Diesel Retrofit Technologies and Experience for On-road and Off-road Vehicles

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EXECUTIVE SUMMARY

Diesel engines are important power systems for on-road and off-road vehicles. These reliable, fuel-efficient, high-torque engines power the vast majority of the world's heavy-duty trucks, buses, and off-road vehicles. While diesel engines have many advantages (e.g., good fuel efficiency, long operating lifetime), they have the disadvantage of emitting significant amounts of particulate matter (PM) and oxides of nitrogen (NOx) into the atmosphere. Companies that manufacture emission controls have responded to the challenge of reducing air pollution from the in-use diesel vehicle fleet by developing a large portfolio of retrofit emission control devices. Many of these diesel retrofit technologies are similar to the advanced emission control technologies that are now available on newer "clean" diesel engines used in highway and off-road applications including diesel oxidation catalysts (DOCs) and diesel particulate filters (DPFs) for reducing diesel PM; and urea-selective catalytic reduction (SCR) systems for reducing NOx. In both the on-road and off-road sectors, diesel retrofit technologies have demonstrated their ability to significantly reduce unwanted emissions from older diesel engines at reasonable cost without jeopardizing vehicle performance.

This report summarizes important features and experiences of successful retrofit program efforts primarily in the U.S. and Europe, as well as highlighting the range of retrofit technologies that have been successfully used to reduce exhaust emissions (including diesel particulate and NOx emissions) from older, existing on-road and off-road diesel engines. This report focuses the retrofit technology discussion on the experience with high efficiency retrofit diesel particulate filters and SCR retrofits, since these retrofit technologies provide the highest reduction efficiencies for diesel particulates and NOx emissions. Diesel retrofit technology verification protocols have been established in both the U.S. and Europe to ensure retrofit technologies provide proven and durable emission reductions. Other important aspects of successful retrofit programs (in addition to using verified technologies) include an application engineering approach that selects the appropriate retrofit technology based on the vehicle/engine application, its duty cycle and available fuel quality, continued maintenance of the engine and retrofit technology, professional installation of the retrofit device, and training programs for end users. The report includes web links to a wide range of information and experience concerning retrofits on both on-road and off-road diesel engines and vehicles.

INTRODUCTION

Diesel engines are important power systems for on-road and off-road vehicles. These reliable, fuel-efficient, high-torque engines power the vast majority of the world's heavy-duty trucks, buses, and off-road vehicles. Diesel engines are easy to repair, inexpensive to operate, and extremely durable. It is common for a diesel engine to last 15-20 years and achieve a one million-mile life (or more). Diesel-powered vehicles have demonstrated fuel economy advantages over their gasoline counterparts, which also translates to lower CO_2 emissions. While diesel engines have many advantages, they have the disadvantage of emitting significant amounts of particulate matter (PM) and oxides of nitrogen (NOx) into the atmosphere. Diesel engines also emit toxic air pollutants. Health experts have concluded that pollutants emitted by diesel engines adversely affect human health and contribute to acid rain, ground-level ozone, and reduced visibility. Studies have shown that exposure to diesel exhaust causes lung damage and respiratory problems and there is increasing evidence that diesel emissions cause cancer in humans. In June 2012 the International Agency for Research on Cancer (IARC) changed their designation for diesel exhaust from probable to a known carcinogen to humans (see: https://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf). Black carbon emissions, a dominant component of diesel PM, is also a significant contributor to climate change. Companies that manufacture emission controls have responded to the challenge of reducing air pollution from the in-use diesel vehicle fleet by developing a large portfolio of retrofit emission control devices. Many of these diesel retrofit technologies are similar to the advanced emission control technologies that are now available on newer "clean" diesel engines used in highway and off-road applications including DOCs and DPFs for reducing diesel PM; and urea-SCR systems for reducing NOx. In both the on-road and off-road sectors, diesel retrofit technologies have demonstrated their ability to significantly reduce unwanted emissions from older diesel engines at reasonable cost without jeopardizing vehicle performance.

Interest in diesel retrofits from the U.S. Environmental Protection Agency (EPA), the California Air Resource Board (CARB), and a number of international entities has grown substantially over the past 20 years. CARB established a mandatory retrofit program for most in-use heavy-duty highway diesel-powered vehicles in California as part of its Diesel Risk Reduction Plan (DRRP). Retrofits are also a compliance option for CARB's in-use off-road fleet regulation. The U.S. EPA has established a voluntary program with state and federal funding under its National Clean Diesel Campaign (hundreds of millions of dollars in funding provided since 2007 to reduce emissions from older highway and nonroad diesel engines). Both EPA and CARB require retrofit devices to complete a rigorous verification program to ensure that the devices meet strict performance and durability requirements.

EPA's clean diesel grants have been largely funded through the Diesel Emission Reduction Act (DERA), a grant program created by the U.S. Congress as part of the Energy Policy Act of 2005 to reduce diesel exhaust from older on-road and off-road engines. According to EPA's February 2016 report to Congress (available at: https://www.epa.gov/cleandiesel/clean-diesel-reports-congress) on their diesel emission reduction program, from 2009 to 2013 EPA awarded $520 million to retrofit or replace 58,800 engines in vehicles, vessels, locomotives or other pieces of equipment. Retrofit projects included the installation of more than 18,000 diesel oxidation catalysts (DOCs) and approximately 3,000 diesel particulate filters (DPFs) in both on-road and off-road applications. Funding was also provided for approximately 6,000 engine replacements or repowers. EPA estimates that the environmental impacts of all 2009-2013 funded projects will result in emission reductions of 312,500 tons of NOx and 12,000 tons of PM2.5 over the lifetime of the affected engines. As a result of these pollution reductions, EPA estimates a total present value of up to $11 billion in monetized health benefits over the lifetime of the affected engines, which include up to 1,700 fewer premature deaths associated with the emission reductions achieved over this same period. These clean diesel projects also are estimated to reduce 18,900 tons of hydrocarbon (HC) and 58,700 tons of carbon monoxide (CO) over the lifetime of the affected engines.

The VERT industry association in Europe has also established a widely used retrofit certification protocol for DPFs that served as one of the important examples that led to a United Nations retrofit emission control (REC) device regulation (UN Regulation Number 132) that was first adopted by the UN's WP29 working group in Geneva, Switzerland in 2014 and subsequently revised in 2015. There are approximately 50 contracting parties/countries that have signed on to the UN 132 retrofit regulation including European Union member states, Egypt, Russia, Turkey, Malaysia, New Zealand, and South Africa. However, few countries are actually utilizing these UN requirements to verify retrofit devices at this time. VERT has certified more than 65 retrofit filter systems for both on-road and off-road applications. Retrofits allow older diesel trucks to comply with numerous urban Low Emission Zone requirements in many European cities and allow construction equipment to comply with various European Low Emission Construction Zone requirements including those in greater London, Berlin, within Switzerland, and in alpine tunneling projects.

This report summarizes important features and experiences of successful retrofit program efforts primarily in the U.S. and Europe, as well as highlighting the range of retrofit technologies that have been successfully used to reduce exhaust emissions (including diesel particulate and NOx emissions) from existing on-road and off-road diesel engines.

A. Key Considerations for Successful Retrofit Projects

Retrofit technologies are not a "plug-and-play" or "fit-and-forget" technology approach for reducing emissions from older, in-use diesel engines. A successful on-road or off-road retrofit program or project should incorporate the following important considerations:

- Application engineering – match the right retrofit technology to the vehicle or equipment
    - EPA and CARB verifies retrofit technologies for specific engine families/ model years and/or maximum engine-out PM levels; passively regenerated DPF verifications include specific exhaust temperature duty cycle constraints
    - Custom designs are often needed to properly fit the retrofit technology into the appropriate vehicle/equipment space
    - Retrofit device designs need to be based on engine displacement and respect engine backpressure constraints
    - EPA and CARB verified retrofit technologies must include labels that can be used to check if the retrofit technology has been applied on engines included in the verification
- Vehicle/engine must be well maintained before considering it as a candidate for a retrofit
    - Gross emitters are generally not good retrofit candidates
    - EPA and CARB retrofit DPF verifications typically limit engine-out PM levels to 0.2 g/bhp-hr (0.27 g/kw-hr) [These PM limits roughly correspond to U.S. 1994 or Euro II and newer heavy-duty highway diesel engines, and U.S.

Tier 2/Euro Stage II nonroad diesel engines with power ratings from 130-560 kW. Engines that are 10 years old or more are likely emitting at PM levels higher than their emission certification limits. Each candidate retrofit engine needs to be assessed for its engine-out emission levels to determine whether it can accept a retrofit technology.]

- Available fuel sulfur levels dictate retrofit options – 50 ppm sulfur diesel fuel is a minimum requirement for precious metal-based, catalyzed retrofit DPFs
- Vehicle duty cycles and exhaust temperature profiles define retrofit options (especially critical for choosing between DPFs with active or passive filter regeneration schemes)
- Use of verified or approved retrofit technologies with proven performance/durability for the application of interest (retrofits for off-road equipment can often pose unique challenges); the most comprehensive retrofit verification or approval programs also include in-use compliance testing to confirm retrofit technologies are performing as verified or approved in the field
- Professional installation is needed to ensure system integrity and operation (retrofit installers must provide an installation warranty in California)
- Maintenance – vehicle/equipment and retrofit devices require regular inspections and maintenance to deliver durable, verified emission reductions
- On-vehicle monitors & diagnostics – these provide important user feedback on retrofit performance and the need for maintenance (EPA, CARB, VERT all have specific vehicle monitor requirements for retrofit DPFs and retrofit SCR systems)
- Training and education needs of vehicle operators and maintenance personnel (In California, training workshops have been offered by retrofit manufacturers, installers and CARB; CARB has retrofit training and educational materials available online at: https://www.arb.ca.gov/msprog/decsinstall/decsinstall.htm).

Although retrofit control technologies can be applied in theory to any appropriate diesel vehicle or engine, it may be easier to administer and control a program by targeting vehicle fleets. Some examples of captive fleets include urban bus fleets, school buses, privately-owned delivery fleets, publicly- and privately-owned construction equipment, publicly-owned diesel-powered vehicles, utility fleets, and construction equipment at a given construction site. The advantage of targeting these vehicles is that they are often centrally fueled and are typically maintained in a more controlled fashion. In addition, training of operators and maintenance personnel is more easily achieved. An important critical first step in determining whether an on-road or off-road engine is a good candidate for a retrofit is performing a pre-installation vehicle inspection (a "healthy" engine is generally a good candidate for a retrofit). This inspection should include:

- Examining the engine for potential pre-existing mechanical faults
- Noting and correcting any issues associated with warning lights or available diagnostic features or diagnostic codes
- Assessing the air intake and exhaust system integrity
- Visually inspecting the turbocharger (if present)

- Correcting any fuel injector problems
- Correcting oil leaks and significant oil consumption issues
- An inspection typically includes opacity or smoke testing of the exhaust to assess the particle emissions of the engine (high opacity or smoke levels can be an indication of an engine problem that needs fixing; SAE standard J1667 provides a recommended practice for an exhaust opacity measurement, see: https://www.arb.ca.gov/enf/hdvip/saej1667.pdf)
- Data logging of exhaust temperatures over at least 24 hours of a typical duty-cycle should be completed to determine if exhaust temperatures match the retrofit operational requirements (e.g., can the application support passive filter regeneration or are exhaust temperatures compatible with SCR catalyst operating conditions).

