ARTICLE IN PRESS

Transportation Research Part D xxx (2008) xxx–xxx

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Cost-minimizing retrofit/replacement strategies for diesel emissions reduction

H. Oliver Gao *, Timon H. Stasko

School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

ARTICLE INFO

Keywords:
Diesel emissions
Diesel retrofits
Cost minimization
Emission reductions
Integer programming

ABSTRACT

The cost effectiveness of various emission reduction diesel retrofits is analyzed, as is early vehicle retirement. An integer program is developed to find cost-minimizing cleanup strategies, given reduction goals for various pollutants, as well as technological and budget constraints. Retrofits are assumed to take place in the present, but benefits and costs can be distributed over time. Budget constraints deal with short-term expenditures, while the overall objective is to minimize the net present value of short and long-term costs. The model is intended as a tool both for fleet owners and for government administrators. A case study examines the potential to clean up a diesel school bus fleet.

1. Introduction

Diesel emissions are a topic of great importance to many Americans. The US Environmental Protection Agency (EPA) (2008a) links thousands of premature deaths, hundreds of thousands of asthma attacks, and millions of lost work days to particulate matter, nitrogen oxides, and air toxic emissions. Recognizing the 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 (US Environmental Protection Agency, 2003a), but much of the existing fleet is not bound by these tighter restrictions. Furthermore, many diesel vehicles have lifespans close to 25 years.

A variety of retrofit technologies are available, each with its own benefits, costs, and usage restrictions. The amount of pollution prevented by a retrofit is a function of the vehicle it is used on. For example, older vehicles generally have higher emissions rates, and see greater improvements from retrofits, but older vehicles also tend to have lower expected remaining usage. Other factors can include vehicle type, operating environment, and usage pattern. Deciding when to apply which retrofits, and when it is simply better to retire a vehicle early, has emerged as an important challenge.

This paper analyzes 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 using school buses as a case study. For the retrofits, the bulk of the financial cost is generally paid close to the time of installation, while the benefit of emission reduction is spread out over time. Early retirement, and subsequent replacement with a new vehicle, has high initial financial cost, usually followed by significant future financial savings, in addition to the emissions reduction. This can cause large discrepancies between the net present value of the cost of replacement and the immediate cost. Both the net present value of the cost and immediate cost are relevant to retrofit/replacement decisions, and both are included in the model. This complexity is one of the reasons integer programming is an attractive method for modeling the diesel retrofit/replacement problem. The discrete nature of the problem (one cannot apply 0.7 retrofits to a bus) also makes integer programming a natural choice.

* Corresponding author. Tel.: +1 6072548334.
E-mail address: hg55@cornell.edu (H. Oliver Gao).

1361-9209/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.trd.2008.11.006

2. Background

The US Environmental Protection Agency (2006) published a report analyzing the cost effectiveness of retrofits for reducing particulate matter (PM) emissions from selected heavy-duty diesel vehicles. The report calculated the approximate cost per ton of PM reduced by DOCs and PDPFs applied to a range of vehicles. It did not consider early retirement, and no pollutants other than PM were considered. The report was also not intended to formulate cost effective retrofit/replacement strategies in the face of budget and technological constraints.

In terms of early retirement programs, Dill (2004) examined assumptions behind emission reduction estimations for accelerated retirement programs, raising the point that a government provided incentive can strongly influence the quality of the vehicles retired. Using surveys, Dill examined possible discrepancies between vehicles retired early and average vehicles of the same model year (such as the retired vehicles having lower expected remaining mileage). While the questions posed are relevant, the conclusions drawn are less so, because the results are a function of the incentive structures and targeted vehicle types, cars and light duty trucks, of the two programs considered.

Spitzley et al. (2005) estimated optimal car lifetimes for a variety of objectives involving personal financial costs, carbon dioxide, carbon monoxide, non-methane hydrocarbons, nitrogen oxides, and an aggregated pollution damage metric. One of the model's strengths is that it recognizes that optimal lifetimes can change over time, but emission reduction retrofits are not considered, and neither are heavy-duty diesel vehicles.

Mostashari et al. (2004) takes a higher level approach to the problem, considering a wide range of options including particulate filters on buses, early replacement programs, hybrid vehicles, and fuel taxes, among other options. The study did not examine the options in great depth, however, ultimately producing cost and emission estimates for a discrete set of only 28 potential strategies, by enumeration.

