# Sacred Cars? Optimal Regulation of Stationary and Non-stationary Pollution Sources

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Preliminary Draft

## Abstract

The goal of environmental regulation is to protect public health by reducing the presence of certain pollutants. The health and environmental damages caused by a specific concentration of a given pollutant in a given location at a given point in time are the same regardless of its source. For political and practical reasons, however, environmental regulations have treated point source polluters, such as power plants, differently from mobile source polluters, such as vehicles. We compare existing regulations designed to reduce Nitrogen Oxide (NOx) emitted from power plants to regulations of NOx emitted from vehicles. We estimate the marginal costs of reducing NOx under these two regulatory programs. We find significant differences in marginal abatement costs across source types with the cost of reducing NOx from cars less than one half of the cost of reducing NOx from power plants. We estimate efficiency losses of over \$2 billion from the current policy approach to regulating NOx emissions.

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# 1   Introduction

A primary goal of environmental regulation is to protect public health by reducing exposure to harmful pollutants. In general, the health and environmental damages caused by a specific amount of a given pollutant in a given location at a given point in time are the same regardless of its source. Optimal environmental regulation should therefore equate the marginal cost of abating a given pollutant across all similarly-located sources.

For political, legal and practical reasons, environmental regulations often apply asymmetric treatment to different sources of the same pollutant. For instance, while any high temperature combustion process emits nitrous oxides (NOx), planes, trains, boats, trucks, cars and power plants, are all subject to different NOx emissions standards. Attempts to rationalize the regulations across sources are limited.

For decades, economists have emphasized the efficiency gains associated with equating marginal abatement costs across sources when trying to achieve a given level of emissions reduction. Indeed, the large-scale shift away from command-and-control approaches to regulating point sources of pollution (such as technology standards) towards market-based approaches (such as cap-and-trade programs) has largely been justified on these grounds. While there has been considerable attention paid to analyzing how efficiently pollution abatement activity is being coordinated across sources subject to the same environmental regulatory program,[1] far less work has been done to evaluate how efficiently abatement activity is being coordinated across regulatory programs and across source types. Here, we are interested in making comparisons *across* regulatory programs. The objective of this paper is to measure the inefficiencies associated with the asymmetric regulation of NOx emissions from power plants and from passenger vehicles.

In principle, there are several reasons why there might be differential regulatory treatment of different pollution sources. Positive political economy theories of regulation such as Stigler (1971) suggest that regulations that impose costs on a small, well-organized and politically powerful interest group and for which the benefits are diffuse are less likely to be adopted than regulations for which the costs are diffuse and the benefits concentrated. While the benefits of reducing NOx are roughly the same regardless of which source is regulated, costly standards are less likely to apply to politically powerful firms. For instance, in the United States, the automobile manufacturers are much more concentrated than the electricity generators, so organizing to oppose regulations of their output may be easier for vehicle manufacturers than for electric generators. From a downstream

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[1] Detailed analyses of the efficiency of the Acid Rain Program include Stavins (1998), Keohane (2005) and Shadbegian et al. (2006). Fowlie(2006) looks at the NOx Budget Program.

perspective, vehicles are all purchased by potential voters, whereas electricity is purchased by both voters (residential customers) and nonvoters (commercial and industrial consumers).

From a practical or political transaction costs perspective, the costs associated with implementing regulations may vary. For instance, boats and airplanes are governed by international laws, so in order for the US to implement NOx standards for these, they would need to coordinate with other countries. By contrast, power plants have long been subject to environmental regulatory oversight.

We aim to measure the extent to which current US environmental policy deviates from the theoretical optimum by comparing the marginal costs of abating NOx emissions from power plants to the marginal cost of abating NOx emissions from passenger vehicles. Specifically, we compare the cost of reducing NOx under the Federal Tier 2 vehicle emissions reduction program to the cost of reducing NOx at power plants subject to the NOx Budget Program. Both programs were implemented to reduce NOx beginning in 2004, and both programs represent incremental steps taken to increase the stringency of the NOx regulations since the Clean Air Act Amendments of 1990.

We construct estimates of NOx marginal abatement costs for power plants using detailed unit-level data and compare these to estimates for light duty car and truck NOx abatement costs based on engineering analyses performed for the regulatory impact analysis for Tier 2. In both cases, we consider the economic assumptions used to transform the engineering estimates to the economically relevant values. We find significant differences in marginal abatement costs across source types. Armed with estimated marginal abatement cost curves, we quantify the efficiency losses from the current policy approach to regulating NOx emissions.

We find there is considerable scope for efficiency gains. Our estimates of the marginal abatement costs for point sources far exceed those of mobile sources. Because we derive the marginal abatement *curves* for both sources, we can calculate the inefficiencies present from failing to equilibrate marginal costs. We estimate that these inefficiencies amount to $1.9 billion; this represents over 7 percent of the total costs incurred to comply with both programs. To put these findings in perspective, our estimates of savings from equalizing marginal abatement costs *across* programs exceed the gains from coordinating abatement costs *within* the critically acclaimed Acid Rain Program, which a recent study estimates to be $94 million, or 17 percent of total compliance costs (Shadbegian et al. [2006]). For a number of reasons discussed below, our estimates likely represent a lower bound on the inefficiencies present.

The rest of the paper proceeds as follows. Section 2 describes the NOx SIP Call and the Tier 2

vehicle emissions reduction programs in more detail. Section 3 describes generically how we will use estimates of the marginal abatement cost curves to measure efficiency losses. Section 4 contains the main results of the paper. We first describe how we construct the marginal abatement cost curves for both power plants and for vehicles, and then presents our results. Section 5 discusses ancillary information we have collected to buttress the engineering cost estimates we use to construct the marginal abatement curves. Section 6 discusses several additional programs aimed at reducing NOx and Section 7 concludes.

# 2    Regulating Nitrogen Oxide Emissions

NOx emissions contribute to the formation of ozone during the summer season. Ozone is recognized as one of the air pollutants most likely to adversely affect human health. High ambient ozone concentrations have been linked to increased hospitalization for respiratory ailments, irreversible reductions in lung capacity, and ecological damages (Grypares, 2004; WHO, 2003).[2] The major sources of anthropogenic NOx emissions are high-temperature combustion processes such as those that occur in cars, trucks, and power plants. Motorized vehicles are responsible for 55 percent of man-made NOx emissions. An additional 30 percent come from electricity generation.

NOx is the only conventional air pollutant for which nationwide emissions have actually increased since the passage of the 1970 Clean Air Act Amendments (CAAA).[3] In 1989, a federal scientific report suggested that controlling NOx constituted a "new direction" for the Clean Air Act. Since the 1990 CAAA, the stringency of regulations governing both mobile and point sources of NOx emissions has increased considerably.

## 2.1    Reducing NOx emissions from point sources

The 1990 CAAA increased NOx emissions standards for new point sources and established NOx emissions standards for existing point sources in non-attainment areas.[4] Because it was anticipated

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[2]The impacts of ozone on mortality have been difficult to establish, possibly because it is difficult to separate deaths from ozone exposure from deaths associated with heat.

[3]A "conventional air pollutant" is defined in ARS §49-401.01 to mean any pollutant for which the Administrator of EPA has promulgated a primary or a secondary national ambient air quality standard (NAAQS) except carbon monoxide.

[4]RACT standards are defined as the lowest emissions limit that a particular source is capably of meeting through the application of control technology that is "reasonably available". The Title I RACT standards for coal-fired boilers varied from 1.00 – 0.38 lbs NOx /mmBtu, depending on the state and the technology type. Sources had to comply with Title 1 RACT standards by May of 1995.

that these measures would be insufficient to bring the northeastern region of the United States into attainment with federal ozone standards, the Amendments also established a commission to assess the degree of ozone transport in the northeast and to recommend strategies to mitigate regional ozone problems. The EPA ultimately determined that transport of ozone from Southeastern states contribute significantly to ozone non-attainment problems in downwind Northeastern states.[5] To address this problem, a cap-and-trade program was introduced.

The NOx Budget Program, officially upheld by the US Court of Appeals in 2000, was designed to facilitate cost effective emissions reductions of nitrogen oxides (NOx) from large stationary sources in 19 Eastern states. The program caps NOx emissions from over 2,500 point sources. A corresponding number of tradable permits are allocated to these polluting facilities. To remain in compliance with the program, affected point sources must hold permits equal to their NOx emissions. The deadline for full compliance was May 2004.