Example pre-installation checklists are available on the Manufacturers of Emission Controls Association (MECA) website for a number of on-road and off-road applications at: http://www.meca.org/diesel-retrofit/resources. Older vehicles and equipment with high exhaust emissions, excessive oil consumption, and poor maintenance histories are generally poor candidates for retrofits. Consideration should be given to scrapping these old dirty vehicles or equipment and replacing them with newer cleaner models.

Retrofits on off-road equipment can pose some unique challenges compared to the highway sector. Off-road issues that deserve consideration in designing a retrofit program/project include:

- Off-road engines can often have higher emissions than on-road, heavy-duty engines (e.g., off-road engines were uncontrolled for emissions before 1996 in the U.S.)
- Off-road engines have more diverse engine/equipment applications than found in the on-road sector (i.e., a large variety of duty cycles and equipment types found in the off-road sector)
- More older equipment (more likely to run into mechanically controlled engines, as opposed to electronically controlled engines)
- Wider power range (e.g., large engines with high power ratings installed on larger construction equipment)
- Greater risk of miss-fueling with high sulfur fuel
- Wider range of operating voltages found in the off-road sector (12V or 24V systems)
- Availability of compressed air for urea injectors on SCR retrofits
- More rigorous operating environment (vibrations, dust, uneven surfaces); can require extensive use of high-grade vibration isolators, especially in track-drive, off-road equipment
- Need for more preventative equipment maintenance (air filters, injectors, and turbochargers); basic inspection and maintenance may be lacking in off-road equipment/engines
- More severe packaging constraints in the off-road sector related to maintaining operator visibility and safety (packaging limitations generally become more significant in retrofitting DPF+SCR systems on off-road equipment)

B. Retrofit Technology Certification/Verification Requirements

Formal retrofit verification programs like those conducted by EPA and CARB in the U.S. provide end users with confidence that the retrofit technology has proven emission reduction performance and durability in the application areas covered by the verification. The EPA and CARB verification programs include an application submission/review; testing program approval phase; emissions testing in an engine test cell before and after the completion of an in-field retrofit hardware durability demonstration using appropriate regulatory test cycles for either the on-road or off-road application space; a 1000 hour durability demonstration in the field on an engine selected from the engine application range included in the manufacturer's approved verification application; and an in-use compliance testing requirement to ensure that the verified retrofit device delivers the verified performance levels during real-world service.

To employ a retrofit device as a compliance option to one of the many in-use fleet regulations put in place by CARB to reduce the public's exposure to diesel exhaust from in-use on-road and off-road diesel engines, the retrofit device must be verified by CARB. CARB finalized a "Retrofit Verification Procedure" to verify the performance of diesel retrofit technologies used in California in June 2003 and has adopted several amendments to their procedure over the past 10+ years. The procedure specifies the testing and other requirements (including mandatory minimum retrofit equipment warranty requirements) a manufacturer must meet to have a retrofit device verified for use in California. The procedures are very detailed and allow companies to verify technologies that achieve different PM and NOx reduction levels. In California, PM reduction technologies are divided into three categories: Level 1 verified technologies must reduce PM emissions from 25 to less than 50% (DOC generally verified as a Level 1 retrofit technology); Level 2 technologies 50 to less than 85% (partial filter generally verified as a Level 2 retrofit technology); and Level 3 technologies 85% and above (wall-flow filter generally verified as a Level 3 retrofit technology). A PM reduction technology can be verified to less than 25% (Level 0) as long as it reduces NOx emissions by at least 25%. NOx control technologies are broken out into 5 categories or Marks in 15% bands of NOx reduction: Mark 1 starts at 25-39% NOx reduction, Mark 2 covers 40-54%, Mark 3 is 55-69%, Mark 4 from 70-84%, and Mark 5 represents anything above 85% NOx reduction. An emission control technology must reduce NOx or PM emissions by at least 25% in order to be verified. As of January 1, 2009, verified retrofit systems in both the CARB and EPA programs have had to limit incremental NO_2 emissions to no more than 20% of the baseline, engine-out NOx levels. Verified retrofit technologies that meet the 20% incremental NO_2 limit are given a "Plus" designation (e.g., Level 3+) by CARB.

CARB's diesel retrofit verification procedure key features include:

- Application requirements/review/approval
- Test plan development/approval
- Emissions performance and durability demonstration
  - PM and NOx emissions before and after completion of 1,000 hour of operation in the field on a representative engine associated with the test group included with the application. Emissions are measured in an engine test cell over the U.S. heavy-duty

FTP for highway applications (includes one cold start test followed by three hot start tests); over the non-road transient cycle (NRTC) for off-road applications (data reviewed by CARB)
    - Verification procedure includes specific durability demonstration requirements (e.g., monitoring of temperatures, exhaust backpressure, urea consumption, etc.)
    - Emission performance for highway applications may also be demonstrated with a complete vehicle using a chassis dynamometer; for chassis dynamometer testing emissions are measured using the UDDS test cycle with 3 hot starts and a suitable low speed, urban test cycle with 3 hot starts (e.g., the New York City Bus Cycle is one example of a low speed, urban test cycle)
    - Emissions data needs to include impacts of any active regeneration events associated with filter regeneration
    - NO_2 emissions post-retrofit device limited to a 20% increase over the baseline test engine (with no retrofit device); verification procedure includes specific NO_2 testing procedures
    - NMHC or NOx emissions with the retrofit device cannot increase by more than 10% over the baseline emissions; CO emissions with the retrofit device cannot exceed the current CARB CO standard for new engines
    - Test engine with the retrofit device cannot increase any air toxic emissions versus the baseline engine (with no retrofit device); ARB can order additional testing related to quantifying potential toxic emissions associated with the retrofit device (an example could be the use of a base metal catalyzed DPF that may increase dioxin emissions across the filter)
    - NH_3 emissions post retrofit cannot exceed 25 ppm over the test cycle (applicable to SCR retrofit technologies)
    - For urea-SCR retrofits, the technology must include suitable inducements and operator warnings associated with monitoring the amount of reductant on-board the vehicle and ensuring the use of urea meeting the applicable quality standards (e.g., inducements may include engine de-rating strategies)
    - Retrofit DPFs must include temperature and backpressure monitors with minimum memory requirements and operator displays with warnings for high engine backpressure conditions (e.g., notify operator that filter cleaning is needed to reduce backpressure on the engine)
    - Verification procedure includes unique requirements for DPFs that utilize a fuel additive-based regeneration scheme, including conducting a multimedia assessment to ensure that there are no adverse impacts to the public or the environment associated with the use of the fuel additive
- Technology designation by PM and NOx emissions reduction (Level 1, 2, 3 for PM; Mark 1, 2, 3, 4, 5 for NOx)
- In-use testing after 500 units sold
    - Minimum 4 units pulled from the field and tested in an engine test cell @ 25% of the minimum warranty period, or after one year of service, whichever comes first (testing done using appropriate regulated test cycle and specified NO_2 testing procedure)

- Minimum 4 units pulled from the field and tested in an engine test cell @ 60-80% of the minimum warranty period (testing done using appropriate regulated test cycle and specified NO_2 testing procedure)
- Verification procedure includes specific in-use testing procedures
- Pass/fail criteria: field tested units must reduce emissions by at least 90% of the lower bound of the performance category associated with the verified device and increase NO_2 emissions by no more than 22% of the baseline test engine (testing can be expanded to up to 10 field units if any of the initial 4 tested units fail emissions testing criteria, with 70% of all units tested above a total of 4 required to pass)
- Additional in-use testing may be required if reported warranty claims exceed 4% of the engines equipped with the verified retrofit device

- Minimum mandatory retrofit device warranty specified
    - Off-road engines 50 hp or greater: 5 years or 4200 hours; 25 hp and under 50 hp: 4 years or 2600 hours; under 25 hp: 3 years or 1600 hours
    - Heavy-heavy duty trucks: 5 years or 150,000 miles (2 years, unlimited mileage for heavy-heavy duty trucks driven more than 100,000 miles/year with less than 300,000 total miles of service on the truck before the retrofit is applied)
    - Medium-heavy duty trucks: 5 years or 100,000 miles
    - Light-heavy duty trucks: 5 years or 60,000 miles
    - Installers of verified retrofit devices are also required to issue a warranty on their installation (same minimum warranty period as issued with the retrofit device)
    - Manufacturers are required to file annual warranty reports with ARB for each verified retrofit technology
- Verification procedure specifies labeling requirements for the verified retrofit technology, approved conditions for component swapping between fleet vehicles or device re-designation to another vehicle, designating the flow direction of the device and utilizing designs that can only be installed in one unique direction
- Verified retrofit technologies can be de-verified and subject to recall if conditions of the verification are not met

EPA's retrofit verification procedure mirrors many of CARB's verification requirements with a few notable exceptions:

- EPA does not use the emission reduction performance banding scheme used by CARB. Instead EPA designates an absolute PM and/or NO_x emissions reduction performance value for each verified technology
- EPA does not mandate any minimum warranty requirements
- EPA does not have any authority to recall verified retrofit technologies but EPA can de-verify a technology if conditions of the verification are not met. Only EPA or CARB verified technologies can be used in projects that receive state or federal incentive funds.

EPA includes the same NO_2 limits and NH_3 limits as required by CARB, and has similar in-use testing requirements. A manufacturer can utilize the same datasets to verify a retrofit technology with CARB and EPA but each agency conducts a separate review of the test data and retains the authority to request specific additional testing as they determine is needed to issue a verification. EPA does not automatically verify a retrofit technology that has been verified by CARB, and vice versa. Additional details of EPA's retrofit verification process can be found at: https://www.epa.gov/verified-diesel-tech. CARB's detailed regulatory requirements covering their verification procedure, warranty and in-use compliance requirements for in-use strategies to control emissions from diesel engines are available at: https://govt.westlaw.com/calregs/Browse/Home/California/CaliforniaCodeofRegulations?guid=I0BC18F70D46A11DE8879F88E8B0DAAAE&originationContext=documenttoc&transitionType=Default&contextData=(sc.Default) [California Code of Regulations, Title 13, Division 3, Chapter 14, sections 2700 through 2711].

