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THE RETROFIT PUZZLE EXTENDED: OPTIMAL FLEET OWNER BEHAVIOR OVER MULTIPLE TIME PERIODS

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16. Abstract

In "The Retrofit Puzzle: Optimal Fleet Owner Behavior in the Context of Diesel Retrofit Incentive Programs" (1) an integer program was developed to model profit-maximizing diesel fleet owner behavior when selecting pollution reduction retrofits. Fleet owners acted in the context of potential government programs including various mandates and financial incentives. Fleet size and the miles remaining for each vehicle were treated as fixed and known at the time retrofits are made. Retrofits were assumed to take place in the present, but benefits and costs are distributed over time. The model was intended as a tool both for fleet owners and for government administrators. In this paper, the model is expanded to allow for retrofits at multiple stages in time. This enhancement enables the model to develop multi-year strategies for retrofit implementation, a capability that is especially important when changing government regulation and incentives, vehicle availability, new retrofit technologies, or other factors make spacing retrofits out over time the most profitable option. A case study is used to demonstrate how a sample fleet owner would respond to various incentives. Potential directions for future research are discussed.

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The retrofit puzzle extended: optimal fleet owner behavior over multiple time periods

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ABSTRACT

In "The Retrofit Puzzle: Optimal Fleet Owner Behavior in the Context of Diesel Retrofit Incentive Programs" (*1*) an integer program was developed to model profit-maximizing diesel fleet owner behavior when selecting pollution reduction retrofits. Fleet owners acted in the context of potential government programs including various mandates and financial incentives. Fleet size and the miles remaining for each vehicle were treated as fixed and known at the time retrofits are made. Retrofits were assumed to take place in the present, but benefits and costs are distributed over time. The model was intended as a tool both for fleet owners and for government administrators. In this paper, the model is expanded to allow for retrofits at multiple stages in time. This enhancement enables the model to develop multi-year strategies for retrofit implementation, a capability that is especially important when changing government regulation and incentives, vehicle availability, new retrofit technologies, or other factors make spacing retrofits out over time the most profitable option. A case study is used to demonstrate how a sample fleet owner would respond to various incentives. Potential directions for future research are discussed.

1. INTRODUCTION

The transportation network is the circulatory system of the nation. However, just as it keeps goods and people moving, the transportation sector emits dangerous 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 PM and NOx emissions (*2*). Vehicle exhaust is also a culprit behind smog, acid rain, and global climate change (*3*). According to the EPA, the transportation sector was the second largest contributor to U.S. greenhouse gas emissions in 2005, slightly behind electricity generation (*4*).

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. Emission standards for new vehicles have been greatly improved. Over the past decade, the maximum allowable PM and NOx emissions for new diesel trucks and busses have been reduced by an order of magnitude (*3*). Despite these and other laudable efforts, NAAQS have proven extremely difficult to meet in some cases. EPA maps reveal that major urban areas across the country fail to meet 8-hour ozone requirements, as do selected non-urban areas and several entire states (*5*).

The benefits of improved emission standards are often substantially delayed by the fact that they are not applied retroactively to vehicles already on the road. This delay is particularly pronounced with diesel vehicles, which can remain in use for 25 years and drive close to a million miles before being retired (*6*). There are over 11 million diesel engines operating in the existing fleet (*2*). They play vital roles in our economy including freight transportation, construction, port operations, and public transportation, but at the same time they spew deadly emissions. According to a report by The Clean Air Task Force, fine particulate matter from diesels shortens the lives of nearly 21,000 people in the U.S. every year (*7*). 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." (*7*).

Fortunately, a wide variety of diesel cleaning technologies are available. Upgrades come at a cost, however. Implementing every possible upgrade on every vehicle is simply not feasible. The question becomes: which subset of potential retrofits best serves society, and how can government best encourage them to take place?

Responsible government policy must take into account both the direct cost of retrofits and the externality borne by society if they are not made. Policy makers must consider that upgrades will not have the same effect on all vehicles and that upgrades might influence each others' effectiveness. Even with good certified retrofitting technologies, unwise application could significantly limit the benefits.

In order to develop policies which encourage fleet owners to conduct the desired retrofits the government must be able to predict fleet owner behavior. 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. Gao and Stasko (*1*) outlined an integer programming model of profit maximizing retrofit selection, in the context of potential government incentives and mandates. It treated fleet size and the miles remaining for each vehicle as fixed and known. Retrofits were assumed to take place in the present, but benefits and costs were distributed over time.