## 2.2   Reducing NOx emissions from mobile sources

For mobile sources, the 1990 CAAA introduced new "Tier One" standards (measured in grams of NOx per mile) that tightened pre-existing standards by 40 percent and 50 percent for cars and light trucks, respectively; the Amendments also required the EPA to assess the merits, cost-effectiveness, and feasibility of tighter emission standards for the 2004 model year and beyond.. The National Low Emission Vehicle program (NLEV), which was passed in 1998 and adopted nationwide in 2001, further reduced NOx emissions by 50% and 19% for cars and light trucks, respectively.

Two recent programs continue the trend of reducing NOx emissions from mobile sources. In November of 1998, California amended its LEV regulations and in December 1999, the EPA signed the "Tier Two" standard which increased the stringency of exhaust emission standards for new passenger cars and light-duty vehicles.[6] The Tier 2 NOx emissions standard of 0.07 gpm represented a 77 percent reduction for cars and a 65-95 percent reduction for trucks. The standard was phased in beginning in 2004. The California program was more stringent than the Tier 2 program.

Since the 1990 CAAA, the stringency of regulations governing mobile and point sources of NOx emissions have increased considerably, culminating in the Tier 2 standards and the NOx Budget Program(NBP), respectively. To the extent that the marginal damages from the two categories

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[5] FR 1997 (1997), EPA, Finding of Significant Contribution and Rulemaking for Certain States in the Ozone Transport Assessment Group Region for Purposes of Reducing Regional Transport of Ozone; Proposed Rule, 216, 62: 60318

[6] The program also established a new maximum sulfur level in gasoline.

of NOx emissions sources are comparable, efficiency would dictate that marginal abatement costs should be set equal across the two programs.

## 2.3 Relative benefits from NOx emissions reductions across source types

Here we will assume that, controlling for location in space and time, NOx emissions from point and mobile sources are associated with similar damages. In fact, empirical evidence suggests that NOx emissions from mobile sources likely cause more harm on average.

A basic understanding of ozone formation helps to illustrate why this is so. Tropospheric ozone is formed by photochemical reactions involving volatile organic compounds (VOCs) and NOx. Although the relationship between NOx, VOCs, and ozone formation is complex, it is generally true that ozone production efficiency per unit of NOx increases as concentrations of VOCs increase (Sillman, 2007). Coal-fired power plants are very concentrated point sources of NOx but do not emit appreciable amounts of VOCs. These conditions are not favorable to ozone production, although ozone concentrations in power plant plumes do increase with distance from the source as NOx emissions become less concentrated and mix with external sources of reactive VOCs. Motor vehicles emit both VOCs and a more diluted form of NOx. Consequently, ozone formation can occur immediately upon emission. This typically results in faster ozone production rates and higher yields in urban plumes as compared to power plant plumes. Measurements taken in aircraft transects of emissions plumes confirm substantial differences in the rate and magnitude of ozone production associated with NOx emissions from mobile and point sources (Luria et al., 1999; Ryerson et al., 2003; Sillman, 2007). These empirical findings suggests that our estimates of the efficiency gains from improved regulatory coordination are likely conservative.

## 3 Measuring Efficiency and Regulatory Coordination

In order to assess the extent to which mobile source and point source NOx regulations have been efficiently coordinated, we construct marginal abatement cost curves for these two classes of sources. Let $p$ and $m$ denote point sources and mobile sources, respectively. Let the required level of emissions reductions required be $R_j^*$, where $j$ denotes the source type $j \in \{p, m\}$. The function $MAC_j(R_j)$ specifies the marginal cost of reducing NOx emissions among sources of type $j$ by $R_j$.

Figure 1 illustrates a case where $MAC_j(R_j) < MAC_k(R_k)$, $j \neq k$. The economic inefficiency resulting from a lack of regulatory program coordination is represented by area B - area A. This efficiency loss $L$ is equal to:

$$L = \int_{R_k^* - \Delta R}^{R_k^*} MAC_k(q)dq - \int_{R_j^*}^{R_j^* + \Delta R} MAC_j(q)dq, \qquad (1)$$

where $\Delta R$ is defined such that:

$$MAC_j(R_j^* + \Delta R) = MAC_k(R_k^* - \Delta R).$$

In the interest of measuring $L$, we first construct estimates of $MAC_p(R_p)$ and $MAC_m(R_m)$. We then identify the levels of emissions reductions $R_p^*$ and $R_m^*$ that correspond to the constraints imposed by the NBP and Tier 2 standards, respectively. Upon finding that $MAC_p(R_p^*) > MAC_m(R_m^*)$, we define $j = m$ and $k = p$ and estimate [1].

## 4 Results

### 4.1 Constructing a Marginal Abatement Cost Curve for the NOx Budget Program

We estimate NOx abatement costs for 632 coal-fired generating units in the NBP. Although gas and oil-fired generators and other industrial point sources were also included in the NBP, these 632 units represent over 95% of the NOx emissions regulated under the program.[7] The US EPA reports that coal-fired electricity generation accounts for almost all of the NOx emissions reductions achieved under the NBP (US EPA, 2005).

Table 1 reports descriptive statistics for this group of generating units.[8] We assume that reductions in NOx emissions from this group of plants are achieved through pollution control technology retrofits. Other possible means of reducing emissions, such as plant retirement or reduced unit utilization rates, are not considered.[9]

Coal plant managers had a variety of NOx control technologies to choose from when they were deciding how to comply with the NBP. The capital costs, variable operating costs and emissions

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[7] Due to data availability constraints, our analysis focuses exclusively on coal-fired plants. The unit-level cost data required to carry out this analysis is not available for gas and oil-fired generators.

[8] Note that the unit of analysis is a generating unit or boiler. There are as many as 11 boilers at a single facility or "power plant" in our dataset.

[9] EPA modeling exercises predicted that less than 0.3% of capacity would be prematurely retired as a result of this program (US EPA, 1998). To date, no program-related retirements have been reported. Because coal -fired generation tends to serve load on an around-the-clock basis, we assume that the utilization rates of these coal plants will not be significantly affected by this regulation. Fowlie (2006) finds empirical support for this assumption.

reduction efficiencies associated with different pollution control technologies vary significantly, both across NOx technology types and across generating units with different technical characteristics. Not all control technologies are compatible with all boiler types.

We generate unit-specific engineering estimates of technology installation and operating costs using detailed unit-level and plant-level data. In the late 1990s, to help generators prepare to comply with market-based NOx regulations, the Electric Power Research Institute[10] developed a software program to generate cost estimates for all major NOx control options, conditional on unit and plant level characteristics.[11] Cost estimation requires detailed data on over 80 unit and plant level operating characteristics, fuel inputs, boiler specifications, plant operating costs, etc. Appendix 1 includes a detailed description of the data. Post-retrofit emissions rates are estimated using the EPRI software, together with EPA's Integrated Planning Model (EPA 2003).

We use the EPRI software to first identify which NOx control technologies are compatible with each boiler, and then to generate cost estimates for each unit, for each viable control technology. Let $j = 1...J_n$ index the NOx control technology options available to the $nth$ electricity generating unit. Let $K_{nj}$ represent the engineering cost estimates of required capital investments specific to unit $n$ and technology $j$; $v_{nj}$ is the corresponding variable operating cost estimate (per kWh) and $e_{nj}$ represents the corresponding post-retrofit emissions rate. Let $e_{n0}$ represent the pre-retrofit emissions rate; this is the amount of NOx the $nth$ unit emits per kWh of electricity generated if it installs no new pollution controls. For each unit, for each compliance option, we calculate the net present value (NPV) of estimated pollution control costs $c_{nj}$ and emissions reductions $R_{nj}$ as follows:

$$c_{nj} = K_{nj} + \sum_{t=1}^{T_n} \frac{v_{nj}Q_n}{(1+r)^t},$$

$$R_{nj} = \sum_{t=1}^{T_n} \frac{(e_{no} - e_{nj})Q_n}{(1+r)^t}.$$

We assume that generating units are retired at 65 years; $T_n$ is set equal to 65 minus the $nth$ unit's age in 2000. Historic ozone season production, $Q_n$, is used to proxy for expected ozone season production. To facilitate cost comparisons across point-source and mobile-source emissions reduction cost estimates, we set $r = 0.07$.[12]

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[10] The Electric Power Research Institute (EPRI) is an organization that was created and is funded by public and private electric utilities to conduct electricity related R&D.

[11] Anecdotal evidence suggests that this software has been used not only by plant managers, but also by regulators to evaluate proposed compliance costs for the utilities they regulate(Himes, Musatti, Srivastra).

