Timon Stasko
Diesel School Bus Emission Reduction in New York City
NYMTC Sept. 11th Memorial Program for Regional Transportation Planning
Final Report
9/17/08

Introduction

Diesel emissions impact the lives of many Americans. The U.S. Environmental Protection Agency (EPA) links thousands of instances of premature mortality, hundreds of thousands of asthma attacks, and millions of lost work days to particulate matter and gaseous emissions (U.S. EPA, 2007a). In response to this problem, the EPA reduced the maximum allowable particulate matter and nitrogen oxides emissions for new diesel trucks and buses by an order of magnitude over the past decade (U.S. EPA, 2003). Much of the existing fleet does not meet these standards, however, and diesel vehicles can have lifespans close to twenty five years.

The effects of diesel emissions can be felt acutely in urban centers such as New York City. In the South Bronx, which has high volumes of diesel truck traffic, NYU researchers were able to link alarmingly high elementary school asthma rates with exposure to particulate matter from diesel trucks (New York University, 2006). Even more frightening, 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).

Numerous retrofit technologies are available, each with benefits, costs, and usage restrictions. The amount of pollution prevented by a retrofit is depends greatly on the vehicle to which it is applied. For example, older vehicles generally have higher emissions rates, and tend to see larger reductions in emissions rates due to retrofits, but older vehicles also tend to have lower expected remaining usage. Other factors can include vehicle type, operating environment, and usage pattern. Many of these factors become important partially because of how they influence exhaust temperature.

Deciding when to apply which retrofit(s), and when it is simply better to retire a vehicle early, has emerged as an important challenge for policy makers. In New York City, the Department of Education faces this challenge when negotiating contracts with school bus fleet owners. What is the most cost effective strategy to reduce diesel emissions from school buses?

This project analyzed the cost effectiveness of Diesel Oxidation Catalysts (DOCs), Passive Diesel Particulate Filters (PDPFs) and Active Diesel Particulate Filters (ADPFs), as well as early vehicle retirement. An early goal of the project was to model fleet owner behavior for each of New York City's school bus fleets, in the context of potential government mandates and incentive programs. This was prevented by the city government's decision to withhold fleet data. Instead, a more detailed cost effectiveness study is presented. Factors influencing cost effectiveness, such as bus age, and previous retrofits are examined. Afterward, a sample fleet is assembled to resemble the combined New York City school bus fleet, and the potential for reducing its emissions is examined.

Input Data: Base Emissions Rates

All base emission rates (rates before retrofits) were taken from the EPA's MOBILE6.2 software. Distinct running (grams/mile) and idle (grams/hour) emission rates were used for each of the pollutants for school buses from each of 25 model years (1984-2008). Idle emission rates for pollutants other than particulate matter are not produced directly by MOBILE6.2. Instead, these rates were obtained from running emission rates at a speed of 2.5mph, as recommended by EPA staff.

Input Data: Retrofit Technologies

Three retrofit technologies are considered. All three are designed to reduce tailpipe exhaust emission rates. The fact that crankcase filters were not included should not be interpreted as a value judgment. As the name suggests, crankcase filters are intended to reduce emissions from the crankcase. For unretrofitted older buses, crankcase emissions are a relatively small portion of PM emissions (Donaldson, 2006). Crankcase filters are known for their ability to improve air quality inside the bus (Clean Air Task Force, 2005). The objective of improving in-bus air quality requires a different measure of effectiveness and cannot be compared to the tailpipe retrofits in an "apples to apples" way.

The costs and percent emission rate reductions for particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC) are given in Table 1. The costs are based on values published by the EPA (2007b) and the Environmental Defense Fund (2007a), as well as discussions with planners in New York City government. They include installation cost, which assumed a labor cost of $20/hour. This was toward the high end of the middle 50% of wages for automotive service technicians and mechanics in 2006, according the Bureau of Labor Statistics (2007). It is important to note that there is a considerable amount of variation in cost estimates for retrofits. When contemplating retrofit/replacement strategies, using the most relevant cost data can be essential to obtaining helpful results. For this reason, the cost estimates used in this project, as well as the results presented later, should not be blindly applied without first examining the applicability of the assumptions which were made. The percent emission rate reductions are based on the EPA's list of verified retrofit technologies (U.S. EPA, 2007c). The Huss ADPF is not on this list, and was assumed to provide the same reductions as a typical PDPF (but without the temperature requirements).

Diesel Oxidation Catalysts (DOCs) have already been applied to a large number of school buses in New York City. They are popular because of their relatively low cost, ease of installation, and versatility. Exhaust temperature requirements are relatively low, typically around 150C (U.S. EPA, 2007d).

Passive Diesel Particulate Filters (PDPFs) are generally catalyzed portions of the exhaust system like DOCs, but they also have a physical filter. The physical filter can stop a much larger fraction of the particulate mass, but it comes with the challenge of disposing of everything it collects. Regenerating filters burn off the particulates stopped by the filters, but they can be quite 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 et al., 2001). A typical passive diesel particulate filter might require that the exhaust temperature be at least 240C at the PDPF inlet for 40% of the duty cycle (U.S. EPA, 2008). With relatively short periods of operation, and frequent stops, urban school buses can have trouble meeting these requirements.

Active Diesel Particulate Filters (ADPFs) attempt to solve the temperature problem by providing additional heat for regeneration. Huss, whose active filters are being used in a trial project on NYC buses, claims that some of its filters have no minimum exhaust temperature (HUSS, 2008). ADPFs are by far the most costly retrofit option considered, however.

