**WP 2007-17**
**October 2007**

# Working Paper

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# Measuring the Effects of Environmental Regulations: The Critical Importance of a Spatially Disaggregated Analysis

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# MEASURING THE EFFECTS OF ENVIRONMENTAL REGULATIONS: THE CRITICAL IMPORTANCE OF A SPATIALLY DISAGGREGATED ANALYSIS[*]

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DATE OF THIS DRAFT: AUGUST 29, 2007

## Abstract

We examine the effects of the 1990 Clean Air Act Amendments (CAAA) on ambient concentrations of $PM_{10}$ in the United States between 1990 and 2005. Consistent with prior literature, we find that non-attainment designation has no effect on the average monitor in non-attainment counties, after controlling for weather, socioeconomic characteristics at the county level and lagged concentrations. In sharp contrast, if we allow for heterogeneous treatment by type of monitor and county, we do find that the 1990 CAAA produced substantial effects. Our estimation results suggest that non-attainment counties with single monitors experienced a drop in concentrations of 10.5% relative to attainment counties. In non-attainment counties with multiple monitors, the overall effect of the regulation is an increase of ambient $PM_{10}$ concentrations by 1.9%. The dirtiest monitors in these counties, however, experienced drops in $PM_{10}$ of 6.1%, which suggest that regulators focus their attention on the dirtiest monitors.

**Keywords:** Air Pollution, Clean Air Act, Spatial Modeling

**JEL Codes:** Q53, Q58

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[*] We thank Calanit Saenger and Ravissa Suchato for excellent research assistance. We thank Peter Berck, Michael Greenstone, Wolfram Schlenker and seminar participants at UC Berkeley and the 2006 ASSA meetings for valuable comments. All errors are ours. For correspondence, contact Maximilian Auffhammer; Phone: (510) 643-5472; Email: auffhammer@berkeley.edu or Antonio Bento, Phone: (607) 255-0626; E-mail: amb396@cornell.edu

# 1. INTRODUCTION

Three empirical regularities characterize the changes in the spatial distribution of particulate matter less than 10 microns in diameter ($PM_{10}$) in the United States between 1990 and 2005: First, average county level ambient concentrations of $PM_{10}$ dropped by about 25%; second, these drops were far from uniform. Of the non-attainment counties in 1990, the average reduction in $PM_{10}$ in counties with single monitors was 27% while in counties with multiple monitors this reduction was only 17%. Third, there was substantial spatial heterogeneity in reductions of $PM_{10}$ in non-attainment counties with multiple monitors; the "dirtiest" monitors in these counties experienced drops that were 9% greater than the average of the remaining monitors.

This naturally raises the following two questions: First, what is the effect of the 1990 Clean Air Act Amendments (CAAAs) - measured by county non-attainment designations - on ambient concentrations of $PM_{10}$? Second, what is the level of spatial aggregation - county versus monitor level - needed for the effects of the regulation to be properly captured? This paper attempts to shed light on these questions by combining monitor level data on annual average $PM_{10}$ concentrations from the EPA's Air Quality System (AQS) between 1990 and 2005 with data from the Federal Code of Regulations on county $PM_{10}$ attainment status. We ask whether county non-attainment status is responsible for the drops in $PM_{10}$ experienced in single and multiple monitor counties. In the case of multiple monitor counties, we are interested both in the overall mean change in $PM_{10}$ concentrations and also in the spatial distribution of these changes, in particular, the changes in $PM_{10}$ at the dirtiest monitors. Conversations with air quality regulators suggest that special attention is paid to the dirtiest monitors in non-attainment counties, which may lead to a heterogeneous treatment effect across monitors within non-attainment counties.

Over the years, researchers have made considerable strides in measuring the effects of federal environmental regulations on the changes of ambient concentration of several criteria pollutants. Henderson (1996) investigated the effects of ground level Ozone regulations in the United States for the period of 1977-1987 on air quality and the migration of polluting facilities, using ambient concentrations of Ozone measured at the monitor level. Along the same lines, Chay and Greenstone (2003) and Chay and Greenstone (2005) examined the effects of total suspended particulates (TSPs) on infant health and capitalization of air quality into property values induced by the 1970 Clean

Air Act Amendments. More recently, Greenstone (2004) examined the effects of the 1970 and 1990 CAAA on Sulfur Dioxide concentration, using comprehensive county-level data files on $SO_2$ concentrations. A key finding in this literature is that *county* non-attainment status designation - the centerpiece of the CAAAs - is responsible for only modest (and often not significant) reductions of Ozone and TSPs during the 80s.[1]

Our concern is that, because of the lack of a spatially-disaggregated analysis that can capture the heterogeneity of ambient concentrations within non-attainment counties with multiple monitors and the failure to differentiate non-attainment counties with single monitors from non-attainment counties with multiple monitors, these studies may have potentially “averaged out” the true effects of environmental regulations. These studies typically use ambient concentrations measured at monitoring stations and are conducted at the county level. The problem is that, by regressing an average of the ambient concentration of the monitors located in a county on a non-attainment dummy, these studies could potentially underestimate the true effects of the regulation if, the ’dirtier’ parts of non-attainment counties reduce ambient concentrations by substantially larger amounts that the ‘cleaner’ ones. In other words, by aggregating the analysis to county level, it looks almost as if non-attainment counties behaved identically to attainment counties, therefore implying that environmental regulations are responsible for only minor reductions in ambient concentrations of criteria pollutants.

Similarly, by not separating the effects of the regulations across single versus multiple monitor counties, prior studies may have failed to identify the effects of the regulations. This could simply happen if, for example, the effects experienced in single monitor counties are partially offset by those experienced in multiple monitor counties.

This paper differs from prior literature in three distinct ways. First, we look at the impact of federal air quality regulation on particulate matter less than 10 microns in diameter, which is often considered to be the ”pollutant of the 90s”. Further, like Henderson (1996), we conduct our analysis at the monitor level, yet we allow the regulation to have a differential effect on concentrations measured at the monitoring site depending on the type of county (single vs. multiple monitors) and type of monitor (highest versus non-highest). Finally using previously unavailable weather

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[1] Henderson (1996) finds that county Non-Attainment status led to an additional 8% improvement in Ozone levels; Chay and Greenstone (2005) report that 1970-1980 TSP declined 12% more in non-attainment counties than in attainment counties

data, we are able to control for weather impacts at the monitor level, allowing for within county heterogeneity of rainfall and temperature.