[12] The US EPA uses a discount rate of 7 percent in their analysis of the Tier 2 standard.

The first two columns of Table 2 present engineering estimates of the NPV costs $c$ and NPV emissions reductions $R$ associated with the technology options available to a 510 MW unit in our data set with $T_n = 31$. These options are listed in order of increasing $R_j$. This particular unit, which is representative of other units in the dataset, has nine compliance options. At one extreme, if the firm relies entirely on the permit market for compliance, $c_0 = R_0 = 0$. At the other extreme, the firm makes a large capital investment in pollution control equipment and reduces emissions by over 19,000 tons.

To comply with the NBP, units must hold pollution permits equal to their uncontrolled emissions. The total quantity of pollution permits allocated to sources in the market is set equal to the pollution cap $\bar{E}$. We assume that the manager of unit $n$ chooses the compliance option that minimizes the NPV of anticipated compliance costs:

$$\min_j \left\{ c_{nj} + \tau \sum_{t=1}^{T_n} \frac{e_{nj}Q_n}{(1+r)^t} \right\}, \; j \in \{0, ..., J_n\}, \tag{2}$$

where $j = 0$ identifies the option that involves a complete reliance on the permit market for compliance. The permit price $\tau$ is assumed to increase over time at the rate of interest.[13]

Let $j_n^*$ identify the investment choice of the $nth$ firm: $j_n^* \in \{0...J_n\}$. The pollution permit price $\tau$ and the vector of investment decisions $\mathbf{j}^* = (j_1^*, ..., j_N^*)$ describe the equilibrium for the permit market if for each $n = 1...N$, $j_n^*$ solves [2] subject to the constraint that $\sum_{n=1}^{N} e_{nj_n^*} \cdot Q_n \leq \bar{E}$.

Figure 2 plots the average cost $\frac{c_{nj}}{R_{nj}}$ as a function of $R_{nj}$ for this representative unit. Note that several of the available compliance options will not be compliance cost minimizing at any permit price. For example, with an average cost of \$0.65/lb, option 2 will never be chosen because option 3, which delivers greater emissions reductions, is associated with a lower average cost of \$0.36/lb. Assuming compliance cost minimizing behavior, options $1, 2, 4$, and $5$ will never be chosen by this unit.

Let $J_n'$ represent the subset of $J_n$: $\forall \; j_n' \in J_n'$ there exists a permit price $\tau$ such that $j_n'$ is the compliance cost minimizing choice. Any compliance choice that is not in $J_n'$ will not be chosen by a compliance cost minimizing plant manager. In the example depicted in Figure 2, $J' = \{0, 3, 6, 7, 8\}$. These compliance options appear in bold face in Table 2.

We calculate unit-specific, choice specific marginal abatement costs $mac_{nj'}$ for all $n$, for all $j_n'$

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[13]This is equivalent to assuming intertemporal arbitrage in the permit market, competitive markets, certainty about future abatement costs, and no intertemporal restrictions on permit banking and borrowing.

$\in J'_n$, where marginal abatement costs are defined as:

$$mac_{nj'} = \frac{c_{nj'+1} - c_{nj'}}{R_{nj'+1} - R_{nj'}}. \tag{3}$$

The numerator represents the additional costs incurred from choosing the next cleanest option in $J'_n$. The denominator represents the additional emissions reductions achieved. Note that the compliance cost minimizing choice for the $nth$ unit is $j'_n$ if $mac_{nj'-1} < \tau < mac_{nj'}$. The third column of Table 2 reports marginal abatement costs for the relevant compliance alternatives available to this particular unit.

In order to construct an aggregate marginal abatement cost curve, we use a model of the NBP pollution permit market mechanism that coordinates these unit-level environmental compliance decisions. We simulate pollution permit market clearing for a range of possible values of $\bar{E}$. We begin by setting the cap equal to uncontrolled emissions $\bar{E}_0 = \sum_{n=1}^{632} e_{n0} \cdot Q_n$. In this benchmark case, the equilibrium permit price is $\tau = \$0$ and $j^* = j_0 \ \forall \ n$. The cap is then incrementally decreased to $\bar{E}_1 = \bar{E}_0 - \varepsilon$. A permit price of \$0 offers no incentive to invest in pollution control equipment. A strictly positive permit price is required to deliver a level of aggregate emissions that satisfies the new constraint $\sum_{n=1}^{N} e_{nj_n^*} \cdot Q_n \leq \bar{E}_1$. The permit price is then incrementally increased until the vector of equilibrium choices $\mathbf{j}^*$ with a corresponding vector of equilibrium emissions $\mathbf{e}_{nj^*}$ satisfies the constraint imposed by $\bar{E}_1$. This entire process is repeated $R$ times. Each time the cap is made incrementally more stringent and the constrained equilibrium price is solved for. The resulting $\{\bar{E}_r, \tau_r\}$ pairs can be used to trace out a marginal abatement cost curve for this group of facilities.

Figure 3 plots aggregate abatement $(\bar{E}_0 - \bar{E}_r)$ versus equilibrium permit price $\tau_r$ for $R = 2000$ and $\varepsilon = 1$. For each level of $R$, the corresponding permit price represents the minimum $\tau$ required to induce an incremental increase in the total quantity of abatement provided by this group of point sources. The vertical line corresponds to the cap imposed by the NBP. $R_p^*$ is set equal to the discounted emissions reductions associated with the technology adoption decisions that these units actually made.[14] The equilibrium permit price $\tau(R_p^*)$ that corresponds to these choices (and the corresponding emissions reductions) is \$1.21.[15]

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[14]Information about which compliance strategies were chosen by coal plant managers was obtained from the Environmental Protection Agency, the Energy Information Administration, the Institute for Clean Air Companies and M.J. Bradley and Associates.

[15]The observed average permit price over the period 2003-2006 was \$1.33.

## 4.2    Constructing a Marginal Abatement Cost Curve for Mobile Sources

NOx is emitted from a variety of mobile sources. We focus our attention on cars and light trucks because the engineering data on the costs of reductions from these sources is most complete. We discuss other modes of transportation in section 6. Because recent regulations for on-highway and non-road diesel vehicles and ships suggests that the marginal abatement cost of these sources is likely lower than that of automobiles, our estimates of efficiency gains are most likely biased downward implying that our results provide a lower bound for potential cost savings.

To construct the marginal abatement cost curve for mobile sources, we rely on the Tier 2 Regulatory Impact Analysis performed by the EPA (US EPA, 1999).[16] As part of the regulatory process, the EPA forecasted total NOx savings and the costs associated with these savings; we discuss each of these in this section.

The costs associated with compliance can be split into increases in vehicles costs, fixed costs associated with engineering, and fixed costs associated with certification. While we refer the reader to the EPA's analysis for all of the particulars, we highlight the important assumptions regarding consumer purchasing behavior and vehicle-level cost of compliance.

As with point sources, there are a variety of ways auto manufacturers can alter vehicles to comply with the new legislation. The least cost method for complying is likely to vary by both a vehicle's size and type of engine. To account for this, the EPA calculates estimates of the least cost method of compliance separately for each vehicle class/number of cylinder combination.[17] These costs are reported in Table 3. After calculating the incremental engineering costs for each vehicle type, the EPA makes two assumptions in the process of transforming the variable costs to marginal abatement costs. For one, the incremental costs are increased by 26 percent to account for "overhead and profits."

Below we present results that use the EPA's assumed markup and results that assume a markup of zero; we do this for two reasons. For one, these markups represent a transfer, rather than a true economic costs. The relevant cost for efficiency calculations is the marginal social cost of abatement, not the marginal cost of abatement faced by consumers. Second, whether, in equilibrium, vehicle prices increase by more than an increase in marginal costs depends on both the assumed game firms

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[16]Tier 2 had two goals—to reduce NOx emissions and gasoline desulfurization. Fortunately, the costs associated with each of these goals can be easily separated since NOx reductions required changes in vehicle characteristics, while desulfurization impacted gasoline refiners.

[17]There are a number of changes that can be made to autos to reduce NOx; changes to the catalytic converter system are likely to be most important. Other areas that manufacturers can alter are: improvements to the fuel injection system, secondary air injection, insulating the exhaust system, engine combustion chamber improvements and exhaust gas recirculation.

are playing, as well as the relative slopes of marginal revenue and demand. Indeed, in the simple model of linear demand and a monopolist prices increase by less than increases in marginal cost, implying a negative "incremental markup."