This paper expands the model to allow for technologies to be added and removed at multiple points in time. Relaxing the assumption that all retrofits take place at once helps the model to better represent reality. Several factors might cause fleet owners to space retrofits out over several time periods. Fleet owners frequently have demands that they must meet, which means they cannot take large numbers of vehicles out of service at once for an upgrade. They might also want to personally observe the effects of the retrofits before conducting them on a large number of vehicles. Allowing retrofits at multiple points in time also allows the model to include technologies which are expected to become available in the future. Fleet owners can then balance the benefits of retrofitting sooner and seeing emission reductions over a longer period with the benefits of waiting for expected future technological advances.

Before describing the model formulation, the paper provides literature review. The model formulation follows, along with a case study and a discussion of computational issues. Finally, applications and avenues for future research are discussed.

2. LITERATURE REVIEW

This paper is a continuation of Gao and Stasko (*1*), which was also submitted for presentation at the 2008 Transportation Research Board Conference. In the prior paper, the authors outlined an optimization model for fleet owner retrofit decisions when all retrofits are made at the same period in time. Apart from said paper, there is relatively little previous work on optimization models to assist fleet owners and diesel retrofit program managers in making informed decisions. Gao and Stasko (*1*) provides an overview of such research, but for the reader's convenience it will also be briefly summarized here.

Past 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.

Much of the research in group a) was done by or for the EPA. The EPA published a report analyzing the cost effectiveness of retrofits for reducing PM emissions from selected heavy-duty vehicles (*8*). In addition, the EPA helped fund a pilot project by Schipper et al. (*9*) which analyzed the impact of retrofits on buses in Mexico City. The EPA's National Mobile Inventory Model (NMIM) represents the state of the practice in quantifying emission reductions from retrofits (*10*). The documentation supporting NMIM contains a great deal of relevant data and analysis. The EPA also publishes information on approved retrofits (*11*), as does the California Air Resources Board (CARB) (*12*). The CARB also publishes descriptions of the criteria they use for selecting retrofit projects to support (*13*).

Several problems in air transport planning have yielded related integer programs. Marsten and Muller (*14*) published a profit maximizing mixed integer program for assigning planes to air cargo movements. More recently, Janic published an integer program for a profit maximizing airline operator selecting how many planes to fly on each route given regulatory constraints (*15*).

Charnes et al. (*16*) described a goal interval programming formulation for a marine environmental protection program. It dealt with externalities, but it did not model individuals and firms responding to government actions. Marino and Sicilian (*17*) studied the profit maximizing monopolist's and utility maximizing consumer's reactions to government regulation of utilities. While a related problem, the regulatory tools used for utilities are distinctly different from those considered for fleet owners in this paper.

As previously mentioned, this paper expands the earlier model of fleet owner behavior to allow for retrofits to be made at multiple periods in time. Multi-period integer programs are commonly used to solve problems ranging from supply chain distribution (*18*) and more general multi-commodity transportation problems (*19*) to production scheduling (*20*). In these problems, allowing for multiple time periods helped the models to better represent reality. None of these models, however, is designed for solving fleet retrofit problems.

3. MODEL FORMULATION

Sets

The set I is defined as the set of all vehicle types in the existing fleet, indexed by i. Let n_i be the number of vehicles of type i in the fleet. Vehicles should be broken down by make, model, year, engine, expected future use, and any other variation that could influence the effectiveness or compatibility of future retrofits. Unlike in the previous model, vehicles need not be broken down by retrofits received in the past, so long as the retrofits received are included in the set of potential retrofits.

The set J is defined as the set of all potential 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 (the issue of remaining miles for replaced vehicles is discussed in a supporting document for Gao and Stasko (*1*), which is available upon request). A fleet owner may wish to combine multiple retrofit technologies. This combination can be considered a separate possible retrofit (in addition to each technology alone). As in the previous model, this approach allows retrofits to influence each others' effectiveness in a nonlinear fashion, while maintaining a linear objective function and constraints (apart from integrality). For this formulation, the set J includes a default case "retrofit" with no technologies. Model users may wish to allow retrofit options that include technologies which are not currently available (but are expected to become available within the lifespan of the fleet).