We address these issues by combining annual average concentrations of $PM_{10}$ at the monitor level between 1990 and 2005 with county attainment designations for $PM_{10}$. Additional data were collected to account for other determinants of changes in $PM_{10}$, including climate and economic activity. We further control for monitor and year fixed effects to remove any unobservable confounding factors constant by monitor or year.

We use these data to estimate two sets of models. The first is a model that replicates existing studies of the effects of environmental regulations on other criteria pollutants (*e.g.,* Greenstone, 2004) measured at the county level. The second is a more disaggregated model where we distinguish single from multiple monitor counties. In addition for multiple monitor counties we allow for the possibility of heterogeneous impacts of the regulation based on the concentration at the 'dirtiest' monitor.

The rest of the paper is organized as follows. Section 2 provides a brief overview of $PM_{10}$ regulations; section 3 describes the data sources and provides summary statistics on the trends in monitoring and $PM_{10}$ concentrations between 1990 and 2005. Section 4 presents the econometric models and section 5 the results. Section 6 concludes.

# 2. BASIC ASPECTS OF $PM_{10}$ REGULATION

## 2.1 Brief Historical Facts About $PM_{10}$ Regulation

Particulate Matter is a term used for a class of solid and liquid air pollutants. Total suspended particulates (TSPs) include particles less than 100 microns in diameter. The 1971 Clean Air Act authorized the Environmental Protection Agency to enforce a National Ambient Air Quality Standard (NAAQS) for TSPs. The standards are phrased as primary and secondary standards. "Primary standards set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards set limits to protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings." (see United States Environmental Protection Agency (2005) for further discussion). Each standard is defined in terms of an annual benchmark average as well as 24 hour benchmarks. From April 30$^{th}$ 1971 until July 1st 1987 the primary annual standard for TSPs was 260 $\mu g/m^3$ for the 24-hour average and 75 $\mu g/m^3$ for the annual average. The secondary standard for TSPs was 150 $\mu g/m^3$ for the 24-hour average and 60 $\mu g/m^3$ for the annual average (National Archives and Records Administration, 1987).

If a county exceeded the primary annual standard for one year or the primary 24-hour standard for more than a single day per year it was considered to be in violation of the standard. By provisions in the Clean Air Act, the EPA can move to designate a county "non-attainment". After a lengthy review process, a non-attainment county was required to submit, in a state implementation plan (SIP), the strategy that it intends to use to become in attainment with the NAAQS. If the deficiency remains uncorrected, or if the EPA "finds that any requirement of an approved plan (or approved part of a plan) is not being implemented", the county is given 18 months to correct the deficiency. If the deficiency continues to be uncorrected the EPA Administrator may impose sanctions on the county in violation, including the withholding of federal highway funds, and the imposition of technological "emission offset requirements" on new or modified sources of emissions within the county (National Archives and Records Administration, 2005). In the first stage of the sanction process, only one of the sanctions is applied at the discretion of the EPA Administrator; if the county continues to be in violation 6 months after the first sanction, then both are applied. These sanctions are enforced not at the state level, but at the political subdivisions that "are principally responsible for such deficiency" (National Archives and Records Administration, 1987).

In 1987, the U.S. Environmental Protection Agency refined their particulate policy to regulate particulates less than 10 micrometers in diameter ($PM_{10}$). The new primary standard required the three year geometric average of $PM_{10}$ concentration for each monitor in a county to be less than 50 $\mu g/m^3$. It further required via a secondary standard that the 24 hour average concentrations at a monitor do not exceed 150 $\mu g/m^3$. This change was implemented because a growing body of scientific evidence indicated that the greatest health concern from particulate matter stemmed from $PM_{10}$, which can penetrate into sensitive regions of the respiratory tract.[2]

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[2] For a concise analysis of the health effects from exposure to $PM_{10}$, see Hall, Winer, Kleinman, Lurmann, Brajer and Colome (1992). For an analysis of the impact of air pollution on infant health, see Currie and Neidell (2005), and Chay and Greenstone (2003).

## 2.2 Sources of $PM_{10}$ Pollution

Particulate matter enters the atmosphere in one of two ways: primary particulate matter is emitted directly into the atmosphere as a solid or liquid; secondary particulate matter is formed in the atmosphere by reactions between precursor gases such as organic gases, nitrogen oxides ($NO_x$), and sulfur oxides ($SO_x$). In general, the contribution of the secondary $PM_{10}$ precursor gases to total ambient $PM_{10}$ is substantially larger than the contribution of primary particulate matter.

In California, for example, the California Air Resources Board estimates that in the year 2000, there were approximately 2,400 tons of primary $PM_{10}$ emitted on a daily basis. Of these 2,400 tons, 6% was emitted by stationary industrial sources, 5% was emitted directly from mobile sources, 15% was generated from paved roads, and the remaining 74% was produced by area-wide sources. The area-wide sources include residential fuel combustion (7%), farming operations (9%), construction and demolition (9%), unpaved road dust (27%), fugitive windblown dust (12%), and burning and waste disposal (10%).

In addition to the primary $PM_{10}$ emissions, 10,847 tons of secondary $PM_{10}$ precursor gases were emitted into the atmosphere on a daily basis in California in the year 2000. These precursor gases include 3,591 tons of $NO_x$, 333 tons of $SO_x$, and 6,923 tons of organic gases (California Air Resources Board, 2001). The actual contribution of the secondary $PM_{10}$ precursor gases to ambient $PM_{10}$ concentration levels depends on the ambient concentrations of the precursor gases themselves, as well as the atmospheric chemistry of the region, including the relative humidity, temperature, wind speed and direction (Foresman, Kleeman, Kear and Niemeier, 2003). In this case one may find two areas with similar secondary $PM_{10}$ precursor gas releases that have different secondary $PM_{10}$ ambient concentrations, depending on their location-specific characteristics. In the case of the South Coast Air Basin, the $PM_{10}$ reduction efficiency calculations, which allow one to estimate the primary and secondary emissions required to produce a single unit increase in the ambient concentration of $PM_{10}$, indicate that $NO_x$ emissions in 1990 contributed to over half of the total ambient $PM_{10}$ concentration (see Foresman et al. (2003) for further discussion).

