Effects of Applying Emissions Averaging, Trading, and Banking to Transit Buses

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In the interests of reducing the burden on heavy-duty vehicle manufacturers imposed by air pollution standards yet preserving the improvements in air quality made possible by them, the Environmental Protection Agency is modifying its traditional method of imposing the emissions standards to allow engines to meet the standards on average instead of individually. In this paper the concept of programs with this kind of flexibility is introduced, and how their value depends on differences in the marginal costs of emissions reduction across the set of engines whose emissions may be averaged is demonstrated. These concepts are applied to the problems facing manufacturers of transit bus engines in meeting the strict standards proposed for 1991. It is concluded that flexible regulatory approaches can make a significant contribution to helping bus engines meet the standard, partly by encouraging the introduction of methanol-fueled and other innovative engines. However, the advantages of the flexible regulatory programs could be offset by unintended increases in emissions. The problem of estimating the total reduction in costs resulting from increasing the flexibility of the regulations can be solved using standard techniques of constrained optimization and incremental emissions cost functions derived from engineering analyses. Sufficiently flexible regulatory programs are shown to have the potential to save as much as $174 million per year without affecting air quality. Savings will be radically lower, however, if strict limitations are imposed on the types of engines included in the programs.

The intent of this paper is to examine the potential effects of including urban buses in a regulatory program allowing emissions averaging, trading, and banking. It is based on work done at the request of, and with funding from, the Environmental Protection Agency's (EPA's) Office of Policy Analysis and Office of Mobile Sources in 1986 (*1*). The purpose of that work was to estimate the effects on the costs of meeting the 1991 emissions standards for heavy-duty (HD) vehicles if the EPA were to allow the averaging, trading, and banking of emissions ("flexible regulations"). That work applied only tangentially to transit buses because the EPA was not considering including buses in these programs. That position has changed; thus, after an introduction to the concepts of averaging, trading, and banking, the implications of these alternative programs for meeting the 1991 standards for transit buses are discussed. The discussion shows that averaging, trading, and banking could be valuable in helping transit buses meet the standards—but possibly at some cost in terms of air quality.

The discussion is followed by a formal demonstration of the way in which emissions trading programs allow the reduction of emissions control costs for given levels of emissions and some discussion of the potential magnitude of the savings for variations of the programs.

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HOW FLEXIBLE EMISSIONS PROGRAMS CAN RESULT IN COST SAVINGS

The EPA will be requiring tight emissions standards for heavy-duty vehicles in 1991: 0.25 grams per brake-horsepower-hour (g/bhp-hr) (0.1 g/bhp-hr for urban buses) for particulate matter (PM), and 5.0 g/bhp-hr for oxides of nitrogen (NO_x) (regulations promulgated March 15, 1985). These standards will force manufacturers to aim at even lower target levels to allow for deterioration of emissions control performance and for engine-to-engine variability. These standards would be troublesome to meet individually; together, the difficulties are compounded because some strategies for reducing NO_x can increase PM emissions.

Compliance costs, taking increases in fuel consumption into account, are estimated to range up to several thousand dollars per vehicle (*1*, Exhibit V-7, p. 36). These costs could be much higher for some vehicles than for others. (See section entitled Estimation Procedures for details.)

In the interests of reducing the burden imposed by these regulations while preserving the improvements in air quality made possible by them, the EPA is modifying its traditional method of imposing emissions standards to allow greater flexibility. For most emissions regulations, the EPA has applied the standards to each individual engine or vehicle, requiring every engine to be at or below the numerical standards. Because the ease with which the standards can be met varies widely for different types of engines, the burden of a given set of standards will fall unevenly across engines and manufacturers. Allowing some engines to emit at levels greater than the standards, on the condition that their excess emissions are balanced by extra emissions reductions by other engines, can help reduce the burden of the regulations while maintaining the desired level of air quality. For example, a naturally aspirated engine would be allowed to emit an extra ton of NO_x during its life if a turbocharged engine emitted 1 ton less than the standard required.

The concept of allowing one engine's excess emissions reductions to cancel out the excess emissions of another can be implemented in a number of ways. A basic choice to be made in designing a program of this type is the definition of which groups of engines may be included within the same set for purposes of emissions averaging. In a restrictive program, a given engine's emissions could be averaged only with other engines in the same family (or model), made by the same firm, in the same year, and using the same fuel. Less restrictive variants might allow averaging with other engine families in the same size class, with all engines using the same fuel and built by the same manufacturer, with all engines using the same fuel built by any manufacturer ("trading"), with all engines of any sort built in the same year, or even with engines built in later years (often referred to as "emissions banking").

Emissions averaging allows manufacturers to save money in two ways, which can be referred to as "windfall" savings and "efficiency" savings. Windfall savings arise when firms are given transferable credits for emissions reductions that would have occurred in any case. The firms can then save money by allowing emissions to increase through the use of the credits. Efficiency savings, in contrast, arise when the same emissions reduction comes about at reduced costs as a result of more rational allocation of emissions control efforts.

As an example of windfall savings, the standards could lead to control of PM emissions at a level below that required. Because of the on-off character of PM traps, all engines might be fitted with traps that pull emissions below the PM standard. Emissions averaging could eliminate this overcontrol. Firms could remove traps from enough vehicles to hit the target without overshooting, using credits generated by the engines with traps to compensate for the excess emissions of the engines without traps.

An example of an efficiency savings arises if an extra ton of emissions can be removed more cheaply from some engines than from others. In this case, reallocating emissions control efforts will increase efficiency. Every ton of emissions "shifted" (through changes in the allocation of emissions control effort) from the high-marginal-cost engine to the low-marginal-cost engine results in savings equal to the difference in marginal costs per ton removed.

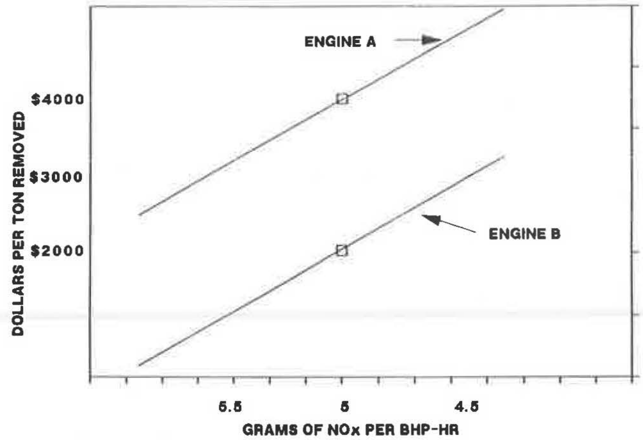

FIGURE 1 Schematic illustration of marginal cost per ton of NO_x removed.