Table 1: Percent Emission Reduction and Cost Assumptions

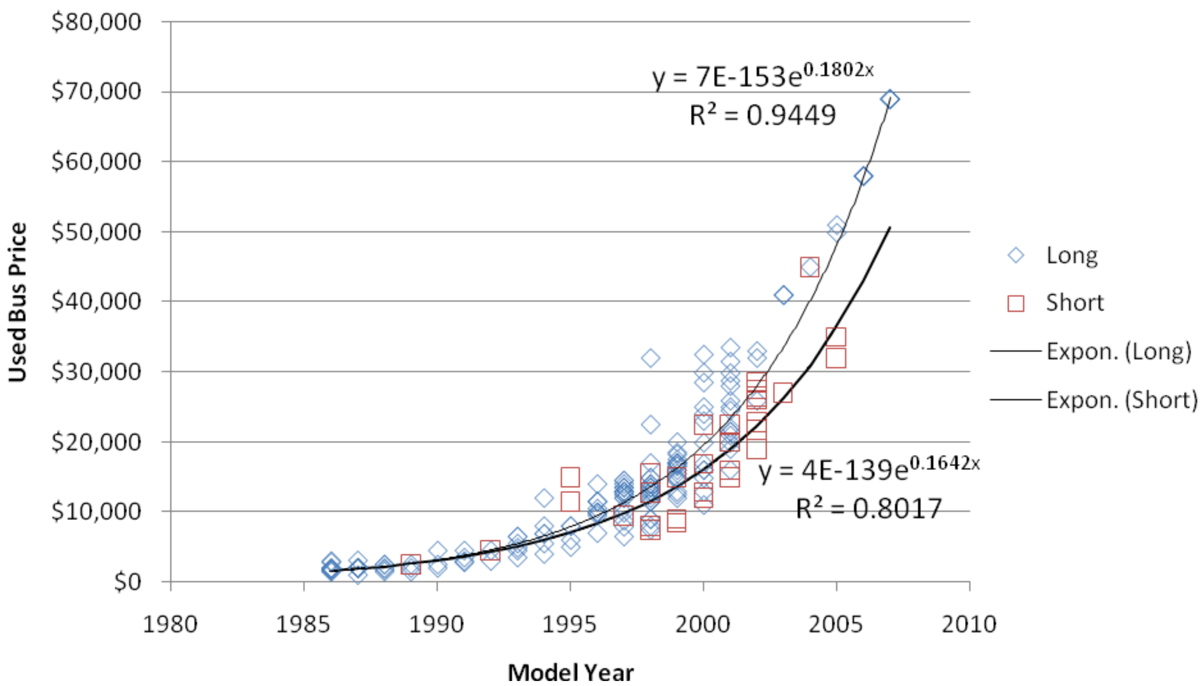
	Percent Reduction				
Technology	**PM**	**CO**	**NOx**	**HC**	**Cost**
DOC	20	40	0	50	$2,060
PDPF	90	85	0	95	$9,160
ADPF	90	85	0	95	$16,320

Input Data: Early Retirement

The costs and benefits of an early retirement are less straightforward than those from retrofits. Assume, for example, that a fleet owner expects to use a bus for another 5 years. If she decides to truly retire that bus early, she removes it from usage as a bus (i.e. she can’t sell it to be used in another district, or by a church). She therefore loses its value as a bus. She can, however, still sell it for scrap. For this project, the cost of early retirement is treated as the market value of the bus minus the scrap metal value of the bus. For young buses, this cost can be higher than that of any retrofit, but for very old buses the scrap metal value can be quite close to the market value of the bus. The scrap values of short and long buses were assumed to be $700 and $1000 respectively.

Hundreds of used bus prices were collected from public and private sellers. These prices were used to develop separate used bus market value functions for short and long buses, with the cost being a function of age. Age was found to be better at explaining value than mileage. The used bus prices, and the functions found through least squares regression, are plotted in Figure 1. The difference in price between short and long buses was found to be smaller for older buses.

Figure 1: Used Bus Prices by Model Year and Size



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 bus 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 bus and its replacement.

Further along in time, the effects become more complicated. Purchasing a new bus today instead of five years from now might mean that the new bus actually has higher emission rates than it would if purchased five years from now. Furthermore, purchasing a new bus five years earlier than previously planned will likely mean that the new bus will also 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. So long as emission rates do not increase, future changes to emission rates will be smaller than those made in recent history. Over the past 25 years, school bus running emission rates for PM2.5, CO, NOx, and HC have been cut by 99%, 95%, 73%, and 78% respectively. Hence, even if all these emission rates were cut to absolutely zero next year, the absolute magnitude of the change would be much smaller than the change over the past 25 years.

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.

Input Data: School Bus Usage

The MOBILE6.2 default annual mileage for school buses (9939 miles/year) was used. Unlike for other vehicle classes, MOBILE6.2 assumes school buses have the same annual mileage, independent of age (U.S. EPA, 2001). Additionally, for this project, school buses are assumed to idle approximately 15 minutes each school day.

Cost Effectiveness Analysis

For every vehicle type, the cost ($) and emissions saved (grams) were calculated for every retrofit technology, as well as replacement. Furthermore, the costs and emission savings were calculated for swapping retrofits and retiring vehicles with retrofits. Each of the several hundred possible actions has a cost effectiveness (grams saved/$ spent) for each pollutant.

Figure 2 plots cost effectiveness at reducing PM2.5 from an unretrofitted large bus for each of the retrofits, as well as replacement, for each of the model years considered. One of the first facts to stand out is that replacement, shown in purple, is far more cost effective than any of the retrofits for older buses. If the graph were expanded to show the entire curve, it would look like Figure 3. This is largely due to the short expected remaining lifespan of these older buses.