Retrofit and replacement decisions with financial and environmental costs are common outside the transportation arena as well. For example, Sohn and Homan (1994) examined the cost of retrofitting and replacing US Army air conditioning and refrigeration equipment to eliminate the use of chlorofluorocarbons. Zelazny and Wang (1998) compared retrofitting and replacing oil/water separators at vehicle washracks. Neither of these reports uses a model for developing strategies comparable to that developed in this paper.

3. Methodology

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), 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. 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). Finally, the set J includes a default state that corresponds to no retrofits or early replacement. P is the set of all pollutants being tracked (e.g. $PM_{2.5}$, NOx)

The parameters used here are: f_{ij}, the number of vehicles of type i in state j in initial fleet; m_i, the remaining mileage for a vehicle of type i; w_i, remaining idle hours for a vehicle of type i; e_{ijp}, the running emission rate (g/mile) of pollutant p for vehicles of type i in state j; ε_{ij}, the idle emission rate (g/h) of pollutant p for vehicles of type i in state j; c_{ijk}, the net present cost to switch vehicle of type i from state j to state k; d_{ijk}, the initial cost to switch vehicle of type i from state j to state k; u_{ijk}, the maximum number of vehicles of type i that can be switched from state j to state k; ρ_p, the required fraction reduction for pollutant p and B, the initial budget for retrofits and early retirements The decision variables 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 that can be between zero and the number of vehicles of type i. These constraints are represented by

$$0 \leqslant r_{ijk} \leqslant u_{ijk} \quad \forall i \in I, \quad j \in J, k \in J. \tag{1}$$

In the retrofit decision, a state must be selected for each vehicle in the initial fleet (recall that there is a no action option where $k = j$)

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

The emissions of each pollutant must be reduced by the fraction specified by ρ_p, as

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

Certain retrofits or replacements may have high initial cost, followed by partial payback in the future. Heavily employing such options could cause short-term budget problems. The current budget is constrained by

$$\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} r_{ijk} \cdot d_{ijk} \leqslant B. \tag{4}$$

The objective is to minimize the net present value of the retrofit/replacement costs, given by

$$\min \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} r_{ijk} \cdot c_{ijk}. \tag{5}$$

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

4. School bus case study

4.1. Input data: Emissions rates and retrofit technologies

Emission rates were taken from the EPA's current on-road mobile emission inventory model, MOBILE6.2. Distinct running (g/mile) and idle (g/h) emission rates are used for particulate matter with aerodynamic diameter less than 2.5 microns ($PM_{2.5}$), carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC) for school buses from each of 25 model years (1984 to 2008). Idle emission rates for pollutants, other than particulate matter, are not produced directly by MOBILE6.2. Instead, these rates were based on MOBILE6.2 emission rates at a speed of 2.5 mph, as recommended by EPA staff.

Three retrofit technologies were considered; all designed to reduce tailpipe exhaust emissions.

- *Diesel Oxidation Catalysts* (DOCs) are catalyzed portions of the exhaust system, generally in a honeycomb-like structure that provides high surface area (US Environmental Protection Agency, 2003b). They are popular because of their relatively low cost, ease of installation, and versatility. Exhaust temperature requirements are relatively low, typically around 150 °C (US Environmental Protection Agency, 2007a). DOCs are assumed to cost $1000, based on conversations with school officials, and the EPA's posted range of $600–$2000 (US Environmental Protection Agency, 2007b). The emissions reductions are assumed to match those of multiple EPA verified products – 20% PM reduction, 40% CO reduction, and 50% HC reduction (US Environmental Protection Agency, 2008b).
- *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 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 PDPF might require that the exhaust temperature be at least 240 °C for 40% of the duty cycle at the PDPF inlet (US Environmental Protection Agency, 2007c). With relatively short periods of operation, and frequent stops, urban school buses can have trouble meeting these requirements. PDPFs are not considered compatible with pre-1994 model year vehicles. They are assumed to cost $8000, based on conversations with school officials, and the EPA's posted range of $5000–$10,000 (US Environmental Protection Agency 2007b). The emissions reductions are assumed to match those of multiple EPA verified products – 90% PM reduction, 85% CO reduction, and 95% HC reduction (US Environmental Protection Agency, 2008b).
- *Active diesel particulate filters* (ADPFs) attempt to solve the temperature problem by providing additional heat for regeneration. Huss, a filter manufacturer 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). Like PDPFs, ADPFs are considered incompatible with pre-1994 model year vehicles. At $16,000, their cost is double that of PDPFs, but their emission reductions are assumed to be the same.