The VERT industry association has evolved its retrofit filter certification process over more than 20 years, with first attention given to retrofit DPFs installed on off-road equipment used in large tunneling construction projects in the Alps. The current VERT certification protocol focuses only on particle filter systems with high particle reduction efficiencies and these same particle filter technologies combined with SCR NOx reduction catalysts. Starting in 2016 a VERT approved retrofit particle filter must demonstrate at least a 98% reduction efficiency for solid particle number emissions in the 20-300 nm range before and after a 2000 hour field durability demonstration (using the Euro PMP particle measurement protocol; particle filtration performance up from a minimum 97% particle reduction requirement in 2007). Particle reduction efficiency must be at least 80% during active filter regeneration events before and after the 2000 hour field durability demonstration (up from at least 70% reduction efficiency in 2012). The filter device is not allowed to increase European cycle-weighted regulated emissions versus the baseline engine. Catalytic conversion of NO to NO_2 within the filter system is capped at no more than 20% over the baseline engine. The filter system can also not increase any secondary emissions versus the baseline engine (e.g., air toxics or other unregulated emissions). All filter systems must have on-board electronic monitoring of back pressure and temperature. Unidirectional designs are required to prevent reverse mounting of the filter element. Manufacturers are required to provide a minimum two year/1000 hour warranty on materials and function. A manufacturer's quality system for production is subject to an annual audit. Filter + SCR retrofit systems may be approved with NOx reduction levels of 55%, 65%, or 75% after 1000 hours of field aging. These NOx reduction systems must also have NH_3 emissions < 25 ppm and N_2O emissions < 10 ppm (peak emissions over the applicable regulatory test cycle). VERT is developing an in-use compliance procedure for approved filters based on Swiss regulation SR 941.242 that requires in-use compliance testing of construction equipment fitted with DPFs (for more on Swiss regulation SR 941.242 see: "Recent Developments in the Measurement of Particle Emissions from Mobile Sources" by Oliver Bischof published in 2015 in *Emission Control Science and Technology*; available at: http://link.springer.com/article/10.1007/s40825-015-0016-9). This filter in-use compliance procedure makes use of approved portable particle number measurement devices to confirm filter integrity annually in the field (in-use compliance testing of VERT certified filters is also subject to an annual VERT audit). Details of one of the Swiss-approved portable particle emission test devices can be found here: http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Spec_Sheets/3795_Nanopartic le_Emission_Tester_US_5001622_WEB.pdf. To retain their VERT approval a manufacturer must prove on an annual basis that the failure rate in the field of each approved filter families remains below 5% for all filters not older than 5 years. The VERT approval system also defines a label that is displayed on certified technologies. Additional details associated with VERT's particle filter technology certification protocol are available at: http://www.vert-certification.eu/. A concise overview of the VERT certification process including details on in-use filter compliance checks using portable nanoparticle instruments are also summarized in 2016 VERT slide presentation made at an air quality conference in Teheran, Iran available at: http://vert-certification.eu/j3/images/pdf/AQM_Teheran_Workshop_2016/5_Inspection_and_Maintenance.pdf.

The UN retrofit device regulation 132 (complete regulatory language and requirements are available at: https://globalautoregs.com/rules/139-retrofit-emission-control-devices) also contains emissions performance testing before and after a 1000 hour durability demonstration (the durability demonstration may be done in the field or in an engine test cell with a specified aging cycle). This regulation specifies emissions measured using the world harmonized heavy-duty transient cycle (WHTC) for highway applications (instead of the heavy-duty FTP cycle used by EPA and CARB), and the NRTC cycle for off-road equipment applications. Retrofit devices must meet minimum emission reduction values of 90% for PM, 97% for solid particle number (PN, measured using the European PMP protocol) and/or 60% for NOx. The engine equipped with an approved retrofit device must also, at a minimum, comply with the next highest Euro engine emission standard for PM and/or NOx (e.g., a Euro III highway engine equipped with a retrofit DPF must not exceed the Euro IV PM limit). PM retrofit devices can be approved at three different NO_2 levels versus the baseline test engine: no increase in NO_2, no more than a 20% increase in NO_2 over the baseline, or no more than a 30% increase in NO_2 over the baseline. Regulation 132 also specifies urea-SCR inducement strategies and NOx diagnostics, filter monitoring requirements, unidirectional orientation for retrofit devices (with no flipping/turning of substrates allowed), labeling requirements, weighting of emissions associated with active filter regeneration events, and the need for an approved production quality system (conformity of production). UN regulation 132 does not include any in-use testing requirements. Approved devices do have a specified emissions durability requirement of 200,000 km or 6 years for highway applications and 4,000 hours or 6 years for off-road applications. Devices must undergo an assessment for secondary emissions, which could include additional emissions testing. In general, the retrofit device cannot increase any secondary emissions above those measured on the baseline engine that does not contain the retrofit device. NH_3 emissions for a urea-SCR retrofit cannot exceed 10 ppm over the appropriate regulatory test cycle (revised downward from an earlier 25 ppm cap in the first version of this regulation; a 10 ppm cap is consistent with the Euro VI NH_3 limits).

Table I compares the verification/certification requirements for retrofit filters and de-NOx technologies (e.g., urea-SCR) between CARB/U.S. EPA, VERT, and UN Regulation 132.

Table I. Verification/Certification Requirements for Retrofit DPFs and Retrofit DPF+SCR Technologies (On-road or Off-road Applications)

Certification/ Verification Criteria	CARB/U.S. EPA	VERT	UN Retrofit Regulation 132
Emissions performance	PM/NOx emissions measured before and after retrofit system aging using appropriate regulated test cycle (e.g., heavy-duty FTP for on-road; nonroad transient cycle for off-road engines)	PM/PN/NOx emissions measured before and after retrofit system aging using appropriate regulated test cycle (e.g., heavy-duty WHTC for on-road; nonroad transient cycle for off-road engines)	PM/PN/NOx emissions measured before and after retrofit system aging using appropriate regulated test cycle (e.g., heavy-duty WHTC for on-road; nonroad transient cycle for off-road engines)
NO_2 limits	+20% increase vs. baseline	+20% increase vs. baseline	+20% or +30% increase vs. baseline
N_2O limits	None specified	< 10 ppm over appropriate test cycle	None specified
NH_3 limits	25 ppm max. over appropriate test cycle	< 25 ppm over appropriate test cycle	10 ppm max. over appropriate test cycle
Secondary (unregulated) emissions	No increase vs. baseline	No increase vs. baseline	No increase vs. baseline
Durability demonstration	1000 hour in-service	2000 hour in-service	1000 hour in-service or on an engine dyno using an accelerated aging protocol
Retrofit classification	CARB: 85% or greater PM reduction efficiency (Level 3); at least 25% NOx reduction with five categories (at least 25%, 40%, 55%, 70%, & 85%) EPA: absolute PM and NOx reduction efficiency demonstrated with field aged hardware	At least 98% PN reduction efficiency (at least 80% PN reduction efficiency during filter regeneration); NOx reduction efficiencies of 55%, 65%, or 75% (after 1000 h of field aging for SCR)	At least 90% PM reduction and 97% PN reduction efficiency; at least 60% NOx reduction efficiency
On-board monitor	Yes, includes monitoring filter	Yes, includes monitoring filter	Yes, includes monitoring filter

	pressure drop, exhaust temperatures; provide diagnostics and inducements to insure urea reductant is used with SCR	pressure drop, exhaust temperatures; provide diagnostics and inducements to insure urea reductant is used with SCR	pressure drop, exhaust temperatures; provide diagnostics and inducements to insure urea reductant is used with SCR
In-use performance testing	Yes, at least four in-service parts tested on an engine dyno to verify PM and/or NOx, NO_2 performance at 25% and 75% of warranty or useful life	Yes, annual filter integrity testing using portable PN measuring device; < 5% failure rate over first 5 years of operation to maintain certification	No in-use testing specified
Warranty	CARB specified mandatory warranty on product and installation of up to 5 years/4200 hours/150,000 miles depending on application class	Minimum product warranty of 2 years or 1000 hours; manufacturer must have an approved quality system in place for production	No specified product or installation warranty; manufacturer must agree to specified retrofit durability requirement of 6 years/4000 hour/200,000 km for retrofits used and maintained per the manufacturer's instructions; manufacturer must have an approved quality system in place for production
Recall authority	CARB can recall defective retrofit hardware; CARB and EPA can revoke verifications	No recall authority but certification can be revoked	No specified recall authority but approval can be revoked

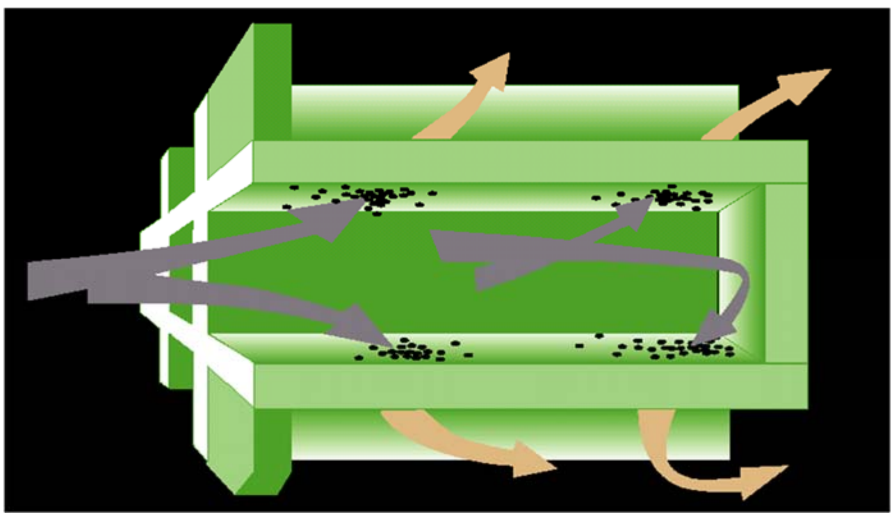
C. Retrofit Technologies for Reducing PM and NOx

A variety of diesel retrofit technologies have been introduced and verified for applications on both heavy-duty highway vehicles and off-road equipment by manufacturers in the U.S., Europe, and Asia. This report will focus on the most effective retrofit technologies for reducing diesel PM and NOx emissions, namely high efficiency wall-flow particulate filters and urea-SCR NOx catalyst systems.

1. Retrofit DPF Technologies for Reducing PM

Retrofit diesel particulate filters (DPFs) remove particulate matter in diesel exhaust by filtering exhaust from the engine. The most common retrofit DPF employs a wall-flow ceramic filter. This retrofit filter design is common with filter designs employed on new vehicles and employs a porous honeycomb structure with alternating flow channels plugged at opposite ends, as shown in Figure 1. This effectively forces the exhaust gases containing the particles through the cell walls causing the particles to be filtered and deposited on the inside wall of the channel as the cleaned exhaust exits through the adjoining flow channel. Wall-flow filters have the highest level of filtration efficiency (> 90 percent) for particles, including ultrafine particles and climate forcing black carbon. Since a filter substrate can fill up over time, engineers that design filter systems must provide a means of burning off or removing accumulated particulate matter. A convenient means of disposing of accumulated particulate matter is to burn or oxidize it on the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or "regenerated."