Figure 2: PM2.5 Reduction Cost Effectiveness for Long Buses (1 of 3)

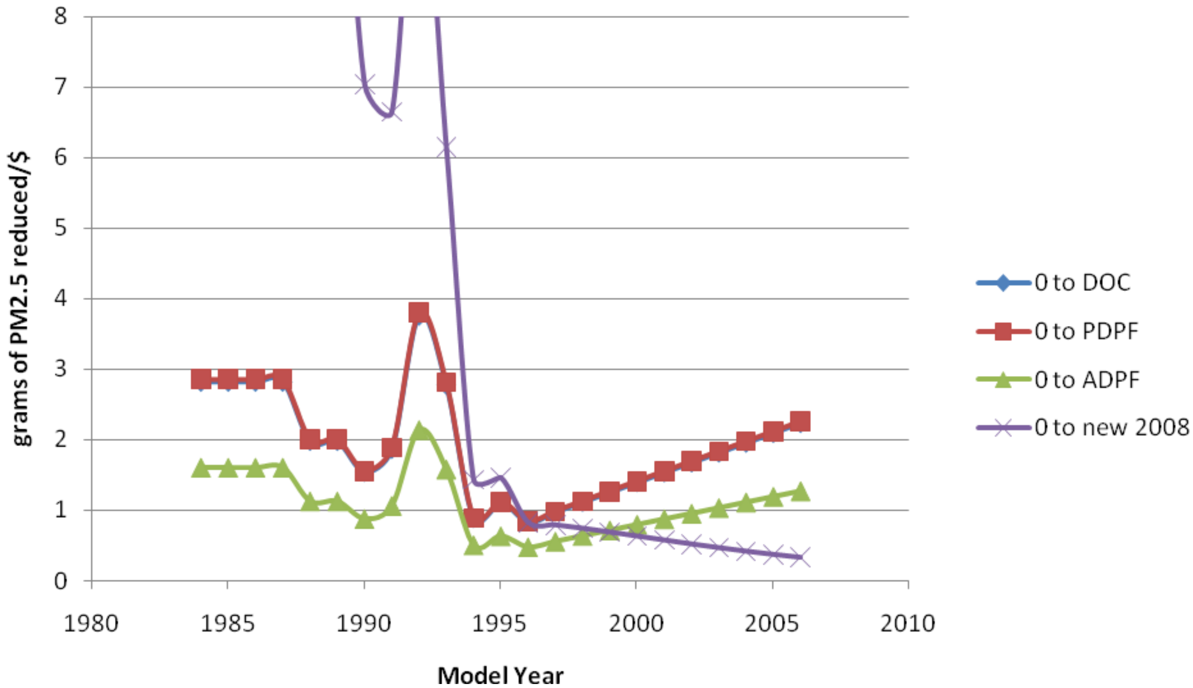

grams of PM2.5 reduced/$
Model Year
0 to DOC
0 to PDPF
0 to ADPF
0 to new 2008
8
7
6
5
4
3
2
1
0
1980
1985
1990
1995
2000
2005
2010

Figure 3: PM2.5 Reduction Cost Effectiveness for Long Buses (2 of 3)

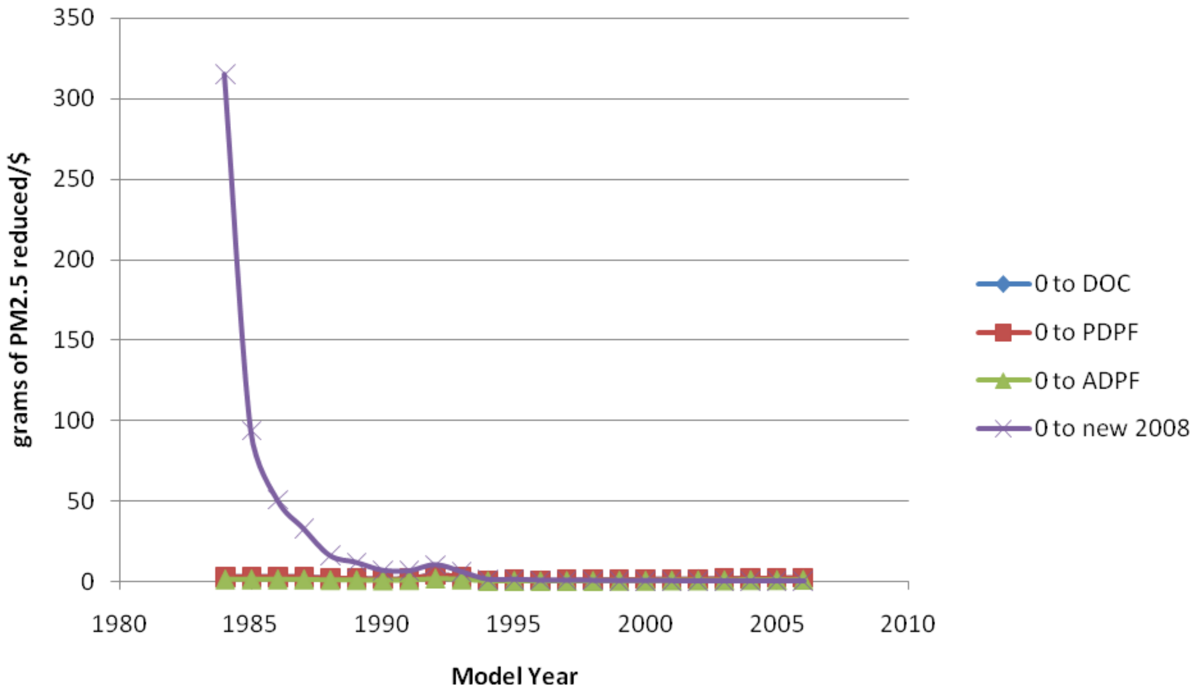
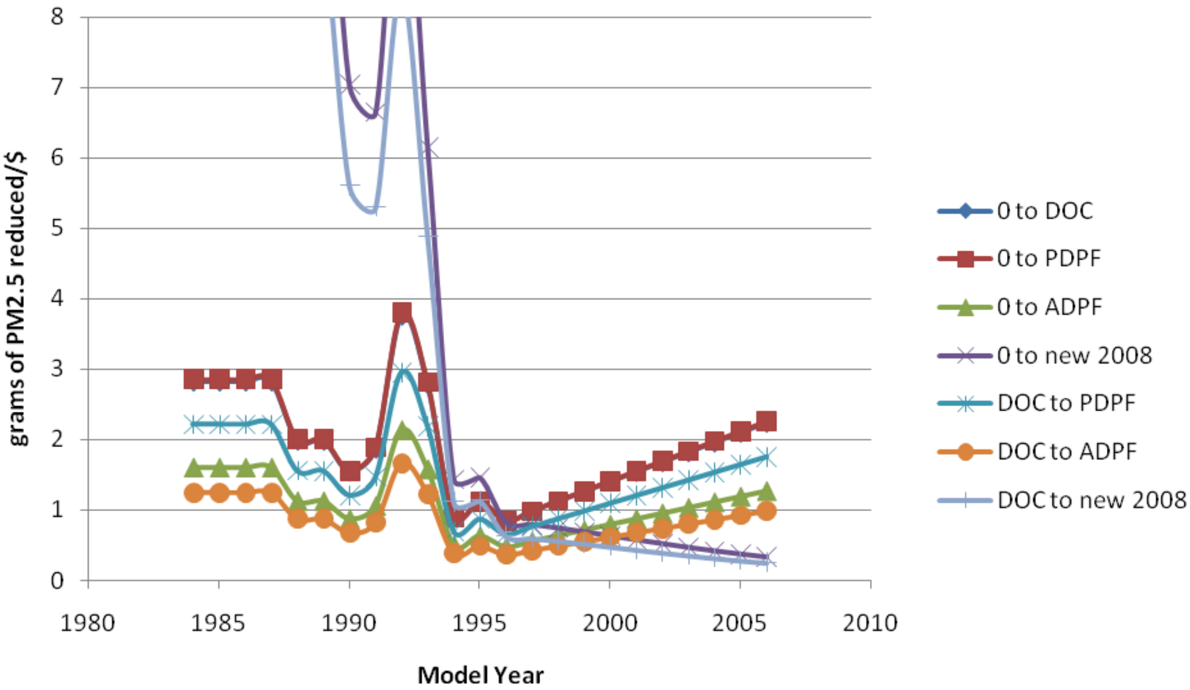