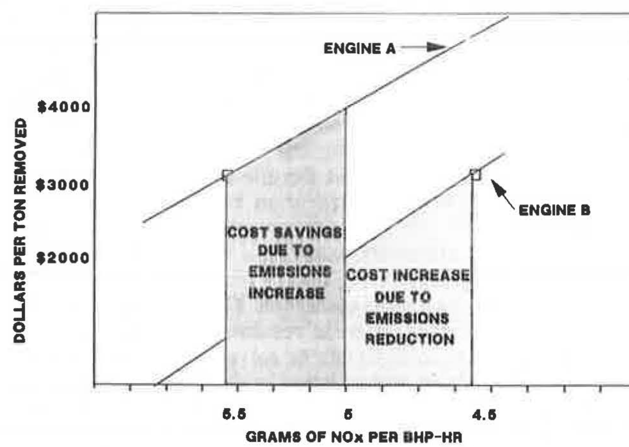

FIGURE 2 Changes in costs under averaging.

INCREASING EFFICIENCY THROUGH FIRM-WIDE EMISSIONS AVERAGING

The source of efficiency savings is shown in Figures 1 and 2. Figure 1 shows the marginal costs per ton removed at different NO_x levels for two engines. (The concepts shown also apply, with some changes, to PM control.) Engine A is expensive to control "at the margin" in that each extra ton removed below 5.0 g/bhp-hr costs $4,000. Engine B is cheaper to control at the margin, costing only $2,000 per extra ton at 5.0 g/bhp-hr. For each engine, these marginal costs per ton rise as emissions are reduced because more and more costly methods are used to eliminate portions of the last few units of emissions.

Under traditional regulatory regimes, each engine would have to meet 5.0 g/bhp-hr exactly (ignoring the need to allow for deterioration and variability). Under averaging, Engine B could be overcontrolled and Engine A could be undercontrolled at considerable aggregate savings. This reallocation of emissions control effort is shown in Figure 2. Engine A now emits 5.5 g/bhp-hr; Engine B now emits 4.6 g/bhp-hr; and these changes are assumed to balance each other in terms of total emissions (because of differences in brake-horsepower-hours per truck and sales volumes). The marginal costs of control are now equal, at about $3,000 per ton, and the total savings are proportional to the difference between the cost decrease for Engine A (the large trapezoid) and the cost increase for Engine B (the small trapezoid).

INCREASING EFFICIENCY THROUGH INDUSTRY-WIDE EMISSIONS TRADING

The EPA also plans to permit averaging across the entire industry, awarding credits to manufacturers whose engines more than meet the standards overall and letting them trade the credits to firms whose engines do not meet the standards. This type of program is known as emissions "trading."

Trading can save money in the same way that reallocating emissions reductions can save money for one manufacturer, as long as the marginal costs of control at the standard differ from one manufacturer to the other. The simplest case with which to illustrate these savings is if each firm sells only one type of engine. Then, savings arise in the way shown in Figure 2 except that Firm B's increased costs will have to be compensated by selling emissions reduction credits to Firm A.

Figure 3 shows trading between the builders of Engine A and Engine B. The levels of emissions each reaches are the same as in Figure 2, but Firm B is compensated for reducing its emissions. Ideally, the compensation to Firm B is X tons' worth of credits at the marginal cost of $3,000 per ton. (This price is ideal because it results in the greatest total savings. In the real

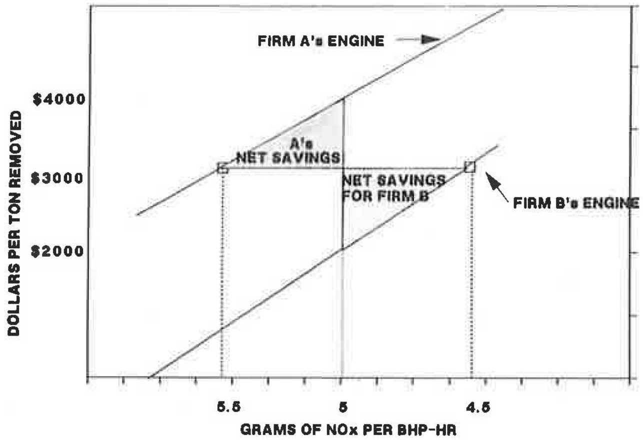

FIGURE 3 Savings under trading.

world, prices of credits could be set in various ways, and prices above or below marginal costs of any market participants would lead to lower total savings and a different allocation of the savings. If the market for credits were sufficiently broad to approximate the operation of a competitive market, however, economic theory predicts that credit prices would tend toward their ideal level.) These credits cost less than X × $3,000 for Firm B to produce, but they are worth more than X × $3,000 to Firm A. This leads to substantial savings for each firm, as indicated by the triangles shown in Figure 3.

An examination of Figure 3 reveals that the total savings are much greater for curves that are far apart—that is, for engines with very different emissions control properties. This becomes particularly important when the effects of flexible regulations on the potential introduction of new transit bus engine technologies, including methanol- and compressed natural gas–fueled engines, are considered.

EMISSIONS BANKING

Emissions banking is yet another flexible program in which credits for engines of one model year are traded to engines of other model years. Savings can arise under banking just as they can under averaging or trading, when engines with low marginal control costs are overcontrolled to allow engines with high marginal control costs to be undercontrolled. These programs are most likely to succeed when standards are expected to be tightened in the future. In that case, firms can overcontrol before standards are tightened, building up credits that ease the transition to the tighter standards.

CALCULATING THE SAVINGS

A procedure for making realistic estimates of the savings that are possible from averaging, trading, and banking is outlined in the section entitled Estimation Procedures. A key part of this procedure is the identification of the shape and position of the marginal emissions control cost curves for each type of engine analyzed. For the work on which this paper was based, the cost curves were based on point estimates of fuel-NO_x and PM-NO_x trade-offs provided by Christopher Weaver of Sierra Research (then of ERC, Inc.), an automotive engineer with extensive experience in emissions control technology. Hyperbolic functions were fit to these point estimates, allowing marginal cost functions to be obtained by differentiation. The marginal functions are shown in Figure 4 for a number of different classes of engines.

The reader will notice that the marginal cost functions for most of the engines (the direct-injection diesels) are not far apart at just under 5.0 g/bhp-hr. This means that the potential

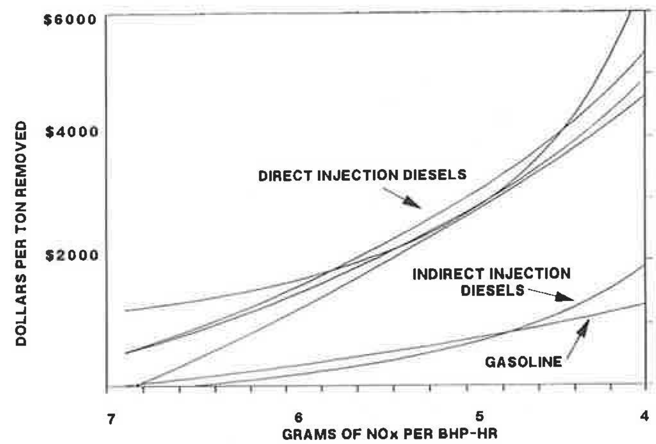

FIGURE 4 Actual marginal cost per ton of NO_x removed (based on data in Tables 2–5 and Figure 5).

savings under an averaging program are quite small for firms selling neither gasoline nor indirect injection (IDI) diesel engines because the marginal cost differences those firms will be able to exploit will be small. Under trading, though, these firms can show substantial savings if they trade with firms selling IDI or gasoline engines. In general, the more unusual an engine is, the greater potential gain it provides under averaging or trading.