Figure 1. Wall-Flow Diesel Particulate Filter



Soot combustion is facilitated at lower temperatures by the use of catalyst coatings applied to the filter substrate surfaces. Catalysts used on DPFs are generally precious metal-based (platinum and/or palladium) but base metal catalysts have also been employed on retrofit DPFs. In addition to the use of a catalyst coated on the filter substrate, another catalyst-based regeneration strategy employs a precious metal-based oxidation catalyst placed upstream of either a catalyzed or uncatalyzed filter. The precious metal-based catalyst filter regeneration strategies facilitate oxidation of nitric oxide (NO) to nitrogen dioxide (NO_2). The nitrogen dioxide reacts with the collected particulate, substantially reducing the temperature required to regenerate the soot collected on the filter substrate. Filters that regenerate in this "passive" fashion cannot be used in all applications because they require exhaust temperatures in the range of 220-250ºC for a minimum amount of their operating time. Manufacturers of passive retrofit DPFs generally specify a percentage of the duty cycle with a minimum exhaust temperature at the filter inlet requirement as an acceptance criteria for using this type of retrofit technology. Data-logging exhaust temperatures of actual vehicles is necessary to determine if an application can use a passively regenerating DPF. Catalyst-based DPFs, in addition to facilitating soot regeneration, also provide high conversion efficiencies for CO and exhaust hydrocarbons (including the soluble fraction of PM). Many of these hydrocarbon exhaust emissions are known air toxics or carcinogens (e.g., aromatic and poly-aromatic hydrocarbons).

The performance, durability, and reliability of catalyst-based DPFs can be negatively influenced by fuel sulfur levels. Sulfur in the fuel is combusted in the engine and forms SO_2 in the exhaust gas. SO_2 affects filter performance by inhibiting the performance of catalytic materials upstream of or on the filter. SO_2 also competes with chemical reactions intended to reduce pollutant emissions and creates particulate matter through catalytic sulfate formation. With precious-metal catalyzed filter technologies, filtration efficiency of particulates generally outweighs the production of sulfate particle emissions at fuel sulfur levels around 50 ppm. Catalyst-based DPF technology works best when fuel sulfur levels are less than 15 ppm. In general, the less sulfur in the fuel, the better the technology performs. The use of ultra-low sulfur diesel fuel (15 ppm sulfur maximum) greatly facilitates filter regeneration at lower temperatures in passive DPF devices. The filtering/regeneration performance of uncatalyzed filters (or an uncatalyzed filter that does not employ an upstream precious metal-containing DOC), such as those used in many actively regenerated filter retrofit devices, is not affected by fuel sulfur.

Retrofit DPF performance can also be potentially negatively impacted by the use of alternative diesel fuels, lubricant formulations, and fuel additives. These fluids may contain potential catalyst poisons that could impact filter regeneration characteristics or ash forming constituents that could impact the build-up of filter backpressure or filter maintenance intervals. CARB's retrofit verification procedure requires that the applicant for a verification must specify the fuel and lubricating oil requirements necessary for proper functioning of the retrofit technology. Based on the information provided, CARB approves which alternative diesel fuel (e.g., biodiesel blends) and or fuel additives will be allowed for use with a particular verified retrofit technology. All terms and conditions for the verification, including a list of all approved alternative diesel fuels and or fuel additives, are specified in CARB Executive Order (EO) issued for each verified retrofit technology. Use of any alternative diesel fuels and or fuel additives not specifically listed in the verification EO is illegal and strictly prohibited. Such operation with a verified retrofit device may adversely affect system performance or durability, and will affect end user warranty rights and protection. Operating with an unapproved alternative diesel fuel or fuel additive violates the Executive Order, negates the verification for that vehicle for compliance with CARB's in-use fleet emission reduction regulations.

A number of filter substrate materials have been used in diesel particulate filters. Wall-flow filter substrates are manufactured by an extrusion-based process from ceramic materials such as, cordierite, mullite, aluminum titanate and silicon carbide. Wall-flow filter substrates are available in a variety of cell densities, wall thicknesses, wall porosities, and cell shapes. All these filter substrate properties influence the filtration efficiency, coatability, pressure drop, and ash retention characteristics of the substrate. Retrofit DPF systems are designed to minimize backpressure on the engine while providing sufficient filtration volume to achieve high filtration efficiencies and effectively manage ash accumulation in the filter. Experience has shown that properly designed DPFs typically result in backpressure-related fuel penalties on the order of one percent or less.

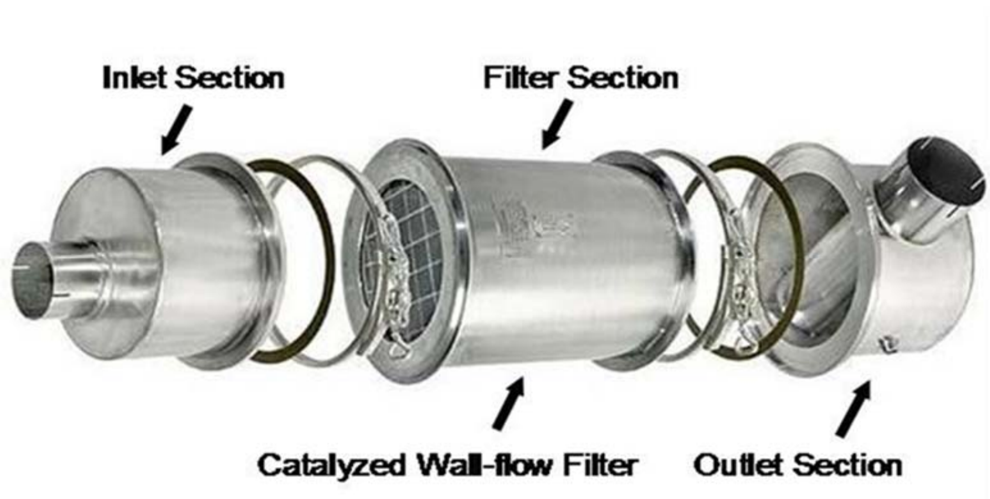
Other "active" filter regeneration strategies can be used to remove captured soot from a diesel particulate filter by adding sufficient energy to the exhaust stream to combust captured soot. Active DPF regeneration strategies include:

- Air-intake throttling to one or more of the engine cylinders to increase the exhaust temperature and facilitate filter regeneration (not a common regeneration strategy for retrofit DPFs)
- Post top-dead-center (TDC) fuel injection of small amounts of fuel in the cylinders of a diesel engine introduces a small amount of unburned fuel in the engine's exhaust gases. Fuel can also be injected into the exhaust pipe ahead of a catalyzed filter or upstream oxidation catalyst. This unburned fuel can then be oxidized in the catalyzed particulate filter or upstream oxidation catalyst to generate heat and combust accumulated particulate matter. Fuel injection upstream of a diesel oxidation catalyst is available in some retrofit DPFs, and is a common active regeneration strategy employed with DPFs on newer highway and off-road diesel engines that comply with more recent U.S. and European emission standards (e.g., U.S. 2007-2010 heavy-duty standards, Euro VI heavy-duty standards, U.S. Tier 4 off-road diesel engine standards, Stage IIIB/Stage IV Euro nonroad mobile machinery standards).
- On-board fuel burners or electrical heaters upstream of the filter can provide sufficient exhaust temperatures to ignite the accumulated particulate matter and regenerate the filter. The most common fuel burners employ on-board diesel fuel. There are burner-based retrofit DPFs design that can regenerate the filter only when the vehicle is stopped, and designs that allow the burner to operate and regenerate the filter under normal service. Electrical heaters are generally employed when the vehicle is stopped or out of service (i.e., between shifts). There are retrofit DPF examples that combine an on-board electrical heater with a catalyzed substrate to minimize active filter electrical regeneration frequency.
- Off-board electrical heaters or fuel burners can be applied to combust trapped particulate matter by blowing hot air through the filter element while removed from the vehicle.
- Fuel-borne catalysts reduce the temperature required for ignition of trapped particulate matter. Fuel-borne catalysts can be used in conjunction with both passive and active filter systems. Typical fuel-borne catalysts used with retrofit filters are iron, cerium or combinations of iron and cerium compounds that are dosed into the fuel system in small quantities by an on-board dosing system. Filter system diagnostics generally include interrupts to the dosing strategy if a filter fault is detected in order to prevent exhaust of the combusted fuel-borne catalyst ultrafine particles into the environment (these ultrafine

metal oxide particles can have negative public health impacts; these ultrafine metal oxide particles are normally captured similarly to other inorganic ash constituents by a properly functioning wall-flow filter). Retrofit DPFs using fuel-borne catalysts have been used sparingly in the U.S. do to California's requirement for completing an expensive and time consuming multimedia environmental analysis.

Generally catalyzed, passively regenerated retrofit DPFs are desired for many on-road and off-road applications because of their lower level of system complexity and cost. Figure 2 depicts a typical catalyzed retrofit DPF arrangement. The application of interest must, however, meet the exhaust temperature duty cycle criteria to ensure regeneration of the filter. Active filter systems are more complex and typically more expensive than passive DPFs. The preferred type of active regeneration scheme deployed by the retrofit DPF may depend on a number of factors including available electrical infrastructure to utilize electrical heaters; interest, duty-cycle, or ability to stop the vehicle to conduct filter regenerations; cost/performance trade-offs; available diesel fuel quality; or packaging constraints on the vehicle.

Figure 2. Catalyzed Retrofit DPF



CARB's and EPA's listings of verified DPFs (with at least 85% PM reduction performance) include more than 40 verified devices (see www.arb.ca.gov/diesel/verdev/vt/cvt.htm and www.epa.gov/verified-diesel-tech/verified-technologies-list-clean-diesel) including:

- On-road passive DPFs (includes one hydrocarbon SCR+DPF, one DPF+EGR, two DPF+SCR technologies)
- On-road active DPFs
- Off-road passive DPFs (includes one DPF+SCR technology)
- Off-road active DPFs

- Level 3 devices for transportation refrigeration units
- Level 3 devices for auxiliary power units
- Level 3 device for rubber tired gantry cranes
- Level 3 devices for stationary engines

Because of California's in-use engine/vehicle regulatory programs aimed at reducing diesel exhaust emissions from all in-use diesel sources (including on-road, off-road, and stationary diesel engines) and hundreds of millions of dollars in federal and state incentives provided for more than ten years in the U.S. for cleaning up older diesel engines, more retrofit DPFs have been successfully deployed in the U.S. than any other world market. MECA's annual sales surveys of retrofit manufacturers have reported more than 100,000 retrofit DPFs for on-road and off-road applications sold in the U.S. since 2001, with more than 60,000 of these retrofit DPFs sold in California alone. The vast majority of the U.S. retrofit DPF applications have been on pre-2007 model year heavy-duty highway vehicles including transit buses, school buses, refuse haulers, and public/private fleet vehicles (starting in 2007 manufacturers installed new heavy-duty highway diesel engines with DPFs to comply with EPA's 2007-2010 heavy-duty PM standards; more than 4 million 2007 and newer heavy-duty highway engines equipped with DPFs are in service across the U.S.). Retrofit DPFs have also been applied in limited numbers in the U.S. on a variety of off-road engines including diesel gen-sets, construction equipment, mining equipment, marine engines, and locomotives. Tables II and IV provide examples of DPF retrofits done on construction equipment in the Northeast U.S. and on a switcher locomotive that operates in California. In general many U.S. highway retrofit DPF applications have exhaust temperatures that are better suited to passive filter regeneration strategies compared to off-road equipment (as reflected by recent MECA retrofit sales surveys that breakdown sales by application area and active vs. passive DPF regeneration strategy).