4.2. 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 the next 5 years. If she decides to truly retire that bus early, she removes it from usage as a bus – i.e. she cannot sell it to be used in another school district, or by a church. She therefore loses its value as a bus. She can, however, still sell it for scrap. Therefore, the long-term cost of early retirement is taken to be 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 close to the market value of the bus. The scrap values of short and long buses were assumed to be $700 and $1000, respectively. The initial cost of early retirement is taken to be the cost of a new bus of equivalent size, minus the scrap metal value of the old bus.

Hundreds of used bus prices were collected from public and private sellers. These prices are used to develop separate used bus market value functions for short and long buses, with the cost being a function of age; this being a better determinant of value than mileage. The used bus prices, and the functions found through least squares regression, are plotted in Fig. 1. New short and long buses are assumed to cost $59,699 and $82,346, respectively (based on the price data). The difference in price between short and long buses was found to be smaller for older buses.

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

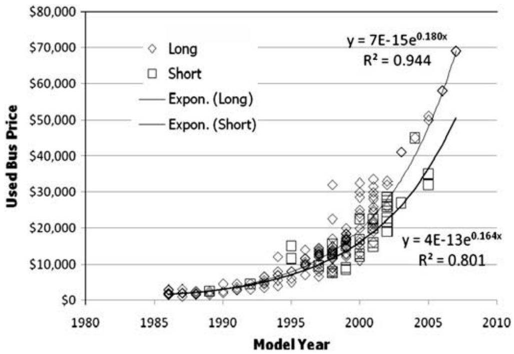

Fig. 1. School bus prices by size and model year.

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 5 years from now might mean that the new bus actually has higher emission rates than it would if purchased 5 years from now. Furthermore, purchasing a new bus 5 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. As 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 $PM_{2.5}$, CO, NOx, and HC have been cut by 99%, 95%, 73%, and 78%, respectively. Hence, even if all these emission rates were cut to 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.

4.3. 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 (US Environmental Protection Agency, 2001). Additionally, school buses are assumed to idle approximately 15 min each school day.

The time a bus is expected to remain in use is determined using the same 1980 heavy-duty diesel survival rates that are used in US Environmental Protection Agency (2006), but they are applied differently. These survival rates give the fraction of vehicles expected to make it to ages 1 through 30. We required not only the survival rate, but also the probability that a given vehicle in the fleet will make it to an age as a function of how old the vehicle is already. Given that s_y is the probability a random vehicle will make it to age y, the probability a vehicle of age a will make it to age $b > a$ is s_b/s_a. The probability each vehicle will make it to each of the 30 ages is computed, given the vehicles' current ages. Their expected remaining usage is then based on these probabilities.

4.4. Cost effectiveness analysis

Fig. 2 plots cost effectiveness at reducing $PM_{2.5}$ emissions from an unretrofitted large bus for each of the retrofits, as well as replacement, for each of the model years considered. The top and bottom graphs are the same except for the scale of the y-axis. The graphs show clearly that the long-term cost effectiveness of replacement greatly exceeds that of any of the retrofits for the oldest buses. This is largely due to the fact that the market value of these buses is relatively close to the scrap value.

Of the retrofits, DOCs emerge as the most cost effective option for all model years. In terms of initial cost, DOCs are more cost effective than replacement for any model year, and in terms of long-term cost, they are more cost effective than replacement on model year 1994 and newer long buses. For short school buses, the curves are slightly different, but 1994 remains the pivotal year. Note that even in terms of initial cost, replacing an older bus can be more cost effective than applying an ADPF or even a PDPF to a newer bus.

The relatively linear trend in retrofit cost effectiveness between model years 1996 and 2006 is largely due to the decreasing expected remaining usage for older buses. The $PM_{2.5}$ emission rate did not change substantially during this period. Retrofits and replacements are more effective for model years 1992 and 1993 than they are for 1994 because the emission rates declined noticeably from 1992 to 1993 and from 1993 to 1994. The $PM_{2.5}$ running emission rate in 1992 was more than eight times the 1994 rate.