By adding a markup to vehicle costs, the EPA will tend to overstate the marginal cost of abatement for mobile sources. If the assumed markup is larger than the markup firms would be able to set in practice, this pushes our reported results to be interpreted as lower bounds on the level of inefficiency.[18]

The EPA also assumes that manufacturers experience learning over the course of Tier 2, beginning in the third year of implementation; this assumption will tend to understate the marginal cost of abatement for mobile sources. Specifically, they assume that each time output doubles a manufacturer experiences a 20 percent reduction in incremental vehicle costs. This assumption pushes in the opposite direction as the markup assumption. In the future, we plan to carry out sensitivity analysis in order to assess the effect of this assumption on total and marginal costs of abatement.

In addition to vehicle equipment costs, the EPA estimates quasi-fixed costs associated with Tier 2. These costs include R&D, tooling and certification costs. R&D costs are assumed to be $5 million per vehicle line (covering 100,000 vehicles), tooling costs are assumed to be $2 million per vehicle line and certification costs are assumed to be $15 million industry wide.[19] When calculating the discounted value of costs, the EPA assumes that fixed costs are spread evenly over the first 5 years.[20] The effects of learning and fixed costs can be seen by examining vehicles costs over time. Table 4 reports vehicle costs, by vehicle type, in years one, three and six. Costs from year one to year three fall by between $5 and $34 because of learning. Costs fall significantly in year six because fixed costs expire.

Combined, the assumptions with respect to variable and fixed costs, markups and learning yield vehicle costs that vary by vehicle type/engine type and year. Table 4 reports the sales weighted average of these costs by vehicle type and year. A final requirement needed to generate estimates of the total discounted costs associated with Tier 2 is a model of consumer vehicle purchase behavior. For this, the EPA relies on a model of driving and purchasing behavior known as MOBILE5.[21] The

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[18] Using Table V-21(A) in the EPA's RIA, we calculate this to add over $3 billion dollars to discounted total costs, reflecting over 19 percent of the total costs associated with NOx reductions.

[19] The EPA has attempted to estimate these costs as incremental fixed costs; that is, those additional fixed costs associated with Tier 2. In each case, however, they suggest that they have erred on the side of overstating these costs.

[20] The EPA uses a 7 percent discount rate for costs and emissions.

[21] They also require an assumption regarding the phase in of the standards. They assume that manufacturers meet the requirements in a least cost manner, essentially progressively using larger and larger vehicles.

vehicle cost and sales data imply total annual costs beginning at $269 million, when Tier 2 is being phased in, and peaking at $1579 million in 2009; annual costs begin to fall after 2009 because of learning.

The EPA uses the cost estimates associated with Tier 2 to calculate an average cost of the proposed NOx reductions; this requires an estimate of the total NOx saved under Tier 2. The amount of NOx saved under Tier 2 will depend on both driving habits and the stock of vehicles in each year. Driving habits come from the MOBILE6 model, while the EPA uses NHTSA survivor rates for each vehicle. This generates annual emissions for the assumed stock of vehicles, which is then summed using a seven percent discount rate.[22] Under these assumptions and the standard EPA assumption for mobile sources to treat NOx and non-methane hydrocarbons as the same, the EPA forecasts a lifetime discounted reductions for NOx+NMHC to be 23.5 million tons. Table 6 reports savings throughout the lifetime of the program; savings increase over time as more and more Tier 2 vehicles are on the road.

Calculating an average cost for the legislation is complicated by the fact that Tier 2 also yields reductions in other pollutants, most notably sulfur and particulate matter. There are two potential ways to deal with this. One, and probably least accurate, is to simply ignore them. A second is to assign a value for these other pollutant reductions and reduce the costs associated with Tier 2 by this amount; this is strategy taken by the EPA. The EPA forecasts the amount of each pollutant saved and credits the costs associated with Tier 2. They assume marginal damages of $2.4/lbs and $5/lbs for sulfur and particulate matter, respectively.[23]

We are also able to separate the *costs* associated with sulfur and PM, since the direct costs associated with NOx reductions correspond to changes in vehicle costs and the desulfurization costs impact refiners. We report one set of estimates using this approach, although this likely understates the cost of NOx abatement. The vehicle cost estimates are predicated on low sulfur fuel because sulfur is a catalyst poisoner that reduces the efficacy of catalytic converters. If the low sulfur fuel legislation was not included in Tier 2, the vehicle costs would increase. However, since it is unlikely that vehicle costs would increase by exactly the difference between the costs of desulfurizaiton and the marginal damage of sulfur, we report the other set of estimates as a benchmark.

We use the additional information in the RIA to subtract out the assumed markup. Table V-53

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[22]Because Tier 2 does not apply to California, Alaska and Hawaii, the EPA adjusts their numbers to represent emission levels for the remaining 47 states.

[23]Recent work by Muller and Mendelsohn (2007) suggests EPA assumptions about marginal damages from PM and sulfur could be high. Muller and Mendelsohn estimate average marginal damages per ton per year of $PM_{2.5}$ ranging from $1.65 to $.25 in urban and rural areas, respectively. Average marginal damages from $SO_2$ are estimated to be $.75 and $.45 per pound per year in large cities and rural areas, respectively.

of the RIA reports the annualized costs separately for the NOx and sulfur portions of the legislation for the years 2004 to 2024; Table V-51 reports annual costs for desulfurization for 2004 to 2030. The analysis also reports that the discounted value of total costs associated with the entire legislation are \$48.5 billion.[24] Using these data, we are able to change the assumption about markups. Table 7 reports the average costs for each of our methods. Evident from this is the that the method for controlling for sulfur and particulate matter is very important. Without crediting for the reductions in both sulfur and particulate matter, the implied marginal abatement cost is \$1.02/lbs. Using the EPA's values for the sulfur and particulate matter reduces this cost to \$0.66/lbs; subtracting out the assumed markup reduces this further to \$0.58/lbs. Ignoring the costs associated with the fuel desulfurization and subtracting the assumed markup yields a cost of \$0.24/lbs

The RIA gives us one point on the total/average cost curve; to calculate the level of inefficiencies across the two markets requires a marginal abatement cost *curve* for mobile sources. The RIA, states that "in the case of our standards, both the emission reductions and the fuel cost as a function of sulfur content are nearly linear, though the vehicle costs do contain some nonlinearity" (page VI-3). This implies that total costs are linear in NOx abatement levels, and that marginal costs are constant. Insofar as the marginal cost curve is upward sloping, we will tend to overstate the inefficiencies present. Assessing the accuracy of this constant marginal cost assumption, and testing the sensitivity of our results to alternative assumptions about the shape of the marginal abatement cost curve will be a focus of future work.

## 4.3   Efficiency Gain from Equalizing Marginal Abatement Costs

Given our estimates of the marginal abatement costs for the two industries, we can calculate the gain in efficiency from equalizing marginal costs. We do this holding the level of abatement constant by decreasing abatement from point sources and increasing abatement by mobile sources.

The potential efficiency gains are best viewed graphically. Figure 4 is a stylized representation of our calculations. The width of the horizontal axis is the total level of abatement from both sources (31.4 million tons), with abatement from point sources going from left to right and abatement from mobile sources from right to left. By graphing it this way, the level of total abatement is constant.

Our calculations imply we are at point A; the marginal abatement costs of point sources exceed those of mobile sources. We can calculate the potential efficiency gains by calculating the area of

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[24]The report also describes annual costs for NOx in Table V-21(A). If we instead use these, we do not get quite the same discounted sum compared to subtracting out the sulfur costs from the EPA's reported total; using the vehicle cost number result in costs that are \$2.3 billion lower. To be conservative, we use the higher of the two total NOx cost numbers.

the triangle E. We do this using a number of methods for accounting for sulfur and particulate matter when calculating the marginal abatement cost for mobile sources. These results are reported Table 7.

Using a MAC for mobile sources of $.66/lbs, we estimate potential efficiency gains of $1.9 billion. To put this number is perspective, the total compliance costs associated with point sources is $8.75 billion, while the total compliance costs for mobile sources is $18.07 billion. The efficiency gains represent over 7 percent of total costs. Again for the reasons discussed above, this likely represents a lower bound on the potential efficiency gains. For example, if we instead assume a markup over variables costs of zero, rather than the EPA's assumed 26 percent, the potential efficiency gains increase to over $2.4 billion. This amounts to 9 percent of total costs.