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, revenues received, or retrofits made. It is indexed by s or t with 1 designating initial time period (when retrofit decisions are made) and ψ designating the last time period. All retrofits are assumed to take place at the start of the period in which they are made. Similarly, all costs are assumed to be incurred at the start of the period and all grants are issued 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).

Variables and Constraints

In the previous model, the only decision variables were the x_{ij}'s, which represented how many vehicles of type i received retrofit j. Because retrofits were made only once, x_{ij} implicitly represented the number of vehicles of type i with retrofit j, during any time period. In the current study, this number is no longer independent of the time period, however. We need to replace x_{ij} with a new variable with an additional time index s. This new variable, z_{ijs}, is the number of vehicles of type i with retrofit j in time period s. It is unclear what retrofitting a fraction of a vehicle would mean, so all z_{ijs} must be integer. In addition, all z_{ijs} must be non-negative. Fleet owners can define u_{ijs} as the maximum number of vehicles of type i they are willing to have with retrofit j in period s. If retrofit j is incompatible with vehicle type i, or if retrofit j includes technologies not available in period s, u_{ijs} is set to zero. These constraints are expressed in equations 1 and 2:

$$z_{ijs} \text{ is integer } \quad \forall i, j, s \tag{1}$$

$$0 \le z_{ijs} \le u_{ijs} \quad \forall i, j, s \tag{2}$$

Given that combinations of technologies are considered distinct alternate retrofits, and that a zero technology retrofit option exists, the sum of the number of vehicles of type i in all retrofit categories during a given period must equal the total number of vehicles of type i, n_i.

$$\sum_{j \in J} z_{ijs} = n_i \quad \forall i, s \tag{3}$$

At first glance, one might suspect that the z_{ijs} variables would provide all the required information to solve the problem, but in fact they do not. Suppose, for example, that in period s half of the vehicles of type i have retrofit package 1 while the other half have retrofit package 2. Further suppose that in period s+1 half of the vehicles have retrofit package 3 while the other half have retrofit package 4. This information would be provided by the z_{ijs} variables. What the z_{ijs} variables would not indicate, however, is which half received which retrofit. Were the vehicles that had retrofit 1 all upgraded to retrofit 3 and all the vehicles with retrofit 2 upgraded to retrofit 4? Was it the other way around? Was it some combination of the two? Such information is irrelevant when calculating emission reductions, but it could very well be essential for calculating the cost of the upgrades.

A new decision variable, v_{ijls}, is introduced to represent the number of vehicles of type i that switch from retrofit j to retrofit l at the start of period s. Like z_{ijs}, this new variable must be integer and non-negative. Furthermore, it can be related to z_{ijs} by expressions 5 and 6.

$$0 \le v_{ijls} \text{ is integer } \quad \forall i, j, l, s \tag{4}$$

$$z_{ils} = \sum_{j \in J} v_{ijls} \quad \forall i, l, s \tag{5}$$

$$z_{ijs} = \sum_{l \in J} v_{ijl(s+1)} \quad \forall i, j, s \ne \psi \tag{6}$$

The initial state should be specified as an input to the problem. Let ξ_{ij} be an input parameter designating the number of vehicles of type i starting out with retrofit package j. Expression 7 is a constraint which insures that all switches made during the first period start at these initial conditions:

$$\xi_{ij} = \sum_{l \in J} v_{ijl1} \quad \forall i, j \tag{7}$$

The government might require, or the fleet owner might insist, that certain technologies are applied to some vehicle types. While the model is not required to predict that the fleet owner will conduct the required upgrades, they should still be included in the model because of the effects they could have on other technologies' effectiveness.

The fleet owner must select retrofits from a subset of J that includes only retrofits which include the required technologies. 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 and time period s is called Jr_{is}. The removal of retrofit packages containing incompatible technologies is optional, however, because the upper bounds in expression 2 are sufficient for expressing such incompatibilities. The required retrofits constraint can be written:

$$\sum_{j \in Jr_{is}} z_{ijs} = n_i \qquad \forall i, s \tag{8}$$

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

$$\sum_{j \in J} \sum_{l \in J} v_{ijls} \cdot w_{ijl} \le a_{is} \qquad \forall i, s \tag{9}$$

The emission rate, er_{iks}, is the amount of pollutant k emitted to the atmosphere in grams per unit mile by vehicle type i in period s. The parameter m_{is} is the expected vehicle miles traveled (VMT) for a vehicle of type i in period s. Estimates of both er_{iks} and m_{is} can be obtained from regulating organizations, such as EPA's MOBILE6 documentation and truck VMT statistics. This is covered in more detail in the case study of Gao and Stasko (*1*).