An example of a successful retrofit application of passively regenerated, catalyzed DPFs from outside the U.S. was completed in Mexico City in 2004-2005 on a fleet of transit buses fueled with ultra-low sulfur diesel fuel (15 ppm max. sulfur levels, obtained from the U.S.). This transit bus retrofit project included funding from the U.S. EPA and utilized retrofit DPF and DOC technologies that had been verified by the U.S. EPA. Buses retrofit with DPFs and fueled with ultra-low sulfur diesel demonstrated PM reductions of approximately 90% versus the baseline bus emissions after accumulating 55,000 km of service. Details of this Mexico City transit bus retrofit project are summarized in Table III and in a set of slides available from the World Bank website at:
http://siteresources.worldbank.org/INTTRANSPORT/Resources/336291-1171658979314/3465102-1175712029532/Cleaning_up_the_fleet.pdf.

Table II. DPF Retrofit Examples on Construction Equipment in the Northeast U.S.

The state of Massachusetts requires contractors working on projects financed by the State Revolving Fund to install retrofit pollution controls on their construction equipment engines (see: http://www.mass.gov/eea/agencies/massdep/water/wastewater/reducing-air-emissions-from-diesel-construction-engines.html; the State Revolving Fund program provides financial assistance for municipal wastewater treatment and drinking water infrastructure projects). To support this effort the Massachusetts Department of Environmental Protection published a guide to retrofitting construction equipment. Included in this guide are several Northeast U.S.-based case studies of construction equipment retrofits with DPFs (and DOCs). This construction equipment retrofit guide is available at: http://www.mass.gov/eea/docs/dep/air/diesel/conretro.pdf. These case studies include the following DPF retrofits on construction equipment:

Type	Make/Model	Year	Rated Power	Fleet Owner or Project Name
2 Loaders	Daewoo DB58TIS	2006	143 hp	New York City Dept. of Sanitation
1 Loader	Case/6T-830	2000	198 hp	New York City Dept. of Sanitation
3 Loaders	Caterpillar/3306	2002	235 hp	New York City Dept. of Sanitation
1 Excavator	Caterpillar/M322C	2004	164 hp	New York City South Ferry Terminal Construction Project
1 Skid Steer	Caterpillar/262B	2004	75 hp	New York City South Ferry Terminal Construction Project
1 Compressor	Yanmar/185WIR	2004	61 hp	New York City South Ferry Terminal Construction Project
1 Generator	John Deere/G330	2004	525 hp	New York City South Ferry Terminal Construction Project
4 Track Drills	Klemm/807		178 hp	New York City South Ferry Terminal Construction Project
4 Compressors	Sullair/1150 xh		525 hp	New York City South Ferry Terminal Construction Project

New Jersey has also been operating a Clean Construction program that provides funding for retrofitting construction equipment with DPFs or DOCs. Details of New Jersey's Clean Construction program are available at: http://www.stopthesoot.org/eoi.htm.

Table III. 2004-2005 Pilot bus retrofit program with oxidation catalysts, particulate filters, and ultra-low sulfur diesel fuel in Mexico City

The Mexico Center for Sustainable Transport (CTS-Mexico), with funding from the U.S. EPA, U.S. Agency for International Development and the World Resources Institute, conducted a pilot project to reduce diesel emissions from existing buses in Mexico. The project was conducted in cooperation with the Mexican local public agencies, such as the Mexican Federal Government's Environmental Ministry (SEMARNAT) and the Mexico City Secretariat of Environment (SMA). For this pilot project, twenty working buses in the Red de Transporte de Pasajeros del Distrito Federal (RTP) fleet were retrofitted with either a diesel oxidation catalyst (DOC) or a diesel particulate filter (DPF) and were fueled with ultra-low sulfur diesel fuel (ULSD, 15 ppm sulfur max.). Twelve of the newer buses (2001 models, with electronic injection systems) were retrofitted with DPFs and eight older buses (with mechanical injection systems) with DOCs. The DPF was a passively regenerating technology that combined a DOC with an uncatalyzed wall-flow ceramic filter element. This DPF technology has been U.S. EPA verified to reduce PM by 90%; CO by 85%; and hydrocarbons by 90%. The DOC was also EPA verified to reduce PM by 20%; CO by 40%; and hydrocarbons by 50%.

Emission testing was measured using RAVEM (Ride-along Vehicle Emissions Measurement), a portable emissions measuring laboratory, to obtain second by second measurement of gaseous and PM emissions during normal Mexico City driving and operating conditions. The buses were assigned to three different routes. Due to budget restrictions, only 15 of the 20 retrofitted buses were chosen for exhaust emissions testing. The emission testing conducted at 4,000 km and 55,000 km for the three routes showed the following emission reductions:

Test Route	Emissions, % reduction from baseline					
	PM		NOx		CO	
	4,000 km*	55,000 km*	4,000 km*	55,000 km*	4,000 km*	55,000 km*
	DOCs					
Modulo 23	12.8	44.5	14.0	5.0	42.7	43.0
Insurgentes Norte	22.4	--	9.8	--	72.4	--
Montevideo	--	29.2	--	11.8	--	77.0
Passively Regenerated, Catalyzed DPFs						
Modulo 23	79.2	91.7	+9.5	+1.1	100	100
Insurgentes Norte	92.6	--	5.1	--	97.9	--
Montevideo	--	90.5	--	+3.0	--	100

1. The baseline emissions measurements were taken with no retrofit devices, using 350 ppm sulfur fuel.
* using 15 ppm sulfur fuel

Table IV. California Switcher Locomotive DPF Retrofit Demonstration

A recent CARB sponsored retrofit technology demonstration program successfully installed passively regenerated, catalyzed DPFs on an older switcher locomotive. The U.S. EPA Tier 2-compliant locomotive used in this project was powered by three 19 liter, 522 kW Cummins diesel gen-sets. Each of the three engines was retrofit with a DOC + catalyzed DPF (passive regeneration) and operated for 3000 hours in switcher rail service with ultra-low sulfur diesel fuel (15 ppm sulfur max.). Emission performance was measured on the retrofitted switcher locomotive after 3000 hours of service with the following results:

- PM levels were reduced by approximately 80% (19 mg/bhp-hr PM measured after 3000 h of service; below the U.S. EPA Tier 4 locomotive PM limit of 30 mg/bhp-hr).
- Hydrocarbon emissions were reduce by about 90% vs. the baseline engine without DPF retrofits.
- CO emissions were reduce about 99% vs. the baseline engine without DPF retrofits.

A report on this switcher locomotive retrofit project is available at: http://www.arb.ca.gov/msprog/aqip/demo.htm.

2. Other PM Retrofit Technologies

Less effective retrofit technologies for reducing diesel PM emissions include:

- Diesel oxidation catalysts (DOCs)
  - Flow-through substrates typically catalyzed with precious metals; can be used at fuel sulfur levels up to 500 ppm but more effective with lower fuel sulfur levels
  - Only reduces soluble fraction of PM emissions (not effective in reducing black carbon or elemental carbon emissions), but is effective in reducing CO and gaseous hydrocarbon emissions
  - Can be applied to older on-road and off-road diesel engines with relatively high engine-out PM emissions that cannot be retrofitted with a DPF
  - In the early 2000s, Hong Kong successfully retrofit tens of thousands of diesel vehicles with DOCs, including light-duty vehicles, heavy-duty trucks, and buses (for more on Hong Kong's DOC retrofit program see: http://www.epd.gov.hk/epd/english/environmentinhk/air/prob_solutions/cleaning_air_atroad.html#point5 and a 2003 SAE publication available at: http://papers.sae.org/2003-01-1391/)
  - U.S. EPA's DERA grant program has funded the installation of tens of thousands of DOCs on older on-road and off-road diesel engines/vehicles since 2007
- Flow-through or partial filters (also called partial oxidation catalysts)
  - Typically designs are metal wire mesh structures or tortuous flow metal substrates that employ sintered metal filtering sheets

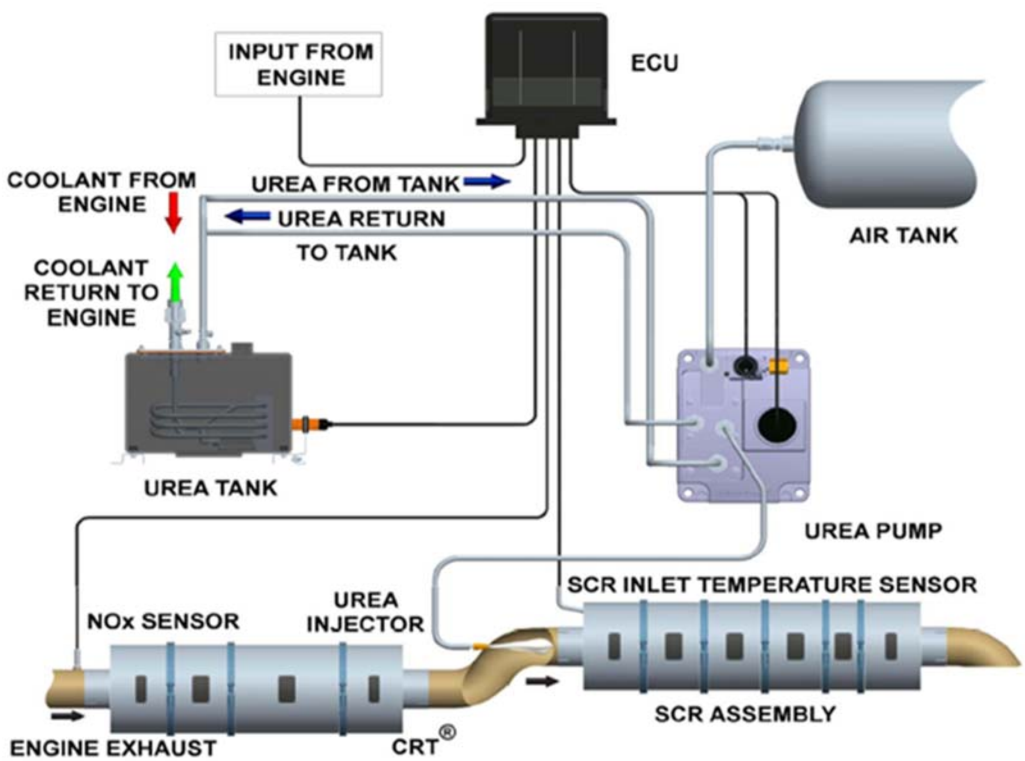
  - Require a properly designed soot regeneration strategy or PM reduction efficiency can be highly variable; significant by-passing or blow-off of soot observed in real-world applications with passive regeneration strategies limiting PM reduction efficiency; catastrophic oxidation of the metal foil/mesh has occurred in retrofit applications under runaway soot oxidation situations resulting in recalls or removal of retrofit devices employing metal-based filters. A number of metal-based retrofit filter technologies have been de-verified by CARB.
  - Several metal-based filter technologies employing active regeneration strategies (e.g., electric heating elements) have been verified by CARB for applications on diesel engines used in some transport refrigeration units, marine engines, rubber tired gantry cranes, and stationary engines both at the Level 2 PM performance band (50-84% PM reduction) and at the Level 3 PM performance band (at least 85% PM reduction).
- Crankcase vent filters
  - Older diesel engines vent the crankcase directly to the environment (newer diesel engines are required to reduce combined PM emissions from the both the exhaust and crankcase)
  - Retrofit crankcase vent filters effectively capture the oil droplets and aerosol particles before circulating the crankcase gases back to the air inlet side of the engine (depending on engine's piston blow-by characteristics, these crankcase emissions are generally a fraction of the exhaust PM emissions from older diesel engines)
  - Most U.S. applications of retrofit crankcase vent filters have focused on older school buses due to exposure concerns of student passengers to crankcase emissions that can enter the school bus cabin
  - Can be combined with DOCs or DPFs for additional PM reductions on older engines

