ENVIRONMENTAL REGULATION AND PRODUCTIVITY: EVIDENCE FROM OIL REFINERIES

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Abstract—We examine the effect of air quality regulation on productivity in some of the most heavily regulated manufacturing plants in the United States, the oil refineries of the Los Angeles (South Coast) Air Basin. We use direct measures of local air pollution regulation to estimate their effects on abatement investment. Refineries not subject to these regulations are used as a comparison group. We study a period of sharply increased regulation between 1979 and 1992. Initial compliance with each regulation cost $3 million per plant and a further $5 million to comply with increased stringency. We construct measures of total factor productivity using Census of Manufacturers output and materials data that report physical quantities of inputs and outputs for the entire population of refineries. Despite high costs associated with the local regulations, productivity in the Los Angeles Air Basin refineries rose sharply between 1987 and 1992, which was a period of decreased refinery productivity in other regions. We conclude that abatement cost measures may grossly overstate the economic cost of environmental regulation as abatement can increase productivity.

I. Introduction

ENVIRONMENTAL regulation is commonly thought to reduce productivity. Despite concerns about productivity, the level and stringency of environmental regulation have continued to increase worldwide since the early 1970s as environmental quality has assumed growing importance on the public agenda. In the United States, total pollution abatement costs are approximately 1.5% to 2.5% of GDP per year.[1] Pollution abatement control expenditures (PACE) in manufacturing, alone, have increased by more than 137% between 1979 and 1993 at a compound annual rate of approximately 6%. By all indications, this trend will continue.

Abatement costs, as measured by PACE, are very high and of growing concern. But do they accurately reflect the economic costs of environmental regulation? If pollution abatement control expenditures miss costs such as the time spent by managers dealing with environmental regulators and regulations, PACE will underestimate the cost of regulation. Alternatively, if environmental regulation induces plants to install cleaner, more efficient technologies, pollution abatement expenditures may be productivity enhancing, so that PACE will overestimate the net economic cost of regulation. In either case, the gross cost of regulating the environment may differ significantly from the net cost, which is properly measured by the induced change in productivity.

The empirical literature often reports that environmental regulation has reduced productivity. Christiansen and Haveman (1981) go as far as implicating these regulations as significant contributors to the U.S. productivity slowdown of the 1970s. On the other hand, more recent discussions cite case study evidence of productivity-enhancing abatement investments. (For a discussion, see Jaffe et al. (1995).) Why is there no consensus in the empirical literature? A potential problem with these results is that estimation may be confounded by heterogeneity bias and measurement error, which may explain the existence of conflicting results. Heterogeneity bias may occur because the "dirtier" plants forced to abate may also tend to be less productive, perhaps because they use older technologies, making abatement appear to be productivity reducing. Conversely, plants that can most easily implement pollution reduction without losing productivity may choose to abate (even without the impetus of regulation), making abatement appear to be productivity enhancing.

Measurement error may also impart a bias, probably toward zero, on the relationship between environmental regulation and economic outcomes that are estimated from a regression of productivity on abatement. Abatement expenditures also may be difficult to classify. For example, if a plant replaces an old boiler and the new equipment is more efficient and thus produces less emissions, managers must decide whether part or all of this expenditure should be classified as abatement. The PACE questionnaires are often confusing on this point, asking them to classify as PACE all expenditures that they would not have made if no pollution regulations were in place.[2] In addition, managerial time devoted to pollution control is difficult to measure. Thus, measurement error in PACE data may be responsible for understating the effect on environmental regulation on productivity.

This paper takes two approaches to investigating the effect of a specific set of environmental regulations on productivity in the petroleum refining industry, one of the

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[1] Gross abatement costs, which include transfers to government agencies. Source: PACE Survey, 1993. The 1993 figure is $17,555, and the 1979 figure is $7,399.9 (in thousands of current dollars).

[2] From an economist's point of view, the questionnaire asks exactly the question of interest, as it asks the respondent to compare actual investment to the counterfactual in the absence of regulation. In practice, after many years of regulation that counterfactual may be difficult to imagine.

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single most regulated industries in the United States. Our first approach is to estimate the effect of regulations on abatement costs. We measure variation between regions in local environmental regulation, which is the source of most regulatory stringency for refineries in the South Coast region. Our use of a panel of plant-level data allows us to treat heterogeneity bias by allowing for plant-specific productivity effects. We avoid bias due to measurement error in abatement by directly estimating the effects of local regulations, which are quite precisely measured. Thus, we examine only variation in abatement behavior of petroleum refineries induced by changes in local environmental regulation, which is the relevant question for policymakers.

In the second approach, we examine the effects of regulation on productivity, allowing for the possibility that abatement expenditures do not accurately reflect the economic costs of regulation, either because of hidden costs or because abatement is productive. We measure total factor productivity using unique data on physical quantities from detailed products and material records in the Census of Manufactures. We compare the productivity of refineries in the South Coast Air Basin, which surrounds Los Angeles, to that of refineries in the rest of the United States, which are subject to much less extreme regulations.

Our method requires substantial variation in regulations and abatement behavior, which we found by examining local regulations and using data on individual plants. In particular, we focus our attention on the set of regional environmental regulations in California enacted by the South Coast Air Quality Management District (SCAQMD), that affect petroleum refining activities. We have constructed a unique data set for this purpose that matches SCAQMD regulations, which we collected, to plant data on production and abatement collected by the Census Bureau. We then study how refineries react to environmental regulations at their adoption dates, compliance dates, and at dates when existing regulations become more stringent. As a robustness check, we use two alternative comparison groups in our analysis: the rest of the United States, and Texas and Louisiana. That comparison allows our results to be interpreted as a prediction of the consequences of applying the local SCAQMD regulations to the average refinery in the comparison region. Doing so allows us to distinguish the effects of local regulation from those of pervasive (state or national) regulations, which apply to both treatment (South Coast) and comparison plants.

The SCAQMD governs air pollution in the South Coast Air Basin of Southern California.[3] Due to a combination of climate, airflow, and population concentration, the South Coast Air Basin had some of the worst air quality in the United States in the late 1970s. Since the development of national ambient air quality standards for six criteria air pollutants,[4] the South Coast Air Basin has been out of compliance with the standards for three of the six, and reached compliance for a fourth only in 1992.[5] In an effort to meet these national standards, the SCAQMD developed the most stringent set of local air pollution regulations in the United States during the 1980s. Regulations developed by the SCAQMD are particularly interesting because some have subsequently been adopted nationally by the U.S. Environmental Protection Agency (EPA) and are often considered for adoption by other air quality management districts.

We find strong econometric evidence that South Coast regulations induced large investments in abatement capital. Surprisingly, we find no evidence that these regulations had more than a transitory effect on the productivity of South Coast refineries. These refineries suffered a productivity decline in the 1980s but recovered to the national average by 1992, despite their heavy regulatory burden. In fact, the productivity of South Coast refineries rose sharply between 1987 and 1992, the period when the most stringent regulations came into effect, a period when productivity was falling for refineries elsewhere in the country.