Figure 2 also shows that the cost effectiveness of a DOC is nearly the same as that of a PDPF, in terms of PM2.5 reduction. The two are so similar that the blue DOC line is nearly completely hidden behind the red PDPF line. The similar cost effectiveness is not surprising when one considers that the DOC eliminates 20% of PM2.5 at a cost of just over $2000, while the PDPF eliminates 90% of PM2.5 at a cost of just over $9000.

The linear trend in retrofit cost effectiveness between 1996 and 2006 model years is largely due to the linear decrease in remaining mileage for older buses. The PM2.5 emission rate did not change substantially during this period. Retrofits and replacements become more effective for 1992 and 1993 than they are for 1994 model year buses because the emission rates declined noticeably from 1992 to 1993 and from 1993 to 1994. The PM2.5 running emission rate in 1992 was more than eight times the 1994 rate.

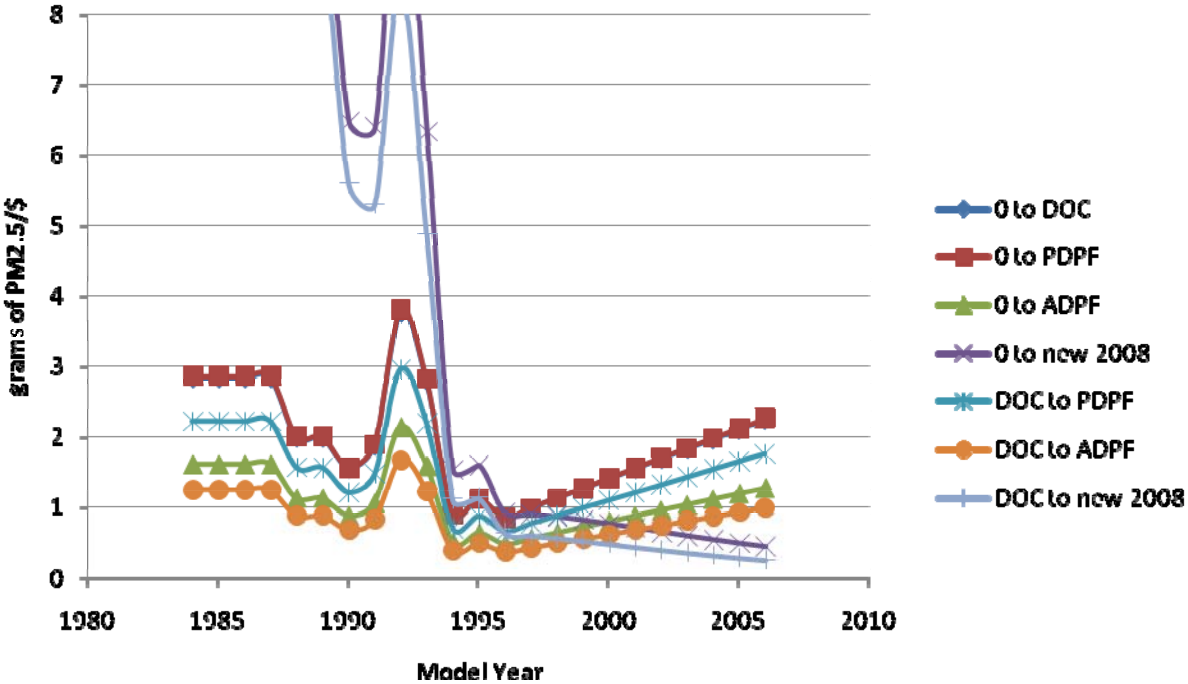
Figure 4 adds to Figure 2 by including cost effectiveness curves for a bus that already has a DOC. Swapping out a DOC for a PDPF is slightly less cost effective than putting a PDPF on an unretrofitted bus, but the shape of the curve is the same. This is due to the fact that the fleet owner must still pay the full PDPF price, but achieves a smaller emission reduction (because the DOC had already reduced PM2.5 emissions). The same idea applies to swapping the DOC out for an ADPF or retiring a bus with a DOC. It is worth noting that retiring the oldest buses, even with DOCs already in place, is still the most cost effective option by far.