3. Retrofit Urea-SCR Technologies for Reducing NOx

Controlling NOx emissions from a diesel engine is inherently difficult because diesel engines are designed to run lean. It is difficult to chemically reduce NOx to molecular nitrogen in the oxygen-rich environment of diesel exhaust. The conversion of NOx to molecular nitrogen in the exhaust stream requires a reductant (NH_3, HC, CO or H_2) and under typical engine operating conditions, sufficient quantities of reductant are not present to facilitate the conversion of NOx to nitrogen. Selective catalytic reduction (SCR) employing a urea/water reductant that breaks down to release ammonia has been used to control NOx emissions from stationary sources for over 40 years. More recently, it has been applied to mobile sources including trucks, off-road equipment, marine vessels, and locomotives. Applying SCR to diesel-powered vehicles provides simultaneous reductions of NOx, PM, and HC emissions. Applications of urea-SCR on new diesel engines include 2010 and newer U.S. heavy-duty highway diesel engines, Euro IV/V/VI-compliant heavy-duty highway engines in Europe, Tier 4 interim/Tier 4 final off-road diesel engines in the U.S. and Stage IIIB/Stage IV nonroad mobile machinery in Europe.

Retrofit urea-SCR systems have been developed as a NOx reduction technology for both older on-road and off-road diesel engines but the number of applications is relatively small compared to retrofit DPFs. There are examples of stand-alone retrofit SCR systems, DOC+SCR retrofit systems, and retrofit systems that combine either passive or active DPFs with SCR catalysts. In retrofit systems that combine DOCs or DPFs with SCR catalysts, the DOC or DPF is typically a separate element that is located upstream of the SCR catalyst. The largest application area for retrofit urea-SCR systems has been the application of DPF+SCR retrofits on transit buses. DPF+SCR transit bus retrofits have been utilized in the United Kingdom (most notably in London-area transit buses), some large city transit fleets in Europe, and in Hong Kong to reduce urban NOx and NO_2 levels. In most cases these DPF+SCR retrofits have employed passive, catalyst-based DPF regeneration strategies. A typical retrofit DPF+SCR system schematic is shown in Figure 3. In some cases these passive DPF+SCR retrofit systems include added insulation to the exhaust system to allow the SCR system to function under thermally challenged, urban duty cycles. SCR catalyst temperatures of at least 200ºC are typically needed to achieve high conversion efficiencies for NOx and urea injection is typically disabled when SCR catalyst temperatures are below this threshold. Congested urban bus routes can sometimes result in low exhaust temperatures and no activation of the SCR catalyst.

Figure 3. Retrofit DPF+SCR System Schematic



The successful application of DPF+SCR systems on older Euro III-compliant transit buses is summarized in a set of 2014 Transport for London presentation slides available at: http://www.iapsc.org.uk/assets/document/1214_F_Coyle.pdf. Some additional details of Hong Kong's DPF+SCR bus retrofit program are provided in Table V and in a 2013 Hong Kong Advisory Council on the Environment report available at: http://www.epd.gov.hk/epd/sites/default/files/epd/english/boards/advisory_council/files/ACE_Paper_8_2013.pdf. PEMS studies conducted by the Hong Kong Environmental Protection Dept. show a strong impact of traffic congestion on SCR catalyst temperature on buses retrofit with DPF+SCR systems. In observed traffic jams, SCR catalyst temperatures can decrease below 200ºC and essentially shut-off the SCR catalyst function (NOx reduction efficiency observed to go to zero). These PEMS results emphasizes the need to select DPF+SCR bus retrofit system designs that are tailored for severe urban duty cycles to maximize real world NOx reduction performance (e.g., compact, heavily insulated retrofit system designs that minimize heat losses between the engine and SCR catalyst; use of Cu-zeolite based SCR catalyst formulations with good low temperature activity). Examples of retrofit DPF+SCR system designs tailored for severe urban duty cycles like those found in Hong Kong include retrofit systems offered by two European-based retrofit technology providers: Eminox (see: http://www.eminox.com/retrofit/credentials) and Proventia (see: https://www.proventia.com/emission_control/retrofit/hong_kong and https://www.proventia.com/emission_control/retrofit/retrofit_systems/noxbuster_city). Recent Hong Kong EPD PEMS data for buses retrofit with DPF+SCR systems were presented at a 2014 University of California – Riverside PEMS conference available at: http://www.cert.ucr.edu/events/pems2014/liveagenda/04wong.pdf.

A recent study completed by University of California – Riverside under a research contract with CARB, has measured activity patterns of heavy-duty trucks and buses operating in California and found many examples of duty cycles that result in low temperature exhaust profiles that can limit SCR effectiveness for controlling NOx emissions from SCR-equipped trucks and buses. This study found that on average the monitored vehicles operate with SCR temperature lower than 250 °C for 42-91% of the time and lower than 200 °C for 11-87% of the time, depending on their application. By assuming a generic NOx reduction curve as a function of SCR temperature for all the vehicles, the weighted average % reduction in engine-out NOx emission ranged from 16% for agricultural trucks to 69% for refuse trucks. Complete results for the UC-Riverside heavy-duty truck and bus activity study are available on the CARB website at: https://www.arb.ca.gov/research/single-project.php?row_id=65196.

An additional retrofit technology that can be applied to DPF+SCR systems (either OEM-installed or retrofit systems) to improve the low temperature performance of the SCR catalyst is a heated urea-dosing element. This electrically heated urea-dosing element breaks down the urea reductant into ammonia, and directly injects the ammonia-containing gas into the exhaust upstream of the SCR catalyst. The injection of ammonia allows for the activation of the SCR catalyst at lower temperatures (as low as 150oC), compared to urea dosing, and prevents the deposition of urea within the exhaust system. Recent testing of a Euro 5 diesel passenger vehicle retrofit with an OEM Euro 6 DPF+SCR system and a retrofit electrically heated urea dosing element demonstrated an 88% reduction in NOx emissions measured over the WLTC test cycle and a 93% reduction in NOx emissions measured by PEMS equipment in a European real world driving emissions testing procedure. Additional information on this electrically heated urea dosing technology that can be retrofit on light-duty, heavy-duty, and off-road diesel applications is available at: http://baumot.twintecbaumot.de/en/products/bnox-scr-system/.

Another alternative SCR reductant strategy that can be retrofit on vehicles to improve low temperature SCR performance replaces the liquid urea/water SCR reductant with a solid reductant that is decomposed with heat addition to allow for the direct injection of gaseous ammonia upstream of the SCR catalyst. This solid reductant-based technology has been retrofit on hundreds of buses in Europe and Asia, changing the NOx emission status of these vehicles from Euro III and IV levels to Euro V and Euro VI NOx levels. Buses have been successfully retrofit with this solid reductant ammonia injection system in London, Copenhagen, Beijing, Shanghai, and Seoul. Details on this solid SCR reductant retrofit technology are available at: http://www.amminex.com/retrofit.aspx.

The development of SCR-coated DPFs that have been recently commercialized for original equipment applications on light-duty diesel vehicles and soon to be released, Stage V-compliant nonroad diesel engines, should be well suited for severe duty cycle, urban transit applications but SCR-coated DPF technology has not yet been offered or validated for DPF+SCR retrofit applications. In May 2017, Vienna University of Technology awarded the Professor Ferdinand Porsche Prize to engineers at Daimler AG for the development of their innovative diesel exhaust gas emission control system installed on the Mercedes 2 liter, OM 654 diesel engine that includes a close-coupled SCR-coated DPF (for more information on the Mercedes OM 654 diesel engine exhaust emission control system see: http://www.greencarcongress.com/2017/05/20170522-om654.html and http://www.greencarcongress.com/2016/02/20160215-mbenz.html).

Table V. Hong Kong's DPF+SCR Bus Retrofit Experience

In an effort to reduce roadside NO_2 emission levels, the Hong Kong government initiated and funded a number of programs in the 2013-2014 timeframe aimed at reducing NOx emissions from mobile sources operating in the metropolitan area including the incentivized retirement and replacement of pre-Euro IV diesel commercial vehicles, the replacement of catalytic converters on LPG taxis and public light buses, and DPF+SCR retrofits on Euro II and Euro III diesel double-decker buses (so-called franchised buses). Approximately 5700 double-decker buses were in operation in Hong Kong in 2013, with more than 4500 at Euro III or lower emission levels. Successful DPF+SCR bus retrofit efforts in several European cities including Barcelona and London, provided Hong Kong with an experience base to draw on. Hong Kong's emission target for their DPF+SCR bus retrofit program was to upgrade the NOx emission performance of their older double-decker diesel buses to Euro IV levels or better (i.e., achieve at least a 60% reduction in NOx emission levels). Before embarking on a large scale retrofit effort, an initial trial program was conducted in 2012-2013 utilizing six buses retrofit with DPF+SCR systems supplied from two different retrofit technology suppliers. The six bus trial retrofit effort utilized three major bus models: Euro II and Euro III Denis Trident buses and Euro II Volvo Olympian buses (these three models comprised 58% of the Euro II and III franchised buses operating in Hong Kong in 2013; all three models had sufficient space available for the selected DPF+SCR retrofit system). DPF+SCR retrofits operated for at least 12 months during the initial trial program. Important findings/results from this initial DPF+SCR retrofit trial program included:

- On average NOx emissions were reduced in the range of 63-81% (exceeded the 60% NOx reduction target); NOx performance strongly tied to SCR catalyst operating temperature. PEMS studies conducted in Hong Kong show greatly reduced or no SCR catalyst NOx efficiency when exhaust temperatures fall below $200^{o}C$ due to traffic congestion.
- No unacceptable emissions of other pollutants such as CO or hydrocarbons; particulate emissions were very low with the retrofit DPF
- Some episodes of high ammonia emissions were observed and corrected with improved urea dosing strategies
- A variety of operational issues were observed and corrected with retrofit system design improvements (e.g., mounting hardware failures, SCR catalyst substrate movement, exhaust leaks, urea deposit issues, high backpressure alarms, uncontrolled DPF regeneration resulting in SCR catalyst damage)
- More intensive maintenance efforts required to minimize soot build-up in the DPF, clean urea deposits in the exhaust system, clean urea injectors
- Average urea consumption rates of 3-7% of fuel consumption, average increase in bus fuel consumption of about 4%; 2013 estimated cost for DPF+SCR retrofit was HK$250,000 per bus

After completing this successful trial DPF+SCR retrofit program, Hong Kong identified about 1400 Euro II and Euro III double-decker franchised buses for DPF+SCR retrofits for their initial large scale retrofit program (targeted for the 2015-2016 timeframe; six different bus models). In 2014 additional DPF+SCR retrofit suppliers were qualified through a 12 month screening trial (retrofit suppliers were required to provide a 4 year warranty). Hong Kong's Environmental Protection Dept. (EPD) and Transport Dept. managed the retrofit program and conducted emission tests on selected retrofitted buses (including PEMS studies).