The results suggest that abatement associated with the SCAQMD regulations was productivity enhancing, so that the gross cost of pollution abatement overestimates the economic cost of regulation. That finding implies a puzzle: if South Coast regulations induced abatement that increased productivity, why aren't the same technologies adopted elsewhere? We discuss a possible exclamation involving "real options" in the conclusions. There we also report on anecdotal evidence gathered in interviews about productivity-enhancing abatement investments.

The rest of the paper is organized as follows. Section II reviews the literature on the effects of environmental regulation on productivity. Section III provides background on petroleum refining and the relevant environmental regulations in California. Section IV derives estimating equations. In section V, we discuss the data. Section VI reports results, and section VII concludes.

II. Literature Review

The belief that environmental regulation is detrimental to productivity is reflected in numerous studies. Some have focused attention on the role of environmental regulation in the productivity slowdown that started in the early 1970s. (See Christiansen and Haveman (1981) for a survey.) The literature has taken several approaches to measuring the effects of environmental regulation on productivity. The three most common are growth accounting (Denison, 1979), macroeconomic general equilibrium modeling (Jorgenson & Wilcoxen, 1990), and econometric estimation (Gray, 1987).

[3] This region includes Los Angeles, Orange, Riverside, and the non-desert portion of San Bernardino counties.

[4] The six criteria air pollutants are SO_x, NO_x, ozone, PM_{10}, airborne lead, and VOCs.

[5] South Coast Air Quality Management District, Annual Report, 1994.

These studies consistently find that environmental regulation has reduced productivity, and sometimes significantly so. However, the accounting and modeling studies are problematic because they make an implicit assumption that the gross costs of abatement are the same as the cost net of any productivity change. The econometric studies may be compromised by heterogeneity bias which (as we discussed above) may overstate the adverse effects of regulation on productivity.

Particularly relevant to our study are papers using plant-level data to examine the effect of abatement costs on productivity. Gray and Shadbegian (1995) use the Longitudinal Research Database (LRD), matched to the Pollution Abatement and Control Expenditures (PACE) survey, and estimate regressions of TFP on abatement costs for oil refineries. Their cross-sectional estimates imply that $1 spent on pollution abatement induces a productivity loss of $1.35. This would imply that abatement expenditures (PACE) understate the full cost of abatement. Gray and Shadbegian also report fixed-effect estimates for the same parameters which are not significantly different from zero. This is important, as the null hypothesis of abatement being productive cannot be rejected for their fixed-effects estimates. A similar pattern occurs for estimates in the paper and steel industries. The authors do not take a strong stand on which estimates are correct, but lean toward the cross-sectional estimates on the grounds that the fixed-effects method exacerbates the bias due to measurement error in abatement (Griliches, 1986).

Morgenstern, Pizer, and Shih (1998) report similar results estimating cost function parameters from the same data. Their cross-sectional estimates imply that abatement expenditures understate the full costs of abatement, while their fixed-effect estimates imply smaller effects on costs, statistically indistinguishable from zero. That paper reviews the arguments for and against fixed-effects estimation, but favors the smaller, fixed-effects estimates on the grounds that heterogeneity bias is more of a concern than measurement error bias.

The approach we pursue in this paper is designed to deal with both heterogeneity and measurement error bias. We do this by calculating fixed-effects estimates that allow for heterogeneity across plants in productivity and by finding an exogenous source of variation in the regulations that induce abatement. These regulations can be measured quite precisely, reducing our concern with measurement error bias, if not eliminating it completely.

III. Background

Petroleum refining is a pollution-intensive activity. It accounted for almost one-half of air pollution abatement investment in manufacturing in 1994, and a little more than one-quarter of air pollution abatement operating costs.[6] In California in 1981, before the South Coast regulations had an effect (and where we have good measures of industrial emissions), refineries accounted for 61% of industrial emissions of sulfurous oxides (SOx), 40% of nitrous oxide (NOx) emissions, and a little more than 25% of emissions of reactive organic gases and particulate matter. California is the fourth largest producer of crude oil in the nation and has 24 operating refineries within the state, with a combined capacity of nearly 1,870,000 bbl/day. This section describes the characteristics of refining technology that are relevant to productivity measurement and provides a description of the regulatory structure under which this industry operates in California.

A. *Petroleum Refining in California*

Petroleum refining converts crude oil into useable products, such as gasoline, asphalt, and jet fuel. This process heats crude oil (or "cracks" its molecular structure) to separate its components into several final products. By altering the temperature and the specific gravity of the crude oil, refineries produce products ranging from kerosene to asphalt. They may alter the mix of final products depending on prices. For example, if the price of jet fuel increased significantly, a refinery may produce less motor gasoline and more jet fuel by changing the temperature to which the crude is heated. This suggests that any measure of refinery productivity must be sensitive to shifts in product prices.

Gasoline, fuel oil, and jet fuel are the three leading products refined in California. The price per barrel of finished product varied widely during this time period, as reported in table 1. Between 1977 and 1992, gasoline prices rose then fell, increasing by approximately 153% over the entire period, with differential fluctuations across products (164% and 168% for fuel oil and jet fuel, respectively).[7] The same is true of inputs. The price of domestic crude almost tripled between 1977 and 1982, then dropped by almost one-half through 1987. Note that the price of domestic crude oil actually rose faster than that of foreign crude in the late 1970s, and over the 1977–1992 period as a whole. These differential changes in prices dictate special care in measuring productivity changes across regions in physical units, because California's refineries rely primarily on domestic sources of crude oil, making them more vulnerable. For U.S. refineries as a whole, 45% of input costs were due to domestic crude and 34% were from foreign crude. (See table 1.) By volume, measured in barrels per day of crude oil, California refineries use 96% domestic crude and only 4% foreign crude. Another relevant issue in cross-regional comparisons of productivity is the quality of inputs. Of the domestic crude refined in California, 43% is extracted in California and 46% is from Alaska.[8] California crude is "heavier" and therefor more expensive to refine than Alas-

[6] U.S. Department of Commerce (1996), Tables 5 and 9.

[7] 1992 Census of Manufactures, Industry Series. Petroleum and Coke Products MC92-1-29A.

[8] California Department of Conservation (1996).

TABLE 1.—VOLUME AND PRICE OF MAJOR PETROLEUM PRODUCTS AND INPUTS

	Outputs			Inputs	
	Motor Gasoline	Distillate Fuel Oil	Jet Fuel: Kerosene	Domestic Crude	Foreign Crude
Percentage of value of Output/input in 1992	47%	17.6%	7%	45%	34%
Price per barrel:					
1977	$15.64	14.00	14.40	10.85	12.87
1982	39.50	36.95	38.55	31.45	32.18
1987	22.97	20.84	21.56	17.50	17.79
1992	24.90	22.62	23.14	18.65	17.75

Source: 1992 Census of Manufacturers, Industry Series. Petroleum and Coal Products MC92-1-29A.

kan ("North Slope") crude. Thus, we might expect California refineries to be less productive on average than those in the rest of the country.