Each retrofit j installed on vehicle type i can reduce pollutant type k by a factor of y_{ijks} in period s. Fleet owners use the parameter y_{ijks} to ensure they meet their goal of reducing their emissions of pollutant k by r_{kt} percent by the end of period t. The percentage reduction r_{kt} 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:

$$\frac{\sum_{i \in I} \sum_{j \in J} \sum_{s=1}^{t} z_{ijs} \cdot m_{is} \cdot er_{iks} \cdot y_{ijks}}{\sum_{i \in I} \sum_{s=1}^{t} n_i \cdot m_{is} \cdot er_{iks}} \ge \frac{r_{kt}}{100} \quad \forall k, t \tag{10}$$

Objective Function

Apart from opportunity cost, the cost of switching from retrofit *j* to *l* on vehicle type *i* in period *s* incurred in period *t* is c_{ijlst}. The parameter c_{ijlst} includes the estimate of the equipment cost, the owner's initial installation cost, change in maintenance cost, and any other additional costs (not including opportunity cost). All costs are expressed in dollars at the point in time when the cost would be incurred.

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. The total cost (less opportunity cost), incurred in all time periods, of switching vehicles of type *i* from retrofit *j* to retrofit *l* in period *s* can be expressed (in period 1 dollars):

$$\sum_{t\in T}\frac{1}{1+\beta_t}\cdot v_{ijls}\cdot c_{ijlst}\ \forall i,j,l,s \tag{11}$$

The opportunity cost for every unit of time a vehicle of type *i* is out of service during period *s* is p_{is}. The total opportunity cost of all retrofits installed in period *s* can be expressed (in terms of period *s* dollars):

$$\sum_{i\in I}\sum_{j\in J}\sum_{l\in J}v_{ijls}\cdot w_{ijl}\cdot p_{is}\qquad \forall s \tag{12}$$

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 reduction of pollutant *k* is expressed (in period 1 dollars):

$$\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot z_{ijt}\cdot m_{it}\cdot er_{ikt}\cdot y_{ijkt}\cdot L_{kt}\qquad \forall k \tag{13}$$

Government agencies might issue grants to fleet owners who perform specific retrofits on specific vehicles. The incentive, G_{ijlst}, is defined as the grant paid in period *t* for changing retrofit *j* to retrofit *l* on a vehicle of type *i* in period *s*. The value of G_{ijls1} may be somewhat less than the funds provided in the initial period, in order to represent the cost of application. In total, a fleet owner will receive the following benefits from such programs (expressed in period 1 dollars):

$$\sum_{i\in I}\sum_{j\in J}\sum_{l\in J}\sum_{s\in S}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot v_{ijls}\cdot G_{ijlst} \tag{14}$$

The objective function contains the total benefits from using retrofit technologies (expression 13 summed over all *k* plus expression 14), minus total costs of retrofit implementation (expression 12 converted to period 1 dollars and summed over all *s* plus expression 11 summed over all *i*, *j*, *l* and *s*). It is expressed by:

$$
\begin{aligned}
Max\ \{&\sum_{k\in K} \Big(\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot z_{ijt}\cdot m_{it}\cdot er_{ikt}\cdot y_{ijkt}\cdot L_{kt}\Big)\\
&+\sum_{i\in I}\sum_{j\in J}\sum_{l\in J}\sum_{s\in S}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot v_{ijls}\cdot G_{ijlst}\\
&-\sum_{i\in I}\sum_{j\in J}\sum_{l\in J}\sum_{s\in T}\frac{1}{1+\beta_s}\cdot v_{ijls}\cdot w_{ijl}\cdot p_{is}-\sum_{i\in I}\sum_{j\in J}\sum_{l\in J}\sum_{s\in T}\sum_{t\in T}\frac{1}{1+\beta_t}\cdot v_{ijls}\cdot c_{ijlst}\}
\end{aligned}
\tag{15}
$$

The final optimization model is an integer program in which the objective is given by expression 15 as a function of decision variables z_{ijs} and v_{ijls}. The constraints are given in expressions 1 through 10. The model results indicate the profit maximizing retrofit strategy for the selected fleet, retrofit technologies, regulations, and incentive programs.