SCR retrofits in the off-road sector have largely focused on stationary diesel engines (e.g., back-up generators or prime power generators) with some very limited demonstrations/applications on off-road construction equipment. A recent technology demonstration completed in California successfully installed an active DPF+SCR system on the engines of a tugboat that operates at the Port of Los Angeles (project report available at: http://www.arb.ca.gov/msprog/aqip/demo.htm). The tugboat was powered by two Detroit Diesel 525 hp, 14 liter, two-stroke turbocharged and supercharged engines, rebuilt to U.S. EPA Tier 2 emission levels. Each engine was retrofit with a catalyzed DPF+SCR system. DPF regeneration was managed by an in-line diesel fuel burner on each DPF. With the use of ultra-low sulfur diesel fuel (15 ppm max. sulfur), PM was reduced by more than 95% (ca. 5-7 mg/ kWh after ca. 200 h service) and NOx emissions were reduced by more than 90%. There are hundreds of examples of SCR installations on large marine engines (both retrofit and OEM installations) to comply with NOx emission limits in designated waterways such as the Baltic Sea in northern Europe. Marine engine manufacturers are also introducing new large marine diesel engines equipped with SCR systems to comply with the International Maritime Organization's Tier III NOx emission standards. Additional information on marine SCR applications is available from the International Association of Catalytic Control of Ship Emissions to Air (IACCSEA) on their website at: http://iaccsea.com/.

A retrofit SCR system uses a metallic or ceramic washcoated, catalyzed honeycomb substrate, or a homogeneously extruded catalyst honeycomb and a urea/water reductant to convert nitrogen oxides to molecular nitrogen and oxygen in oxygen-rich exhaust streams. The urea solution is injected into the exhaust stream upstream of the SCR catalyst and hydrolyzes to form ammonia and CO_2. Reductant addition is controlled by an on-board control unit that initiates reductant addition based on the catalyst NOx light-off characteristics (typically reductant delivery is initiated when the SCR catalyst inlet temperature reaches 200ºC or higher). The reductant is added at a rate calculated by an algorithm that estimates the amount of NOx present in the exhaust stream. The algorithm can relate NOx emissions to engine parameters such as engine revolutions per minute (rpm), exhaust temperature, backpressure and load, or may also utilize the input of a NOx sensor located upstream of the SCR catalyst. Typical reductant usage rates for a retrofit SCR system are 2-4% of diesel fuel usage rates. Due to the sensitivity of SCR catalysts to poisoning by impurities that may be introduced through the use of low purity urea, such as that designed for agricultural fertilizer applications, it is imperative that only high purity urea/water reductant fluid (complies with ISO 22241-1 quality standard; the urea/water reductant carries the name AdBlue in Europe and diesel exhaust fluid [DEF] in the U.S.) be used that is specifically designed for urea-SCR NOx control systems.

Retrofit SCR systems can employ either zeolite-based or vanadia-based SCR catalyst formulations that are similar to the catalysts used in new engine SCR applications. In combined DPF+SCR retrofit systems, the DPF or DOC+DPF substrates are located upstream of the SCR catalyst to allow the DPF to be located in the hottest exhaust position to facilitate filter regeneration. The SCR catalyst formulation defines an operating temperature window with high NOx conversion efficiencies in the presence of sufficient ammonia, thermal stability, fuel sulfur impacts, and NOx reduction performance impacts of NO/NO_2 inlet catalyst composition.

Vanadia-based SCR catalyst formulations can be used with higher sulfur fuels compared to base metal zeolite formulations (e.g., Cu or Fe zeolite SCR catalysts), but can have thermal stability issues that can result in the loss of vanadium oxide species into the exhaust above about 550ºC. Zeolite-based SCR catalysts are thermally stable under typical filter regeneration temperatures. Catalyst-based DPF+SCR retrofit systems should be used with ultra-low sulfur diesel fuel regardless of the SCR catalyst formulation. Retrofit SCR systems are generally open loop control-based (no feedback loop on NOx performance). These open loop SCR systems can reduce NOx emissions from 60 to 90%. Closed loop control algorithms have been employed on stationary engines and can achieve NOx reductions of greater than 95%. SCR systems can reduce hydrocarbon emissions up to 80% and PM emissions 20 to 30% (PM reductions associated mostly with soluble PM fraction). Combining DPFs with SCR catalysts can reduce PM, ultrafine particulates, and black carbon emissions by more than 90%.

CARB's and EPA's verified retrofit technology lists includes:

- On-road and off-road passive DPF+SCR technology
- Off-road SCR-only technology
- Locomotive SCR-only technology

4. Hydrocarbon-SCR Retrofit Technologies

There has been some limited application of retrofit SCR technology in the U.S. that utilizes on-board diesel fuel as the reductant. Compared to urea-SCR retrofits, this hydrocarbon-SCR approach (also termed lean NOx catalysts) has limited NOx reductions (20-40%) with a diesel fuel usage penalty. In the U.S. this retrofit hydrocarbon-SCR catalyst has been combined with a wall-flow DPF to provide high efficiency reductions in PM. This combined DPF+hydrocarbon SCR retrofit system has been applied to both older highway and nonroad diesel engines that operate in California using ultra-low sulfur diesel fuel. Only a highway retrofit application remains verified by CARB that offers 25% NOx reduction combined with a wall-flow filter for Level 3 PM reduction (85% or greater PM reduction).

5. Retrofit Technology Prices

Some qualitative information on retrofit technology selling prices are provided here based on information published by various sources on retrofit costs in the U.S. (e.g., MECA's November 2014 retrofit technology white paper available at: http://www.meca.org/diesel-retrofit/resources; various "average" DPF retrofit installed costs to end users published by CARB in various regulatory documents associated with their in-use fleet emission reduction regulations) There is no public database available in the U.S. with specific retrofit cost information by application or project. U.S. retrofit pricing takes into consideration the cost of verifying a retrofit technology with CARB or EPA, and the cost of in-use compliance testing required by both agencies. The verification and in-use testing costs incurred by retrofit manufacturers can be substantial and range from $250,000 to $1,000,000 or more depending on the complexity of the testing required to verify a retrofit technology (there is no public disclosure of U.S. retrofit verification costs). Pricing in markets that do not require the use of verified technologies or in-use testing may be different from the U.S. market.

- Passive retrofit DPFs for typical highway and off-road applications range in price from $8000-$20,000 depending on engine size. The addition of an active DPF regeneration strategy to a retrofit DPF can increase costs by about 50% above a passive DPF.
- DPF+SCR retrofit systems are in the $20,000-$30,000 price range for systems that employ a passive DPF regeneration strategy, with some additional premium for systems that employ an active DPF regeneration strategy.
- Retrofit DOCs range in price from hundreds of dollars to a few thousand dollars depending on engine size.
- Retrofit crankcase vent filters are typically less than $1000 for most engine sizes.

D. Importance of Engine and Retrofit Maintenance

To operate as designed, all engines require proper maintenance (engine manufacturers define maintenance schedules for their engines). Installing a retrofit emission control system is not a substitute for conducting proper maintenance on an older engine. Benefits of conducting preventive maintenance include:

- Maintains low emissions
- Helps save fuel costs
- Maximizes truck/equipment performance
- Maximizes engine life
- Reduces down-time

The California Council on Diesel Education and Technology (CCDET), a non-profit cooperative group of California Community Colleges, the diesel industry and government agencies, supporting training and educational programs for diesel mechanics, has recently published: "Preventative Maintenance for Heavy Duty Trucks." The free handbook, available in both hardcopy and online, was developed to help truck owners save fuel costs, reduce downtime and maximize truck performance, engine life and overall operational efficiency. This truck maintenance handbook is available at: https://www.arb.ca.gov/msprog/truckstop/faq/truckstopblogger.htm.

Improper care of engine and retrofit emission controls can lead to:

- Expensive repairs and replacement parts
- Voided warranty
- Engine malfunction or breakdown
- Loss of horsepower and de-rated engine

With particularly dirty engines, periodic cleaning of a DOC or SCR catalyst might be needed. Diesel oxidation and SCR catalysts employing larger cell density substrates (e.g. 50 to 200 cells per square inch) can considerably minimize the risk of plugging and fouling. For engines equipped with a retrofit DPFs, backpressure should be monitored using monitoring equipment supplied with the DPF. If backpressures become excessively high, the filter should be cleaned according to the procedures specified by the filter supplier. A typical filter ash cleaning interval for a retrofit DPF is once a year but could be more frequent depending on vehicle duty cycle and engine lubricant consumption rates. For more on filter maintenance practices see MECA's filter maintenance practices white paper available at: http://www.meca.org/diesel-retrofit/resources. Retrofit systems should be regularly inspected to ensure that exhaust installation hardware remains in good condition. Inspections should include checking for warning lights on the backpressure monitor, inspecting the mounting brackets for looseness or damage, checking for signs of soot on the inside of the exhaust pipe and inspecting backpressure sensor tubing for any signs of condensation. Thermocouples included with the retrofit system are a common maintenance-related replacement part.

Regular maintenance becomes critical once a retrofit DPF is installed because the presence of smoke in the exhaust can no longer be used as an indicator of engine operation problems. High smoke opacity could be a sign of excessive oil consumption or a bad fuel injector, both of which result in high engine-out PM that may lead to plugging of the filter. Once a DPF is installed in the exhaust system, it will capture the PM and mask any signs of high smoke. A recommended regular maintenance practice is to have an opacity-based check of the engine-out exhaust, each time a filter is removed for cleaning.

In a recent 2015 report CARB summarized a multi-year assessment of the performance and reliability of DPFs equipped on trucks (both originally equipped DPFs and retrofit DPFs). The overall project findings included:

- PM filters do not increase the likelihood of truck fires and are manufactured in accordance with federal and state safety requirements (some trucking groups in California have filed lawsuits against CARB related to safety and potential fire hazards of DPFs);
- PM filters are effective in removing more than 98% of toxic diesel PM emissions;
- PM filters are operating properly, and most trucking fleets are not having problems with their engines or PM filters; and
- Some fleets are experiencing problems with their PM filters, but engine durability issues and inadequate maintenance practices are the primary reasons for these problems.

The full CARB 2015 report on DPF performance and reliability is available at: https://www.arb.ca.gov/msprog/onrdiesel/documents/DPFEval.pdf. Roadside opacity testing of trucks equipped with DPFs to assess filter integrity was one component of this assessment. CARB studies have shown that opacity levels above 3-5% are an indication of a damaged filter. The CARB report summarized recent California roadside opacity checks of about 900 trucks equipped with DPFs: about 8% of the DPF-equipped trucks showed opacity levels above 5%. Current California roadside truck smoke inspection requirements have opacity limits in the 40-55% range, making this inspection/maintenance program insensitive to finding damaged filters in the field using the SAE J1667 snap acceleration smoke test procedure.