Figure 4: PM2.5 Reduction Cost Effectiveness for Long Buses (3 of 3)



The cost effectiveness curves for a short bus, shown in Figure 5, are quite similar to those for a long bus given in Figure 4. Short buses have a noticeably smaller used bus value for later model years, making replacement less costly and hence more cost effective. The difference between short and long bus values becomes smaller for older buses.

Figure 5: PM2.5 Reduction Cost Effectiveness for Short Buses



The cost effectiveness curves are not the same for every pollutant. Emission rates for all of the pollutants have changed over the past 25 years, but not to the same degree, and not at the same times. Also, the retrofits have different percent reductions for different pollutants. Figures 6, 7, and 8 plot the cost effectiveness curves for CO, NOx, and HCs respectively. None of the retrofits reduce NOx, so only replacement has non-zero cost effectiveness on Figure 7.

Figure 6: CO Reduction Cost Effectiveness for Long Buses

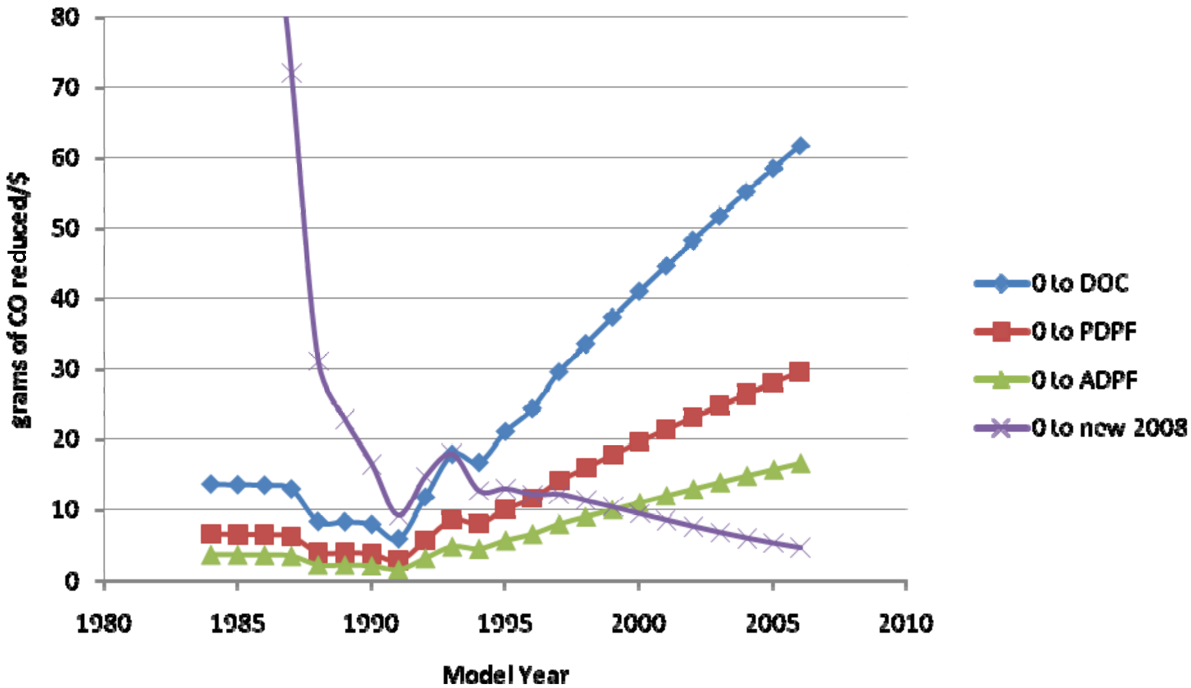


Figure 7: NOx Reduction Cost Effectiveness for Long Buses

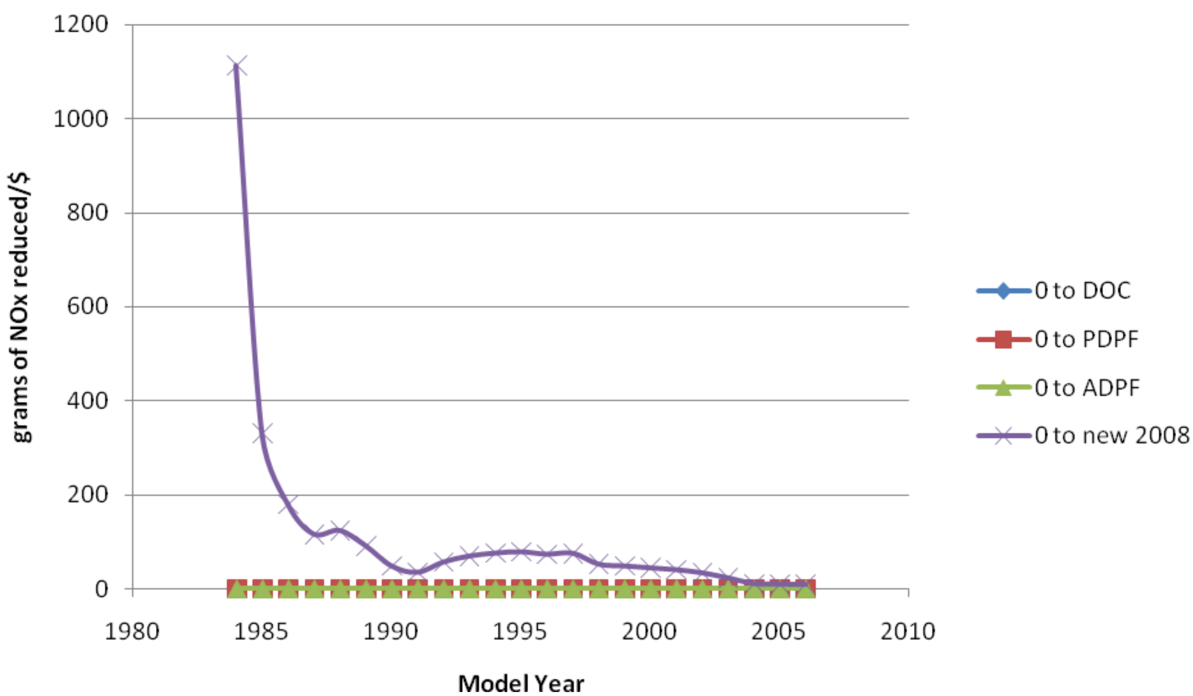
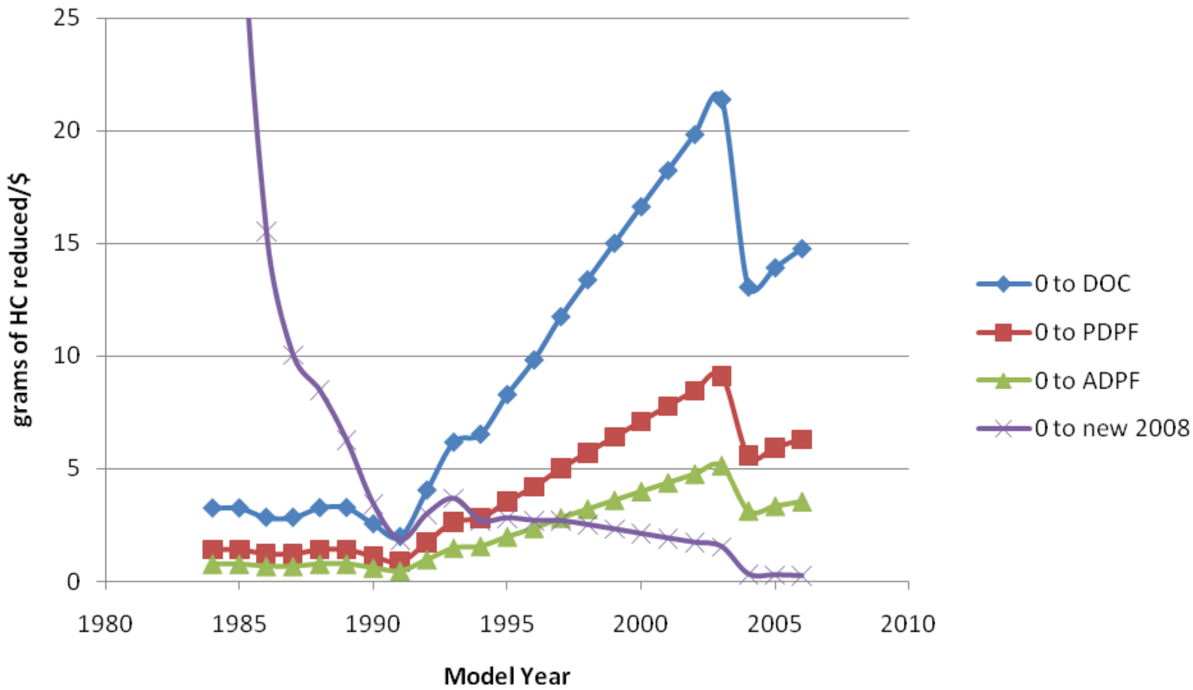


Figure 8: HC Reduction Cost Effectiveness for Long Buses



Looking at all pollutants for both short and long buses, several trends emerge. For older buses, it is far more cost effective to retire early than retrofit. For PM2.5, CO, NOx, and HCs, it is more cost effective to replace than retrofit a pre-1991 model year unretrofitted bus (short or long). For PM2.5, CO, and HCs, it is more cost effective to retrofit than replace a post-1996 model year