B. Air Pollution Regulations and Petroleum Refining in California

Federal involvement in environmental regulation started in 1970 with the creation of the EPA. Prior to 1970, environmental regulation fell under state and local jurisdiction. The lack of coordination between states and locales in setting environmental standards, as well as a belief that environmental regulation was costly to industry and inhibited competition, led to a fear that there would be a "race to the bottom" in setting environmental standards. Therefor, one of the EPA's primary mandates was, and remains, to set uniform national standards for environmental quality. Individual states are responsible for developing state implementation plans (SIPs) that must be approved by the EPA and that indicate how the state will meet the federal environmental standards. States that fail to provide acceptable SIPs may have federal monies withheld by the EPA or lose control over setting environmental regulations within their own state.[9]

In general, federal environmental regulation is limited to setting national standards based on health criteria. Some exceptions are the minimum-level environmental regulations imposed on all new sources of pollution (New Source Performance Standards (NSPS)) and regulations in effect for nonattainment regions and regions considered to be "pristine" (Prevention of Significant Deterioration (PSD) regions).[10] Existing sources of pollution and mobile sources are typically regulated at the state and local level.

Within California, air pollution is regulated by the California Air Resources Board (CARB). Individual air basins are regulated by local authorities that fall under the jurisdiction of the CARB. California has 34 local air pollution control districts (APCD). Typically, mobile sources of pollution are regulated by the state, and stationary sources are regulated by APCDs.

California's petroleum refineries are largely concentrated in three APCDs: the South Coast Air Quality Management District, the San Joaquin Valley United Air Pollution Control District, and the Bay Area Air Quality Management District.[11] The South Coast is further from attainment of the national ambient air quality standards than any other large region, hence the unprecedented severity of regulations that came into force in the mid-1980s. Severe air pollution in the Basin is partly due to weather patterns. The Basin is arid, with little wind, abundant sunshine, and poor natural ventilation—conditions that exacerbate air pollution, especially the formation of ground-level ozone.[12] It is also densely populated with high concentrations of motor vehicles and industry. In 1990, the Basin contained 4% of the U.S. population and 47% of the population of California.

When the air quality standards were first established, the Basin was out of attainment for four of the six criteria pollutants. Hall et al. (1989) report that nonattainment of federal standards between 1984 and 1986 increased the death rate by one in 10,000 (a risk that doubles in San Bernardino and Riverside counties).[13] More than half of the Basin's population experienced a Stage 1 ozone alert annually, during which children were not allowed to play outdoors. The average resident suffered sixteen days of minor eye irritations and one day on which normal activities were substantially restricted.

The South Coast responded with local air quality regulations, over and above those imposed by the EPA and the state. These included heavy regulation of industrial emis-

[9] For a more comprehensive overview of air pollution regulation in the United States, good references include Portney (1990), Hahn (1989), and Hahn and Hester (1989).

[10] Federal environmental regulation may have had differential effects on various locations due to bubble, offset, and banking programs that were developed in the late 1970s. Of particular interest are the offsets that were purchased in the South Coast by petroleum refineries to get around nonattainment area restrictions on expanding existing sources of pollution. See Hahn and Hester (1989) for further details. These offsets, however, do not exempt the plants from local South Coast regulations and, therefor, do not affect the interpretation of our results.

[11] Smaller refining centers are located in the Santa Barbara County, Ventura County, and Monterey Bay Air Pollution Control Districts.

[12] Ozone is produced by a combination of volatile organic compounds, NOx, and sunlight.

[13] For comparison, the risk of death from an automobile accident in California is two in 10,000.

TABLE 2.—AIR EMISSIONS BY SOUTH COAST REFINERIES PERCENTAGE OF CALIFORNIA INDUSTRIAL EMISSIONS

	Pollutant	
Year	SOx	NOx
1981	18.3	21.3
1991	16.8	16.7
Change	−1.5	−3.8

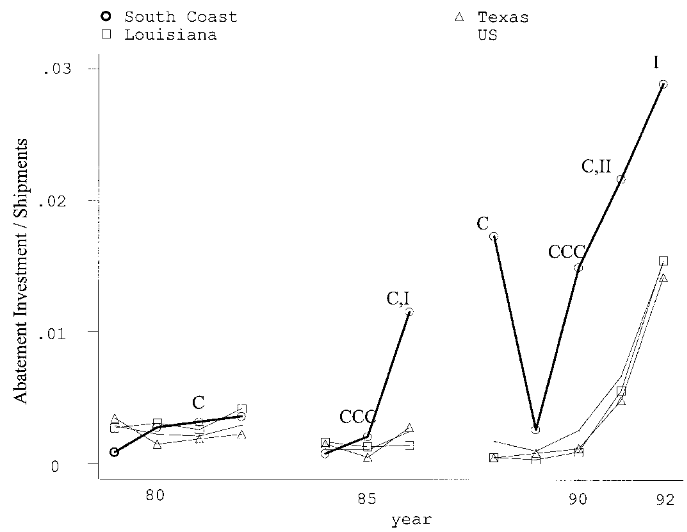
Source: California Emissions Database. Numbers are based on authors' calculations. Figures reported are a percentage of industrial emissions in the entire state of California, in all industries.

sions, generally mandating emission reductions and investment in emission control equipment. Between 1979 and 1991, South Coast manufacturing plants increased air pollution abatement costs by 138%, nearly twice the national rate of increase, and increased air pollution abatement investment by 127%, ten times the national rate of increase.[14] The SCAQMD's annual budget is, on average, more than eight times as large as that of the Louisiana Air Quality Program, and in 1999, approximately as large as that spent by the entire state of Texas for their Clean Air Account.[15] South Coast refineries incurred the lion's share of increased abatement costs, accounting for the majority of abatement investment and operating costs by 1991.

Refineries have been targeted by South Coast regulators because of their large contribution to emissions. Table 2 reports on the success of that program in reducing emissions from refineries. It shows that, although South Coast refineries accounted for a large share of state industrial emissions of NOx and SOx in 1981, they managed to reduce their proportion of state industrial emissions by substantial amounts. For NOx, the reduction was 3.8 percentage points (or 18%), and for SOx the reduction was by 1.5 percentage points (or 8%).

