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The retrofit puzzle: optimal fleet owner behavior in the context of diesel retrofit incentive programs

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December 31, 2007

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
The retrofit puzzle: optimal fleet owner behavior in the context of diesel retrofit	December 31, 2007
	6. Performing Organization Code
7. Author(s) H. Oliver Gao, Ph.D., Timon H. Stasko	8. Performing Organization Report No.
9. Performing Organization Name and Address School of Civil and Environmental Engineering Cornell University Ithaca, NY 14853 USA	10. Work Unit No.
	11. Contract or Grant No. 49777-1418 (subcontract No.)
12. Sponsoring Agency Name and Address University Transportation Research Center – Region 2 138th Street and Convent Avenue, NYC, NY 10031	13. Type of Report and Period Covered Final Report – January – December 2007
	14. Sponsoring Agency Code

15. Supplementary Notes

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17. Key Words	18. Distribution Statement
Diesel retrofits; Profit maximization: Emission reductions; Integer programming	

19. Security Classif (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified	46	

Form DOT F 1700.7 (8-69)

* 2. Manuscript

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Abstract

Potential government regulations and financial incentives for encouraging pollution reduction retrofits on diesel vehicles are discussed. An integer program is developed to model profit-maximizing fleet owner behavior in the context of potential government programs. The model is intended as a tool both for fleet owners and for government administrators. It allows for mandated retrofits, mandated percent reductions of specified emissions, fixed grants for performing retrofits, and grants per gram of pollution prevented. It treats the fleet size and miles remaining for each vehicle as fixed and known at the time retrofits are made. Retrofits are all assumed to take place in the present, but benefits and costs are distributed over time. A case study is used to demonstrate how a sample fleet owner would respond to various incentives. Potential directions for future research are discussed.

Keywords: Diesel retrofits; Profit maximization: Emission reductions; Integer programming

1. Introduction

Air pollution is an issue of growing importance to the public health, ecosystem, and social welfare (National Research Council, 2004). As our understanding of the science of emissions improves, the severity of their impact on public health is becoming increasingly clear. Vehicles in particular emit large amounts of nitrogen oxides (NOx), particulate matter (PM), hydrocarbons (HC), and other damaging pollutants. The U.S. Environmental Protection Agency (EPA) attributes thousands of instances of premature mortality, hundreds of thousands of asthma attacks, and millions of lost work days to particulate matter and nitrogen oxides emissions (U.S. Environmental Protection Agency, 2007a). Vehicle emissions are also a major culprit in global warming. According to the EPA, the transportation sector was the second largest contributor to U.S. greenhouse gas emissions in 2005, slightly behind electricity generation (U.S. Environmental Protection Agency, 2007b).

With the passage of the Clean Air Act (CAA) in the 1970's and subsequent amendments in the 1990's, the U.S. government began addressing the problem. National Ambient Air Quality Standards (NAAQS) were declared, and a system was put in place to enforce them at both regional and local scales. The system allows for context-appropriate solutions through state implementation plan (SIP) development, transportation conformity rules, and other National Environmental Policy Act (NEPA) procedures. Despite laudable efforts, NAAQS have proven extremely difficult to meet in some cases, with some areas of the country seemingly stuck in non-attainment status. EPA maps reveal that major urban areas across the country fail to meet the 8-hour ozone requirements, as do selected non-urban areas and several entire states (U.S. Environmental Protection Agency, 2007c).

One of the challenges facing administrators is that no matter how strict emission standards become for new vehicles, it will be many years before older vehicles that operate outside those standards are off the road. This delay is particularly pronounced with diesel vehicles. Heavy-duty trucks and busses use diesel engines largely because of their reliability and relatively low operating cost. This reliability means that their average lifespans are substantially greater than those of gasoline powered cars. Diesel vehicles already on the road today could very well be in use for another 25 years and drive close to a million miles before being retired (U.S. Environmental Protection Agency, 2007d). Furthermore, the size of the current fleet is substantial. There are over 11 million diesel engines operating in the existing fleet (U.S. Environmental Protection Agency, 2007a). These vehicles fill vital roles in our economy including freight transportation, construction, port operations, and public transportation. Over the past decade, the maximum allowable particulate matter and nitrogen oxides emissions for new diesel trucks and busses have been reduced by an order of magnitude (U.S. Environmental Protection Agency, 2003), but much of this existing fleet is not bound by these tighter restrictions.

Unfortunately, applying the same standards to the older vehicles is not a viable option. The cost would simply be prohibitive. Nonetheless, older vehicles cannot be ignored when addressing our emissions problem. The health effects of diesel exhaust are real and immediate. Lower pollution levels in twenty years are not an adequate solution for people who are developing health problems today. According to a report by The

Clean Air Task Force, fine particulate matter from diesels shortens the lives of nearly 21,000 people every year (Clean Air Task Force, 2005). The same report states that “nationally, diesel exhaust poses a cancer risk that is 7.5 times higher than the *combined* total cancer risk from all other air toxics.” (Clean Air Task Force, 2005)

Fortunately, diesel retrofit options are available. Fuel delivery and air intake systems can be optimized (U.S. Environmental Protection Agency, 2007d). Particle traps and catalytic converters can treat exhaust before it exits the vehicle, transforming harmful pollutants into more benign compounds (U.S. Environmental Protection Agency, 2007d). Unfortunately, all of these upgrades come at a cost. Implementing every possible upgrade on every existing vehicle is simply not feasible. The question becomes: which subset of potential retrofits is optimal?

Society’s objective is to minimize the total cost – both the direct expense of upgrades, and the externality imposed on society when upgrades are not made. Responsible government policy must take both types of costs into account. Policy makers must consider that upgrades will not have the same effect on all vehicles. In particular, older vehicles may experience a greater emission reduction from an upgrade, but older vehicles are also likely to be retired sooner. Furthermore, upgrades might influence each others’ effectiveness. Fleet owners are unlikely to be able to take large numbers of trucks off the road for upgrades at once, so practical scheduling is essential.

Each upgrading strategy has its own strengths, weaknesses and variability/uncertainty in emission reduction efficiency[1]. The emissions reductions due to

[1] Engine replacements and recalibration can be effective and may result in enhanced fuel economy and lower maintenance costs, but can be expensive. Switching to cleaner fuels might be easy, as in the case of switching to lower sulfur fuel or biodiesel blends, but has nominal air quality benefit on its own. Switching to alternative fuels, like natural gas, can be very effective, but one has to establish a new fueling and

retrofits are subject to many uncertain external factors, including environmental factors (e.g., temperature, humidity), fleet characteristics (e.g., age distribution of fleet, distribution of VMT by vehicle class, number and types of vehicles), activity measures (e.g., speed distributions, distribution of VMT by roadway type), and fuel characteristics (e.g., sulfur content, Reid vapor pressure (RVP)) (U.S. Environmental Protection Agency, 2006e). Retrofit devices need to be used in the right application. Even with good certified retrofitting technologies, unwise decisions in operations and deployment of a retrofit program could significantly limit the benefit.

In addition to determining which retrofit implementations are wise, the government must decide how to encourage fleet owners to conduct them. Without regulation or incentives, fleet owners can't necessarily be counted on to make upgrades. The primary justification for retrofits is an externality which substantially affects large numbers of people, but not a firm's profit maximization. How can the government encourage fleet owners to conduct justified retrofits, while stimulating development of new upgrades and not imposing undue costs on fleet owners?

In order to develop such policies, the government will have to predict fleet owner behavior. This paper outlines an integer programming model to better understand profit maximizing retrofit selection, in the context of possible government programs. It allows for mandated retrofits, mandated percent reductions of specified emissions, fixed grants for performing retrofits, and grants per gram of pollution prevented. It treats the miles remaining for each vehicle as fixed and known. The fleet size is also regarded as fixed

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maintenance infrastructure in addition to engine and fuel system modifications. Aftertreatment devices need to be used in the right application and are generally effective only for two or three of the four targeted categories of pollutants (PM, NOx, hydrocarbons, and CO). Anti-idling strategies are a winner across almost all applications and save fuel and money. However, these programs are difficult to monitor, quantify and enforce.

and known. Retrofits are all assumed to take place in the present, but benefits and costs are distributed over time. When run, the program reveals which retrofits will be conducted, what costs are borne by whom, and what emission reductions are experienced.

Before describing the model formulation, the paper provides literature review covering past work on diesel retrofits and similar integer programs. Next, potential government policies are outlined and a subgroup is selected for use in the model. Once the selections have been described, the model is formulated. The formulation is followed by a case study. Finally, applications and avenues for future research are discussed.

