

**Diesel Retrofit Assessment for NYS DOT to Retrofit its Existing Engine Fleet**

**Research Project C-07-12**

**Final Report**

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16. Abstract: The NYS DEC has required the use of retrofit technologies for various state agency, state public authority, and regional public authority heavy duty vehicles, as well as heavy duty vehicles used on behalf of such agencies and authorities. This report was compiled to assist NYS DOT in its efforts to comply in the most cost effective manner possible, without compromising its core functions. The results of the literature review and key points from conversations with fleet managers and retrofit/engine manufacturers form the basis of the quantitative analysis of benefits and costs calculated for various retrofit technologies. These benefits and costs naturally depend on many aspects of the vehicle in question, such as its size, model year, and usage pattern. In the long term, the most cost effective way to reduce PM emissions is to replace the oldest trucks. Another decently cost effective option is to install level 1 retrofits on relatively new class 8 dump trucks, starting with the newest which are compatible. While the long term cost effectiveness should be a key factor in developing emission reduction strategies, there are several other important factors to consider: near-term budget constraint; other possible options; and vehicle and duty cycle compatibility.			
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## 1. Executive Summary

Diesel vehicles perform vital roles in a wide range of fleets, and the New York State Department of Transportation (NYS DOT) fleet is no exception. At the same time, exposure to diesel exhaust, and its components, is associated with numerous serious health problems, from asthma to cancer. While newer diesel vehicles emit substantially lower levels of many pollutants, older vehicles in legacy fleets continue to operate with high emission rates. Fortunately, there are numerous retrofit techniques which can lower these emission rates. New York's Environmental Conservation Law (ECL) mandates that NYS Department of Environmental Conservation (NYS DEC) regulate the use of retrofit technologies for various state agency, state public authority, and regional public authority heavy duty vehicles, as well as heavy duty vehicles used on behalf of such agencies and authorities (NYS DEC, 2009a). The NYS DEC has adopted such regulations, and the NYS DOT is seeking to comply in the most cost effective manner possible, without compromising its core functions.

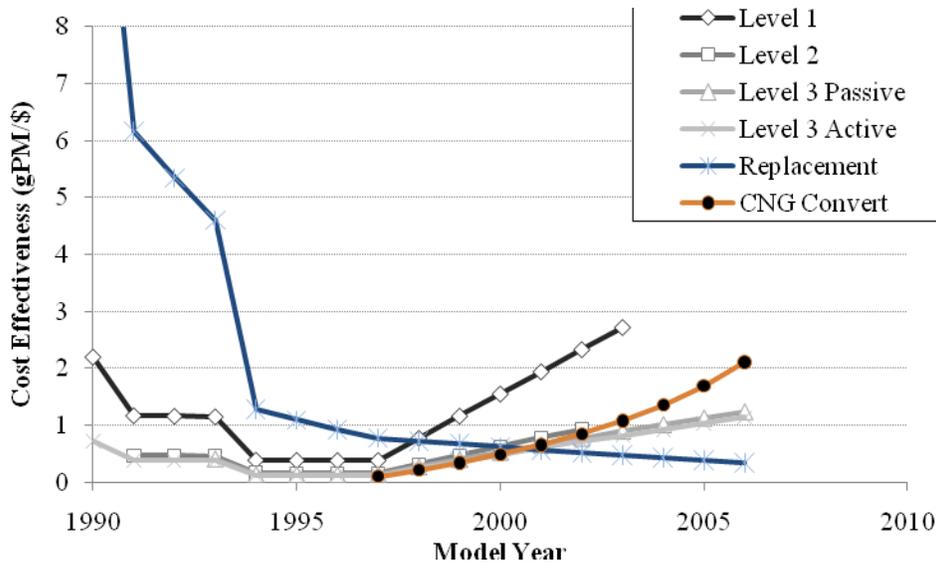
This report was compiled to assist NYS DOT in its efforts. The authors conducted literature searches regarding health impacts of diesel emissions, available retrofit technologies, and retrofits conducted in the past. Fleet managers who have conducted retrofits were contacted, as were retrofit manufacturers, engine manufacturers, and retrofit installers. The results of the literature review and key points from conversations were compiled into sections on health impacts, retrofit technologies, previous clean diesel projects, and retrofit impacts on vehicle operation, maintenance, and warranties. They also form the basis of the quantitative analysis of benefits and costs associated with different diesel emission reduction strategies.

NYS DEC regulation breaks most retrofits down into three levels, based on California Air Resources Board (CARB) verifications of particulate matter (PM) emission reduction (NYS DEC, 2009c). Level 1 means  $\geq 25\%$  reduction; level 2 means  $\geq 50\%$  reduction; level 3 means  $\geq 85\%$  reduction. For NYS DOT purposes, level 1 retrofits are diesel oxidation catalysts (DOCs), possibly supplemented by a crankcase filter. The only level 2 technology relevant to NYS DOT is the flow through filter (FTF). All CARB verified level 3 retrofits include a diesel particulate filter (DPF) (CARB,

2009b). Higher level retrofits generally come at higher costs, and with more compatibility requirements. Outside of this three level framework, another option is converting a vehicle to run on an alternate fuel.

The benefits and costs of various retrofit technologies were calculated, and compared to those of early vehicle replacement. These benefits and costs naturally depend on many aspects of the vehicle in question, such as its size, model year, and usage pattern. The most common vehicle type in the NYS DOT fleet is the class 8 dump truck, with well over a thousand in use. Figure 1 shows the long term cost effectiveness, or “bang per buck” for emission reduction techniques applied to class 8 dump trucks from a range of model years. The units are grams of PM emission prevented per dollar spent. The costs used are long term costs, meaning that that future costs such as filter cleanings, and benefits such as fuel savings, are discounted and included.

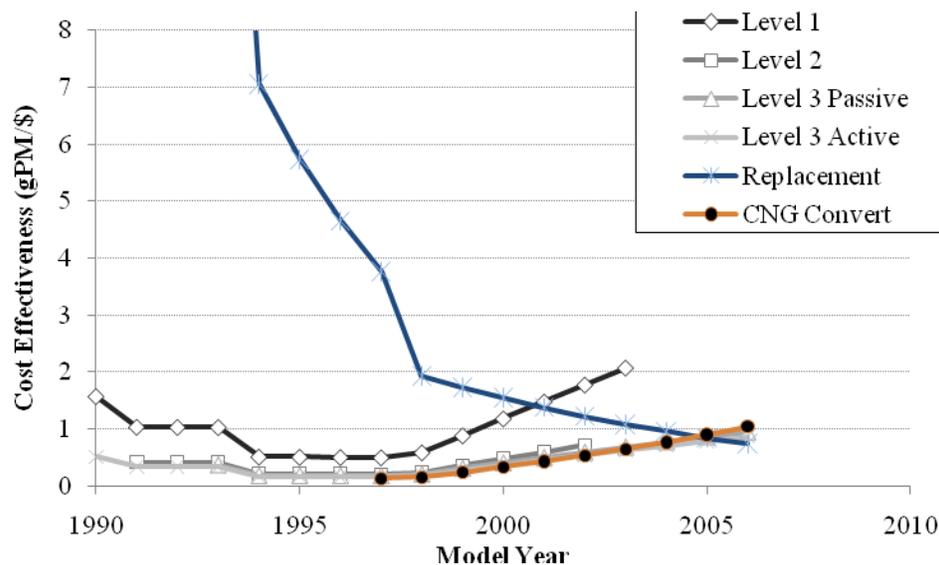
Figure 1: Class 8 Dump Truck Long Term Cost Effectiveness Comparison



In the long term, the most cost effective way to reduce PM emissions is to replace the oldest trucks. Another decently cost effective option is to install level 1 retrofits on relatively new class 8 dump trucks, starting with the newest which are compatible. It is generally more difficult to find cost effective methods of reducing PM emissions for trucks too new for level 1 DOCs, or for trucks from the mid 1990's.

The cost effectiveness picture for class 6 stake trucks (another substantial component of the NYS DOT fleet) is shown in Figure 2. It is similar to the class 8 picture, with a few adjustments. First, retrofits are somewhat less effective due to the class 6 trucks' lower emission rates. Second, replacement is more cost effective due to the lower vehicle value. Third, CNG conversion is less effective due to both the lower emission rates and lower fuel consumption. The general picture of replacement being most cost effective for older vehicles, and DOCs for some younger vehicles, still applies. Replacement is the most cost effective option up through newer model years than for the class 8 trucks, however.

Figure 2: Class 6 Stake Truck Long Term Cost Effectiveness Comparison



While the long term cost effectiveness should be a key factor in developing emission reduction strategies, there are several other important factors to consider. First, some options, such as vehicle replacement, can wreak havoc on the current year's budget despite being extremely cost effective in the long term. Second, other options might offer a lot of "bang per buck," without offering sufficient bang. They might not offer sufficient emission reductions for NYS DOT goals or regulatory mandates. Third, vehicle and duty cycle compatibility might limit application of certain technologies, as could operational impacts.

One of the key compatibility concerns for FTFs and DPFs is the exhaust temperature. If temperatures are too low to support regeneration for a long period, the buildup can burn at too high a temperature when finally ignited. Exhaust temperature profiles of 76 class 8 dump trucks were compared to retrofit requirements, revealing that passive DPFs would not provide a reliable retrofit solution for NYS DOT class 8 dump trucks. The same can be said for level 2 flow through filter technology.

Active DPFs are not incompatible with the temperature profiles, but they can pose another problem. Vehicle availability during winter storms could be compromised by the use of active DPFs with substantial regeneration times, potentially posing a public safety risk. NYS DOT has expressed that regeneration times over 20 minutes could cause problems. Most active filters take 2-5 hours to regenerate, while one Huss filter takes roughly 30 minutes and the ESW ThermaCat regenerates during normal operation. However, NYS DOT's class 8 dump trucks exceed the maximum horsepower for the ESW device, and many class 6 trucks violate other requirements such as model year and incompatibility with exhaust gas recirculation (EGR).

Based on the long term cost effectiveness, it makes sense for NYS DOT's strategy to start with early retirement of old vehicles. Older vehicles should be retired and (when necessary) replaced to the extent allowed by current budgets, starting with the vehicles with the lowest value. Given compatibility issues, and that active DPFs are deemed prohibitively disruptive to winter maintenance, level 1 technology is the next best option for most newer class 8 trucks. Level 1 DOCs, or DOC/crankcase filter combinations, can be applied to many such trucks, but there are some exceptions.

It is particularly difficult to find a suitable retrofit strategy for model year 2004-2006 class 8 dump trucks. These vehicles have temperature profiles which violate the requirements of passive DPFs, and their use of EGR is incompatible with active DPFs, apart from the Cleaire Horizon, which has a burdensome 5 hour regeneration time. None of the level 1 DOCs are compatible with model years 2004-2006, and neither is the level 2 FTF. For such vehicles, there are two options. CNG conversion might provide the greatest emission benefits, assuming a certified CNG conversion kit is available for the vehicle, and the current budget can bear the initial cost. CNG conversion compatibility will have to be evaluated on a vehicle by vehicle basis due to complexities arising from

extremely narrow certifications, and an intense certification process. Otherwise, a non-level 1 DOC may prove to be the best option. The EPA has verified DOCs without model year restrictions to provide a 20% reduction in PM. When combined with use of biodiesel, these could essentially provide level 1 emission benefits, even if not technically verified to do so for these newer vehicles.

Although not a CARB or EPA verified retrofit technology, and therefore not considered BART under NYS DEC regulations, LED lights have the potential to reduce idling time, and therefore emissions. The potential for emissions prevention is particularly pronounced for heavy dump trucks which idle around construction sites to protect workers. The primary reason for idling as opposed to parking is to keep lights flashing without draining the battery. Section 10 quantitatively analyzes the costs and benefits of converting lights to LEDs, as a means of going beyond regulatory requirements. The elimination of work zone idling generally provides a smaller PM<sub>2.5</sub> reduction than installing a DOC on the same vehicle, but the two actions are not mutually exclusive. Costs vary considerably, depending on the vehicle and impact attenuator, but could be quite reasonable in some cases, especially once fuel savings are considered. There is precedent for CMAQ funding, and the fact that LED technology is not included in NYS DEC regulation might make federal grant managers more likely to fund it.

## **2. Health Impacts of Diesel Emissions**

Diesel exhaust is a combination of many different gaseous compounds and heterogeneous particles. Potential health impacts range from frustrating to life threatening. According to a 2005 report by the Clear Air Task Force, diesel fine particles shortened over 2,700 lives in the New York metropolitan area in 1999, more than in any of the other 39 regions studied (Clean Air Task Force, 2005). More minor impacts include eye and nose irritation (Rudell et al., 1996) and increased susceptibility to allergic materials (Wargo et al., 2002).

Exposure to components of diesel exhaust has been found to increase the risk of stroke (Tsai et al. 2003; Hong et al. 2002). Tsai et al. (2003) compared hospital admissions for primary intracerebral hemorrhage and ischemic stroke with pollutant concentrations on the same day, while Hong et al. (2002) compared stroke mortality data with pollutant concentrations. The studies took place in different Asian cities and both took into account other factors such as temperature. The studies found that PM<sub>10</sub> and NO<sub>2</sub> concentrations were significantly associated with admissions and mortality. Results for other pollutants were more mixed (Tsai et al. 2003; Hong et al. 2002).

The evidence linking diesel exhaust with cancer led multiple bodies to formally recognize the probability of diesel exhaust acting as a carcinogen. Based on human exposure studies and animal testing, diesel exhaust was declared a probable human carcinogen by the International Agency for Research on Cancer (IARC, 1998). In 1996, the World Health Organization found that diesel exhaust is probably carcinogenic (CARB, 2008a). The California EPA found a causal link between diesel exhaust and lung cancer in 1998, and by 2000, the U.S. Department of Health and Human Services' National Toxicology Program listed diesel exhaust as reasonably anticipated to be a human carcinogen (CARB, 2008a; US DHHS, 2005).

Numerous components of diesel exhaust have been identified as particularly dangerous. A 2001 EPA rule designated "diesel particulate matter and diesel exhaust organic gases" as one of the 6 priority Mobile Source Air Toxics (MSAT) categories (Carr et al., 2007; Claggett and Houk, 2006). Other components of diesel exhaust are considered priority MSATs, including acrolein, benzene, and formaldehyde (US OSHA,

2009). Acute exposure to benzene is associated with drowsiness, dizziness, headaches and unconsciousness. Chronic inhalation of benzene can cause blood disorders through its effects on bone marrow. Exposure to formaldehyde or acrolein has been shown to cause eye, nose, and throat irritation. The EPA considers benzene to be a known human carcinogen, while it considers formaldehyde to be a probable human carcinogen. The EPA considers current data related to acrolein to be insufficient to determine carcinogenic effects (US EPA, 2009a).

Other gaseous components of diesel exhaust include carbon dioxide, carbon monoxide, and nitrogen oxides, none of which are considered MSATs. Carbon dioxide is well known for its contribution to global climate change. Carbon monoxide can have cardiovascular effects, with those who suffer from heart disease facing the greatest threats. Exposure to high levels of carbon monoxide is associated with central nervous system effects (US EPA, 2009b). Short term exposure to nitrogen dioxide has been linked to adverse respiratory effects (US EPA, 2009c). Nitrogen oxides are also known for their complicated role in influencing concentrations of ozone, which has its own negative health impacts.

Asthma is a major concern for both children and adults. It is one of the most common long-term diseases in children (US CDC, 2009). Diesel exhaust exposure has been linked to exacerbated childhood asthma (Tolbert et al., 2000; Slaughter et al., 2003). The development of asthma in children who tend to play outdoors in areas with high levels of air pollution may be linked to ozone exposure (McConnell et al., 2002). Asthma imposes significant costs on society. In 2002, asthma medications were estimated to cost \$500 per child per year (Wargo et al., 2002). A study on the cost of adult asthma found that the total cost averaged \$4912 per person per year, with pharmaceuticals accounting for \$1605 of the cost. Other major components were lost work time and hospital visits (Cisternas et al., 2003). Selgrade et al. (2006) approximates that the annual cost of treating asthma in children under 18 years old is \$3.2 billion per year, and that asthma causes 14 million absentee days from school per year. One study found children with asthma were more likely to have learning disabilities, even after adjustment for demographic factors (Fowler et al., 1992).

The health impacts of particulate matter are especially difficult to study because levels are usually measured with rather coarse metrics, such as total mass or mass of particles under a single specified aerodynamic diameter (usually 2.5 or 10 micrometers). Such metrics neglect the vast heterogeneity in particles, both in terms of physical properties (e.g. size and density) and chemical composition. Li et al. (2003) found that ultrafine particles (<0.1 micrometers) were most potent toward inducing cellular heme oxygenase-1 expression (a sensitive marker for oxidative stress) and depleting intracellular glutathione. The small size of ultrafine particles allows them to penetrate tissue more effectively. Heme oxygenase-1 expression was also correlated with the high organic carbon and polycyclic aromatic hydrocarbon (PAH) content of the ultrafine particles.

Naturally, there is some dissent regarding the negative health impacts of diesel exhaust, including the carcinogenic effects. Hesterberg et al. (2005) reviewed animal testing research and concluded that life-span bioassays have demonstrated that chronic inhalation of high concentrations of diesel exhaust caused lung tumors in rats but not in mice or Syrian hamsters. The authors expressed concern that the results in rats could be species specific, and therefore not applicable to humans. Polycyclic aromatic hydrocarbons, which are found in diesel exhaust, produced skin cancer when painted on mouse skin (Hesterberg et al., 2005). At the time the review was published, Hesterberg was an employee of International Truck and Engine Corporation. Industry is not alone in pointing out uncertainty regarding health effects, especially when it comes to quantifying risks and acceptable concentrations. The EPA provides acute reference concentrations (RfCs), which are estimates of the acute continuous inhalation exposure that is likely to be without an appreciable risk of deleterious effects in humans during a lifetime. The EPA concedes its estimates of these concentrations have uncertainty spanning as much as an order of magnitude (US EPA, 2009d).

### **3. Effects of Retrofit Technologies**

#### *3.1 Vehicle Modifications*

Emissions can be produced from both the crankcase and the tailpipe of a diesel vehicle. Several emission reduction technologies are available to aid in the reduction of

crankcase and tailpipe emissions. This section will outline the basics of how the technologies function, without going into the details of differences between brands and models. Specific models, and their applications to the NYS DOT fleet, are examined in Section 7 and Section 8.

Crankcase emissions are caused by smoke excretions necessary to eliminate high pressure buildup in the crankcase (Hill et al., 2005). These excretions release fine particulate matter (Hill et al., 2005). According to Cummins, crankcase emissions can constitute up to 25% of total emissions (Cummins, 2009a). Closed crankcase ventilation systems (CCVS) are used to reduce these emissions by rerouting engine blow-by back into the engine intake, filtering out particulate matter, and recombusting air toxics. Emissions which are not combusted on second pass through the engine can still be treated by an emissions control device in the exhaust system. Both the EPA and CARB verify CCVS only when used with an emission control device in the exhaust system. EPA grant funds cannot be used to install a CCVS by itself (US EPA, 2009e).

Once emissions have reached the exhaust system, two major types of reduction technologies are used; diesel particulate filters and diesel oxidation catalysts. Both work by oxidizing hazardous diesel particulates into less harmful chemical compounds, but the particulate filter includes a physical ceramic filter (US EPA, 2007a). Some devices use less intense filters than others. This results in a spectrum of retrofit devices, rather than two strictly distinct categories. Devices with less intense filters are sometimes referred to as “flow through filters.”

Exhaust temperature requirements for diesel oxidation catalysts are relatively low, typically around 150°C (US EPA, 2007b), but much of the particulate mass flows through. As more intense filters are added, a much larger fraction of the particulate mass is stopped, but this comes with the challenge of disposing of the buildup. Regenerating filters burn off the particulates stopped by the filters, but they can be sensitive to temperature. If temperatures are too low to support regeneration for a long period, the buildup can burn at too high a temperature when finally ignited. The resulting temperature gradients can be damaging to the exhaust system (van Setten, 2001). A typical passive diesel particulate filter might require that the exhaust temperature be at least 240°C for 40% of the duty cycle at the filter inlet (US EPA, 2007c). Active diesel

particulate filters attempt to solve the temperature problem by providing additional heat for regeneration, at additional cost. Huss, a filter manufacturer whose active filters are being used in a trial project on NYC school buses, claims that some of its filters have no minimum exhaust temperature (Huss, 2008). Using ultra low sulfur diesel fuel tends to help with buildup problems, and is typically required for particle filters. Though not required for diesel oxidation catalysts, the EPA believes ultra low sulfur diesel can prevent diesel oxidation catalysts from increasing ultrafine particulate matter (US EPA, 2007d). ULSD can also extend the useful life of all retrofits, by reducing levels of sulfuric acid in the exhaust system (M DEP, 2008).

Catalysts can cause soot to oxidize through direct physical contact, or they can catalyze the formation of a gaseous molecule (such as  $\text{NO}_2$  from  $\text{NO}$  and  $\text{O}_2$ ), which is more reactive than  $\text{O}_2$  itself. The reactive gas molecule (e.g.  $\text{NO}_2$ ) can then oxidize soot, or other gaseous molecules such as  $\text{CO}$ . In doing so,  $\text{NO}_2$  would revert to  $\text{NO}$ , and the process could repeat in a cycle (van Setten, 2001). Concern over the potential for catalyzed retrofits to increase  $\text{NO}_2$  emissions led the EPA to issue limits on  $\text{NO}_2$  increases for all retrofits on its verified technology list, following a similar move by CARB (US EPA, 2007e). As of January 1<sup>st</sup>, 2009, all retrofits on the EPA's verified technology list must not increase  $\text{NO}_2$  emissions by more than 20 percent (US EPA, 2007e). Increased  $\text{NO}_2$  emissions, sometimes referred to as  $\text{NO}_2$  slip, can pose problems because  $\text{NO}_2$  is a potent oxidizer (NJ DEP, 2006). Rim et al. (2008) found the addition of a diesel oxidation catalyst did not appear to increase in-cabin  $\text{NO}_2$  concentration. Another study tested tailpipe nitrogen oxides when high performance diesel oxidation catalysts (also referred to as "flow-through filters") were deployed on school buses in New Jersey. No significant overall reduction in  $\text{NO}_x$  was found (none was expected), and post-retrofit tests actually yielded a slightly lower  $\text{NO}_2$  to  $\text{NO}$  ratio (NJ DEP, 2006). Retrofits can, and sometimes do, employ multiple stages of catalysts. Oxidation catalysts can be employed upstream of  $\text{NO}_2$  reduction catalysts (Johnson Matthey, 2009).

The degrees to which emission control technologies prevent PM, CO, and hydrocarbon emissions have been studied by numerous authors. Hill et al. (2005) found crankcase emissions to be an extremely strong source of  $\text{PM}_{2.5}$  inside a school bus, and that a Donaldson Spiracle closed-crankcase filtration device eliminated this form of self-

pollution. Clark et al. (2002) reported that tests on a 1992 model year refuse truck revealed a PM reduction of 24% and a CO reduction of 8.3%, due to a catalyst. Herner et al. (2009) tested four heavy-duty and medium-duty diesel vehicles with four different particulate filters. They found the filters realized more than 95% PM mass reduction on both duty cycles. They found a catalyzed filter removed 99% of hydrocarbons and 94% of CO, but an uncatalyzed filter did not produce such benefits. Low exhaust temperatures reduced the effectiveness of the catalyzed filter at controlling hydrocarbons, and nearly eliminated its ability to control CO.

There has been some concern that emission control technologies which reduce PM mass may actually increase nanoparticle number concentrations (Holm  n and Ayala, 2002). Kittelson et al. (2006) found that one type of particulate filter produced large quantities of nuclei mode particles, while another did not. For the filter which produced the large quantities, the number increased with higher exhaust temperatures. Biswas et al. (2008) found that two types of particulate filters efficiently suppressed nucleation mode particles. They hypothesized that the young age of a filter could contribute to its ability to store sulfur. Holm  n and Ayala (2002) found that a passive DPF manufactured by Johnson-Matthey yielded both accumulation and nuclei mode number concentrations of particles which were lower than those from the same vehicle using an oxidation catalyst by a factor of 10-100, under most test conditions. Nuclei mode particles are smaller than accumulation mode particles. Nuclei mode particles tend to make up a large percentage of the number of particles in diesel exhaust, while constituting a very low fraction of the total mass (Kittelson et al., 1998).

It can be difficult to develop a single % effectiveness of a given technology at reducing a given pollutant (even when considering installation on only one potential vehicle). This is largely due to the effect of duty cycle. Measuring particle emissions can be particularly challenging, as the manner in which exhaust is diluted after leaving the tailpipe can influence results (Holm  n and Ayala, 2002).

For practical purposes, the verified technology lists produced by the EPA and CARB are good sources of product specific emission reduction estimates. EPA numbers are based on engine dynamometer tests (US EPA, 2002a). CARB's verification procedure allows the applicant limited flexibility in choosing between engine and chassis

dynamometer testing, depending on what kind of reduction they are seeking to verify (CARB, 2009a).

In order to meet new vehicle emission standards, manufacturers have been incorporating DPFs into their new models, both in the United States and other countries such as Japan. In the United States, the 2007 standard for particulate matter was a driving force behind the change. Selective Catalytic Reduction (SCR) is being used to curtail NO<sub>x</sub> emissions. SCR works by reducing NO<sub>x</sub> on a selective catalyst using an ammonia reductant (commonly from urea). The systems are often quite complex, partially in order to withstand freezing and thawing of the urea. On the positive side, highly efficient NO<sub>x</sub> removal allows engines to operate at maximum fuel efficiency (high engine-out NO<sub>x</sub>, low PM) (Johnson, 2009). As a result of these changes to new vehicle designs, replacing a vehicle can lead to lower emissions than retrofits, and should be considered as alternate emission reduction strategy, particularly for older vehicles. This will be discussed in greater detail in Section 8.

### *3.2 Alternative Fuels and Additives*

Aside from vehicle retrofits, alternative cleaner fuels are used to reduce emissions. Many alternate fuel blends and additives can be used without extensive or costly modifications to a diesel vehicle, while others can require a complex vehicle conversion.

Historically, one of the most widely used alternative fuels has been ultra-low sulfur diesel fuel (ULSD), which contains considerably less sulfur content than older diesel blends, with a ceiling of 15 parts per million. Sulfur is naturally present in crude oil, and is in a volatility range which causes it to be incorporated into diesel. Sulfur does increase the lubricating capacity of the fuel, but it can be oxidized to form sulfur trioxide, which binds with water to form sulfuric acid. Sulfuric acid contributes to particle emissions, and can cause corrosion inside the engine and exhaust system (Morawska et al., 2008). Ristovski (2006) found lower particle number emissions when using lower sulfur diesel fuel, based on tests using a chassis dynamometer, confirming results from several earlier studies (Morawska et al., 2008). Use of ULSD is now so widespread that it is no longer an alternative fuel for most applications within the United States. Due to EPA

standards, most diesel fuel in the United States became ULSD on June 1<sup>st</sup>, 2006. Some phasing in is still in progress, especially with non-road applications (WS DOE, 2009).

Another relatively common alternative fuel is biodiesel. Biodiesel is an often domestically produced, renewable, biodegradable fuel made from vegetable oil and animal fat blended with petroleum gas. Biodiesel is actually an old idea. Rudolph Diesel, inventor of the diesel engine, experimented with a range of fuel sources including peanut oil (US EIA, 2004). The emissions benefits of biodiesel increase as more of it is blended with petroleum. One of the main advantages of biodiesel is the lack of mechanical modifications required for running some blends of the fuel (US EPA, 2007a; US EIA, 2004). Because biodiesel has better lubricity than low-sulfur petroleum diesel, (500 ppm by weight), it can be blended with low or ultra-low sulfur diesel to provide lubrication benefits. Biodiesel isn't necessarily the most cost effective means of increasing lubricity, however. Biodiesel does not handle cold weather as well as petroleum diesel, particularly when the biodiesel is made from yellow grease. Vehicles running on B20 are expected to achieve approximately 2.2 percent fewer miles per gallon of fuel, due to the fact that the energy content of a gallon of biodiesel is 11 percent lower than that of a gallon of petroleum diesel. There is little difference in the fraction of the energy content used by an engine running on biodiesel and an engine running on petroleum diesel (US EIA, 2004).

