluble organic fractions of diesel PM. The primary benefit of this combination is a reduction in the amount of NO_2 generated as a proportion of NO_x.

D. Engines

There are several types of engines that will qualify as best available control technology (BACT) and meet the 0.01 g/bhp-hr standard.

1. New Diesel Engine Meeting 0.01 g/bhp-hr for PM Either as a Repower or as Original Equipment

The particulate emission standard of 0.01 grams per brake horsepower-hour (g/bhp-hr) for heavy-duty highway diesel engines will take effect nationally and in California beginning with MY 2007, except for urban bus engines to be sold in California. The same standard for urban bus engines is already in effect in California for engines produced after October 1, 2002. These standards are based on the use of high-efficiency catalytic exhaust emission control devices or comparably effective advanced technologies. Because the devices expected to be used to meet the standard are made less efficient by sulfur in the exhaust stream, the level of sulfur in highway diesel fuel will also be reduced by 90 percent, relative to California diesel fuel sulfur levels, by mid-2006 to less than 15 ppmw.

Any engine certified to this standard in California meets BACT. Another option is to re-engine, or repower, an older vehicle by installing a pre-2007 MY engine along with a DECS. For example, any 1994 to 2002 MY engine with an aftermarket verified DPF would achieve PM emissions near 0.01 g/bhp-hr and would be considered to meet BACT.

a. In-Use Experience with 0.01 g/bhp-hr Engines

There is, as yet, little experience with a new engine certified to this low PM standard because the certification standard for truck engines is not required until 2007. Currently Detroit Diesel Corporation and Caterpillar have each certified engines to the California urban bus standard of 0.01 g/bhp-hr, using a DPF to achieve the low PM standard. Cummins, Inc. reported it will certify an urban bus engine to this standard by the third quarter of 2003. Experience with this bus engine is still developing, but there is no reason to expect that these engines will experience any service problems.

b. BACT Status of 0.01 g/bhp-hr Engines

Prior to 2007, staff expects that engines certified to the 2007 PM standard may be offered for sale if there is consumer demand. This proposed rule may create this demand, as some owners will likely prefer installing a new engine as a repower over installing a DECS onto an older engine. Repowering engines is a widespread practice by owners of heavy-duty trucks to extend the useful life of an expensive vehicle. From 2007 on, all heavy-duty engines will be certified to this standard.

2. Alternative-Fuel Engines

Conventional diesel engines are internal combustion, compression-ignition engines. In contrast, engines that operate on an alternative fuel, such as CNG, liquified natural gas (LNG), and liquid petroleum gas (LPG), are spark-ignited. Engines certified to operate on alternative fuels produce substantially lower PM and NO_x emissions than diesel-fueled engines not equipped with exhaust aftertreatment. Alternative-fuel engines are available for most of the same applications as heavy-duty diesel applications.

a. In-Use Experience with Alternative-Fuel Engines

Alternative-fueled engines are being used in SWCVs today and are feasible. LNG is the most widely used alternative fuel to power collection vehicles. Over 3,000 LNG vehicles are currently in use nationwide (EIA 2002). The City of San Francisco is converting entirely to LNG when technically feasible. In addition, a large collection vehicle owner in Northern California has stated it plans to adopt this technology in the near future (Olson 2001). Over 13,000 total alternative-fueled vehicles are in use by California state agencies. Approximately 8,000 of those are heavy-duty alternative fuel vehicles. Waste Management has approximately 300 natural gas vehicles currently operating in California. The City of Los Angeles has over 200 alternative fuel vehicles currently in use in their fleet, with an additional 120 on order (Wunder 2002). The City of Long Beach is converting it's fleet to alternative fueled vehicles also.

The South Coast Air Quality Management District (SCAQMD) adopted Rule 1193 in 2001. The rule requires solid waste collection companies in the South Coast Air Basin to purchase or lease alternative fuel trucks when adding to their fleets. The number of alternative-fuel SWCVs in California will, therefore, increase over time as the majority of the population is found in the South Coast Air Basin.

b. BACT Status of Alternative-Fuel Engines

Alternative-fuel engines are currently certified and available for use on SWCVs.

3. Heavy-Duty Pilot Ignition Engine

A heavy-duty pilot ignition engine is a compression-ignition engine that operates on natural gas but uses diesel as a pilot ignition source. The total use of diesel is around six percent of the fuel consumed. ARB has defined this engine in its fleet rule for transit agencies and in the proposed rule for SWCVs as an engine that uses diesel fuel at a ratio of no more than one part diesel fuel to ten parts total fuel on an energy equivalent basis. Furthermore, the engine cannot idle or operate solely on diesel fuel at any time. An engine that meets this definition and is certified to the lower optional PM standard (0.01 g/bhp-hr) would be classified as an alternative-fuel engine.

a. In-Use Experience with Heavy-Duty Pilot Ignition Engines

Cummins Westport Inc. states the ISXG is currently being field tested with over two million miles of experience so far in road trials. Norcal, a solid waste collection company in northern California, is one of the companies demonstrating the ISXG engine (NREL 2002).

b. BACT Status of Heavy-Duty Pilot Ignition Engines

Westport Fuel Systems, Inc., currently has California certification on a base Cummins ISX (14.9 L) engine. Although the engine was certified for MY 2001 in California, the ISXG is slated for commercial production in mid-2004, with the smaller ISMG on schedule for commercial production in 2005 (Cummins Westport 2003).

V. In-Use Experience and Demonstrations

The previous section of this report discussed in-use experiences with specific DECSs, including experiences with new diesel engines complying with the 0.01 g/bhp-hr PM standard and alternative-fuel engines. This section will expand on the in-use experience with DPFs in three specific areas: the City of Los Angeles's experience with retrofitting its solid waste collection trucks, experiences outside of the United States, and demonstrations conducted in California under the supervision of the ARB.

A. City of Los Angeles

Through 2002, SCAQMD and various agencies with heavy-duty diesel vehicles have spent approximately $18 million to retrofit over 2800 diesel vehicles to reduce PM emissions (Appendix D) in the South Coast Air Basin, including collection vehicles with the City of Los Angeles. The City of Los Angeles began its experience with DECS in 1999, when it agreed to participate in an experimental program to study the durability, performance, and emission characteristics of passive DPFs used with low sulfur diesel fuel. The willingness by the City to try DPF technology was then reflected in a City Council resolution to retrofit all City owned vehicles. ARB staff has inspected most of the vehicles that have been retrofitted and discussed future plans with City of Los Angeles officials. The following describes the experience by Los Angeles, primarily in terms of its fleet of collection vehicles.

1. BP-Arco Demonstration

The City of Los Angeles participated in the EC-Diesel Technology Validation program from 1999 to 2001, funded by SCAQMD in conjunction with Cummins Cal/Pacific. Installations began in June 1999 and testing was completed by May 2001. The program provided passive-DPF and low sulfur diesel fuel to be used on 15 of the City's collection vehicles during routine operations. The 1999 Peterbilt vehicles were equipped with Cummins ISM 10.8 liter engines rated at 305 hp with five speed automatic transmissions.