Figures 1 and 2 describe abatement costs associated with emissions reductions for South Coast refineries, with abatement costs for the United States, Texas, and Louisiana reported for comparison. Figure 1 reports air pollution abatement investment as a proportion of output for South Coast refineries and refineries in the comparison regions. That proportion increased sharply in 1986, deviating from the pattern in other regions, and remains considerably higher for the remainder of the sample period, with the exception of 1989. Figure 2 reports abatement operating costs as a proportion of output for South Coast refineries and refineries in the comparison regions. Abatement costs were approximately 1% of output through 1985 in the South Coast, as in the comparison regions, but almost doubled in 1986, exceeding 2% for four more sample years before falling in 1992. For both investments and abatement operating costs, abatement in the South Coast became much

FIGURE 1.—ABATEMENT INVESTMENT/VALUE OF SHIPMENTS IN REFINERIES

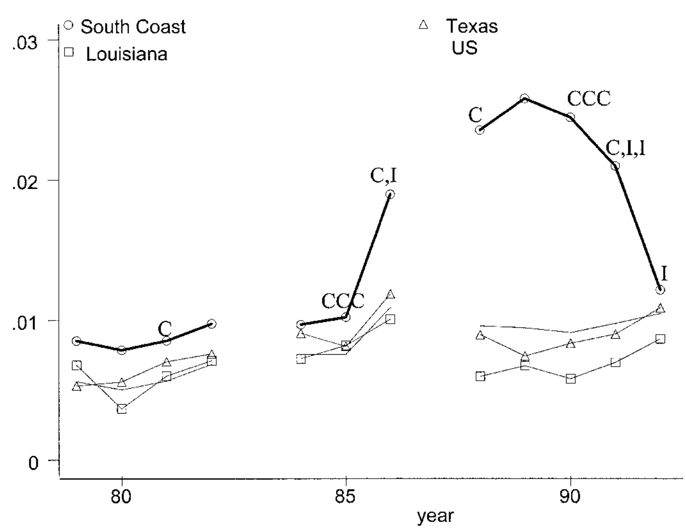


Source: PACE Survey. The graph compares air pollution abatement investment in oil refineries in the South Coast region to that in the refineries of Texas, Louisiana, and the entire United States. Abatement investment is calculated from the PACE survey. Each compliance date for a South Coast regulation is labeled with a "C", and each date of increased stringency is labeled with an "I". For instance, in 1991, one regulation had a compliance date and two had dates of increased stringency. Abatement investment data are unavailable in 1983 and 1987.

more expensive in 1986 and remained high for the remainder of the sample period.

The period beginning in 1986 is when the bulk of South Coast regulations had compliance dates. An example of a regulation adopted by the SCAQMD affecting petroleum refineries is Rule 1109. This regulation was adopted in March of 1984 and required that between July 1, 1988 and December 31, 1992, all petroleum refineries "reduce emissions of nitrogen oxides such that if those units were operated at their maximum rated capacity, the refinery-wide rate of nitrogen oxide emissions from these units would not

FIGURE 2.—ABATEMENT COST/VALUE OF SHIPMENTS



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[14] See Berman and Bui (2001) for a general description of the South Coast air pollution abatement program.

[15] Data were taken from various annual reports for the South Coast Air Quality Management District, Texas Natural Resource Conservation Commission, and the Louisiana Department of Environmental Quality.

exceed" a given level, depending upon fuel input type (gaseous versus liquid). Emissions standards were made more stringent after 1992. A full list of regulations is given in appendix A.

IV. A Framework for Estimation

To estimate the effects of regulation on abatement and productivity, we coded regulations as a set of binary indicators. Regression on binary indicators will provide a method of dealing with both measurement error and heterogeneity biases. In this section, we derive estimating equations and discuss estimation. First, we present a model of production that includes quasi-fixed factors that have their levels set by constraints rather than by cost minimization alone. We treat as quasi-fixed those inputs constrained by environmental regulation: pollution abatement capital and abatement operating costs (which include costs of labor, materials, and services). Labor, materials, and capital are variable factors.

Assume a cost-minimizing firm operating in perfectly competitive markets for inputs and output. There are M "quasi-fixed" inputs and L variable inputs. The variable cost function has the form:

$$CV = H(Y, Z_1, \ldots, Z_M, P_1, \ldots, P_L), \tag{1}$$

where Y is output, the Z_m are quantities of quasi-fixed inputs, and P_1 are prices of variable inputs.

Petroleum refineries are subject to a variety of air quality regulations. Generally, these regulations mandate the use of certain abatement equipment or set maximum emission levels, although there are other forms of regulation. (For a full description, see appendix A.) Refineries typically comply by installing equipment, redesigning production processes, changing their mix of inputs, increasing maintenance, and putting much more effort into measuring and reporting emissions.

Let R be a binary variable measuring regulation. Denote the effect of regulation on abatement activity as

$$\frac{dZ_m}{dR} \text{ for } m = 1 \text{ to } M \text{ quasi-fixed inputs.} \tag{2}$$

The demand for variable input X_i may be derived from the solution to the profit maximization problem and approximated with a linear function of the form[16]

$$X_l = \alpha_l + \pi_l Y + \sum_m^M \beta_{lm} Z_m + \sum_j^L \gamma_{lj} P_j, \quad \text{for } l = 1 \text{ to } L \text{ variable inputs.} \tag{3}$$

[16] A linear approximation is due to data limitations on pollution abatement capital services, where investment flows are measured rather than capital stocks.

Environmental regulation potentially affects the demand for variable inputs X_i through its effect on output, abatement activity (Z) and factor prices.

A. *Two Approaches to Measuring Effects on Productivity:*

Total factor productivity is given by

$$TFP = \frac{Y}{V},$$

$$\text{where } Y = \sum_k^K p_k Y_k, \tag{4}$$

$$V = \sum_m^M q_m Z_m + \sum_l^L q_l X_l.$$

Here, p and q represent output and input prices, respectively. This form accommodates both multiple inputs and multiple outputs in production. Refineries produce a large range of products other than gasoline. Approximately 80% of the value of inputs is crude oil.

A divisia index of total factor productivity growth is then

$$\dot{TFP} \equiv \sum_k^K s_k \dot{Y}_k - \sum_m^M s_m \dot{Z}_m - \sum_l^L s_l \dot{X}_l. \tag{5}$$

A dot over the variable indicates a (percentage) rate of change over time, s_k is the share of output k in total output ($s_k = p_k Y_k / Y$), and s_m, s_l are the cost shares of abatement and other inputs, respectively. This equation indicates that the effects of regulation on productivity growth can be directly measured by examining its effects on abatement inputs, dZ/dR, under three assumptions. First, the elasticity of substitution between abatement activity and all other inputs, X, is zero. This implies that $\beta_{lm} = 0$ for all abatement inputs (m) in equation (3). Second, regulations have no direct effect on other inputs, X (that is, $dX_l/dR = 0$). And third, regulations have no direct effect on output ($dY_k/dR = 0$). These three assumptions imply that measured abatement costs capture the entire cost associated with environmental regulations, net of possible productivity gains. This is the approach taken by Gray (1987) in measuring the cost of abatement by measuring Z.

Our experience visiting oil refineries leads us to question these assumptions. Costs of abatement are incompletely measured if they are only part of the job of a manager or engineer. Similarly, air pollution is sometimes abated by switching to higher quality and more expensive crude oil. That extra cost was not included in reported abatement costs in the two refineries we visited. On the other hand, abatement activities may be productive. For example, they may induce productive recycling of gases which increase output or recycling of emissions to co-generate power, decreasing inputs.

A more general approach to measuring the effects of environmental regulation on productivity is to ignore the distinction between abatement and other inputs in the measurement of total factor productivity. This allows us to relax the three assumptions made above. In this case, we revert to a more standard definition of TFP, where (in contrast to equation (4)), V_l measures the sum of abatement and conventional inputs of type l (labor, capital services, crude oil, and other materials):

$$TFP' = \frac{Y}{\sum_l^L q_l V_l}. \tag{6}$$

We then examine the effects of regulation on productivity by comparing changes in TFP' between South Coast refineries and refineries in regions without comparable increases in local environmental regulation.