unretrofitted bus. For the 1991-1996 model year buses, the most cost effective action depends both on the size of the bus, and on the relative importance of pollutants to the policy maker. If PM2.5 is the primary concern it will make more sense to retire younger buses than if HCs are the primary concern, for example.

Of the retrofit technologies considered, DOCs are generally the most cost effective, followed by PDPFs and then ADPFs. DOCs are the most cost effective for all years for short and long buses for CO and HCs. For PM2.5, DOCs and PDPFs have almost exactly the same cost effectiveness (PDPFs are slightly higher) and for NOx all retrofits considered have zero cost effectiveness.

The fact that DOCs are generally the most cost effective retrofit does not necessarily mean that they are always the best retrofit technology to apply. They reduce pollution less than PDPFs do, and might not be sufficient to meet policy goals. The fact that PDPFs are more cost effective than ADPFs does not necessarily mean that ADPFs should never be applied. There may be buses which cannot use a PDPF because of exhaust temperature constraints.

Finally, it is important to note that the high cost effectiveness of early retirement is partly due to recently implemented emissions standards on new diesel vehicles. If the new vehicles weren't much cleaner than those being retired, there would be little benefit. Several years ago, replacements were not as cost effective. This means that some retrofits made in the past might have been the most cost effective option at the time they were made, even if they would not be the most cost effective option today.