The researchers designed a study in which vehicles used a mixture of fuel types and filter types (**Table 2**) to test the effects of the low sulfur diesel fuel alone and in conjunction with one of two types of filters, Engelhard's DPX and Johnson Matthey's CRT. BP-Arco's two fuels ECD and ECD-1, differed only in their aromatics content and cetane number, of which the ECD had a lower aromatics content and higher cetane number than the ECD-1, whose specifications more closely matched current CARB diesel fuel (Le Tavec *et al.* 2002).

Table 2. City of Los Angeles Collection Vehicle Passive Diesel Particulate Filter Demonstration Parameters (LeTavec *et al.* 2002).

Vehicle Type	Number	Fuel Type	Diesel Emission Control System
Control	2	CARB	Factory Muffler
Test	3	CARB	Factory Muffler
	2	ECD	Factory Muffler
	1	ECD	Engelhard DPX DPF
	2	ECD	Johnson Matthey CRT DPF
	3	ECD-1	Factory Muffler
	1	ECD-1	Engelhard DPX DPF
	2	ECD-1	Johnson Matthey CRT DPF

Five of these vehicles were tested for emissions at the beginning and end of an 11 month time frame during which they were driven about 20,000 miles (LeTavec *et al.* 2002). A 95 percent reduction in PM emissions was measured in a comparison between collection vehicles equipped with factory mufflers and DPFs. No deterioration of the filter efficiencies occurred. There was no apparent difference detected between the use of the two fuels, ECD and ECD-1, signifying that the sulfur content is the critical component, over aromatics and cetane, for filter efficiency.

2. ARB Inspection of Study Vehicles

In order to determine the on-going retrofit experience and to understand the maintenance aspects of the demonstration, ARB staff inspected and gathered information on the City of Los Angeles collection vehicles in early 2003. Fleet supervisors, mechanics, and operators supplied information on service, maintenance and operation of collection vehicles with passive DPFs installed.

Cummins Cal/Pacific, SCAQMD and the DECS manufacturers were in charge of all installation, maintenance and repairs of the passive DPFs on this fleet. Fleet supervisors were instructed to notify Cummins Cal/Pacific representatives or the appropriate DECS manufacturer, either Johnson Matthey or Engelhard, if any problems or repairs were necessary. If a vehicle was out of service an excess of five days, the original muffler was replaced to return the vehicle to service until the DPF could be replaced.

The City has experienced no problems with these units, with the longest DPF in operation for about three and a half years. Four of the original filters are still in service and have been operated over 141,500 miles since installation. The rest of the filters have been removed by the manufacturers for analysis and evaluation, both for confirmation of filter durability and future product improvements. Replacement filters were installed on all of the test vehicles.

During the early stages of DPF use, the City of Los Angeles also participated in an EGR retrofit demonstration that was not successful. Cummins introduced EGR controls on four engines equipped with Johnson Matthey CRT units to reduce NO_x emissions, but some of these units experienced clogging or blockage problems and spent a lot of time out of service. One collection vehicle remained in the shop at Cummins for repairs of an Engelhard DPX filter with EGR for over 30 days (**Table 3**). Also, of the four Cummins ISM electronic engines equipped with EGR, two had experienced fuel injector problems, which led to clogging of the DPX filters and their subsequent replacement. The EGR systems appear to have been the source of problems with these DPFs as the other DPFs functioned with minimal incident.

Table 3. DPF plus EGR Technical Issues by Collection Vehicle.

Technical Issue	Resolution
DPF + EGR problem	Repair/replacement required over 30 days in the shop.
Smoke opacity 20 to 25 percent under load conditions	Repaired.
Excessive white smoke during warm-up	Repaired.
DPF burned up	New unit installed in February 2002.
Backpressure light problems, showed DPF clogged regularly	Repaired.

With the resolution of the EGR issues, fleet managers and drivers have been comfortable and satisfied with the operation of the DPF-equipped collection vehicles.

3. Expansion of Retrofit Program

In 2000, the Los Angeles City Council adopted a motion that all City-owned diesel trucks would be retrofitted with DPFs by the end of 2002, if retrofitting is feasible. The motion was later amended to require retrofit of 50 percent of the diesel truck fleet within 18 months of ARB verification of a DPF and 100 percent within 30 months of verification. Based on the initial ARB DPF verification letter date of August 2, 2001, those deadlines would be the end of February 2003 for 50 percent installation and the end of February 2004 for 100 percent installation. Propelled by the City Council resolution, City staff scheduled retrofitting all 354 1996 and newer automated collection vehicles for July 2002 through January 2003.

ARB staff inspected the vehicles and maintenance shops in January 2003. At that time, 339 of the collection vehicles were retrofitted with DPFs (**Table 4**). Boerner Truck Center installed and services the units while under warranty. DPFs installed are the Engelhard DPX, and all units inspected had been installed vertically on the trucks. Boerner did all installations of the Engelhard DPX filters after 2:00 a.m. so there would be no vehicles out of service for installations. In-use exhaust temperatures were recorded through datalogging on a small subset of collection vehicles before installation.

Table 4. Summary of Diesel Particulate Filter Installations for the City of Los Angeles Bureau of Sanitation.

Engine Model	Model Year	Engine Family	Number
Cummins L10	1995	SCE611EGDARW	20
Cummins M11	1995	SCE611EJDARW	2
Cummins M11	1995	SCE611EJDARA	4
Cummins M11	1996	TCE661EJDARA	90
Cummins ISM	1999	XCEXHO66AMA1	39
Cummins ISM	2000	YCEXH0661MA1	73
Cummins ISM	2001	1CEXHO661MAP	55
Caterpillar 3126	2001	YCPXHO442HRK	56
TOTAL	-	-	339

The sanitation trucks have logged over 966,000 miles on DPF units with only a few minor problems. According to City staff, all problems have been resolved satisfactorily with Boerner Truck Center. In one case, the back pressure warning light came on. In two cases, the weld on the can came apart. The City of Los Angeles' mechanics welded the cans shut, and Boerner agreed to provide the

City with four new cans to replace the two that broke and provide them with two spares.

4. Future Retrofit Plans by City of Los Angeles

The City's refuse fleet comprises approximately 683 trucks, 661 of which belong to the Bureau of Sanitation. The City has determined not all of the trucks are able to be retrofit with DPFs because of age, duty cycle, or other factors. An additional 75 collection vehicles, including rear loaders, front loaders, transfer and roll-off trucks, for a total of 429, will be retrofitted.

For the remainder of the Sanitation fleet, the City is replacing older trucks with new dual-fuel (Caterpillar/Clean Air Partners) trucks, which are allowed under the SCAQMD Rule 1193. The City has 120 of these dual-fuel trucks on order, with an option for 120 more if the first ones are satisfactory. A DECS will need to be added to these dual fuel collection vehicles to meet the requirements of the both the SCAQMD Rule 1993 and the ARB proposed regulation for SWCVs.