The emission effects of various biodiesel blends have been studied by numerous authors. Clark and Lyons (1999) tested class 8 truck emissions with a chassis dynamometer, using standard No. 2 diesel and a 35% biodiesel blend. They found that CO emissions were lower with the biodiesel for engines from Detroit Diesel, Cummins, and Mack. PM and hydrocarbon emissions were lower with biodiesel for engines from Detroit Diesel and Cummins, but not the Mack engines. They also found that NO<sub>x</sub> emissions were slightly higher with biodiesel with all three engine types. Wang et al. (2000) measured emissions of heavy-duty diesel trucks running on a 35% biodiesel blend and on conventional No. 2 diesel, using a chassis dynamometer. They found the same trucks running on the biodiesel blend had significantly lower PM, and moderately lower carbon monoxide and hydrocarbon emission rates, but that NO<sub>x</sub> emissions were generally the same. Yanowitz et al. (2009) tested North American engines, using both engine dynamometer and vehicle tests. They found B20 consistently reduces particulate matter,

hydrocarbon, and carbon monoxide emissions, but had varying impacts on NO<sub>x</sub>. Effects on NO<sub>x</sub> were not statistically significant if pre-1992 2-cycle engines (which are uncommon) were ignored.

Several variations to biodiesel fuel blends have been considered to prevent any increase in NO<sub>x</sub> emissions. Adding cetane enhancers, in particular di-tert-butyl peroxide at 1 percent or 2-ethylhexyl nitrate at 0.5 percent, can reduce nitrogen oxide emissions from biodiesel. For B20, these options were estimated to cost 17 cents/gallon and 5 cents/gallon respectively, in terms of 2002 cents (US EIA, 2004). The cetane number of diesel fuel is a measure of how easily the fuel is ignited. Engine manufacturers generally recommend diesel fuel with a cetane number of at least 40 (Exxon Mobile, 2009a). The EPA has verified cetane enhancers for a NO<sub>x</sub> reduction of 0 to 5 percent, for diesel heavy duty diesel vehicles without EGR. They provide a spreadsheet for calculating the exact reduction (US EPA, 2008a). Blending biodiesel with Fischer-Tropsch diesel or kerosene instead of conventional diesel could also create a NO<sub>x</sub> neutral blend (McCormick et al., 2003). Kerosene is commonly blended with diesel in the Northeast during the winter. Any kerosene blended with ULSD must meet the ULSD sulfur standard, even if it would not otherwise be required to do so (US EPA, 2004a). There is a fuel economy penalty associated with switching from diesel to kerosene, but one study on a Detroit Diesel engine found that kerosene could match diesel's fuel economy if the duration of injection was lengthened to compensate for lower fuel density (Fernandes et al., 2007).

Some research has been done on the interaction of biodiesel blends with catalyzed diesel particulate filters. Williams et al. (2006) found that even a 5% biodiesel blend caused a measurable increase in regeneration rate. They found no significant differences in NO<sub>x</sub> emissions at steady state regeneration. They concluded that the increased regeneration rate was instead caused by the soot from biodiesel blends being more reactive. Higher biodiesel content led to more oxygen in the soot, as well as the soot being more reactive in oxygen.

The EPA provides an excel spreadsheet for calculating the verified emission reductions of biodiesel blends (US EPA, 2008b). The spreadsheet takes inputs such as the percent biodiesel in the blend, and the biological oil source. It then provides estimated percent changes in PM, CO, NO<sub>x</sub>, HC, and fuel economy. Although the degree varies,

PM, CO, and HC are generally reduced, while NO<sub>x</sub> emissions increase and fuel economy worsens.

Emulsified fuel is yet another alternative fuel. It is a blend of diesel, water, and other additives which can reduce both particulate matter and nitrogen oxide emissions without mechanical modifications to the engine (US EPA, 2007a, CARB, 2004). PuriNOx emulsified diesel is the only brand currently EPA or CARB verified. CARB verified it as a level 2 device (greater than or equal to 50 percent PM reduction), with a 15% NO<sub>x</sub> reduction (CARB, 2004), while the EPA verified it with different emission reductions for different applications (US EPA, 2008c). Emulsions are able to reduce NO<sub>x</sub> emissions because of water's cooling effect in the engine, while PM is reduced by the water functioning as a source of additional oxygen during combustion, creating a less fuel rich environment (US EPA, 2002b).

EPA tests on PuriNOx found that emulsified diesel led to substantially higher hydrocarbon emissions, sometimes more than double those produced by the same engine running on standard diesel with 500ppm sulfur. Carbon monoxide was found to increase for emulsified diesel in some applications, while it decreased in others. Fuel consumption typically increases by 15% with PuriNOx (US EPA, 2008c).

Emulsified diesel is not a new idea, but the concept has historically run into problems with corrosion of engine parts which occurs when they come into direct contact with water. These problems can be ameliorated by insuring that water droplets remain suspended in the fuel. This is made difficult by the fact that water is denser than diesel fuel, and therefore has a natural tendency to settle. Other additives included in PuriNOx may also have a tendency to separate due to varying densities. In their tests for Texas DOT, Baker et al. (2004) found no corrosion so long as the emulsion remained well mixed, but that corrosion did occur in the transparent upper portion of the fuel after separation. It was not clear which additives were causing the corrosion. Baker et al. (2004) suggested that this corrosion may explain increased injector and pump failures, as well as hard starting reported by Texas DOT.

The speed at which water droplets coalesce and settle can be reduced through a variety of means including high shear mixing to insure droplets start off very small, and increased surfactant concentration. Surfactants reduce surface tension. These and other

techniques have been demonstrated to slow fuel stratification, but the EPA has stated that eventually stratification is inevitable (US EPA, 2002b). The EPA verified PuriNOx only for engines which run for at least 15 minutes every 30 days (US EPA, 2008c). For this reason, the EPA recommends that school bus operators may want to phase out the use of emulsified diesel toward the end of the school year (US EPA, 2003a). During their trial, Texas DOT started each vehicle twice per week to prevent separation, even if the vehicle did not need to be used. The fuel and labor costs required to idle such vehicles were significant (Baker et al., 2004). Given the potential for separation, NYS DOT management is very concerned about the potential for engine damage resulting from the use of a fuel containing water.

There can also be problems with power loss when using PuriNOx at maximum engine horsepower. The CARB verification warns that the application must be able to tolerate a 20 percent reduction in peak engine power (CARB, 2004). In a Texas DOT trial, some vehicles such as telescoping boom excavators could not maintain a speed of 45mph when driving on the highway using PuriNOx (Baker et al., 2004). PuriNOx is not compatible with optical or conductivity type fuel sensors (US EPA, 2008c). The EPA has only verified the summer blend, which cannot be used in ambient temperatures below 20°F (US EPA, 2008c). CARB's verification does not specify whether it applies to both winter and summer blends (CARB, 2004). In their report for Texas DOT, Baker et al. (2004) recommended not using winter-grade PuriNOx because health risks resulting from the inclusion of methanol "anti-freeze," as well as potential fire hazards.

Baker et al. (2004) also found that a low emission diesel strategy was much more cost effective for reducing emissions than PuriNOx, and recommended discontinuing use of PuriNOx. The question became a non-issue when PuriNOx was discontinued in the United States (Port of Houston Authority, 2006). Emulsified diesel is therefore not considered a feasible emission reduction strategy at this time.

Natural gas is another alternate fuel. It is composed of a variety of hydrocarbons, mainly methane. According to the Energy Information Administration, 84% of the natural gas used in the United States in 2007 was domestically produced (NREL, 2008). In addition to being a fossil fuel, natural gas can be created by currently decaying organic materials, such as those in a landfill (NREL, 2008). Natural gas vehicles are far from

homogeneous. There are spark ignited engines which operate exclusively on natural gas, spark ignited engines which operate on either natural gas or gasoline, but not on both at the same time, and compression ignition engines which operate primarily on natural gas, but use diesel as a “pilot.” These three types of engines are sometimes referred to as dedicated, bi-fuel, and dual fuel, but this nomenclature is not universal (Yborra, 2009). Natural gas can be stored as compressed natural gas (CNG) or liquefied natural gas (LNG). LNG is typically used in heavier duty vehicles while CNG is primarily used in lighter duty vehicles, but there are plenty of exceptions (NREL, 2008). One reason that CNG vehicles are far more common in light duty fleets is the reduction in payload area due to the space required for the CNG tank (NYS DOT, 2007).

Unfortunately, information on the emissions impacts of CNG conversion is not as conveniently available as that on exhaust system retrofits, or other alternate fuels such as biodiesel. Neither the EPA nor CARB has verified CNG conversion as a retrofit technique (US EPA, 2009f; CARB, 2009b). A natural next step is to look to the EPA’s MOBILE model for CNG emission rates. The MOBILE model was the state of the practice in emissions modeling for every state except California, while the MOVES model was still in development at the time this analysis was conducted. MOBILE’s CNG emission factors for model year 2004 and later are actually higher than the corresponding emission factors for Tier 2 gasoline vehicles. The MOBILE User Guide admits this is probably not a realistic assumption and recommends users find alternate CNG factors for these years (US EPA, 2003b). California’s model, EMFAC2007, does not include CNG as a fuel type (CARB, 2007).

Wang et al. (1997) analyzed the results of emission tests on over 300 buses and heavy trucks, all running on the Central Business District (CBD) driving cycle. Natural gas vehicles had an average particle mass emission rate of 0.03 g/mile, compared to 0.96 g/mile and 1.48 g/mile for No.1 and No.2 diesel respectively. The emission differences were deemed statistically significant at the 5% level for particle mass, but not for NO<sub>x</sub>. The authors explained natural gas’s low particle mass emissions with the fact that natural gas is largely methane, a simple molecule with one carbon and four hydrogen atoms. Hence, unburned and partially oxidized hydrocarbons from natural gas vehicles tend to be physically smaller than those from other vehicles. While the hydrocarbons are smaller,

there are more of them. Natural gas vehicles had average HC emissions of 14.8 g/mile, statistically significantly greater than 2.6 g/mile and 2.1 g/mile for No.1 and No.2 diesel respectively. CO emissions for natural gas and No. 2 diesel vehicles were not statistically significantly different, but CO emissions for No.1 vehicles were statistically significantly lower than those of both natural gas and No. 2 diesel vehicles.

Jayaratne et al. (2009) used a chassis dynamometer to measure emissions from 13 CNG and 9 ULSD powered transport buses at three steady engine loads. The median particle mass emission factor of CNG buses was less than 1% of that of the diesel buses for all loads. Particle number emissions factors for CNG and ULSD were not statistically significantly different. CO<sub>2</sub> emission factors were roughly 20-30% higher for the diesel buses than the CNG buses. Holm  n and Ayala (2002) found that a CNG bus without a catalyst had accumulation mode concentrations 10-100 times lower than those of a diesel bus with an oxidation catalyst, but that the CNG bus often displayed large nuclei modes. The authors said that the nuclei modes could be made larger by the lack of an oxidation catalyst, but also that several measurement issues could have contributed. Graham et al. (2008) found that greenhouse gas emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, when combined in terms of CO<sub>2</sub> equivalents, were 9% lower for a CNG urban bus than for a diesel bus. Methane made up a substantially larger portion of greenhouse gas emissions for the CNG bus.

#### **4. Clean Diesel Projects in the United States**

##### *4.1 Description of Projects and Feedback from Fleet Managers*

Clean diesel projects have become increasingly common. The EPA knows of over 1000 such projects nationwide, drawing on a wide variety of funding sources (US EPA, 2009g). The authors reviewed lists of projects funded by multiple federal and state sources, and searched for projects being promoted by the agencies and municipalities involved. The authors also sought out regulations similar to the recent public fleet regulations put in place by the NYS DEC. A selection of relevant regulations and projects is provided in this section.

Perhaps the most analogous situation to that of NYS DOT is that facing CalTrans. California has a broad public fleet rule which applies to any city, county, public agency

or utility that owns, leases, or operates on-road diesel vehicles from model years 1960-2006 over 14,000 lbs GVW. There are exemptions for military and emergency vehicles, as well as school and urban buses and garbage trucks. Non-exempted vehicles must apply the “best available control technology” according to a sequence of deadlines, on December 31<sup>st</sup> of 2007, 2009, and 2011. There are alternative later deadlines for low population counties. “Best available control technology” can mean an engine certified to 0.01g/bhp-hr PM or an engine with the highest level emission control strategy verified for that engine, similar to “best available retrofit technology” in the NYS DEC regulations (CARB, 2006).

California’s fleet rule has been the subject of some controversy. The costs of emissions reductions drew criticism from the Legislative Analyst’s Office (LAO), California’s nonpartisan fiscal and policy advisor for the legislature. CalTrans estimated it would cost \$260 million in total to comply with four sets of state air quality regulations. CARB’s on-road and non-road diesel regulations account for roughly 90 percent of these costs. These estimates are based on filters costing about \$20,000 each (LAO, 2009). Caltrans told the LAO that it is facing problems fitting the filters onto some of its trucks, necessitating further modifications to the vehicles. CARB insists that no such modifications are required to be in compliance. Exemptions are available, but must be filed for each individual vehicle, unless CARB reevaluates its regulations. CARB advised the LAO that it may reevaluate its regulations and issue across-the-board exemptions (LAO, 2009). Such actions could serve as important precedent in NYS DOT’s dealings with NYS DEC. Multiple attempts to contact CalTrans management for comment went without response. NYS DOT might have more luck communicating directly on a peer-to-peer level.

Staff members at several other public entities in California were successfully contacted, and they shared their experiences with retrofits. As of January 20<sup>th</sup>, 2009, the County of Los Angeles was on schedule to meet regulatory requirements which apply to 698 diesel vehicles operated by county departments ranging from Public Works to Parks & Recreation. The county had retrofitted 355 vehicles at an approximate cost of \$2 million, offset by roughly \$850,000 in grants. The anticipated remaining cost was \$4.9 million (Fujioka, 2009). Some vehicles are considered no longer needed, or too expensive

to retrofit, and are therefore sold in accordance with CARB rules. DPFs are typically installed on other vehicles (Nunez, 2009).

Marie Nunez, of the county government, outlined the purchase process for the retrofits. She considers it a good practice to perform an opacity test prior to installing a DPF, to find any potential engine problems which could clog the filter. Each unit is also inspected for potential installation issues. Vendors recommend technologies based on inspections and exhaust gas temperature data logging. The county found it works best to have the vendor also perform the data logging, for the best warranty support. The county has used both passive and active filters made by Huss, Donaldson and Cleaire. Installation time varies from several hours to a couple of days, depending on the application, while DPF Costs ran from \$9,500 to \$14,000. Labor accounted for roughly 20% of the costs (Nunez, 2009).

Marie Nunez also provided a description of some operation and maintenance practices. In her experience, regenerating the plug-in type DPFs every night reduces downtime, as they take six hours to regenerate. For comparison, the diesel fuel fired DPF units regenerate in roughly 30 minutes. The county has also been pulse cleaning with compressed air two or more times per year, at an average cost of \$500 per cleaning. DPF manufacturers are held accountable for any failures brought on by their devices, but Marie knew of no such failures occurring as of September 8<sup>th</sup>, 2009. The county has not seen any changes in fuel consumption or vehicle performance. They use ULSD and low ash engine oil, and provide training to drivers on reducing idling time (Nunez, 2009).

The city of Oakland initially complied with the CARB fleet rule by replacing ten 2001 model year diesel-powered street sweepers and 38 heavy-duty trucks with 2008 model year vehicles. The plan for maintaining compliance was to install Cleaire's Horizon filters on 27 vehicles. The city's vehicles accumulate relatively low mileage, and are naturally used on heavily urban duty cycles, leading to a need for active regeneration. The plan was to purchase six electrical charging stations for regeneration. Staff estimated the vehicles would need to be plugged into a station once every two weeks for 5 hours. The filters were estimated to cost \$15,240 each, including tax and installation, while the charging stations were estimated to cost \$6,000 each, including installation. The retrofitted vehicles would then be replaced as scheduled in the ten-year replacement

program. Oakland was in the process of applying for funding (OPWA, 2007). An attempt to contact city of Oakland staff for further details and lessons learned went without response.

Historically, California's Carl Moyer Program has funded numerous diesel retrofit projects in California. It provides incentive grants for cleaner than required engines and equipment. This includes meeting mandatory emission requirements early, as well as going beyond requirements (CARB, 2009c). Santa Clara County received several grants for installing a level 3 retrofit technology (85% and above PM reduction) on a diesel truck. The grants were typically for less than three thousand dollars each, making them unlikely to cover the entire cost (BAAQMD, 2009). An attempt to contact Santa Clara County staff for further details and lessons learned went unanswered. The County of Contra Costa received multiple larger grants for retrofits (BAAQMD, 2009). Four buses were about to receive Cleaire Longview DPFs and at least one Ford F450 was to receive a Cleaire Horizon DPF. They hired vendors to do the installations, which took 2-3 days each. The cost of parts and labor for the Cleaire Longviews was \$20,355 each (Ranger, 2009).

New York City has its own set of laws regarding diesel emissions from public fleets and fleets operating under contract with the city. Many of the relevant local laws apply only to vehicles filling specific functions. These laws are frequently similar in many respects, both to each other and to NYS DEC diesel fleet regulation. NYS DEC has expressed that its regulations, discussed in Section 5, were partly based on NYC Local Laws, in order to promote consistency (NYS DEC, 2009a).

NYC Local Law 42, adopted in 2005, required use of ULSD and "best available retrofit technology" for school buses serving public schools, excluding buses used exclusively for special education students (NYCC, 2005a). Despite this gap in the law, NYC plans to apply the best available retrofit technology to all diesel buses, including smaller buses (the majority of smaller school buses used in NYC are diesel powered) (NYC, 2009). Conducting retrofits requires working closely with the companies which own and operate school buses under contract with the city. As of April 2008, DOCs and crankcase filters have already been installed on over 3,000 buses. A pilot study for DPFs was performed (NYC, 2009). City staff were concerned that passive filters would not

perform well on the heavily urban duty cycles of most school bus routes, but they were also wary of the costs of active filters. Federal CMAQ funding was being sought to offset DPF costs.

NYC Local Law 77, adopted in 2003, requires the use of ULSD and “best available technology” for reducing emissions from non-road diesel vehicles owned by the city, as well as private equipment used on city construction projects (M.J. Bradley & Associates and Gruzen Samton, 2004). NYC Local Law 39, adopted in 2005, requires that diesel vehicles owned or operated by city agencies use ULSD. Of these vehicles, those over 8,500 lbs in gross vehicle weight must either use an engine certified as meeting the 2007 EPA particulate matter standard or use the “best available retrofit technology” by July 1, 2012. A phase in scheme requires increasing percentages of vehicles to meet the mandate starting with 7% by January 1, 2007 (NYCC, 2005b).

The Port Authority of New York and New Jersey was awarded an EPA grant of \$280,500 to retrofit 30-40 utility trucks operated by the Port Authority with DPFs (US EPA, 2009h). Port Authority staff indicated that the retrofit plan may be redesigned in the context of a larger program for replacing older trucks (Goldman, 2009). The utility trucks are a relatively small part of a much broader Port Authority plan to reduce emissions from ocean going vessels, cargo handling equipment including cranes, cargo trucks, and trains (PA NYNJ, 2009).

Local Law 40, adopted in 2005, requires that solid waste or recyclable material contracts specify that diesel vehicles used to perform said contracts, and which operate primarily within NYC, use ULSD. All such vehicles must also use the best available retrofit technology by March 1, 2006.

The NYC Department of Sanitation operates a wide range of vehicles both on and off-road. The department is responsible not only for handling residential trash, but also for clearing snow and salting city streets in the winter (M DEP, 2008). On-road equipment includes collection trucks, street sweepers, and salt spreaders, while off-road equipment includes front end loaders. In total, the department operates approximately 5,700 vehicles (DSNY, 2009). DSNY began retrofitting off-road equipment to comply with Local Law 77 in 2004. DOC retrofits were installed on 212 loaders from model year 1994 to 2006, at costs between \$1,300 and \$2,800 per unit. DOCs were generally

purchased from the OEM, helping to simplify installations which typically took less than two hours. A half dozen loaders received DPFs, costing up to \$17,000 and taking up to 16 hours to install. As of January 2008, DSNY had not experienced increased equipment downtime or maintenance costs as a result of these retrofits. Spiro Kattan, Supervisor of Mechanics for DSNY, was quoted as saying that “Complying with the requirements of Local Law 77 has not been as difficult as some thought it would be. Our experience with retrofitting off-road equipment has been very positive.” (M DEP, 2008)

The NYC Department of Sanitation has since expanded its retrofit program to on-road vehicles. Roughly 200 salt spreaders have received DOCs. Approximately 150 refuse trucks have received Johnson Matthey CCRT DPFs, while approximately 300 refuse trucks have received Cleaire Longview DPFs. The Johnson Matthey CCRT and Cleaire Longview cost approximately \$12,000 and \$17,000 respectively (Kim, 2009). DSNY did receive some funding from a massive (roughly \$1 billion) 1998 settlement of a Clean Air Act court case against seven manufacturers of heavy duty diesel engines (US EPA, 2004a). Installations of the DPFs were performed by DSNY technicians, and took approximately 16 man-hours each. Annual cleanings remove inorganic ash, at a cost of roughly \$250-\$300 per cleaning. The filters do not tolerate engine problems such as failed turbochargers or injectors, but do not appear to impact vehicle maintenance. No data was collected on fuel economy impacts (Kim, 2009).

When asked for general advice related to retrofits, Dr. Kangwook Kim, a research scientist with the NYC Department of Sanitation, recommended exhaust gas temperature data logging and pilots prior to large-scale deployment, as well as the use of CJ-4 motor oil with DPF retrofits (Kim, 2009). CJ-4 is a low ash oil, with lower amounts of trace elements such as calcium, zinc, and phosphorous (Cummins, 2009b). Inevitably, some motor oil will be burned along with the fuel, and these elements will be present in particles trapped by the DPF. The organic portions of the particles will be oxidized, leaving the trace elements in the form of inorganic ash (M DEP, 2008). The higher ash content of CI-4 oil increases ash loading of the DPF and shortens cleaning intervals. CJ-4 oils are designed to work with ULSD (Cummins, 2009b). Exxon Mobil also recommends low ash oils for vehicles with DPFs (Exxon Mobile, 2009b).

While many of the California and NYC fleet managers described above faced regulatory frameworks particularly similar to those facing NYS DOT, fleet managers across the country have also conducted clean diesel projects. The EPA's National Clean Diesel Campaign has awarded over 300 grants alone, including several to state DOTs (US EPA, 2009i). These grants include \$40,000 for Utah DOT to retrofit 20 snowplows with DOCs and CCVs, \$280,000 for CalTrans to retrofit 14 off-road construction vehicles with DPFs, \$25,000 for the Georgia DOT to retrofit 8 pieces of highway and off-road equipment with DPFs and DOCs, and \$98,600 to NYS DOT to retrofit 20 highway maintenance vehicles with DOCs and fuel them with ULSD (US EPA, 2009j). The South Carolina DOT also received money through a multi-organization National Clean Diesel Campaign grant. They used the funding for diesel oxidation catalysts (SDC, 2009). Retrofit funding received a substantial boost with the Recovery Act. Connecticut DOT applied for Recovery Act funds to retrofit and replace trucks in 2009. They selected 28 dump trucks from model years 2000-2002 for DOC retrofits, and 26 dump trucks from model years 1993-1996 for replacement. They were requesting 25% of the replacement cost (CT DOT, 2009).

Washington State DOT retrofitted 29 dump trucks, sweepers, and other equipment pieces in Yakima with DOCs and DPFs in 2005 and 2006, with the help of grants from the EPA and Washington Department of Ecology (WS DOT, 2007). Joe Stinton at WS DOT stated that the retrofits were purchased from Cummins North West, who also performed the installations. The DOCs were installed on International vehicles of GVWR 30,000lbs and above, at a cost of \$4,000 per unit. No changes to fuel consumption or maintenance costs were experienced. Joe Stinton noted that the retrofits would not have taken place without the grant support (Stinton, 2009). A 2007 Transportation Improvement Program (TIP) project brought in \$1,500,000 in CMAQ funds, to be combined with \$234,104 in state and local funds to retrofit WS DOT vehicles in the Puget Sound area, and to employ LED light technology on the vehicles, as discussed in more detail in Section 10.

Many cities have conducted retrofits of utility vehicles. Baltimore, Maryland used \$30,000 to retrofit 23 dump trucks with DOCs and CCVs in 2006. In the same year, Baltimore also used \$160,000 to retrofit 98 trash haulers with DOCs and CCVs (M DOE,

2009). Chicago retrofitted four street sweepers and four refuse trucks with DPFs, as well as at least 75 refuse trucks with DOCs (City of Chicago, 2009). Worthington, Ohio won EPA funding (via the Ohio Environmental Council) to retrofit 8 public works vehicles with DPFs. Cleveland Heights, Ohio won EPA funding (also via the Ohio Environmental Council) to retrofit 5 public works vehicles with DPFs (OEC, 2009).

Cleveland Heights staff referred questions to the Ohio Environmental Council. David Celebrezze, of the Ohio Environmental Council, responded that the DPFs need to be cleaned once per year or every 100,000 miles. Cleaning equipment costs \$10,000-\$17,000. He acknowledged that there might be a 1-2% fuel efficiency reduction, but he had not seen any such fuel impacts in any of his numerous DPF projects (Celebrezze, 2009).

#### *4.2 Summary of Best Practices*

The experiences of the fleet managers described above were used to compile a set of best practices. These practices were then combined with recommendations made in the EPA's "Tips for a Successful Diesel Retrofit Project" (US EPA, 2009k) and a guide to diesel retrofits in construction published by the Massachusetts Department of Environmental Protection (M DEP, 2008), as well as instructions in manuals. The results are summarized in an outline below. As with any such summary of manageable length, the outline is not intended to include a detailed description of every action which should be taken. Documentation for the products involved should always be consulted when conducting retrofits, and the recommendations of said documentation should take precedence over general best practices provided below. More detail on retrofit maintenance can also be found in manual summaries in Section 12, which is broken down by retrofit category.

#### Preparation for Retrofits

- Collect vehicle data to make informed retrofit decisions: on-road/off-road status, class (e.g. 6 truck), vehicle manufacturer, vehicle model, vehicle year, engine manufacturer, engine model, engine year, displacement, horsepower, EPA engine family name, and whether there is a turbocharger or exhaust gas recirculation. These data are important for ensuring retrofit compatibility.
- Conduct data logging of exhaust temperature data.

- Check for proper engine operation and motor oil consumption before installation.
- Consult engine warranties before making retrofits or switching fuel types.

### Installation

- Ensure the retrofitted exhaust system is properly supported. DOCs generally don't add much weight, and typically don't need additional support. DPFs frequently add weight and require more robust or more numerous brackets.
- Quick release clamps can make removal of DPFs for cleaning easier.
- Installing a DPF as close to the engine's exhaust manifold as possible, just downstream of turbocharger, can help to maintain a high exhaust temperature.
- Insulating wraps on piping upstream of a DPF can help maintain desirable temperatures.
- As PM collects on a DPF, backpressure can build and exceed the level for which the engine was designed. For this reason, backpressure monitors should be installed with every DPF.
- Remote displays with indicator lights should be installed in the cabin where they are visible to the driver, so the driver can react quickly when a DPF requires regeneration.

### Operational Changes

- Switch to ULSD if not using it already, especially if installing DPFs. ULSD is a good idea even if not installing DPFs, and should be very easy to obtain given EPA mandates phasing it in as standard. Use of higher sulfur content fuels can clog DPFs and increase exhaust system corrosion.
- Use low ash motor oil in any vehicles with a DPF. Higher ash motor oils can cause a need for more frequent cleanings, imposing both financial cost and vehicle downtime.
- Low exhaust temperatures for long periods can cause problems with PM buildup in a DPF. If too large a buildup is ignited, it can damage the exhaust system. Avoid unnecessary idling to reduce the chance of potentially damaging buildups.