ESTIMATED SAVINGS FROM AVERAGING AND TRADING FOR HEAVY-DUTY TRUCKS

Estimates of the cost-saving potential of averaging and trading for heavy-duty trucks showed that averaging within firms could save as much as $230 million per year, an amount equal to almost 4 percent of the total revenues from heavy-duty engine sales (*2*, pp. 6–9). Of this total, approximately $151 million would be attributable to windfall savings associated with removing traps from some engines (thereby allowing an increase in PM emissions over a baseline without averaging), and the other $79 million would be due to increases in the efficiency of meeting given air quality goals. Interfirm trading could allow the saving of as much as an additional $95 million, all of it related to increases in efficiency. Thus total savings could be $325 million, including $174 million in efficiency savings.

The maximum efficiency savings are based on the assumption that averaging and trading would be allowed to operate freely. Only if no constraints were imposed on the types of engines that could be used in emissions trading would averaging and trading lead to the reallocation of control efforts from the types of engine most difficult to control to those least difficult to control. The analysis showed that if the regulations prevented averaging and trading between gasoline and diesel trucks, the efficiency savings would decline by more than 70 percent (to under $50 million from $174 million), because emissions trading could be done only among engines with fairly similar marginal emissions control cost functions. A proposed restriction on trading across truck size classes would prevent most emissions trades between indirect and direct injection diesels. This would eliminate almost all efficiency savings, cutting them to below \$0.1 million per year. These findings underscore the contribution of disparate engine types to the cost savings potential of averaging and trading programs.

IMPLICATIONS OF AVERAGING, TRADING, AND BANKING PROGRAMS FOR TRANSIT BUSES

The EPA is now considering the extension of flexible emissions regulations to transit bus engines. This may affect both the cost and the difficulty of meeting the standards for transit buses, as well as the quality of air in cities.

Making reliable predictions of the effects on transit buses of flexible emissions regulations involves engineering analyses beyond the scope of this paper. The engineering issues actually become more difficult when averaging, banking, and trading are allowed because there are more degrees of freedom: it is necessary to know not only what the costs would be of meeting a given standard with given technologies, but also how much more it would cost to overshoot or undershoot the standard. Still, some possibly useful observations can be made.

Even if all engines used in buses were quite similar,

- If a trap would let one bus get significantly below the standard, averaging would allow manufacturers to reduce the number of traps used, leading to considerable savings. These are the windfall type of savings.
- Second, traps reduce one of the disadvantages of tighter NO_x control (by capturing most of the added engine-out PM emissions). Firms would therefore have the incentive to overcontrol engines with traps for NO_x, thereby generating valuable NO_x reduction credits.
- Third, buses could be overcontrolled for NO_x and PM in the years before 1991, building up banked credits. These credits would allow buses in the 1991–1993 period to exceed the standards, at significant cost savings.

Even greater benefits, though, could come with the introduction of different engine types, assuming (as has been proposed) that "cross-fuel" trading and averaging would be allowed:

- Sales of a small number of low-emission methanol engines could make it easier for diesels to meet the standards by selling diesels enough PM credits to let them avoid using traps or catalysts, or by selling enough NO_x credits to lower their engine-out PM levels. The introduction of methanol engines would be encouraged by allowing them to gain from selling the credits that they might generate in any case. Small, in his paper in this Record, when analyzing the relative costs and values of different PM reduction techniques, for example, did not consider the value of NO_x credits that methanol engines might be able to generate—for a vehicle exerting 500,000 bhp-hr over its life, each g/bhp-hr would be worth half a metric ton of emissions reduction—or about \$1,500 (Figure 4).
- Even gasoline engines could become attractive, because PM and NO_x credits could be sold. These engines could generate enough credits for manufacturers to allow them to be sold at deep discounts, offsetting their poorer fuel efficiency and durability.
- Compressed natural gas engines would also be encouraged and would help meet the standard.
- Additional advantages would arise if NO_x credits purchased from truck manufacturers could be used for bus engines. Buses are not permitted to trade with trucks because of the need to keep emissions from rising in cities where air quality is lower and there is greater exposure. (With unlimited averaging and trading, PM emissions credits would be generated outside cities and used inside. The tighter standard for buses would be rendered almost meaningless.) However, Santini and Schiavone, in their paper in this Record, point out that avoiding increased NO_x emissions in cities is much less important than avoiding increased PM emissions. Thus it might be acceptable to allow NO_x credits to be traded between buses and trucks. It could be beneficial for bus manufacturers to purchase NO_x credits and increase the NO_x levels of buses somewhat while meeting the PM standards more easily. (It might be even better to let bus manufacturers trade PM credits for NO_x credits—resulting in a pure economic and air quality gain. This has not, however, been discussed by the EPA.)

IMPLICATIONS FOR AIR QUALITY

The advantages of flexible regulations will not come entirely without cost, however; air quality goals could be compromised to some degree by allowing manufacturers of buses to average and trade. Some of the ways air quality could be affected follow:

- There will be a net increase in emissions to whatever extent the flexible regulatory programs generate windfall savings and allow firms to reduce the extent of overcontrol. Fewer traps and excess reductions from other types of engines (gasoline, methanol, and CNG) that will be cashed in for credits instead of going to cleaner air are both potential sources of this problem.
- Bus purchasers will naturally exploit differences in their usage patterns. Purchasers intending to use a bus intensively will prefer to buy engines with higher emissions if they get better mileage as a result. In contrast, purchasers with less intensive applications, who are less sensitive to fuel consumption costs, will be willing to accept lower-emitting, higher-fuel-consumption engines if they are given a discount by the manufacturer. If the regulations are set up to assume that both types of buses will be used with the same intensity, then total emissions will go up: 200,000 mi of use of a bus that emits 1 g/bhp-hr below the standard will not make up for 400,000 mi of use of a bus that emits 1 g/bhp-hr above the standard.
- Pollutants not included in the averaging and trading system may grow in importance. These pollutants, including aldehydes from methanol engines and carbon monoxide and hydrocarbons from the largest gasoline engines, are either unregulated or underregulated at present, partly because the types of engines that emit these substances are not sold in large enough numbers to warrant regulation. If manufacturers are given incentives to produce these engines, however, their uncontrolled or undercontrolled emissions could become more serious.