2. Literature Review

There is little previous work on optimization models for fleet owners and diesel retrofit program managers to assist them in making informed decisions on their diesel fleet and retrofit programs respectively. Applicable research generally falls into one of two categories: a) research done by or for government agencies on the viability, efficiency, effectiveness, and cost of retrofits or b) research done on integer programs for related problems.

In order to reduce diesel emissions, the EPA collaborates with the state and local governments as part of the National Clean Diesel Campaign (NCDC). The program includes technical and financial assistance to fleet owners looking to lessen emissions from their fleets, as well as regulation (U.S. Environmental Protection Agency, 2007a). The EPA's National Mobile Inventory Model (NMIM) can be used to quantify emission reductions from retrofits (U.S. Environmental Protection Agency, 2006a). NMIM includes two EPA emission estimation programs: MOBILE 6.2 for on-road emissions and NONROAD for off-road emissions (U.S. Environmental Protection Agency, 2006b). The

EPA publishes documentation on the development of these models, as well as information on verified retrofits.

The California Air Resources Board set up the Carl Moyer Memorial Air Quality Standards Attainment Program to provide incentives for cleaner than required vehicles (California Air Resources Board, 2007a). Like the EPA, they publish information on retrofits that they verify (California Air Resources Board, 2007b). They also publish descriptions of the criteria they use for selecting retrofit projects to support (California Air Resources Board, 2006).

The EPA published a report analyzing the cost effectiveness of retrofits for reducing particulate matter emissions from selected heavy-duty vehicles (U.S. Environmental Protection Agency, 2006c). In particular, the report looked at two principle types of retrofit technologies: diesel oxidation catalysts (DOCs) and catalyzed diesel particulate filters (CDPFs) (U.S. Environmental Protection Agency, 2006c). They calculated the approximate cost per ton of reducing PM emissions on selected vehicle types using these retrofits. After comparing their results with the costs of other programs, they found retrofits could be a cost effective way to reduce air pollution (U.S. Environmental Protection Agency, 2006c). In addition, Schipper (2005) analyzed the impact of a pilot project of retrofits on buses in Mexico City. The primary goal of the study was to analyze the impact of Mexico City's high altitude on the retrofits' effectiveness. The findings from both studies are important, and the analyses used to produce the results are highly relevant, but they provide no means of predicting fleet owner behavior in the context of multiple government programs. They also only provide cost effectiveness estimates of a small subset of potential retrofit options.

Independently, integer programs have been developed for problems with similar characteristics to the fleet owner's retrofit selection. Marsten and Muller (1980) published a profit maximizing mixed integer program for assigning planes to air cargo movements. More recently, Janic published another integer program for a profit maximizing airline operator selecting how many planes to fly on each route (Janic, M., 2003). Similar to diesel fleet owners, the airline operators in Janic's model are bound by constraints imposed by the government to control externalities. Janic's model does not include government subsidies or taxes which would directly impact the airline's profit.

Charnes et al. (1976) described a goal interval programming formulation for a marine environmental protection program. It was designed to minimize weighted deviations from a set of government goals. It did not, however, incorporate a model of individuals and firms responding to government actions. Marino and Sicilian studied the profit maximizing monopolist's and utilility maximizing consumer's reactions to government regulation of utilities. In particular, the paper examined the incentive for conservation investment given a government imposed constraint on the rate of return on capital (Marino and Sicilian, 1988). While a related problem, the regulatory tools used for utilities are distinctly different from those considered for fleet owners in this paper.

3. Potential Government Approaches

A multitude of potential government policies exist. In general, such polices either require retrofits, or encourage them with incentives. More specifically, many potential programs fit into the following categories:

1. Mandates

a. Mandate some percentage reduction of selected pollutants for fleets meeting some criteria (e.g. size above 100 vehicles);
b. Mandate vehicles in a given vehicle class are upgraded with a given technology, within fleets meeting some criteria;
c. Set maximum average grams of pollution per mile for a given pollutant for fleets meeting some criteria.

2. Grants
    a. Give money for every vehicle of a certain class receiving a specific upgrade;
    b. Give money for every gram of a specific pollutant saved by conducting a retrofit.
3. Loans
    a. Give low interest loans for certain upgrades on certain vehicle classes.
4. Taxing pollution
    a. Charge fleet owners for each gram of a given pollutant their fleet emits;
    b. Charge fleet owners for each gram of a given pollutant their fleet emits beyond a certain threshold (e.g. current emissions)[2];
    c. Charge fleet owners for each gram of a given pollutant their fleet emits, and allow them to trade pollution credits;

[2] Such tax programs are particularly attractive because they lower the costs imposed on fleet owners, while maintaining the incentive to reduce emissions at the margins (Vollebergh, 1997). Similar grandfathering programs were analyzed in the context of carbon emissions by Vollebergh et al. (1997) and in a general optimal tax reform context by Zodrow (1992).

d. Charge fleet owners for each gram of a given pollutant their fleet emits beyond a certain threshold (e.g. current emissions), and allow them to trade pollution credits[3].

Government approaches 1a, 1b, 2a, and 2b were selected to be explicitly included in the model of this study.

First, the government may mandate some percentage reduction of selected pollutants for fleets meeting some criteria (e.g. size above 100 vehicles). Fleet owners take the appropriate percentage reduction requirements for each pollutant for their fleet, and plug them into their maximization program as constants. It is completely possible that for some fleets and pollutants the reduction requirement will be zero.

Second, the government may mandate specific vehicle types receive specific upgrades. This was included despite the fact that there is no choice involved on the part of the fleet owner. The model is in no way required to predict these retrofits will take place, but the fact that they are taking place can impact decisions made regarding other retrofits (by changing their effectiveness, for example). They were included solely for this reason.

Third, the government can issue grants for vehicles of a given type receiving a specific upgrade. This has potential as a practical incentive program, which would be feasible to execute.

Fourth, the government can issue grants per gram of specific pollutants reduced. These grants would be challenging to administer, but they have the potential to be highly

[3] A similar grandfathering program was analyzed in the context of carbon emissions by Vollebergh et al. (1997).

effective. The differences between these grants and the previous type are discussed in Appendix A.

Caps on the fleet's pollution per mile were not included as a mandate because this would require modeling the fleet as a whole (including newly purchased vehicles not intended to directly replace older vehicles).

While loans were not explicitly included in the model, they can be effectively represented as a series of grants. Money paid by the government to the fleet owner would be a positive grant, while a payment by the fleet owner back to the government would be a negative grant.

Taxes were also not included explicitly, but from a fleet owner behavior perspective some taxes are very similar to grants. If fleet owners were taxed per gram of a given pollutant, it would have the same effect on their behavior as being taxed a flat fee equal to the tax they would pay on pollution if they performed no retrofits, and then awarded grants per gram of pollution reduced by retrofits. The marginal benefits of retrofits would be the same. In other words, switching from grants to taxes requires we add a constant to the objective function, which would not impact the solution of the integer program[4]. On the whole, taxes would make the fleet owner less well off while grants would make the fleet owner better off, but this is a concern when dealing with social welfare, not when modeling fleet owner behavior. For a more detailed explanation, see Appendix B.

Tax programs that include emissions markets cannot be accurately modeled by the grant programs in this model. Such markets would require modeling several fleet

[4] So long as the constant is non-zero the optimal objective value would change. The optimal values of the decision variables, on the other hand, would never change (Gürdal et al., 1999).

owners, and possibly their interactions among themselves and with the environmental management agencies. Such a task is beyond the scope of this paper, but this paper does provide a stepping stone for moving in such a direction.

4. Model Formulation

The set I is defined as the set of all vehicle types in the fleet, indexed by i. Vehicles should be broken down by make, model, year, engine, expected future use, and any past retrofits or variation that could influence the effectiveness or compatibility of future retrofits. Let n_i be the number of vehicles of type i currently in the fleet.

The set J is defined as the set of all possible retrofits, indexed by j. Each retrofit includes a set of compatible pollutant control technologies. If the retrofit is selected, all its technologies are applied. Cleaner fuels are considered a possible pollutant control technology, as is replacing an older engine with a newer and cleaner engine. This permits the model to optimize the balance between retrofitting and replacing engines. (Issues regarding the miles remaining for a replaced engine or vehicle are discussed in Appendix C). A fleet owner may wish to combine two or more retrofit technologies if the combination reduces more pollutants than using either retrofit technology alone. This combination can be considered a separate possible retrofit (in addition to each technology alone). By treating combinations of diesel cleaning technologies in this fashion, retrofits can influence each others' effectiveness in a nonlinear fashion, while maintaining a linear objective function and constraints (apart from integrality). Finally, for this formulation, the set J includes a default case "retrofit" with no retrofitting.