Please cite this article in press as: Oliver Gao, H., Stasko, T.H. Cost-minimizing retrofit/replacement strategies ... Transport. Res. Part D (2008), doi:10.1016/j.trd.2008.11.006

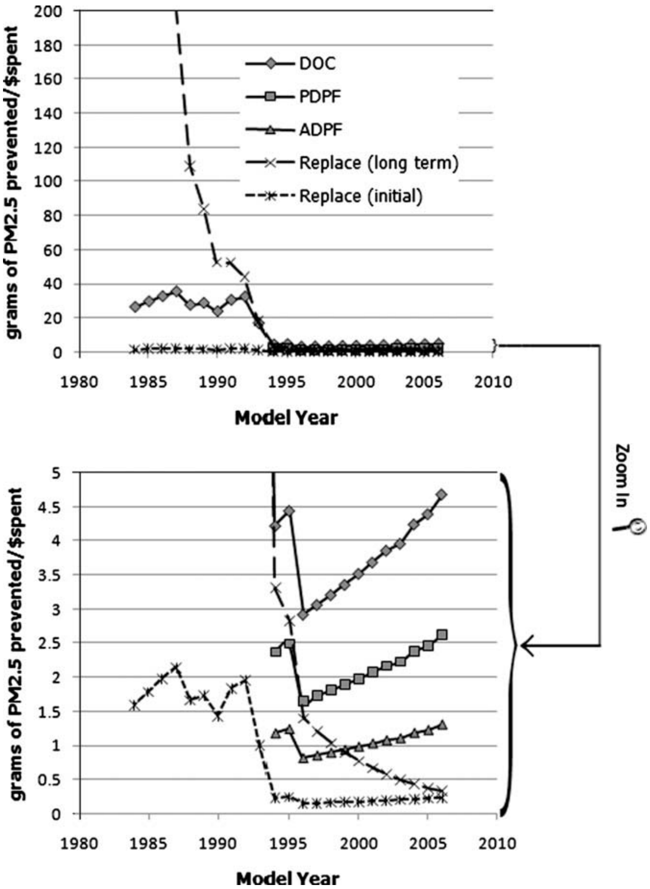

Fig. 2. $PM_{2.5}$ reduction cost effectiveness for previously unretrofitted long buses.

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. Fig. 3 plots cost effectiveness curves equivalent to those in Fig. 2, but for HC reduction. None of the retrofits reduce NOx, so only replacement has non-zero cost effectiveness for this pollutant.

The results show that DOCs are generally the most cost effective retrofit option (for $PM_{2.5}$, CO, and HC), but this does not necessarily mean that DOCs are always the best choice of retrofit technology. They reduce pollution less than PDPFs, and might not be sufficient to meet policy goals. Likewise, the conclusion 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 long-term cost effectiveness of early retirement is partly due to recently implemented emissions standards on new diesel vehicles. If the new vehicles were not 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 that time, even if they would not be the most cost effective option today.

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 $PM_{2.5}$ emissions). The same idea applies to swapping the DOC out for an ADPF or retiring a bus with a DOC. The integer program incorporates these complications.

4.5. Input data: Initial sample fleet

The case study fleet is composed of 124 long and 75 short buses. Half a dozen of the long buses have been retrofitted with PDPFs, and another half dozen with ADPFs, as a pilot project. Half of the remaining long buses have DOCs. Roughly one third of the buses are considered ineligible for PDPFs, due to temperature constraints.