CONCLUSION

It is difficult to predict how much could be saved through the application of flexible emissions regulations to transit bus engines. If predictions for heavy-duty trucks could be assumed to be applicable to transit buses, the predicted savings might be in the range of several percent of the value of the engines themselves. Because of differences in the PM standard for transit buses and trucks, and because the transit bus engine market differs substantially in size and structure from the truck engine market, the truck engine results cannot be expected to be a reliable guide to possible savings for bus engines. The general results, however, especially the prediction that quite significant savings can arise if different engine types are included within an averaging or trading program, suggest significant cost-saving potential and strong incentives for introducing new types of engines.

In addition to contributing to substantial cost savings, implementing a relatively unrestricted program of emissions averaging, trading, and banking for transit buses could be the deciding factor in helping engine manufacturers meet the 1991 standards for transit buses. To avoid undercutting the social benefits to be derived from these programs, however, regulators must be sensitive to the tendency for flexible regulations to lead to increases in emissions.

ESTIMATION PROCEDURES

In this section the introductory discussion of the potential savings from averaging and trading is placed in a more rigorous framework, and the methods used to generate the estimates of cost savings are documented. The intention is to demonstrate that flexible regulations amount to relaxing some of the constraints on the industry's ability to meet given levels of air quality at minimum cost. It is also demonstrated that the savings offered by flexible programs can be analyzed by measuring the difference between costs that have been minimized under differing constraints.

To simplify the discussion, and because the analytical issues are not changed appreciably by limitations in the scope of flexibility allowed, only two cases are considered and compared:

- Averaging, in which emissions from any heavy-duty engine may be averaged with emissions from any engine produced in the same year by the same firm, and
- Trading, in which emissions from any heavy-duty engine may be averaged with emissions from any engine produced in the same year by any firm.

Other variants, including cases in which additional restrictions are imposed on averaging and trading and cases in which intertemporal averaging (banking) is allowed, are discussed only briefly.

Given data relating emissions characteristics to costs for various types of engines, and information about market shares of the different engine types by firm, estimates can be made of the potential resource savings provided by allowing trading in addition to averaging. In the sections that follow the types of engines analyzed, the firms examined, and the general ways in which costs are related to emissions of NO_x and PM are introduced. The conditions necessary for an efficient allocation of emissions reduction activities are discussed, and how the gains attributable to allowing trading in addition to averaging can be derived is demonstrated.

After the theoretical analysis, the actual cost functions used in the analysis are presented. The solution method used is then described, and some results of the analysis of cost savings are presented.

Elements of the Analysis

The analysis of resource savings is based on differences among eight types of heavy-duty engines, nineteen engine manufacturers, and two pollutants.

Engine Types

On the basis of an engineering analysis done for the EPA by Christopher Weaver, the heavy-duty engine industry has been divided into eight types or classes of engines with technically distinct emissions characteristics: light heavy-duty gasoline engines (LHDGE), medium heavy-duty gasoline engines (MHDGE), light heavy-duty diesel engines employing indirect fuel injection (LHDDE-IDI), light heavy-duty diesel engines employing direct fuel injection (LHDDE-DI), naturally aspirated medium heavy-duty diesel engines (MHDDE-NA), turbocharged (or "premium") medium heavy-duty diesel engines (MHDDE-TC), heavy-duty diesel engines intended for line-haul applications (HHDDE-LH), and heavy-duty diesel engines for vocational or non-line-haul applications (HHDDE-NLH).

The greatest distinctions among these types are between the two gasoline-fueled types (LHDGE and MHDGE) and the diesels. Although gasoline-fueled engines are less efficient and durable, they emit virtually no particulate matter and are simpler to control for NO_x emissions. Similarly, the LHDDE-IDI is less efficient and less durable but lower in NO_x emissions than the other diesels. Other distinctions among the classes are smaller in magnitude, or reflect differences in intensity and duration of service more than differences in emissions.

The quantitative analysis requires assumptions about a number of engine cost and usage characteristics (Table 1).

Firms

Nineteen domestic and foreign engine manufacturing firms were included in the analysis. They are distinguished analytically not by differences in their abilities to control emissions from a given type of engine but solely by their patterns of market shares of the types of engines. Although it is likely that some differences will exist in the costs related to emissions reduction among firms for the same engine types, there was no solid engineering basis on which to predict these differences for the future period covered by the analysis. Interfirm differences for given engine types would tend to increase the potential resource savings for trading compared with averaging. Table 2 gives the market shares assumed for each of the nineteen numbered firms. (Projected annual sales for each engine type are given in Table 1.) The firms vary widely not only in overall shares but in their degree of specialization in different types of engines. It is this latter variability that provides the basis for savings under emissions trading.

TABLE 1 DATA BY ENGINE TYPE (*1*)

Engine Type	bhp-hr per Useful Life of Truck (*Be*)	Annual Sales	Percentage Efficiency of Traps (*Etrap* = 1 − *q*)	Capital and Maintenance Cost per Trap ($)	Increase in Fuel Use Caused by Trap (%)	Dollars per 1% Increase in Fuel Consumption (*FCe*)	Total Cost per Trap ($)
LHDGE	78,540	361,907				51	
MHDGE	164,450	63,866				105	
LHDDE-IDI	86,460	178,801	80	370	1.25	54	438
LHDDE-DI	86,460	504	80	370	1.25	54	438
MHDDE-NA	338,365	44,839	80	448	1.25	259	772
MHDDE-TC	364,820	58,301	80	448	1.25	259	772
HHDDE-LH	788,800	114,468	80	574	1.25	705	1,455
HHDDE-NLH	788,800	30,627	80	574	1.25	705	1,455

TABLE 2 SALES SHARE BY FIRM NUMBER AND ENGINE TYPE

	1	2	3	4	5	6	7
LHDGE	8.2%	26.8%	0.0%	0.0%	0.0%	0.0%	65.0%
MHDGE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LHDDE-IDI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	35.5%
LHDDE-DI	0.0%	0.0%	90.6%	0.0%	0.0%	0.0%	0.0%
MHDDE-NA	0.0%	0.0%	0.0%	37.3%	0.4%	0.0%	27.1%
MHDDE-TC	0.0%	3.6%	0.6%	14.7%	5.2%	0.2%	17.4%
HHDDE-LH	0.0%	0.0%	60.2%	12.4%	0.1%	0.0%	7.2%
HHDDE-NLH	0.0%	0.0%	35.4%	18.2%	0.0%	0.5%	34.7%

	8	9	10	11	12	13	14
LHDGE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MHDGE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LHDDE-IDI	63.6%	0.0%	0.0%	0.0%	0.5%	0.0%	0.3%
LHDDE-DI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MHDDE-NA	32.3%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%
MHDDE-TC	44.3%	0.4%	0.5%	0.0%	0.0%	0.5%	0.3%
HHDDE-LH	0.0%	0.0%	0.0%	19.6%	0.0%	0.0%	0.0%
HHDDE-NLH	0.0%	0.0%	0.0%	10.6%	0.0%	0.0%	0.0%

	15	16	17	18	19
LHDGE	0.0%	0.0%	0.0%	0.0%	0.0%
MHDGE	0.0%	0.0%	0.0%	0.0%	0.0%
LHDDE-IDI	0.0%	0.1%	0.0%	0.0%	0.0%
LHDDE-DI	0.0%	0.1%	0.0%	0.0%	9.3%
MHDDE-NA	0.0%	0.1%	1.4%	0.0%	0.0%
MHDDE-TC	0.5%	0.1%	1.1%	3.0%	7.5%
HHDDE-LH	0.0%	0.0%	0.0%	0.4%	0.0%
HHDDE-NLH	0.0%	0.0%	0.0%	0.6%	0.0%

NOTE: Based on certification data. Firms are identified by number to preserve confidentiality.
SOURCE: Office of Mobile Sources, Environmental Protection Agency.