A supporting document for Gao and Stasko (*1*) discussed several elements which are notably and intentionally absent from this model. These included budget constraints and changes in fuel efficiency. Neither has been explicitly added, but both can be modeled using similar methods to those discussed in Gao and Stasko (*1*).

4. CASE STUDY

The purpose of the case study is to show the types of results that the model is capable of producing. The example is fictional, but input parameters are selected to be realistic.

Sample Fleet

The fleet, which is the same as that in Gao and Stasko (*1*), 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) (*21*). The HDDV8A classification indicates a heavy heavy-duty diesel truck (gross weight over 60,000 lbs) (*21*).

Expected Mileages and Emission Rates

Expected mileages in each of the next five years, along with the unretrofitted emissions rates, are unchanged from Gao and Stasko (*1*). The expected mileages fall into the general range of averages published by The Federal Highway Administration (FHWA) (with the exception of the last years of the vehicles' lives, when their usage is assumed to taper off) (*22*). Emission rates are general averages based on EPA documents M6.HDE.001 (*23*) and M6.HDE.004 (*21*), as well as an analysis of the cost effectiveness of retrofits for reducing particulate matter (*8*), and the EPA's NMIM software. A more detailed explanation is available in Gao and Stasko (*1*).

Potential Retrofits

The same three technologies are considered: a Continuously Regenerating Technology (CRT) Particulate Filter, Platinum Plus Purifier System (fuel borne catalyst plus diesel oxidation catalyst), and cetane enhancers. Their individual effects on PM, CO, NOx, and HC are taken directly from the EPA's list of verified retrofit technologies (*11*), with the mean of the two bounds used where ranges are provided. Combinations are assumed to be possible and the reductions are combined according to the following formula:

$$\phi_T = 1 - (1 - \phi_1)(1 - \phi_2) \tag{16}$$

where φ_T is the combined reduction and φ_1 and φ_2 are the reductions due to the individual technologies.

The only incompatibility considered is that the HDDV2B trucks cannot receive any retrofits which include the CRT Particulate Filter because they were manufactured before 1994.

Grants

The same grants per gram are used, still based on the CARB's guidelines for funding emissions reduction retrofits through the Carl Moyer Program (*24*). For a more detailed description, see Gao and Stasko (*1*).

Fixed grants are only issued in the period the retrofits are made, and are as follows: $200 for an HDDV2B vehicle receiving a Platinum Plus Purifier System, $400 for an HDDV8A vehicle receiving a CRT Particulate Filter, and $250 for a HDDV8A receiving a Platinum Plus Purifier System.

Retrofit Costs

The costs cannot be explicitly included in the paper, due to the fact that there are 3200 values in the table. In general, costs follow the same system used in the case study of Gao and Stasko (*1*) (with each of the technologies costing the same as before to install and maintain). In addition, CRT Particulate Filters are assumed to cost $250 to remove, Platinum Plus Purifier Systems $200, and cetane enhancers nothing. All nominal prices are assumed to remain fixed over the duration of the problem, but they could be allowed to change.

Opportunity Cost and Required Demand

As before, HDDV2B trucks cannot be out of service for a combined time greater than 300 hours per year. Similarly, HDDV8A trucks cannot be out of service for a combined time greater than 200 hours per year. So long as these constraints are met, it costs nothing for an HDDV2B truck to be out of service, 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 based on those in Gao and Stasko (*1*) with the additional assumption that retrofits take one third of their installation time to remove.

Interest Rate

The fleet owner still expects a yearly return of 7% on investments. 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
The fleet owner is required to reduce PM and CO emissions by at least 50% and to cut HC emissions by a more moderate 20%. Recognizing that NOx emissions are particularly difficult to reduce, they are only required not to increase. These requirements apply to combined emissions over all five years.

Results
The model predicts 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, all in period 1. From the fleet owner's perspective, these retrofits are profitable, and allow the fleet to easily meet the required percentage reductions. This example was constructed to mimic the case study in Gao and Stasko (*1*), so it is not surprising that the fleet owner behavior is the same.