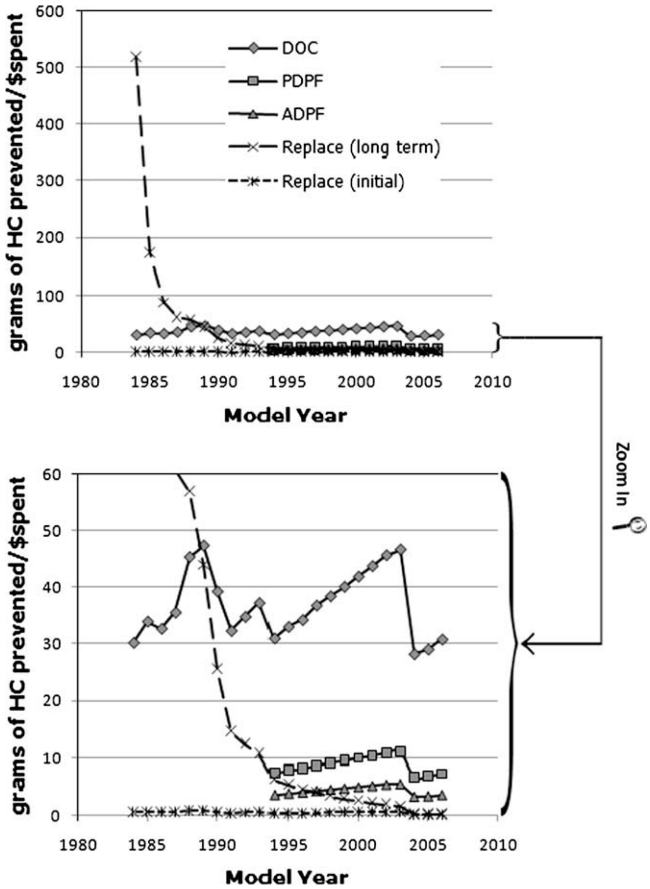

Fig. 3. HC reduction cost effectiveness for previously unretrofitted long buses.

4.6. Case study results: Cost effective strategies for the sample fleet

Particulate matter is often regarded as an especially dangerous pollutant and a top priority for reduction. A natural series of questions follow the form "How much would it cost in the long term to reduce $PM_{2.5}$ emissions by __ percent within an initial budget of $_____?" Fig. 4 plots the cost to meet several $PM_{2.5}$ reduction targets for the sample fleet, given a range of potential short-term budgets. The graph is the result of several dozen runs of the long-term cost minimizing integer program.

With no initial budget restriction, $PM_{2.5}$ can be reduced by 10% for a long-term cost of under $1000. This is the long-term cost of replacing 4 of 4 25 year old unretrofitted long buses, and 4 of 4 25 year old long buses with DOCs. These buses' market

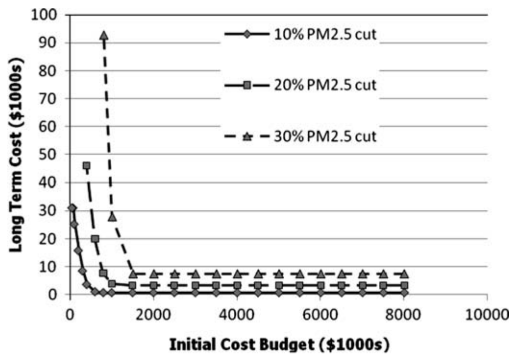

Fig. 4. Long-term cost of meeting $PM_{2.5}$ reduction goal and initial budget.

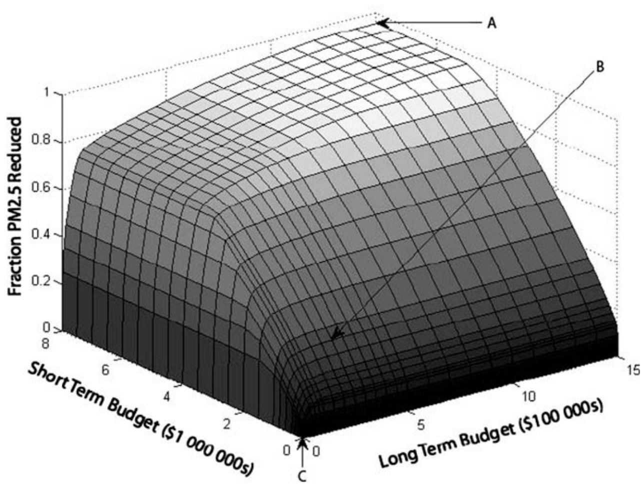

Fig. 5. Maximum $PM_{2.5}$ reduction under initial and long-term budgets.

values are very close to their scrap metal values. Initially, however, this replacement costs over $650,000. If the initial budget is lower than this, the long-term cost increases, reaching $31,000 for an initial budget of $50,000. With this budget constraint, the reduction is achieved exclusively by application of DOCs. With initial budgets of $25,000 and under, it is simply impossible to achieve a 10% $PM_{2.5}$ reduction.