# 5 Additional Evidence on the Marginal Abatement Costs

## 5.1 Power Plants

One potential check on the engineering estimates reflected in the aggregate marginal abatement cost curve for power plants is to compare the prices that have emerged in the market for permits under the NOx Budget Program to the prices that would be predicted by the engineering estimates we use. Specifically, if one considers the level of emissions reductions required under the NOx Budget Program, the price corresponding to this level of emissions reductions on our marginal abatement cost curve is $1.33/lbs. By comparison, over the period 2003-2006, permits in the NOx Budget Program traded at an average price of $1.26/lbs.

While these numbers are quite close, several caveats are in order. For one, previous work suggests that firms did not choose the least cost compliance options as suggested by the MAC curve that we use. Fowlie (2007) shows that electric utilities that were subject to economic regulation were considerably more likely to adopt capital intensive technologies, such as a selective catalytic reduction system, which achieve greater NOx removal rates. On the other hand, there is anecdotal evidence to suggest the engineering cost estimates reflected in our marginal abatement cost curve might overstate realized costs.

## 5.2 Vehicles

We consider several benchmarks for the vehicle costs. First, as discussed in Section 2.2, the Tier 2 program was the most recent in a series of regulations aimed at reducing NOx emissions from cars.

The Tier 1 program, also part of the Clean Air Act Amendments, promulgated standards ranging from 0.60 grams/mile to 1.53 grams/mile depending on the vehicle weight (compare this to the Tier 2 requirement that fleets achieve an average emissions rate of 0.07 grams/mile). The Tier 1 standards became effective in 1991. At the end of the 1990s, the National Low Emissions Vehicle program represented a voluntary agreement between the EPA and the automobile manufacturers to reduce emissions ahead of Tier 2 by designing cars that achieved the California Low Emissions Vehicle standards. Under the program, vehicles were required to achieve emissions rates of 0.2 grams/mile by 2001.

If the technology for reducing NOx has been roughly constant over the 1990s, cost estimates from these programs can provide several points along the MAC for NOx from vehicles.[25] Essentially, each program brought about incremental reductions in NOx. If the costs of the later programs were much higher than the earlier programs, this would suggest a steeply sloped MAC. In fact, engineering estimates from these two programs suggest that the steps were associated with roughly the same cost per pound reduced, and if anything were higher than the costs associated with Tier 2.[26]

While this pattern is consistent with a gently sloped or even constant marginal abatement curve up to the level of reductions achieved by Tier 2, it does not provide any insight on the costs of requiring reductions beyond Tier 2. Further, if the costs of the NLEV program truly are higher than the costs of Tier 2, the assumption of constant technology seems dubious, which calls into question the ability of the earlier programs to say anything about the incremental costs at Tier 2. To get a sense for the costs of achieving reductions beyond those in Tier 2, we looked for evidence of steps that could have been taken but weren't at the time that the Tier 2 regulations were adopted.

Our read of the relevant engineering literature suggests that available technology could have yielded reductions beyond those mandated by Tier 2. For instance, MECA (2003) describes the three important ways in which NOx can be reduced using the conventional three-way catalytic converter technologies: placing the catalytic converter closer to the exhaust ports ("close-coupled" converters), denser substrates–the material which holds the catalyst, changing the process by which the catalyst is applied to the substrate and the specific mix of catalytic materials. They go one to describe tests done to large vehicles which demonstrate that using existing technologies, the vehicles

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[25] The three-way catalytic converter has been the primary NOx control technology used in US light-duty vehicles since the 1980s (MECA 2003).

[26] The regulatory impact analysis for Tier 1 reports cost effectiveness estimates of $1-$1.35/lbs. The RIA for the NLEV cites a $/lbs figure drawn from a report done in 1994 analyzing the costs of extending California's LEV plan to the states in the ozone transport region. That report cites a figure of $1.53/lbs, higher than the costs for either Tier 1 or Tier 2, although the report notes in words that technologies that the 1994 report expected to be required are no longer necessary (US EPA 1997 http://www.epa.gov/otaq/regs/ld-hwy/lev-nlev/sfrm-ria.pdf).

could achieve up to 80% lower emissions than those required under Tier 2 (see MECA 2003, Figure 13). We are in the process of trying to use the detailed descriptions of the steps taken (e.g. more palladium used in the catalyst, denser substrates) to derive estimates of the $/lbs reduced. The evidence thus far is at least suggestive that requiring greater emissions reductions from cars than was required under Tier 2 would not have involved dramatically different technologies, so it is unlikely that the MAC beyond the Tier 2 reduction levels is steeply sloped.

The second indication that technologies were available to get additional reductions comes from the fact that different vehicles have achieved very different reductions. Under Tier 2, manufacturers were allowed to do fleet averaging. Specifically, each manufacturers' fleet had to achieve an average emissions level of 0.07 grams/mile, but individual vehicles could be tested up to a level of 0.14 grams/mile.[27] We have obtained data on the dispersion in the emissions rates by vehicle in 2007, the first model year for which the full Tier 2 regulations were effective for the smaller trucks and cars. The average ratio of emissions rates at manufacturers' 10th and 90th percentile vehicle was above 10. Although some of this variation is driven by differences in vehicles fuel efficiency levels, Figure 5 depicts the variation in the grams of NOx per gallon. The figure uses 2007 model year data, and only vehicles for which the Tier 2 standards were fully binding (i.e. the phase in period had ended) are included. We are in the process of trying to assign costs to the NOx reduction systems of individual vehicles in order to use the cross-vehicle differences to derive estimates of the cost of pushing all vehicles to the lower end of the emission rate distribution. Qualitatively, the fact that the technology existed to reduce some vehicles emissions to such low levels relative to other vehicles again suggests that the MAC is likely to be relatively flat for reductions beyond the Tier 2 levels.

# 6    Other NOx Programs

The bulk of our analysis focuses on comparing the costs of reducing NOx from passenger vehicles to the costs of reducing NOx from power plants. As depicted in Figure 6, these two sources account for less than half of the man-made NOx in the US: passenger, or light-duty, vehicles emitted 18% of US NOx in 2002, just before the Tier 2 standards came into effect, and electric utilities emitted 24%. The remaining emissions come from non-highway mobile sources, such as farm and construction equipment (20%), heavy-duty highway vehicles (19%) and industrial processes and sources (19%). Trends in emissions from these five categories suggest different time paths of emissions reductions.

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[27]This maximum will not become binding for the large trucks and sport-utility vehicles until 2009. (See Federal Register Vol. 65, No. 28, pp. 6855-6856, 6858, 6866.)

As shown in Figure 7, there have been dramatic improvements in the emissions of NOx from light-duty vehicles, while the emissions from the other sources have remained more constant.[28]

Recently, both heavy-duty highway and non-highway mobile sources have been subject to more stringent regulations, and the regulatory impact analyses provide indications of the relative costs of reducing NOx from these sources. Over the past ten years, there have been two sets of regulations aimed at heavy-duty highway vehicles. Regulations promulgated in 1997 and effective in 2004 required a number of minor changes to heavy-duty diesel and gasoline trucks. For instance, the regulatory impact analysis forecast that engine manufacturers could achieve the standards by using existing technologies and, for instance, improving the fuel injection system or the air circulation system.[29] These changes were estimated to be extremely cost effective at a range of roughly $.05-$.15 per pound including markups. The next set of regulations, enacted in 2000 to be effective in 2007, required new technologies, and entailed costs per ton that were approximately an order of magnitude higher. These cost estimates are also very close to the cost estimates for vehicles under Tier 2.[30] Engineers with whom we have spoken contend that doing anything beyond what is required by the 2007 regulations would involve implementing new and as yet untested technologies and could involve much higher costs. In light of this, and in light of the cost difference between the 2004 and 2007 regulations, it seems reasonable to conclude that the marginal abatement curve for heavy-duty highway sources is steeply sloped. This suggests that replacing abatement from power plants with abatement from these sources may not lead to substantial efficiency savings.

Non-road diesel vehicles and engines are another story.[31] NOx standards for non-road diesel engines have historically been extremely lax. In 1998, standards were adopted that reduced NOx and particulate matter by as much as two-thirds for some engines. The EPA calculated the cost of achieving these reductions for a wide array of engine sizes, ranging from 25 horsepower to over 1000 horsepower. For many of these engines, the legislation simply required using technologies already in use for on-road vehicles. Using assumptions similar to those for the Tier 2 analysis (their assumed markup is 29 percent), the EPA calculated the average cost of abatement for six engines sizes. The average cost of abatement varies across the engine size, but for the largest size (also the largest

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[28] Kahn and Schwartz (2006) also provide evidence suggesting that NOx emissions from vehicles has declined dramatically.