It quickly becomes apparent, however, that slight deviations from this example can easily lead to behavior that the model from Gao and Stasko (*1*) could not have predicted. For example, if the fleet owner was only willing to take vehicles out of service for half as many hours a year, the first model would conclude it was impossible to meet the emission mandates. This model, on the other hand, is able to formulate a strategy to meet the emission mandates by adding retrofits in later years. The same is true if the fleet owner is hesitant to retrofit too many of his vehicles without seeing the results in person, and lowers his or her upper bounds in expression 2.

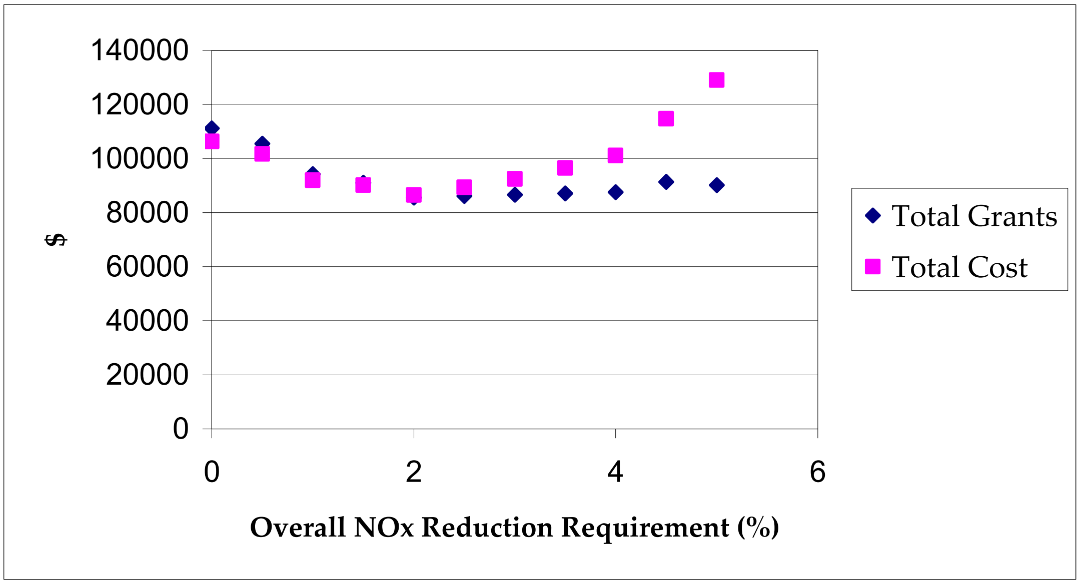
In addition to being able to predict how fleet owners will respond when constraints force them to conduct retrofits later than the first period, this model can predict when it is the most profitable option to conduct retrofits later. If the grant structure were changed slightly, such as increasing the grants per gram for NOx in period 5 (or any number of other possible modifications to grants or costs) the fleet owner might decide adding retrofits down the line is a good idea. This would not be apparent using the first model.

Sensitivity Analysis: Required NOx Reduction
The formulation developed in this study can be rerun for a range of parameter values to produce a sensitivity analysis. As in Gao and Stasko (*1*), nitrogen oxides were given low priority when assigning grants, and no requirement was set for their reduction. It would be reasonable to ask what the effect would be of requiring a 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 of more than 5 percent in NOx emissions is infeasible (no retrofits reduce NOx by more than 5 percent). It is worth noting that while the fleet owner modeled by this case study can achieve a NOx reduction of 5 percent, this was not the true of the case study in Gao and Stasko (*1*). The fleet owner in the prior case study, unable to conduct retrofits after the first period, found NOx reductions of 4.2 percent or more to be infeasible.

As the fleet owner adjusts his or her behavior to meet stricter requirements, profit falls at an increasing rate. This is apparent in Figure 1, which graphs grants received and the total cost of retrofits (both in period 1 dollars) for various NOx reduction requirements.