Los Angeles will be retrofitting another 592 on-road medium and heavy heavy-duty diesel trucks by the end of January 2004, to comply with the City Council motion to retrofit everything that can be retrofitted with ARB verified technologies. Of these, the City plans to retrofit 82 trucks, including tractors and dump trucks, by March 2003. Trucks owned by the Fire Department, Department of Water and Power, Los Angeles World Airports, and Ports are not included, and the Fire Department is exempt.

B. International Experiences

In 2000, the ARB established the International Diesel Retrofit Advisory Committee, which met six times from 2000 through 2002, to provide ARB with technical information regarding retrofitting diesel vehicles. In addition to technical experts in the United States, ARB invited knowledgeable persons from countries in Europe and Asia with diesel vehicle retrofit programs to join the group. The following summarizes some of the information ARB gained as a consequence of working with international experts on retrofit experiences in countries other than the United States.

1. Sweden

Sweden requires heavy-duty diesel trucks operating in certain urban areas to have reduce diesel PM emissions. Because of this, ARB contracted with MTC AB of Sweden to describe the number and success of vehicles operating in Sweden using DECS (MTC AB 2003). Of all the vehicles surveyed, there were 46 collection vehicles equipped with DPFs, which ranged in engine MY from 1991 to 2001. Twenty-four of the DPFs were installed as original equipment and the rest were retrofitted.

The engine manufacturers represented in the study were Scania and Volvo. While Scania does not sell engines in the California market, Volvo represents a significant portion of California's engine fleet, especially in the model years surveyed (about 13 percent). The vehicle types surveyed were rear loaders, roll offs, front loaders, and others not covered by the proposed regulation, such as sludge tankers (**Figure 1**). All except one vehicle are automatic transmissions and all of the collection vehicles operate in a city stop-and-go duty cycle.

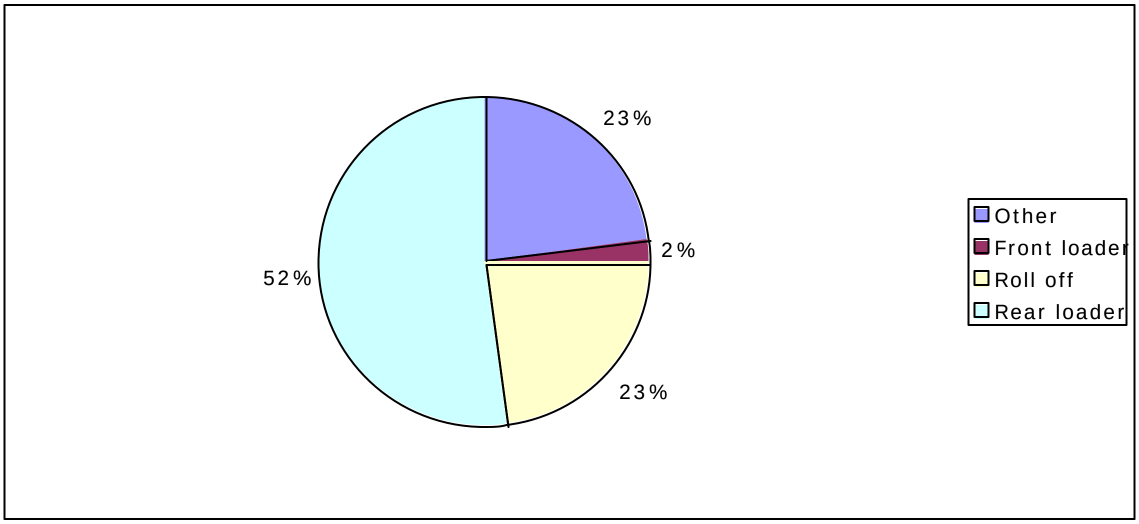

Figure 1. Types of Collection Vehicles with Passive Diesel Particulate Filters in Sweden.

For these 46 refuse haulers, no filter-related problems were reported related to fuel consumption or driveability. Fleet owners also reported no problems with clogged filters. Owners reported they regularly clean the filters during an annual or biannual service, depending on the mileage traveled. The average annual mileage for these vehicles was about 21,700 miles.

2. Switzerland

The Swiss Agency for the Environment, Forests, and Landscape (SAEFL) has sponsored research on the technical aspects of retrofitting all heavy-duty vehicles with DPFs (SAEFL 2000). As of 1999, Switzerland had approximately 66,000 heavy-duty vehicles registered, including 1,230 disposal trucks. The study concluded most vehicles could be retrofitted, except for those with high emissions, and excessive fuel and oil consumption.

As of the report, about a dozen trucks and a few hundred buses had been operating successfully with DPF systems for almost ten years and over 311,000 miles.

3. Japan

The Tokyo government has adopted regulations to reduce diesel PM emissions from cars and trucks operating within the city. An ordinance was adopted in December 2000 and the major provisions are establishment of PM emission standards and the prohibition of operation in Tokyo of diesel vehicles that do not meet those standards. The regulations take effect October 2003 and apply to vehicles more than seven years old. Installation of a PM reduction filter, replacement with gasoline-fueled or other non-diesel vehicles, or use of vehicles meeting the PM standard are allowable strategies (Tokyo Metro 2003). ARB has no data at this time specifically on collection vehicles, however.

4. Hong Kong

In 2000, the Hong Kong government adopted a program to retrofit approximately 30,000 delivery vans, sanitation trucks, construction equipment, and other diesel vehicles with DOCs (DieselNet 2003). The program is voluntary for vehicle owners, but the Hong Kong government is providing rebates to cover the cost of the installation. The current program covers vehicles operating in the Hong Kong Special Administrative Region, but will be extended to vehicles that travel to the mainland in 2003. For the Hong Kong program, qualifying emission control devices must reduce PM emissions by 35 percent when new and by 25 percent at 250,000 kilometers or five years. For the vehicles that travel to the mainland, which must use fuel with a higher sulfur content than available in Hong Kong, required PM emission reductions are 25 percent when new and at 250,000 kilometers or five years.

C. Demonstrations

While ARB bases much of its evaluation of technological feasibility on the immense amount of worldwide experience on many vehicle categories, smaller test programs on SWCV fleets are being conducted by ARB to investigate various technologies operating outside of the areas already demonstrated worldwide. Some of the technology being tested has already been proven on certain model years and applications and the focus of the demonstration is to examine if it can be expanded out to other engines and operating conditions. Other technologies being tested are under development and may become commercially available in the near future. The BP-Arco demonstration was discussed above in the context of the City of Los Angeles' sanitation vehicles, so it will not be discussed here.

All of ARB's demonstrations are scheduled to continue operating into the future. Since the technologies being tested would only broaden the availability of technology, staff felt it was not necessary to wait for them to be concluded. Preliminary results are discussed below.

1. DPF Use on Older Collection Vehicles

In July 2001, ARB initiated a demonstration with a privately-owned solid waste collection company, Burrtec Waste Industries, Inc., to gain information on the emission reduction potential, as well as the durability, of passive and active particulate filters when operated on older collection vehicles. Six pre-1994 collection vehicles (**Table 5**), operating in Riverside, California, were selected for the demonstration. Johnson Matthey (JM) and Clean Air Systems (CAS) installed DPFs in July 2001, and the project is expected to be completed by December 2003. The cost of the demonstration was shared between ARB and Burrtec Waste Industries, Inc.