[29] US EPA 1997.

[30] US EPA 1997.

[31] The EPA distinguishes on-road diesel engines from non-road by the following four factors: (1) the engine is used in a piece of motive equipment that propels itself in addition to performing an auxiliary function (such as a bulldozer grading a construction site); (2) the engine is used in a piece of equipment that is intended to be propelled as it performs its function (such as a lawnmower); (3) the engine is used in a piece of equipment that is stationary but portable, such as a generator or compressor; or (4) the engine is used in a piece of motive equipment that propels itself, but is primarily used for off-road functions.

polluters), the costs ranged from $.005-.05 per pound; the average abatement cost for the smaller sizes are typically below $.30 per pound.

There are two reasons to believe these are actually upper bounds. For one, these calculations do not account for the reduction in particulate matter; the particulate matter reductions were considerable. Second, many of the compliance strategies improve the operating efficiency of the engines. Factoring in the reduced operating costs suggest negative average abatement costs for many engines. While one can view the negative abatement costs with some skepticism, the improved efficiency certainly reduces the social abatement costs. We are in the process of collecting more information on the costs of expanding the reductions from these sources, although there appears to be less detailed engineering information. In addition, the diverse types of engines included in this category may make it harder to pin down a particular assumption on the costs.

# 7    Conclusions and Discussion

The Clean Air Act (CAA) prohibits the EPA from considering anything but health benefits when setting ambient air quality standards for criteria pollutants such as NOx. However, the CAA does require that economic cost considerations guide the implementation of the standards set under CAA provisions (see, for example, Section 109(d)(2)(C)). As air pollution regulations and standards become progressively more stringent, there is increasing pressure on policy makers to rationalize the costs of air quality improvements.

Large scale, market-based air pollution regulations such as the Acid Rain Program and the NOx Budget Program have successfully taken advantage of significant gains from trade among large industrial sources of pollution. Here, we present evidence to suggest that there is likely equal, if not greater, potential for efficiency improvements from coordinating abatement activity across mobile and point source pollution types. Based on data that were available when the NBP and Tier 2 program were being designed, we estimate that the total compliance costs incurred are almost 10 percent (or more than $2 billion) higher than the minimum costs required to achieve the combined reductions mandated by these two programs.

These findings are particularly relevant to the ongoing debate over how to design policies to address climate change. There is tremendous pressure on regulators to find ways to keep the economic costs of achieving proposed greenhouse gas reduction targets to a minimum. In theory, an economy wide tax or cap-and-trade program should ensure that marginal abatement costs are equated across all sources. Several of the proposed pieces of climate change legislation would

have point and mobile sources of greenhouse gas emissions regulated under the same market-based regulatory program.[32] Others have argued that the transportation sector, which accounts for 27 percent of total US greenhouse gas emissions, should be regulated separately from large point sources (Farrell and Sperling, 2007). This paper illustrates the potential for inefficiency when sectors and source types are regulated separately.

In this analysis, we have yet to account for some important factors which vary across source types, and which could bias our estimates. For example, we make no attempt to account for the fact that mobile and point source NOx emissions are distributed differently across space and time. These differences will have implications for the relative health damages caused by pollution from these different source types. Future work will address some of this variation. Although we do account for differences in monitoring and enforcement costs in our analysis, differences in the transaction costs of regulating mobile versus point sources may partially explain our results, though it is hard to imagine that they explain the entire efficiency loss we estimate.

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[32] Four bills currently under consideration in the U.S. Senate are set mandatory caps on economy-wide greenhouse gas emissions and either mandate or recommend a market-based cap-and-trade permit system.

# A Tables and Figures

## A.1 Tables

**Table 1:** Generating Unit Characteristics

| Variable | |
|---|---|
| # Units | 632 |
| # Facilities | 221 |
| Capacity | 275 |
| (MW) | (261) |
| Age | 35 |
| (years in 2000) | (13) |
| Pre-retrofit Emissions | 0.50 |
| (lns NOx/kWh) | (0.22) |

**Table 2:** Costs and emissions reductions for a representative unit

| $j$ | $c_j$ ($) | $R_j$ (lbs NOx) | $MAC_j$ ($/lb) |
|---|---|---|---|
| **0** | **0** | **0** | **0.36** |
| 1 | 6,996,353 | 10,721,079 | – |
| 2 | 6,077,613 | 12,353,775 | – |
| **3** | **4,864,353** | **13,460,610** | **0.85** |
| 4 | 1,0102,121 | 16,200,778 | – |
| 5 | 12,854,121 | 18,940,960 | – |
| **6** | **11,884,707** | **21,729,188** | **1.74** |
| **7** | **40,955,514** | **38,476,679** | **56.06** |
| **8** | **51,532,575** | **38,665,359** | **∞** |

**Table 3:** Variable Costs Associated with Tier 2

|                      | LDV   | LDT 1 | LDT 2 | LD 3   | LDT 4/MDPV |
|----------------------|-------|-------|-------|--------|------------|
| 4 Cylinder           | 24.99 | 13.16 | 8.16  | N/A    | N/A        |
| 6 Cylinder           | 65.16 | 91.46 | 90.98 | 238.86 | N/A        |
| 8 Cylinder           | 75.42 | N/A   | 70.97 | 171.99 | 171.99     |
| Larger 8/10 Cylinder | N/A   | N/A   | N/A   | N/A    | 291.54     |
| *Sales Weighted*     | *44.69* | *39.87* | *84.27* | *178.74* | *187.53* |

Notes: LDV = Light Duty Vehicles, LDT = Light Duty Trucks,

MDPV = Medium Duty Personal Vehicle (i.e., vehicles in excess of 8,500 lbs.)

**Table 4:** Variable, Fixed, Markups and Learning

|                              | LDV   | LDT 1 | LDT 2  | LDT 3  | LDT 4/MDPV |
|------------------------------|-------|-------|--------|--------|------------|
| First and Second Year        | 82.43 | 73.80 | 129.54 | 248.92 | 267.57     |
| 3rd Year: Learning begins    | 75.22 | 68.50 | 119.90 | 222.60 | 233.52     |
| 6th Year: Fixed Costs Expire | 53.19 | 49.03 | 100.64 | 202.99 | 212.34     |

**Table 5:** Emissions and Savings due to Tier 2 for the 47 States Affected

|      |                      | Contribution by Vehicle Class | | | |
|------|----------------------|-------|--------|---------|-----------|
| Year | Light Duty Emissions | LDV   | LDT1/2 | LDT 3/4 | Savings   |
| 2000 | 3,548,883            | 52.1% | 30.0%  | 17.9%   | —         |
| 2004 | 3,612,395            | 43.5% | 37.1%  | 19.4%   | 326,556   |
| 2007 | 3,681,990            | 37.3% | 41.0%  | 21.7%   | 959,512   |
| 2010 | 3,817,070            | 33.0% | 42.7%  | 24.3%   | 1,554,442 |
| 2015 | 4,116,074            | 28.6% | 44.3%  | 27.1%   | 2,527,309 |
| 2020 | 4,502,761            | 26.9% | 45.2%  | 27.8%   | 3,205,571 |
| 2030 | 5,323,860            | 27.1% | 45.5%  | 27.4%   | 4,049,687 |

**Table 6:** EPA's Estimates of 2030 NOx Sources With and Without Tier 2

|  | Without Tier 2 | With Tier 2 |
|---|---|---|
| Light Duty Vehicles | 19% | 5% |
| Stationary Sources | 45% | 53% |
| Other On-Highway | 7% | 8% |
| Off-Road | 29% | 34% |

**Table 7:** Average Costs Associated with Tier 2 and Potential Efficiency Gains

|  | Average Cost |  |
|---|---|---|
| **Method for dealing with other emissions** | **($/lbs of NOx+NMHC)** | **Inefficiency** |
| Uncredited Method | 1.02 | — |
| Crediting for Sulfur and PM* | .66 | $1.9 billion |
| Crediting for Sulfur and PM*, and assuming a variable cost markup of zero | .58 | $2.4 billion |
| Separating Tier 2 Costs, crediting for PM*, and assuming a variable cost markup of zero | .24 | $5.7 billion |

*Assumes $10,000/ton for PM (a total credit of $3.5 billion) and $4,800/ton for Sulfur (a total credit of $13.8 billion)