CARB initiated an effort in 2016 to develop a future comprehensive heavy-duty vehicle inspection/maintenance program based on today's modern engines equipped with emission controls like DPFs and SCR catalysts. CARB staff presentation slides shown at public workshops that discuss the goals and issues related to the development of an enhanced heavy-duty inspection/maintenance program are available at: https://www.arb.ca.gov/msprog/hdim/hdim.htm. In a first step CARB intends to reduce opacity limits used in their truck inspection programs. CARB has proposed a 30% opacity limit for 1991-1996 model year, non-DPF equipped trucks, a 20% opacity limit for 1997-2006 model year, non-DPF equipped trucks and a 5% opacity limit for DPF-equipped trucks (2007 and newer model year trucks and older trucks equipped with a retrofit DPF). In a second step, CARB intends to integrate OBD checks into their truck inspection effort for 2013 model year and newer trucks. This second phase enhanced inspection/maintenance program is also likely to include some form of heavy-duty repair shop/mechanic licensing requirement.

The Dutch independent laboratory TNO has recently explored the use of portable particle number measurement devices as part of a periodic technical vehicle inspection test method aimed at checking for the presence and proper functioning of diesel particulate filters on light-duty diesel vehicles. Their work is summarized in a May 2017 report available at: https://www.tno.nl/en/focus-areas/urbanisation/mobility-logistics/clean-mobility/emissions-of-particulate-matter-from-diesel-cars/. Their results show that measuring particle number emissions during a low speed idle test is more sensitive than the conventional smoke testing procedure used in the Netherlands for diesel vehicle emissions inspections. Their testing shows that a particle number-based inspection test method is capable of identifying vehicles with a malfunctioning or removed DPF. The types of portable particle number measurement devices evaluated by TNO are similar to portable particle number measurement devices validated for use by the Swiss government in their required emissions inspection program for DPF-equipped, off-road equipment.

With respect to retrofit DPF reliability there are some additional noteworthy published data including:

- Both MECA and CARB findings of 2010-2012 warranty claims on retrofit DPFs found filter-related warranty claims to be less than 1% of sales in California
- A 2003 VERT survey of 3,848 construction retrofit DPF installations from 2001 to 2003 in Europe found a failure rate of only 1-2%, after some early issues were addressed. The root causes of these failures included poor filter cleaning and poor engine maintenance practices, as well as, ignoring of warning alarms by the operators (see SAE paper number 2004-01-0076 available on the SAE website at www.sae.org).
- The experience with retrofit DPFs on New York City bus fleet is described in two SAE papers (SAE paper numbers 2001-01-0511 and SAE paper number 2002-01-0430 available on the SAE website at www.sae.org). In the first phase of their efforts to clean up the bus fleet, half of the bus fleet was retrofitted with DPFs and the other half was used as a control population. Each fleet of vehicles represented several hundred transit buses. After a year of normal operation, with proper maintenance, the transit authority observed no statistical difference in down time between buses equipped with DPFs and

those that were not. At the conclusion of the program, the city decided to retrofit the remainder of the diesel buses in its fleet with DPFs.

- In-use testing of diesel emission control technologies is an integral component of EPA's verification program (device manufacturers are required to complete in-use testing once 500 units have been sold). Additionally, EPA conducts test programs on randomly selected retrofit devices from installations completed with grants by the National Clean Diesel Campaign. In a 2014 SAE publication (SAE paper number 2014-01-2347), EPA summarizes in-use testing results for a range of verified retrofit technologies. In this test program, EPA identified and recovered a variety of retrofit devices, including DPFs and DOCs, installed on heavy-duty diesel vehicles (on-highway and nonroad applications). All of the devices were tested at Southwest Research Institute in San Antonio, Texas. This study's goal was to evaluate the durability, defined here as emissions performance as a function of time, of retrofit technologies aged in real-world applications. A variety of operating and emissions criteria were measured to characterize the overall performance of the retrofit devices on an engine dynamometer. This paper focuses on pollutant removal efficiency, which is calculated from measurements of the engine's baseline emissions as compared to emissions with the emission control device installed. Results show emissions reduction effectiveness in line with those originally verified for the devices. Testing also revealed DOCs and DPFs significantly reduced emissions of gaseous and particle-bound poly-aromatic hydrocarbons (PAHs) as well as mobile source air toxics. This EPA SAE publication is available at: http://papers.sae.org/2014-01-2347.

E. Retrofit application examples and other retrofit resources available on the internet

1. MECA has a number of retrofit resources available at: http://www.meca.org/diesel-retrofit, including a retrofit technology white paper (the retrofit technology information for this memo draws from information found in MECA's 2014 retrofit technology report; this retrofit white paper includes reference web links to retrofit programs in a variety of countries), fact sheets, pre-installation checklists, case study reports for several nonroad application sectors (marine, locomotive, construction equipment, mining equipment, stationary engines), and a number of retrofit-related slide presentations. Press releases associated with MECA's annual retrofit sales surveys are available by year at: http://www.meca.org/news/press-releases.

2. The Brussels-based industry association AECC (Association for Emission Control by Catalysts) has some retrofit technology information and European retrofit project examples associated with Low Emission Zones found in various European cities available at: http://www.aecc.eu/applications/retrofit/. Detailed information about European Low Emission Zones including retrofit-related compliance requirements are available at: http://www.urbanaccessregulations.eu/. London's Low Emission Construction Zone requirements including the use of retrofits on nonroad mobile machinery for compliance are detailed on its website at: http://nrmm.london/nrmm.

3. The Clean Diesel Clearing House (CDCH, available at: http://tool.cleandieselclearinghouse.org/) is a web-based tool (initially commissioned by the New York State Energy Research and Development Authority [NYSERDA]) that enables users to determine the best available emission reduction technology (BAT), including verified products (and other product options allowed by specific program requirements) for retrofitting diesel-powered vehicles and equipment. The CDCH can be used to support retrofit products, clean fuel options and clean fuel vehicle selections that satisfy BAT regulations, as well as voluntary emission reduction program requirements.

4. CARB has a large number of retrofit resources available on their website at: https://www.arb.ca.gov/msprog/decsinstall/decsinstall.htm. Here you can find links to CARB's verified retrofit technologies list, information on how to find and install a retrofit device, engine and retrofit maintenance information, answers to frequently asked questions concerning retrofits, and training information/videos related to retrofits and CARB's various in-use diesel fleet emission reduction regulations. Since 2009 CARB has provided funding for a number of advanced technology demonstration projects that includes DPF or DPF+SCR retrofits on locomotive and marine engines. The complete listing of CARB-funded advanced technology demonstration projects with links to project reports is available at: https://www.arb.ca.gov/msprog/aqip/demo.htm.

5. EPA's National Clean Diesel Campaign provides lots of resources related to diesel retrofits through their NCDC web portal found at: https://www.epa.gov/cleandiesel. Here you can find links to information about federal funding for clean diesel projects that include retrofits, listings of projects funded by EPA, EPA reports to Congress on EPA's Diesel Emission Reduction Act (DERA) program, EPA's listing of verified retrofit technologies, and sector-specific clean diesel activities related to school buses, construction and agriculture equipment, and ports. Information on retrofit diesel particulate filters and diesel oxidation catalysts is available at: https://www.epa.gov/verified-diesel-tech/information-diesel-particulate-filters-and-diesel-oxidation-catalysts.

6. The VERT website (http://www.vert-certification.eu/) provides information about their retrofit particle filter system certification process, a listing of certified particle filter systems, a directory of applications that employ VERT certified retrofit filters, and a number of reports about retrofit filter projects conducted by VERT outside of Western Europe including China, Colombia, Chile, Israel, and Iran. Many of these VERT international retrofit projects target the retrofit of DPFs on transit buses in large cities. Some highlights of these VERT retrofit DPF activities include:

- Santiago, Chile: participation in Santiago's program that has retrofitted hundreds of buses with DPFs, detailed in the following report: http://www.vert-certification.eu/j3/images/pdf/article/25/Report_on_the_Santiago_de_Chile_DPF_Program.pdf.
- Bogota, Columbia: initial focus on retrofitting hundreds of small and large transit buses with VERT certified DPFs (DPF retrofits applied mostly to Euro II and Euro III engines): http://www.vert-certification.eu/j3/index.php/projects/retrofit-projects/columbia.

- China: participation in DPF retrofit demonstration projects on buses in Nanjing and Xiamen, and on construction equipment in Beijing: http://www.vert-certification.eu/j3/index.php/projects/retrofit-projects/china.
- Tel Aviv, Israel: participation in DPF retrofit project on buses with EGGED, operators of the largest bus fleet in Israel: http://www.vert-certification.eu/j3/index.php/projects/retrofit-projects/israel.
- Teheran, Iran: participation in DPF bus retrofit project involving more than 1,000 buses in Teheran along with Air Quality Control Company (AQCC) based in Tehran, Sharif University of Technology, and the Tehran City Bus Company: http://www.vert-certification.eu/j3/index.php/projects/retrofit-projects/iran.

Details are also provided by VERT for the recently implemented regulations in Berlin covering low emission construction equipment. These regulations require the purchase of new equipment meeting Euro nonroad Stage IIIA, IIIB, or IV emission standards depending on power rating and certified filter retrofits on older equipment. Details of the Berlin low emission construction equipment requirements are available at: http://vert-certification.eu/j3/index.php/projects/retrofit-projects/berlin.

7. Andreas Mayer (consultant associated with VERT) and many other co-authors published a comprehensive book on particle filter retrofits for diesel engines in 2008. An on-line book preview is available at: https://books.google.com/books?id=kxxGpt9zKTwC&pg=PA110&lpg=PA110&dq=VERT+in-use+compliance+testing&source=bl&ots=5-8FXhKjXO&sig=i3tw1ntBeYuColaXXHDe84qGZRE&hl=en&sa=X&ved=0ahUKEwjq9IuQjKTSAhVN1mMKHeI2AjcQ6AEIPDAF#v=onepage&q=VERT%20in-use%20compliance%20testing&f=false. Note that this on-line book preview does not include all pages included with the book. This retrofit filter reference book is available for purchase from www.amazon.com.

8. Hong Kong's March 2013 Clean Air Plan (available at: http://www.enb.gov.hk/sites/default/files/New_Air_Plan_en.pdf) includes some information about Hong Kong's efforts to retrofit buses with DPFs and SCR catalysts to reduce PM and NOx emissions. Hundreds of buses are operating in Hong Kong with retrofit DPF+SCR systems installed on older Euro II and Euro III-compliant buses. A case study report prepared for Hong Kong's Business Environment Council prepared by Eminox Ltd. that summarizes Hong Kong's earlier efforts to retrofit Hong Kong buses with passively regenerated DPFs is available at: https://bec.org.hk/files/images/Resource_Centre/Case_Studies/Air_pollution/1_-_Reducing_Exhaust_Particulates_from_Buses1.pdf.