Pollutants

Two pollutants are considered in the analysis: PM and NO_x. Under the regulations, manufacturers are expected to try to limit emissions of PM to 0.22 g/bhp-hr and of NO_x to 4.2 g/bhp-hr. (It is unclear whether gasoline-fueled engines, which emit virtually no PM, will be included in PM averaging along with diesel engines. For the purposes of this analysis, they are assumed to be excluded from PM averaging and required to have zero PM emissions.)

The costs of controlling these pollutants were modeled in a somewhat simplified way, designed to capture only the most important relationships among resource costs and the pollutants. Reductions in NO_x emissions (beyond those achievable by altering the basic design of the engines and of the add-on devices, such as turbochargers, and the use of electronic controls) are assumed to be obtained by changing engine operating parameters—notably fuel injection timing. These changes will have adverse effects on fuel consumption that become progressively more severe at low NO_x emissions levels. These changes will also worsen the problem of PM emissions; again, engineering analysis predicts that the PM-NO_x trade-off worsens at lower levels of NO_x emissions.

Given PM emissions levels that have been reduced as much as possible by changes in engine and turbocharger design and operation, and have been adversely affected by efforts to lower NO_x emissions, it is assumed that PM emissions can be brought down only by the addition of a mufflerlike exhaust filter known as a trap oxidizer (or, simply, a trap). Traps are expensive to manufacture, install, and maintain and increase fuel consumption slightly, but they can reduce the PM emissions from an engine (the "engine-out" emissions) by about 80 percent.

Traps can be put on or removed from any given engine family, or any individual engine within a family, but their efficiency is not considered to be a variable. Thus the addition of a trap to control PM emissions has a binary, on-off character. For every engine sold to meet a moderately tight PM standard, it might be necessary for every engine to be fitted with a trap that pulls emissions down well below the standard. Under averaging schemes, however, traps could be removed from some percentage of engines, allowing the standard to be reached exactly while saving the costs of traps for many of the engines.

Defining the Least-Cost Method of Achieving Given Emissions Standards

Under traditional regulations requiring each individual engine to meet a numerical emissions standard, and given costs per trap and functions relating NO_x levels to changes in fuel costs and engine-out PM emissions, estimating the total cost of imposing the standards can be calculated in a straightforward way. NO_x emissions for each engine are set at the standard (or at a target slightly below the standard to allow a cushion for deterioration and variability), which determines the increase in fuel consumption for that engine. The NO_x emissions level, along with the engine's basic characteristics, determines the engine-out PM level. If this level is above the standard (again, adjusted to provide a cushion), a trap must be fitted, adding to costs by a set amount. Assuming the costs of reduced fuel efficiency can be calculated, applying these procedures to all engines results in estimates of the total resource costs of meeting the standards for each firm and the industry.

Under averaging or trading, finding the lowest total cost for meeting the standards is more complex. The added flexibility of averaging across engines can allow for resource savings but requires that a separate level of emissions be chosen for each distinct engine type while keeping total emissions below the standards.

Choosing a set of values to reduce costs as much as possible while meeting an overall target is a natural application of the techniques of constrained optimization (*3*, pp. 376–382). To apply these techniques, it must be possible to define the independent variables, the objective function, the constraints, and the dependence of the objective function and the constraints on the levels of the independent variables.

The independent variables for a given firm are as follows:

NOXiet ≡ NO_x levels in g/bhp-hr

where

i = one of the 19 firms,
e = one of the eight engine types, and
t = the engine is fitted with a trap;

NOXien ≡ NO_x levels in g/bhp-hr

where n indicates that the engine is not fitted with a trap; and

TRAPie ≡ Percentage of engines of type e sold by firm i that are fitted with traps.

Additional variables needed for the analysis are

PMiet ≡ Engine-out PM emissions in g/bhp-hr for engines of type e sold by firm i and fitted with traps

where

$$PMiet = f(NOXiet),\quad f' < 0, \text{ and } f'' > 0.$$

PMien ≡ Engine-out PM emissions in g/bhp-hr for engines of type e sold by firm i and not fitted with traps

where

$$PMien = f(NOXien),\quad f' < 0, \text{ and } f'' > 0.$$

Etrap ≡ Efficiency of traps in reducing engine-out PM emissions

$q = 1 - Etrap$ ≡ Remaining percentage of engine-out PM in exhaust with a trap

CTRAPe ≡ Discounted cost of a trap per vehicle, including initial cost, maintenance cost, and cost of increased fuel use over the life of the vehicle

NFUELien and *NFUELiet* ≡ Increase in fuel cost per vehicle where $NFUELien,t = f(NOXien,t)$; $f' < 0$; and $f'' > 0$.

Vie ≡ Sales for firm i of type e

For simplicity, sales are assumed to be constant in this analysis. Indeed, however, depending on manufacturers' pricing decisions and purchasers' attitudes, the introduction of flexible emissions regulations could change sales patterns substantially. This issue is of particular importance for new types of engines the potential market penetration of which may be changed radically by the opportunity to trade emissions with other engine types.

NOXTONSien ≡ Tons (metric) of NO_x emitted by a single engine of type e built by firm i, without a trap = $NOXien * Be * 10^{-6}$

where Be is the total bhp-hr exerted by a truck with engine type e over its useful life, and 10^{-6} is the number of metric tons per gram.