# 3. OVERVIEW OF THE TRENDS IN $PM_{10}$ CONCENTRATIONS AND REGULATIONS

To implement the analysis, we compiled the most detailed data available on concentrations, non-attainment status and other relevant determinants of concentrations, including climate and economic activity. This section describes the data sources and presents summary statistics on national trends in $PM_{10}$, the distribution of monitors and mean concentrations of between 1990 and 2005.

## 3.1 $PM_{10}$ Concentrations and Attainment Status Data

The concentrations data were obtained from the *Air Quality Standards* (AQS) database, maintained by the EPA. For each $PM_{10}$ monitor operating between the 1990 and 2005 period, these data include a number of monitor characteristics including the location of the monitor, and hourly readings during operation. For estimation purposes, we calculated the annual monitor averages across hourly readings from the set of monitors that operated for at least 75% of the year, which is how the EPA designates a monitor as active.

The annual county attainment status designations were determined from the annual Code of Federal Regulations (CFR). For each of the criteria pollutants, the CFR reports the county attainment status in one of the following categories: “does not meet primary standards”, “does not meet secondary standards”, “cannot be classified” and “better than national standards”. For some criteria pollutants, CFR indicates that only part of a county did not meet the primary standards. Based on this information, we assigned a county to be non-attainment if the whole county or parts of it failed to meet the “primary” or “secondary” standards.

## 3.2 Additional Data: Attainment Status with other criteria pollutants, Climate and Economic Activity

We supplement the data on $PM_{10}$ concentrations and attainment status with additional relevant data, reflecting the need to capture other determinants of the change in $PM_{10}$. Since attainment status is not only assigned for $PM_{10}$, but for five other criteria pollutants, it is important to separate the impact of policy induced reductions in precursor emissions to the pollutant of interest. We therefore control for yearly county non-attainment status for TSP, Ozone, $SO_x$ and $NO_x$ collected from the CFR.[3]

In addition to regulation, there are other physical factors influencing ambient concentrations of $PM_{10}$. Temperature and rainfall affect the formation of secondary $PM_{10}$ as well the presence of primary particulates. Since microclimates vary greatly within states and large counties, we do not use county averages, but use rainfall and temperature at the monitor. We control for February and July rainfall and temperatures, which have been shown to be highly correlated with particulate concentrations, since they proxy for how cold/wet each winter was and how warm/dry each summer was at the monitor level. We use the PRISM Group (2007) dataset, which provides monthly data based on all US weather stations extrapolated to a set of 4km grids covering the continental United States between 1990 and 2005, allowing us to construct weather observations at the pollution monitor location.

Finally, emissions of particulate matter are strongly correlated with economic activity. While GDP is not available at the county level, the Bureau of Economic Analysis (BEA) releases annual estimates of personal income at the county level. This indicator has been widely used in the Environmental Kuznets Curve literature at the state level (*e.g.,* Millimet, List and Stengos, 2003). We include the county level real personal income for each year and county in our sample.

## 3.3 National Trends in Monitoring and concentrations

### 3.3.1 Distribution of monitors by Counties

Table 1 presents annual summary information on counts of monitors by county for monitors that were active at least 75% of the year. The second column reports the number of counties with active monitors. As a result of the 1990 CAAA, both the number of operating monitors and the geographical coverage of $PM_{10}$ readings increased substantially between 1990 and 2005. In 1991 only 2 counties had active monitors; by the end of our sample 95 counties had active monitor readings.

Columns (3)-(10) present the count of counties as well as the mean of monitors by attainment status in 'single' and 'multiple' monitor counties. In the year 2000, for example, a total of 51 counties had active monitors at least 75% of the year. Of these, 28 were single-monitor attainment

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[3] In 1997 the EPA began to regulate fine particulates. Non-attainment designations for fine particulates were first assigned in 2005. We further do not control for lead non-attainment status.

counties, 16 single-monitor non-attainment counties, 4 multiple monitor attainment counties, and 3 multiple monitor non-attainment counties. The number of monitor years from multiple monitor non-attainment counties is 42% larger than the number of monitors in multiple monitor attainment counties.

The spatial distribution of monitors active during our sample period across the United States is quite varied. In 2005, Maricopa (AZ), Dona Ana (NM) and Allegheny (PA) were the counties with the largest number of monitors. As of 2005, the population in counties monitored were 153 million people, which is about 52% of the total US population. The overall spatial distribution of monitors reflects the EPA's concerns of measuring concentrations of in areas that are heavily populated.[4]

### 3.3.2 Trends in $\mathrm{PM}_{10}$ between 1990 and 2005

Table 2 shows the mean annual concentrations between 1991 and 2004 by attainment status and "single" versus "multiple" monitor counties based on all active monitors. The following trends stand out: First, by 1991 the mean annual concentrations in non-attainment counties were already below the national air quality primary standard (NAAQS) for $\mathrm{PM}_{10}$. In single-monitor non-attainment counties concentrations were 38.19 $\mu g/m^3$. In multiple-monitor non-attainment counties, concentrations were 35.30 $\mu g/m^3$. More surprisingly, the average of the monitors with the highest mean annual concentration in non-attainment counties was below the NAAQS.

Second, as figure 2 shows, the relative reductions in $\mathrm{PM}_{10}$ concentrations between 1991 and 2004 were remarkable, regardless of initial attainment status. On average, single monitor counties experienced a larger drop in $\mathrm{PM}_{10}$. Single monitor attainment counties experienced a reduction in of about 29.5%, and single monitor non-attainment counties experienced a reduction of 35.12%. The drops in multiple-monitor counties were less dramatic: 17.26% and 19.33% for attainment and non-attainment counties, respectively.

Third, a comparison of the last two columns of table 2 reveal that between 1990 and 2005, the reductions in the annual mean concentrations of $\mathrm{PM}_{10}$ for the highest monitor were 39.46%, which is very close to the drop experienced by single monitor non-attainment counties. This provides some evidence in support of the hypothesis that regulators targeted the 'dirtiest' areas in

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[4] A map of monitor location can be found at the EPA's website: http://www.epa.gov/airtrends/pm.html. A map of monitors active for more than 75% of the year which are used in this paper is available upon request.

multiple monitor non-attainment counties.

Fourth, most of the additional effort to reduce in non-attainment counties took place between 1990 and 1997. In fact, Table 2 reveals that in non-attainment counties concentrations actually leveled off or slightly rose after 1997, especially in multiple monitor counties.