## A.2 Figures
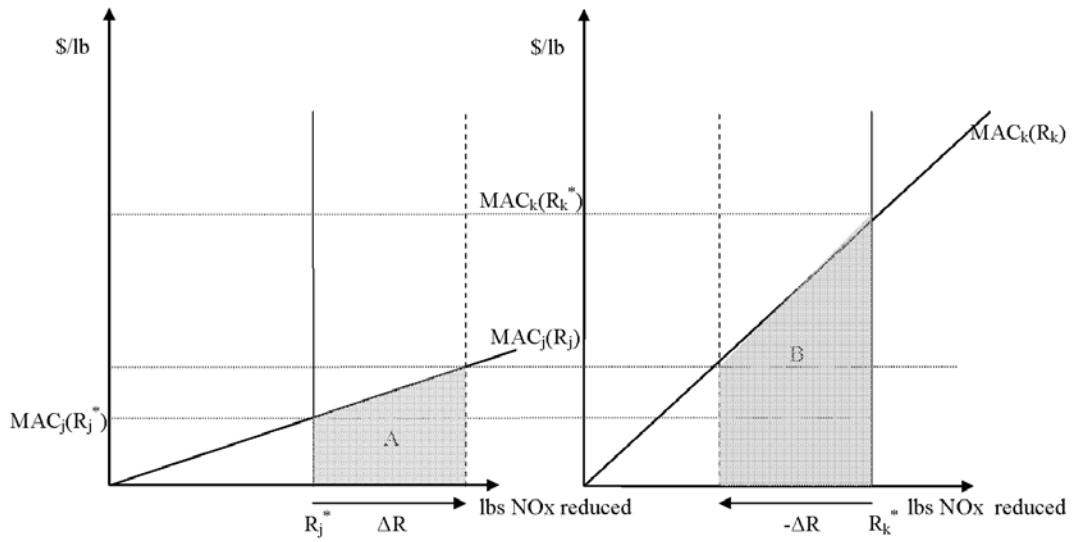


Figure 1: NBP Marginal Abatement Cost Curve
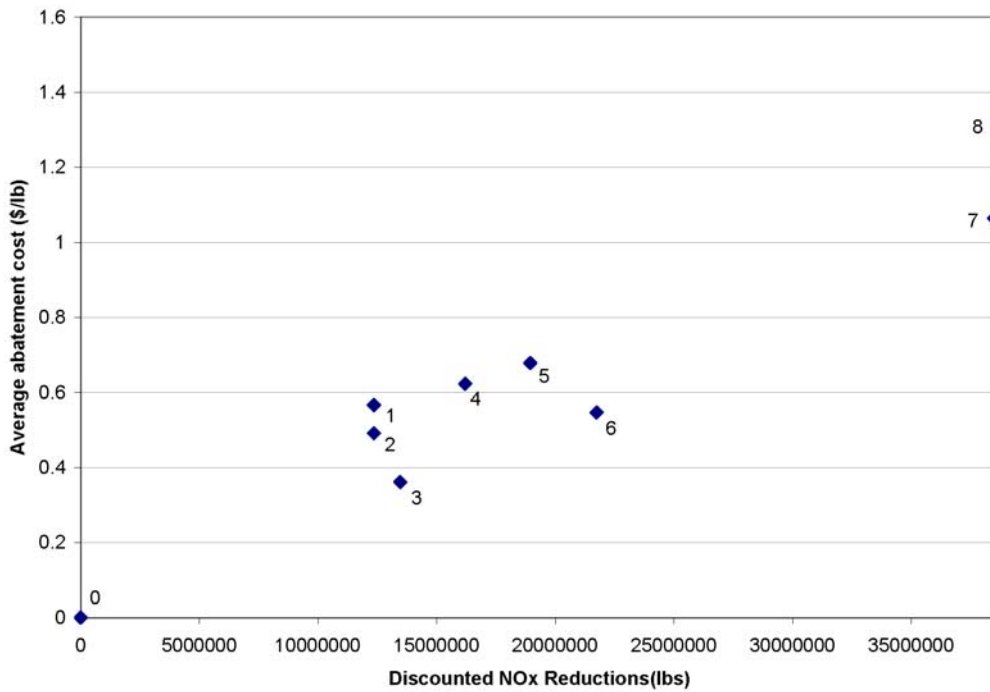


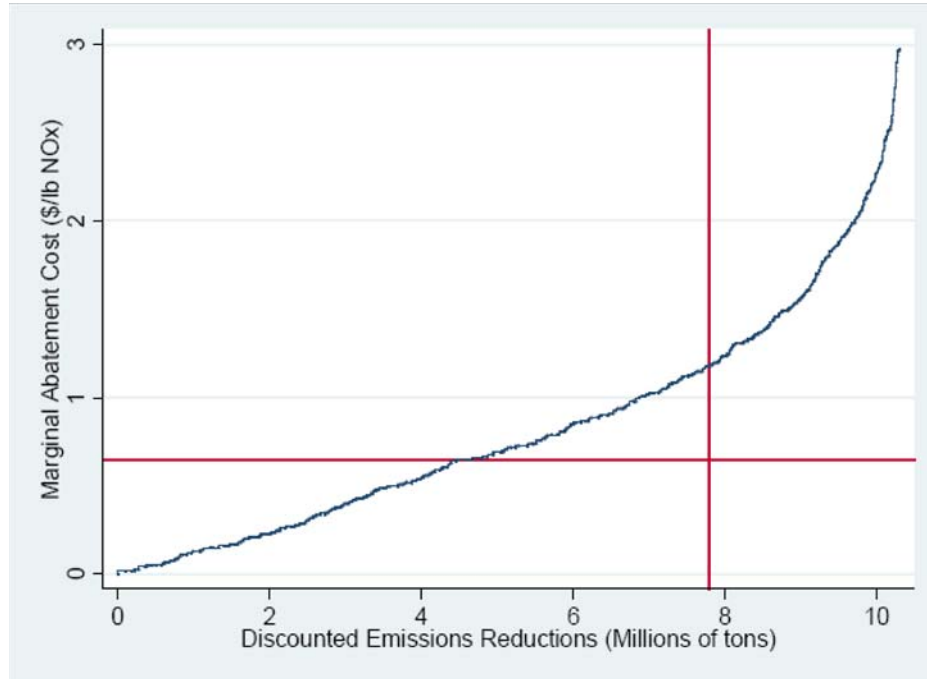Figure 2: NOx control costs for a representative unit