Table 5. Collection Vehicles Involved in Demonstration.

Vehicle ID	Engine Model Year	Engine Model	Vehicle Type	Trap Type
3623	1991	Volvo TD73EB	Side Loader	Passive JM CRT
3710	1991	Cum L10	Side Loader	Passive JM CRT
2443	1989	Cat 3208-T	Side Loader	Active JM CRT
3722	1990	Cum L10	Side Loader	Active JM CRT
2764	1987	Cat 3306	Side Loader	Passive CAS
3708	1991	Cum L10	Side Loader	Passive CAS

a. Demonstration Emission Results

Two vehicles were tested for emissions pre- and post-installation of DPF at ARB's vehicle emissions testing lab in Los Angeles. The results for these two vehicles indicate a decrease in PM, HC, CO, and NO_x for the DPFs. While the HC and CO reductions are consistently high, the PM reductions are lower than expected. The trucks demonstrated good PM reduction for the first few months after DPF installation, however.

For vehicle #3710 (**Table 6**), the reduction of 72 percent PM experienced is likely a result of a filter blow-out due to high engine backpressure (see section below). Even with a blown-out filter, however, the truck had a significant reduction in diesel PM emissions. In addition, this vehicle experienced a slight fuel economy benefit of five percent.

For vehicle #3722 (**Table 7**), the active DPF reduced PM emission by a higher percentage, 88 percent. Emission reductions for HC and CO were also high. In this case, however, NO_x emissions increased slightly by four percent. The data show a fuel economy penalty of seven percent.

Table 6. Pre- and Post-Installation Test Results under UDDS Test Cycle For Passive DPF-Equipped Collection Vehicle (ID # 3710).

Date	PM (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	MPG
1/17/02	1.06	2.70	4.26	15.53	5.78
11/26/02	0.30	0.04	0.18	15.17	6.06
%Change	-72 %	-99 %	-96 %	-2 %	-5%

Table 7. Pre- and Post-Installation Test Results under UDDS Test Cycle For Active DPF-Equipped Collection Vehicle (ID # 3722).

Date	PM (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	MPG
11/20/01	1.04	2.44	6.63	18.44	5.37
3/28/02	0.12	0.25	0.27	19.23	4.98
%Change	-88 %	-90 %	-96 %	+4%	+7 %

b. Demonstration Operations Results

Two of the six units have been operating successfully since installation. ARB staff inspected and smoke-tested these two vehicles, trucks #3623 and 3708, in early 2003 and found operations to be as expected with very low smoke emissions. A third unit, an active DPF on truck #2764, was operating successfully for nearly a year until early 2003. The DPF was installed under the truck floor and was damaged while the truck was driving on rugged terrain at a landfill.

The other three units experienced failures for various reasons.

Truck #3710 exhibited high backpressure readings in late October 2002. According to automated data collection on-board, the collection vehicle continued to be operated despite the warning light with no service call to the manufacturer and as a result the passive DPF eventually failed.

Truck #2443 was equipped with an active filter that required overnight regeneration using a wall-plug. Data suggest maintenance personnel did not properly regenerate the system over several days resulting in partial DPF failure.

Truck #3722 had been operating well until a turbocharger failure caused sudden excessive PM emissions, resulting in trap failure.

c. Lessons from the Demonstration

This demonstration illustrated some of the challenges of retrofitting with passive DPFs, especially on pre-1994 trucks. First, operation on older diesel engines with mechanical engine control and operating under extreme duty cycles may not be a good match for the passive DPF. Second, successful operation of DPF requires a commitment from the drivers and maintenance staff to service the units promptly and correctly. Third, placement of the DPF requires drivers take care during operation not to damage the unit.

Many solid waste collection companies operate and depend on older pre-1994 trucks to perform a significant percentage of their daily operations. It may be prudent to utilize other PM control strategies, such as FTFs and DOCs, that offer less PM emissions benefits (25 to 50 percent efficiency), but higher probabilities of good durability, with these older vehicles.

2. Fuel-Borne Catalyst Effect Demonstration

In September 2002 ARB began a demonstration on collection vehicles with 1992 and 1996 model year engines using Clean Diesel Technologies and Clean Air Systems DECS. The solid waste collection partner is Waste Management. The objective of this demonstration is to quantify the emission reduction potential and in-use durability of using a Platinum-Based Fuel Additive (FBC) combined with three different aftertreatment technologies: a DOC, a DOC combined with a flow through particulate filter (FTF), and a lightly catalyzed (LC) ceramic wall flow DPF, on six collection vehicles with differing certified PM emission levels. Engines from 1992 were certified to 0.25 g/bhp-hr PM, whereas the 1996 engines were certified to 0.1 g/bhp-hr PM.

Table 8. Test Vehicles and Installed DECS.

Engine & Type	Device
1992 Cummins L10 Residential Front Loader	DOC/FTF
1996 Cummins C8.3 Automated Side Loader	DOC/FTF
1992 Cummins L10 Recycling	DOC (LC)
1996 Cummins C8.3 Commercial Rear Loader	DOC (LC)
1992 Cummins C8.3 Recycling Side Loader	DPF (LC)? FTF
1996 Cummins C8.3 Automated Side Loader	DPF (LC)? FTF

The DECS manufacturers installed the emission control devices in Fall 2002. ARB completed baseline testing of three trucks in October 2002. The second round of testing is scheduled for 2003 and results are not yet available. The final round of testing will be conducted after the test vehicles have completed at least one year of in-use operation to assess durability. The demonstration has provided data already on proper dosing of the FBC in combination with the add-on technologies.

Two issues have arisen thus far. First, a malfunction of the dosing system for the FBC caused untreated low sulfur diesel to be delivered to the demonstration trucks for several weeks. One of the lightly-catalyzed DPFs was damaged and replaced. Second, in March it was determined that, even with the FBC, the lightly-catalyzed DPFs were not regenerating sufficiently. Rather than changing the dosage, staff decided to remove the lightly-catalyzed DPFs and replace them with stand-alone FTFs.

3. Older SWCVs and Lower Efficiency DECSs

In addition to the demonstrations already discussed, ARB has also committed additional funding to demonstrate DOCs and FTFs on older collection vehicles using Johnson Matthey technology. This demonstration will begin in mid-2003 and is expected to last for a minimum of one year after DECS installation. The DECSs are to be installed on a range of engines in front and side loaders owned by up to three companies (**Table 9**). The goal is to demonstrate the durability of DOCs and FTFs operating successfully on collection vehicles not compatible with DPF technology.

Table 9. Proposed Matrix for DOC & FTF Demonstration on Older SWCVs.

Engine	Model Year	DECS
CAT 3208	1985	FTF
CAT 3208	1988	FTF
CAT 3208	1984	DOC
Mack E7	1988	DOC
Mack E7	1988	DOC
Mack E7	1989	FTF
Mack E7	1993	FTF
Volvo TD-73	1993	FTF
Cummins M11	1997	FTF

ARB has committed funding long term for demonstrations in SWCVs to assess durability and operations over time, in addition to measuring emission reductions. ARB is continuing demonstrations to provide additional data to collection vehicle owners regarding operating characteristics of the various diesel emission control technologies. In addition, ARB staff has collected useful data during these demonstrations that we will pass on to owners through outreach programs.