# 4. ECONOMETRIC MODEL

In this section, we describe the econometric strategy adopted to measure the effects of $PM_{10}$ attainment status on changes in concentrations. Let $D_{j,t}$ be an indicator variable that equals one when the entirety or part of county $j$ is designated non-attainment in year $t$ and 0 if it is in attainment. Let $Y_{i,t}^{j}$ denote the $PM_{10}$ concentrations of monitor $i$ in county $j$ in year $t$. Consistent with the literature, our basic econometric model is equation 1 below:

$$\frac{Y_{i,t+1}^{j} - Y_{it}^{j}}{Y_{it}^{j}} = \alpha D_{j,t} + \boldsymbol{X}_{j,t}\boldsymbol{\beta} + \boldsymbol{P}_{i,t}\boldsymbol{\varphi} + \theta_t + \delta_i + \eta_{i,t} \tag{1}$$

where $\alpha$ is the parameter of interest and measures the difference in the percent change in $PM_{10}$ concentrations between non-attainment and attainment counties. Formally, $\alpha$ represents the average treatment effect of attainment status in non-attainment counties, and is given by:

$$\alpha = \mathrm{E}\left[\frac{Y_{i,t+1}^{j} - Y_{it}^{j}}{Y_{it}^{j}} | D_{j,t} = 1\right] - \mathrm{E}\left[\frac{Y_{i,t+1}^{j} - Y_{it}^{j}}{Y_{it}^{j}} | D_{j,t} = 0\right]$$

$\boldsymbol{X}_{j,t}$ is a vector of controls, which vary over time at the county level. These include non-attainment status of monitors in county $j$ for other criteria pollutants (i.e TSP, NOx, SOx and Ozone) in the same year that $D_{j,t}$ is measured and a county-level measure of income. $\boldsymbol{p}_{i,t}$ is a vector of controls, which vary at the monitor level. In this paper we include rainfall and temperature at the monitor level, as described in the data section. $\theta_t$ is a year fixed effect that is common to monitors located in attainment and non-attainment counties, $\delta_i$ is a monitor fixed effect that controls for monitor specific unobservables that are invariant over time, and $\eta_{i,t}$ is the idiosyncratic unobserved component of the percent change in $PM_{10}$ concentrations, which is assumed to be stationary ergodic.

Further, we follow Greenstone (2004) and include one lag of $PM_{10}$ concentrations in order to remove the unwanted correlation between $D_{j,t}$ and $\eta_{i,t}$. In this paper we present models with a one-period linear lag.[5]

The model described by equation (1) is appropriate to measure the average effect of attainment status on the average percent change of $PM_{10}$ county concentrations. However, it does not allow us to disentangle the potential differential impact of the non-attainment status across single versus multiple monitors' counties and across 'dirtier' versus 'cleaner' monitors' within non-attainment counties. In order to address these concerns, we estimate an augmented specification of equation (1).

$$\frac{Y^j_{i,t+1}-Y^j_{it}}{Y^j_{it}} = \alpha D_{j,t}+\gamma_1 D_{j,t}M_{j,t}+\gamma_2\left(1-D_{j,t}\right)M_{j,t}+\lambda D_{j,t}M_{j,t}H_{i,t}+\boldsymbol{X}_{j,t}\boldsymbol{\beta}+\boldsymbol{P}_{i,t}\boldsymbol{\varphi}+\theta_t+\delta_i+\eta_{i,t} \quad (2)$$

where $M_{j,t}$ takes the value 1 if a non-attainment county has multiple monitors, zero otherwise. $H_{i,t}$ is a dummy equal to one, if a monitor has the highest concentration during the non-attainment designation year out of all active monitors in the county. It therefore only equals one if a monitor is the highest monitor in a multiple monitor county during the designation year.

Equation (2) allows for the effects of the regulation to have differential impacts. In contrast to equation(1), $\alpha$ isolates the effect of non-attainment status on non-attainment counties with single monitors. $\gamma_1$ captures the additional effect of the regulation on a monitor located in non-attainment counties with multiple monitors (in these counties the effect of the regulation is given by $(\alpha+\gamma_1)$). Since dirtier counties are likely to have more monitors, we would expect $\gamma_1$ to be positive. $\gamma_2$ captures the additional effect of the regulation on a monitor located in an attainment county with multiple monitors relative to that experienced by a single monitor county. Finally, $\lambda$ isolates the difference in percent annual reductions of ambient concentrations of the highest monitor in a multiple-monitor non-attainment county with respect to the other ("non-highest") monitors in the same county. The effect of the regulation on the percent change in concentrations at the highest monitor in a multiple monitor non-attainment county is given by $(\alpha+\gamma_1+\lambda)$. If indeed regulators targeted the dirtier areas of non-attainment counties, $\lambda$ should be negative.

$\lambda$ is an estimate of the average treatment effect for the dirtiest monitor in the multiple monitor counties. The concentrations at these dirtiest monitors will vary, and one would expect

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[5] However, since the true lag structure is unknown, we experimented with different lag lengths using the SIC and found that only the first lag was significant. We therefore include a single lag of ambient concentrations.

more effort to be expended at dirtier monitors within this cohort. Therefore we will allow for a heterogeneous treatment effect at the highest monitors. We will interact $\lambda D_{j,t} M_{j,t} H_{i,t}$ with the once lagged concentration at the monitor. A significant and negative coefficient would suggest that the higher the concentrations are at the dirtiest monitor, the larger the percent reductions.

Models (1) and (2) address the potential impact of regulation on the annual average concentrations. From Table 1 we can clearly tell that many counties, which are not in attainment, had annual average concentrations below the non-attainment concentration. Non-attainment, however, can also be due to violating the hourly standard. Model (3) below explains variation in the share of operating days monitor exceeded the hourly standard:

$$V_{i,t+1}^{j} - V_{i,t}^{j} = \alpha D_{j,t} + \gamma_1 D_{j,t} M_{j,t} + \gamma_2 \left(1 - D_{j,t}\right) M_{j,t} + \lambda D_{j,t} M_{j,t} H_{i,t} + X_{j,t} \beta + P_{i,t} \varphi + \theta_t + \delta_i + \eta_{i,t} \quad (3)$$

Where $V_{i,t}^{j}$ is the number of days in year $t$ for which monitor $i$ in county $j$ exceeded the 24 hour primary standard over the number of days the monitor was active. We would expect the coefficient estimates on regulation to be negative and significant. For this measure, it is not clear a priori at which geographic level of aggregation regulation is going to have a detectable impact on ambient concentrations.