### Maintenance of Retrofit Devices

- DOCs generally do not require substantial maintenance.
- Replace CCV filter cartridges as recommended by the manufacturer. The frequency required is, very roughly speaking, once per year, but it can depend on the product and the vehicle usage pattern.
- Regenerate active DPFs to oxidize built up PM according to their documentation. The intervals between regenerations vary depending on technology and application, but are often close to once per day. Depending on the method, the process can take as little as 30 minutes or as much as 6 hours. Regenerating filters every night as a matter of routine can work well. When regenerating a filter, it is important to park in a well ventilated area which is far from combustible materials (e.g. tall grass).

- Clean DPFs to remove inorganic ash. This generally requires special equipment to heat the filter and blow air through it. If the DPF is properly used, these cleanings are needed far less frequently than regeneration is on active DPFs. The frequency can vary from twice per year to once every two years. Applicable laws must be followed regarding disposal of any ash cleaned from retrofit devices.
- Keep records of maintenance performed, including receipts.

#### Impacts of Retrofits on Non-retrofit Maintenance

- Be sure to track fuel and motor oil consumption. Retrofits may mask changes to exhaust caused by running too fuel rich or burning motor oil, making it more important to monitor fuel and motor oil consumption directly.
- Retrofits do not tolerate some engine problems, such as failed turbochargers or injectors, making it especially important to address these problems quickly.

#### Training

- Conduct appropriate training for staff involved in each of the actions outlined above (e.g. drivers taught about idle reduction and responding to backpressure alerts).

### **5. Legislative Context for NYS DOT**

Section 19-0323 (L. 2006, c.621) of New York’s Environmental Conservation Law (ECL) mandates that NYS Department of Environmental Conservation (NYS DEC) promulgate regulations requiring the use of ULSD and Best Available Retrofit Technology (BART) for various state agency, state public authority, and regional public authority heavy duty vehicles, as well as heavy duty vehicles used on behalf of such agencies and authorities (NYS DEC, 2009a). The requirements of NYS DEC regulations naturally play a major role in determining which strategies NYS DOT can pursue for reducing emissions. This section provides a summary of 6 New York Codes, Rules, and Regulations (NYCRR) Part 248, which was adopted with attendant amendments to Part 200 in the summer of 2009 (NYS DEC, 2009b). The summary was not prepared by a lawyer, and is included only for the convenience of the reader. Compliance decisions should be based on the complete regulations.

### *5.1 What vehicles does the regulation apply to?*

Part 248 requirements apply to all covered heavy duty vehicles owned by, leased by, operated by, or on behalf of NYS DOT. Switching from an owning model to a leasing model, would therefore not allow NYS DOT to avoid the requirements. Heavy duty vehicles include both on-road and off-road diesel vehicles with GVW over 8,500lbs. There are, however, numerous exceptions.

Authorized emergency vehicles are not included (NYS DEC, 2009c). Authorized emergency vehicles are defined by section 101 of New York Vehicle and Traffic Law (VTL). The definition includes “environmental emergency response vehicle” and “sanitation patrol vehicle.” Initially, these may sound promising for NYS DOT exemptions, especially considering that NYS DOT operates street sweepers and that the NYC Department of Sanitation is responsible for snow removal. However, section 115-d specifies that environmental emergency response vehicles must be responding to the release, spill or leak of a hazardous substance, and section 141-a specifies that sanitation patrol vehicles only include those operated by the sanitation police of the NYC Department of Sanitation.

There is another category of exemptions which does appear to apply to the NYS DOT, however. Heavy duty vehicles does not include “road rollers, tractor cranes, truck cranes, power shovels, road building machines, snow plows, road sweepers, sand spreaders, ... earth movers, which shall mean motor-driven vehicles in excess of eight feet in width equipped with pneumatic tires designed and constructed for moving or transporting earth and rock in connection with excavation and grading work.” (NYS DEC, 2009c) Slightly later, “farm type tractors and all terrain type vehicles used exclusively for agriculture or mowing purposes, or for snow plowing” are listed as not being included in heavy duty vehicles (NYS DEC, 2009c). These clauses appear to exclude many on-road and off-road NYS DOT vehicles. The exclusion of street sweepers might be especially reassuring, as NYS DOT staff have expressed concern that these vehicles might prove especially challenging to retrofit. As of January 1<sup>st</sup>, 2008, NYS DOT operated 35 street sweepers.

The exemption of snow plows would be of paramount importance to NYS DOT, if could be broadly applied. Well over a thousand NYS DOT diesel vehicles function as snow plows in the winter. It is not entirely clear from the regulation whether a truck which operates as a snow plow for a portion of the year and in another function in the summer would be considered a snow plow. Currently, roughly 30% of NYS DOT large dump trucks are used exclusively for snow and ice removal. NYS DEC did not respond to requests to clarify the definition of “snow plows,” but NYS DOT staff informed us that they understand only vehicles which can only be used for snow removal are exempt, such as snow blowers. According to the regulation, vehicles used exclusively as snowplows under contract with a regulated entity are not included, though it is not clear if the definition of snow plow is equally narrow in this case (NYS DEC, 2009c).

*5.2 What vehicles were already in compliance before NYS DOT responded to the regulation?*

Vehicles using an engine certified to meet the 2007 EPA PM standard (0.01 g/bhp-hr) are considered to be in compliance. Any heavy duty vehicle which has been retrofitted with an EPA or CARB approved conversion kit to enable it to run on a combination of CNG and ULSD is considered to be in compliance. Heavy duty vehicles retrofitted with an EPA or CARB verified device prior to February 12, 2007 are considered in compliance, so long as the device is maintained for the rest of the vehicle’s life. All such vehicles should still use ULSD whenever using diesel (NYS DEC, 2009c).

*5.3 What must be done for other vehicles to be in compliance?*

Covered vehicles owned by, leased by, operated by, or on behalf NYS DOT must use ULSD, unless a waiver is approved. Given the broad availability of ULSD resulting from EPA mandates and ULSD’s relatively low marginal cost, this requirement should be relatively easy to satisfy.

Covered heavy duty vehicles which are diesel powered must also use the Best Available Retrofit Technology (BART). This requirement is phased according to the following schedule:

1. at least 33 percent of all such vehicles use BART by December 31, 2008

2. at least 66 percent of all such vehicles use BART by December 31, 2009
3. all such vehicles use BART by December 31, 2010.

There are three basic types of approaches for dealing with a vehicle which is not in compliance. First, the vehicle can simply be retired (and possibly replaced with a compliant vehicle). It appears that the vehicle can be kept for spare parts if the engine is removed. Second, the vehicle can be repowered. The vehicle will become compliant if its engine is replaced with an engine certified to meet the 2007 EPA PM standard (0.01 g/bhp-hr). It will also become compliant if its engine is replaced with one which operates on an approved alternative fuel, provided that model year 2004-2006 alternative fuel engines are certified to the optional, reduced emissions standards specified in title 13, California Code of Regulations, section 1956.8(a)(2)(A) (see Table 1, Section 200.9 of this Title). Approved alternative fuels include natural gas, propane, ethanol, methanol, gasoline (when used in hybrid electric vehicles only), hydrogen, electricity, fuel cells, or advanced technologies that do not rely solely on diesel fuel or a diesel/non-diesel fuel mixture. Note that bi-fuel CNG vehicles which use diesel as well as CNG are not on the list of alternative fuel vehicles, but they are considered in compliance if they were converted with an EPA or CARB approved conversion kit (as were NYS DOT's trial conversions). Third, the vehicle can go through the BART evaluation and selection process described in Part 248 (NYS DEC, 2009c).

All BART must be either EPA or CARB verified. There are three levels, corresponding to the three levels of CARB PM reduction verification. Level 1 means  $\geq 25\%$  reduction; level 2 means  $\geq 50\%$  reduction; level 3 means  $\geq 85\%$  reduction or  $\leq 0.01$  g/bhp-hr. NYS DOT is expected to consider level 3 retrofits first. Level 2 retrofits can only be considered if no level 3 retrofits are compatible with the vehicle and application. Similarly, level 1 retrofits can only be considered if no level 2 or 3 retrofits are compatible with the vehicle and application. If multiple products of the same level are compatible with the vehicle and application, the product which offers the greatest  $\text{NO}_x$  reduction must be selected if it is less than or equal to 30% more expensive than the other options of the same level. None of the products selected can result in an increase in  $\text{NO}_x$ .

NYS DOT can apply for a waiver of BART requirements if a vehicle and application are incompatible with all technologies of all levels (NYS DEC, 2009c).

Any vehicles subject to the ULSD or BART requirements, and to the consent decree, must have the approved low NO<sub>x</sub> rebuild kits installed prior to any BART device (NYS DEC, 2009c). This requirement is connected with a 1998 court settlement. In the mid-1990s, the U.S. Department of Justice (US DOJ), EPA, and CARB discovered that seven major engine manufacturers had designed model year 1993-1998 heavy duty diesel engines to operate differently when cruising steadily, as opposed to when speed patterns resembled emissions testing duty cycles. The steady highway cruising mode of operation improved fuel economy, but also caused excessive NO<sub>x</sub> emissions. The resulting court settlement required the manufacturers to provide dealers with modified software, called low NO<sub>x</sub> rebuild kits or chip reflash. These kits must be installed free of charge when conducting an engine rebuild, or upon owner/operator request (CTC & Associates, 2006). The companies were Cummins, Volvo Truck, Detroit Diesel, Mack Trucks, Caterpillar, Navistar International and Renault Vehicules Industriels (US DOJ, 1998).

Part 248 also has numerous record keeping, reporting and labeling requirements, such as annual inventories and low NO<sub>x</sub> rebuild labels on engines which had low NO<sub>x</sub> rebuild kits installed (NYS DEC, 2009c).

## **6. Compiling Fleet Inventory and Characteristics**

NYS DOT provided a basic snapshot of its diesel fleet as of January 1<sup>st</sup>, 2008, including vehicle equipment numbers, serial numbers, manufacturer, model, model year, weight class, region, past retrofits, and a brief description. This information was later supplemented with a list of vehicle equipment numbers for vehicles with exhaust gas recirculation (EGR). Additional data indicated horsepower and whether a vehicle was turbocharged for a subset of the fleet.

There were 2617 units in the January 1<sup>st</sup> 2008 NYS DOT diesel fleet snapshot, 1504 of which were class 8. The vast majority of these class 8 vehicles are some variety of large dump truck, making class 8 dump trucks the core of the NYS DOT fleet. Roughly 30% of these large dump trucks are dedicated to snow and ice removal in the winter, while 70% are also used for summer operations. There were also 951 class 6

vehicles in the snapshot. The vast majority of these vehicles are either dump trucks or stake trucks (essentially a flatbed with a fence around it). This leaves only 162 vehicles of other weight classes, including several different types of stake truck, pickups, and street sweepers. There are also a couple of class 8 street sweepers, and 30 class 6 street sweepers, making them a significant secondary component of the NYS DOT fleet.

Retrofit verifications vary substantially in their scope. Some retrofit technologies are verified for use on a wide range of vehicles. Others apply to only a narrow selection of applications. CARB can be particularly detailed in its descriptions of appropriate vehicle types. In order for a retrofit to be verified for use on a particular vehicle, the vehicle may have to meet requirements regarding its model year, horsepower, displacement, use of EGR, number of strokes, gross vehicle weight (GVW), exhaust temperature profile, original PM emission certification, whether it is turbocharged or naturally aspirated and any previous retrofits. Additionally, CARB provides a list of EPA engine family names for which retrofits are verified (CARB, 2009d 2009e 2009f).

EPA engine family names are 12 character codes. The first character designates the model year, followed by three identifying the manufacturer, one for the family type (e.g. H for heavy duty), four for displacement in liters or cubic inches (if there is a decimal point it is in liters), and finally three characters which ensure the uniqueness of every engine family. These final three characters make it difficult to construct an engine family name based on other information about an engine. Some vehicles in the NYS DOT fleet do not have EPA engine family names, as the standard system was developed in 1995 to meet 1998 regulatory requirements (US EPA, 1999).

In order to acquire more relevant fleet data, several different approaches were attempted for gathering EPA engine family names. An email to the EPA staff member whose contact information is listed with engine family name documents did not receive a response. The serial numbers provided by NYS DOT are in the format of what are commonly referred to as vehicle identification numbers (VINs). The National Highway Traffic Safety Administration (NHTSA) established the 17 character standard VIN general format with the 1981 model year (NHTSA, 2009). There is still considerable flexibility left to the manufacturers, within the general format. Manufacturers send the NHTSA descriptions of the codes they use. An inquiry was made to the Federal DOT,

and the response included a link to an excel document of links to nearly 5,000 letters sent by various manufacturers. There does not appear to be any standard format for such letters, and none of those examined contained any information on EPA engine family names.

DOT staff provided contacts at engine and vehicle manufacturers including Cummins, Mack, International, Ford, GM, and Chrysler. The authors pursued all of these contacts, and the other people they referred. GM was able to help determine the engine family names for many of the GMC and Chevy vehicles. Unfortunately, many of these engine names were not definitive, as the models listed in the NYS DOT database are often incomplete. For example, there is an entry for a 2002 Chevy 3500, but it could be the Silverado C3500 or the G3500 van, which use different engines. Some model numbers listed in the NYS DOT database did not match with any in other in the files sent by GM. Horsepower ratings in EPA certification spreadsheets associated with engine family names provided by Cummins did not match the horsepower ratings in DOT records of bid specifications. Despite these and other obstacles, as much data as possible was gathered, for use in the analysis described in the following sections.

## **7. Retrofit Compatibility**

### *7.1 Initial Technology Screening*

As discussed in Section 5, the definition of heavy duty vehicle in Part 248 excludes a wide array of off-road vehicles including road rollers, tractor cranes, truck cranes, power shovels, road building machines, sand spreaders, earth movers (meaning motor-driven vehicles over eight feet wide with pneumatic tires designed and constructed for moving or transporting earth and rock in connection with excavation and grading work), as well as farm type tractors and all terrain type vehicles used exclusively for agriculture or mowing purposes, or for snow plowing (NYS DEC, 2009c). For this reason, as well as issues of data availability, this analysis will focus on on-road vehicles. The same methodology could be applied to off-road vehicles, with appropriate modifications, in the event of future legislation. For off-road vehicles, emission rates would either come from NONROAD or MOVES (as opposed to the MOBILE which provides on-road emission

rates). At the time of this analysis, MOVES does not include off-road emission rates, making NONROAD the current source for such data, but this could change in the future.

Given the focus on on-road vehicles, a relatively large portion of verified technologies can be removed from consideration for relatively simple reasons, such as being designed for use exclusively on stationary motors or off-road vehicles. The remaining technologies can then be examined to greater depth. Table 1 provides a list of EPA and/or CARB verified technologies which were ruled out for the on-road fleet during the initial screening, as well as the reasons why.

Table 1: Verified Technologies Ruled out for On-road Use

<b>Device</b>	<b>Reason</b>
Catalytic Exhaust Products Ltd. Dieselytic SXS-SC DPF	for generators and pumps
Caterpillar DPF	for off-road
Caterpillar Emissions Upgrade Group	for off-road
Cleaire Lonestar	for off-road
Cleaire Phoenix	for off-road
CleanAIR Systems PERMIT	for generators
DCL International Inc.	for off-road
DCL International Inc.	for generators, off-road
Engine Control System Purifilter (High Load)	for off-road
Engine Control System Combifilter	for off-road
Johnson Matthey CRT	for generators
MIRATECH Corporation combiKat	for generators
Rypos, Inc. HDPF/C™	for generators and pumps
Süd-Chemie Inc EnviCat-DPF™	for generators and pumps
Teleflex Clear Sky DPF	for auxiliary power units
Thermo King eDPF	for auxiliary power units
Engine Control System AZ Purimuffler/Purifier	for off-road
Lubrizol PuriNOx	no longer available in US
Proventia FTF TM	for refrigeration units
Rypos ADPF	for stationary engines
Rypos, Inc. DPF/LETRU™	for refrigeration units
Thermo King PDPF™	for refrigeration units
Donaldson 6000 + Spiracle (off-road)	for off-road port

## 7.2 Non-Duty Cycle Requirements

The fleet data obtained as described in Section 6 were used to identify incompatibilities between retrofit technologies not eliminated in the initial screening, and

common diesel vehicles in the NYS DOT fleet. As noted in Section 6, fleet data are not complete. Numerous vehicle characteristics, such as horsepower and displacement, are unknown for many vehicles. Some data obtained were contradictory, leading to uncertainty regarding compatibilities. An effort is made to indicate which incompatibilities have particularly high uncertainty. This section does not consider exhaust temperature profile or regeneration requirements which are related to duty cycles. Duty cycle requirements are discussed in the next section.

Although diverse, the NYS DOT diesel fleet has a number of staple vehicles which make up much of the fleet. The top ten vehicles in the January 1<sup>st</sup>, 2008 snapshot made up roughly 50% of the fleet, with more than 100 of each present. The top 20 make up more than 75% of the fleet. Common vehicles are listed in Table 2, along with basic characteristics.

Table 3 lists incompatibilities between the pre-2007 vehicles in Table 2 and level 3 active filters, while Table 4 lists incompatibilities with level 3 passive filters and Table 5 lists incompatibilities with level 2 flow through filters as well as level 1 diesel oxidation catalysts. Only verifications for sufficient PM reductions to meet these levels have been included. The EPA has verified some DOCs to provide a 20% reduction in PM without model year restrictions, as opposed to the 25% reduction required for level 1 (US EPA, 2009f). It is important to note these tables only list incompatibilities found with the available data, and that if complete data were available on all vehicles there would likely be more incompatibilities. As noted, several retrofit technologies are associated with other engine modifications such as crankcase filters and exhaust gas recirculation.

Table 2: Common Vehicles in the NYS DOT Diesel Fleet

Count	Class	Manufacturer	Model	Year	Typical Uses	EGR
29	8	International	7600	2003	Large Dump/Spread	N
83	8	International	7600	2004	Large Dump/Spread	Y
114	8	International	7600	2005	Large Dump/Spread	Y
24	8	International	2574	1993	Large Dump Truck	N
84	8	International	2574	1995	Large Dump Truck	N
12	8	International	2574	1996	Large Dump Truck	N
83	8	International	2574	1997	Large Dump Truck	N
197	8	International	2574	1998	Large Dump Truck	N

102	8	International	2574	1999	Large Dump Truck	N
113	8	International	2574	2000	Large Dump Truck	N
135	8	International	2574	2002	Large Dump Truck	N
79	8	International	2574	2003	Large Dump Truck	N
23	8	Mack	CV713	2006	Large Dump Truck	Y
153	8	Mack	CV713	2007	Large Dump Truck	Y
107	8	Mack	CV712	2006	Large Dump Truck	Y
72	8	Mack	CV712	2007	Large Dump Truck	Y
105	6	Ford	F650	2007	Dump and Stake	Y
39	6	International	4700	1996	Stake and Dump	N
51	6	International	4700	1997	Stake, Dump, Sweeper	N
67	6	International	4700	1998	Stake, Dump, Sweeper	N
145	6	International	4700	2000	Stake and Dump	N
116	6	International	4700	2002	Stake and Dump	N
38	6	International	4600	1990	Stake and Dump	N
43	6	International	4600	1992	Stake and Dump	N
95	6	International	4600	1994	Stake and Dump	N
51	6	International	4200	2004	Stake and Dump	Y
36	6	International	1654	1989	Stake Truck	N
2196 total						

Table 3: Incompatibilities Found Between Common Vehicles and Level III Active Filter Technologies

					Level III					
					Active Filters					
Count	Class	Manufacturer	Model	Year	Cleaire Horizon	Cleaire Vista	ESW Canada ThermaCat	Donaldson Semi- Active Electric Filter (SEF )	Engine Control Systems Purifilter Plus	HUSS Umwelttechnik FS- MK
29	8	International	7600	2003			HP			
83	8	International	7600	2004		EGR	EGR	EGR	EGR	EGR
114	8	International	7600	2005		EGR	EGR	EGR	EGR	EGR
24	8	International	2574	1993			HP			
84	8	International	2574	1995			HP			
12	8	International	2574	1996			HP			
83	8	International	2574	1997			HP			
197	8	International	2574	1998		too high PM*	HP		too high PM*	
102	8	International	2574	1999			HP			
113	8	International	2574	2000			HP			
135	8	International	2574	2002			HP			
79	8	International	2574	2003			HP			
23	8	Mack	CV713	2006		EGR	EGR	EGR	EGR	EGR
107	8	Mack	CV712	2006		EGR	EGR	EGR	EGR	EGR
39	6	International	4700	1996						
51	6	International	4700	1997						
67	6	International	4700	1998						
145	6	International	4700	2000						
116	6	International	4700	2002						
38	6	International	4600	1990		year	year	year	year	
43	6	International	4600	1992		year	year		year	
95	6	International	4600	1994						
51	6	International	4200	2004		EGR	EGR	EGR	EGR	EGR
36	6	International	1654	1989		year	year	year	year	

\* dependent on engine family name which is uncertain

Note this table does not include incompatibilities with exhaust temperature profiles.

Table 4: Incompatibilities Found Between Common Vehicles and Level III Passive Filter Technologies

					Level III						
					Passive Filters						
Count	Class	Manufacturer	Model	Year	Claire Longview	Donaldson Low NO2 Filter (LNF)	Donaldson Low NOx (LXF) Muffler	Engine Control System Purifier	Johnson Matthey ACCRT	Johnson Matthey CRT reformulated	Johnson Matthey EGRT <sup>^</sup>
29	8	International	7600	2003							year
83	8	International	7600	2004	EGR					EGR	year
114	8	International	7600	2005	EGR					EGR	year
24	8	International	2574	1993			year		year	year	year
84	8	International	2574	1995			year		year		year
12	8	International	2574	1996			year		year		year
83	8	International	2574	1997			year		year		year
197	8	International	2574	1998	too high PM*	too high PM*	year	too high PM*	year	too high PM*	
102	8	International	2574	1999			year		year		
113	8	International	2574	2000			year		year		
135	8	International	2574	2002							
79	8	International	2574	2003							year
23	8	Mack	CV713	2006	EGR					EGR	year
107	8	Mack	CV712	2006	EGR					EGR	year
39	6	International	4700	1996			year		year		year
51	6	International	4700	1997			year		year		year
67	6	International	4700	1998			year		year		
145	6	International	4700	2000			year		year		
116	6	International	4700	2002							
38	6	International	4600	1990	year	year	year	year	year	year	year
43	6	International	4600	1992	year	year	year	year	year	year	year
95	6	International	4600	1994			year		year		year
51	6	International	4200	2004	EGR					EGR	year
36	6	International	1654	1989	year	year	year	year	year	year	year

\* dependent on engine family name which is uncertain

<sup>^</sup> includes EGR as well as filter

Note this table does not include incompatibilities with exhaust temperature profiles.

Table 5: Incompatibilities Found Between Common Vehicles and Level II and I Retrofit Technologies

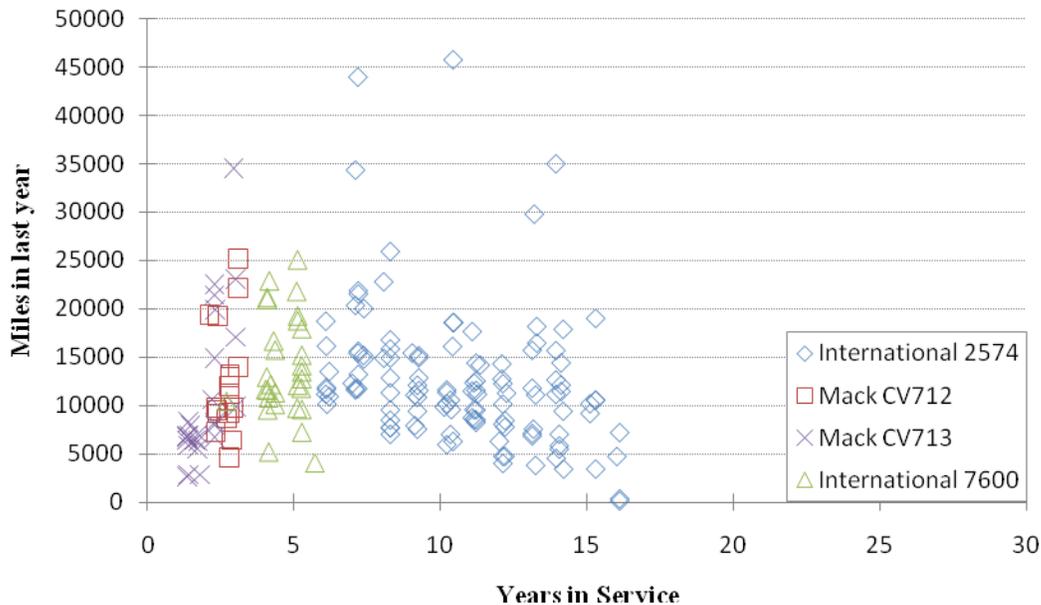
					Level II	Level I					
					Flow Through Filter	Diesel Oxidation Catalysts					
Count	Class	Manufacturer	Model	Year	DFM diesel multi-stage filter (DMF)	Donaldson DCM 6000	Donaldson 6000 + Spiracle~	Donaldson DCM 6100	Donaldson DCM 6100 + Spiracle~	Engine Control System AZ Purifier & Purifmuffler	Cummins Filtration DOC and CCV System~
29	8	International	7600	2003	year	year	year	year	year		
83	8	International	7600	2004	year	year	year	year	year	year	year
114	8	International	7600	2005	year	year	year	year	year	year	year
24	8	International	2574	1993		year		year			
84	8	International	2574	1995		year					
12	8	International	2574	1996		year					
83	8	International	2574	1997		year					
197	8	International	2574	1998		year					
102	8	International	2574	1999		year					
113	8	International	2574	2000		year					
135	8	International	2574	2002		year					
79	8	International	2574	2003	year	year	year	year	year		
23	8	Mack	CV713	2006	year	year	year	year	year	year	year
107	8	Mack	CV712	2006	year	year	year	year	year	year	year
39	6	International	4700	1996		year					
51	6	International	4700	1997		year					
67	6	International	4700	1998		year					
145	6	International	4700	2000		year					
116	6	International	4700	2002		year					
38	6	International	4600	1990	year			year	year	year	year
43	6	International	4600	1992		year		year			
95	6	International	4600	1994		year					
51	6	International	4200	2004	year	year	year	year	year	year	year
36	6	International	1654	1989	year			year	year	year	year

~ includes crankcase filter as well as DOC

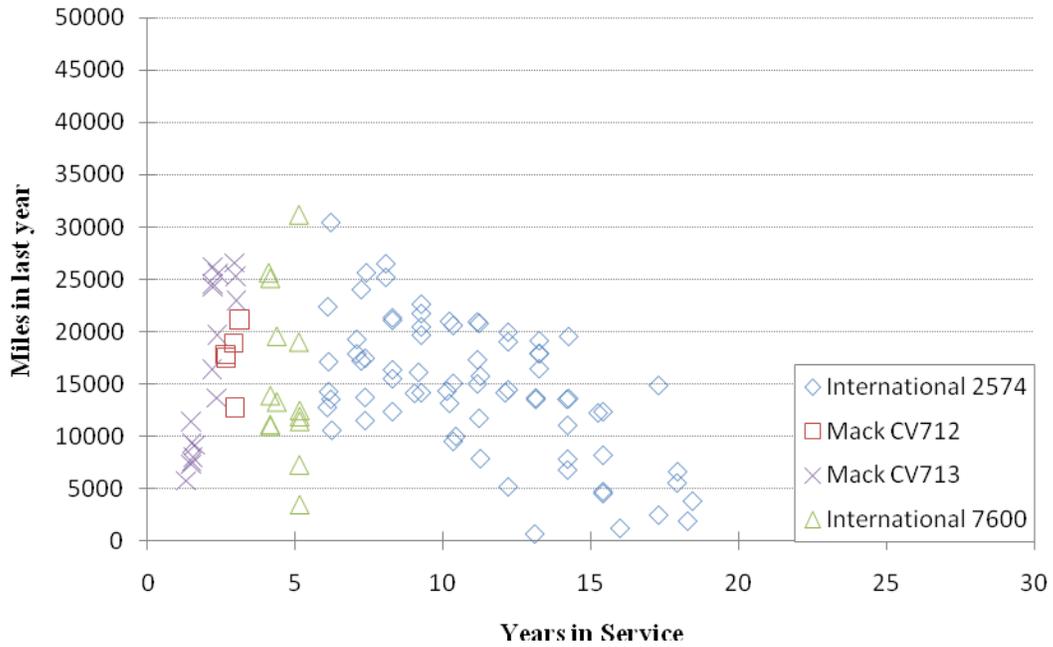
### 7.3 Duty Cycle Requirements

The duty cycles of NYS DOT vehicles are, of course, heterogeneous. Different vehicle types often have substantially different duty cycles. The region in which a vehicle is used can play a major role. International 2574, International 7600, Mack CV712, and Mack CV713 are four common types of large class 8 dump trucks. Miles travelled in the last 12 months for these vehicles in regions 1, 2, 8 and 10 are plotted in Figures 3-6, respectively. Although there is definitely variability within each region, there is also a clear regional trend. International 2574 trucks in regions 1 and 2 average roughly 14,200 miles/year and 15,700 miles/year respectively, while the same kind of truck in regions 8 and 10 averages 7,100 miles/year and 4,100 miles/year respectively. As Figure 7 shows, regions 1 and 2 are further from the highly dense NYC region, while regions 8 and 10 contain a large amount of fairly dense suburbs. Climate differences might also contribute to the discrepancy.