Additional Input Data: "NYCesque" Fleet

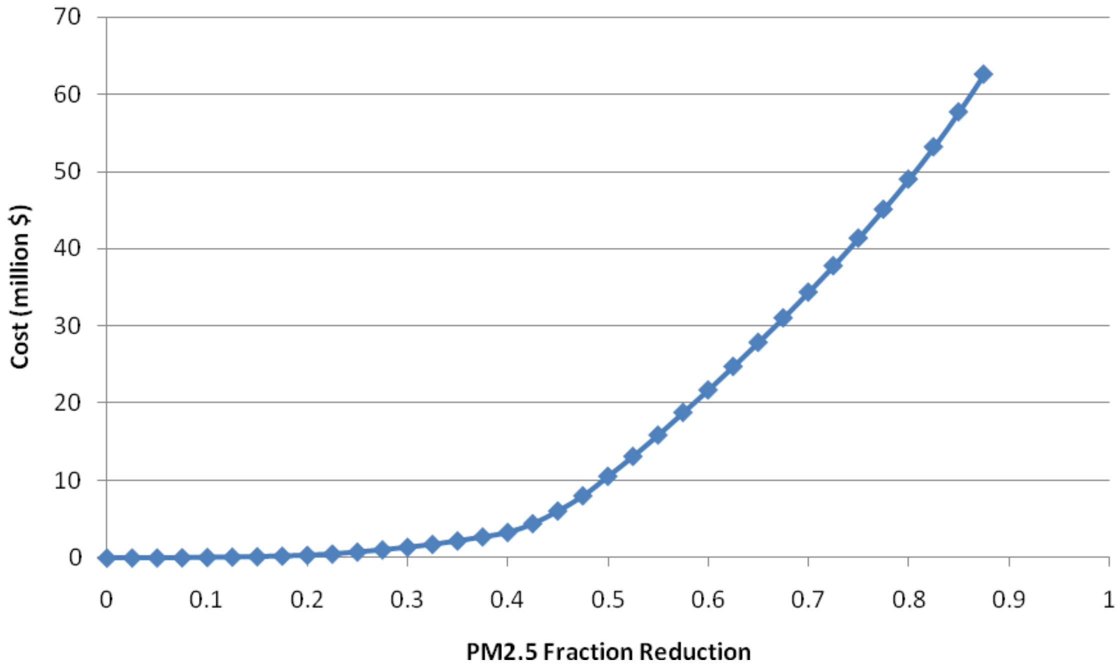
Regardless of whether past decisions were optimal, planners are faced with the deciding what to do with fleets as they exist. Without data on the school bus fleets in New York City, it is impossible to provide precise cost estimates for meeting emission reduction goals. A sample fleet was constructed to resemble the combined school bus fleets used in New York City. This fleet was based on pieces of information from numerous sources, but they do not combine to provide a complete picture. Hence, cost estimates based on this fleet are only very rough approximations of those that would apply to the real New York City school bus fleets.

PDPFs are only permitted to be placed on buses operating on Staten Island. It is assumed that only these buses would sustain high enough exhaust temperatures. It is further assumed that the fraction of buses operating on Staten Island is the same as the fraction of people under 18 living in NYC who live on Staten Island. All population figures used were 2006 census estimates (U.S. Census Bureau, 2008).

Case Study Results: Potential Emission Reductions for "NYCesque" Fleet

Particulate matter is often regarded as an especially dangerous pollutant. A natural series of questions follow the form "How much would it cost to reduce PM2.5 emissions by __ percent?" Figure 9 plots the cost to achieve a range of fraction reductions in PM2.5 for the NYCesque fleet. The graph is the result of several dozen runs of a cost minimizing integer program.

Figure 9: Cost vs. PM2.5 Fraction Reduction



The cost to reduce PM2.5 emissions by the first 40% is much smaller than the cost for the second 40%. The first 40% reduction of PM2.5 is achieved entirely through replacing older buses, starting with the very oldest and moving to buses as young as model year 1993. Many buses are retired despite having been retrofitted with DOCs in the past. To reduce PM.25 by more than 40%, the strategy becomes more complicated and costly. DOCs and PDPFs are installed on 2006 model year buses, and then older buses. Previously installed DOCs are replaced with PDPFs and newer buses are retired. The cost escalates at an increasing pace as the more cost effective options are exhausted. Even with the most aggressive strategy, it isn't quite possible to reduce PM2.5 emissions by 90%.

Retiring pre-1994 buses could be called the "low hanging fruit" of PM2.5 reduction. The amount of "low hanging fruit" actually available is highly dependent on the actual age distribution of the NYC fleet. If this differs substantially from the MOBILE6.2 national average, Figure 9 could look very different.

Installing retrofits with the goal of achieving a given PM2.5 reduction at minimum cost will also cause emission reductions of other pollutants. Given that the strategy is selected with these criteria, the fraction reductions of the four pollutants are plotted for different levels of cost in Figure 10. The absolute reductions (tons) of the four pollutants are plotted for each level of cost in Figure 11.

Figure 10: Emission Fraction Reductions for PM2.5 Targeted Retrofits

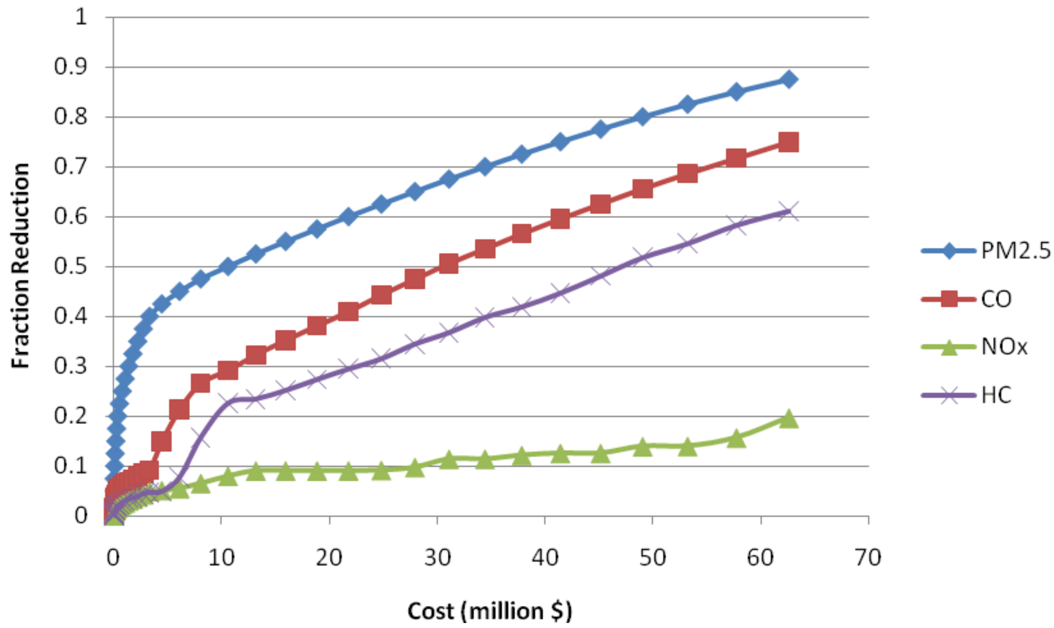
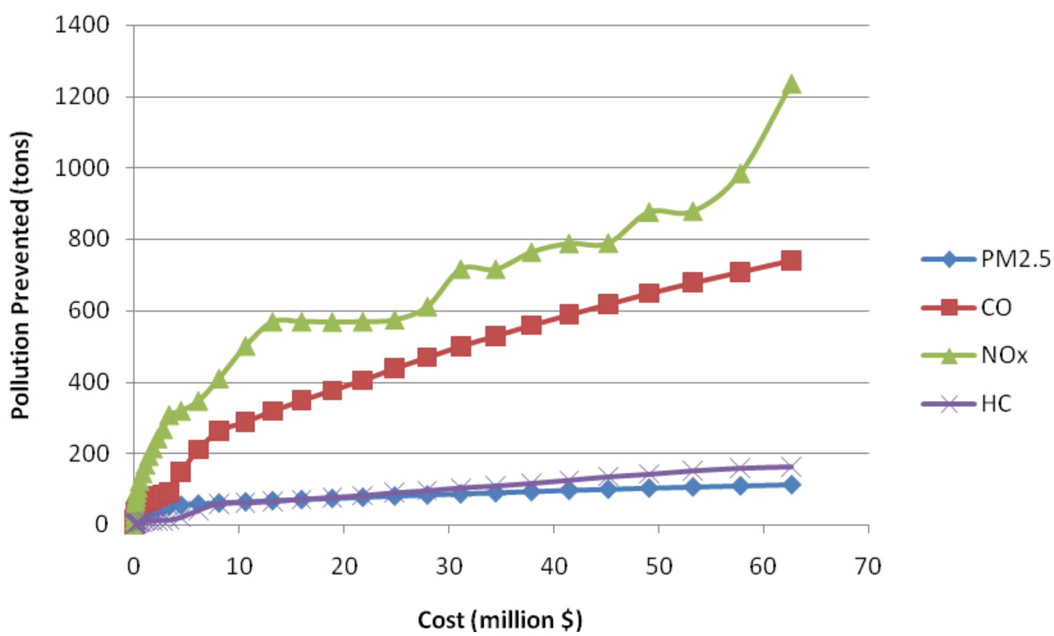