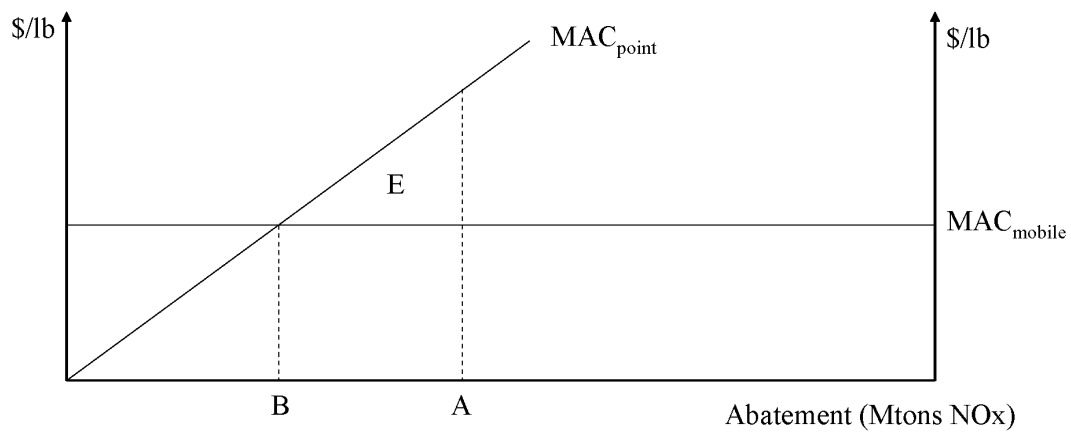Figure 3: Marginal Abatement Cost Curve for Coal-Fired Electricity Generators
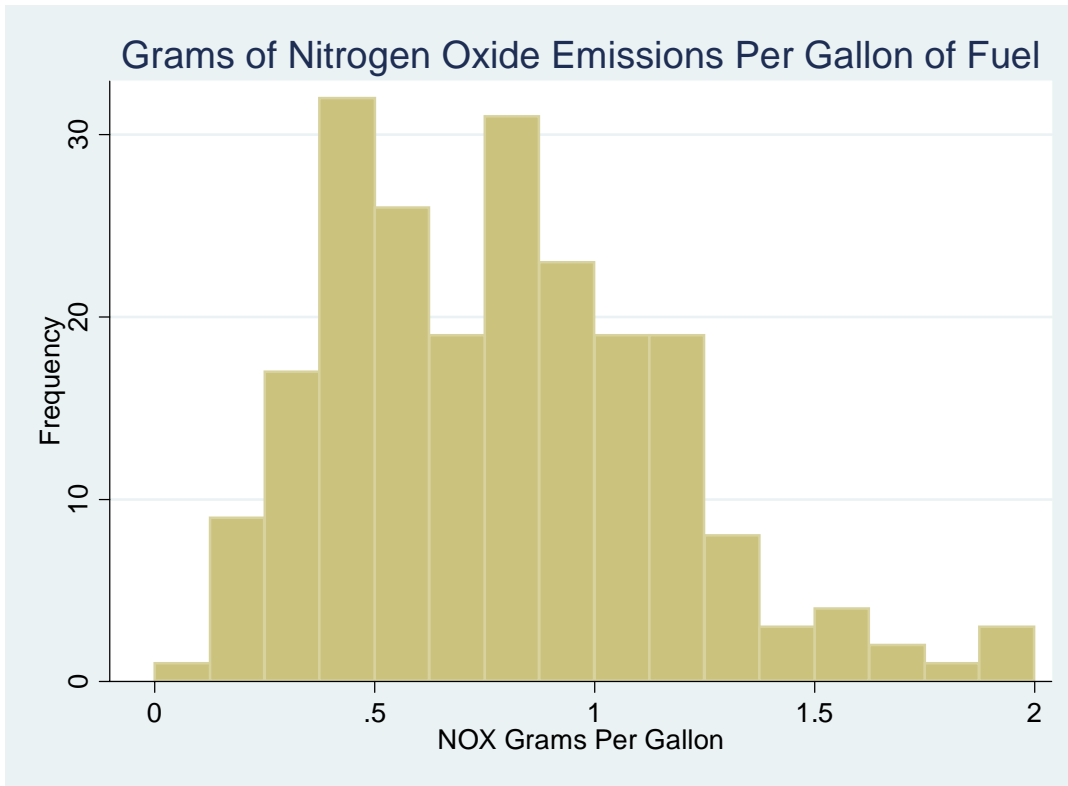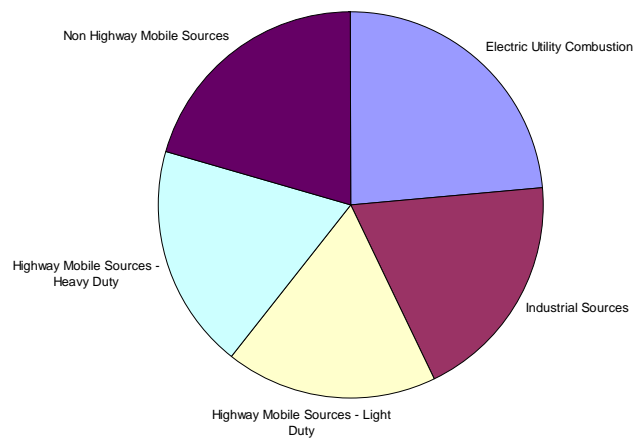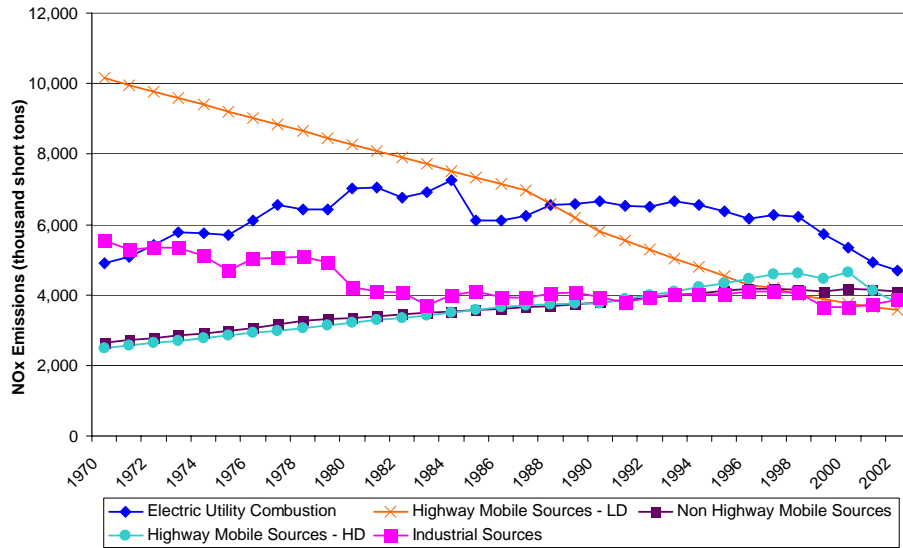


Figure 4: Measuring Efficiency Gains

Figure 5: Distribution of grams of NOx Emissions per Gallon



Source: National Emissions Inventory (NEI) Air Pollutant Emissions Trends, http://www.epa.gov/ttn/chief/trends/

**Figure 7: NOx Emissions by Source, 1970-2002**

# B   Data Appendix

**Unit-level compliance strategy choices**

1.      EPA Electronic Data Reporting for the Acid Rain Program/subpart H. The EPA collects hourly data from over 900 U.S. power plants who are required by law to install and operate Continuous Emissions Monitoring Systems (CEMS). All units that are affected by the Acid Rain Program, the NOx Budget Trading Program and/or the NOx SIP Call are subject to the monitoring and reporting provisions of Subpart H. Units must report what type of NOx controls they are operating, installation dates and hours of operation.

2.      Energy Information Administration (EIA). Facilities must also report information about NOx controls annually to the EIA.

3.      Institute for Clean Air Companies: Collects information about pollution control retrofits from press releases, annual reports, and other sources.

4.      MJ Bradley & Associates: Maintains a comprehensive database containing unit-specific information regarding pollution control equipment.

**Data required to estimate control costs at the unit level**

1.      U.S. EPA National Electric Energy System (NEEDS): (see above). Includes over 20 unit level variables, including capacity, heat rate, online year, firing and bottom types. Data is annual; most recent data is 2000.

2.      EPA Electronic Data Reporting for the Acid Rain Program/subpart H: The EPA collects hourly data from over 900 U.S. power plants who are required by law to install and operate continuous emissions monitoring systems (CEMS). All the plants in my sample are subject to the monitoring and reporting provisions of subpart H. This database contains thousands of variables, most of which are measured hourly at the unit level. Data is available with approximately a six month lag.

3.      U.S. EPA Emissions and Generation Integrated Database (EGRID): EGRID consolidates available plant level data for all U.S. power plants that are obliged to report data to the U.S. government. EGRID reports data on an annual level for hundreds of variables at the boiler, plant, company, parent company and state level. The most recent data is 2000.

4.      Energy Information Administration (EIA) Form 767 : Power plants(non-nuclear) larger than 10MW are required to submit form EIA-767 annually. The forms collect data on plant opera-

tions and equipment design (including boilers, generators, cooling systems, flue gas desulfurizations, flue gas particulate collectors, and stacks). Most recent data is 2002.

5.       Energy Information Administration (EIA) Form 860: Power plants(non-nuclear) larger than 10MW are required to submit form EIA-767 annually. The forms collect generator-specific information such as initial date of commercial operation, generating capacity, ownership and energy sources.

6.       Platts BaseCase: A comprehensive database covering supply, electric demand, transmission interfaces, and Platts fuel price forecasts, as well as unit-level hourly data. Compiled from EIA, FERC, NERC, CEMS, RUS, utility reports, manufacturers' publications, and Platts sources.

7.       Raftelis Financial Consultants Water and Wastewater Rate Survey.

8.       Bureau of Labor Statistics: Regional estimates of boilermaker and construction wages.

9.       Personal Correspondence: Representatives from the major coal-fired boiler manufacturers (Alstom Engineering, Babcock Power, Foster Wheeler, Riley Power Inc.) provided valuable information about the technical specifications of the boilers in the sample De-NOx Technologies LLC provided data on reagent and reagent transportation costs. Other technical assistance was provided by Cichanowicz Consulting Engineers LLP.

**Permit Price/Transaction Data**

1.       Evolution Markets LLC

**Estimates of anticipated post-retrofit NOx emissions rates (conditional on boiler characteristics)** constructed using the following sources:

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