The set K is the set of all relevant pollutants (e.g., NOx, PM, etc.), indexed by k.

The set T is the set of all time periods in which retrofit costs could be incurred or revenues received, indexed by t with t=1 designating initial time period (when retrofit decisions are made and retrofits are conducted). All periods are assumed to be evenly spaced, and all costs are assumed to take place at the start of the period. Model users (e.g., fleet managers, government agencies managing diesel retrofit) can choose the length of periods, balancing the desire for a more accurate model (with shorter periods) and a simpler one (with longer periods).

Let x_{ij} be the number of vehicles of type i to receive retrofit j. It is unclear what retrofitting a fraction of a vehicle would mean, so all x_{ij} must be integer. In addition, all x_{ij} must be non-negative. If a fleet owner wants to allow for the removal of a retrofit technology, he or she can simply define this removal as another retrofit. Furthermore, fleet owners can define u_{ij} as the maximum number of vehicle type i they are willing to give retrofit j. If vehicle type i is incompatible with retrofit j, u_{ij} is set to zero. These constraints are expressed in equations 1 and 2:

$$x_{ij} \text{ is integer} \quad \forall i, j \tag{1}$$

$$0 \leq x_{ij} \leq u_{ij} \quad \forall i, j \tag{2}$$

Given that combinations of technologies are considered as distinct alternate retrofits, and that a zero technology retrofit option exists, the total number of retrofits performed on vehicles of type i must equal the total number of vehicles of type i, n_i.

$$\sum_{j \in J} x_{ij} = n_i \quad \forall i \tag{3}$$

The government might require, or the fleet owner might insist, that certain technologies are applied to some vehicle types. One might argue that because applying such technologies is no longer a choice, they could be removed from the model without any impact. While it is true that the model is not required to predict that the fleet owner will conduct the required upgrades, they should still be included because of the effects they could have on other technologies' effectiveness.

In order to meet the emission reduction goals, the fleet owner must select retrofits from a subset of *J* that includes all retrofits which include the required technologies, and no retrofits that do not. If there are no required technologies for vehicle type *i*, this subset contains all retrofits in *J*. Also, any retrofits which contain technologies incompatible with vehicle type *i* can be removed from the subset. The resulting subset for a given vehicle type *i* is called Jr_i. The removal of retrofit packages containing technologies incompatible with the vehicle type is optional, however, because the incompatibility can be sufficiently expressed by the upper bounds in expression 2. A method for representing incompatibilities implicitly is discussed in Appendix D. Whether incompatible retrofits are removed from Jr_i or not, the requirement can then be expressed as follows:

$$\sum_{j \in Jr_i} x_{ij} = n_i \qquad \forall i \tag{4}$$

The time a vehicle of type *i* must be taken out of service to receive retrofit *j* is w_{ij}. A fleet owner may have demands that must be met, and consequently can define a_i as the maximum acceptable time out of service for all vehicles of type *i*.

$$\sum_{j \in J} x_{ij} \cdot w_{ij} \le a_i \qquad \forall i \text{ with a time-out-of-service requirement} \tag{5}$$

The opportunity cost for every unit of time a vehicle of type i is out of service is p_i. The total opportunity cost of all retrofits installed can be expressed:

$$\sum_{i \in I} \sum_{j \in J} x_{ij} \cdot w_{ij} \cdot p_i \tag{6}$$

Apart from opportunity cost, the cost of installing retrofit j on vehicle type i incurred in period t is c_{ijt}. The parameter c_{ijt} includes the estimate of the equipment cost for applying retrofit j to vehicle type i, $c_{equipment\_ijt}$, the owner's initial installation cost, $c_{installation\_ijt}$, and change in maintenance cost, $c_{maintenance\_ijt}$. An additional cost c_{other_ijt} is included to capture other costs not mentioned. Some of these costs (such as installation) may be non-zero at the initial time period, while others (such as change in maintenance cost) may only be non-zero at later periods. All costs are expressed in dollars at the point in time when the cost would be incurred. The total cost (less opportunity cost) of installing retrofit j on vehicle type i, incurred in period t, is c_{ijt}:

$$c_{ijt} = c_{equipment\_ijt} + c_{installation\_ijt} + c_{maintenance\_ijt} + c_{other\_ijt} \quad \forall i, j, t \tag{7}$$

Future costs are brought back to period 1 using an interest rate deemed appropriate by the fleet owner. Let β_t be the appropriate interest rate for bringing values from period t back to period 1. We know that β_1 will be 0, but the other values depend on the time value of money to the fleet owner. The total cost (less opportunity cost), for all time periods, of installing retrofit j on x_{ij} vehicles of type i can be expressed:

$$\sum_{t \in T} \frac{1}{1+\beta_t} \cdot x_{ij} \cdot c_{ijt} \quad \forall i, j \tag{8}$$

The emission rate er_{ikt} is the amount of pollutant k emitted to the atmosphere in grams per unit mile by vehicle type i in period t. The parameter m_{it} is the expected vehicle miles traveled (VMT) for a vehicle of type i in period t. Estimates of both er_{ikt} and m_{it} can be obtained from regulating organizations, such as EPA's MOBILE 6 documentation and truck VMT statistics. This is covered in more detail in the case study.

Each retrofit j installed on vehicle type i can reduce pollutant type k by a factor of y_{ijkt} in period t. The parameter y_{ijkt} is important because it affects the total amount of pollutant k emissions reduced when vehicles of type i receive retrofit j.

Fleet owners use the emission reduction parameter y_{ijkt}, to ensure they meet their goal of reducing their emissions of pollutant k by r_k percent through retrofitting. The percentage reduction r_k could be regulated by the government, or it could be a goal set by ambitious fleet owners who are motivated to go beyond government standards. In either case, this constraint can be expressed as:

$$\frac{\sum_{i\in I}\sum_{j\in J}\sum_{t\in T} x_{ij}\cdot m_{it}\cdot er_{ikt}\cdot y_{ijkt}}{\sum_{i\in I}\sum_{t\in T} n_i\cdot m_{it}\cdot er_{ikt}} \geq \frac{r_k}{100} \quad \forall k \tag{9}$$

Calculating the total benefits of the retrofit-replacement strategies (in the eyes of the fleet owner) requires an estimation of the monetary value of reducing pollutant k by installing retrofit technologies in the fleet. The fleet owner sets L_{kt} as the conversion factor to dollars from grams of pollutant k (units \$/gram) in period t. This conversion factor is likely to be highly dependent on government programs. It could, for example, be set equal to a government subsidy provided per gram of pollutant k saved by retrofits. It could also be determined in an emission trading market. Once all L_{kt} are set, the dollar value of the emissions reduction of pollutant k is expressed by:

$$\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot x_{ij}\cdot m_{it}\cdot er_{ikt}\cdot y_{ijkt}\cdot L_{kt} \qquad \forall k \tag{10}$$

It is possible federal, state, or local government might have an incentive program in place which issues grants to fleet owners who perform specific retrofits on specific vehicles. We will define incentive, G_{ijt}, as the grant paid in period t for retrofit j being performed on a vehicle of type i. Before the state and local governments provide this assistance, fleet owners are typically required to apply for this assistance. As a result, the value of G_{ij1} may be somewhat less than the funds provided in the initial period, in order to offset the cost of application. In total, a fleet owner will receive the following benefits from such programs:

$$\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot x_{ij}\cdot G_{ijt} \tag{11}$$

The objective function contains the total benefits from using retrofit technologies (expression 10 plus expression 11), minus total costs of retrofit implementation (expression 6 plus expression 8 summed over all i and j). It is expressed by:

$$\begin{aligned}Max\ \{&\sum_{k\in K}\ (\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot x_{ij}\cdot m_{it}\cdot er_{ikt}\cdot y_{ijkt}\cdot L_{kt})\\ &+\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot x_{ij}\cdot G_{ijt}-\sum_{i\in I}\sum_{j\in J}x_{ij}\cdot w_{ij}\cdot p_i-\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot c_{ijt}\cdot x_{ij}\}\end{aligned} \tag{12}$$

The final optimization model is an integer program in which the objective is given by expression 12 as a function of decision variables x_{ij} and the constraints are given in expressions 1, 2, 3, 4, 5 and 9. The model results indicate the profit maximizing retrofit-replacement strategy for the selected fleet, retrofit-replacement technologies, regulations, and incentive programs.