VIII. Predicting Retrofit Feasibility for Solid Waste Collection Vehicles

In addition to the demonstrations, ARB staff has carried out three studies to determine the potential success and limitations of implementing this proposed regulation given the use of DECS as BACT. The studies were initially focused on testing the feasibility of the passive DPF, but the data collected have been expanded to the feasibility of additional DECS technologies. The results of the most narrowly focused study, the engine exhaust temperature study, are applicable to any technology that relies on engine exhaust temperature for successful operation – at present the DPF and FTF technologies fit this description.

In combination with the demonstrations, the fleet maintenance (Appendix A), engine exhaust temperature (Appendix B), engine inventory (Appendix C) studies have enabled staff to determine not only technical limitations of DECS, but also develop realistic expectations of implementation. Details about each study are found in the appendices of this document. This section will discuss the results and conclusions as they relate to the feasibility of implementing the proposed regulation of SWCVs.

A. DECS Technical Limitations

Each DECS verified thus far is limited to specific engines and operating conditions. DECSs may have additional limitations based on the duty cycle experienced by the vehicle, environmental conditions, and the willingness of the operator to perform required maintenance. The DECS technical limitations discussed here represent a conservative analysis of data collected from the studies, demonstrations, verifications, and published literature. Some of these limitations may be a consequence of lack of data on in-use experience. Some of these limitations may disappear when new technology is verified. Thus the following discussion is based on currently available data and is not a prediction of the applicability of all DECS that may be available in the future.

1. Passive DPF

Forty-four percent of California collection vehicles have 1994 and newer model year engines (**Table 10**). Passive DPFs are verified for nearly all of the engine families used in these 1994 and newer collection vehicle engines, for a total of approximately 42[2] percent of California SWCVs theoretically being able to be retrofit with a DPF. Thus, about 42 percent of the collection vehicles could have their PM emissions reduced by 85 percent diesel.

ARB's study of engine exhaust temperatures (Appendix B), however, plus data from a private collection vehicle company (Stoddard 2001) and a DECS manufacturer (Donaldson 2003), suggest that many collection vehicles may not achieve the engine exhaust temperatures required by the two currently verified passive DPFs, depending on the duty cycle of each specific vehicle.

Meeting a minimum engine exhaust temperature is a technical limitation of a DPF because a minimum temperature is required to ignite the soot for regeneration. The minimum required temperature may vary depending on the amount of catalyst material, but the two verified passive DPF devices must achieve an

[2] This figure assumes verification will be extended to 2003 to 2006 model year engines, which are predicted to comprise approximately ten percent of the collection vehicle fleet in California.

average temperature of 225 degrees Celsius with ten percent of the duty cycle above 300 degrees Celsius, and a temperature of 260 degrees Celsius for 40 percent of the duty cycle, respectively (ARB 2001b; ARB 2000).

Engine exhaust temperatures were found to vary between the four main types of collection vehicles: front, side, and rear loaders and roll offs (**Figure 2**). Applying the results from the study to the inventory by engine model year group and vehicle type (**Table 10**), approximately 32 percent of 1994 to 2002 model years are expected to be able to use passive DPFs. If verification of these passive DPFs is extended to 2003 to 2006 engine model years, then the same percentage of those vehicles are expected to be able to use passive DPFs.

Table 10. Fleet Composition by Engine Model Year Group and Vehicle Type.

Engine Model Year Group	Collection Vehicle Type				
	Front Loader	Rear Loader	Roll Off	Side Loader	Total
1960-1987	5%	8%	3%	2%	18%
1988-1990	6%	9%	2%	4%	21%
1991-1993	5%	4%	1%	7%	17%
1994-2002	10%	6%	3%	25%	44%
Total	26%	27%	9%	38%	100%

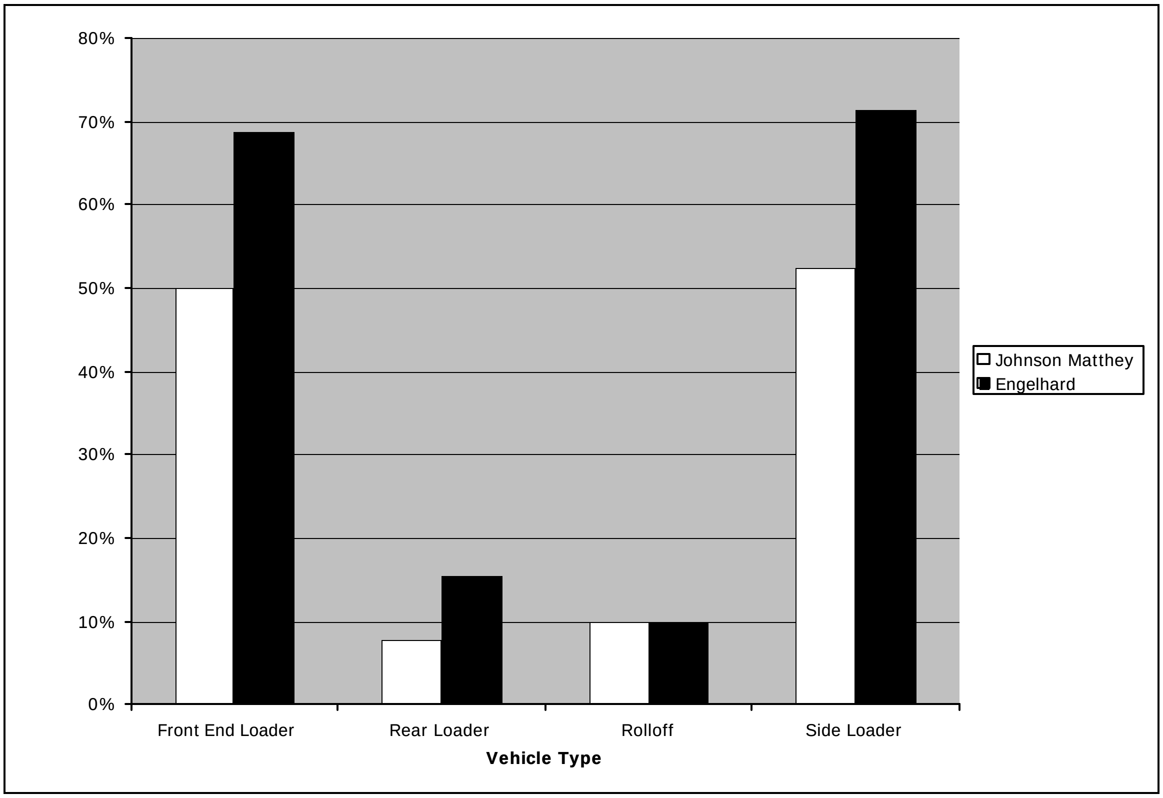

Figure 2. Percentage of Collection Vehicles by Vehicle Type that Met Engine Exhaust Temperature Requirements for Two Variations of Passive Diesel Particulate Filters.