B. Estimation

Beginning with the first approach, we estimate the effects of regulation on Z by measuring regulations directly. That procedure is designed to avoid the biases due to measurement error and any potential omitted variables that would occur if we used Z as a regressor, which is the common practice in the literature. R is a count of the number of regulations in effect.

The effect of regulation on abatement inputs, Z, can be estimated by

$$Z_m = a_m + b_m R. \tag{7}$$

We expect the sign of b_m to be positive, as regulations generally increase abatement activity. (An exception would be a regulation that increased one type of abatement activity but decreased another through substitution.)

The panel of plants allows us to treat heterogeneity bias by allowing plant effects, c_{mi}, in abatement. Equation (7) can be taken to data as

$$Z_{mit} = c_{mi} + d_{mt} + b_m R_{it} + e_{mit}, \quad \text{for } i = 1 \text{ to } N_t \text{ plants}, \tag{7$'$}$$

assuming $E(R_{it}, e_{mit}) = 0$.

We choose to estimate in first differences as

$$\Delta Z_{mit} = \Delta d_{mt} + b_m \Delta R_{it} + \Delta e_{mit}, \tag{7$''$}$$

assuming $E(\Delta R_{it}, \Delta e_{mit}) = 0$ for $i = 1, \ldots, N_t$ plants and $t = 1, \ldots, T$ years.[17] In some specifications, we include separate intercepts in equation (7$''$) for regions. Note that, for each South Coast refinery subject to a new regulation, the effect of regulation, b_m, is identified by comparison with a refinery in another region that is not subject to the new regulation.[18]

An alternative way to measure the productivity effects of environmental regulation is to examine the effects of regulations on productivity directly, using the more general TFP formula in equation (6). This can be calculated for fixed prices in Census years. Census materials and product files allow a rare opportunity to estimate TFP controlling for changes in the value of inputs (including some quality change) using fixed input prices. This has several advantages over the standard practice of fixing the shares, s, using regression coefficients, and calculating TFP as a residual. First, measurement error does not impart a bias on estimated averages as it does on regression coefficients. As discussed above, measurement of PACE and capital are especially suspect, particularly at the plant level.[19] Second, this approach allows us to be nonparametric about a production function, avoiding possible bias due to misspecification. Third, we avoid the possibility of endogeneity bias if output affects the choice of inputs. Finally, and most importantly, we can calculate productivity using measures of physical quantities for a number of outputs and inputs that would imply an impractical number of covariates in regression analysis even with fairly large samples. With these Census estimates, we compare productivity changes in the South Coast refineries to contemporaneous changes in comparison regions.

V. The Data

We use plant-level data for petroleum refineries (SIC 2911) from four sources. The Survey of Pollution Abatement and Control Expenditures (PACE) is linked at the plant level to the Longitudinal Research Database (LRD) panel compiled from the Annual Survey of Manufactures by the Center for Economic Studies of the Census Bureau. The Annual Survey of Manufactures samples the population of manufacturing plants, including large plants (250 or more employees) with certainty. Entry and exit of large plants are well measured by their presence or absence on a year-to-year basis. From these data we use the employment, value added, and capital investment variables. To measure total factor productivity, we use plant-level observations on the prices of inputs and outputs from a third source, the Census of Manufactures.

Our fourth source is data on local SCAQMD regulations, which we collected by examining regulatory documents and interviewing regulators.[20] This regulatory data matches individual air pollution regulations to specific plants in the South Coast. We identified eleven separate regulations af-

[17] At most two regulations were introduced per year, and none were withdrawn, so $0 \leq \Delta R \leq 2$.

[18] The coefficient b_m should be interpreted as the average effect of a number of regulations.

[19] See Griliches (1986) for a discussion of measurement error bias in plant-level data.

[20] For a more complete description of the data collection process, see Berman and Bui (2001).

TABLE 3.—DESCRIPTIVE STATISTICS FOR OIL REFINERIES PACE, LRD, AND REGULATORY DATA

	Mean	Standard Deviation
Value of shipments*	1,707,848	2,890,197
Value added	118,772	231,349
Employment	372	500
Air pollution abatement investment	2,096	7,618
Net abatement investment	1,495	7,475
Depreciation of abatement capital	601	1,796
Abatement operating costs	6,586	16,607
Change in abatement operating costs	141	6,951
New regulation adoption dates	0.053	0.369
New regulation compliance dates	0.041	0.267
New increased stringency dates	0.012	0.136
South coast indicator	0.055	0.228
California indicator	0.129	0.335
Texas indicator	0.208	0.406
Louisiana indicator	0.094	0.292

* Thousands of 1991 dollars deflated by the Producer Price Index.
Source: Pollution Abatement Costs and Expenditures microdata.
The sample contains 1,914 observations weighted by PACE sampling weights to represent 2,425 plant-years in the population. Sampled from 1979–1991, excluding 1983 and 1987. Data from 1992 and 1993 were excluded due to errors. Change in operating costs is from year to year and is defined only for plants observed for two consecutive sampled years. Employment is measured in persons.

fecting petroleum refining in the SCAQMD between 1979 and 1993. For each regulation, we tracked their adoption dates, compliance dates, and dates of increased stringency, as well as the pollutant involved and the required method of compliance. This mapping of regulations to affected industries was done in consultation with the local regulators and with two environmental quality engineers at refineries who hosted plant visits. From this information, we created the variable ΔR_{it}, which is a count variable for the number of new regulations in effect for industry i in year t.

Table 3 describes the PACE-LRD sample of refineries and regulatory information. Petroleum refineries are large, capital-intensive operations with relatively few employees. Average output is $1.7 billion (1991) with average employment of 372. Air pollution abatement investment is costly, averaging $2.1 million per year or 2% of value added. In our sample, 12.9% of plant-years in the population are in California, and 5.6% are in the South Coast Air Basin, which is a significant oil refining center.[21] The proportion of national refining capacity in the South Coast is approximately the same as the regions' proportion in the U.S. population, indicating that these oil refineries generally serve the local market.

[21] Petroleum refining is concentrated in the Long Beach area of the South Coast Air Basin, just south of Los Angeles.

Census Bureau disclosure regulations prevent a separate description of the South Coast Air Basin refineries. They are slightly larger than the national average in employment, value added, and shipments, and they follow similar patterns to the national figures in the cyclicality of value added.

South Coast refineries make up 5.5% of plant-years, as opposed to 20.8% in Texas and 9.4% in Louisiana. Among all plant-years (including those outside the South Coast), the mean of new regulations adopted is 0.052; for compliance, it is 0.041, and for increased stringency it is 0.012.

Regulations are recorded annually from 1977 to 1993, as is abatement (except for 1983 and 1987 when data are missing). Productivity is measured in census years 1977, 1982, 1987, and 1992.