Figure 3: Select Class 8 Vehicle Yearly Mileages (Region 1)



**Figure 4: Select Class 8 Vehicle Yearly Mileages (Region 2)**



**Figure 5: Select Class 8 Vehicle Yearly Mileages (Region 8)**

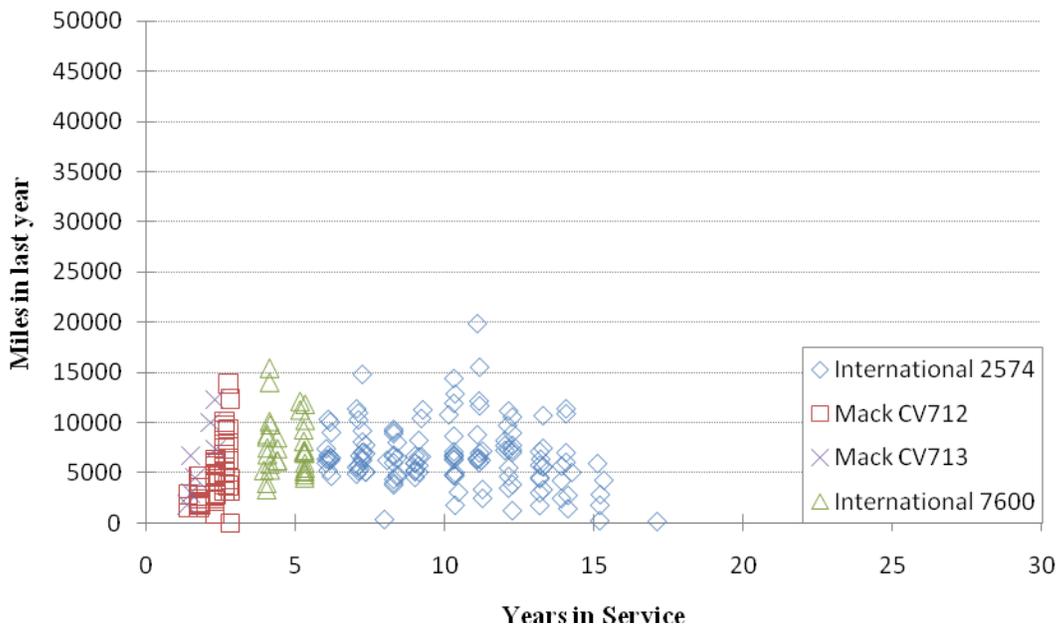


Figure 6: Select Class 8 Vehicle Yearly Mileages (Region 10)

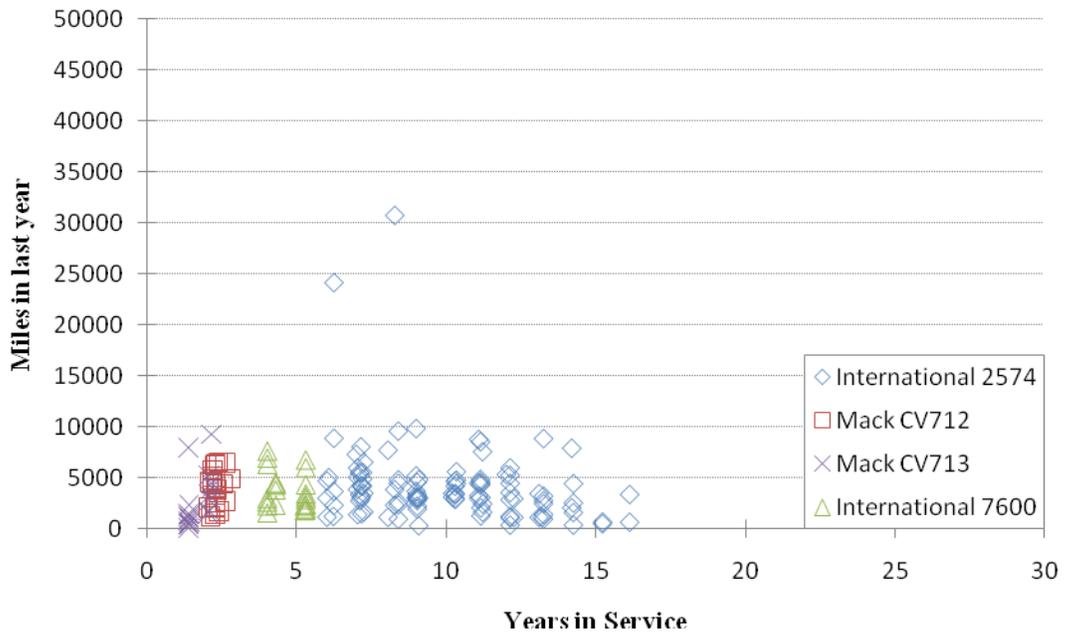
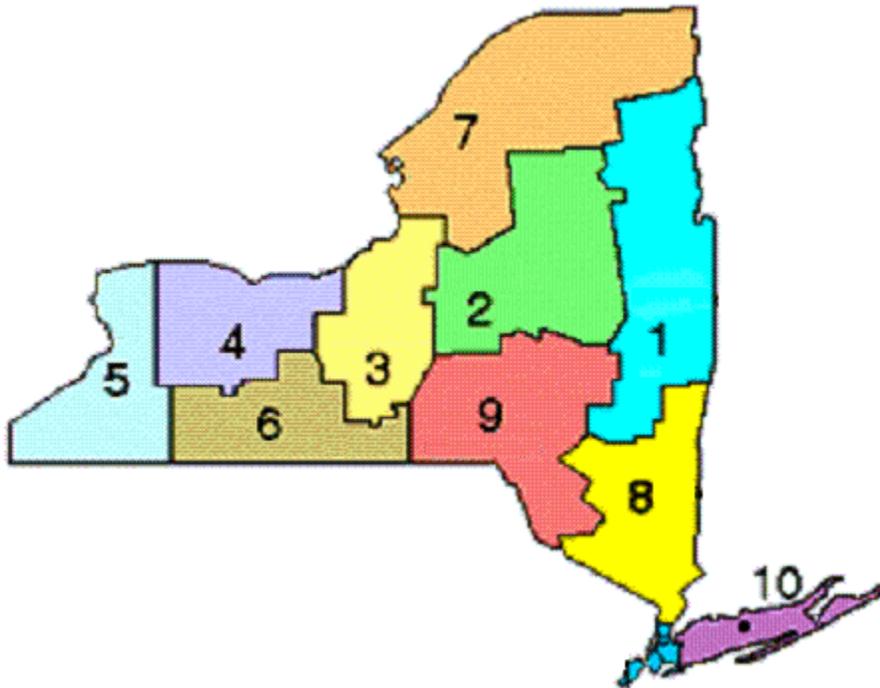


Figure 7: Map of NYS DOT Regions



There is also a seasonal component to the duty cycle of some vehicles. Heavy duty dump trucks, a major component of NYS DOT's diesel fleet, are largely used as snow plows in the winter, which involves considerable highway driving at relatively steady speeds. Many of the same trucks are used for work zone protection in the summer, which involves idling for extended periods (sometimes for over 6 hour stretches) in order to keep lights flashing without depleting the batteries.

NYS DOT contracted with Cummins to have exhaust temperature data logging devices installed on numerous large dump trucks in all ten regions. The vehicles included International 2574 model years 2000-2003 and International 7600 model years 2003-2005. NYS DOT wanted to be able to collect data over a much longer period than the standard three day process, which required devices with relatively high storage capacity. Exhaust air temperature was recorded every 5 minutes (Phelps, 2009). The first set of data logs was compiled in winter, and the second was compiled in the late winter and early summer.

The resulting temperature profiles from 76 tested vehicles were checked for compatibility with each of 9 technologies with substantial temperature requirements that were not eliminated for other reasons. Table 6 summarizes the requirements and the results of the 684 checks. Active DPFs without significant temperature requirements were not included in the table. DOCs can have minimum temperature requirements, but they are generally so relaxed (e.g. 100 C) that they cause no concern, so DOCs were left out of the table as well.

Table 6: Temperature Profile Compatibility with On-Road Verified Retrofits\*

Technology	Level	Type	Temperature Requirement	% incompatible
ESW Canada ThermaCat	3	Active DPF	$\geq 210$ C for $\geq 15\%$ cycle	5.3%
Cleaire Longview	3	Passive DPF	$260^\circ$ C for at least 25% time	55.3%
Donaldson Low NO2 Filter (LNF)	3	Passive DPF	$\geq 235$ C for $\geq 40\%$ cycle, or $\geq 300$ C for $\geq 10\%$ cycle, or average $\geq 237$ C	56.6%
Donaldson Low NOx (LXF) Muffler	3	Passive DPF	$\geq 245$ C for $\geq 40\%$ cycle, or 310 C for $\geq 10\%$ cycle, or average $\geq 263$ C	68.4%
Engine Control System Purifier	3	Passive DPF	$\geq 282$ C for $\geq 25\%$ cycle	85.5%
Johnson Matthey ACCRT	3	Passive DPF	$\geq 240$ C for $\geq 40\%$ cycle	84.2%
Johnson Matthey CRT reformulated	3	Passive DPF	$\geq 240$ C for $\geq 40\%$ cycle	84.2%
Johnson Matthey EGRT	3	Passive DPF/EGR	$\geq 260$ C for $\geq 40\%$ cycle	93.4%
Donaldson DFM diesel multi-stage filter (DMF)	2	Flow Through Filter	1991 - 1993 engines: $\geq 230$ C for $\geq 40\%$ cycle and average $\geq 215$ C, 1994 - 2002 engines: $\geq 210$ C for $\geq 40\%$ cycle and average $\geq 210$ C	79.6%

\* Technologies without significant minimum exhaust temperature requirements are not listed.

The final column of Table 6 is the percentage of tested vehicles which had a temperature profile incompatible with the retrofit. The higher this percentage, the less likely this retrofit is to be compatible with vehicles like those tested. This percentage should definitely not be interpreted to mean that the remainder of the vehicles is compatible with the retrofit. At least three aspects of the testing approach will tend to make retrofits appear more compatible than they are.

First, the testing used to compile Table 6 was conducted during periods of relatively high activity (large dump trucks tested nearly exclusively in the winter). Compatibility is quite likely to be lower when idling around construction in the summer. A small amount of summer testing was conducted. Temperature profiles from a class 8 truck collected on each of two 6-hour summer days were incompatible with all passive filters, and exhibited a median temperature of only about 150 C. A 1-hour test yielded a slightly higher temperature profile more in line with winter results, but it is unclear whether the truck idled significantly (or at all) during this test.

Second, recall that exhaust temperature profile testing is usually done over shorter intervals than were used here. If vehicles aren't coming close to meeting temperature requirements in mid May, it won't be of much help that back in early February there was a snow storm which caused some high exhaust temperatures. Put another way, there may be enough high temperatures in the duty cycle, but they may not be spaced at regular enough intervals for proper regeneration.

Third, vehicles were only tested in one year of their life. Vehicles may be compatible at one stage of their life, but not later on as their usage profile changes. Vehicles may not be assigned to the same route, location, or even region throughout their life, as they are statewide assets and need to be utilized in response to changing demands, including emergency needs.

Even at first glance, these test results provide fairly strong evidence that four of the seven passive DPF technologies are incompatible with the exhaust temperature profiles of NYS DOT's class 8 dump trucks. Engine Control System's Purifilter, Johnson Matthey's ACCRT, Johnson Matthey's CRT reformulated, and Johnson Matthey's EGRT are all incompatible with more than 84% of the vehicles tested. There is also considerable

evidence that Donaldson's DFM DMF, the only level 2 FTF, is incompatible with NYS DOT's large dump trucks, given its incompatibility percentage of 79.6.

For the first three passive DPFs, the test results are less immediately conclusive. The Cleaire Longview, Donaldson LNF, and Donaldson LXF were found to be incompatible with 55 to 68 percent of tested vehicles. There was no clear pattern, such as model 17600 trucks being compatible while model 2574 are not. There were incompatibilities in every region, though they did appear especially common in region 10. In short, there did not appear to be any straightforward way of predicting which vehicles would be compatible. Furthermore, there is no reason to believe that a vehicle which is compatible one year will remain so the next. For this reason, the authors suspect that passive DPFs would not provide a reliable retrofit solution for NYS DOT class 8 dump trucks. Were NYS DOT to install the more tolerant PDPFs on its class 8 dump trucks, it is unlikely that every single vehicle would have regeneration problems, but the risk of many vehicles encountering substantial problems would be very high.

The lowest incompatibility was achieved by the ESW Canada Thermacat. Barely over five percent of temperature profiles were incompatible, but it was also the only active DPF listed. Some other active DPFs list no minimum temperature constraints. Temperature profile considerations do not, therefore, prevent active DPFs (or DOCs) from being used on NYS DOT heavy duty dump trucks.

#### *7.4 Other Compatibility Requirements*

Although not a formal requirement declared in retrofit verifications, vehicle availability is a major concern for much of the NYS DOT fleet. NYS DOT officials are understandably concerned about the possibility of having to take plows off the road at a critical time. Imagine a blizzard moves into New York and plows are immediately sent out before dawn to keep the roads clear. Late that day it is still snowing heavily, and many plows now need to actively regenerate their filters. Plows start to arrive back at their depots and plug in for five hours of regeneration. It's hard to argue that such a situation would not make the roads more dangerous and consequently pose a public safety risk. The regeneration time does not have to be five hours for there to be potential

problems. DOT staff have expressed that 20 minutes of downtime can be too much, particularly if it cannot be accurately predicted.

The approximate regeneration times for the Cleaire Horizon, Cleaire Vista, Donaldson Semi-Active Electric Filter and Engine Control Systems Purifilter Plus are 5 hours, 2 hours, 4.5 hours and 2.5-4 hours respectively (Cleaire, 2008, 2009b; Donaldson, 2008; Engine Control Systems, 2008). According to Volvo, the Huss MK DPF (which is available as a retrofit) takes no more than 35 minutes to regenerate (Volvo North America, 2010). No manual could be found on Huss's website to confirm this number, and none was provided upon request. The county of Los Angeles has one Huss DPF which regenerates in roughly 30 minutes. It came installed on a new truck when they purchased it (Nunez, 2009; 2010). This 30 minute regeneration time may still be too long for NYS DOT, and there may be other compatibility issues such as a lack of space for installation. Despite being marketed as an active filter, the ESW ThermaCat regenerates during normal operation (ESW, 2009). However, NYS DOT's class 8 dump trucks exceed the maximum horsepower for the device, and many class 6 trucks violate other requirements such as model year and incompatibility with EGR.

Spatial compatibility is another concern. Larger exhaust treatment devices might not fit without significant vehicle modifications. New trucks are often built differently to accommodate filters, and hydraulics had to be moved to install a trial DPF.

## **8. Cost-Benefit Analysis of Retrofit/Replacement Strategies**

### *8.1 Application of Verified Retrofits*

The manufacturers of all retrofit devices not eliminated in the initial screening described in Section 7.1 were contacted and asked for equipment prices. These prices were compared with prices reported by the fleet managers mentioned in Section 4. The resulting equipment price estimates were \$1,400 for a level 1 DOC, \$8,000 for a level 2 flow through filter, and \$15,000 for a level 3 DPF. There is inevitably some uncertainty surrounding these numbers, due to factors such as the volume ordered. The \$15,000 figure matches a recent CARB estimate of the capital cost of an ADPF (CARB, 2008b). At first glance, one might wonder why PDPFs aren't given a lower equipment price, as the CARB report estimates their cost at \$12,000 per heavy heavy-duty vehicle. Lower

priced passive DPFs are indeed available, but the higher price PDPFs have substantially more relaxed exhaust temperature requirements. As discussed in Section 7.3, NYS DOT vehicles often come nowhere near meeting the duty cycle requirements for the less tolerant PDPFs. Even relatively expensive PDPFs have serious compatibility issues, but for the purpose of the cost benefit analysis in this section, they will be assumed to be compatible.

Installation cost was added to the equipment prices. The shop labor rate was assumed to be \$65/hour. This labor rate was provided by NYS DOT, and it resembles shop labor rates reported in a recent survey of auto body shops (NV DMV, 2010). Installation times were based on NYS DOT experience as well as company estimates (e.g. Donaldson, 2008, 2009a). They were 4 hours for level 1 and 2 retrofits, 6 hours for level 3 PDPFs, and 9 hours for level 3 active ADPFs.

Although a relatively small portion of the overall retrofit cost, installation costs are not necessarily inconsequential. If NYS DOT were to retrofit every vehicle in the January 1<sup>st</sup>, 2008 snapshot with a DOC (the simplest retrofit installation), at the NYS DOT experience install time of 4 hours/DOC, the total time required would be over 10,000 hours. This equates to more than five full time mechanics working a whole year at 40 hours/week and 50 weeks/year. With level 3 retrofit technologies, the cost would be substantially greater.

In addition to retrofit equipment and installation costs, PDPFs and ADPFs have periodic costs from ash removal. The interval between cleanings was estimated to be 1 year, based on EPA figures (US EPA, 2009e), a CARB report (CARB, 2008b), a Massachusetts Department of Environmental Protection report (M DEP, 2008), equipment manuals (Donaldson, 2009c; Engine Control Systems, 2006; 2008), and DSNY experience (Kim, 2009), all of which either put the interval at 1 year or a range including 1 year. The cost was assumed to be \$300 per cleaning, roughly in the middle of estimates of \$250-300 by DSNY (Kim, 2009), \$200-400 by M DEP (2008), \$400 by CARB (2008b), and \$500 by the county of Los Angeles (Nunez, 2009). The costs of future cleanings were discounted to the present using a 5% interest rate. Newer vehicles with longer expected remaining lifetimes had more expected cleanings, making them more expensive to retrofit.

One more cost was included for ADPFs, and that was the cost of regeneration stations. This equipment is needed much more frequently than de-ashing equipment (sometimes daily regenerations are warranted), and consequently it was assumed that NYS DOT would purchase the equipment. A charging station is not necessarily required for every vehicle, both because filters don't always need to be regenerated daily, and because recharging stations can sometimes be set up to conduct multiple regenerations in sequence overnight (Donaldson, 2008). Our cost estimates were based on an Oakland Public Works Agency proposal, which called for 6 stations, costing \$6000 each, to serve 27 filters (OPWA, 2007). This amounts to a cost of \$1333 per ADPF purchased.

The benefits of exhaust treatment retrofits are, of course, the emission reductions. Unretrofitted vehicle emission rates, in grams/mile, were obtained from the EPA MOBILE model. The emissions impacts of verified retrofit technologies, in terms of percentage reductions, were obtained from EPA and CARB verified technology lists. Retrofits are verified to reduce PM, CO, HC, and (infrequently) NO<sub>x</sub>. PM is the basis for CARB's technology levels (CARB, 2009b) and the tiers in NYS DEC regulations (NYS DEC, 2009c), and will therefore be the focus of this analysis. Based on fuel usage and mileage reading data, annual mileage is assumed to be 13,750. All vehicles of age 13 or younger are assumed to remain in use until they reach age 14. Vehicles already 14 or older are assumed to remain in use for one more year. The grams of PM emissions prevented by applying different types of retrofits to different vehicles are plotted in Figures 8 and 9 for class 8 and 6 trucks, respectively.

Figure 8: Emission Reductions from Retrofits of Class 8 Trucks

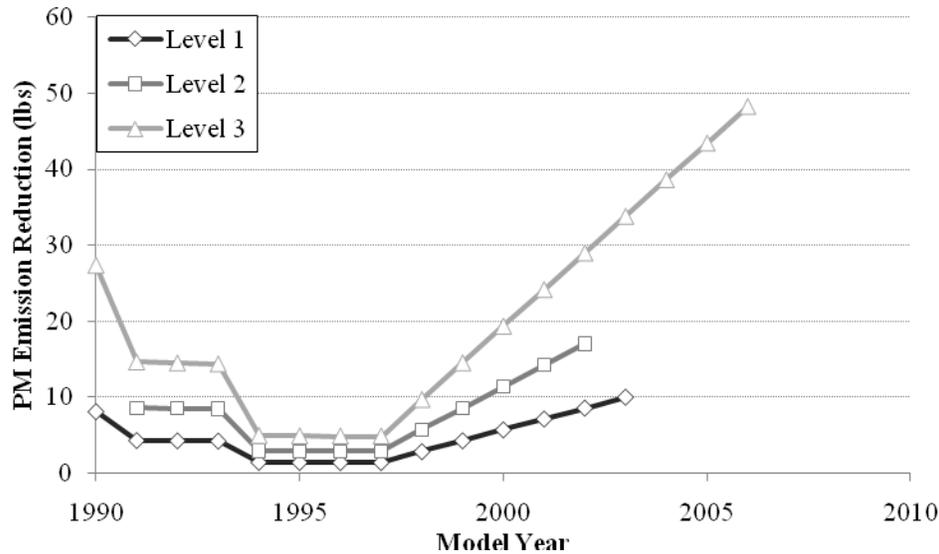
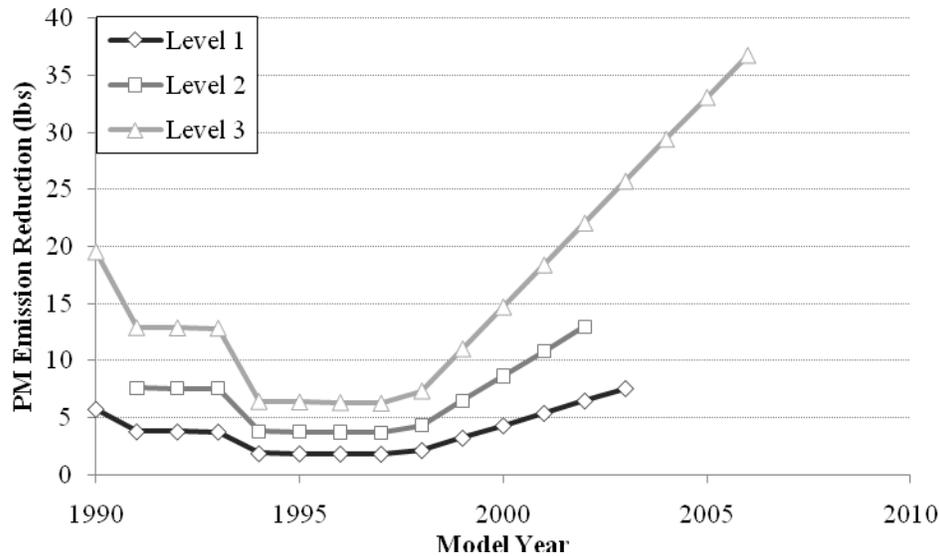


Figure 9: Emission Reductions from Retrofits of Class 6 Trucks



Emissions prevented are plotted for all model years for which it is plausible that one of the EPA or CARB verified retrofits is compatible. Given the incomplete fleet data described earlier, it is likely that several incompatibilities are not represented. Most of the incompatibilities represented are based on model year and EGR. The Cleaire Horizon

does not have a hard minimum model year, or an EGR restriction, which is why ADPFs are given such broad apparent compatibility.

Regardless of the level of the retrofit, retrofitting the newest (pre-2007) vehicles generates the largest emissions savings. The lower expected remaining mileage of older vehicles is what drives down their emission reductions. Pre-1994 vehicles start to have substantially higher emission rates, causing larger emission reductions.

In order to account for the different costs of different level retrofits, the benefits are divided by the costs, to produce a cost effectiveness measure. The grams of PM emission prevented per dollar spent are plotted in Figures 10 and 11 for class 8 and class 6 trucks, respectively. This essentially provides a “bang per buck” metric, with higher values meaning more emissions reduced per dollar spent. Level 3 is broken down into passively regenerating and actively regenerating technology. Although emissions benefits are generally comparable, these different types of filters have different costs and vehicle compatibility.

Figure 10: Long Term Cost Effectiveness of Retrofitting Class 8 Trucks

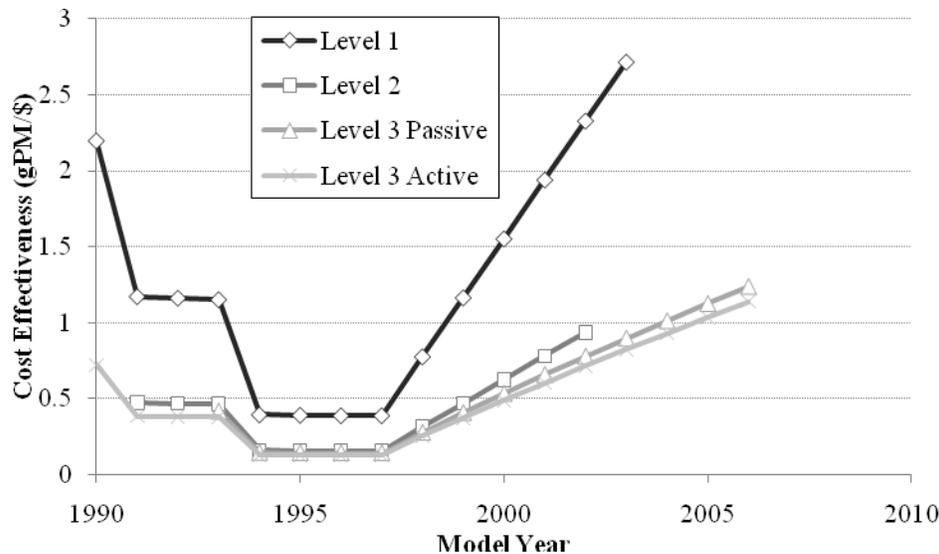
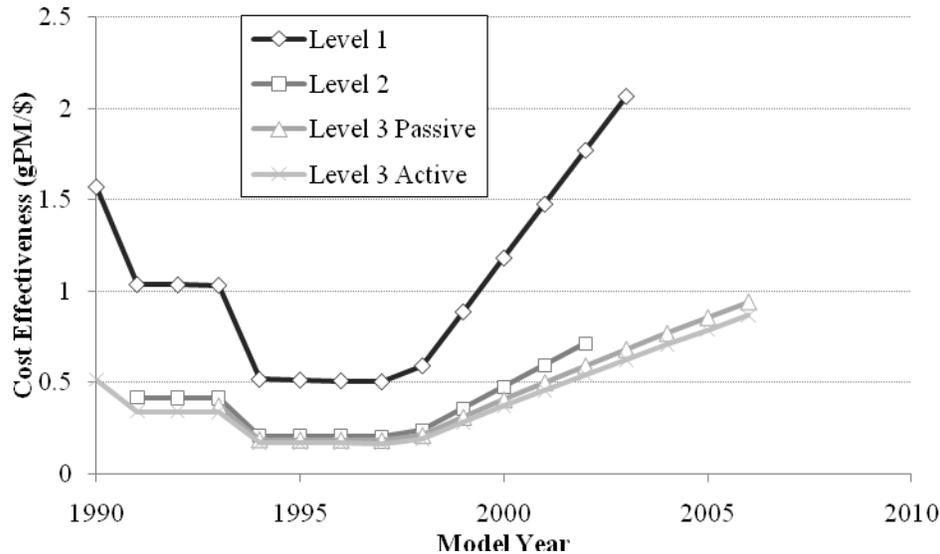


Figure 11: Long Term Cost Effectiveness of Retrofitting Class 6 Trucks



The general shape of the cost effectiveness curves matches that of the emissions curves, and is driven by the same factors. The cost effectiveness curves are scaled by costs, which makes it apparent that level 1 retrofits (DOCs) offer the highest bang per buck, despite providing the lowest emission benefits.