NOXTONSiet ≡ Tons of NO_x emitted by a single engine of type e built by firm i, with a trap = $NOXiet * Be * 10^{-6}$

PMTONSien ≡ Tons of PM emitted by a single engine of type e built by firm i, without a trap = $PMien * Be * 10^{-6}$

PMTONSiet ≡ Tons of PM emitted by a single engine of type e built by firm i, with a trap = $PMiet * Be * 10^{-6} * q$

TPi ≡ Total tons of PM emitted by all of firm i's engines

TNi ≡ Total tons of NO_x emitted by all of firm i's engines

For a given firm i with eight types of engines (e = 1 to 8), the objective function can be specified as follows:

$$TCi = \sum_{e=1}^{8} Vie * \{[NFUELien * (1 - TRAPie)] + [(NFUELiet + CTRAPie) * TRAPie]\} \quad (1)$$

The constraints to be met on emissions, expressed in tons of total emissions, can be defined as follows:

$$Ypmi = \sum_{e=3}^{8} Vie * Spm * Be * 10^{-6} \quad (2)$$

and

$$Ynoxi = \sum_{e=1}^{8} Vie * Snox * Be * 10^{-6} \quad (3)$$

where Spm is the PM target for diesels in g/bhp-hr; $Snox$ is the NO_x target in g/bhp-hr; and e = 1 and e = 2 are gasoline-fueled engine types, which are assumed to emit no PM and to be excluded from PM averaging, and e = 3 through e = 8 are diesel engines. Including the gasoline engines in the PM averaging program (as may be the case for transit buses) would, clearly, have the effect of increasing *Ypmi* and relaxing the PM constraint.

Total PM emissions must be less than or equal to *Ypmi*, and total NO_x emissions must be less than or equal to *Ynoxi*. These constraints can be written as follows:

$$Ypmi \geq TPi = \sum_{e=3}^{8} Vie * [PMTONSien * (1 - TRAPie) + PMTONSiet * TRAPie] \quad (4)$$

and

$$Ynoxi \geq TNi = \sum_{e=1}^{8} Vie * [NOXTONSien * (1 - TRAPie) + NOXTONSiet * TRAPie] \quad (5)$$

To find the least-cost set of independent variables for firm i, the following lagrangian expression is established:

$$£ = -TCI\ (NOXi1n \ldots NOXi8n,\ NOXi1t \ldots NOXi8t,\ TRAPi3 \ldots TRAPi8) - \lambda pi * [Ypmi - TPi\ (NOXi1n \ldots NOXi8n,\ NOXi1t \ldots NOXi8t,\ TRAPi3 \ldots TRAPi8)] - \lambda ni * [Ynoxi - TNi\ (NOXi1n \ldots NOXi8n,\ NOXi1t \ldots NOXi8t,\ TRAPi3 \ldots TRAPi8)] \quad (6)$$

Changing the sign on the total cost term implies that the expression should be maximized. The determination of the first-order conditions would be as follows, if the variables were unconstrained:

$$0 = -TCi'_{NOXi1n} - \lambda pi * TPi'_{NOXi1n} - \lambda ni * TNi'_{NOXi1n}$$

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$$0 = -TCi'_{NOXi8t} - \lambda pi * TPi'_{NOXi8t} - \lambda ni * TNi'_{NOXi8t}$$
$$0 = -TCi'_{TRAPi3} - \lambda pi * TPi'_{TRAPi3} - \lambda ni * TNi'_{TRAPi3}$$

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$$0 = -TCi'_{TRAPi8} - \lambda pi * TPi'_{TRAPi8} - \lambda ni * TNi'_{TRAPi8} \quad (7)$$

$$Ypmi \geq TPi \quad (8)$$

$$Ynoxi \geq TNi \quad (9)$$

Rearranging yields

$$\lambda ni = (TCi'_{NOXien,t} + \lambda pi * TPi'_{NOXien,t}) / TNi'_{NOXien,t} \quad (10)$$

$$\lambda pi = (TCi'_{TRAPie} + \lambda ni * TNi'_{TRAPie}) / TPi'_{TRAPie} \quad (11)$$

This can be simplified for purposes of explanation in two ways. First, TNi'_{NOXien} is a constant, equal to the change in the number of NO_x tons per g/bhp-hr of emissions, and related simply to the number of bhp-hr exerted by all trucks using engines of type e sold by firm i. Dividing all of the terms on the right side of Equation 10 by this constant yields

$$\lambda ni = TCi'_{TNie} + \lambda pi * TPi'_{TNie} \quad \text{for all } e \quad (12)$$

which implies that the marginal cost per reduced ton of NO_x, plus the shadow price of PM removal times the change in PM per unit of NO_x, should be the same for all engine types.

Second, the effects of a change in *TRAPie* can be examined for cases in which *NOXien* = *NOXiet*; that is, for cases in which the NO_x levels are the same for the same engine with and without traps. If this were the case, changing the percentage of traps used on one type of engine would not change the NO_x emissions levels for that type of engine. Thus, TNi'_{TRAPie} would be zero, and the first-order conditions would then state that

$$\lambda pi = TCi'_{TRAPie} / TPi'_{TRAPie} \quad \text{for } e = 3\text{–}8 \text{ (i.e., diesels)} \quad (13)$$

implying that the ratio of the added costs per trap to the number of tons of PM that the trap removes should be the same for all diesels.

More realistically, it can be shown that *NOXien* will be greater than *NOXiet*. This is because, if the two values are the same,

$TCi'_{TNien} + \lambda pi * TPien'_{TNien}$ would be greater than

$TCi'_{TNiet} + \lambda pi * TPiet'_{TNiet}$

because TCi'_{TNien} would equal TCi'_{TNiet}, and $TPien'_{TNien}$ would exceed $TPiet'_{TNiet}$ by a factor of $1/q$. This difference would result because the trap would limit the change in PM emissions accompanying changes in NO_x levels for engines with traps. For the first-order conditions to be met, then, TCi'_{TNien} would have to be smaller than TCi'_{TNiet}, implying that *NOXiet* < *NOXien*. The common-sense interpretation of this is that it is worth exerting the effort to control NO_x to a greater degree on engines with traps, because the traps mitigate some of the adverse impact of the more stringent NO_x control.

The differences between *NOXiet* and *NOXien* levels for trap and nontrap engines complicates the first-order conditions for *TRAPie*-values somewhat. They become

$$\lambda pi = (TCi'_{TRAPie} + \lambda ni * TNie'_{TRAPie}) / TPi'_{TRAPie} \quad \text{for } e = 3\text{–}8 \quad (14)$$

Substituting the expression for λni from Equation 12 yields

$$\lambda pi = [TCi'_{TRAPie} + (TCI'_{TNie} + \lambda pi * TPi'_{TNie}) * TNie'_{TRAPie})] / TPi'_{TRAPie} \quad (15)$$

which, after solving for λpi, becomes

$$\lambda pi = [TCi'_{TRAPie} + (TCi'_{TNie} * TNie'_{TRAPie})] / [TPi'_{TRAPie} - (TPi'_{TNie} * TNie'_{TRAPie})] \quad (16)$$

which must hold for all e. Finally, the two constraints must be met.