VI. Results

A. Abatement Investment and Costs

We begin with the restrictive approach to measuring the effects of regulation on productivity, assuming that abatement investment and costs are a complete measure of productivity losses, as in equation (5). Figure 1 and 2 provided evidence that South Coast refineries had more abatement activity than those in the United States as a whole during the late 1980s.

Table 4 reports the result of estimating a regression of abatement investment on a count of new regulations (equation (7″) in section IV). It shows that regulations caused substantial investment in abatement capital. The first column reports that South Coast refineries spend $3.2 million more annually on abatement investment than do other refineries in California, and $4.3 million more than those in the remainder of the United States. In the second column, the regulations are introduced. These completely explain the effect of being in the South Coast. Compliance dates with new regulations seem to induce approximately $3 million in abatement investment for the average refinery, whereas increases in stringency of regulations induce approximately $5 million in abatement investment. Adoption dates have no significant effect. That result is robust to using net rather than gross investment, to weighting the regression using sample weights and to using Louisiana and Texas as a

TABLE 4.—AIR POLLUTION ABATEMENT INVESTMENT AND REGULATION

	1	2	Net Investment 3	Weights 4	CA, TX, LN 4
South Coast	3,161 (1,366)	128 (2,230)	605 (2,118)	376 (2,190)	1,646 (2,318)
California	1,113 (648)	1,127 (652)	831 (645)	674 (581)	−281 (851)
Louisiana					914 (1,052)
Adoption		−645 (806)	−791 (755)	−481 (809)	−2,024 (898)
Compliance		3,247 (1,556)	2,675 (1,345)	3,332 (1,567)	3,220 (1,598)
Increased Stringency		5,645 (3,317)	5,225 (3,072)	6,393 (3,288)	4,674 (3,398)
Observations	1,914	1,914	1,914	1,914	920
R^2	0.055	0.076	0.0845	0.0699	0.0998

Standard errors in parentheses. All specifications include a full set of year effects. The omitted state is Texas in column 5. See table 3 for descriptive statistics.

TABLE 5.—AIR POLLUTION OPERATING COSTS AND REGULATION

	Levels 1	Levels 2	Differences 1	Differences 2
South Coast	2,373 (1,936)	−448 (2,916)	97 (868)	1037 (1,049)
California	5,021 (1,412)	5,020 (1,415)	277 (631)	272 (632)
Adoption		266 (1,109)		−598 (974)
Compliance		2,798 (2,038)		17 (514)
Increased Stringency		2,298 (3,251)		−2,437 (1,548)
Observations	1,914	1,914	1,552	1,552
R^2	0.0180	0.0194	0.0063	0.0084

Standard errors in parentheses. All specifications include a full set of year effects. The omitted state is Texas in column 5. See table 3 for descriptive statistics.

comparison group rather than the rest of the United States. Texas and Louisiana make a good comparison group for California because they represent a counterfactual with similar concentrations of refining but with far less stringent local air quality regulation. Texas and Louisiana use the National Ambient Air Quality Standards as opposed to the stricter California standards. Those two states are out of compliance only for ozone, whereas the SCAQMD was out of compliance with four of the six criteria air pollutants throughout our sample period. Finally, Texas and Louisiana have weaker regulatory structures than does California.

In table 5, we report our attempt to estimate the same equation (7″) using abatement operating costs rather than abatement investment. The change in operating costs is too noisy to learn anything from it. This may be because investment is measured in first differences, whereas the abatement cost measure must be differenced to fit our specification, which may increase the ratio of measurement error variance to true variance in abatement costs. Column 3 and 4 are the specifications in first differences suggested in equation (7″).

Overall, the evidence in figure 1 and 2 and the abatement investment results in table 4 would lead us to infer that regulations force expensive abatement activity on refineries. Assuming that the gross and net economic costs of abatement are equal, as in Gray (1987), we would conclude that local environmental regulations cost millions of dollars in lost product, per regulation, for each plant.

B. *Productivity*

Taking the more general approach described above requires a measure of productivity. Figure 3 reports the ratio of all costs to shipments, for the South Coast and three comparison regions, between 1979 and 1992.[22] This is the inverse of TFP in equation (6) using current, plant-specific prices. South Coast plants seem to have relatively high costs in 1986, but by 1991 and 1992 they are far below the average for U.S. refineries, suggesting a surprising increase in productivity in the period of the greatest increase in regulation and abatement costs.

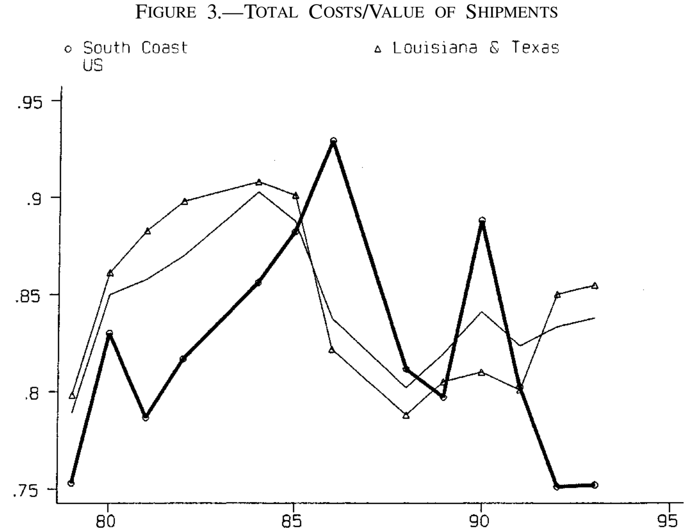
Shipment-to-cost ratios are potentially misleading as a measure of productivity because they may be confounded by variation in prices and quality of both inputs and products. In section III, we noted that, over the oil crises, input prices changed differentially across regions because the mix of foreign and domestic crude oil differs across regions. Input quality also differs across regions.

To calculate productivity more precisely, we used information from the Census of Manufactures product and materials files, a unique resource that allows unusual accuracy in calculating total factor productivity changes at fixed prices.[23] Products and materials are identified by detailed (seven-digit SIC) codes. Value (price × quantity) is reported for all codes and quantities are recorded (whenever they are well defined). This method is extremely well suited for analysis of petroleum refineries because, unlike many industries, the majority of materials have well-defined quantities. Approximately 80% of materials consumed fall into two seven-digit categories: domestic and foreign crude oil.

[22] Capital service costs are imputed as the capital stock is unavailable from 1988 onwards. Imputation was performed using estimated coefficients from a regression of capital stock on lagged capital stock and current investment, separately for building and machinery. Capital stock was then recursively predicted through 1992 and multiplied by 0.1 to estimate capital services. Results in figure 3 are robust to changes in this method. The imputation program is available upon request.

[23] Very little research has used this data source. An exception is Roberts and Supina (1996), who use these data to study cross-plant variation in prices and markups.