2. Level 1 and 2 DECS

Staff expects fewer limitations with the use of DECS technologies other than the passive DPFs discussed above. Following is a discussion of specific verified and potential DECS Level 1 and 2 technologies.

a. Fuel-Water Emulsion

A fuel-water emulsion, such as that produced by PuriNOx™, is not limited by engine model year, PM emissions, or engine exhaust temperature, and could potentially be utilized in all collection vehicles. Some limitations, however, may exist with this technology. Winter-time temperatures, turnover of fuel in storage tankage, and the power loss associated with the fuel-water emulsion may limit its application. Low winter temperatures cause an increase in viscosity, and the fuel-water emulsion has separated if allowed to sit for too long. In addition, a company that operates its vehicles to the maximum power available on a frequent basis, such as one operating in a hilly area, may have difficulty using a fuel-water emulsion.

b. Flow Through Filter

An emerging technology, FTF, has the potential to achieve verification at Level 2, although addition of a fuel additive may be necessary for Level 2 emission reduction. This technology is expected to be more widely applicable, but achieve lower emission reductions, than a DPF. The technology does have a requirement for minimum engine exhaust temperature, but that minimum is lower than required for a passive DPF.

Although ARB does not have any FTF verified yet, at least one manufacturer requires that the exhaust temperature from vehicles reach 200 degrees Celsius for approximately 50 percent of the duty cycle to use an FTF. ARB's analysis of the engine exhaust temperature study shows that 80 percent of the collection vehicles are capable of achieving this temperature in-use (**Figure 3**, Appendix B). Based on the data, all front end loaders, 62 percent of rear loaders, 40 percent of roll-offs, and 95 percent of side loaders could use a flow-through filter.

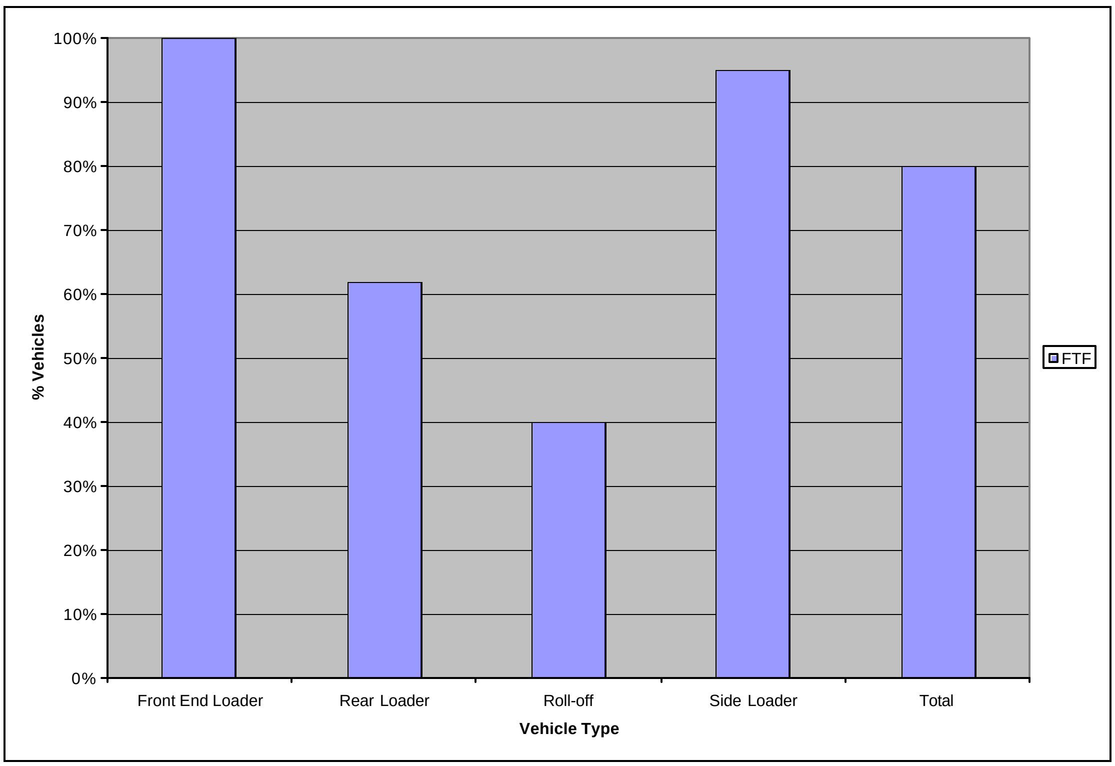

Figure 3. Percentage of Collection Vehicles by Vehicle Type that Met Engine Exhaust Temperature Requirements for Flow-Through Filters.

c. Diesel Oxidation Catalyst

DOCs are expected to be widely applicable in collection vehicles. Technical limitations may be associated with retrofitting pre-1988 collection vehicles with the verified DOC with closed loop crankcase, however, based on the verification conditions. Engine emissions from pre-1988 collection vehicles vary significantly and in some cases may be too high for effective operation.

B. Engine Repower Limitations

Repowering to a 0.01 g/bhp-hr engine is not always possible. The engine compartment may not be large enough to install a newer, electronic controlled engine where previously a mechanical engine was housed. Otherwise, the cost of converting from mechanical to electronic fuel injection may outweigh the value of the vehicle or remaining vehicle life.

Alternative-fueled engines do not have widespread acceptance among SWCV companies because of perceived issues with higher maintenance, unavailability and high cost of fueling infrastructure, horsepower, and other factors related to reliability, durability, and cost. Within the SCAQMD, where companies are required to acquire alternative-fuel vehicles when purchasing or leasing, fueling infrastructure is rapidly expanding and many companies are purchasing dual-fuel and 100% alternative fuel collection vehicles.

Heavy-duty pilot ignition engines will have the same fueling infrastructure problem as 100 percent natural gas engines, but may have more acceptance because of the inherent features of the compression-ignition engine, such as reliability, durability, and power.

These limitations are not expected to hinder many collection vehicle owners from purchasing or repowering engines, rather than using DECS. A new engine has many benefits over retrofitting an old engine, such as longer useful life, engine warranty, and familiarity with the technology.

C. Impact of Fleet Maintenance Practices

Fleet maintenance practices will play a critical role in the successful implementation of this proposed regulation. A company with good maintenance practices will have greater success with using DECSs on its vehicles than a company with poor maintenance practices. In addition, diagnosis of engine problems will be more difficult given the masking of excessive smoke caused by the use of DECS. If the only mechanism used by fleet maintenance personnel to detect engine problems is the appearance of excessive smoke, then problems may not be detected until so much PM is generated that damaged is caused to the DECS. A well-maintained vehicle, therefore, is crucial to the operating success of BACT on SWCVs.

Lack of maintenance is reportedly responsible for 50 percent of engine and equipment failures in SWCVs (Dolce 2000). ARB staff conducted a study on sixty solid waste collection companies and found most were well-maintained according to the maintenance parameters captured (Appendix A). Based on observed maintenance practices, the publicly-owned fleets have the highest probability of successfully retrofitting their collection vehicles with DECS, followed by the large then small private companies.