Several constraint types are notably and intentionally absent from this model. For example, it might appear reasonable to add a budget constraint. Fleet owners are inevitably bound by budgets, and these budgets influence their decisions. It might seem logical to require the sum of all costs remain less than some budget. A profit maximizing fleet owner, however, would be willing to accept higher costs if the benefits compensated for the costs. Thus, a more appropriate constraint would require that benefits minus costs are greater than some cutoff. This constraint is effectively already represented by the objective function. The integer program will return the highest possible objective value (benefits minus costs). If the result is less than the owner's cutoff*,* he or she will know that there is no feasible solution that meets the cutoff, and must adjust the cutoff or constraints accordingly. If the result does exceed the cutoff, the fleet owner will know she has the best feasible solution.

Also apparently absent are the effects of retrofits on fuel consumption. Fuel consumption is important to fleet owners because it contributes substantially to operating costs. Fortunately, these effects can actually be included within the current model framework. In addition to typical diesel pollutants (such as NOx or particulate matter), the set K could include fuel consumption as a "pollutant." If fuel consumption is considered a "pollutant" its "emission rate," er_{ikt}, will be the fuel consumption rate of the vehicle prior to any retrofits. It makes sense to use units of gallons/mile for fuel, unlike other pollutants which typically have emissions rates expressed in grams/mile. The constant y_{ijkt} would be the fraction reduction in fuel consumption in period t when retrofit j is applied to vehicle type i. If a retrofit makes a vehicle less fuel efficient, which is completely possible, y_{ijkt} can simply be a negative number. The fleet owner could set L_{kt} equal to the average price he or she expects to pay for standard diesel fuel in period t. Thus, assuming the vehicles use standard fuel both before and after the retrofits, the monetary benefits of retrofits to fuel consumption will be given by expression 10, where k is set equal to the index corresponding to fuel in the set K. If a vehicle uses non-standard fuel, either before or after the retrofit, or both, then obviously L_{kt} (the expected price of standard diesel fuel for period t) will not be sufficient for describing fuel costs. Even in these cases, however, no new variables or parameters need to be added. The incremental cost of the non-standard fuel can be included by adjusting c_{ijt}.

5. Case Study

The purpose of this case study is to demonstrate the types of results that the model can produce. The particular fleet in question is fictional, as are the government programs. Nonetheless, they are intended to provide reasonable examples of how this model could be used and how the results could be interpreted.

Sample Fleet:

Our sample fleet includes 10 HDDV2B trucks from 1989 with 200,000 miles of use, as well as 20 HDDV8A trucks from 1994 with 400,000 miles of use. The HDDV2B classification, which is used by the EPA for classifying emissions rates, indicates a light heavy-duty diesel truck (gross weight between 8,501 and 10,000 lbs) (U.S. Environmental Protection Agency, 2002a). The HDDV8A classification indicates a heavy heavy-duty diesel truck (gross weight over 60,000 lbs) (U.S. Environmental Protection Agency, 2002a).

For this example, we will use periods of years. Furthermore, we will say that all HDDV2B vehicles in the fleet are expected to be in use for another four years, while the HDDV8A vehicles will be in use for another five years. Expected mileage in each of the next five years, along with the unretrofitted emissions rates, are given in Table 1.

The Federal Highway Administration (FHWA) publishes estimates of the average miles traveled by trucks in various uses (U.S. Department of Transportation, 2007), and our expected mileages fall into the general range of their averages (with the exception of the last two years of the vehicles' lives, when their usage is assumed to taper off and drop below average).

Emissions Rates:

Fleet owners could estimate emissions rates for their vehicles in several different ways. They could use data provided by the vehicles' manufacturers and the EPA, combined with their own knowledge of the environment and mode in which their vehicles normally operate (altitude, speed, etc) to develop their own unique emission rates.

Alternatively, fleet owners could use more general averages for a rougher estimate. It is plausible (even likely) that government agencies would use more general averages for enforcement purposes, in order to avoid having to trust data provided by the fleet owners themselves. If the government was using such averages to distribute grants, it would make sense for fleet owners to use them in their own calculations. Consequently, we will do just that in this example.

We will draw carbon monoxide, nitrogen oxides, and hydrocarbons emission rates from EPA document M6.HDE.001, which provides emissions rates for use in the EPA's mobile emissions model, MOBILE 6.2 (U.S. Environmental Protection Agency, 2002b). MOBILE 6.2 is currently used by the EPA and represents the state of the practice. Emission rates in document M6.HDE.001 are in units of grams per brake-horsepower-hour, however, which we cannot use without a conversion factor. Another EPA document, M6.HDE.004 (U.S. Environmental Protection Agency, 2002a), provides these conversion factors to change the units to grams per mile. Conversion factors are dependent on the vehicle type, as well as the density of the fuel it is using.

Particulate matter emission rates are not described in either of the above documents. The rates we use are based on values from files that come as a part of the National Mobile Inventory Model (NMIM), which is an EPA software package including MOBILE 6.2. We multiply the PM_{10} emission rates in these files by a factor of 2.3, as discussed in the EPA's analysis of the cost effectiveness of particulate matter reducing retrofits (U.S. Environmental Protection Agency, 2006c). The factor of 2.3 is designed to compensate for the difference between older engine dynamometer tests and more accurate chassis dynamometer tests (U.S. Environmental Protection Agency, 2006c). Even though the factor of 2.3 was developed only from data for HDDV8A trucks, we apply it to the HDDV2B PM emission rate as well because no comparable factor is available. The EPA made a similar assumption in applying the factor to vehicles of class 6 and 7 (U.S. Environmental Protection Agency, 2006c). Unlike carbon monoxide, nitrogen oxides, and hydrocarbons, the HDDV8A particulate matter emission rate is assumed to be constant over the period of analysis. The HDDV2B particulate matter emission rate increases slowly with vehicle usage.

For this example, the emission rates (g/mile) are listed in Table 1.

[Insert Table 1 about here]

Potential Retrofits:

We will assume that there are three technologies available, all from the EPA's list of verified retrofit technologies (U.S. Environmental Protection Agency, 2007e): a Continuously Regenerating Technology (CRT) Particulate Filter, Platinum Plus Purifier System (fuel borne catalyst plus diesel oxidation catalyst), and cetane enhancers. Their individual emission reducing effects on particulate matter, carbon monoxide, nitrogen oxides, and hydrocarbons are taken directly from the EPA's list of verified retrofit technologies, with the mean of the two bounds used where ranges are provided. These reductions are assumed to be constant with time in the example, but they could be allowed to change with time. Combinations are assumed to be possible and the reductions are combined according to the following formula:

$$\phi_T = 1-(1-\phi_1)(1-\phi_2)$$

where φ_T is the combined reduction and φ_1 and φ_2 are the reductions due to the individual technologies. Overall, there are eight retrofit options, all outlined in Table 2.

[Insert Table 2 about here]

Incompatibilities and Mandatory Retrofits:

It is worth noting here that because the HDDV2B trucks were manufactured before 1994, they are incompatible with the CRT Particulate Filter and therefore cannot receive any retrofits that include it. Otherwise, there are assumed to be no incompatibilities. We will model this using the required technology constraints. For the purposes of this example, no technologies will be required. The subset Jr_i (used in equation 4) is 1,3,4, and 7 for HDDV2B trucks and 1,2,3,4,5,6,7,8 for HDDV8A trucks.

Grant Programs:

Grants issued on a per gram basis are assumed to be as listed in Table 3.

[Insert Table 3 about here]

The California Air Resources Board's guidelines for funding emissions reduction retrofits through the Carl Moyer Program require all potential projects cost no more than $14300 per "weighted ton of surplus NOx, ROG, and PM 10" where ROG stands for reactive organic gasses. They defined the "weighted tons of surplus" as the tons of NOx plus the tons of ROG, plus twenty times the tons of PM. Particulate matter is given more weight because it has been identified as a toxic air contaminant (California Air Resources Board, 2005).

The grants per gram are based on this requirement. The value of reducing NOx HC, or CO, by a ton in the first year is taken to be $14300, while the value of reducing PM by a ton is taken to be twenty times as much. Correspondingly, the grants per gram are twenty times as high for PM as for other pollutants.

For two reasons, the grants per gram are not the full "value" of the emissions reduction, however. First, some funding is being given out in the form of fixed grants, meaning that if the full "value" was paid in grants per gram, more than the "value" would be paid in total. Second, the government has limited funds with which to promote retrofits. It is in the interest of the government to pay as little as possible per gram while still achieving desired reductions. This issue will be explored in more detail in *Sensitivity Analysis* section. For now, grants per gram are 25% of the “value” of the emissions reduction. Any costs beyond these grants are to be covered by fixed grants and the fleet owner.

In addition, grants per gram are to be increased at a rate of 2% per year, in an attempt to keep up with inflation. Two percent is used as the rate of inflation because the Consumer Price Index for all items and all urban consumers increased by roughly 2% between January 2006 and January 2007 (Bureau of Labor Statistics, 2007).