FIGURE 3.—TOTAL COSTS/VALUE OF SHIPMENTS



Source: PACE survey

TABLE 6.—TOTAL FACTOR PRODUCTIVITY OF REFINERIES

	Region				
	USA	California	Louisiana	Texas	South Coast
A. 1977–1992 average productivity using various prices					
P_{it}^{1} (transaction prices)	1.14	1.20	1.15	1.14	1.18
P_{t}^{2} (fixed prices across plants in each year)	1.15	1.10	1.18	1.17	1.10
P^{3} (fixed prices over plants and years)	1.13	1.09	1.17	1.15	1.09
B. Annual TFP Using Fixed Prices (P)					
1977	1.10	1.08	1.16	1.09	1.08
1982	1.16	1.12	1.19	1.17	1.09
1987	1.14 (0.01)[4]	1.03 (0.03)	1.21 (0.03)	1.20 (0.03)	1.07 (0.06)
1992	1.12	1.10	1.14	1.15	1.10
1987–1992 difference	−0.02 (0.01)[4]	0.07 (0.03)	−0.7 (0.03)	−0.05 (0.03)	0.03 (0.06)
1982–1992 difference	−0.04	−0.02	−0.05	−0.02	0.01
US/South Coast Difference in difference: 1987–1992					0.05 (0.07)[5]
1982–1992					0.05

Calculated TFP excludes outliers plants with TFP < 0.3 or TFP > 3. Figures including these outliers give a larger productivity gain in the South Coast between 1987 and 1992.

Material inputs and outputs (percentage of input/output value) for which we calculate fixed prices: Inputs: Domestic crude (45%), Foreign crude (34%), Foreign unfinished oils (1.7%), Natural gas C_4, 80% purity (1.6%), Isopentane and natural gasoline (1.1%).

Outputs: Motor gasoline (47%), Distillate fuel oil (17.6%), Jet fuel, kerosene type (7%), Heavy fuel oils (3.2%), Liquefied refinery gas, other uses (1.6%), Jet fuel: naphtha type (1.2%), Paving grade asphalt (1.0%). Percentages are from 1992 statistics. See footnote 8 for sources.

[1] P_{it}: Productivity measure calculated using current plant-specific implicit prices (value/quantity for each plant year).

[2] P_t: Productivity measure calculated using the weighted average of P_{it} in each year.

[3] P: Productivity measure calculated using the weighted average of P_{it} in all years.

[4] Calculated TFP in 1987 for California does not include the entire population due to missing data on materials prices. (See footnote 20.) For this reason, the standard error is included. For all other observations the Census reflects the entire population so standard errors are not reported.

[5] Calculated treating 1992 TFP as parameters. If 1982 and 1992 TFP are treated as random variables, the standard error for difference-in-difference estimates would be 0.08 for 1987–1992 and 0.07 for 1982–1992.

For that reason, these data provide uniquely high-quality measurement of total factor productivity for refineries.

We measure TFP = Y/V as in equation (6) using both varying and fixed prices.[24] Table 6 reports TFP in the South Coast and in four other regions for comparison, using three different measures. The first measure, P_{it}, uses plant-specific transaction prices for each input and output to calculate TFP. Here, prices are calculated by dividing values of inputs or outputs by quantities. This productivity measure is simply an output-to-cost ratio, as in figure 3. Using this measure, the South Coast appears to be relatively productive over the 1977–1992 period, with shipments exceeding costs by 18%, as opposed to the U.S. average of 14%, as reported in the first row of panel A.

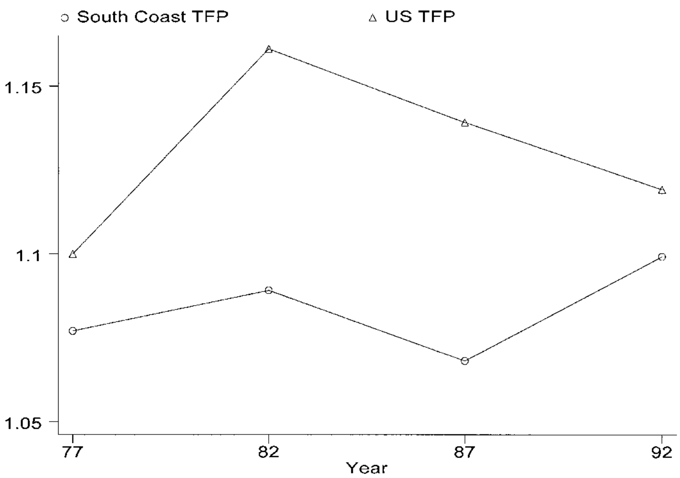
Yet, at fixed prices, the South Coast refineries are revealed to be less productive than average over the period as a whole. The measure P_t uses as a fixed price the annual national average of P_{it} for each material input and output, weighted by quantities. Thus, it fixes prices of materials and output across plants within the same year. Wage bill and capital services (which are together a small proportion of costs) are not converted into physical units. Capital services are assumed to be the sum of 5% of the book value of capital, repair costs, and depreciation. At fixed prices, South Coast refineries have a TFP of 1.10, lower than the national average of 1.15. The third measure of TFP, P, uses as a fixed price the four period average of P_t, weighted by quantities of inputs. (These fixed-price calculations could be conducted for the 84% of inputs and the 79% of outputs that had well defined quantities. For a complete list, see the note to table 6. For all other inputs and outputs, we used the transaction price, P_{it}.) This exercise produces the same conclusion: that California refineries in general had high shipment/cost ratios because of a price advantage. That advantage probably stems from their use of a higher proportion of cheaper domestic crude oil from California and Alaska, the latter being of particularly high quality, as discussed in section III.

Panel B uses fixed prices (P) to examine the development of refinery productivity over time. The rightmost column reports productivity in the South Coast refineries. Beginning at 1.08 in 1977, it rises slightly to 1.09 in 1982, drops in the beginning of the heavily regulated period in 1987 to 1.07 and then rises to 1.10 during the period of highest induced abatement between 1987 and 1992. That is, the apparent productivity increase in the early 1990s in South Coast refineries reported in figure 3 is replicated in the Census data even when we measure total factor productivity using fixed prices.

Figure 4 illustrates the contrast between productivity growth in the South Coast and the general U.S. trend (the leftmost column of table 6). U.S. refineries as a whole showed productivity declines between 1982 and 1992, even as productivity increased in the South Coast during the period of increased abatement investment and operating costs. Those diverging trends yield a "difference in difference" estimate of a gain of five percentage points in the productivity of South Coast refineries in 1987–1992, when measured relative to the national trend. Unfortunately, 1987 is a year in which measurement of physical quantities of

[24] An additional option would be to use the Tornquist approach, averaging prices over pairs of years for the same plant. The large number of missing plants in the materials records in 1987 and difficulties matching plants between Census years preclude this approach.