The most important recommendation arising from this study is for companies to ensure their mechanics are well-trained on proper engine care. Secondly, the mechanics must be trained appropriately on inspection, maintenance and service of DECS. Finally, the operators must be aware of and drive with care and attention to the DECS to avoid damage or failure from driver error.

D. Implications for Solid Waste Collection Vehicle Fleet Retrofit Feasibility for Emission Reductions

Based on the foregoing, staff developed three implementation scenarios for calculating technology usage from the proposed rule: a scenario based on currently verified DECS, a scenario based on expected verifications of DECS, and a scenario based on potential verifications of DECS. Each of these three scenarios assumes some engines would either be repowered to 0.01 g/bhp-hr engines or would purchase new 0.01 g/bhp-hr engines. The option of converting to alternative-fuel or heavy-duty pilot ignition engines exists for all engines either through vehicle replacement or conversion of the engine.

Each scenario was then fed into ARB's mobile source emission inventory, EMFAC2002, to generate predicted emission benefits from implementation of this rule. The inventory methodology is discussed in more detail in the Staff Report: Initial Statement of Reasons for this proposed rule and Appendix E of that document.

1. Scenario 1: Currently Verified DECS

The first scenario is based on the use of currently verified DECS (**Table 11**). Staff assumed no additional technologies would be verified before implementation of the proposed regulation begins in 2004 and no new technologies would be verified throughout the implementation phase-in period to 2010. This scenario is weighted more so on the use of the currently verified Level 1 DECS, and the use of engines meeting a 0.01 g/bhp-hr PM emissions standard, either through repowering or as an original engine purchase.

In Group 1, the 1994 to 2002 MY engines would use a combination of passive DPF Level 3 DECS, Level 1 DECS, and repower. As discussed above, passive DPF is technically limited by engine exhaust temperature requirements and high PM emissions on pre-1994 engine model years. Staff assumes a new engine, through repower or new vehicle purchase, would only become available with the 2007 engine model year, and, therefore, the first three implementations dates would be met only by the use of DECS.

Also in Group 1, the 1991 to 1993 MY engines would use primarily the Level 1 DECS throughout the four years of implementation phase-in. Again, staff assumes a new vehicle or engine repower would only become available with MY 2007.

The Group 1 1988 to 1990 MY engines would not have any verified DECS available. Therefore, staff assumes new vehicle or engine repower will be implemented beginning in 2007. Since no DECS are currently available for those engine model years, staff assumed 50 percent of the engines would receive a delay in implementation.

All vehicles in Group 2 are expected to repower or replace with a 0.01 g/bhp-hr engine because of the requirements of the proposed regulation and lack of other available technologies. Companies with fewer than 15 vehicles would be expected to receive a delay in this requirement.

Group 3 MY engines would use either DECS Level 3 or passive DPF or Level 1, but would also be able to use 0.01 g/bhp-hr engines. Staff expects some owners would purchase these 0.01 g/bhp-hr engines new, but this assumption is not critical to the scenario.

This scenario produced the following estimated technology use (**Table 11**).

Table 11. Implementation Scenario 1 (Current).

Group	Eng MY	%BACT	Implementation Date	Technology Option (By Percent Phase-In) Level 1	Level 2	Level 3[a]	Repower	OE[h] 0.01
1	1994-2002[g] 32% of fleet	10%	12/31/2004	2.0%		8.0%		
		25%	12/31/2005	7.0%		8.0%		
		50%	12/31/2006	17.0%		8.0%		
		100%	12/31/2007	25.0%		5.0%	20.0%	
1	1991-1993[g] 14% of fleet	10%	12/31/2004	10.0%				
		25%	12/31/2005	15.0%				
		50%	12/31/2006	25.0%				
		100%	12/31/2007	30.0%			20.0%	
1	1988-1990[c] 18% of fleet	10%	12/31/2004					
		25%	12/31/2005					
		50%	12/31/2006					
		100%	12/31/2007				50.0%	
		Delay	12/31/2008				50.0%	
2	1960-1987[b] 27% of fleet	25%	12/31/2007				22.8%	
		50%	12/31/2008				22.8%	
		75%	12/31/2009				22.8%	
		100%	12/31/2010				22.8%	
		Delay	12/31/2011				9.0%	
3	2003-2006[d,e] 9% of fleet	50%	12/31/2009	14.1%		15.9%		20.0%
		100%	12/31/2010	14.1%		15.9%		20.0%
Percent of California's Collection Vehicle Fleet Total:				30%	0%	12%	54%	4%

[a] Only 1994-2002 MY engines were considered for passive diesel particulate filters based on verification data. Assumption based on manufacturer with lowest engine exhaust temperature requirement.
[b] Nine percent of 1960-1986 vehicles are owned by companies with less than 15 vehicles (63 percent of surveyed companies).
[c] Assume all vehicles will repower and have BACT delays since no DECS are currently available.
[d] Assume current Level 3 verification will be extended to 2003-2006 MYs.
[e] Assume current Level 1 verification will be extended to 2003-2006 MYs.
[f] Assume small fleets (<15 vehicles) will have no DECS available and receive implementation delay to 2011.
[g] Assume 20 percent repower even though DECS currently available to these model years due to preference by some collection vehicle owners.

2. Scenario 2: Potential 1 DECS

The second scenario is based on a combination of currently verified DECS and DECS that may be verified before the beginning of the implementation period (**Table 12**). For this scenario, staff assumes verification of Level 1 DECS technologies would be extended to all engine model years of collection vehicle engines.

1991 to 2002 engine MYs in Group 1 remain unchanged in this scenario. 1988 to 1990 engine MYs would now have the option of using a Level 1 DECS, but would still be expected to repower a fraction of these vehicles. The use of 0.01 g/bhp-hr diesel engines is still weighted heavily because, based on discussions with fleet owners, staff assumes given the option many owners will opt to use such an engine in lieu of retrofitting their engines. This is especially true given that Level 1 technologies would be permitted for use on the collection vehicles for a limited timeframe of ten years for Groups 1 and 2 and five years for Group 3.

Group 2 vehicles are expected to be able to use a Level 1 DECS on some portion of their fleet. PM emissions are expected to limit applicability to 1960 to 1987 MY engines, especially the highest emitters. Repowers are, therefore, still heavily weighted.

Group 3 remains unchanged in this scenario relative to the first scenario.

Table 12. Implementation Scenario (Potential 1) - No Level 2 Verified.