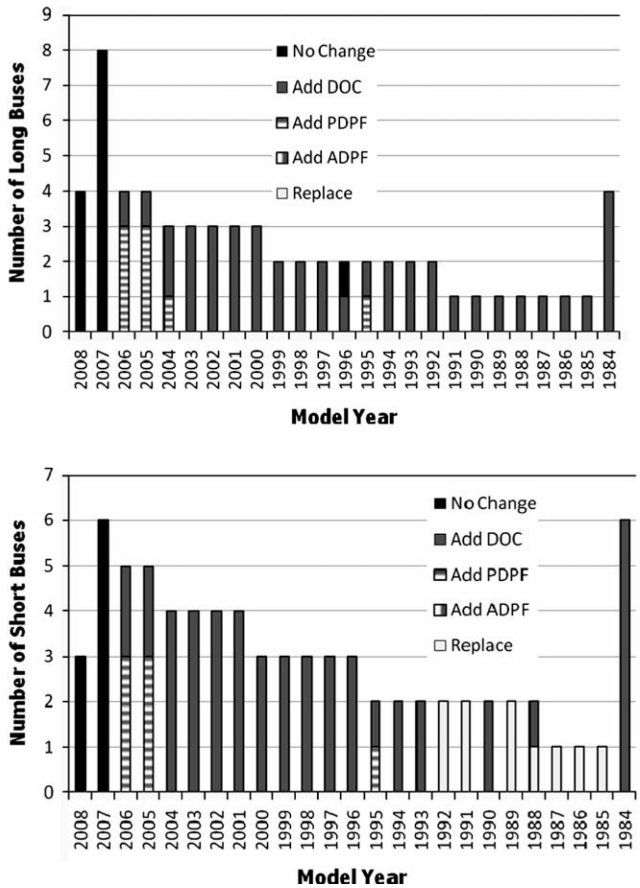

Fig. 6. Retrofits and replacements conducted on previously unretrofitted buses at point *B* in Fig. 5.

Please cite this article in press as: Oliver Gao, H., Stasko, T.H. Cost-minimizing retrofit/replacement strategies ... Transport. Res. Part D (2008), doi:10.1016/j.trd.2008.11.006

Another natural question to consider is "Given initial and long-term budgets, how much can $PM_{2.5}$ emissions be reduced?" This question can be answered with slight modifications to the integer program. A long-term budget constraint (similar to the initial budget constraint in Eq. (4) is added, and the objective is changed to represent grams of $PM_{2.5}$ emissions. The highest possible fraction reduction of $PM_{2.5}$ emissions for 754 potential budget scenarios is plotted in Fig. 5.

Point *A* has extremely relaxed (nonbinding) budget constraints. If money is no object, the highest possible reduction is just above 95%. This is achieved by retiring all buses from model year 1993 and earlier, and putting PDPFs or ADPFs on the 1994–2006 model year buses. At the opposite end of the graph, point *C* has an initial and long-term budget of only $5000. $PM_{2.5}$ can be cut by at most just under 2%, through use of DOCs.

Point *B* has more moderate budgets of $250,000 in the long term and $800,000 initially. $PM_{2.5}$ can be cut by at most just over 31%. The strategy required to do so is more complex than that used at points *A* or *C*. Still, it so happens that all of the retrofits and retirements are conducted on previously unretrofitted vehicles (which is certainly not always the case). The strategy is described in Fig. 6.

A few results from the point *B* strategy are predictable. First, no model year 2007 or 2008 buses are touched. These buses are incompatible with all retrofits, and have the same emissions as a replacement bus. Second, only small buses are retired. This is not surprising, given the binding initial budget constraint and the fact that short buses have a lower purchase cost. Other elements of the strategy are less straightforward. Why replace several short buses of different years, but none of the oldest model year 1984 short buses? In the long term, 1984 model year short buses are the most cost effective short buses to replace, but initially they are not. This balancing of initial and long-term cost effectiveness is a difficult challenge, and is well suited for an integer programming approach. Simpler techniques, such as ranking retrofits by long term or initial cost effectiveness, would not be able to develop the sophisticated strategies provided by the integer program.