Thus, if the independent variables could take on any values, and if the functions had the proper curvature to ensure that all of the ratios could be set equal, the solution to the problem would be the familiar one that the ratios of the marginal costs of emissions reduction actions to the changes in emissions they produce should be equal for all actions. This appears to be the case for NO_x control. For PM control, however, the problem is that

$$TCi''_{TRAPie} = 0$$

and

$$TPi''_{TRAPie} = 0$$

for all e, and that it is necessary that $0 \leq TRAPie \leq 1$ hold. That is, both the cost per added trap and the reduction in total PM emissions per added trap are constants for any engine type, so the ratios of the two will also be constant. It is extremely unlikely that these constant ratios will be equal by chance; thus the simple technique of setting all of the ratios equal cannot be employed. In addition, the percentage of traps on any given type of engine must be between 0 and 100 percent. This means that the proper framework for finding the lowest cost solution is one with two added inequality constraints for each type of engine with a trap, modifying the first-order conditions to take the new constraints into account. Applying the Kuhn-Tucker conditions (*3*, pp. 704–710) to the problem then yields the intuitively reasonable answer: for all types of engines with *TRAPie* between 0 and 1 (that is, those for which the added constraints do not bind), the cost-effectiveness of every trap (the expression in Equation 16) must equal λpi, the shadow price of PM reduction; for types of engines with *TRAPie* = 0, the cost-effectiveness must be greater than the λpi; and for all engine types with *TRAPie* = 1, it must be less than λpi.

In other words, those types of engines on which traps are unusually cost-effective should all have traps; those types of engines on which traps are not cost-effective should not have any traps. For at least one type of engine, and probably for exactly one type, the cost-effectiveness of traps will equal λpi. This type of engine can be referred to as the marginal engine type because any marginal adjustments in the level of PM emissions will have to be made by changing the trap percentage for this type of engine.

Given fixed *NOXien*- and *NOXiet*-values, the least-cost solution for each firm can be found by steadily removing traps from engines starting with the types of engines with the lowest trap cost-effectiveness until the PM constraint is exactly satisfied. The cost-effectiveness value for the marginal type of engine then provides the value of λpi, the shadow price of PM removal, that is used in calculating the shadow price of NO_x removal. Adjusting the levels of *NOXien* and *NOXiet* appropriately will then allow the first-order conditions to be met for NO_x control. The minimum-cost solution is found by repeating the process of allocating traps and iterating.

Summing the minimum costs under averaging for all firms yields the minimum industrywide cost for this program.

Analysis of Trading

A similar analysis can be used to show that achieving the minimum cost for the entire industry of 19 firms requires that the shadow cost of removing a ton of NO_x be equalized across all firms as well as all engine types and that, as is the case for a single firm, traps should be allocated first to those types of engines with the lowest ratio of cost per ton of PM removed.

The constraints for PM and NO_x emissions are expressed in terms of the industrywide total allowed, rather than on a firm-by-firm basis. That is, instead of individual constraints for each firm,

$$Ypmi \geq TPi$$

and

$$Ynoxi \geq TNi \quad \text{for all } i$$

the constraints become

$$\sum_{i=1}^{19} Ypmi \geq \sum_{i=1}^{19} TPi$$

and

$$\sum_{i=1}^{19} Ynoxi \geq \sum_{i=1}^{19} TNi$$

This means that some firms' engines could emit more under trading than under averaging, as long as some of the engines of other firms emitted less. The difference in tons emitted by each firm's engines in the averaging case and the trading case indicates the number of tons of emissions reduction credits the firms must exchange for bookkeeping purposes.

The total costs under trading will be no more than those under averaging, and will generally be less, because under averaging the marginal costs of emissions reduction will usually differ from one firm to the next; the trading analysis indicates that under those circumstances total costs cannot be at their minimum from an industrywide perspective. Whether firms actually traded the correct number of units of credits under a trading system to reach the optimal solution would probably depend on the credit pricing system that was developed. If prices in a credit market were set competitively, and if there were no transactions costs, it could be expected that the prices would come to equilibrium at the shadow prices of emissions reductions for each of the two pollutants.

Cost Functions and Data Used

The relationships between NO_x levels and increases in fuel consumption and engine-out PM emissions used in this paper are based on point estimates for a number of NO_x emissions levels provided by Christopher Weaver in work for the EPA (Tables 3 and 4). To transform these points into continuous, differentiable functions for use in the optimization analysis, hyperbolic functions were fit through the points. The form and parameters of the functions fit to the point estimates are given in Tables 5 and shown in Figure 5; they track the point estimates closely over the relevant range of NO_x-values (Tables 6 and 7).

Data on trap costs, the resource costs associated with changes in fuel consumption, and bhp-hr per truck by engine type are given in Table 1. This information was provided by the EPA's Office of Mobile Sources and is based on data from the Regulatory Impact Analysis of the 1988 emissions standards (*4*). Some observers have predicted significantly higher costs and fuel consumption penalties related to trap oxidizers (see paper by Small in this Record); the use of higher cost estimates could lead to higher estimates of savings.

Optimization Program

The cost minimization concepts developed in the beginning of this section were made operational by using the data inputs in Tables 2–5 and Figure 5 and an optimization program implemented in Lotus 1-2-3. The program begins by calculating the PM and NO_x constraints; estimating costs per ton of PM removed for each type of engine (provisionally assuming each engine exactly meets the NO_x target) and sorting from high to low; lowering the percentage of engines using traps (starting with those engines with the highest cost per ton of PM removed) until the PM constraint is met; calculating the marginal costs of NO_x removal for each engine type, and adjusting NO_x levels until the marginal costs are equal. The program then inserts the newly computed NO_x-values into the routine for estimating PM removal costs and iterates until the process converges.

This process is repeated for each of the 19 firms, using the sales share distributions of each firm to weight the results. The

TABLE 3 PERCENTAGE INCREASE IN FUEL CONSUMPTION OVER BASELINE LEVELS, POINT ESTIMATES (*1*)

	NOXe (g/bhp-hr)							
Engine Type	2.5	3	3.5	4	4.5	5	6	8
LHDGE	6.5	5.0		2.5		1.0	0.0	0.0
MHDGE	6.5	5.0		2.5		1.0	0.0	0.0
LHDDE-IDI	15.0	8.0		2.0		0.0	0.0	0.0
LHDDE-DI			12.0		6.0		1.0	0.0
MHDDE-NA			16.0		7.0		3.0	0.0
MHDDE-TC			12.0		6.0		1.0	0.0
HHDDE-LH			8.0		4.0		0.5	0.0
HHDDE-NLH			10.0		5.0		1.0	0.0

TABLE 4 *PMe* LEVEL AS A FUNCTION OF *NOXe* LEVEL, POINT ESTIMATES (*1*)

	NOXe (g/bhp-hr)							
Engine Type	2.5	3	3.5	4	4.5	5	6	8
LHDDE-IDI	0.60	0.52		0.46		0.45		
LHDDE-DI			0.65		0.50		0.34	0.30
MHDDE-NA			0.75		0.60		0.44	0.40
MHDDE-TC			0.58		0.44		0.32	0.28
HHDDE-LH			0.45		0.37		0.28	0.25
HHDDE-NLH			0.54		0.40		0.30	0.27

NOTE: Units are g/bhp-hr.