Fixed grants are assumed to take place only in period 1, and are listed in Table 4, along with costs and time out of service.

[Insert Table 4 about here]

Retrofit Costs:

The up front costs for CRT Particulate Filters and Platinum Plus Purifier Systems are loosely based on approximate costs for particulate filters and oxidation catalysts listed in a letter from the Manufacturers of Emissions Controls Association posted on the EPA website (U.S. Environmental Protection Agency, 2000).

The cost of the fuel borne catalyst is based on the fuel economies of the trucks (taken from EPA document M6.HDE.004), the expected mileages for the trucks, and a price for a fuel borne catalyst posted on the EPA website (U.S. Environmental Protection Agency, 2006d).

The cost of the cetane enhancer is also based on the fuel economies and expected mileages of the trucks, in addition to the cost and usage directions of a particular brand of cetane enhancer (AMSOIL, 2007). Table 4 lists the costs of installing these retrofits to the selected truck classes. No costs are set prohibitively high for the purpose of dealing with incompatibility.

Opportunity Cost and Required Demand:

The fleet owner does require that the HDDV2B trucks be out of service for a total time no greater than 300 hours. Similarly, the HDDV8A trucks cannot be out of service for a total time greater than 200 hours. So long as these absolute constraints are met, it costs nothing for an HDDV2B truck to be out of service for an hour, but it costs $50 for each hour a HDDV8A truck is out of service. The time out of service for the different truck retrofit combinations are listed in Table 4.

Interest Rate:

We will assume the fleet owner expects a yearly return of 7% on investments, which is a couple percent higher than online savings accounts presently offer. Recall that β_t is defined as the interest rate used to bring dollars from the beginning of period t to the beginning of period 1. This fleet owner's beta values are therefore 0, 0.070, 0.145, 0.225, and 0.311 corresponding to periods 1, 2, 3, 4, and 5 respectively.

Fleet Owner Hesitancy:

The fleet owner is assumed not to set any explicit constraints on the number of vehicles of a given type to receive a given retrofit. This implies the fleet owner is prepared to retrofit any number of vehicles with any retrofit, so long as other constraints are met.

Emission Reduction Mandates:

Finally, we need the required reductions in emission levels. We will set the bar high for particulate matter and carbon monoxide at 50% reduction. We will set a more moderate goal of 20% reduction for hydrocarbons, and recognizing that nitrogen oxides are particularly difficult to reduce, not require any reduction.

Computations:

For this case study, the integer program was formulated and run in AMPL. AMPL is capable of handling integer programs far larger than this case study, and solved the program almost instantly. Techniques for solving large scale integer programs are beyond the scope of this paper.

Results:

If we run the model, it tells us the profit maximizing fleet owner will retrofit all 10 of the HDDV2B trucks with Platinum Plus Purifier Systems, and 18 of the 20 HDDV8A trucks with CRT Particulate Filters. From the fleet owner's perspective, these retrofits are profitable, and allow the fleet to easily meet the required percentage reductions. The fleet owner is unable to retrofit the last two trucks because the time HDDV8A trucks spend out of service would exceed the cap (causing the fleet owner to be unable to meet required demand).

We can further analyze the results by following the money. For consistency, all dollars are brought back to the beginning of year 1 using the fleet owner's chosen interest rate of 7% per year. The fleet owner received $9,200 in fixed grants ($200 for each of the 10 HDDV2B retrofits, and $400 for each of the 18 HDDV8A retrofits) from the government. In addition, the government paid the fleet owner $101,564 in grants for reducing emission on a per gram basis. The fleet owner paid about $96,394 for the retrofits, not including opportunity cost. The opportunity cost was $9,900 ($550 for each of the 18 HDDV8A retrofits, and nothing for the HDDV2B retrofits) for the time the vehicles spent out of service. In total, the fleet owner made a profit of just over $4,469 and the government paid $110,764.

The resulting percentage emissions reductions are 67.5% for PM, 72.5% for CO, 0.2% for NOx, and 79% for HC.

Sensitivity Analysis (grants per gram):

When grants per gram were chosen to be 25% of the "value" of the reduction, the selection of 25% might have seemed somewhat arbitrary. No reasons were given for selecting 25% as opposed to 50% or 10%. We can examine the implications of our selection by rerunning the model using different "grant factors." We will simply define "grant factor" to be the factor we multiply the "value" of a reduction by to obtain the grants per gram issued. In the case of 25% it would be .25.

Although it might not be wise to implement a grant factor greater than 1, there is no reason the model cannot be used to examine results for higher grant factors. The model was rerun with grant factors ranging from 0 to 1.1. The resulting fleet owner profit and government grants are displayed in Figure 1.

[Insert Figure 1 about here]

Clearly, fleet owner profit is closely tied to the grants per gram issued. In this example, grants per gram make up the vast majority of government grants for all but the lowest grant factors.

It is apparent from looking at the graph that both grants per gram and profit generally increase linearly with the grant factor. There is, however, an exception between grant factors of .2 and .25. On either side of this gap, the behavior is linear, albeit with different slopes. This result is a symptom of the fact that between grant factors of .2 and .25 the optimal retrofit package changes. Outside of this range, it does not. If the optimal retrofit package does not change, the only change in profit is from the increasing grants per gram for the same retrofits.

Changes in optimal retrofit packages are the source of changes in emission reductions. Consequently, in Figure 2 we see no changes in emission reductions outside of the region between .2 and .25.

[Insert Figure 2 about here]

With these two graphs in mind, it seems to make little sense to use a grant factor much higher than .25 in this case. The fleet owner is already making a small profit off the retrofits, and higher grants per gram will not lead to any more emissions reductions.

In our example, it would be reasonable to say that one of the principle goals of the government is to achieve the greatest reductions possible per dollar it spends. We can quantify this by using the weighted sum of the mass reductions divided by the total grants (where we weight particulate matter emissions with 20 and all other emissions with 1 as discussed in the Grant Programs section). We can calculate this measure of success for our range of emission factors (Figure 3).

[Insert Figure 3 about here]

This tells us roughly how our "bang per buck" changes as we issue higher grants per gram. Unsurprisingly, we obtain the greatest "bang per buck" when we issue no grants per gram (but still a small amount of fixed grants). The regulated mandates impose the bulk of the retrofit cost on the fleet owners themselves, allowing the government to pay very little. This may not be a popular move, and the government will have to decide how much cost it is willing to impose on fleet owners. At the same time, some grant factors may simply be infeasible given restrictions of available government funds. These constraints, combined with the results of this model, could help the government to make informed decisions about which grant factor to use.

Sensitivity Analysis (required PM reduction):

In addition to varying its grant programs, the government might want to examine the impacts of different required percentage reductions. Assuming a grant factor of 0.25, we can rerun the model for a range of reduction requirements.

Given that particulate matter emissions are treated as especially important, it makes sense to start by analyzing its reduction requirement. Recall that the original reduction requirements were 50% for PM and CO, 0 for NOx, and 20% for HC. Also, recall that when the model was run with these requirements and a grant factor of 0.25 the resulting emission reductions were 67.5% for PM, 72.5% for CO, 0.2% for NOx, and 79% for HC.

If we rerun the model with no PM reduction requirement, the optimal retrofit package does not change, and as a result neither do the achieved percentage reductions.

The requirement was not binding because the retrofits were profitable. So long as the requirement for PM reduction is less than or equal to 67.5 it has no effect on the optimal retrofit package for this fleet.

If we rerun the model with a PM reduction requirement of 68% we find that the problem is infeasible. We weighted PM reductions very heavily when we assigned grants per gram. This drove the fleet owner to select retrofits which reduce PM. In particular, it turned out that the retrofit package which achieved the greatest reduction in PM was in fact the most profitable retrofit package. As a result, PM reduction requirements serve no purpose in this example.

Sensitivity Analysis (required NOx reduction):

Nitrogen Oxides were given far lower priority than particulate matter when assigning grants, and no requirement was set for their reduction. It would be reasonable to ask what the effect would be of requiring just a small reduction in NOx emissions.

In order for such a requirement to have any effect, it would have to exceed the achieved reductions when no requirement was imposed (.2 percent). At the same time, a reduction in NOx emissions of 4.2 percent or greater is infeasible in our example. The retrofit packages with the highest NOx reductions (7 and 8) reduce NOx by 5 percent, but they cannot be applied to all vehicles without violating other reduction constraints.

Fleet owner profit in the context of several possible NOx reduction requirements is plotted in Figure 4.