### 8.2 Early Retirement

The cost structure of early vehicle retirement is inherently quite different from that of retrofits. Early vehicle replacement has very high initial costs, but these costs can be substantially offset by future savings. Imagine, for example, that a vehicle slated for retirement in 3 years is replaced today instead. This requires that the NYS DOT spend the full purchase price of the replacement vehicle. Selling the replaced truck, whether for scrap or for use as a vehicle, does not generate revenue for NYS DOT to offset the purchase price. Three years from now, however, the planned replacement does not have to be made. This difference in when costs and savings are experienced can cause dramatic differences between the initial and long term cost effectiveness of vehicle replacements, assuming no financing option is utilized.

Two of NYS DOT's most common diesel vehicle types are examined: class 8 dump trucks and class 6 stake trucks. The new vehicle purchase prices of class 8 dump

trucks and class 6 stake trucks are assumed to be \$160,000 and \$63,000, respectively (based on NYS DOT estimates). This is the initial cost of replacement. Normally, it could be reasonably argued that the long term cost of losing a vehicle (with no revenue compensation), and consequently having to replace said vehicle, is simply the market value of that vehicle. NYS DOT is in a somewhat unusual situation, however, which makes the picture more complicated. From the NYS DOT perspective, used vehicles are less valuable than they are to most fleet owners. This is because most fleet owners would include future scrap revenue in their estimation of a used vehicle's value. For older vehicles, this might even be the majority of the vehicle's value. For the NYS DOT, there is no scrap revenue, making older vehicles less valuable from their perspective. For this reason, sale values of used vehicles are computed, and then adjusted to create NYS DOT values of used vehicles. For newer vehicles, scrap is a relatively small portion of the sale value, making the sale and NYS DOT values very close, but the NYS DOT values drop more sharply with age.

The fact that NYS DOT does not keep vehicle auction revenue has naturally encouraged NYS DOT to wait until vehicles are in very poor condition before selling them. Harsh operating conditions, especially during snow removal, can contribute to vehicle deterioration. It is not unusual for NYS DOT technicians to remove parts which might be needed as spares before selling a vehicle. This makes sense, , but it means that historic auction prices don't provide a complete picture of used vehicle sale value throughout the vehicle lifetime. Historic auction data can be used to estimate vehicle lifetime under current practices, as well as vehicle scrap value, however. Auction data from 2005 to 2009 was used to estimate a large diesel truck lifetime of 14 years, and scrap sale values of roughly \$2,115 and \$1,270 for class 8 dump trucks and class 6 stake trucks respectively.

The above information provides the sale value of a new truck, and of a very old truck, but not the sale value of any truck in between. These intermediate sale values were filled in using the assumption that the sale price of a used diesel truck decreases exponentially with age, following a pattern similar to that found for diesel school buses (Gao and Stasko, 2009). The resulting truck values are plotted in Figure 12. Note that these are intended as best guesses, only knowing the vehicle type and age. Individual

vehicle values will naturally vary depending on factors such as mileage and condition. Adjusted NYS DOT perspective vehicle values are plotted in Figure 13. These are the long term replacement costs.

Figure 12: Expected Vehicle Sale Price by Age

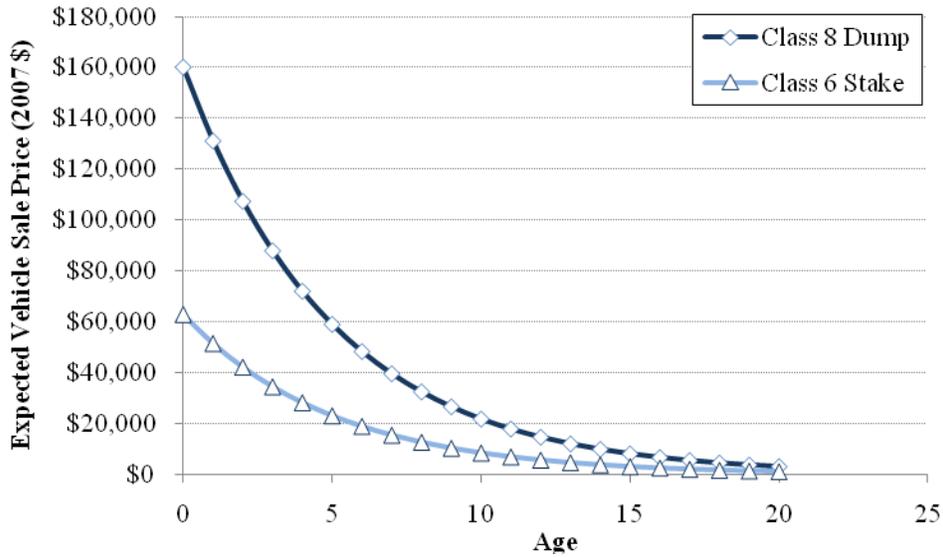
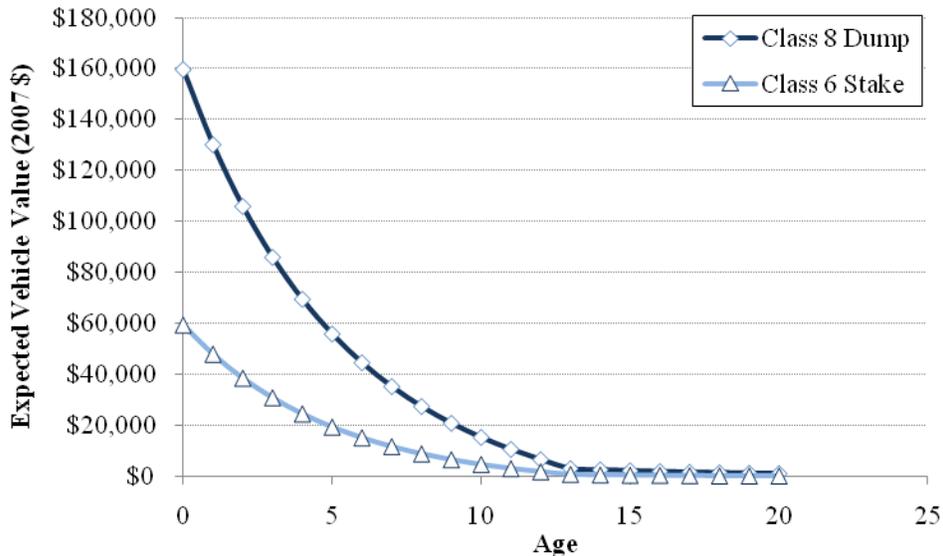


Figure 13: Expected Vehicle NYS DOT Value by Age



The emissions reduction achieved from an early replacement is also somewhat less straightforward than that from a retrofit. The most obvious change occurs when the

retired vehicle would have operated, but does not because of the early retirement. For these years, the emissions reduction can be computed based on the difference between the emission rates of the retired vehicle and those of its replacement.

Further along in time, the effects become more complicated. A replacement vehicle purchased today might have higher emission rates than a replacement vehicle purchased in three years. Furthermore, purchasing a replacement three years earlier than previously planned will likely mean that the new vehicle will also have to be replaced earlier than planned. This effect can be carried further and further into the future, with decreasing certainty.

Historically declining emission rates limit the importance of these uncertainties, however. As long as emission rates do not increase, future changes to emission rates will be smaller than those made in recent history. Figures 14 and 15 provide simplified histories of PM and NO<sub>x</sub> emission standards for new trucks, as presented in (US EPA, 2003c). EPA standards are complicated by sophisticated phase in schemes which ease transitions. The 0.2g/bhp-hr NO<sub>x</sub> standard, for example, does not take full effect until 2010 (US EPA, 2001). Nonetheless, the general trends in Figures 14 and 15 hold true. Between the late 1980s and 2010, both PM and NO<sub>x</sub> emission rate caps have been lowered by over 98%. This means that even if both PM and NO<sub>x</sub> emission rates were cut to absolutely zero in 2011, the change would be dramatically smaller than those seen over the past couple decades.

Figure 14: New Truck PM Standard

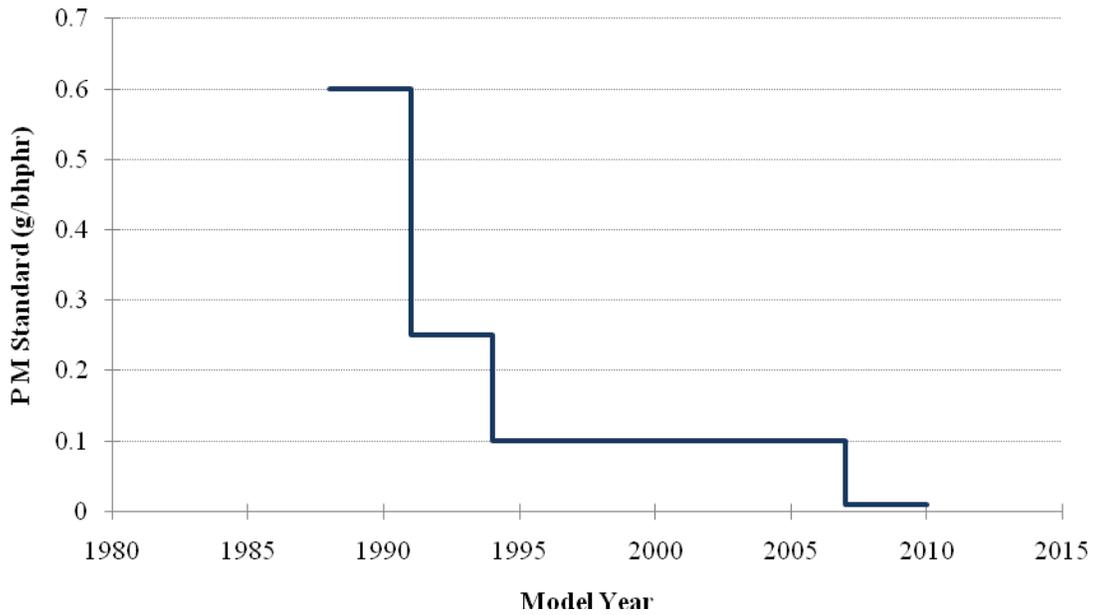
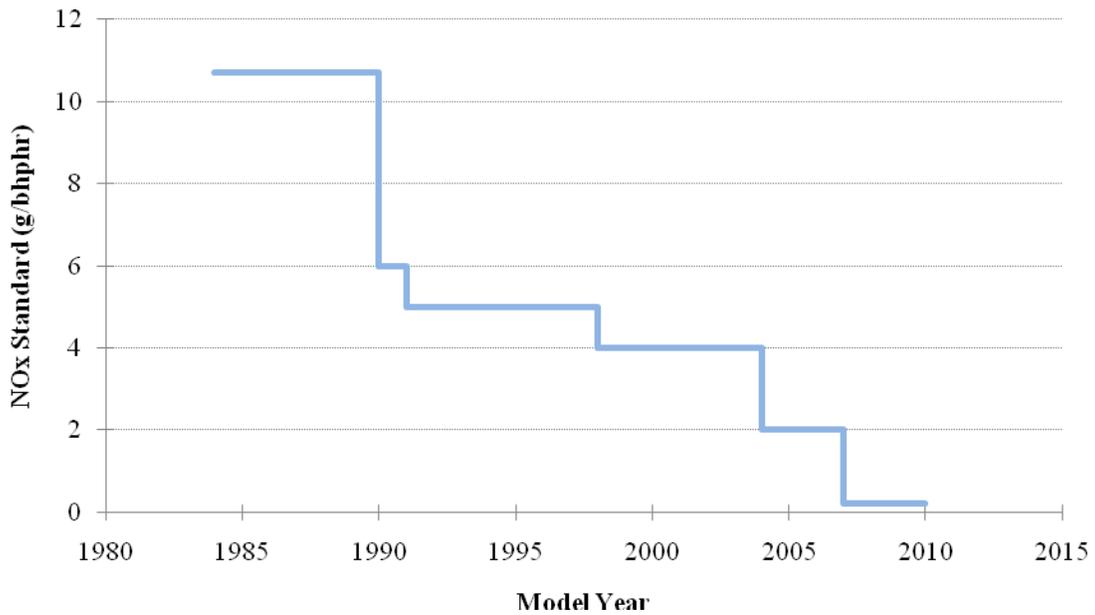


Figure 15: New Truck NO<sub>x</sub> Standard



For the purpose of this analysis, future changes to emission rates are ignored. The emission reduction from an early retirement is assumed to be the change in emissions for the additional years the retired vehicle would have been operating if not retired early.

A few additional assumptions are made in order to compute the cost effectiveness of vehicle replacement. As in the previous section on retrofits, annual mileage is assumed to be 13,750. All vehicles of age 13 or younger are assumed to remain in use until they reach age 14. Vehicles already 14 or older are assumed to remain in use for one more year. The resulting long term cost effectiveness (in terms of grams of PM emissions prevented per dollar spent) are plotted in Figures 16a and 16b as a function of model year and vehicle type. The only difference between the two figures is that Figure 16b zooms in on the lower portion of Figure 16a to reveal the variation in recent model years.

Figure 16a: Long Term Cost Effectiveness of Replacement (Zoomed Out)

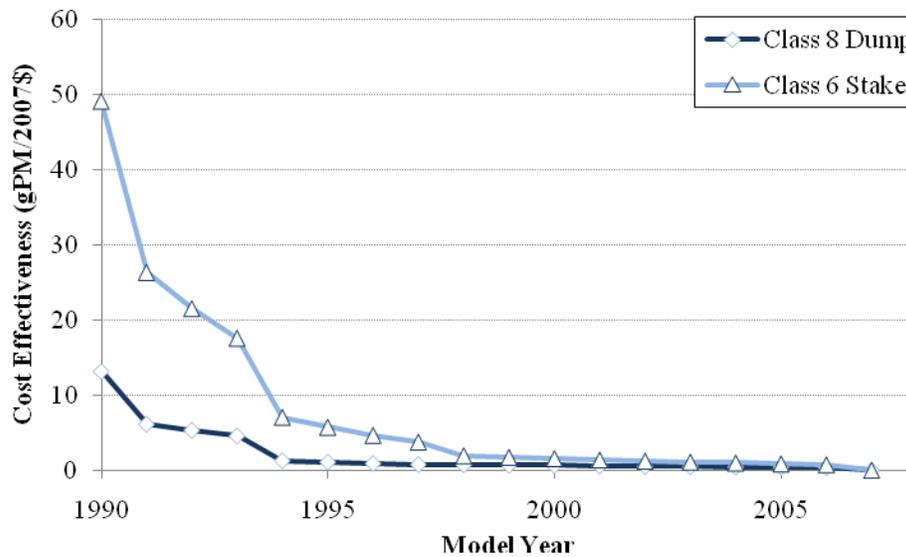
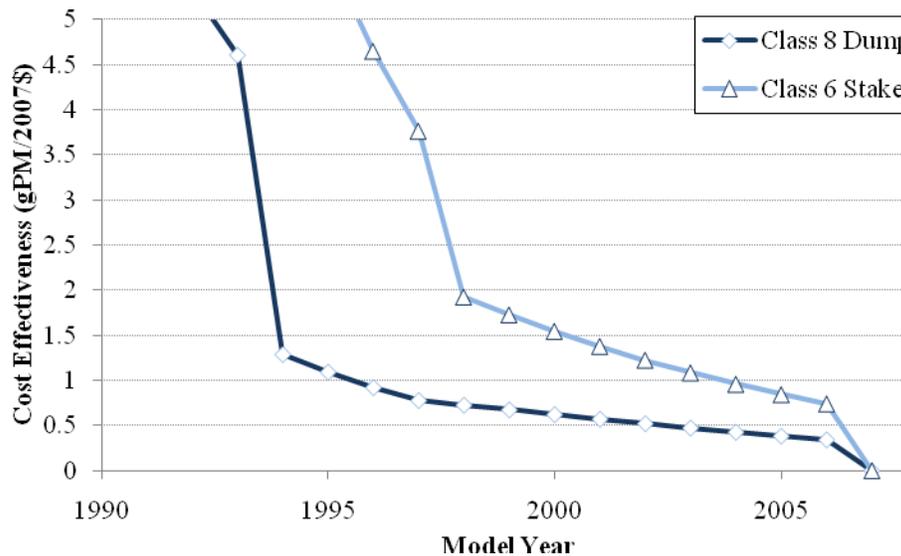


Figure 16b: Long Term Cost Effectiveness of Replacement (Zoomed In)



Numerous factors influence the shape of the long term cost effectiveness curves. These can be explained by starting with model year 2007 and then gradually looking at older vehicles (moving from right to left across Figures 16a and 16b). Replacing a model year 2007 vehicle has no PM emission benefit because the replacement vehicle would have the same emissions rate as the original vehicle. This means the cost effectiveness of replacing a model year 2007 (or newer) vehicle is zero.

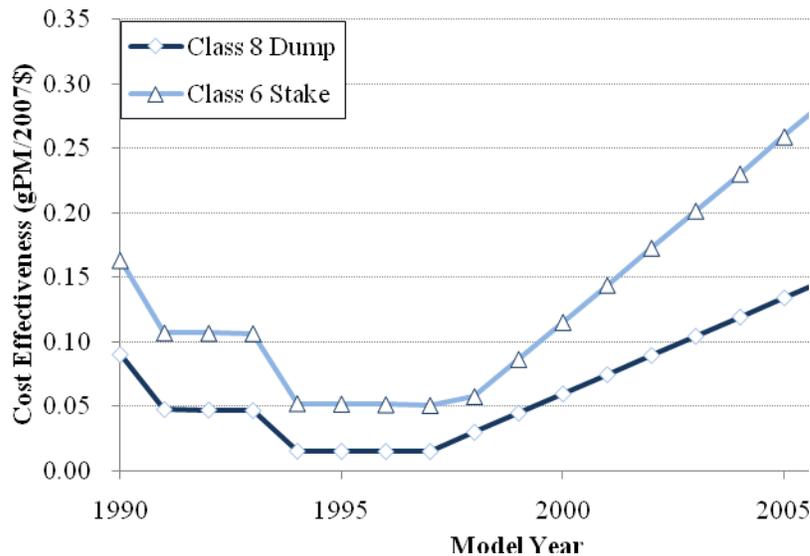
For both truck types, model year 2006 PM emission rates are more than 13 times those for model year 2007. This means there is considerable emissions savings from replacing a model year 2006 truck. Class 6 diesel PM emission rates were unchanged 1998-2006, while the class 8 diesel PM emission rates were unchanged 1996-2006. Within these intervals, long term cost effectiveness gradually increases as vehicles get older. Two competing factors are at work. Older vehicles tend to have lower remaining mileage, meaning lower expected emissions savings. Older vehicles also have lower value, meaning lower long term replacement cost. The former factor makes replacing older vehicles less cost effective, while the latter (dominant) factor makes replacing older vehicles more cost effective.

For the oldest vehicles on the far left side of Figures 16a and 16b, the shape of the curve changes, shooting upward quickly. By the time vehicles are this old, their expected

remaining mileage is low but fixed, meaning that this factor no longer influences the shape of the curve. The vehicle values are still decreasing with age, driving down the long term replacement cost. Changes in emission rates also play an important role. These changes were especially large going from 1993 to 1994 and from 1990 to 1991. Both of these factors make older vehicles more cost effective to replace. The cost effectiveness would continue to grow as vehicles become older if the graphs were extended to the left and earlier model years were added. A quick glance at Figure 16a indicates that replacing the oldest vehicles is likely to be one of the most cost effective emission reduction techniques in the long term, but that replacing new vehicles would be much less cost effective. This difference would be made even more pronounced if multiple unreliable old vehicles could be replaced with a single reliable new vehicle.

The short term cost effectiveness of replacement, based on the new vehicle price, is plotted in Figure 17. The short term cost effectiveness curve looks quite different from the long term cost effectiveness curve. The far right of both curves is the same, as the lack of emissions benefit from replacing a model year 2007 vehicle gives this action a cost effectiveness of zero, regardless of timeframe. The eras of unchanging emission rates which resulted in a slow increase in long term cost effectiveness for older vehicles now exhibit lower short term cost effectiveness for older vehicles. Older vehicles still tend to have lower remaining mileage, meaning lower expected emissions savings. The competing effect of older vehicles having lower market values is gone, however. The short term cost is independent of model year, as the new vehicle price is independent of the age of the vehicle replaced. Emission rate changes still drive the curve upward on the far left side of Figure 17, but they are no longer compounded by cost changes, making the rise much less dramatic.

Figure 17: Short Term Cost Effectiveness of Replacement



### 8.3 CNG Conversion

As discussed in Section 3.2, natural gas powered vehicles are by no means homogeneous. Three general categories are spark ignited engines which operate exclusively on natural gas, spark ignited engines which operate on either natural gas or gasoline, but not both at the same time, and compression ignition engines which operate primarily on natural gas, but use diesel as a “pilot.” Also, natural gas can be stored as compressed in its gaseous phase, or as a liquid. NYS DOT already has a large number of CNG fueled vehicles in its light duty fleet, as well as a few pilot CNG-diesel dual fuel heavy duty vehicles. In 2007, NYS DOT reduced its petroleum consumption by more than 750,000 gallons by using CNG (NYS DOT, 2008).

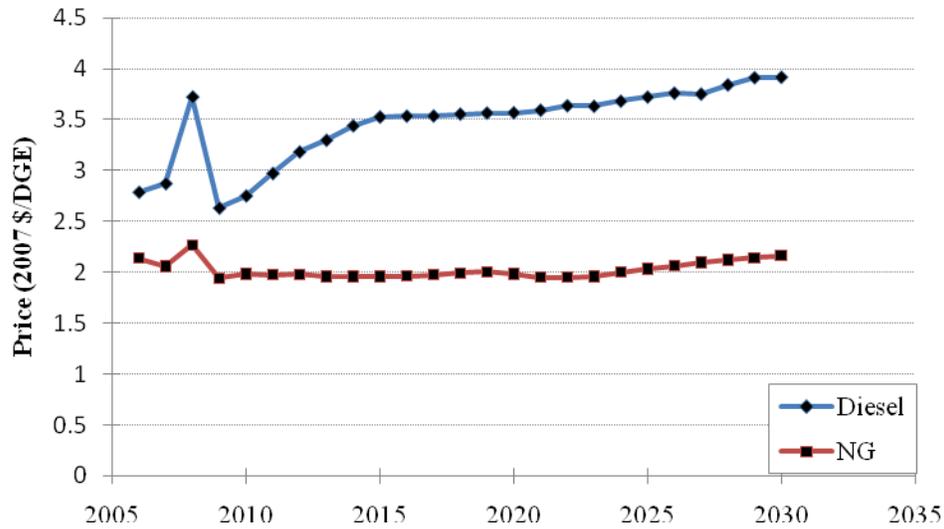
Recent NYS DEC regulation focuses attention on the heavy duty diesel vehicles. As of August of 2008, 30 heavy duty trucks had been modified to run on dual fuel, which allows them to displace up to 80% of the diesel fuel normally used (NYS DOT, 2008). These vehicles can still run exclusively on diesel, however. They maintain the same diesel tank, with a capacity of approximately 80 gallons, in addition to a CNG tank with a capacity of approximately 35 diesel gallon equivalents (DGE). This configuration effectively extends the range of the vehicles between refueling without payload

reduction, but it also contributes to problems with driver compliance. Running on 80% CNG requires more refueling than when running on diesel, making it inconvenient (Darling, 2009). Despite this, CNG has displaced petroleum consumption for these vehicles, but exact figures are not available from the fuel tracking system.

The conversions cost \$25,000 per truck, \$20,000 of which came from federal funding. This cost is slightly lower than a U.S. Department of Energy estimate of the marginal cost of heavy duty natural gas vehicles, which they place between \$30,000 and \$50,000 per vehicle (NREL, 2008). Joe Darling of NYS DOT estimates an average savings of \$1.00/gallon, and that the converted trucks consume between 2,500 and 3,000 gallons annually. Given imperfect compliance, such vehicles are assumed to displace 50% of their 2,750 gallons of annual fuel usage. If the average savings of \$1/gallon holds, this means an annual savings of \$1,375.

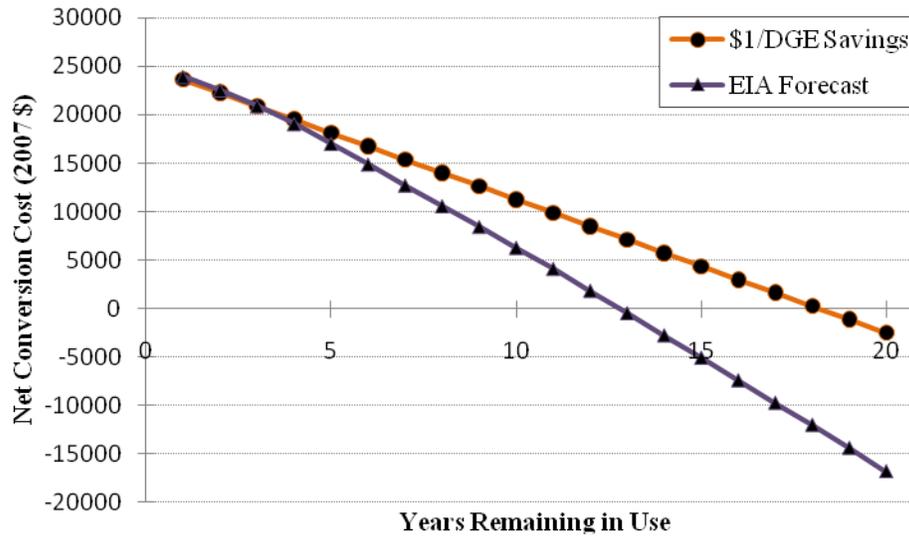
There is considerable uncertainty surrounding future fuel prices. For 2007, the average diesel price was approximately \$0.81/gallon higher than the average price of natural gas delivered for use in transportation (expressed in \$/diesel gallon equivalent). Keeping the units as 2007 \$/DGE, the difference jumped to \$1.46/DGE in 2008, and is likely to be back below \$1.00/DGE for 2009 (US EIA, 2009). According to forecasts released by the U.S. Energy Information Administration in March of 2009, the price gap between diesel and natural gas will grow significantly in the between 2010 and 2015. These forecasts are presented with a brief price history in Figure 18. The gap passes \$1.50/gallon by 2015, and never drops back below this value for the duration of the projection. Long range fuel price forecasts are notoriously difficult to make. Taking this into consideration, the \$1/gallon assumption seems to be a reasonable, perhaps somewhat conservative estimate of cost savings.