As further robustness checks, we will run models (1) and (2) using the level difference in concentrations as the dependent variable instead of using percentage changes. This specification is more sensitive to outliers, which is why we prefer the percent change specification. In addition, we will explore the removal of California from the sample as well as an alternate definition of the highest monitor.

## 5. RESULTS

Table 3 displays the central estimation results. The entries are the parameter estimates and their estimated robust standard errors (in parentheses). Models (1) and (2) refer to equation (1), while models (3)-(5) refer to equation (2). We remind the reader that the dependent variable is the percent change in $PM_{10}$. Since the coefficients of interest are $\alpha$, $\gamma$ and $\lambda$, the table displays the estimates of these parameters. However, at the bottom, we identify the additional set of controls used in each model. Models (1) - (5) include the weather and income variables linearly. Models (6) - (10) are identical specifications, yet income and weather enter as second order polynomials. This improves the fit of the models significantly. We will therefore restrict our discussion to models (6) - (10).

The key finding from the first two specifications is that, independent of the fact whether one includes lagged ambient $PM_{10}$ levels as covariates, the county non-attainment designation does not explain a statistically significant share of the variation in the percent reductions in $PM_{10}$. This finding is consistent with Greenstone (2004), albeit for a different pollutant and time period.

Once we augment specification (1) by dummies for multiple monitor counties, we obtain a statistically significant and sizeable estimate of the treatment effect for single monitor non-attainment counties. The estimated coefficient can be interpreted as non-attainment designation leading to a 10.9% decrease in ambient concentrations. For multiple monitor non-attainment counties this effect is actually a 2.1% increase in ambient concentrations on average.

The results differ drastically when we allow for differentiated impacts of the regulation on non-attainment counties. Model (9) in table 3 highlights our key findings. Three results stand out: First, unlike models (6)-(7), even after controlling for lagged $PM_{10}$, county non-attainment designation is associated with a decrease in $PM_{10}$ of about 10.5% in non-attainment counties with single monitors.

Second, the estimate of $\gamma$ - the additional effect of the regulation in non-attainment counties with multiple monitors - is positive, suggesting that in response to the regulation, non-attainment counties with multiple monitors reduced $PM_{10}$ by lower amounts that non-attainment counties with single monitors. Indeed, this specification suggests that non-attainment status is associated with an *increase* in $PM_{10}$ in non-attainment counties with multiple monitors of about 2%. By not allowing for the distinction between single and multiple monitor counties, equation (1) fails to identify this effect of the regulation.

Third, the estimate of $\lambda$ - which isolates the behavior of the highest monitor in non-attainment counties with multiple monitors - is negative, suggesting that indeed regulators appear to have targeted dirtier areas in non-attainment counties. Compared with other monitors in non-attainment counties with multiple monitors, the highest monitor experienced a reduction of about 8.1% more in response to the regulation. Compared to attainment counties, our model suggests that non-attainment status is associated with a reduction in $\text{PM}_{10}$ in the highest monitor of about 6.1%. Figure 2 shows the evolution of ambient concentrations for Los Angeles county using the monitors which were active for all years. This figure highlights two important points: First, the monitors do not move together, suggesting that averaging them removes valuable within monitor time series information, which is the source of identification in these models. Second, one can see that the highest monitor at the time of non-attainment designation experienced the largest concentration drops out of all monitors in this county. Model (10), which includes the heterogeneous treatment effect mirrors these findings.

Together these findings reveal the two key limitations of equation (1) and the existing literature. By not allowing for the distinction between single and multiple monitor counties, equation (1) fails to identify the true effect of the regulations because the reduction in single monitor counties is combined with the increase in concentrations in multiple monitor counties. In addition, equation (1) fails to identify the targeting of 'dirtier' areas in non-attainment counties, which can have serious implications for the distributional impacts of environmental policies.

Models (1) - (4) in table 4 show the results from estimating equation (3), which is an attempt to quantify the effects of regulation on the frequency of violations of the 24-hour standard. The findings here are even stronger in favor of our specification. The only two variables which are marginally significant are the highest monitor dummy and interaction term. The non-attainment designation according to these estimation results seems only to slightly decrease the frequency of 24-hour violations only at the highest monitors in multiple monitor counties.

Models (5) - (8) in this table replace the percent change dependent variable with a difference in level concentrations. The results are qualitatively similar. Specification (7) in table 4, which is conceptually equivalent to specification (9) in table 3, suggests that single monitor non-attainment counties experienced a 2.7 microgram decrease in ambient concentrations. The highest monitors in non-attainment counties experience a 4.7 microgram decrease in concentrations, which on average is 5.2 micrograms higher than the other monitors in the same county.

Table 5 shows the results from two additional robustness checks. Models (1)-(4) remove California from the sample, addressing concerns that California's well documented stringent air quality regulations and enforcement are driving these results. The results are almost identical to those in table 3. The highest monitors are estimated to experience a 5.9% decrease in ambient concentrations. Finally, models (5)-(8) show estimation results from changing the definition of highest monitor. Instead of using the monitor with the highest concentration in the non-attainment designation year, we designate the highest monitor definition every year. The findings for single monitor non-attainment counties are very similar to those previously found. What differs here, is that we no longer find evidence of larger decreases at the highest monitor. We interpret this finding as consistent with the idea that air quality managers put in place local programs to decrease emissions, which work at the sites that earned them the original non-attainment designation.

# 6. Conclusions

This study contributes to the literature on the effects of environmental regulations (e.g. Henderson, 1996; Greenstone 2004) by testing whether the decline in $PM_{10}$ concentrations between 1990 and 2005 can be attributed to the 1990 CAAA.

We have conducted our analysis at the monitor level and allowed the regulation to have a differential impact on concentrations measured at the monitoring site depending on the type of county (single vs. multiple monitors) and type of monitor (highest vs. non-highest). In addition to controlling for the standard determinants of criteria pollutants changes, we use a novel weather data set, which allows us to construct weather observations at the pollution monitor location.

Our key finding reveals the importance of spatial disaggregated analysis in order to properly assess the effects of environmental regulations. Two aspects of spatial heterogeneity are crucial: first, the difference between single and multiple monitor counties; second, the heterogeneity in reductions of $PM_{10}$ within multiple monitor counties.