[Insert Figure 4 about here]

It is clear that in order to reduce NOx noticeably beyond .2 % the fleet owner must start to give up profits. One might presume that this is because the fleet owner is being forced to take on more costly retrofits. This is not necessarily the case, however. If we plot the cost of the retrofits we can see that at first it actually decreases as the NOx requirement increases. The fleet owner is forced to drop expensive retrofits (namely CRT Particulate Filters) that greatly reduce PM, CO, and HC, in order to implement less expensive retrofits (namely Platinum Plus Purifier Systems) that achieve small reductions in NOx in addition to moderate reductions in PM, CO, and HC. Consequently, these new retrofits come with lower grants. The grants decrease slightly faster than the costs, which accounts for the fleet owner's declining profit.

This trend continues until the NOx reduction requirement is in the neighborhood of 2 percent, and is presented in Figure 5.

[Insert Figure 5 about here]

The trend of declining costs and grants clearly does not apply on the right half of the graph. The fleet owner's reaction to increasing requirements clearly changes. At a NOx reduction requirement of 2 percent, cetane enhancers are added to the optimal retrofit package. The number of vehicles using them continues to increase for the remainder of the graph. Cetane enhancers reduce NOx by 3%, but have no effect on any other emissions. Even though their cost is not enormous, they bring in very little in the way of additional grants. The fleet owner is stuck paying nearly the entire cost of these additional retrofits. As a result, fleet owner profit declines more quickly than before.

One would hope that with stricter regulation and declining fleet owner profit there would at least be significant gains in air quality. Unfortunately, such a claim would be debatable at best. When the fleet owner swapped retrofits in order to meet the NOx requirement, substantial improvements in PM, CO, and HC emissions were lost. The additional NOx reductions are barely noticeable in comparison (Figure 6).

[Insert Figure 6 about here]

In order for a NOx reduction requirement to make sense in this case, NOx emissions would have to be viewed as far more important than PM, CO, and HC.

6. Conclusions

The types of results produced by this integer programming model, such as those in the case study, are relevant to two principle groups of decision makers: diesel fleet owners looking to select pollution control retrofits, and government officials looking to predict fleet owner behavior.

For a fleet owner, the model provides guidance on how to maximize profits through the selection of retrofits for his or her particular fleet. The model accounts for a considerable range of potential regulatory and incentive environments, as well as constraints imposed by the business environment (such as needing to meet specific demands). Furthermore, the fleet owner can benefit from knowing how his or her profit would change if regulations were altered. Such knowledge could inform a targeted lobbying campaign.

From the government's perspective, this model can serve as a tool to predict how a particular fleet might respond to government programs designed to encourage retrofits. As the case study revealed, tighter regulation does not always necessarily yield cleaner air. Regulations can cause enhancements of some aspects of air quality while causing degradations of others. A model that predicts such results can help policy makers select the appropriate tradeoffs.

There are numerous directions for future research in this field. Several assumptions could be relaxed. The remaining miles for vehicles could be treated as a variable as opposed to a constant. Retrofits need not all take place at the same period in time. A second level could be added to the optimization problem to represent the behavior of a regulatory agency supervising multiple fleets. An emissions market could be modeled.

Given the severe impacts of diesel emissions, and the immediate nature of the problem, such continued research has the potential to provide substantial benefits to society.

Acknowledgements

The authors would like to thank the dedicated staff at the EPA, especially David Brzezinski and Larry Landman, who took the time to provide thorough documentation and to answer questions on EPA models and research. We are also grateful to Joanne Lee for her help in the early preparation of the study. This research was partly supported by a mini paper grant from University Transportation Research Center, Region II.

Appendix A: Grant Types

Given that the remaining mileages are fixed and known for all vehicles, one might argue that grants per gram could effectively be included in the "fixed" grants G_{ijt}. This is completely true. Recall that the grants per gram were given by expression 10. Let δ_{ijt} be defined by:

$$\delta_{ijt} = \frac{1}{1+\beta_t} \cdot m_{it} \cdot er_{ikt} \cdot y_{ijkt} \cdot L_{kt} \tag{A.1}$$

The grants per gram can then be given by the simplified expression:

$$\sum_{i \in I} \sum_{j \in J} \sum_{t \in T} x_{ij} \cdot \delta_{ijt} \tag{A.2}$$

The grants per gram received in period t for performing retrofit j on vehicle type i is δ_{ijt}. One could simply increase G_{ijt} by δ_{ijt} to model the grants per gram and drop expression 10 from the objective function given in expression 12. In this model, however, the decision was made to keep grants per gram as a distinct type of incentive. This decision was made primarily for two reasons. In the short term it makes the model easier to use. In the long term, it will prove more compatible with future expansions to the model.

Including L_{kt} as a separate input parameter to the integer program can make the model easier to use when performing sensitivity analysis. If the user wants to try a collection of grant per gram programs and observe the results, he or she will only have to change the L_{kt} values and rerun the model. No explicit preprocessing would be required to adjust the G_{ijt} parameters. Once run, the model can provide the total grants per gram issued, separate from all other grants. This number may be of interest, and it would have to be found by post-processing the solution if the L_{kt} values were not inputs to the integer program.

Including L_{kt} as an input parameter could become much more important as the model is expanded. The miles remaining for a particular vehicle need not be treated as a constant completely beyond the fleet owner's control. If it was treated as a variable, δ_{ijt}

would no longer be a constant and could not be added to G_{ijt} as one. Also, the L_{kt} values themselves could be treated as variables in an emissions market. This would cause δ_{ijt} to become a variable as well.

Appendix B: Modeling Taxes

Assume there is a tax on pollutant k. In particular, a fleet owner pays ε_{kt} dollars for every gram of the pollutant that his or her fleet emits in period t. The total taxes paid will equal the taxes that would be paid if no retrofits were made, minus the savings resulting from retrofits. The taxes that would be paid if no retrofits are made can be expressed:

$$\sum_{i \in I} \sum_{t \in T} \frac{1}{1+\beta_t} \cdot n_i \cdot m_{it} \cdot er_{ikt} \cdot \varepsilon_{kt} \qquad \text{(B.1)}$$

Note that the taxes that would be paid if no retrofits are made is completely independent of the decision variables of this program, namely which retrofits are made. This is not true of the tax savings due to retrofits, which can be expressed:

$$\sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \frac{1}{1+\beta_t} \cdot x_{ij} \cdot m_{it} \cdot er_{ikt} \cdot y_{ijkt} \cdot \varepsilon_{kt} \qquad \text{(B.2)}$$

Expression (B.2) can be subtracted from expression (B.1) to produce the total taxes paid on pollutant k.

$$\sum_{i \in I} \sum_{t \in T} \frac{1}{1+\beta_t} \cdot n_i \cdot m_{it} \cdot er_{ikt} \cdot \varepsilon_{kt} - \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \frac{1}{1+\beta_t} \cdot x_{ij} \cdot m_{it} \cdot er_{ikt} \cdot y_{ijkt} \cdot \varepsilon_{kt} \qquad \text{(B.3)}$$

This tax could be modeled by subtracting expression (B.3) from the objective function in expression 12. The resulting objective function would be:

$$Max\ \{\sum_{k\in K}\ (\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot x_{ij}\cdot m_{it}\cdot er_{ikt}\cdot y_{ijkt}\cdot L_{kt})$$

$$+\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot x_{ij}\cdot G_{ijt}-\sum_{i\in I}\sum_{j\in J}x_{ij}\cdot w_{ij}\cdot p_i-\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot c_{ijt}\cdot x_{ij}$$

$$-\sum_{i\in I}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot n_i\cdot m_{it}\cdot er_{ikt}\cdot \varepsilon_{kt}+\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot x_{ij}\cdot m_{it}\cdot er_{ikt}\cdot y_{ijkt}\cdot \varepsilon_{kt}\}$$

(B.4)

Profit maximizing behavior can be modeled without this change, however. The term representing taxes paid if no retrofits are made is constant with respect to the decision variables, so it will have no effect on which retrofits are optimal. It can therefore be dropped from the objective function. The term representing tax savings due to retrofits looks exactly like a grant per gram for pollutant *k*. It can therefore be modeled simply by increasing L_{kt} by ε_{kt}. The tax can be included in this manner, while maintaining the objective function in expression 12 and only changing L_{kt}.

While this method of representing taxes will produce the same optimal retrofit selections, the value of fleet owner profit could be different (if the tax rates are non-zero). The fleet owner profit can be adjusted by subtracting the tax paid if no retrofits are made, which is the constant that was dropped from the objective function.