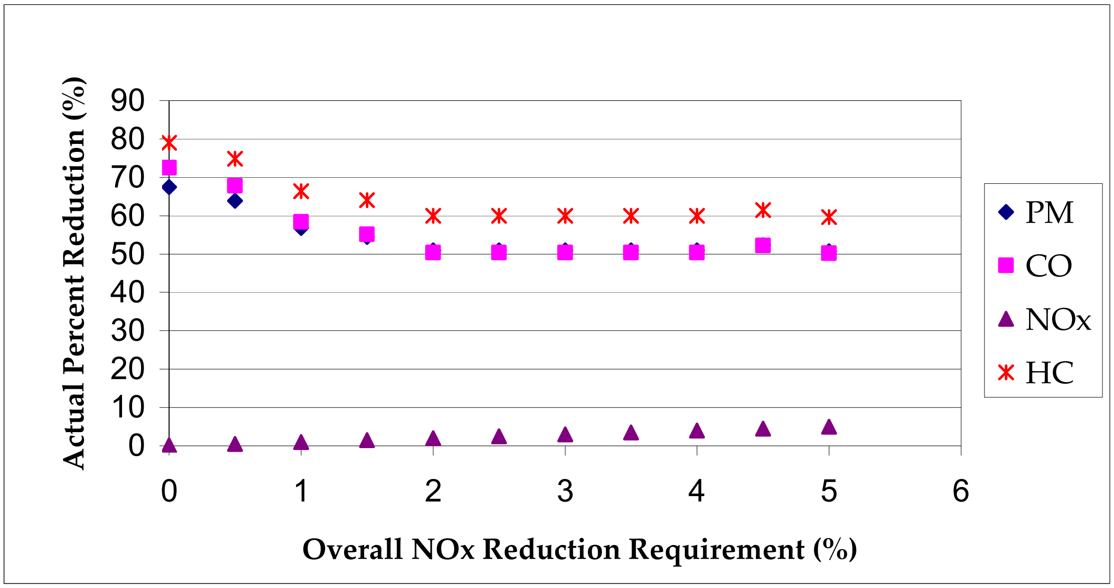
Figure 1. Total Grants and Cost vs Required NOx Reduction



Some of the fleet owner's behavior adjustments are the same as those predicted by the prior model. The fleet owner drops expensive retrofits (with CRT Particulate Filters) that greatly reduce PM, CO, and HC, in order to implement less expensive retrofits (with Platinum Plus Purifier Systems) that achieve small reductions in NOx in addition to moderate reductions in PM, CO, and HC. This switch causes grants to decrease slightly faster than the costs. The fleet owner also adds cetane enhancers, which are not very expensive, but hardly bring in any additional grants. The fleet owner is stuck paying much of their cost. The fleet owner in this case study takes advantage of greater flexibility in using cetane enhancers. Before, cetane enhancers had to be applied to a vehicle for five years or not at all. Now, cetane enhancers can, and are, sometimes used for only a year at a time. The fleet owner also has the ability to add CRT Particulate Filters back into the retrofit schedule by performing them in the second year. This allows the fleet owner to install more Platinum Plus Purifier Systems without failing to meet PM and CO reduction requirements.

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 improvements from CRT Particulate Filters being added in the second period are not nearly enough to completely offset the losses.

Figure 2. Actual Reductions vs Required NOx Reduction



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.

5. COMPUTATIONAL ISSUES

Gao and Stasko (*1*) did not discuss issues of computation. This was because many foreseeable implementations of the integer program it outlined would not be particularly large by modern standards. The case study had one variable for each of the 16 vehicle type and retrofit package combinations. It solved virtually with the stroke of the "enter" key.

The case study in this paper, which is designed to be almost identical to that of Gao and Stasko (*1*) except that retrofit changes are allowed to take place in any of the five time periods, has 720 variables. For each period, there are 16 z_{ijs} variables (one for each vehicle type and retrofit package combination). In addition, for each time period, there are 128 v_{ijls} variables (one for the number of each vehicle type and retrofit package combination that will switch to each retrofit type). The case study still solved almost instantly, but with only 2 vehicle types and 3 technologies it was a relatively small example. It is completely plausible that a realistic example could have thousands of variables (for a more detailed discussion of the number of variables and constraints, a supporting document is available upon request).

In order to examine these computational issues, a series of additional case studies was performed. These additional case studies were all based on the first case study, including all the same vehicle types, retrofit options, and criteria pollutants. They all included extra retrofit options as well, which increased the number of variables by nearly an order of magnitude to 6000. Several input parameters such as percent reduction requirements, time available for retrofits, and grant values were changed to add variety.