Figure 18: Diesel and Natural Gas Price Forecasts from EIA



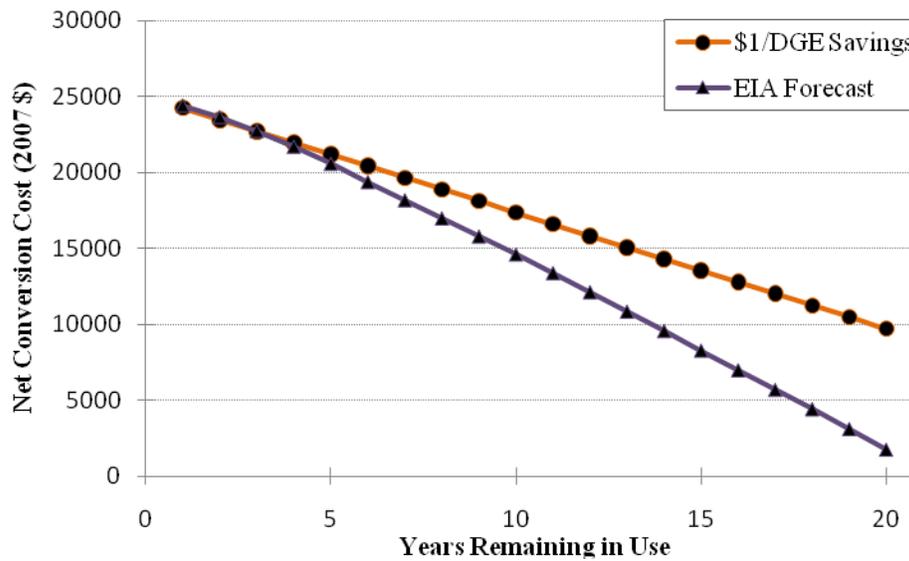
Given the \$25,000 initial cost, and the assumption that fuel savings remain constant at \$1,375/year, in terms of 2007 dollars, the net cost of a class 8 truck CNG conversion follows the plot in Figure 19, as a function of the number of years the vehicle remains in use after being converted. For comparison, the net cost is also plotted if EIA fuel price projections are exactly on target. For conversions of older vehicles, it hardly matters which of the two fuel price projections are used, but conversions of newer vehicles will be noticeably less costly with the EIA forecast. It's important to note that NYS DOT generally prefers to retire vehicles around age 13, meaning that very few conversions would completely pay for themselves. Converting some newer vehicles may just about break even if the EIA forecast is correct, but converting the newest vehicles (which meet 2007 emission standards) will provide much smaller emissions benefits than converting pre-2007 vehicles.

Figure 19: Net Class 8 CNG Conversion Cost vs. Years of Remaining Usage



Class 6 vehicles are assumed to follow the same assumptions, except for a higher fuel efficiency (9.0 mi/DGE instead of 5.0 mi/DGE), meaning less fuel use for the same mileage. The resulting costs are therefore higher, as shown in Figure 20.

Figure 20: Net Class 6 CNG Conversion Cost vs. Years of Remaining Usage



The fact that very few CNG conversions would be likely to completely pay for themselves with fuel savings does not mean CNG conversions should be completely ignored, however. Recall that any heavy duty vehicle which has been retrofitted with an EPA or CARB approved conversion kit to enable it to run on a combination of CNG and ULSD is considered to be in compliance with the NYS DEC regulations. Fuel savings partially offsetting CNG conversion costs can be enough to make CNG conversion less expensive than many DPFs. In other words, CNG conversion is unlikely save money when compared to a base case of leaving the vehicle as is, but it could save money compared to retrofitting the vehicle with a DPF.

Estimating the emission reductions from CNG conversion will allow us to compute the cost effectiveness in terms of grams/\$. As discussed in Section 3.2, traditional sources of emission rates do not provide good values for CNG vehicles, whether they are new or repowered. For regulatory reasons discussed later in this section, vendors who perform conversions should have emissions test data available for the specific conversions they perform. Based on NYS DOT's past experience with such retrofits, converted vehicles will be assumed to meet the 2007 PM standard, and have the same PM emissions as a new model year 2007 diesel vehicle. These emission rates, in grams/mile, were obtained from the EPA MOBILE model. The 2,750 diesel gallon equivalents used corresponds to 13,750 miles for a fuel efficiency of 5.0 mi/DGE, and vehicle life is fixed at 14 years (an estimate based on the ages of vehicles auctioned by NYS DOT). Given these assumptions, the cost effectiveness is plotted in Figure 21 for class 8 trucks from a range of model years. Figure 22 plots the cost effectiveness for class 6 diesel trucks, using the same assumptions except for class 6 emission rates and a higher fuel efficiency of 9.0 mi/DGE, resulting in lower fuel usage for the same mileage.

Figure 21: Long Term Cost Effectiveness of CNG Conversion of Class 8 Truck

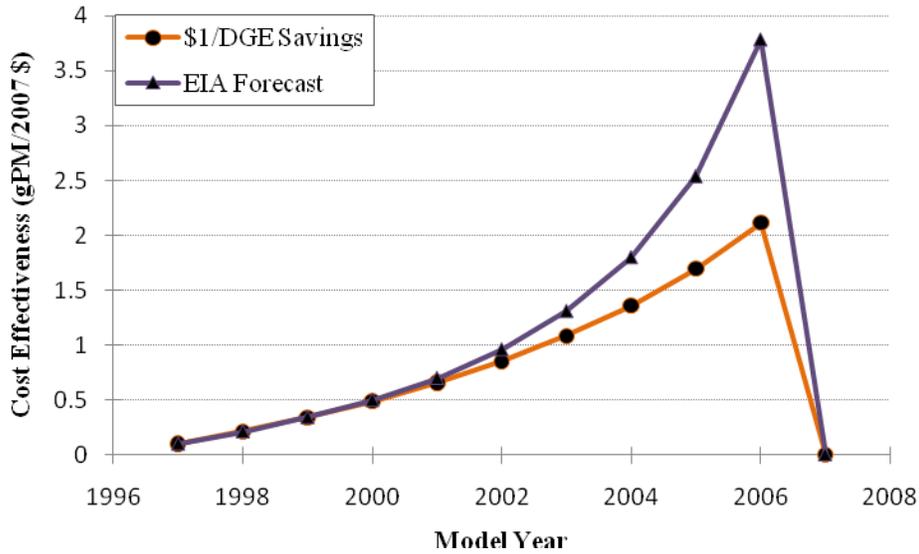
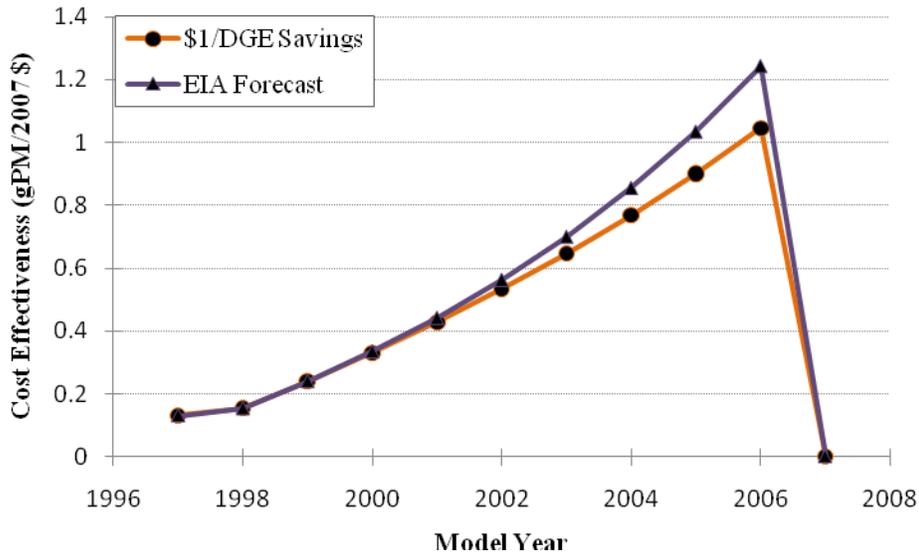


Figure 22: Long Term Cost Effectiveness of CNG Conversion of Class 6 Truck



Regardless of which fuel price forecast is used, cost effectiveness increases for newer vehicles up to model year 2006. The longer remaining life of these newer vehicles means both more emissions savings (due to more post-conversion miles) and lower net conversion cost (due to more post-conversion fuel usage). The increase in cost effectiveness for newer vehicles is more pronounced with EIA fuel price forecasts

because the EIA predicts the fuel price gap will grow in the future. Cost effectiveness drops to zero for model year 2007 vehicles because they already meet the 2007 PM standard, meaning no PM emissions improvement according to our assumptions. Even if a conversion could achieve a PM emission rate reduction on such vehicles, it would be negligible compared to that achieved on older vehicles. These results indicate that future CNG conversions should prioritize newer vehicles, so long as they are pre-2007 model year. Also, all else being equal, class 8 trucks should be prioritized over class 6 trucks because of their higher emission rates and fuel usage.

Unfortunately, it is likely that converting many NYS DOT vehicles will be infeasible. In the truck conversion project mentioned earlier in this section, BAF Technologies converted several NYS DOT vehicles running on International T444E and Cummins ISM11-305 engines (NYS DOT, 2007). BAF had completed testing required for certification before installing the fuel systems on NYS DOT vehicles, and found they met the 2007 PM standard (Darling, 2009). In order to legally convert a vehicle to operate on CNG, a vendor (often referred to as a “small volume manufacturer”) must have their alternative fuel system tested and approved by either the EPA or CARB, depending on the state. EPA certificates of conformity and CARB certifications are very narrow, approving the use a specific system on a specific test group of engine models. The certification process is not a matter of mere paperwork. It entails emissions testing, and costs both time and money. Furthermore, certifications expire yearly if not renewed (meaning that the vendor would no longer be permitted to install the fuel system on the applicable engines), but renewal does not require new testing data (US DOE, 2009). Nonetheless, this means that a conversion being performed before does not mean it will be legal to do so again. Natural Gas Vehicles for America maintains a list of natural gas engines and EPA/CARB certified retrofit systems, which was last updated on 11/30/09 (Yborra, 2009).

Performing widespread conversions on the NYS DOT fleet would likely prove highly impractical if not impossible, given certification obstacles and the tight timeframe of NYS DEC regulations. Even so, if a select group of vehicles would otherwise have to employ an active DPF, CNG conversion could prove to be a cost effective alternative, particularly if the vehicles are expected to remain in heavy use for more than 5 years.

Given certification and regulatory requirements, however, this question will need to be addressed on a vehicle by vehicle basis using detailed engine and duty cycle information which is not available at this time.

Even if CNG conversion does not make sense for any of NYS DOT's current fleet, purchasing new natural gas powered vehicles may prove to be a wise move, especially if EIA price projections prove correct and NYS DOT is able to increase the frequency with which drivers fuel up with natural gas. NYS DOT staff have indicated that the intention of the initial conversions was not to be the start of a wider conversion process as much as it was intended to demonstrate that natural gas powered heavy duty trucks could satisfy NYS DOT requirements. This could be a stepping stone to purchasing new natural gas powered vehicles. NYS DOT's Office of Fleet Administration and Support has made it a goal to eventually displace all diesel with LNG (NYS DOT, 2008).

#### *8.4 Benefits and Cost Comparison*

Retrofits, replacement, and CNG conversion were deliberately analyzed using comparable assumptions, to allow "apples to apples" comparison. For the comparisons in this section, the assumption of \$1/DGE savings from CNG is used. The costs of all options considered are plotted together in Figures 23 and 24 for class 8 dump trucks and class 6 stake trucks respectively.

Figure 23: Class 8 Dump Truck Long Term Costs/Vehicle

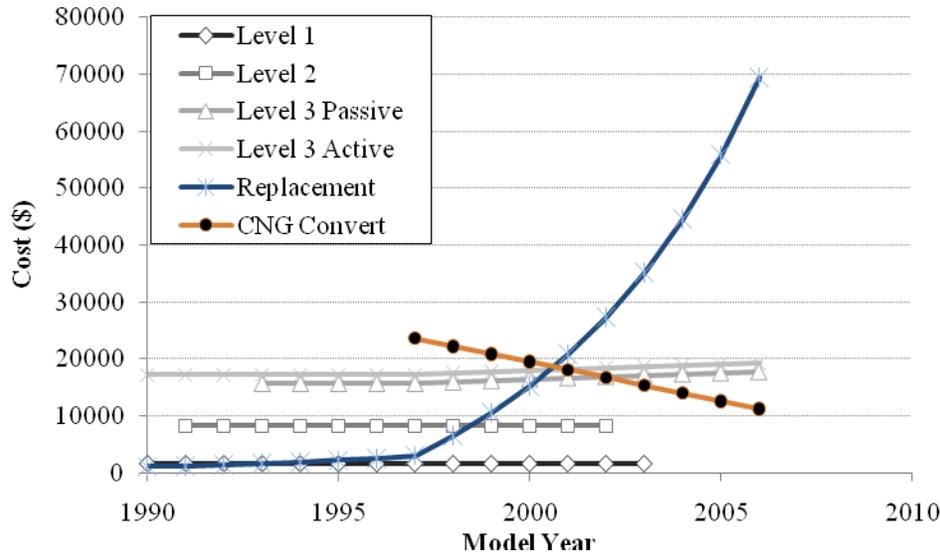
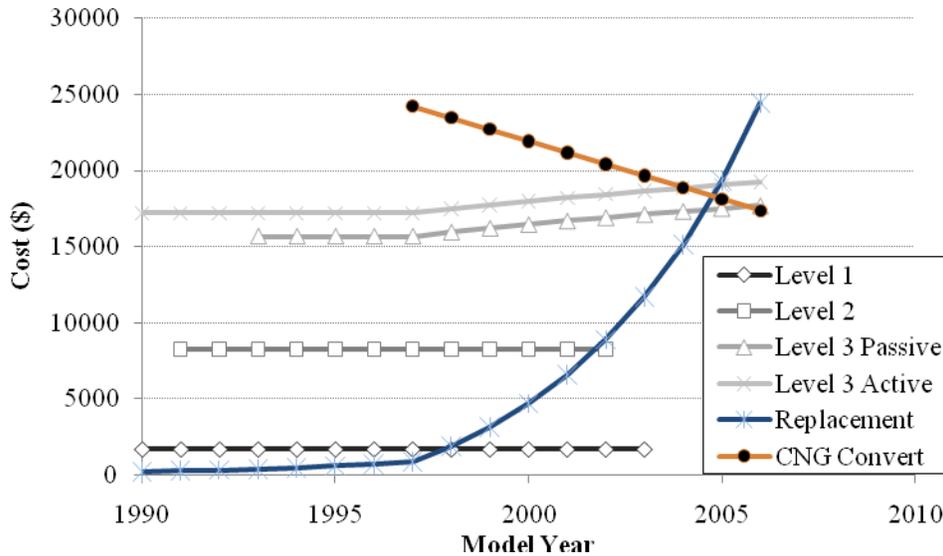


Figure 24: Class 6 Stake Truck Long Term Costs/Vehicle



Not surprisingly, level 1 retrofits are the cheapest option for all the trucks with more than a couple years of expected life left. For the oldest trucks of either type, it is cheaper in the long term just to replace the vehicle than to retrofit with any level technology. The value of the vehicle to NYS DOT is actually less than the cost of retrofitting, even with a DOC. Unsurprisingly, replacing the newest vehicles is the most

costly action. Unfortunately, there isn't a good cheap option for vehicles which are too new for level 1 DOCs. For class 8 dump trucks, CNG conversion is worth considering if an appropriate conversion kit is available. Class 8 dump trucks cost less to convert than class 6 stake trucks in the long term because they use more fuel and hence experience more fuel cost savings.

PM emissions prevented are plotted in Figures 25 and 26 for class 8 and class 6 trucks, respectively. CNG conversion offers the same benefits as replacement, which are the highest benefits possible. The benefits of level 3 technologies follow closely, with level 2 and 1 further behind. Class 6 diesel vehicles have lower emission rates to start with, leading to lower benefits.

Figure 25: Class 8 Dump Truck Emission Reductions/Vehicle

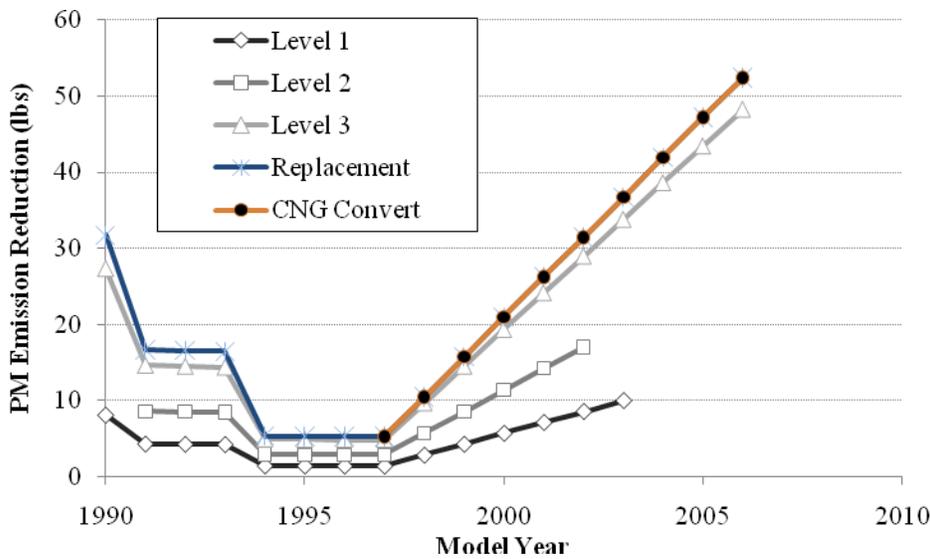
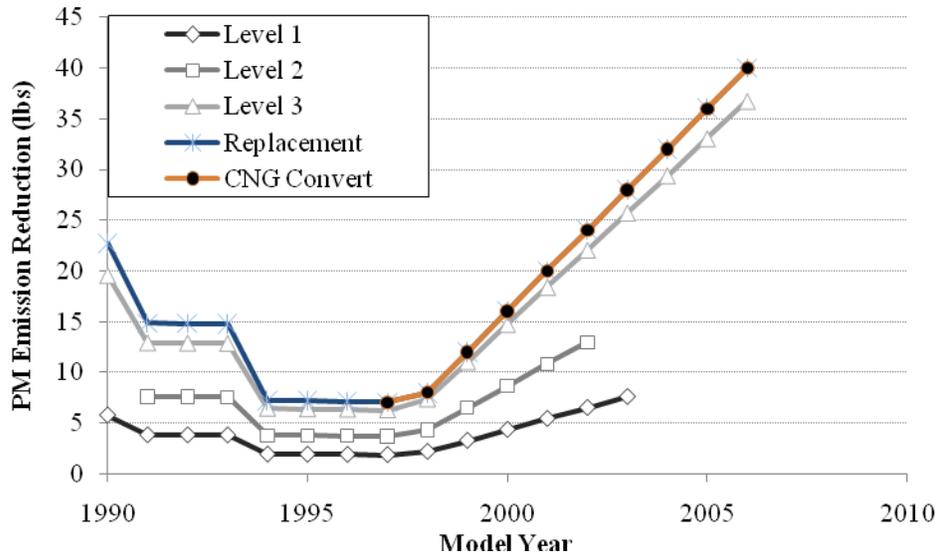


Figure 26: Class 6 Stake Truck Emission Reductions/Vehicle



The long term cost effectiveness curves for class 8 dump trucks and class 6 stake trucks are plotted in Figures 27 and 28. In the long term, the most cost effective way to reduce PM emissions is to replace the oldest class 6 stake trucks. The second most cost effective option is to replace the more valuable old class 8 dump trucks. Another relatively cost effective option is to install level 1 retrofits on relatively new class 8 dump trucks, starting with the newest which are compatible. Installing level 1 retrofits on new class 6 stake trucks is also decently cost effective, but less so than for the class 8 dump trucks, with their higher PM emission rates. It is generally more difficult to find cost effective methods of reducing PM emissions for vehicles too new for DOCs, or from the mid 1990's. CNG conversion may be the most cost effective option (as well as the cheapest) for the newest class 8 dump trucks, but this will have to be evaluated on a vehicle by vehicle basis because of the complexities discussed in Section 8.3.

Figure 27: Class 8 Dump Truck Long Term Cost Effectiveness Comparison

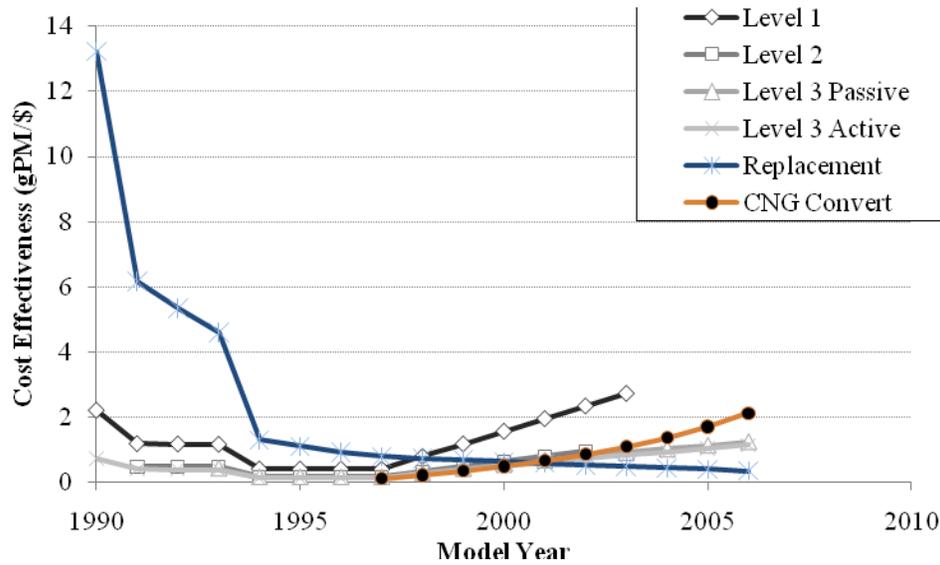
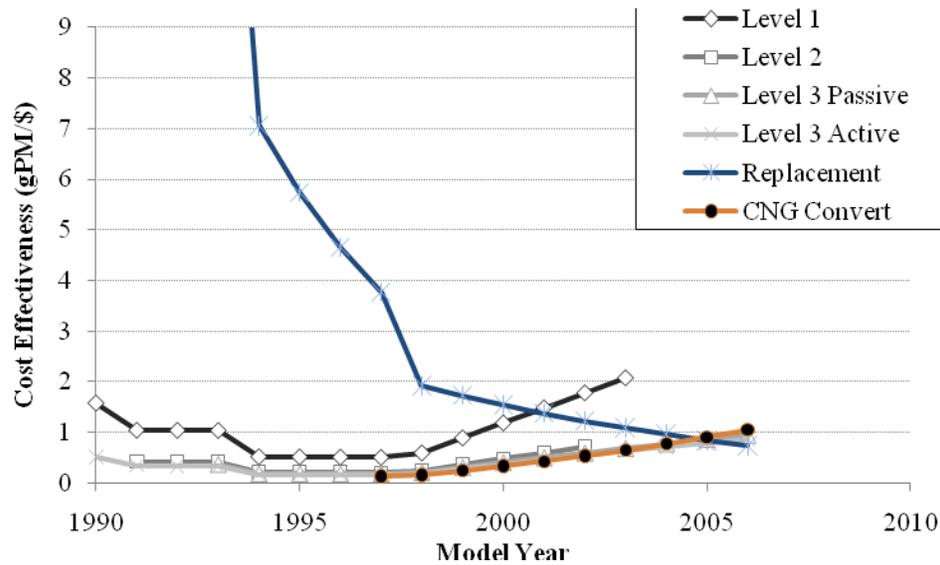


Figure 28: Class 6 Stake Truck Long Term Cost Effectiveness Comparison



## 9. Optimization Model and Sample Fleet Strategies

Several aspects of the emission reduction strategy decision facing NYS DOT make it well suited for an integer programming approach. If there was no difference between the long and short term costs of retrofits and replacements, it would be much

more straightforward to simply rank solutions by their cost. When one option costs less in the long term, but puts less strain on this year's budget, simple ranking becomes more difficult. Integer programming is able to balance long term and short term costs, while considering the fleet as a whole. Also, integer programming is designed to handle discrete decisions, meaning that we can retrofit 4 vehicles or 5 vehicles, but we cannot retrofit 4.381 vehicles. Many traditional optimization techniques have difficulty handling this kind of constraint.

### 9.1 Mathematical Model

The set  $I$  is the set of all vehicle types. Vehicles of the same type are assumed to have the same emission rates (before retrofits), retrofit compatibility, remaining usage, market value, and scrap value.

The set  $J$  is the set of all retrofit/replacement states. A vehicle may only be in one state, but a state may correspond to more than one retrofit technology (e.g. DOC and CCV combination). By treating combinations of diesel cleaning technologies as distinct states, technologies can influence each others' effectiveness in a nonlinear fashion, while maintaining a linear objective function and constraints (apart from integrality). This is important for solution methods discussed in the next section. Finally, the set  $J$  includes a default state which corresponds to no retrofits or early replacement.

The set  $P$  is the set of all pollutants being tracked (e.g. PM<sub>2.5</sub>, NO<sub>x</sub>).

The input parameters are:

$f_{ij}$	number of vehicles of type $i$ in state $j$ in initial fleet
$m_i$	remaining mileage for a vehicle of type $i$
$w_i$	remaining idle hours for a vehicle of type $i$
$e_{ijp}$	running emission rate (g/mile) of pollutant $p$ for vehicles of type $i$ in state $j$
$\varepsilon_{ijp}$	idle emission rate (g/hour) of pollutant $p$ for vehicles of type $i$ in state $j$
$c_{ijk}$	net present cost to switch vehicle of type $i$ from state $j$ to state $k$
$d_{ijk}$	initial cost to switch vehicle of type $i$ from state $j$ to state $k$
$u_{ijk}$	maximum number of vehicles of type $i$ that can be switched from state $j$ to state $k$

- $\rho_p$  required fraction reduction for pollutant  $p$   
 $B$  initial budget for retrofits and early retirements

The decision variables to solve for are:

- $r_{ijk}$  number of vehicles of type  $i$  switched from state  $j$  to state  $k$  (integer values only)

Only a non-negative number of vehicles can switch from state  $j$  to  $k$ . For any given switch, there is an upper bound which can be between 0 and the number of vehicles of type  $i$ . This can be used to enforce compatibility restrictions. These constraints are represented by expression (1).

$$0 \leq r_{ijk} \leq \mathbf{u}_{ijk} \quad \forall i \in I, j \in J, k \in J \quad (1)$$

Each vehicle in the initial fleet must be assigned a state (recall that there is a no action option where  $k = j$  meaning that the state is the same as before). This constraint is given by expression (2).

$$\sum_{k \in J} r_{ijk} = f_{ij} \quad \forall i \in I, j \in J \quad (2)$$

The emissions of each pollutant must be reduced by the fraction specified by  $\rho_p$ , as indicated in expression (3).

$$\sum_{i \in I} \sum_{j \in J} \sum_{k \in J} r_{ijk} (m_i \cdot e_{ikp} + w_i \cdot \varepsilon_{ikp}) \leq (1 - \rho_p) \sum_{i \in I} \sum_{j \in J} \sum_{k \in J} r_{ijk} (m_i \cdot e_{ijp} + w_i \cdot \varepsilon_{ijp}) \quad \forall p \in P \quad (3)$$

Certain retrofits or replacements may have high initial cost, followed by partial payback in the future (e.g. CNG conversion). Heavily employing such options could cause short term budget problems. The current budget is constrained by expression (4).

$$\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} r_{ijk} \cdot d_{ijk} \leq B \quad (4)$$

The objective is to minimize the net present value of the retrofit/replacement costs, given by expression (5).

$$\min \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} r_{ijk} \cdot c_{ijk} \quad (5)$$

The fleet being modeled is assumed to be small enough not to impact market prices with its purchases.

## 9.2 Solution Methods

Integer programs are a common mathematical tool in operations research. They are used in fields ranging from airline scheduling to facility location and supply chain management. Numerous algorithms have been developed to solve integer programs. These algorithms are often based on the general idea of “relaxing” integrality constraints, meaning that we temporarily forget that we can’t retrofit 0.728 vehicles. The resulting problem is referred to as a “linear program” and can be solved using the simplex algorithm, among others. If the solution to this relaxed problem doesn’t involve any partial retrofits or replacements, then it is a solution to our original problem. If there are partial retrofits or replacements, the relaxed problem is adjusted to avoid making the same mistake, and resolved. This process is not mathematically guaranteed to find an optimal solution quickly, but in practice it often works quite well, even with problems involving hundreds of thousands of variables.