Appendix C: Miles Remaining for Replaced Vehicles

The formulation in this study assumes that the number of miles remaining for any vehicle is fixed and independent of the retrofits it receives. This may make sense for most retrofits, but it seems counterintuitive for engine or vehicle replacement. If an old vehicle is replaced with a new one, the new vehicle will almost certainly drive more miles before being retired than the old vehicle would have. It is essential to realize, however, that all the miles driven by the new vehicle need not provide emission reductions. Initially, the replacement vehicle is driving miles that the old vehicle would have driven, and for these miles our model calculates the reductions. Afterwards, the replacement vehicle is driving miles that another, possibly different, new vehicle would have driven. Furthermore, the decision to replace a vehicle early could quite possibly influence when other vehicles are retired further down the line. Quantifying the emission reductions resulting from these changes is extremely difficult, given the level of uncertainty regarding future emissions standards. For this reason, only the pollution reductions from the miles that the original old vehicle would have driven are used in calculations.

Appendix D: Implicit Representation of Incompatibilities

As previously discussed, there may be some occasions when vehicle type i is incompatible with retrofit j. This can be dealt with explicitly in either the upper bounds in expression 2 or the required technologies constraints in expression 4. Alternatively, if there are no required technologies or other needs for upper bounds, the fleet owner may wish to remove constraint 4 and the upper bounds in constraint 2 (leaving the non-negativity constraints) to simplify the problem. This can be accomplished while implicitly forcing x_{ij} to remain zero for incompatible pairings. Set c_{ijt} to high positive numbers for all t while setting y_{ijkt} equal to zero for all k and t. By looking at the objective function, one can discern that if y_{ijkt} is zero for all k and t, and both w_{ij} and p_i are non-negative, the only benefit corresponding to x_{ij} will be G_{ijt}. So long as c_{ijt} is set to be greater than G_{ijt} for all t, implementation of the retrofit j on vehicle type i will only decrease the objective function. Implementation will not help the fleet owner to meet any requirements on emission reductions (due to y_{ijkt} being 0 for all k and t) or reduce the time out of service (due to w_{ij} being non-negative). So long as there exists a "do nothing" retrofit option with no costs, benefits, or time spent out of service, retrofit j will never be selected for vehicle type i. With this technique, we need not explicitly formulate the incompatibilities. This helps to reduce the complexity of the model.