Group	Eng MY	%BACT	Implementation Date	Technology Option (By Percent Phase-In)				
				Level 1	Level 2	Level 3[a]	Repower	OE[g] 0.01
1	1994-2002[f]	10%	12/31/2004	2.0%		8.0%		
	32% of fleet	25%	12/31/2005	7.0%		8.0%		
		50%	12/31/2006	17.0%		8.0%		
		100%	12/31/2007	25.0%		5.0%	20.0%	
1	1991-1993[c, f]	10%	12/31/2004	10.0%				
	14% of fleet	25%	12/31/2005	15.0%				
		50%	12/31/2006	25.0%				
		100%	12/31/2007	30.0%			20.0%	
1	1988-1990[c, f]	10%	12/31/2004	10.0%				
	18% of fleet	25%	12/31/2005	15.0%				
		50%	12/31/2006	25.0%				
		100%	12/31/2007	30.0%			20.0%	
2	1960-1987[b,c, f]	25%	12/31/2007	2.3%			22.8%	
	27% of fleet	50%	12/31/2008	2.3%			22.8%	
		75%	12/31/2009	2.3%			22.8%	
		100%	12/31/2010	2.3%			22.8%	
3	2003-2006[d,e]	50%	12/31/2009	14.0%		16.0%		20.0%
	9% of fleet	100%	12/31/2010	14.0%		16.0%		20.0%
Percent of California's Collection Vehicle Fleet Total:				47%	0%	12%	37%	4%

[a] Only 1994-2002 MY engines were considered for passive diesel particulate filters based on verification data.

Assumption based on manufacturer with lowest engine exhaust temperature requirement.

[b] Nine percent of 1960-1986 vehicles are owned by companies with less than 15 vehicles (63 percent of surveyed companies).

[c] Assume current Level 1 verification will be extended to 1960-1993 MYs.

[d] Assume current Level 3 verification will be extended to 2003-2006 MYs.

[e] Assume current Level 1 verification will be extended to 2003-2006 MYs.

[f] Assume 20 percent repower even though DECS either currently or expected to be available to these model years due to preference by some collection vehicle owners.

[g] Original equipment – purchased new.

3. Scenario 3 – Potential 2 DECS

The third scenario is more optimistic regarding the verification of Level 2 technology (**Table 13**). Examples of potential Level 2 technologies include a fuel-water emulsion or a FTF plus a fuel additive. These verifications may be limited as discussed above and therefore, especially for older vehicles, Level 1 DECSs are still predicted to fulfill a small percentage of the compliance requirements for these collection vehicles.

In Group 1 1991 to 2002 MY engines, no changes would occur for the use of Level 3 DECSs, but a shift from using Level 1 to Level 2 DECSs would occur. Additionally for Group 1 1988 to 1990 MY engines and Group 2 MY engine, a portion of the fleets would use Level 2 DECSs. Group 3 assumptions remain unchanged.

Table 13. Implementation Scenario (Potential 2) – All Levels Verified.

Group	Eng MY	%BACT	Implementation Date	Technology Option (By Percent Phase-In)				
				Level 1	Level 2	Level 3[a]	Repower	OE[h] 0.01
1	1994-2002[c, e] 32% of fleet	10%	12/31/2004		2.0%	8.0%		
		25%	12/31/2005		7.0%	8.0%		
		50%	12/31/2006		17.0%	8.0%		
		100%	12/31/2007		25.0%	5.0%	20.0%	
1	1991-1993[c,e] 14% of fleet	10%	12/31/2004		10.0%			
		25%	12/31/2005		15.0%			
		50%	12/31/2006		25.0%			
		100%	12/31/2007		30.0%		20.0%	
1	1988-1990[c,e,f] 18% of fleet	10%	12/31/2004	2.0%	8.0%			
		25%	12/31/2005	2.0%	13.0%			
		50%	12/31/2006	2.0%	23.0%			
		100%	12/31/2007	2.0%	28.0%		20.0%	
2	1960-1987[b,e,f] 27% of fleet	25%	12/31/2007	2.0%	0.25%		22.75%	
		50%	12/31/2008	2.0%	0.25%		22.75%	
		75%	12/31/2009	2.0%	0.25%		22.75%	
		100%	12/31/2010	2.0%	0.25%		22.75%	
3	2003-2006[d,e] 9% of fleet	50%	12/31/2009		14.0%	16.0%		20.0%
		100%	12/31/2010		14.0%	16.0%		20.0%
Percent of California's Collection Vehicle Fleet Total:				4%	43%	12%	37%	4%

[a] Only 1994-2002 MY engines were considered for passive diesel particulate filters based on verification data. Assumption based on manufacturer with lowest engine exhaust temperature requirement.
[b] Nine percent of 1960-1986 vehicles are owned by companies with less than 15 vehicles. (63 percent of surveyed companies.)
[c] Assume 20 percent repower even though DECS currently or expected to be available to these model years due to preference by some collection vehicle owners.
[d] Assume current Level 3 verification will be extended to 2003-2006 MYs.
[e] Assume a PuriNOx+DOC Level 2 could be verified for all model years.
[f] Assume a small percentage of fleet may not be able to use Level 2 devices.
[g] Assume low sulfur fuel used for only installed diesel particulate filters before 2006.
[h] Original equipment – purchased new.

4. Predicted Emission Benefits

According to the emissions benefits calculated by the EMFAC2002 model using these three scenarios, California's SWCV fleet would be able to achieve between 72 and 81 percent diesel PM emission reductions by 2010, between 71 and 85 percent diesel PM emission reductions by 2015, and between 67 and 82 percent diesel PM emission reductions by 2020 (**Table 14**). Natural fleet turnover accounts for the slightly lower predicted PM reductions in 2020.

Table 14. Percent Reduction in Diesel PM Emissions From California's Solid Waste Collection Vehicle Fleet.

Calendar Year	Baseline Inventory (tpd)	Reduction		
		Current	Potential 1	Potential 2
2005	1.57	3%	6%	10%
2010	1.42	81%	72%	79%
2015	1.36	85%	71%	78%
2020	1.12	82%	67%	75%

The "current" scenario achieves the greatest percent reductions in PM emissions because staff assume a higher use of repowers, whereas in the two "potential" scenarios staff assumes a higher usage rate for Level 1 and 2 technologies. As this rule allows owners to choose from a menu of options, with differing levels of effectiveness, staff is unable to predict the emission benefits with more precision than shown here.

None of these scenarios assumes Level 3 DECS will be verified for a wider range of engines than currently. Additionally, the widespread use of alternative-fuel and heavy-duty pilot ignition engines would reduce diesel PM emissions further. ARB staff is certain alternative-fuel and heavy-duty pilot ignition engines will used in the SWCV fleet motivated in part by municipality and air quality district edicts, such as SCAQMD's Rule 1193 (SCAQMD 2000) and, in part, by companies' self-motivation.

The three scenarios are, therefore, conservative in their emissions benefits reduction estimates. With the additional emission benefits from the use of alternative-fuel and heavy-duty pilot ignition engines, all three scenarios would be able to meet the goals of 75 percent reduction in diesel PM by 2010 and 85 percent reduction in diesel PM by 2020 in the SWCV fleet.

IX. Conclusions and Recommendations

A variety of options are available for applying BACT to California's SWCV fleet today. By the time implementation begins, staff predicts that additional DECS options will have been verified, with the result of wider applicability of DECSs for the vehicles and engines.

Staff recommends that owners and operators of collection vehicles be sufficiently informed and trained in maintenance practices for these BACTs. This should take the form of appropriate training of mechanics and operators and establishment of procedures to meet any potential issues that might arise as a result of a new technology being available.

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