Our results suggest that county level analysis of air quality regulations typically fail to identify the effects of the regulation. In a more disaggregated analysis, the three primary findings are that: (1) the effects of regulations on non-attainment counties with single monitors is to reduce $PM_{10}$ by about 11%; (2) the effects of attainment status in non-attainment counties with multiple monitors is actually to increase the county mean concentrations by about 6%; and (3) non-attainment status is associated with a reduction in $PM_{10}$ in the highest monitor of about 1%.

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Figure 1: Percent Changes in Average Concentrations of $PM_{10}$ for all monitors from 1991-2004

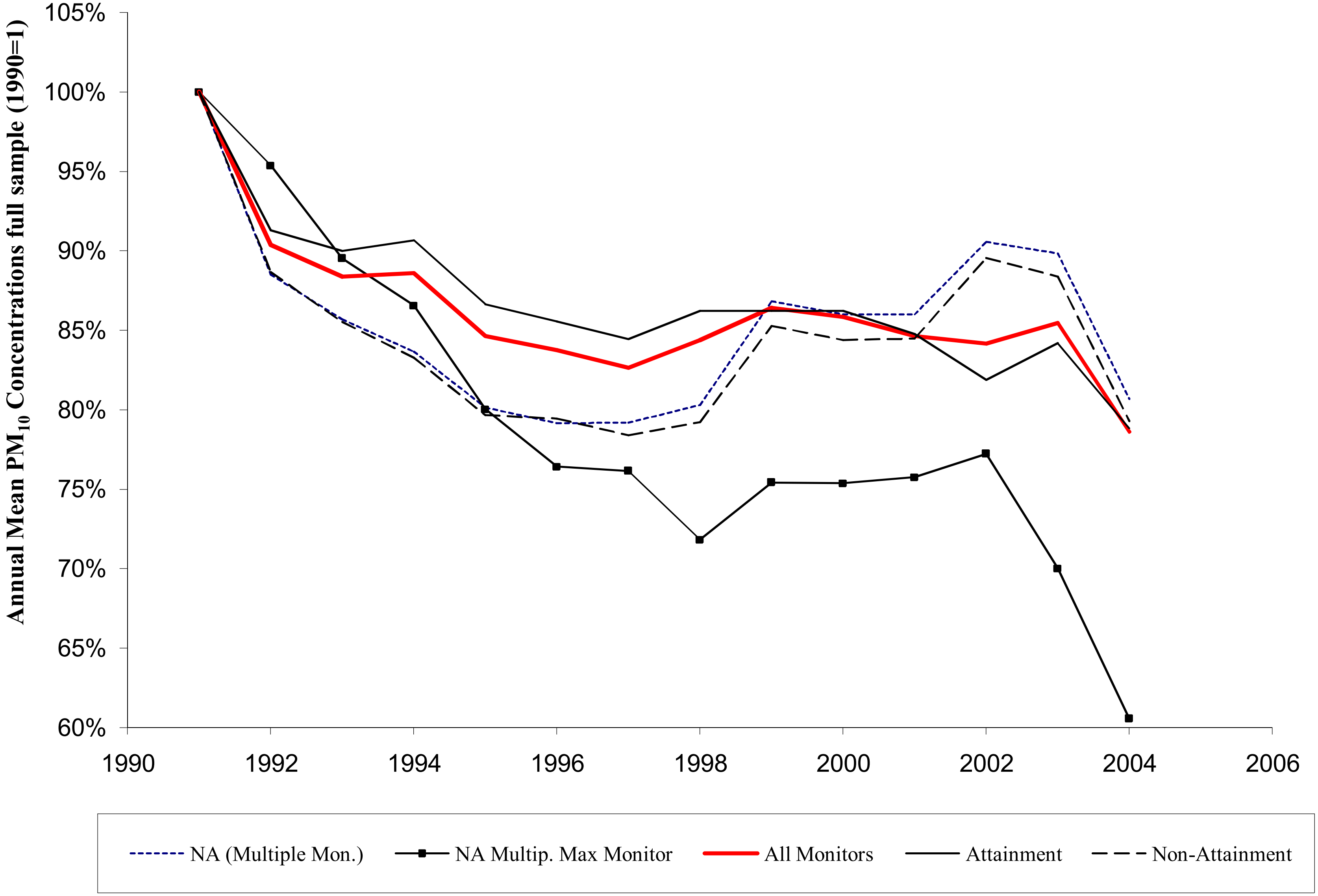

Figure 2: Percent Changes in $PM_{10}$ Concentrations in Los Angeles County for four monitors with annual readings from 1991-2004