The integer program described in Section 9.1 was coded into AMPL, which is a specialized algebraic modeling language originally developed by Bell Laboratories.

Scripts written in AMPL can be run within the AMPL environment. AMPL is available for purchase from ILOG (an IBM company) (IBM, 2009). AMPL can call a variety of “solvers” to find solutions to mathematical problems coded into the AMPL language. Some solvers are open source and freely available to certain users, while others are only available for purchase. Solvers are frequently designed for specific categories of problems, meaning that a single solver might not suffice for every type of problem.

Vehicle retrofit/replacement problems were solved successfully using the CPLEX solver. CPLEX is a solver which was designed to work with AMPL. CPLEX is commonly used to solve challenging integer programs, which makes it a sound choice for the retrofit/replacement model. Like AMPL, it is available from IBM (IBM, 2009). In our experience, CPLEX is a very reliable solver for integer programs.

### *9.3 Case Study on Sample Fleet*

In general, input parameters are from the same sources used for the cost-benefit analysis in Section 8. One major difference is that instead of assuming a single typical annual mileage, multiple usage patterns are considered. The sample fleet is composed of 68 vehicles. There are 2 class 8 and 2 class 6 trucks from each model year from 1990 to 2006. One in each pair is a high mileage (16,000 miles/year), while the other is low mileage (8,000 miles/year). In addition, idle times are added. Based on typical workzone idling practices, discussed in Section 10, heavy duty trucks are assumed to idle 160 hours per year in workzone protection. Additional idling of 20 hours per year is added for a total of 180 hours/year for class 8 trucks. This assumption was checked with the idle time found on two engine control module readings. Class 6 trucks are assumed not to idle in workzone protection.

Idle and running emission rates for unretrofitted vehicles are from the EPA’s MOBILE software. The emissions impacts of verified retrofit technologies are from EPA and CARB verified technology lists. CNG conversion is treated as a retrofit in the model, and the associated emission rates are assumed to match those of a 2007 model year diesel truck.

The cost assumptions match those used in Section 8. Initial and long term costs are tracked separately. The distinction between the two for vehicle replacement is the

same as in Section 8. For DOCs and FTFs, initial and long term costs are the same. For PDPFs and ADPFs, the long term cost includes discounted cleaning costs discussed in Section 8, while the initial cost does not. For CNG conversion, the initial cost is not adjusted to account for future fuel savings, while the long term cost is.

Retrofit compatibility is treated the same way as in Section 8, meaning that retrofits are considered as options based on a generous reading of compatibility. Basic limitations, such as model year and EGR, are applied, while others such as exhaust temperature profiles are left out. The intention behind this approach is to gather information on cost effectiveness for retrofits which are broadly conceivable.

The integer program was set to minimize the long term cost, given a range of PM percent reduction targets. The integer program developed a long term cost minimizing strategy for every percent reduction from 1 to 87. Reducing PM emissions from the sample fleet by 88% or more was determined to be impossible. The long term and initial costs of meeting the reduction goals are plotted in Figure 29 and 30, respectively. In general, higher targets cause both higher long term and initial costs, but in some cases long term costs can increase while initial costs decrease. This could occur when switching from a strategy with high up-front costs and future savings, to one with lower up-front cost and lower future savings.

**Figure 29: Long Term Cost to Meet PM Reduction Targets for Sample Fleet**

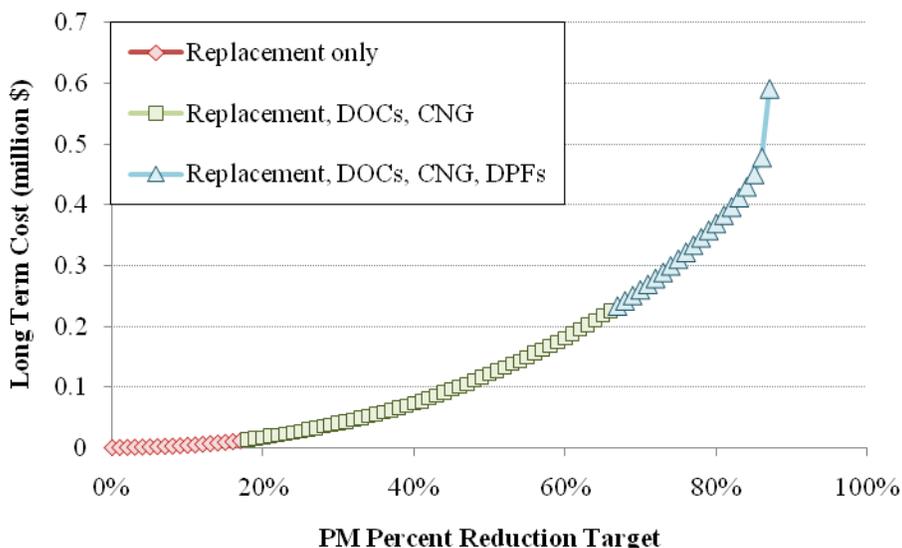
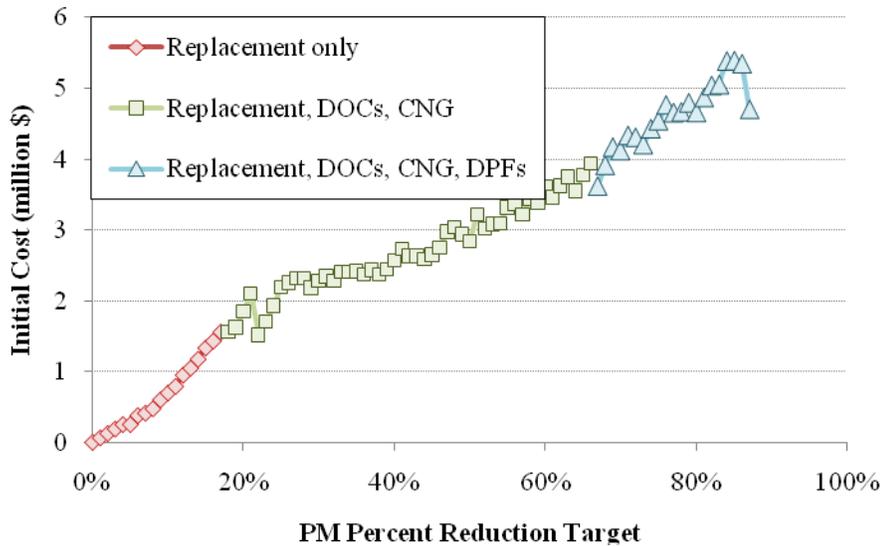


Figure 30: Initial Cost to Meet PM Reduction Targets for Sample Fleet



Up to a reduction of 17%, the long term cost minimizing strategies only replace old vehicles. These replacements start with the oldest class 6 high usage trucks. Lower usage and newer class 6 trucks come next, followed by high usage class 8 trucks and eventually low usage class 8 trucks. At a reduction target of 18%, DOCs begin to be included in the strategies selected. The DOCs are applied to relatively new high usage class 8 trucks first, followed by new high usage class 6 trucks, with lower mileage trucks coming later. At a reduction of 22%, CNG conversion first enters the strategy. This CNG conversion is conducted on the model year 2006 high usage class 8 truck. As the reduction target continues to increase, the bulk of the actions taken remain replacements and DOC installations, with occasional CNG conversions conducted on relatively new high usage trucks. Particulate filters don't become a part of picture until the reduction target hits 67%. The first filters are installed on relatively new low usage class 8 trucks. The new high usage class 8 trucks are being converted to CNG at this point.

These model results reinforce the key findings of the cost benefit analysis in Section 8. The model results also add some insights on the effect of varying usage levels. In general, both retrofits and replacements are more cost effective on higher usage trucks, as they emit more (and in the case of CNG experience greater fuel cost savings). When reducing PM at minimum long term cost, start with replacing the oldest vehicles,

especially those with relatively low value. Next, apply DOCs, starting with relatively new high usage vehicles. Third, consider CNG conversions where feasible. Finally, if these actions are not enough, consider DPFs, starting with newer vehicles not converted to CNG.

## **10. LED Technology and Emission Reduction**

Although not a CARB or EPA verified retrofit technology, and therefore not considered BART under NYS DEC regulations, LED lights have the potential to reduce idling time, and therefore emissions. The potential of LED lights to reduce idling and therefore emissions has been recognized by state and local officials, and there is precedent for CMAQ funding. The potential for emissions prevention is particularly pronounced for heavy dump trucks which idle around construction sites to protect workers. The primary reason for idling as opposed to parking is to keep lights flashing without draining the battery.

When idling for work zone protection, a truck will often have as many lights flashing as possible, including those on the truck (e.g. brake lights, rotating beacon) as well as those on the attenuator. NYS DOT has a highly heterogeneous set of attenuators. Some attenuators have only a few tail lights, while others come with a complete arrow board. Some newer models use LEDs, while many older models do not.

NYS DOT often chooses newer trucks when mounting attenuators, because of the time required to weld an attenuator mount to a truck frame. This can have the impact of limiting the potential idle emissions, as newer vehicles have dramatically lower emission rates for many pollutants (as shown in Figures 31-32). Attenuators can still be used with relatively old trucks, however, because the attenuator mounts could have been installed when the trucks were new.

Figure 31: Class 8 Truck PM2.5 and NMHC Idle Emission Rates

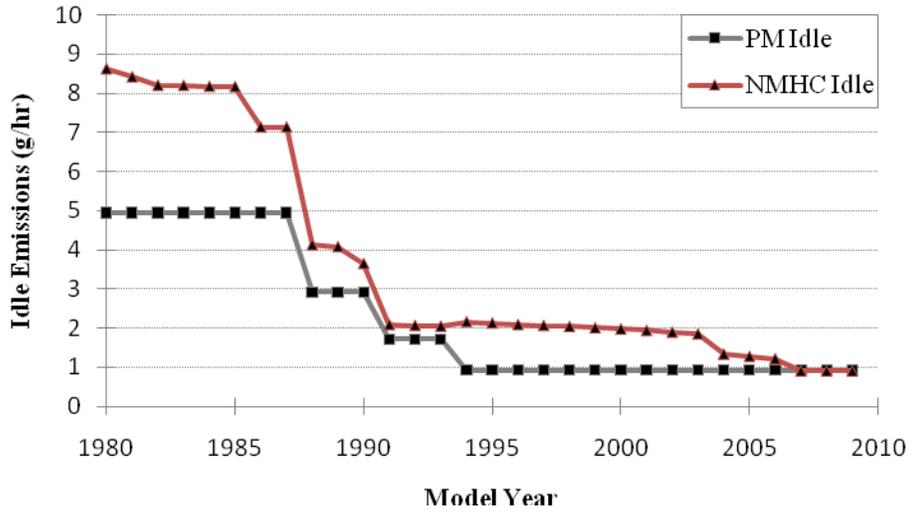


Figure 32: Class 8 Truck NO<sub>x</sub> and CO Idle Emission Rates

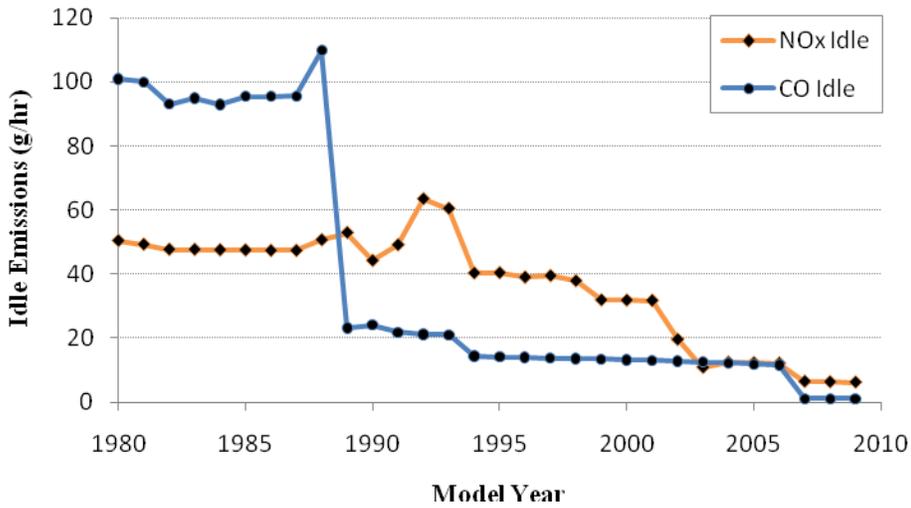
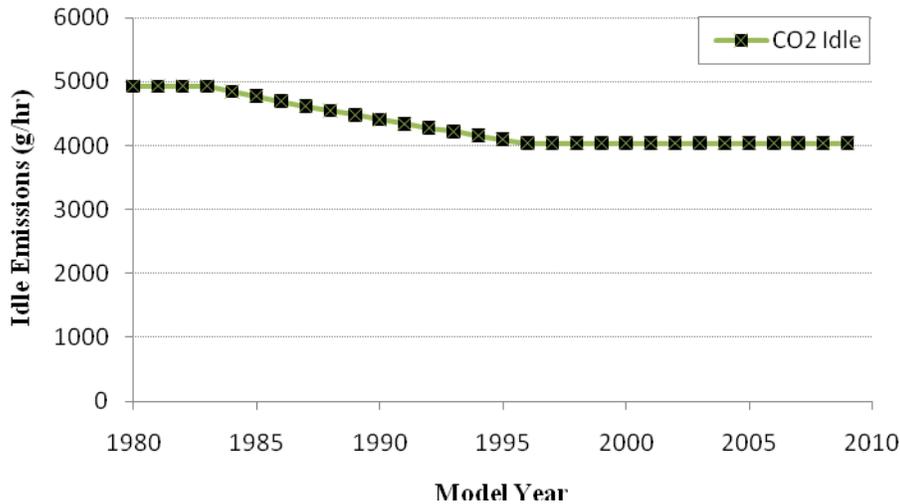


Figure 33: Class 8 Truck CO<sub>2</sub> Idle Emission Rate



All of the emission rates in Figures 31-33 are based on a 2010 year of operation, using ULSD. MOBILE6.2 provides PM<sub>2.5</sub> idle emission rates directly, while gaseous idle emission rates are computed from running emission rates using an assumed speed of 2.5mph, as recommended by EPA staff (Brzezinski, 2008).

Given these emission rates, how large would the emission savings be if a truck was able to avoid idling at work zones for an entire summer season? The average weekly deployment of a heavy truck with attenuator is 4 times a week for 4 hours per instance, during summer operation (Spadaro, 2009). If ten weeks of this idling is eliminated, the emissions savings would be that plotted in Figures 34-36, as a function of the truck's model year.

Figure 34: Annual PM<sub>2.5</sub> and NMHC Idle Emission Savings per Vehicle

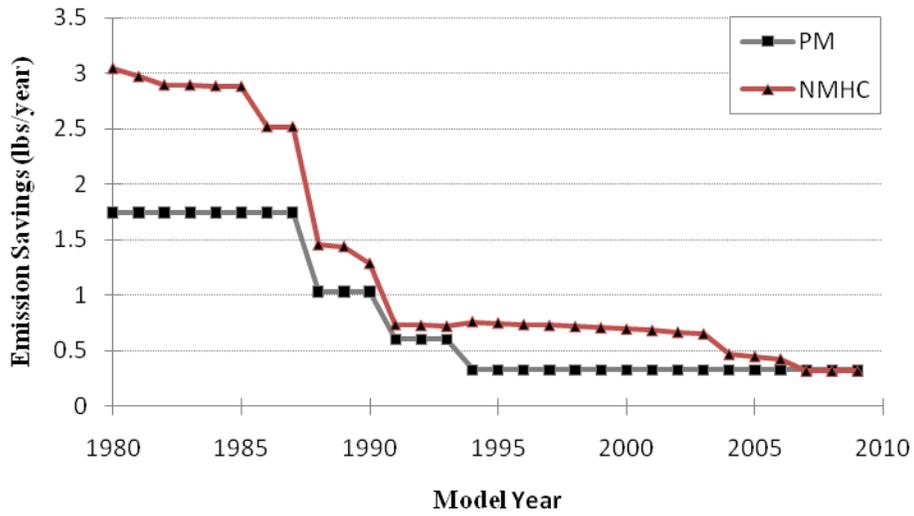


Figure 35: Annual NO<sub>x</sub> and CO Idle Emission Savings per Vehicle

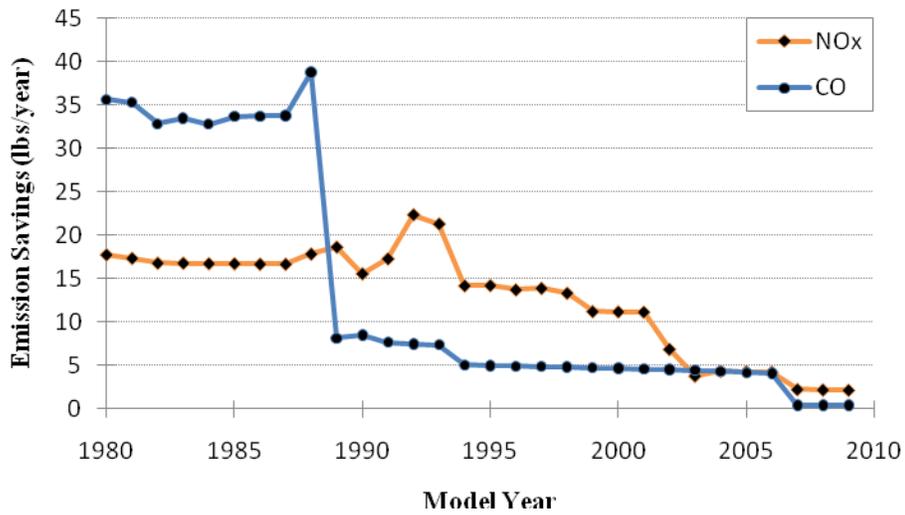
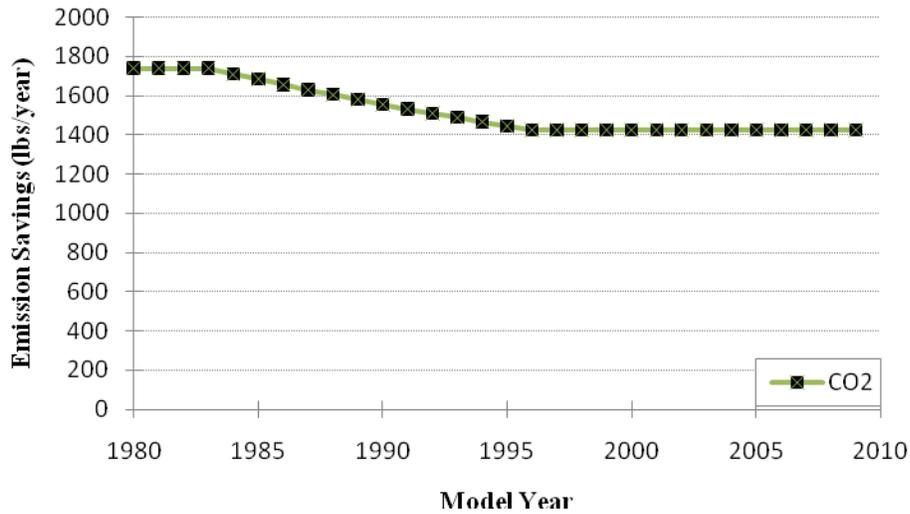


Figure 36: Annual CO<sub>2</sub> Idle Emission Savings per



Vehicle

The savings presented in Figures 34-36 can be compared to emission savings from a typical DOC, to provide a sense of perspective. For 1994-2006 model year class 8 trucks, not idling for one summer provided comparable PM<sub>2.5</sub> savings to driving just over 3,000 miles with a DOC that reduces PM<sub>2.5</sub> by 25%. NYS DOT large dump trucks average substantially more than 3000 mileage of usage per year, though region 10 (Long Island) has average mileage accumulation much closer to 3,000 than the rest of the state. The result is that installing a DOC can generally be expected to provide greater PM<sub>2.5</sub> reduction than the elimination of work zone idling by the same vehicle. The PM<sub>2.5</sub> reductions achieved from work zone idling reduction will naturally be lower for trucks already outfitted with DOCs, because DOCs lower their PM<sub>2.5</sub> emission rate. Eliminating idling does have other emission benefits, however, such as NO<sub>x</sub> and CO<sub>2</sub> reduction, which is not associated with the use of a DOC.

Unlike most emission reducing retrofits, LEDs that reduce idling offer fuel savings to offset the installation cost. A 2004 model year truck operating at the average weekly deployment for the summer would save roughly 63 gallons of diesel by not idling. Fuel efficiency has not changed nearly as dramatically as emission rates in recent history, so the number would be comparable for trucks of similar age. At \$3/gal, this is an annual savings of \$190.

The cost of replacing lights with LEDs would inevitably vary substantially across the heterogeneous trucks and impact attenuators. A new LED “rotating” beacon costs a few hundred dollars (PSE Amber, 2008), while entirely replacing an impact attenuator can easily cost over \$15,000. In situations where only the former is required, the retrofit would clearly be cost effective, while in the latter case it would not. Most cases are somewhere between the two. NYS DOT staff can evaluate the cost effectiveness using the cost for the particular vehicle, as well as the emission benefits summarized in this report.

The primary risk associated with running lights off the battery is, of course, that the battery will become too drained to restart the truck. Class 8 trucks can be more difficult to jump start than a typical car. Even if LEDs reduce power consumption enough to run lights off the battery much of the time, there could quite possibly be longer deployments for which running off the battery would be too risky. According to a NYS DOT staff member, guardrail repair might only take a couple hours, while clearing an accident scene could take 8 to 10 hours. NYS DOT has already begun testing LED and standard lighting by running them off battery for 6 hours, and then restarting the vehicle. For both the Ford F650 tested on 9/29/08 and the Mack with attenuator tested on 10/16/08, the vehicles were able to restart without a problem. The results are promising, but there still may be some idle situations in which the vehicle cannot be trusted to restart. It will be important to develop practices based on further tests, and on operator experience.

LED lights have received a fair amount of attention from other state DOTs, including several which operate in similar climates to NYS DOT. These states include Colorado, Idaho, Minnesota, Vermont, Washington, and Wisconsin (Stidger, 2003; CTC & Associates, 2003). Idaho uses LED taillights on all its plows, while Colorado puts LEDs on the wingtips of plows (Stidger, 2003).

In addition to putting LEDs on the wingtips of plows, Vermont made the LEDs standard new vehicle equipment for body marker, ICC lights, stop/tail/directional, and rear corner post strobes, all before 2003 (CTC & Associates, 2003). George Combes, Superintendent of the Vermont DOT, cited lower amperage draw as the primary reason, but also noted lower maintenance costs (especially where there is a lot of vibration).

Curt Gegoux, Northwest Region Equipment Superintendent for the Washington State DOT, was quoted in a 2003 report as saying “the jury is still out regarding [LED] longevity and overall cost saving,” (CTC & Associates, 2003) but responded to a 2008 email by declaring that “The jury is no longer out. We believe that with the cost of fuel, vehicle longevity concerns, the cost of LED technology declining, and the cost of emissions, our overall cost savings (tangible and intangible) will be well worth the effort and investment.” Washington state DOT established a statewide “no idle” policy which allows idling for halogen warning lights, but they believe that LED lighting will not require idling (Gegoux, 2008). Washington DOT received \$1.5 million in CMAQ grant money to pay for LED conversions, as well as diesel exhaust retrofits (Puget Sound Regional Council, 2009). NYS DOT may want to look into federal grant opportunities. The fact that LED technology is not included in NYS DEC regulation might make federal grant managers more likely to fund it.

There are numerous vendors of LED products appropriate for DOT applications, and this report does not endorse any. Washington State DOT planned to use Whelen Engineering for mini LED light bars and beacons, at least initially. They planned to use Superior Signal Inc. for LED arrow boards (Gegoux, 2008). Vermont DOT uses Whelen Engineering as well. George Combes, Superintendent of the Vermont DOT, said that they have “an excellent working relationship” and emphasizes the importance of Whelen allowing them to field test lights (CTC & Associates, 2003).

In academia, John Bullough at RPI is a leader in evaluating LED technology. He has conducted multiple studies on various applications (ranging from traffic lights to snow plows), including work with the NYS DOT on snow plow visibility. He has been quoted as saying “For applications like brake lights and turn signals, it seems a ‘no-brainer’ in the sense that LED devices tend to be much more efficient and long-lasting than the filtered incandescent lamps they would replace.” (CTC & Associates, 2003)

## **11. Retrofit Impacts on Vehicle Operation, Maintenance, and Warranties**

### *11.1 Impacts on Operation and Maintenance*

This section will address changes in vehicle operation and maintenance resulting from retrofits, excluding operation and maintenance of the retrofit technology itself.

Operation and maintenance of the retrofit technology, including topics such as regeneration and de-ashing, is covered later in Section 12.

Fleet managers were surveyed regarding changes in maintenance as a result of recently performed retrofits. None of the fleet managers reported any impact on vehicle maintenance. Fleet managers responding included those from Washington DOT (had installed DOCs) (Stinton, 2009), LA County (had installed PDPFs and ADPFs) (Nunez, 2009), County of Contra Costa (had installed PDPFs) (Ranger, 2009), and DCNY (had installed PDPFs) (Kim, 2009).

There is concern that some diesel retrofits, especially DPFs, can increase fuel consumption. A guide to diesel retrofits in construction published by the Massachusetts Department of Environmental Protection states that passive DPFs may increase fuel use by 1-3%, while filters which use diesel fuel injection may increase fuel use by up to 7% (M DEP, 2008). The EPA also provides estimates of the fuel efficiency penalty for numerous retrofits, with some reaching up to 7% (US EPA, 2009). Herner et al. (2009) tested four different DPFs using a chassis dynamometer and did not find a fuel penalty.

The authors of this report asked fleet managers across the country whether they witnessed fuel usage changes after retrofits. Some stated that they had heard about the potential for fuel efficiency reductions, but none had actually witnessed any personally. These fleet managers had installed DOCs as well as active and passive DPFs. Not all fleet owners had been tracking fuel efficiency and looking for changes. It is completely possible that small changes in fuel efficiency due to retrofits could be masked by normal fluctuations due to varying duty cycles and seasonal fuel blends. Apart from fuel composition changes (e.g. PuriNOx) and filters which inject diesel fuel, any fuel efficiency penalties are likely to be minor.

Filters which burn diesel fuel to promote regeneration may be marketed as either active or passive. Cleaire describes the Vista as an active filter (Cleaire, 2010a). It burns fuel when the engine is off (Cleaire, 2009b). Although considered “passive” by Cleaire (2010b), the Longview does inject fuel into the exhaust stream to promote regeneration while the engine is running (Cleaire, 2009a). The manual estimates a 3-5% increase in fuel consumption (Cleaire, 2009a).

## 11.2 Impacts on Warranties

CARB has established warranty requirements as part of its verification process. All applicants must include a statement written by CARB in the owner’s manual (CARB, 2009g). This statement includes a clause which promises that if any emission related part of the diesel control system is defective (in design, materials, workmanship, or operation) causing the system to fail to meet its verified performance level within the warranty period, the applicant must repair or replace it (including parts and labor) (CARB, 2009g).

The CARB statement also includes coverage of damage to the engine resulting from retrofit failure. The precise wording is as follows (CARB, 2009g):

In addition, (applicant’s name) will replace or repair the engine components to the condition they were in prior to the failure, including parts and labor, for damage to the engine proximately caused by the verified diesel emission control strategy. This also includes those relevant diagnostic expenses in the case in which a warranty claim is valid. (Applicant’s name) may, at its option, instead pay the fair market value of the engine prior to the time the failure occurs.

CARB establishes minimum warranty periods for its verified retrofits, which depend on the application and engine size. They are outlined in Table 7 (CARB, 2009g).