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3. Table

Figure 1. Fleet Owner Profit and Grants vs Grant Factor

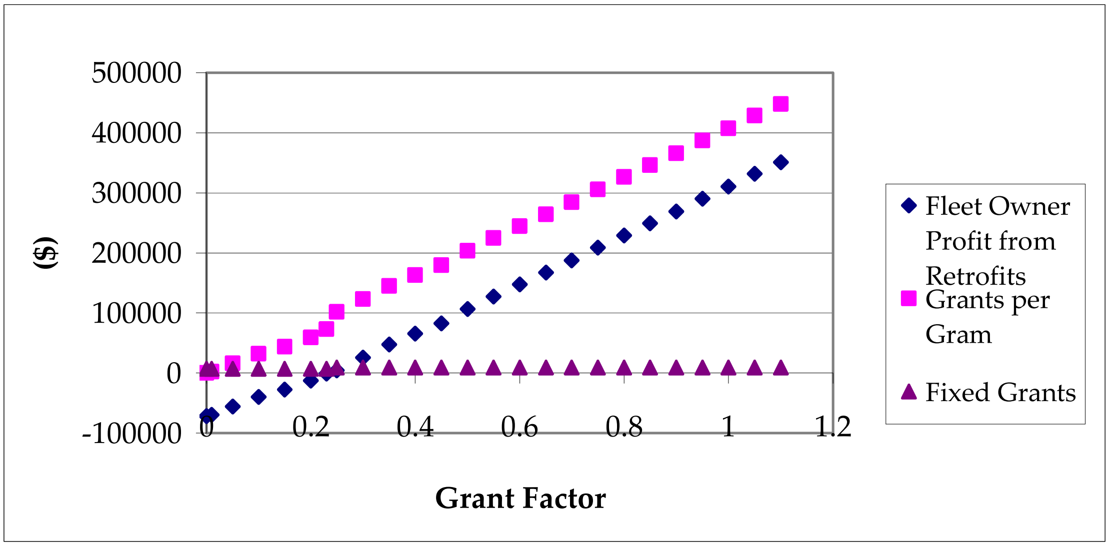

Figure 2. Percentage Emission Reductions vs Grant Factor

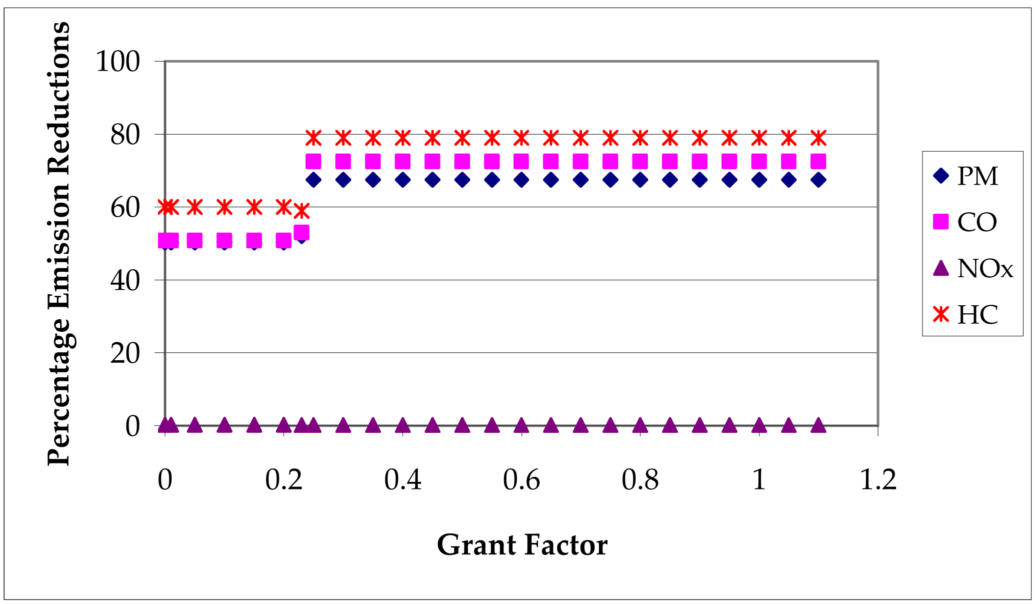

Figure 3. Weighted Emissions Reduction/Total Grants vs Grant Factor

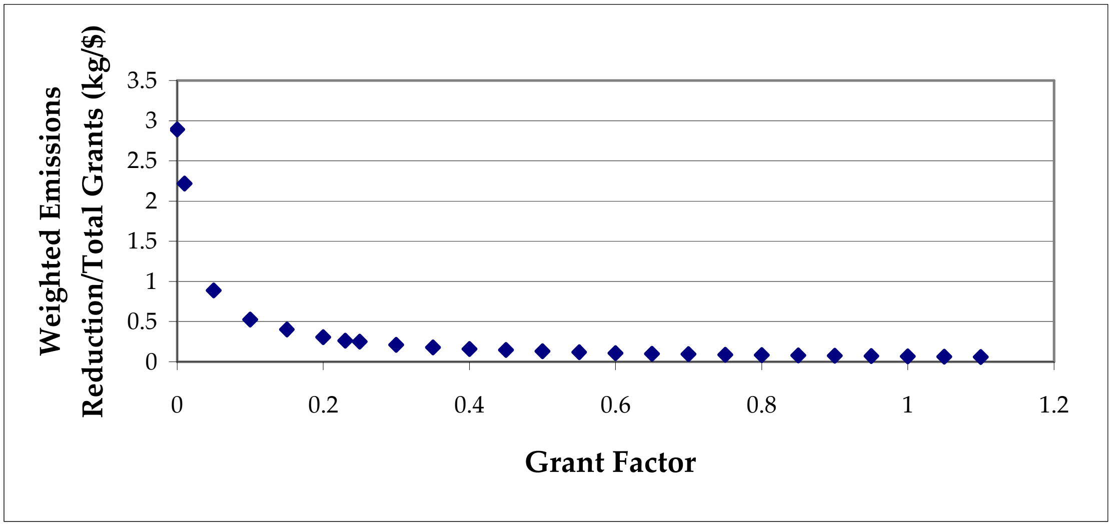

Figure 4. Fleet Owner Profit vs NOx Requirement

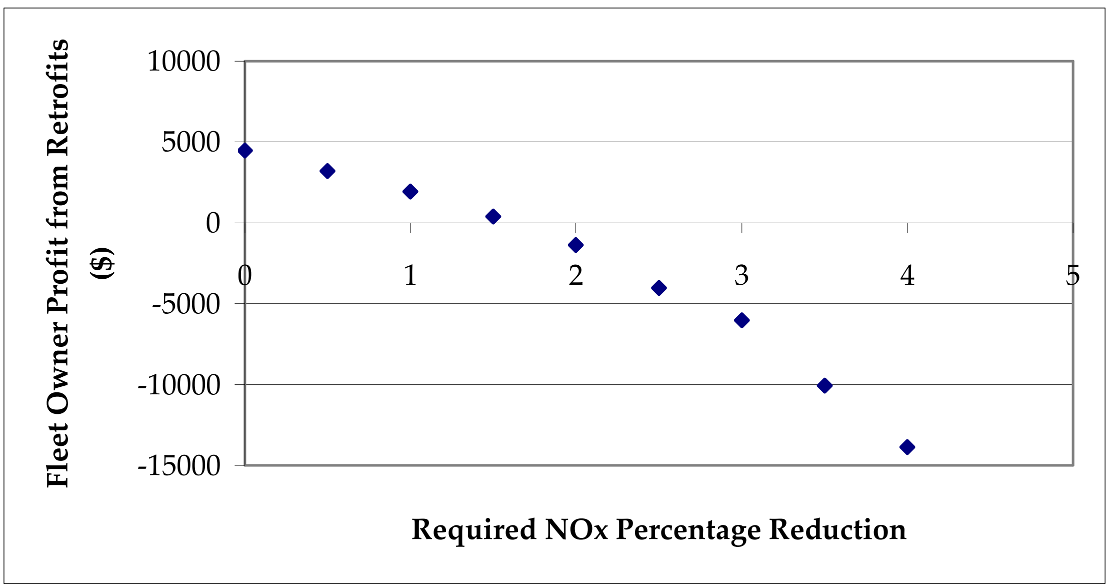

Figure 5. Total Grants and Cost vs NOx Requirement

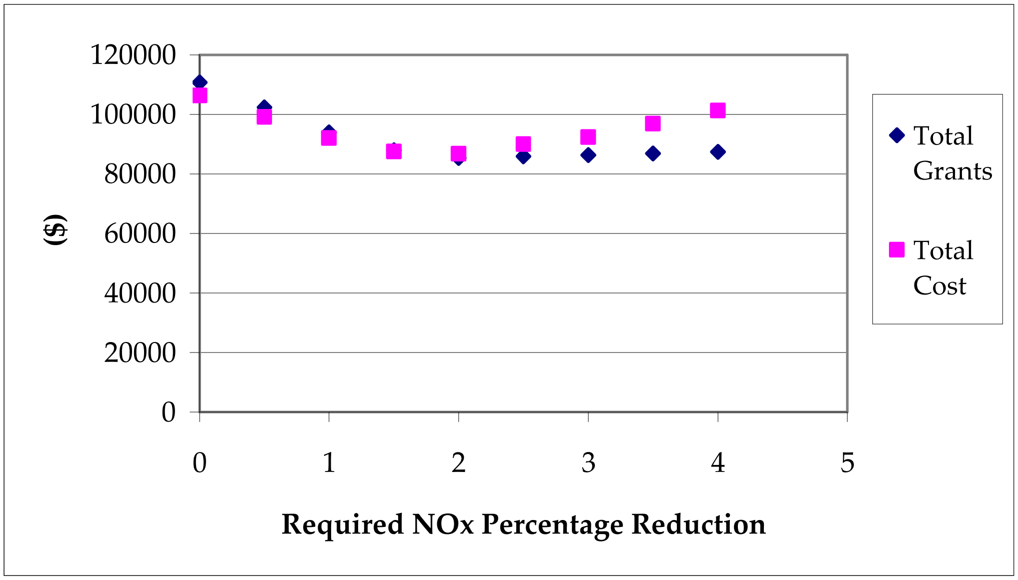

Figure 6. Percentage Emission Reductions vs Required NOx Reduction

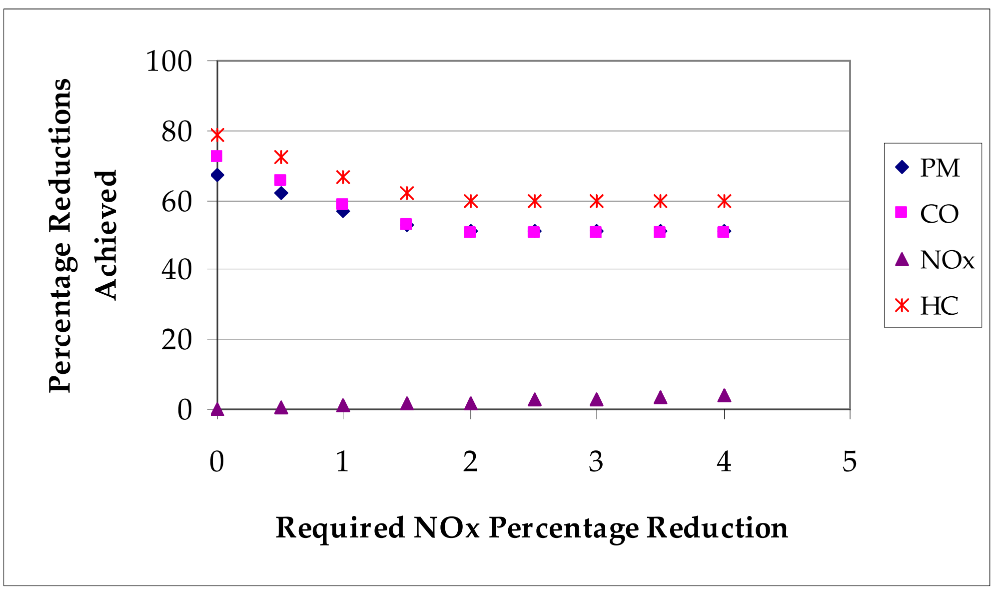

Table 1. Expected Mileages and Emission Rates for the Sample Fleet

			Unretrofitted Emission Rates (g/mi)							
	Vehicle Miles		HDDV2B				HDDV8A			
Year	HDDV2B	HDDV8A	PM	CO	NOx	HC	PM	CO	NOx	HC
1	12000	25000	1.35	1.83	4.82	0.75	0.56	3.47	13.28	0.73
2	12000	25000	1.35	1.86	4.83	0.75	0.56	3.49	13.30	0.74
3	8000	25000	1.36	1.88	4.83	0.75	0.56	3.52	13.32	0.75
4	4000	15000	1.36	1.90	4.83	0.76	0.56	3.54	13.34	0.75
5	0	5000	1.36	1.90	4.83	0.76	0.56	3.56	13.35	0.76

Table 2. Eight Retrofit Options and Their Emission Reduction Efficiency Parameters

	Retrofit Technologies			Emission Reduction Factors			
Retrofit Type	CRTPF	PPPS	CE	PM	CO	NOx	HC
1	no	no	no	0.00	0.00	0.00	0.00
2	yes	no	no	0.90	0.85	0.00	0.95
3	no	yes	no	0.38	0.33	0.03	0.45
4	no	no	yes	0.00	0.00	0.03	0.00
5	yes	yes	no	0.94	0.90	0.03	0.97
6	yes	no	yes	0.90	0.85	0.03	0.95
7	no	yes	yes	0.38	0.33	0.05	0.45
8	yes	yes	yes	0.94	0.90	0.05	0.97

Table 3. Grants Issued on a per Gram Basis

	Grants per Gram ($/g)			
Year	PM	CO	NOx	HC
1	0.079	0.004	0.004	0.004
2	0.080	0.004	0.004	0.004
3	0.082	0.004	0.004	0.004
4	0.084	0.004	0.004	0.004
5	0.085	0.004	0.004	0.004

Table 4. Fixed Grants, Costs, and Time out of Service

		Costs Beyond Opportunity Cost ($)					Out of Service (hours)	Fixed Grants in Year 1 ($)
	Retrofit Type	Year 1	Year 2	Year 3	Year 4	Year 5		
HDDV2B	1	0	0	0	0	0	0	0
	2	4500	0	0	0	0	12	0
	3	1450	50	33	17	0	10	200
	4	60	60	40	20	0	0	0
	5	5950	50	33	17	0	21	0
	6	4560	60	40	20	0	12	0
	7	1510	110	73	37	0	10	200
	8	6010	110	73	37	0	21	0
HDDV8A	1	0	0	0	0	0	0	0
	2	4500	0	0	0	0	11	400
	3	1694	194	194	116	39	10	250
	4	233	233	233	140	47	0	0
	5	6194	194	194	116	39	20	650
	6	4733	233	233	140	47	11	400
	7	1927	427	427	256	86	10	250
	8	6427	427	427	256	86	20	650