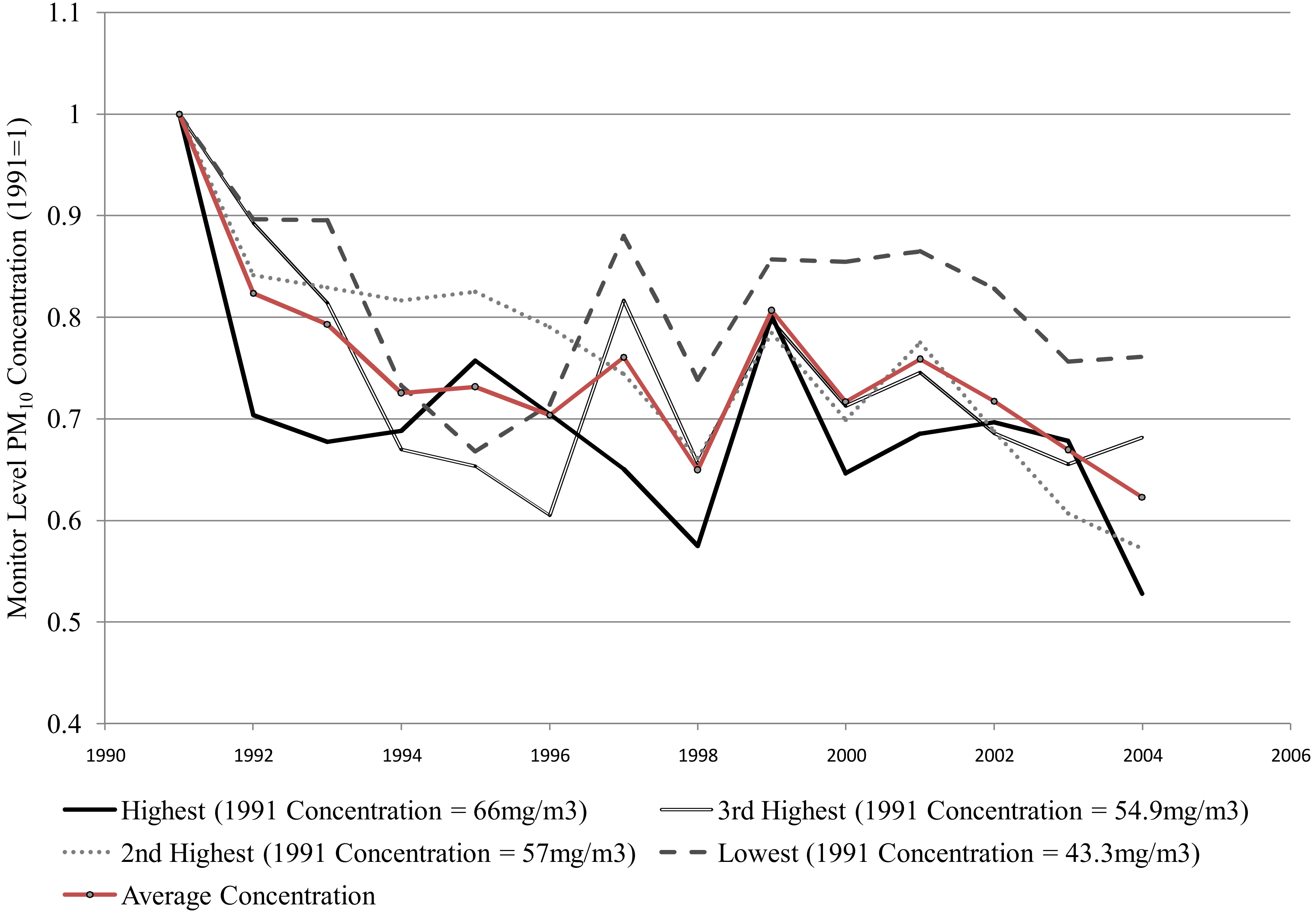

Table 1:Number of counties by attainment status and monitor count for monitors active >75% of the year

| Year | Monitored Counties | Attainment single monitor | | Non-Attainment single monitor | | Attainment multiple monitors | | Non-Attainment multiple monitors | |
|---|---|---|---|---|---|---|---|---|---|
| | Count | Count | Mean # of Monitors | Count | Mean # of Monitors | Count | Mean # of Monitors | Count | Mean # of Monitors |
| 1990 | 0 | | | | | | | | |
| 1991 | 2 | | | 2 | 1 | | | | |
| 1992 | 3 | | | 3 | 1 | | | | |
| 1993 | 10 | 4 | 1 | 4 | 1 | 1 | 2.00 | 1 | 4.00 |
| 1994 | 14 | 7 | 1 | 6 | 1 | | | 1 | 3.00 |
| 1995 | 34 | 18 | 1 | 10 | 1 | 2 | 2.00 | 4 | 3.50 |
| 1996 | 44 | 27 | 1 | 10 | 1 | 2 | 2.00 | 5 | 4.00 |
| 1997 | 49 | 36 | 1 | 6 | 1 | 1 | 2.00 | 6 | 5.00 |
| 1998 | 44 | 29 | 1 | 8 | 1 | 2 | 2.00 | 5 | 4.20 |
| 1999 | 47 | 30 | 1 | 12 | 1 | 2 | 2.00 | 3 | 5.00 |
| 2000 | 51 | 28 | 1 | 16 | 1 | 4 | 2.50 | 3 | 5.00 |
| 2001 | 57 | 35 | 1 | 13 | 1 | 6 | 2.33 | 3 | 4.67 |
| 2002 | 91 | 63 | 1 | 14 | 1 | 9 | 2.22 | 5 | 3.80 |
| 2003 | 96 | 66 | 1 | 13 | 1 | 11 | 2.36 | 6 | 3.33 |
| 2004 | 95 | 64 | 1 | 11 | 1 | 14 | 3.00 | 6 | 2.17 |
| Total County Years | 637 | 407 | | 128 | | 54 | | 48 | |
| Total Monitor Years | 855 | | 407 | | 128 | | 132 | | 188 |

Table 2: Mean Ambient Concentration of $PM_{10}$ ($\mu g/m^3$) by County Type (All Monitors)

| | Single Monitor | | Multiple Monitors | | | |
|---|---|---|---|---|---|---|
| | Attainment | Non-Attainment | Attainment | | Non-Attainment | |
| | Mean Monitor | Mean Monitor | Mean Monitor | Highest Monitor | Mean Monitor | Highest Monitor |
| 1991 | 27.29 | 38.19 | 26.46 | 30.85 | 35.30 | 40.95 |
| 1992 | 24.96 | 33.27 | 24.16 | 27.48 | 31.24 | 39.05 |
| 1993 | 23.84 | 33.15 | 23.99 | 26.47 | 30.25 | 36.66 |
| 1994 | 23.56 | 29.88 | 24.47 | 27.12 | 29.53 | 35.44 |
| 1995 | 23.02 | 27.30 | 23.04 | 25.96 | 28.29 | 32.77 |
| 1996 | 22.21 | 26.25 | 22.74 | 24.91 | 27.95 | 31.29 |
| 1997 | 21.96 | 25.09 | 22.75 | 25.50 | 27.95 | 31.18 |
| 1998 | 22.32 | 24.63 | 23.26 | 25.98 | 28.34 | 29.41 |
| 1999 | 21.81 | 26.72 | 23.65 | 26.46 | 30.65 | 30.88 |
| 2000 | 21.69 | 25.99 | 23.69 | 25.97 | 30.36 | 30.86 |
| 2001 | 21.23 | 26.05 | 23.44 | 25.60 | 30.35 | 31.02 |
| 2002 | 20.52 | 27.94 | 22.61 | 24.02 | 31.97 | 31.62 |
| 2003 | 20.86 | 25.44 | 23.32 | 24.51 | 31.71 | 28.67 |
| 2004 | 19.44 | 24.94 | 21.98 | 23.70 | 28.48 | 24.79 |

Table 3: Fixed Effects Estimation Results - Linear and Non-linear Weather and Income Specifications