Table 7: CARB Minimum Warranty Periods

Application	Engine Size	Minimum Warranty Period (whichever comes first)
On-Road	Light heavy-duty, 70 to 170 hp, Gross Vehicle Weight Rating (GVWR) less than 19,500 lbs.	5 years or 60,000 miles
	Medium heavy-duty, 170 to 250 hp, GVWR from 19,500 lbs. to 33,000 lbs.	5 years or 100,000 miles
	Heavy heavy-duty, exceeds 250 hp, GVWR exceeds 33,000 lbs.	5 years or 150,000 miles
	Heavy heavy-duty, exceeds 250 hp, GVWR exceeds 33,000 lbs., and the truck is: 1. Typically driven over 100,000 miles per year, and 2. Has less than 300,000 miles on the odometer at the time of installation.	2 years, unlimited miles

Off-Road	Under 25 hp, and for constant speed engines rated under 50 hp with rated speeds greater than or equal to 3,000 rpm	3 years or 1,600 hours
	At or above 25 hp and under 50 hp	4 years or 2,600 hours
	At or above 50 hp	5 years or 4,200 hours

The CARB statement also includes a portion on the vehicle owner’s responsibilities, which include performing maintenance required by the owner’s manual, and keeping records of said maintenance (such as receipts). Warranty coverage might be denied if maintenance is not performed or records are not kept (CARB, 2009g). The warranty might also be voided if the warranty registration card is not filled out and mailed in promptly after installation (Donaldson, 2004).

NYS DOT had expressed particular concern that existing warranties might be invalidated by installing retrofits. Retrofit manufacturers were contacted and asked if they could provide written certification that their products won’t void existing warranties. Some did not state in writing that existing warranties would not be voided. Darrell Trueman of Engine Control Systems did state in an email “Our products have no impact on OEM warranties.” (Trueman, 2010) Marty Lassen of Johnson Matthey provided further explanation “The bottom line is that it is illegal for an OE to void his warranty for their engine if a retrofit device is added. To do so is a restraint of trade.” (Lassen, 2010)

Lassen provided a “Letter of ‘No Objection’” from Mark Craig at Caterpillar (Craig, 2002). The letter states that Caterpillar does not object to the use of aftertreatment devices such as oxidation catalysts and particle traps on its highway truck engines, given that emissions (regulated and unregulated) do not increase, and total exhaust system backpressure does not exceed specifications. Naturally, Caterpillar recommends Caterpillar filters, but Craig states plainly “When auxiliary devices, accessories, and/or consumables (filters, oil, and fuel additives, synthetic oil, catalyst, etc.) made by other manufacturers are used on Caterpillar products, the Caterpillar warranty is not affected simply because of their use.” (Craig, 2002) Craig goes on to say “The Caterpillar Warranty continues to cover defects caused by our material and workmanship. Failures resulting from the installation or usage of other manufacturers products are not

Caterpillar factory defects, and, therefore, are not covered by Caterpillar warranty.” (Craig, 2002) Lassen stated that there were comparable letters from other engine manufacturers (Lassen, 2010).

Retrofit manufacturers were quick to defend the reliability of their products. Darrel Trueman of Engine Control Systems said “There are no reported incidents of engine damage related to ECS or our competitors emission control products.” (Trueman, 2010) Tom Swenson of Cleaire pointed out that as of January 12<sup>th</sup>, 2010, they have had very few progressive damage claims, and not a single case in which engine damage turned out to be caused by the retrofit (Swenson, 2010).

Engine and vehicle manufacturers were also asked directly whether verified retrofits would void their warranties. Not all manufacturers responded, but those responses received supported the general findings discussed above. Brian Grozier of Ford said “if the emission component causes damage to the engine, then the answer would be there would be no coverage of the existing warranty. If the component was not at fault then there would be coverage.” (Grozier, 2010) Gary Bigness of Cummins stated “it is my understanding that the vehicle is not impacted by the devices therefore nothing changes the warranty.” (Bigness, 2010)

## **12. Retrofit Maintenance Procedures**

Manuals and parts lists were requested from manufacturers and compiled. These will be forwarded to NYS DOT. It is important to utilize the product specific manual when operating and maintaining a given retrofit technology. This section contains summaries of common themes found in manuals for technology categories. It is intended only as an introduction to the operation and maintenance requirements of the different technologies. In general, it is important to keep records of maintenance performed, including receipts, in order to avoid invalidating warranty claims (CARB, 2009g). From DOCs to ADPFs, the manuals also make it clear that applicable laws must be followed, including those regarding disposal of any ash cleaned from retrofit devices (e.g. Donaldson, 2004; Engine Control Systems, 2008)

### *12.1 Crankcase Filters*

Crankcase filters are intended to have little to no impact on day to day activity. The manual for the Donaldson Crankcase Filtration System (Donaldson, 2009b) reminds users to monitor the filter change indicator frequently, and to change the filter when required. It warns not to attempt to clean the filters. Some crankcase filtration systems use a catch bottle for oil drain, while others use the engine sump. If a bottle is used, it will need to be emptied periodically. Engine blow-by flow rate should be tested before installation, and retested annually to ensure it remains within system specifications. When conducting scheduled maintenance, also inspect the crankcase filtration system. In particular, look for leaks, cracks, and loose connections (Donaldson, 2009b).

### *12.2 Diesel Oxidation Catalysts*

Of the tailpipe retrofits, DOCs generally have the lowest impact on operations and maintenance. The manual for Donaldson DOC Mufflers (Donaldson, 2004) warns users to be careful regarding lube oil. Low ash lube oil should be used, and lube oil should not be blended into the fuel. Lube oil consumption should be monitored to ensure it is not being consumed faster than engine manufacturer specifications indicate. Failing to follow these rules can cause deposits in the DOC which increase backpressure, voiding the engine warranty. In general, no unapproved additives should be blended with fuel (Donaldson, 2004).

It is important to be on the watch for plugging. Decreasing fuel economy can be an indication of plugging. If plugging is suspected, backpressure should be tested by installing a manometer or backpressure gauge near the DOC inlet. If necessary, the DOC can be removed and cleaned with compressed air (Donaldson, 2004). The manual for Engine Control Systems AZ Purifier and Purimuffler (Engine Control Systems, 2007) states that most purifiers installed on newer, well maintained engines will never require cleaning. Both the Donaldson and Engine Control Systems manuals warn that long periods of idling can cause plugging. Users should be vigilant for excessive blue or black smoke, which indicates an engine problem exists which could negatively impact DOC

performance, as well as strong odors, which can also indicate an engine problem, or the need for DOC cleaning (Engine Control Systems, 2007).

When conducting scheduled maintenance, also inspect the DOC. In particular, look for leaks, cracks, loose connections and problems with mounting brackets (Donaldson 2004).

### *12.3 Flow Through Filters*

Only one relevant flow through filter was found, and it's operational and maintenance requirements closely resembled those of a DOC. The manual for Donaldson Diesel Multi-stage Filter (DMF) Muffler (Donaldson, 2006) also warns users to be careful regarding lube oil. Low ash lube oil should be used, and lube oil should not be blended into the fuel. Lube oil consumption should be monitored to ensure it is not being consumed faster than engine manufacturer specifications indicate. Failing to follow these rules can cause deposits in the FTF which increase backpressure, voiding the engine warranty. In general, no unapproved additives should be blended with fuel (Donaldson, 2006).

As with a DOC, plugging can occur, though routine maintenance is not typically required. In the case of suspected plugging, backpressure should be tested by installing a manometer or backpressure gauge near the FTF inlet. If necessary, the FTF can be removed and cleaned with compressed air (Donaldson, 2006).

When conducting scheduled maintenance, also inspect the FTF. In particular, look for leaks, cracks, loose connections and problems with mounting brackets (Donaldson 2006).

### *12.4 Passive Diesel Particulate Filters*

Passive diesel particulate filters generally require significantly higher maintenance than DOCs or FTFs. A backpressure indicator light indicates when a cleaning is needed (Engine Control Systems, 2006; Cleaire, 2009a; Donaldson, 2009c). Sometimes, an additional light will give a warning one week ahead of time (Donaldson, 2009c). Manuals indicate that cleanings are needed at least yearly, and sometimes more often for heavily used vehicles (Engine Control Systems, 2006; Cleaire, 2009a;

Donaldson, 2009c). Ash cleanings can require specially designed and approved equipment, in order to avoid invalidating warranties (Donaldson, 2009c). Extended idling can cause plugging (Donaldson, 2009c).

As with other retrofits, owners should be on the lookout for unusual emissions or odors, as these can indicate engine problems. Particulate filters can be very sensitive to engine problems, especially those which could create oil leaks, as these can cause excessive temperatures in the filter. If turbo is lost, the engine should be shut off as soon as possible (Cleaire, 2009a).

Although considered “passive” by Cleaire (2010b) the Longview does inject fuel into the exhaust stream to promote regeneration (Cleaire, 2009a). The fuel pump should be checked, and the filter replaced, at least once per year or after 50,000 miles. The system should also be checked if fuel usage spikes (Cleaire, 2009a).

Passive DPFs have similar requirements to DOCs and FTFs when it comes to lube oil and fuel additives. Low ash lube oil should be used, and lube oil should not be blended into the fuel. Lube oil consumption should be monitored to ensure it is not being consumed faster than engine manufacturer specifications indicate. In general, no unapproved additives should be blended with fuel (Donaldson, 2009c).

When conducting scheduled maintenance, also inspect the DPF. In particular, look for leaks, cracks, loose connections and problems with mounting brackets (Donaldson 2009c; Cleaire, 2009a). In addition to keeping maintenance records, owners can be expected to keep records of backpressure measurements as well (Engine Control Systems, 2006).

### *12.5 Active Diesel Particulate Filters*

Active diesel particulate filters generally require more maintenance than any other kind of exhaust system retrofit. In addition to de-ashings, they must be actively regenerated relatively often. Backpressure lights indicate the need for regeneration, with an additional light sometimes providing a couple of days advance notice (Engine Control Systems, 2008; Cleaire, 2008, 2009b). If the light begins flashing soon after regeneration, the filter might need de-ashing, as described in the passive DPF subsection (Cleaire, 2009b). Regeneration of the technologies for which manuals were obtained takes between

2 and 5 hours, with the fuel burning regeneration of the Cleaire Vista being the fastest of the technologies for which manuals were obtained (Engine Control Systems, 2008; Cleaire, 2008, 2009b). When regenerating a filter, it is important to park in a well ventilated area which is far from combustible materials (e.g. tall grass) (Cleaire, 2009b). Engine Control Systems recommends a proactive regeneration schedule based on data logging (Engine Control Systems, 2008). This gives the user more control over when regenerations take place, hopefully avoiding work disruptions.

Manuals list many inspections and other actions to be conducted regularly. Intervals vary from once a year to at every ash-cleaning or at every oil change. These include general inspections of hardware, electrical, and air lines, as well as checking the backpressure monitor and logger are working correctly, inspecting the water trap and filter in the backpressure monitor, and cleaning if necessary (Engine Control Systems, 2008). Make sure turn out stacks or rain caps are functioning properly, to prevent water from entering vertical stacks (Cleaire, 2008, 2009b). Mileage should be recorded and backpressure data should be downloaded and reviewed for evidence of changes in duty cycle or faults in the system (Engine Control Systems, 2008; Cleaire, 2008, 2009b). Smoke opacity measurements might be required as well (Engine Control Systems, 2008). Any air or fuel pumps should be inspected, and their filters replaced (Cleaire, 2008, 2009b). New sealing gaskets may need to be installed (Engine Control Systems, 2008).

As with other retrofits, owners should be on the lookout for unusual emissions or odors, as these can indicate engine problems. Particulate filters can be very sensitive to engine problems, especially those which could create oil leaks, as these can cause excessive temperatures in the filter. If turbo is lost, the engine should be shut off as soon as possible (Cleaire, 2008, 2009b).

Active DPFs have similar requirements to DOCs, FTFs and PDPFs when it comes to lube oil and fuel additives. Low ash lube oil should be used, and lube oil should not be blended into the fuel. Lube oil consumption should be monitored to ensure it is not being consumed faster than engine manufacturer specifications indicate. In general, no unapproved additives should be blended with fuel (Cleaire, 2008, 2009b).

### 13. New York State Area Distributors and Lead Times

#### 13.1 New York State Area Distributors

Retrofit manufacturer websites typically include a section labeled “dealers” or “distributors” or “partners” which lists appropriate businesses and their contact information. When these lists were not found, or not clear (e.g. possibly distributors of company products other than retrofits), the retrofit manufacturer was contacted for more information. The resulting distributor list, broken down by retrofit manufacturer, is provided in Table 8.

Table 8: Retrofit Distributors in New York Area

<b>Cleaire</b>				
<i>Company</i>	<i>Address</i>	<i>Phone</i>	<i>E-mail</i>	<i>Website</i>
Cummins Northeast, Inc.	101 Railroad Ave. Albany, NY	518-459-1710		<a href="http://www.cumminsnortheast.com">www.cumminsnortheast.com</a>
Cummins Power Systems, LLC	890 Zerega Ave. Bronx, NY	800-564-7373 718-892-2400		
Cummins Northeast, Inc.	700 Aero Drive Buffalo, NY	716-631-3211		<a href="http://www.cumminsnortheast.com">www.cumminsnortheast.com</a>
Hallahan Truck Center	763 Blue Point Rd. Holtsville, NY	800-834-7242 631-475-8220	<a href="mailto:info@hallahantrucks.com">info@hallahantrucks.com</a>	<a href="http://www.hallahantrucks.com">www.hallahantrucks.com</a>
E Global Solutions	17 Deerfield Road Port Washington, NY	516-767-5138	<a href="mailto:info@eglobalsolutions.net">info@eglobalsolutions.net</a>	<a href="http://www.eglobalsolutions.net">www.eglobalsolutions.net</a>
Cummins Northeast, Inc.	6193 Eastern Ave. Syracuse, NY	315-437-2751		<a href="http://www.cumminsnortheast.com">www.cumminsnortheast.com</a>
JESCO	118 St. Nicholas Ave. South Plainfield, NJ	800-241-7070 908-753-8080 ext1300		<a href="http://www.jesco.us/">www.jesco.us/</a>
Cummins Power Systems, LLC	41-85 Doremus Ave. Newark, NJ	800-433-7884 973-491-0100		
Cummins Power Systems, LLC	914 Cromwell Ave. Rocky Hill, CT	888-762-7744 860-529-7474		
<b>Donaldson</b>				
<i>Company</i>	<i>Address</i>	<i>Phone</i>	<i>E-mail</i>	<i>Website</i>
Atlantic Detroit Diesel Allison	281 Old Wolf Road Latham, NY	518-452-0000		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>

	12110			
Atlantic Detroit Diesel Allison	3025 Veterans Memorial Highway Ronkonkoma, NY 11779	631-981-5800		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	1135 Kings Highway Saugerties, NY 12477	845-247-8045		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	180 Route 17 South, P.O. Box 950 Lodi, NJ 07644	201 489-5800		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	169 Old New Brunswick Rd Piscataway, NJ 08854	732-752-7100		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	South Burlington, VT 05403	802-865-4672		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Penn Detroit Diesel Allison	7044 Interstate Island Road, Syracuse, NY 13209	315-451-3840		<a href="http://www.penndda.com/">www.penndda.com/</a>
Penn Detroit Diesel Allison	1280 Jefferson Road, Rochester, NY 14623	585-232-6610		<a href="http://www.penndda.com/">www.penndda.com/</a>
Penn Detroit Diesel Allison	350 Bailey Avenue, Buffalo, NY 14210	716-823-7242		<a href="http://www.penndda.com/">www.penndda.com/</a>
Penn Detroit Diesel Allison	1080 Hanover Street, Wilkes-Barre, PA 18706	570-208-1192		<a href="http://www.penndda.com/">www.penndda.com/</a>
<b>Engine Control Systems</b>				
E Global Solutions, Inc.	265 Irving Avenue, Port Washington, New York, 11237	516-767-5138	<a href="mailto:info@eglobalsolutions.net">info@eglobalsolutions.net</a>	<a href="http://www.eglobalsolutions.net">www.eglobalsolutions.net</a>
Environmental Fuel Combustion Solutions	240 Church Street, Suite 9, Albany, New York, 12202	518-435-8067	<a href="mailto:info@efcsinc.com">info@efcsinc.com</a>	<a href="http://www.efcsinc.com/">www.efcsinc.com/</a>

Mondial Automotive	P.O. Box 560248 114-14 14 Road, College Point, New York, 11356	718-461-1103	<a href="mailto:Sales@mondialauto.com">Sales@mondialauto.com</a>	<a href="http://www.mondialauto.com">www.mondialauto.com</a>
Ward Clean Air Products	133 Philo Road West, Elmira, New York, 14903	607-796-0149	<a href="mailto:sales@wardcleanairproducts.com">sales@wardcleanairproducts.com</a>	<a href="http://www.wardcleanairproducts.com">www.wardcleanairproducts.com</a>
<b>HUSS</b>				
Halahan Truck Sales	763 Blue Point Rd. Holtsville, NY 11742	800-834-7242		<a href="http://www.hallahantrucks.com">www.hallahantrucks.com</a>
<b>Johnson Matthey</b>				
Atlantic Detroit Diesel Allison	281 Old Wolf Road Latham, NY 12110	518-452-0000		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	3025 Veterans Memorial Highway Ronkonkoma, NY 11779	631-981-5800		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	1135 Kings Highway Saugerties, NY 12477	845-247-8045		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	180 Route 17 South, P.O. Box 950 Lodi, NJ 07644	201 489-5800		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	169 Old New Brunswick Rd Piscataway, NJ 08854	732-752-7100		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Atlantic Detroit Diesel Allison	South Burlington, VT 05403	802-865-4672		<a href="http://www.atlanticdda.com/">www.atlanticdda.com/</a>
Caterpillar HO Penn	783 Bloomingburg RD, Bloomingburg, NY 12721	845-733-6400	<a href="mailto:swashburn@hopennmachinery.com">swashburn@hopennmachinery.com</a>	<a href="http://www.hopenn.com/">www.hopenn.com/</a>
Caterpillar HO Penn	699 Brush Avenue Bronx, NY 10465	718-863-3800	<a href="mailto:swashburn@hopennmachinery.com">swashburn@hopennmachinery.com</a>	<a href="http://www.hopenn.com/">www.hopenn.com/</a>
Caterpillar HO Penn	660 Union Avenue Holtsville, NY	631-758-7500	<a href="mailto:swashburn@hopennmachinery.com">swashburn@hopennmachinery.com</a>	<a href="http://www.hopenn.com/">www.hopenn.com/</a>

	11742			
Caterpillar HO Penn	122 Noxon Road Poughkeepsie, NY 12603	845-452-1200	<a href="mailto:swashburn@hopennmachinery.com">swashburn@hopennmachinery.com</a>	<a href="http://www.hopenn.com/">www.hopenn.com/</a>
Cummins Power Systems, LLC	890 Zerega Ave. Bronx, NY	800-564-7373 718-892-2400	<a href="mailto:ed.j.hall@cummins.com">ed.j.hall@cummins.com</a>	<a href="http://www.cummins.com">www.cummins.com</a>
Cummins Power Systems, LLC	41-85 Doremus Ave. Newark, NJ	800-433-7884 973-491-0100	<a href="mailto:ed.j.hall@cummins.com">ed.j.hall@cummins.com</a>	<a href="http://www.cummins.com">www.cummins.com</a>
Cummins Power Systems, LLC	914 Cromwell Ave. Rocky Hill, CT	888-762-7744 860-529-7474	<a href="mailto:ed.j.hall@cummins.com">ed.j.hall@cummins.com</a>	<a href="http://www.cummins.com">www.cummins.com</a>
Foley Inc. Caterpillar	833 Centennial Avenue Piscataway, NJ 08854	732-885-8034	<a href="mailto:aisrael@foleyinc.com">aisrael@foleyinc.com</a>	<a href="http://www.foleyinc.com">www.foleyinc.com</a>
<b>SK Energy</b>				
Mondial Automotive	P.O. Box 560248 114-14 14 Road, College Point, New York, 11356	718-461-1103	<a href="mailto:Sales@mondialauto.com">Sales@mondialauto.com</a>	<a href="http://www.mondialauto.com">www.mondialauto.com</a>

Retrofit distributors other than Cummins were contacted by phone and email, and asked to provide references, as well as general background on how much experience they had with retrofits. They were also asked whether they conduct retrofits on both on-road and off-road vehicles. NYS DOT has already purchased retrofits from Cummins, making this type of background check less necessary. The responses received from other distributors follow, in alphabetical order.

Caterpillar HO Penn has been involved in on-road and off-road retrofits since 2003, when Local Law 77 was passed in New York City. They have performed hundreds of retrofits (including DPFs and DOCs) on a wide range of equipment types.

E Global Solutions has installed 4,000 retrofits over the last 9 years, for clients including the DSNY and NYC DOT. They install both on-road and off-road retrofits and do training as well as installations.

Environmental Fuel Combustion Solutions (formerly TYMARK) has been in operation since 2006. They have performed retrofits for over 100 customers. They provide consulting as well as installations.

Hallahan Truck Center does both on-road and off-road retrofits. They have been conducting retrofits for at least 3 years.

JESCO does off-road retrofits. They have roughly 4 years of experience, and have worked with approximately a dozen clients. D'Annunzio is the largest.

Penn Detroit Diesel Allison (Penn DDA) has been installing retrofits for roughly 4 years. They retrofit both on-road and off-road vehicles, and have worked with multiple school districts.

### *13.2 Lead Times*

All manufacturers of retrofits not eliminated in the initial screening were contacted and asked to provide estimates of lead times. Responses received were quite comparable across manufacturers. All were ranges in the ballpark of 3-8 weeks. It was pointed out that some of the lead time resulted from common upstream lead times, in particular the silicon carbide component manufactured by Corning.

## **14. Conclusions**

### *14.1 Fuel Use*

- Complying with the NYS DEC regulatory requirement to use ULSD in diesel vehicles should not pose major problems for NYS DOT, considering that the EPA has made ULSD standard nationwide. (Section 3.2)
- Emulsified diesel is not a feasible option for a number of reasons, the simplest of which is that the only verified brand was discontinued in the United States. Other reasons include safety, corrosion, and cost concerns (Section 3.2).

### *14.2 Retrofit Requirements and Compatibility*

- Many NYS DOT vehicles do not require retrofits under NYS DEC regulation, including street sweepers, snow blowers, and much of NYS DOT's off-road fleet.

(Section 5.1) Other vehicles are already in compliance, including those with previously installed CNG conversion kits, as well as diesel vehicles meeting the 2007 diesel PM standard (Section 5.2).

- Due to exhaust temperature profile restrictions, passive DPFs would not provide a reliable retrofit solution for NYS DOT class 8 dump trucks. Were NYS DOT to install the more tolerant PDPFs on its class 8 dump trucks, it is unlikely that every single vehicle would have regeneration problems, but the risk of many vehicles encountering substantial problems would be very high. The same can be said for level 2 FTF technology. (Section 7.3)
- Vehicle availability during winter storms could be compromised by the use of active DPFs with substantial regeneration times, potentially posing a public safety risk. NYS DOT has expressed that regeneration times over 20 minutes could cause problems. Most active filters take 2-5 hours to regenerate, while one Huss filter takes roughly 30 minutes and the ESW ThermaCat regenerates during normal operation. However, NYS DOT's class 8 dump trucks exceed the maximum horsepower for the ESW device, and many class 6 trucks violate other requirements such as model year and incompatibility with EGR. (Section 7.4)
- It is particularly difficult to find a suitable retrofit strategy for model year 2004-2006 class 8 dump trucks. These vehicles have temperature profiles which violate the requirements of passive DPFs, and their use of EGR is incompatible with active DPFs, apart from the Cleaire Horizon, which has a burdensome 5 hour regeneration time. None of the level 1 DOCs are compatible with model years 2004-2006, and neither is the level 2 FTF. The EPA has verified DOCs without model year restrictions to provide a 20% reduction in PM. When combined with use of biodiesel, these could essentially provide level 1 emission benefits, even if not technically verified to do so for these newer vehicles. (Section 7)

- Due to narrow certification of conversion kits, widespread CNG conversion is likely infeasible, but a small number of conversions may be possible. (Section 8.3)

#### *14.3 Retrofit and Replacement Cost Effectiveness*

- In the long term, the most cost effective way to reduce PM emissions is to replace the oldest class 6 stake trucks. The second most cost effective option is to replace old class 8 dump trucks. (Section 8.4)
- Although level 1 DOCs offer less PM emission reduction than level 2 FTFs or level 3 DPFs, they do provide more PM emission reduction per dollar spent. (Section 8.1)
- Fuel savings from CNG conversion is unlikely to completely pay back the initial capital cost, but the net cost can be lower than that of a DPF. CNG conversions should prioritize newer vehicles, so long as they are pre-2007 model year. All else being equal, class 8 trucks should be prioritized over class 6 trucks because of their higher emission rates and fuel usage. (Section 8.3)
- In general, both retrofits and replacements are more cost effective on higher usage trucks, as they emit more (and in the case of CNG experience greater fuel cost savings). (Section 9.3)

#### *14.4 Other Findings*

- When conducting retrofits, it is important to be aware of relevant best practices regarding preparation, installation, operation, and training. Best practices are summarized in Section 4.2, but product-specific manuals should also be consulted.
- LED lights have the potential to reduce time spent idling in workzone protection, and therefore emissions (including PM, CO, NMHC, NO<sub>x</sub>, and CO<sub>2</sub>). Trucks idle

to keep lights flashing without draining the battery. Costs could be partially offset by fuel savings. There is precedent for CMAQ funding, and the fact that LED technology is not included in NYS DEC regulation might make federal grant managers more likely to fund it. LED conversion is compatible with other retrofits being considered, and might be an effective way for NYS DOT to go beyond NYS DEC regulations. (Section 10)

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## 16. Abbreviations

ADPF	active diesel particulate filter
BAAQMD	Bay Area Air Quality Management District
CARB	California Air Resources Board
CMAQ	Congestion Mitigation and Air Quality (Improvement Program)
CCVS	closed crankcase ventilation system
CBD	central business district
CNG	compressed natural gas
CT DOT	Connecticut Department of Transportation
DMF	diesel multi-stage filter
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
DSNY	Department of Sanitation of New York City
EGR	exhaust gas recirculation
EIA	Energy Information Administration
ESW	Environmental Solutions Worldwide
FTF	flow through filter
IARC	International Agency for Research on Cancer
LAO	(California) Legislative Analyst's Office
LED	light emitting diode
LNF	low NO <sub>2</sub> filter
LNG	liquefied natural gas
LXF	low NO <sub>x</sub> filter
M DEP	Massachusetts Department of Environmental Protection
M DOE	Maryland Department of the Environment
MSAT	Mobile Source Air Toxics
NHTSA	National Highway Traffic Safety Administration
NJ DEP	New Jersey Department of Environmental Protection
NREL	National Renewable Energy Laboratory
NV DMV	Nevada Department of Motor Vehicles
NYC DOT	New York City Department of Transportation
NYCRR	New York Codes, Rules, and Regulations
NYS DOT	New York State Department of Transportation
NYS DEC	New York State Department of Environmental Conservation
OEC	Ohio Environmental Council
OEM	original equipment manufacturer
OPWA	Oakland Public Works Agency
PA NYNJ	Port Authority of New York and New Jersey
PDPF	passive diesel particulate filter
PM	particulate matter
PAH	polycyclic aromatic hydrocarbon
SDC	Southeast Diesel Collaborative
ULSD	ultra-low sulfur diesel
US BLS	U. S. Bureau of Labor Statistics

US CDC	U.S. Centers for Disease Control and Prevention
US DHHS	U.S. Department of Health and Human Services
US DOE	U.S. Department of Energy
US DOJ	U.S. Department of Justice
US EPA	U.S. Environmental Protection Agency
VTL	New York Vehicle and Traffic Law
WI DOT	Wisconsin Department of Transportation
WS DOE	Washington State Department of Ecology
WS DOT	Washington State Department of Transportation