All of the case studies were solved with AMPL using the CPLEX 10.1.0 solver on a standard desktop computer (1.8GHz processor, 512MB of RAM). Every case study solved to completion, but the time required varied considerably. Many solved nearly instantly, requiring only a few hundred MIP simplex iterations and no branch-and-bound nodes. Others required a few thousand branch-and-bound nodes, and solved in a matter of minutes. A few case studies, however, required considerably more work to solve. The longest took approximately two hours to complete, processing over a million branch-and-bound nodes and over five million simplex iterations. This is long enough to warrant considering actions to speed up the process.

AMPL, like other mathematical programming software, already makes substantial efforts to simplify the problem before solving it. One of the simpler functions of AMPL's presolve is to search for equality constraints with only one variable and to drop these variables from the problem (*25*). AMPL's presolve algorithm is, of course, imperfect. It won't necessarily pick up on every variable that can be fixed to simplify the problem. In fact, the integer program described in this paper is particularly prone to having components of the optimal solution which are obvious to an informed user, without necessarily being obvious to AMPL. The problem solving process can often be significantly hastened by making what is obvious to the user obvious to AMPL.

This technique was applied to numerous case studies with considerable success. The general approach was to find a set of variables whose values in the (or an) optimal solution can be relatively easily and accurately predicted, and then to explicitly set the variables equal to those values with constraints. AMPL's presolve algorithm can then recognize the variables are not needed, and remove them. These variables might have been able to hold multiple values before the additional constraints were added, so long as it was clear what their values would be at the desired solution. In other words, the constraints can remove feasible integer solutions, so long as they do not remove the solution the user is looking for.

Which variables are candidates for being fixed depends on details of the case study. A fleet owner might have vehicles he or she expects to use for different numbers of years. The number of periods, however, is the same for all vehicle types. There can, therefore, be variables intended to describe retrofit switches made after a vehicle is no longer on the road. A fleet owner in this situation might want to prohibit changes in retrofits after a vehicle is no longer in use. This could be accomplished by requiring that $v_{ijlt} = 0$ for all t after vehicle type i is retired, as long as j is not the same as l.

It might also be apparent that some technologies are not worth removing once they have been added. This could very well be the case for a technology with a high initial cost and benefits distributed over time. A considerable number of variables might be eliminated by not allowing changes in retrofits that remove such a technology. Once again, this can be accomplished by setting the $v_{ijlt} = 0$ that correspond to such changes.

Both of these additional constraint types were added to several case studies and the case studies were resolved. AMPL was able to eliminate more than two thousand more variables from each case study. In every case, it returned a solution with the same objective value as when it was solved without the additional constraints, and nearly all solved considerably faster. Most case studies solved in significantly less than half the time they required before, some requiring less than a quarter of the time. There was no guarantee of an improvement, however. One of the case studies which had solved in roughly 10 minutes before actually examined more branch and bound nodes than it had before (though not enough to significantly change the solution time).

It is worth noting that even case studies took hours to solve, they still frequently reached optimal or nearly optimal solutions relatively quickly. The best integer objective value was typically within half a percent of the upper bound before a minute had passed, even on the tougher problems.

6. CONCLUSIONS

The types of results produced by this integer programming model are relevant both to diesel fleet owners looking to select pollution control retrofits, and to 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. Furthermore, by informing the fleet owner of how his or her profit would change if regulations were altered, the model 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 seen in the case study, responses can sometimes seem counterintuitive (such as air quality worsening as regulations are tightened).

By allowing retrofits to be performed at different points in time, this model is able to better predict fleet owner behavior than the model described in Gao and Stasko (*1*), which is essentially a special case of the model presented in this paper. In situations that encourage fleet owners to space retrofits out over time, this model is able to predict the most profitable retrofit schedule. As discussed, such a situation could be caused by changing regulations or incentives, anticipated technological advances, fleet owner reluctance to try retrofits, or many other factors. The capability to accurately model these factors is key both when predicting retrofit expenses and when computing pollution reductions.

Numerous possibilities remain for future research in this field. The remaining miles for vehicles could be treated as a variable as opposed to a constant. The model could be expanded to include the impact of infrastructure investment (such as building alternative fuel stations) on retrofit decisions. 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 immediate and lasting impacts of diesel emissions, and the importance of an informed strategy for reducing them, such continued research has the potential to provide substantial benefits to society.

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