Figure 11: Emission Weight Reductions for PM2.5 Targeted Retrofits



As mentioned earlier, these results are a function of many assumptions regarding New York City's school bus fleet. Without anything close to complete data on the fleet, there is a high probability that the actual curves deviate, at least slightly, from those shown in Figures 9, 10, and 11. Cost-effectiveness calculations shown in Figures 2-8 do not depend on the makeup of the New York City fleet, but they do depend on other assumptions, many of which are described above. The greatest uncertainty surrounds the price of the retrofits. For these reasons, I advise readers against blindly using numbers from this project without ensuring the relevant assumptions apply.

Acknowledgments

It has been a pleasure working on this project through the September 11th Memorial Program for Regional Transportation Planning. I would like to thank my academic advisor Oliver Gao, my professional advisor Mark Simon, as well as Todd Goldman, Penny Eickemeyer, and everyone else who took time to help me with this project.

Sources Cited

Clean Air Task Force, 2005. Diesel health in America: the lingering threat. Clean Air Task Force, Boston.

Donaldson. (2006) Eliminate Crankcase Emissions and Improve In-Cab Air Quality. http://www.donaldson.com/en/exhaust/support/datalibrary/002423.pdf. Accessed 10/28/2008.

Environmental Defense Fund. (2007a) What Are the Best Retrofit Options? http://www.edf.org/page.cfm?tagID=15567

Environmental Defense Fund. (2007b) New York City Tackles School Bus Pollution. http://www.edf.org/page.cfm?tagID=15578

HUSS. (2008) Product Overview. http://www.huss-umwelttechnik.com/en/products/product-overview.php. Accessed 10/28/2008.

New York University, 2006. Asthma Symptoms Linked to Soot Particles From Diesel Trucks in South Bronx. Retrieved 06 Mar. 2007, from http://www.nyu.edu/public.affairs/releases/detail/1263.

NYC Department of Education. (2007) Pupil Transportation. http://schools.nyc.gov/Offices/Transportation/default.htm

U.S. Census Bureau. (2008) State and County Quickfacts: New York (city), New York http://quickfacts.census.gov/qfd/states/36/3651000.html

U. S. Department of Labor: Bureau of Labor Statistics. (2007) Occupational Outlook Handbook 2008-09 Edition. http://www.bls.gov/oco/ocos181.htm

U.S. Environmental Protection Agency. (2001) Fleet Characterization Data for MOBILE6: Development and Use of Age Distributions, Average Annual Mileage Accumulation Rates, and Projected Vehicle Counts for Use in MOBILE6. http://www.epa.gov/otaq/models/mobile6/r01047.pdf

U.S. Environmental Protection Agency. (2003) Diesel exhaust in the United States, USEPA #420-F-03-022. http://www.epa.gov/otaq/retrofit/documents/420f03022.pdf. Accessed 5/28/07.

U.S. Environmental Protection Agency. (2007a) National clean diesel campaign. http://www.epa.gov/cleandiesel/

U.S. Environmental Protection Agency. (2007b) Clean School Bus USA: Retrofit. http://www.epa.gov/cleanschoolbus/retrofit.htm

U.S. Environmental Protection Agency. (2007c) Voluntary diesel retrofit program: verified products. http://www.epa.gov/otaq/retrofit/verif-list.htm

U.S. Environmental Protection Agency. (2007d) Diesel Retrofit Technology Verification: Verified Retrofit Technologies from Donaldson. http://www.epa.gov/otaq/retrofit/techlist-donaldson.htm#donaldson2

U.S. Environmental Protection Agency. (2008) Diesel Retrofit Technology Verification: Verified Retrofit Technologies from Johnson Matthey. http://www.epa.gov/otaq/retrofit/techlist-johnmatt.htm#jm6

Van Setten, B. A. A. L., Makkee, M., Moulijn, J. A., 2001. Science and Technology of Catalytic Diesel Particulate Filters. Catalysis Reviews 43(4), 489-564.