TABLE 5 PARAMETERS FOR FUNCTIONAL RELATIONSHIPS (*1*)

Engine Type	X1	X2	X3	X4	X5	X6	X7
LHDGE	–59.37	500	6	3			
MHDGE	–59.37	500	6	3			
LHDDE-IDI	–11.6	24	–1.5	1	0.407	0.134	–1.8
LHDDE-DI	–115.9	800	4	6.15	0.15	0.85	–1.9
MHDDE-NA	2.41	15.3	–2.5	–0.63	0.29	0.65	–2.1
MHDDE-TC	–115.9	800	4	6.15	0.18	0.6	–2.1
HHDDE-LH	–427.8	7,100	15	15	0.16	0.6	–1.5
HHDDE-NLH	–369.1	6,200	15	12.5	0.15	0.67	–1.8

TABLE 6 PERCENTAGE INCREASE IN FUEL CONSUMPTION BASED ON FUNCTIONAL RELATIONSHIPS (calculated from data in Figure 5 and Table 5)

	NOXe (g/bhp-hr)							
Engine Type	2.5	3	3.5	4	4.5	5	6	8
LHDGE	7.0	5.2		2.6		1.1	0.3	0.3
MHDGE	7.0	5.2		2.6		1.1	0.3	0.3
LHDDE-IDI	14.9	7.4		2.0		0.3	–0.3	0.1
LHDDE-DI			12.3		5.9		1.0	–0.0
MHDDE-NA			15.5		7.2		3.0	0.2
MHDDE-TC			12.3		5.9		1.0	–0.0
HHDDE-LH			8.4		3.7		0.2	0.8
HHDDE-NLH			9.8		5.1		1.1	0.4

TABLE 7 ENGINE-OUT PM LEVELS BASED ON FUNCTIONAL RELATIONSHIPS (calculated from data in Figure 5 and Table 5)

	NOXe (g/bhp-hr)							
Engine Type	2.5	3	3.5	4	4.5	5	6	8
LHDDE-IDI	0.60	0.52	0.49	0.47	0.46	0.45	0.44	0.43
LHDDE-DI			0.68		0.48		0.36	0.29
MHDDE-NA			0.75		0.56		0.46	0.40
MHDDE-TC			0.61		0.43		0.33	0.28
HHDDE-LH			0.46		0.36		0.29	0.25
HHDDE-NLH			0.54		0.40		0.31	0.26

NOTE: Units are g/bhp-hr.

NO_x-control-related increase in fuel consumption (percent):

$$X1e + X2e * (NOXie + X3e)^{-1} + X4e * NOXie$$

NO_x-control-related increase in fuel cost, by *NOXie* level:

$$[X1e + X2e * (NOXie + X3e)^{-1} + X4e * NOXie] * FCe$$

Marginal change in fuel costs per one unit change in *NOXie*:

$$X2e * -(NOXie + X3e)^{-2} + X4e] * FCe$$

NO_x-control-related increase in fuel costs per ton of NO_x:

$$[X2e * -(NOXie + X3e)^{-2} + X4e] * FCe * Be^{-1} * 1{,}000{,}000$$

PMie (in g/bhp-hr) as related to *NOXie*:

$$X5e + X6e * (NOXien + X7e)^{-1} = PMien$$

Marginal change in PM tons per NO_x ton:

$$X6e * -(NOXien + X7e)^{-2} = PMien'NOXien$$

Total with trap:

$$[X5e + X6e * (NOXiet + X7e)^{-1}] * q = PMiet$$

Marginal with trap:

$$[X6e * -(NOXiet + X7e)^{-2}] * q = PMiet'Noxiet$$

FIGURE 5 Assumed functional relationships based on point estimates (values of parameters *X1* through *X7* are given in Table 5).

total costs for each of these firms are summed to produce the estimated costs of emissions control for the industry under averaging. To estimate the total costs under trading, the optimizing program is rerun as though the sales of the entire industry were accounted for by firm, thereby taking advantage of the fact that trading is essentially interfirm averaging. Finally, the incremental savings provided by trading are found by subtracting the costs under trading from the costs under averaging.

Analysis of Other Regulatory Options

The framework developed to compare averaging with trading under the assumption that emissions of any engine may be traded with those of any other engine can be extended easily to examine regulatory programs with various restrictions. As one important example, a program without any averaging can be simulated by establishing separate emissions constraints for each individual engine and forcing each to meet the standards individually. Comparing the costs under this no-averaging case with the costs under averaging then yields an estimate of the savings attributable to averaging alone.

Changing the structure of the constraints makes possible analysis of related regulatory programs. For example, emissions banking can be modeled by establishing a single constraint for total emissions over a number of years instead of one constraint for each year. Realistic results of an analysis of banking, however, would require knowledge of how emissions control technologies will change over time.

TABLE 8 SAVINGS COMPARED WITH A BASELINE WITHOUT AVERAGING OR TRADING (*1*)

	Averaging Without Trading ($ millions/ yr)	Trading and Averaging ($ millions/ yr)
Including Windfall Savings Due to Removal of Some Traps		
No restrictions	230	325
Fuel restrictions (gasoline and diesel kept separate for NO_x as well as PM)	191	199
Subclass and fuel restrictions (gasoline and diesel kept separate, and size classes kept separate)	151	151
With Estimated Windfall Savings of Approximately $151 Million Removed		
No restrictions	79	174
Fuel restrictions (gasoline and diesel kept separate for NO_x as well as PM)	40	48
Subclass and fuel restrictions (gasoline and diesel kept separate, and size classes kept separate)	(<1)	(<1)

More restrictive cases of averaging or trading may also be modeled by changing the structure of the constraints. Gasoline engines may be separated from diesel engines by forcing each fuel class to meet its own emissions constraints. This restriction may be combined with "subclass" restrictions, forcing each of the three subclasses of diesels (light, medium, and heavy heavy-duty diesels) to meet separate emissions constraints. Each added constraint reduces the potential gains from regulatory flexibility.

Results

Table 8 gives the results of the analysis of the cost-saving potential of flexible regulations for a number of different regulatory programs. Total emissions control costs in the absence of averaging or trading were predicted to fall in the range of $1.1 billion per year; thus flexible programs offer potential savings of as much as 30 percent of baseline costs.

Incremental savings from trading (that is, over and above those attributable to averaging alone) are greatest in the unrestricted case, at approximately $95 million per year. These incremental savings are, however, extremely sensitive to the restrictiveness of the trading program. If manufacturers of gasoline engines are prevented from selling NO_x credits to manufacturers of diesel engines (all of the analysis assumes that gasoline engines do not generate PM credits), the savings from trading drop to about $8 million. Further restrictions (on trading between truck size subclasses) virtually eliminate the incremental savings from trading, cutting it to only about $0.07 million per year.

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