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Dependent Variable | % Change | % Change | % Change | % Change | % Change | % Change | % Change | % Change | % Change | % Change |
| Attainment $PM_{10}$ | -0.014 | -0.045 | -0.081 | -0.076 | -0.075 | -0.026 | -0.050 | -0.109 | -0.105 | -0.105 |
| | (0.74) | (1.67)* | (2.18)** | (2.05)** | (2.04)** | (1.43) | (1.59) | (2.52)** | (2.46)** | (2.46)** |
| Multiple Non-Attainment | | | 0.097 | 0.091 | 0.089 | | | 0.130 | 0.125 | 0.124 |
| | | | (3.34)*** | (3.13)*** | (3.02)*** | | | (4.23)*** | (3.92)*** | (3.86)*** |
| Multiple Attainment | | | 0.035 | 0.033 | 0.033 | | | 0.023 | 0.022 | 0.022 |
| | | | (1.65) | (1.55) | (1.56) | | | (1.25) | (1.19) | (1.19) |
| Lagged Dummy | | | | -0.120 | | | | | -0.081 | |
| Maximum Monitor (Multiple/NA) | | | | (5.93)*** | | | | | (3.28)*** | |
| Lagged Concentration | | | | | -0.003 | | | | | -0.002 |
| Maximum Monitor (Multiple/NA) | | | | | (5.91)*** | | | | | (3.24)*** |
| Observation | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor |
| Monitor/Year FEs | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Lagged $PM_{10}$ Concentrations | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Other Attainment Status | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| County Income | Linear | Linear | Linear | Linear | Linear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear |
| Weather | Linear | Linear | Linear | Linear | Linear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear |
| California | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Maximum Monitor Definition | Initial | Initial | Initial | Initial | Initial | Initial | Initial | Initial | Initial | Initial |
| Observations | 855 | 855 | 855 | 855 | 855 | 855 | 855 | 855 | 855 | 855 |
| Number of Groups | 214 | 214 | 214 | 214 | 214 | 214 | 214 | 214 | 214 | 214 |
| R-squared | 0.08 | 0.38 | 0.39 | 0.40 | 0.40 | 0.16 | 0.44 | 0.46 | 0.46 | 0.46 |

Table 4: Fixed Effects Estimation Results - Percent Change in Daily Violations / Differences in Levels

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| Dependent Variable | Δ Daily Violations | Δ Daily Violations | Δ Daily Violations | Δ Daily Violations | Difference (μg/m3) | Difference (μg/m3) | Difference (μg/m3) | Difference (μg/m3) |
| Attainment $PM_{10}$ | 0.021 | 0.037 | 0.059 | 0.073 | -1.383 | -2.879 | -2.677 | -2.558 |
| | (0.38) | (0.50) | (0.95) | (1.21) | (1.49) | (2.21)** | (2.12)** | (2.08)** |
| Multiple Non-Attainment | | 0.004 | -0.039 | -0.067 | | 3.506 | 3.157 | 2.956 |
| | | (0.05) | (0.68) | (1.12) | | (4.13)*** | (3.67)*** | (3.33)*** |
| Multiple Attainment | | 0.041 | 0.031 | 0.025 | | 0.832 | 0.758 | 0.734 |
| | | (0.42) | (0.31) | (0.25) | | (1.32) | (1.22) | (1.19) |
| Lagged Dummy Maximum Monitor (Multiple/NA) | | | -0.76 | | | | -5.179 | |
| | | | (1.47) | | | | (2.82)*** | |
| Lagged Concentration Maximum Monitor (Multiple/NA) | | | | -0.026 | | | | -0.155 |
| | | | | (2.00)** | | | | (3.96)*** |
| | | | | | | | | |
| Observation | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor |
| Monitor/Year FEs | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Lagged $PM_{10}$ Concentrations | No | No | No | No | Yes | Yes | Yes | Yes |
| Other Attainment Status | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| County Income | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear |
| Weather | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear |
| California | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Maximum Monitor Definition | Initial | Initial | Initial | Initial | Initial | Initial | Initial | Initial |
| Observations | 855 | 855 | 855 | 855 | 855 | 855 | 855 | 855 |
| Number of Groups | 214 | 214 | 214 | 214 | 214 | 214 | 214 | 214 |
| R-squared | 0.05 | 0.05 | 0.08 | 0.11 | 0.49 | 0.50 | 0.52 | 0.53 |

Table 5: Fixed Effects Estimation Results - Robustness Checks (Without California / Alternate Highest Monitor Definition)

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| Dependent Variable | % Change | % Change | % Change | % Change | % Change | % Change | % Change | % Change |
| Attainment $PM_{10}$ | -0.045 | -0.089 | -0.087 | -0.086 | -0.05 | -0.109 | -0.108 | -0.106 |
| | (1.72)* | (2.33)** | (2.30)** | (2.29)** | (1.59) | (2.52)** | (2.51)** | (2.49)** |
| Multiple Non-Attainment | | 0.108 | 0.106 | 0.105 | | 0.13 | 0.129 | 0.128 |
| | | (3.21)*** | (3.12)*** | (3.08)*** | | (4.23)*** | (4.16)*** | (4.04)*** |
| Multiple Attainment | | 0.023 | 0.022 | 0.022 | | 0.023 | 0.023 | 0.022 |
| | | (1.32) | (1.31) | (1.32) | | (1.25) | (1.24) | (1.22) |
| Lagged Dummy Maximum Monitor (Multiple/NA) | | | -0.078 | | | | -0.02 | |
| | | | (3.18)*** | | | | (0.89) | |
| Lagged Concentration Maximum Monitor (Multiple/NA) | | | | -0.002 | | | | -0.001 |
| | | | | (3.76)*** | | | | (1.61) |
| | | | | | | | | |
| Observation | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor | Monitor |
| Monitor/Year FEs | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Lagged $PM_{10}$ Concentrations | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Other Attainment Status | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| County Income | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear |
| Weather | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear | Nonlinear |
| California | No | No | No | No | Yes | Yes | Yes | Yes |
| Maximum Monitor Definition | Initial | Initial | Initial | Initial | Yearly | Yearly | Yearly | Yearly |
| Observations | 736 | 736 | 736 | 736 | 855 | 855 | 855 | 855 |
| Number of Groups | 182 | 182 | 182 | 182 | 214 | 214 | 214 | 214 |
| R-squared | 0.40 | 0.41 | 0.42 | 0.42 | 0.44 | 0.46 | 0.46 | 0.46 |

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