FIGURE 4.—SOUTH COAST AND U.S. TFP



Source: COM, table 6

materials is incomplete in the Census, with approximately 40% of refinery inputs missing. For that reason, the figures reported in 1987 are based on a sample, so we report standard errors as a guide to precision, both for levels and for differences. (Standard errors are calculated treating TFP for each plant as a random variable and calculating a mean weighted by costs, in which the costs are treated as constants.) The estimate of five percentage points has a standard error of seven percentage points, making it statistically insignificant at conventional levels. These basic findings are robust to selecting only those plants available in all Census years.[25] They are not due to reallocation of production from less efficient to more efficient plants, including reallocation due to entry and exit, but to increased productivity within plants.[26] As an alternative, the table also reports the 1982–1992 differential growth in productivity, again reporting the contrast between the South Coast and the U.S. average. That figure is also five percentage points, with no question about precision, as it reflects the population.[27]

Because the figures in table 6 reflect the population, they leave no doubt that refinery productivity increased in the South Coast during the 1982–1992 period by five percentage points more than the (declining) national average. Yet, one might wonder if that differential increase in productivity is itself a chance draw from some super-population. For that purpose, standard errors would be appropriate, even in reporting population "parameters." Those standard errors are 0.07 for the 1982–1992 difference-in-difference estimate (of 0.05) and 0.08 for the 1987–1992 difference-in-difference estimate (also of 0.05). Viewing these as draws from a super-population, we could not reject the hypothesis of no significant change in productivity; however, four comments are in order. First, a five-percentage-point productivity differential in a multibillion dollar industry is an event of huge economic significance. Second, figure 1 and 2 suggest that abatement investments and costs induced by local regulations in the South Coast were approximately 2% of annual output from 1986 to 1992. Thus, the null hypothesis suggested by much of the literature (which equates gross and net economic costs of abatement) would be a two-percentage-point productivity decline. This would leave us with a (5 + 2 =) seven-percentage-point differential gain in productivity levels. Third, given the precision with which regional productivity can be measured, even with the entire population of data, taking the super-population approach to testing would require productivity increases of thirteen or fourteen percentage points (when the standard error is about seven percentage points) to reject a null hypothesis of no difference in levels at conventional α levels. That magnitude of increase would be absurd. Finally, our interviews with plant managers and environmental engineers suggested that productivity increases were not accidental. They resulted from a careful redesign of production processes induced by the need to comply with environmental regulation. For example, low NOx burners and co-generation of electricity using waste gases are technological innovations that enhanced productivity while abating emissions. Together, these arguments suggest that productivity enhancing abatement in the South Coast is not a fluke, but reflects a statistical possibility result that should not be ignored.

VII. Concluding Remarks

We have found that, during an era of unprecedented increases in air quality regulation and unprecedented investment in abatement, South Coast petroleum refineries increased productivity. This is especially true when South Coast refineries are compared to refineries in other regions

[25] There is also some true exit and entry of refineries in the population. The basic patterns in figure 4 are preserved in a sample of continuously present plants. They also reflect the experience of a majority of plants rather than that of a few outliers.

[26] A useful decomposition of productivity change into within-plant productivity improvements on the one hand, and reallocations of inputs between plants with differing efficiency on the other, is

$$\Delta \frac{Y}{V} = \sum_{i}^{I} \Delta\left(\frac{Y}{V}\right)_i \left(\frac{\bar{V}_i}{V}\right) + \sum_{i}^{I} \left(\frac{\bar{Y}}{V}\right)_i \Delta\left(\frac{V_i}{V}\right),$$

where $i = 1 \ldots I$ plants, variables without subscripts are aggregates, and an overstrike represents an average over time. The second term, reflecting reallocation between plants, includes reallocation of input use share due to exit and entry. Entry and exit are possible consequences of regulations (Henderson, 1996; Becker & Henderson, 2000). Unfortunately, the combination of confidentiality rules, small samples, and missing materials in 1987 (see previous footnote) prevent reporting this decomposition at fixed input prices for the key 1987–1992 period. Nevertheless, a calculation of the value of input at varying input prices reveals that the between-plant effect (the second term) is negative in 1987–1992 for South Coast refineries, so that the productivity gains reported in table 6 reflect within-plant productivity gains.

[27] The only sense in which this is not the full population is that a few small outliers with productivity above 3 or below 0.3 have been omitted. South Coast productivity increases slightly faster between 1987 and 1992 if these are included, so the reported increase in table 6 is conservative.

of the United States. The fact that abatement expenditures did not decrease productivity in this case brings into question the general interpretation of measured abatement costs (that is, PACE) as a net cost of regulation. Abatement costs may severely overstate the true cost of environmental regulation.

Although surprising, these results are not inconsistent with other estimates in the literature that allowed for heterogeneity bias (Gray & Shadbegian, 1995; Morgenstern, Pizer, & Shih, 1998). These generally implied negative productivity effects but were not precisely enough estimated to rule out productivity increases.

The most puzzling question arising from this work is, why haven't other plants adopted the new technology if it is truly more productive? One possible explanation comes from the "real options" theory of investment under uncertainty (Dixit & Pindyck, 1994). Plants located outside the local regulatory region face considerable uncertainty both about the costs and efficacy of untested abatement technologies and about the requirements of future regulations. Under these conditions, a plant may optimally choose to defer even an investment with high expected returns if downside risk can be reduced by waiting to see how the technology works elsewhere, perhaps in the South Coast.[28] Our discussions with environmental engineers have lent some support to that explanation.

The fact that abatement costs are sometimes productive should refocus the debate about costs and benefits of environmental regulation. Using PACE measures, costs are commonly estimated at 1% to 2% of GDP. This may be a gross overestimate of true economic costs. A more appropriate measure would be the cost net of increased production due to abatement activity. A priority in this discussion should be discovering the net economic cost of environmental regulation in other industries and periods.

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[28] In this case, we might see productivity gains associated with the adoption of the South Coast abatement technologies outside of the South Coast with some lag. Thus far, the necessary data that we would need to test this hypothesis are not yet available.

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APPENDIX

The following is a list of the major environmental regulations imposed on petroleum refining activities in the South Coast Air Quality Management District, Bay Area Air Quality Management District. These regulations were compiled using the regulatory data books along with consultation with the regulators.

From this table, all the regulation variables may be constructed. For example, the adoption date variable will take on the value of 0 for all years for which no regulations are adopted and will take on the value of 1 in 1978, 4 in 1979, 1 in 1982, 2 in 1984, 2 in 1989, and 1 in 1990.

SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT

Rule #	Adoption Year	Compliance Year	Increased Stringency	Name
1105	1978	1986	—	Fluid Catalytic Cracking Units—Oxides of Sulfur
1108	1979	1985	—	Cutback Asphalt
1108.1	1979	1981	1986	Emulsified Asphalt
1109	1984	1988	1992	Emissions of Oxides of Nitrogen from Boilers and Process Heaters in Petroleum Refiners
1119	1979	1983	—	Petroleum Coke Calcining Operations—Oxides of Sulfur
1123	1979	1990	—	Refinery Process Turnarounds
1146	1990	1991	—	Emissions of Oxides of Nitrogen from Industrial, Institutional, and Commercial Boilers, Steam Generators, and Process Heaters
1148	1982	1985	—	Thermally Enhanced Oil Recovery Wells
1158	1984	1985	—	Storage, Handling and Transport of Petroleum Coke
1173	1989	1990	1991	Fugitive Emissions of VOCs
1176	1989	1990	1991	Sumps and Wastewater Separators

Compliance and increased stringency dates in January recorded as occurring in the previous year.