5. Conclusion

This paper addressed several questions regarding the cost effectiveness of emission reduction retrofits and early replacement. One such question is "Is it more cost effective to retrofit younger or older buses?" This question does not have a simple answer. As discussed in Section 4.5, the cost effectiveness of a retrofit is a function of both emission rates of the vehicle and the expected remaining usage. The result is that retrofitting an older bus can be more cost effective than retrofitting a younger bus, or the other way around, even if the retrofit costs the same amount in each case.

Another question considered was "When is retrofitting more cost effective than replacement, and when is replacement more cost effective than retrofitting?" This question does not have a simple answer either. As seen, long term and initial cost effectiveness of vehicle replacement can be very different. The integer program presented is able to balance the two types of cost effectiveness when composing cleanup strategies. The discrete nature of the problem makes integer programming a natural choice, and it is indeed able to produce sophisticated strategies that would not otherwise be readily apparent.

Acknowledgements

The authors would like to thank the staff at the US EPA, especially David Brzezinski, who took the time to provide thorough documentation and to answer questions on US EPA models and research. We are appreciative of all those who took the time to discuss their experiences with us. We are also grateful to Joanne Lee for her help in the early preparation of the study. This work was partly supported by NYSERDA Project 10026, NYSDOT Project C-07-12 and a mini paper grant from University Transportation Research Center, Region II.

References

Dill, J., 2004. Estimating emissions reductions from accelerated vehicle retirement programs. Transportation Research Part D 9, 87–106.

HUSS, 2008. Product Overview, viewed 28 October 2008, <http://www.huss-umwelttechnik.com/en/products/product-overview.php>.

Mostashari, A., Sussman, J.M., Connors, S.R., 2004. Design of robust emission reduction strategies for road-based public transportation in Mexico City, Mexico. Transportation Research Record 1880, 90–98.

Sohn, C.W., Homan, K.O., 1994. Estimated Retrofit and Replacement Costs for Army Air-Conditioning and Refrigeration Equipment Presently Using Chlorofluorocarbons (TR FE-84/07). US Army Center for Public Works, Alexandria.

Spitzley, D.V., Grande, D.E., Keoleian, G.A., Kim, H.C., 2005. Life cycle optimization of ownership costs and emissions reduction in US vehicle retirement decisions. Transportation Research Part D 10, 161–175.

US 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 (EPA420-R-01-047). US EPA, Washington, DC.

US Environmental Protection Agency, 2003a. Diesel Exhaust in the United States (EPA420-F-03-022). US EPA, Washington, DC.

US Environmental Protection Agency, 2003b. Technical Highlights: Questions and Answers on Using a Diesel Oxidation Catalyst in Heavy-duty Trucks and Buses (EPA420-F-03-016). US EPA, Washington, DC.

US Environmental Protection Agency, 2006. Diesel Retrofit Technology: An Analysis of The Cost-Effectiveness of Reducing Particulate Matter Emissions from Heavy-Duty Diesel Engines Through Retrofits (EPA420-S-06-002). US EPA, Washington, DC.

US Environmental Protection Agency, 2007a. Verified Retrofit Technologies from Donaldson, viewed 28 October 2008, <http://www.epa.gov/otaq/retrofit/techlist-donaldson.htm>.

US Environmental Protection Agency, 2007b. Clean School Bus USA: Retrofit, viewed 28 October 2008, <http://epa.gov/cleanschoolbus/retrofit.htm>.

US Environmental Protection Agency, 2007c. Verified Retrofit Technologies from Johnson Matthey, viewed 28 October 2008, <http://www.epa.gov/otaq/retrofit/techlist-johnmatt.htm>.

US Environmental Protection Agency, 2008a. National Clean Diesel Campaign, viewed 28 October 2008, <http://www.epa.gov/cleandiesel/>.

US Environmental Protection Agency, 2008b. Diesel Retrofit Technology Verification: Verified Technologies List, viewed 27 October 2008, <http://www.epa.gov/OMS/retrofit/verif-list.htm>.

Van Setten, B.A.A.L., Makkee, M., Moulijn, J.A., 2001. Science and technology of catalytic diesel particulate filters. Catalysis Reviews 43, 489–564.

Zelazny, D., Wang, Z., 1998. Replacing or Retrofitting Oil/Water Separators: A Case Study at Fort Lee, VA (SFIM-AEC-ET-CR-9802). US Army Environmental Center, Aberdeen Proving Ground.